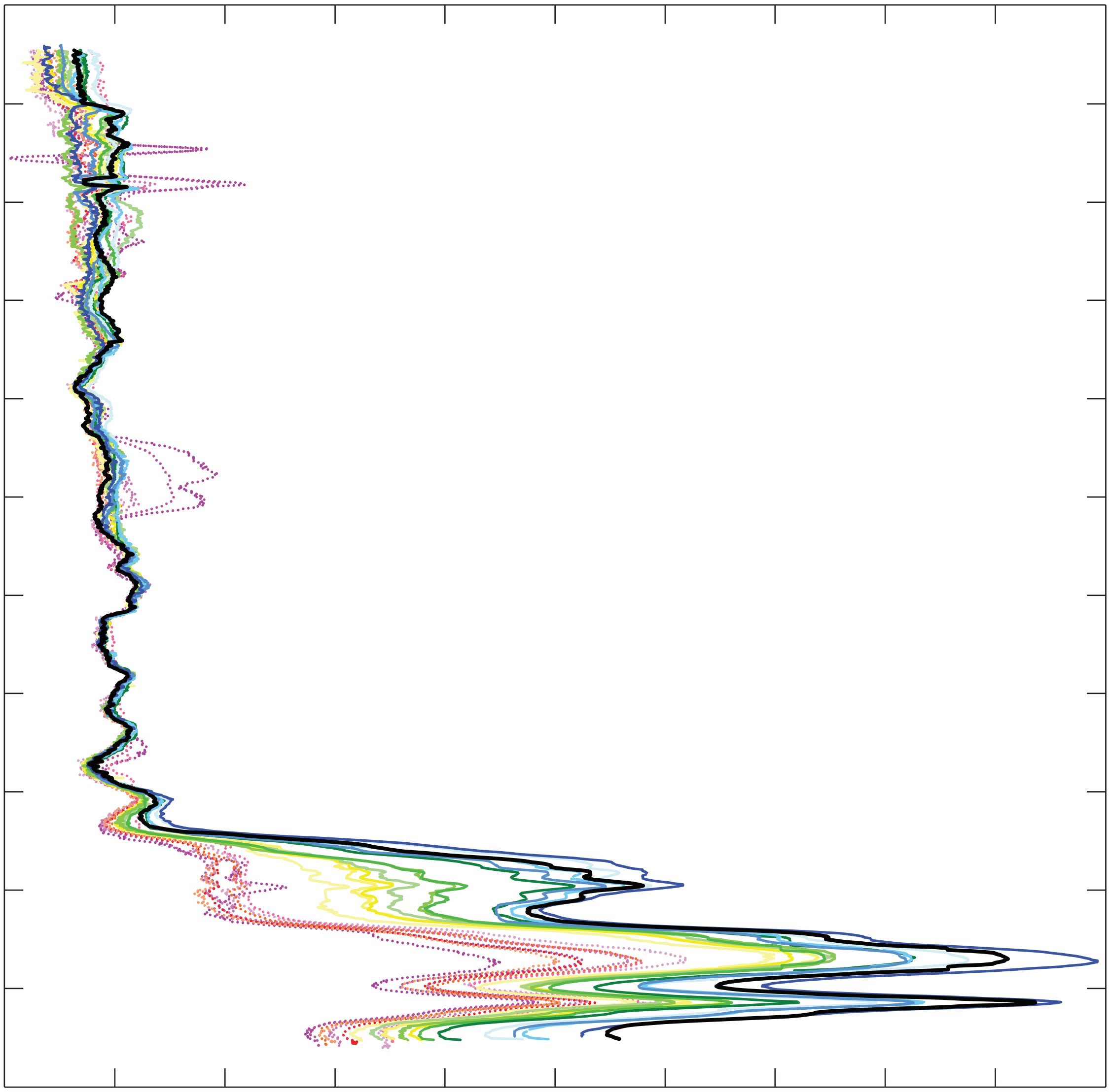
Collection, Processing, and Quality Assurance of Time-Series Electromagnetic-Induction Log Datasets, 1995–2016, South Florida



Open-File Report 2016–1194

U.S. Department of the Interior
U.S. Geological Survey

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By Scott T. Prinos and Robert Valderrama

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Contents

Figures

Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)

Multiply	By	To obtain
	Electrical conductivity	
siemens per meter (S/m)	1,000	millisiemens per meter (mS/m)
siemens per meter (S/m)	10,000	microsiemens per centimeter (µS/cm)

Electrical conductivity σ in millisiemens per meter [mS/m] can be converted to electrical resistivity ρ in ohm-meters [ohm m] as follows: $\rho = 1{,}000/\sigma$.

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Supplemental Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

bls	below land surface
cps	counts per second
EMI	electromagnetic induction
kHz	kilohertz
PVC	polyvinyl chloride
RMSE	root mean squared error
TSEMIL	time-series electromagnetic-induction log (dataset)
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

Time-series electromagnetic-induction log (TSEMIL) datasets are collected from polyvinyl-chloride cased or uncased monitoring wells to evaluate changes in water conductivity over time. TSEMIL datasets consist of a series of individual electromagnetic-induction logs, generally collected at a frequency of once per month or once per year that have been compiled into a dataset by eliminating small uniform offsets in bulk conductivity between logs probably caused by minor variations in calibration. These offsets are removed by selecting a depth at which no changes are apparent from year to year, and by adjusting individual logs to the median of all logs at the selected depth. Generally, the selected depths are within the freshwater saturated part of the aquifer, well below the water table. TSEMIL datasets can be used to monitor changes in water conductivity throughout the full thickness of an aquifer, without the need for long open-interval wells which have, in some instances, allowed vertical water flow within the well bore that has biased water conductivity profiles. The TSEMIL dataset compilation process enhances the ability to identify small differences between logs that were otherwise obscured by the offsets. As a result of TSEMIL dataset compilation, the root mean squared error of the linear regression between bulk conductivity of the electromagnetic-induction log measurements and the chloride concentration of water samples decreased from 17.4 to 1.7 millisiemens per meter in well G–3611 and from 3.7 to 2.2 millisiemens per meter in well G–3609. The primary use of the TSEMIL datasets in south Florida is to detect temporal changes in bulk conductivity associated with saltwater intrusion in the aquifer; however, other commonly observed changes include (1) variations in bulk conductivity near the water table where water saturation of pore spaces might vary and water temperature might be more variable, and (2) dissipation of conductive water in high-porosity rock layers, which might have entered these layers during drilling. Although TSEMIL dataset processing of even a few logs improves evaluations of the differences between the logs that are related to changes in the salinity, about 16 logs are needed to estimate the bulk conductivity within ±2 millisiemens per meter. Unlike many other types of data published by the U.S. Geological Survey, the median of TSEMIL datasets should not be considered final until 16 logs are collected and the median of the dataset is stable.

Introduction

This report describes the procedures for the collection, processing, and quality assurance of time-series electromagnetic-induction log (TSEMIL) datasets for monitoring saltwater intrusion. Much of the information included in this report is copied from Prinos and Valderrama (2015), Prinos and others (2014), and Prinos and others (2005), but this report summarizes the most current procedures for these datasets and the reasons for the procedures selected.

Saltwater has intruded many coastal aquifers, including those in southern Florida (fig. 1). The U.S. Environmental Protection Agency secondary standard for chloride in drinking water is 250 milligrams per liter (mg/L) or less (U.S. Environmental Protection Agency, 2014), whereas seawater generally has a chloride concentration of about 19,000 mg/L (Stumm and Morgan, 1981); therefore, a relatively small fraction of seawater can render the water in the intruded part of the aquifer nonpotable. Saltwater intrusion monitoring is typically conducted by collecting water samples from wells to determine the salinity of the water in the aquifer. Geophysical methods can augment this monitoring by providing information where there are no wells or by adding information about the distribution of saltwater in the aquifer, above or below the screened intervals of existing wells.

Beginning in 1995, electromagnetic induction (EMI) logs collected from polyvinyl chloride (PVC) cased or uncased monitoring wells were used by the U.S. Geological Survey to evaluate changes in water conductivity over time in the aquifers of south Florida (fig. 1). The EMI logs are collected using a geophysical logging tool called a “probe” that is lowered into a monitoring well. The probe includes a transmitter coil and a receiver coil. The transmitter coil emits an alternating electromagnetic signal that induces a primary electromagnetic field in the formation surrounding the well, which in turn

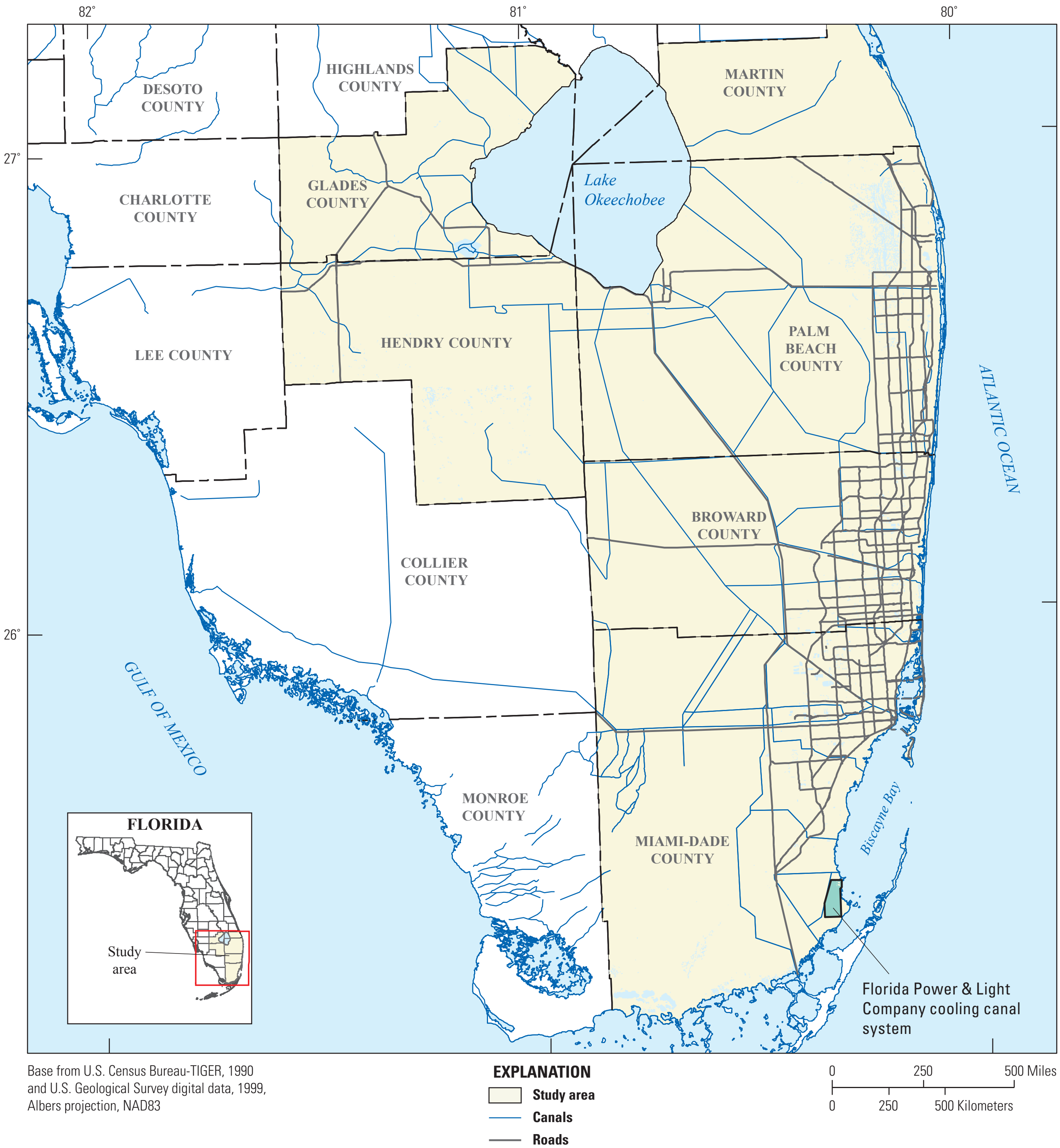


Figure 1. Location of the study area in southern Florida.

produces a secondary electromagnetic field that is measured by the probe receiver coil (Taylor and others, 1989). The strength of the secondary electromagnetic field is proportional to the bulk electrical conductivity (henceforth referred to as “bulk conductivity”) of the formation. The EMI probe measures the bulk conductivity within an approximately 8- to 40-inch (in.) doughnut-shaped area from the center of the probe (McNeill and others, 1990).

A TSEMIL dataset is a compilation of individual electromagnetic-induction (EMI) logs that have been collected annually, semiannually, bimonthly, or monthly from a monitoring well and processed to eliminate minor uniform offsets, likely caused by variations in calibration. This processing improves the ability to detect relatively minor changes in the bulk conductivity of the aquifer through time. Because the porosity and lithology of materials adjacent to the well do not change appreciably through time, these TSEMIL datasets can be used to assess increases or decreases in the water conductivity through time that are caused by changes in water salinity resulting from movement of the saltwater interface.

The U.S. Geological Survey (USGS) produced TSEMIL datasets or updated existing TSEMIL datasets through the collection, processing, and compilation of EMI logs. These TSEMIL datasets are published in USGS data releases on an ongoing basis (U.S. Geological Survey, var. dated b).

Purpose and Scope

The purpose of this report is to describe the procedures used to collect, process, and quality assure TSEMIL datasets used to monitor saltwater intrusion, including documentation of the methods used to (1) calibrate EMI logging equipment, (2) collect and correct EMI logs, (3) process EMI logs into TSEMIL datasets, and (4) quality assure TSEMIL datasets. This report includes a discussion of the accuracy of TSEMIL datasets and presents comparisons of the bulk conductivity of adjusted EMI logs and the corresponding chloride concentrations collected at about the same depth.

Description of Study Area

The study area (fig. 1) is primarily the southeastern part of Florida including Broward, Glades, Hendry, Martin, Miami-Dade, and Palm Beach Counties. This area is relatively flat and poorly drained. The monitoring wells described in this report are near the east coast, where saltwater from the ocean has intruded or might intrude the surficial aquifer, and near Lake Okeechobee (fig. 2), where saltwater is in the shallow aquifer.

The wet and dry tropical climate of south Florida is created by a combination of its latitude and proximity to the Atlantic Ocean and the Gulf of Mexico (fig. 1; Hagemeyer, 2012). A wet season occurring from May through September is typified by afternoon thunderstorms that produce relatively heavy rainfall that is augmented by rainfall from tropical storms and hurricanes. A dry season occurring from October to April is created by low sea-surface temperatures, low humidity, and decreased solar radiation, which greatly reduce the occurrence of afternoon thunderstorms. Water levels in the aquifers are typically highest in late September and early October and lowest in April or May (Prinos and others, 2014). Annual EMI logs are usually collected in April or early May when water levels are low and the potential for saltwater intrusion is high.

Hydrogeologic Setting

EMI logs have been collected from monitoring wells in the Biscayne aquifer in Miami-Dade and southern Broward Counties and the surficial aquifer system in northern Broward, Glades, Hendry, Martin, and Palm Beach Counties (figs. 2 and 3); in southern Broward and Miami-Dade Counties, the Biscayne aquifer is the uppermost part of the surficial aquifer system. The Biscayne aquifer is the principal source of water supply for the residents of Miami-Dade and Broward Counties and has been designated as a sole source aquifer (Federal Register Notice, 1979). Near the coast, saltwater from the ocean has intruded the Biscayne aquifer and surficial aquifer system. This saltwater began to intrude into the aquifers of south Florida early in the 20th Century when canals were installed to drain freshwater marshes (Prinos and others, 2014).

Near the eastern and southern edge of Lake Okeechobee in Glades, Hendry, Martin, and western Palm Beach Counties, saltwater is present beginning at depths of 30 to 120 feet (ft) below land surface (bls). The ratios of strontium-87 to strontium-86 in water samples indicate that the saltwater is probably residual intruded or relict seawater (Reese and Wacker, 2009). To reduce the risk of failure of a dike surrounding Lake Okeechobee, the U.S. Army Corps of Engineers (USACE) began a project in 2007 to install a seepage barrier (or cut-off wall) to prevent water from seeping through or immediately under the dike (U.S. Army Corps of Engineers, 2013). The seepage barrier is a wall of grout that diverts the flow of water below the dike into the surficial aquifer system and immediately beneath it, which prevents internal erosion of the dike by piping; however, in some places, the flow has been diverted into the residual saltwater in the aquifer. The monitoring wells near Lake Okeechobee were designed to detect any changes in salinity or movements of the saltwater interface resulting from this diversion of flow (Prinos and Valderrama, 2015).

Previous Studies

The USGS began collecting EMI logs for routine monitoring of saltwater intrusion in Miami-Dade and Broward Counties in 1995. Since its inception, this logging program has expanded to additional locations in south Florida. EMI logging techniques and the induction logging tool are described in ASTM International (2007), McNeill and others (1990), and Mount Sopris Instrument Co., Inc. (2002).

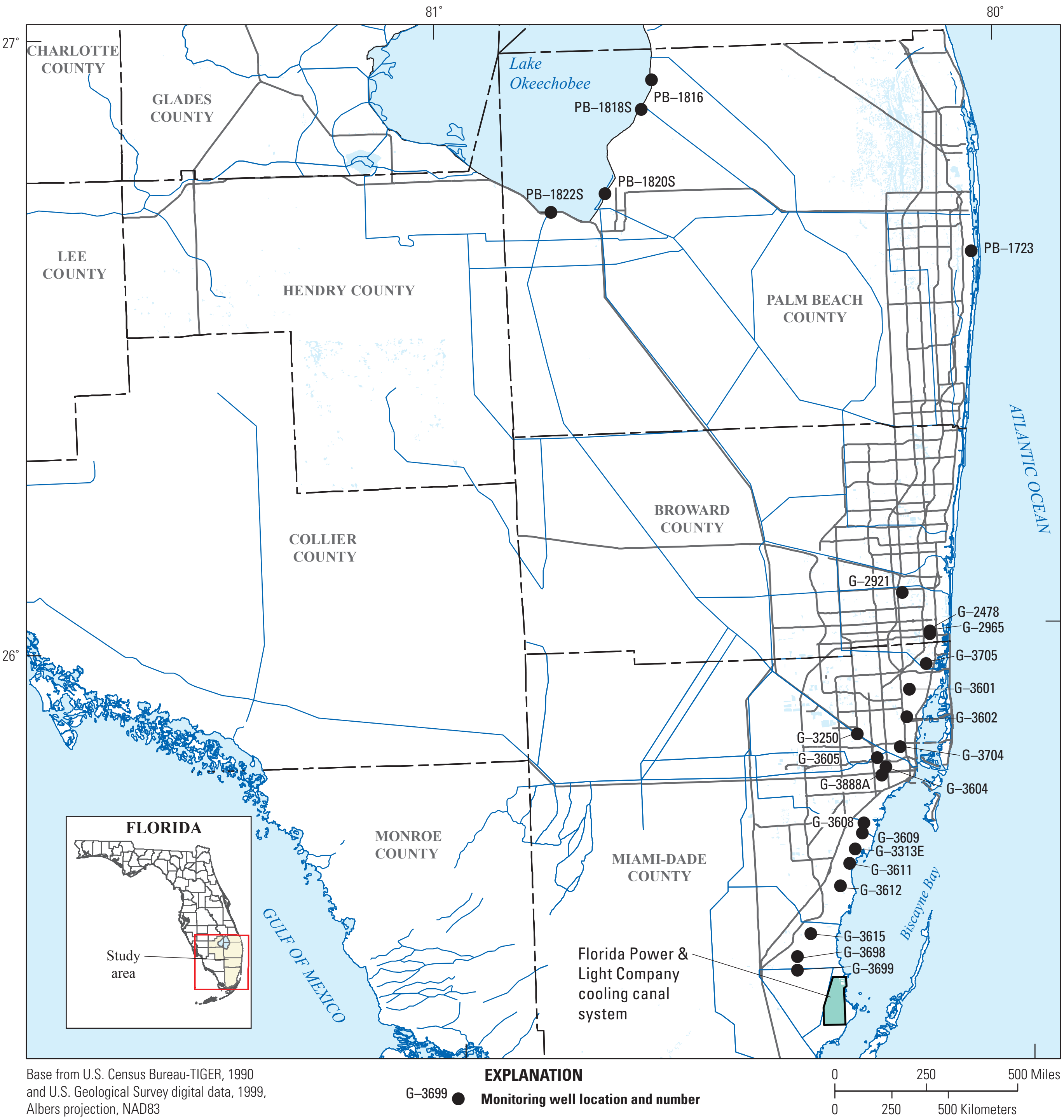
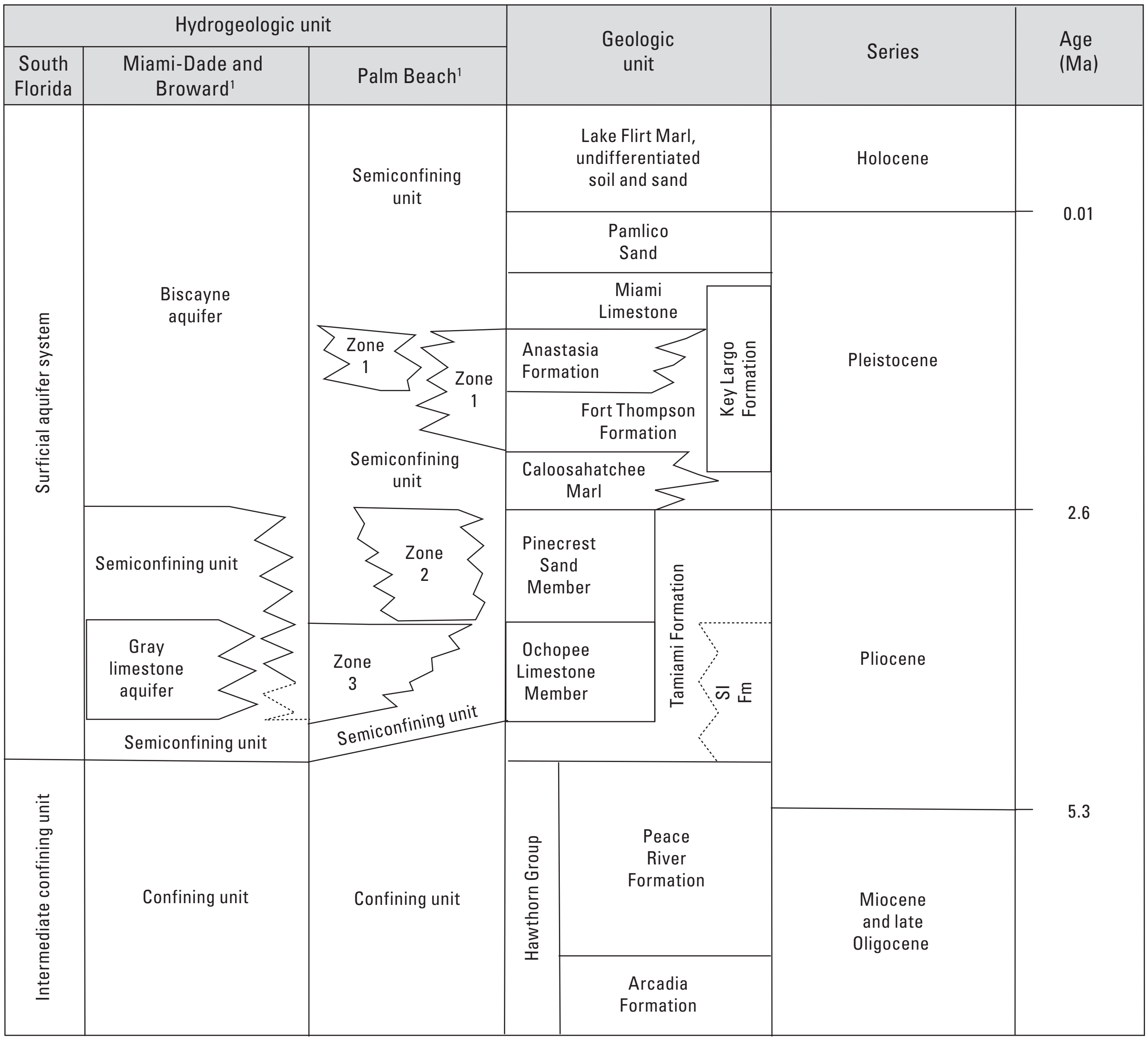


Figure 2. Locations of selected monitoring wells in the study area. This map does not include all sites where electromagnetic-induction logs are collected, but only those wells specifically named in this report.



[1]Reese and Wacker (2009) designated three permeable zones that were mapped in Palm Beach County and a short distance into northern Broward County.

Figure 3. Generalized hydrostratigraphic framework of the surficial aquifer system in Broward, Miami-Dade, and Palm Beach Counties, Florida. Modified from Prinos and others (2014) and Reese and Wacker (2009). Permeable zones and semiconfining and confining units designated by Reese and Wacker (2009). [SI Fm, Stock Island Formation]

EMI logs collected between 1995 and 2012 were published in volume 2B of the annual Water Resources Data Reports for Florida or on the Annual Water Data Reports Web page (Prinos and others, 2001, 2002, 2003, 2004, 2005, and 2006; U.S. Geological Survey, var. dated a). Annual water data reports generally refer to a water year, which is defined as the 12-month period from October 1 of a given year through September 30 of the following year. The water year is designated by the calendar year in which it ends. Unless a full date is specified, years referenced in this report always refer to water years.

The collected EMI logs have always been published as datasets showing the logs collected from a given well; however, the measured bulk conductivities of individual logs were not adjusted as described in this report until the 2009 publication. Between 2001 and 2008, the datasets were published as graphs that included a black line representing the most recent log in the dataset and a gray shaded area that indicated the range in measured bulk conductivity with depth for previous logs in the dataset (fig. 4). The logs published in 2008 (including logs collected up until 2007) also included a blue line representing the log of the previous year (2006). Beginning with the 2009 annual water data report, each log in the dataset was shown using a different color (fig. 5), and most of the methods described in this report were used to process the TSEMIL datasets. Given the number of logs being collected, it will become necessary to omit some of the older logs from the graphs by including only a representative subset of previously collected and published logs. A brief description of TSEMIL datasets is provided in a Web page linked to each of the published logs (U.S. Geological Survey, 2009).

Fitterman and Prinos (2011) used TSEMIL datasets to describe temporal changes in water conductivity at two sites in Miami-Dade County and compared EMI logs to proximal time-domain electromagnetic soundings collected concurrently. Prinos and others (2014) provided a detailed description of the process used to create TSEMIL datasets and used these datasets to evaluate changes in water conductivity in Miami-Dade County. The report compared the changes in chloride concentration of water samples to the changes in bulk conductivity evident in the TSEMIL datasets at or near the same depth as the open interval of a given well. Prinos and Valderrama (2015) used TSEMIL datasets to evaluate changes in the saltwater interface near Lake Okeechobee resulting from the installation of a seepage barrier and compared these datasets to results from water samples collected from proximal long-screened interval wells at depth intervals of about 5 to 10 ft using straddle packers to isolate each sampling interval.

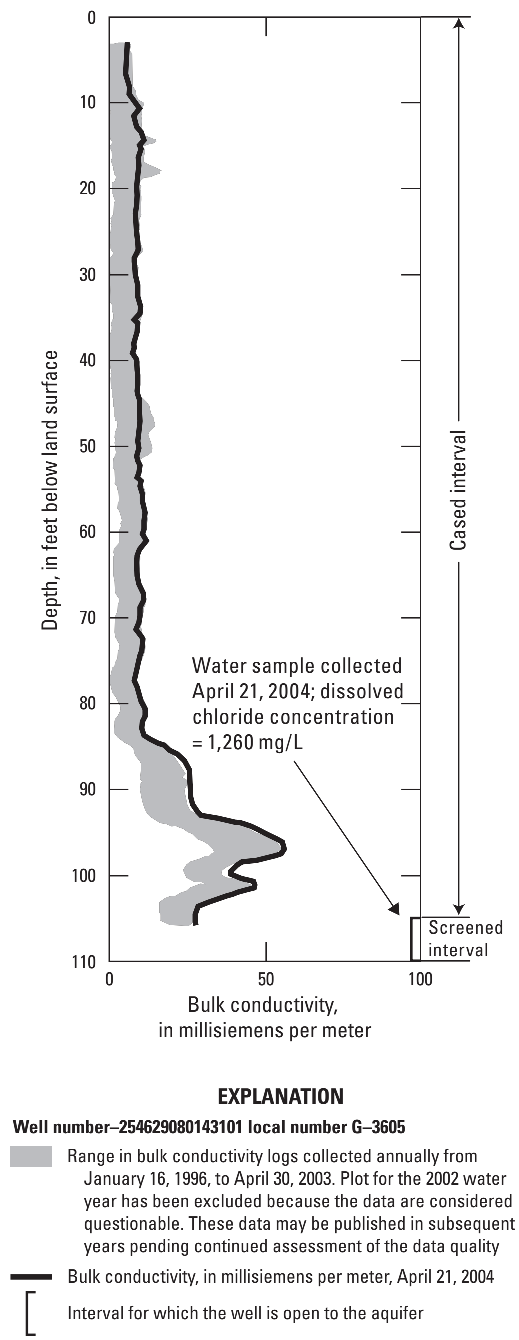


Figure 4. Example of the type of graph published between 2001 and 2008 to show electromagnetic-induction logs collected in south Florida. Graph shows the logs collected between January 16, 1996, and April 21, 2004, from well G–3605. Modified from Prinos and others (2005). Location of well shown in figure 2.

Electromagnetic Induction Logging

Individual EMI logs are collected by lowering an EMI probe into a monitoring well. As the EMI probe passes through different layers of rock or sediment outside of a well, the different physical and chemical properties of each layer will result in variations in the recorded bulk conductivity

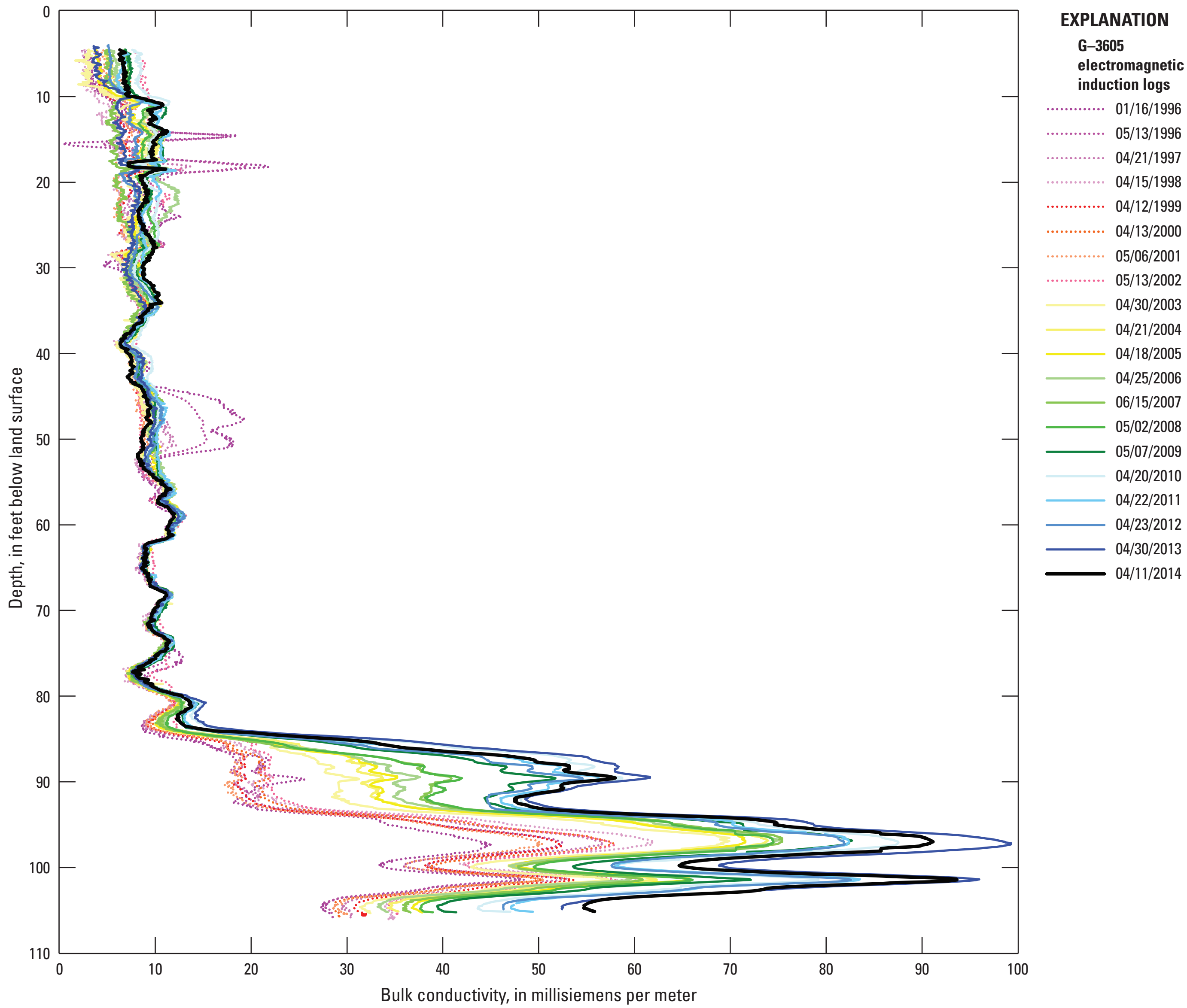


Figure 5. Example of the type of graph currently being published to show time-series electromagnetic-induction log datasets collected in south Florida. Graph shows the logs collected between January 16, 1996, and April 11, 2014, from well G–3605. Location of well shown in figure 2.

values. The EMI tool used provides appreciable sensitivity extending about 39 in. from the well axis (McNeil and others, 1990). PVC casings do not interfere with EMI measurements. Collection of these logs in cased wells allows for monitoring of water conductivity in the aquifer throughout its full thickness, without the potential for vertical water flow within the well bore that can bias water conductivity profiles in some instances (Johnson and others, 2002; Shapiro, 2002; Oki and Presley, 2008; Runkel and others, 2008; Shalev and others, 2009; Prinos and Valderrama, 2015).

Measurements of bulk conductivity are affected by the physical and chemical properties of an aquifer, including the dissolved-solids concentration of the pore water and the lithology and porosity of the rock. Sand or sandstone will generally produce lower bulk conductivity values than clay or mudstone. Although the properties of the geologic strata adjacent to a well will remain relatively constant from log to log, those of the pore water might change because of saltwater intrusion.

Fitterman and Prinos (2011) and Fitterman (2014) established relations between bulk conductivity from EMI logs and chloride concentrations of water samples collected in the Biscayne aquifer of Miami-Dade County, Florida, on the basis of 17 and 35 comparisons respectively. Using these data, formation factors of 5.1 and 5.5 were established for eastern Miami-Dade County and Everglades wells, respectively (Fitterman, 2014). A formation factor is the ratio of the resistivity of rock that is 100 percent water saturated to the resistivity of the water with which it is saturated (Archie, 1942).

Given these formation factors and the relation between chloride concentration and water resistivity (fig. 6*A*), parts of the aquifer containing water having about 1,000 mg/L of chloride would have bulk resistivity values of about 14 to 15 ohm-meters (ohm m; fig. 6*B*), equivalent to bulk conductivity values of about 65 to 70 millisiemens per meter (mS/m).

A more comprehensive analysis using all available data from the wells that were logged and sampled in the Biscayne aquifer, and surficial aquifer system within the study area (fig. 1), indicated a range in the formation factor of about 1.5 to 13 and that parts of the aquifers containing water with 1,000 mg/L of chloride could have bulk resistivity values ranging from about 4 to 36 ohm m (equivalent to bulk conductivities of about 30 to 250 mS/m) (fig. 6*A*–*B*). This analysis was based on 728 comparisons of formation and water resistivity. Of these comparisons some were selected to show changes in water resistivity and bulk resistivity where seawater is intruding, and to indicate the wells from which the data emanated (fig. 6*B*). Data from some of these wells corresponded to formation factors of about 5 to 6, including wells from both aquifers and several counties (fig. 6*B*, wells G–2965, G–3601, G–3608, G–3704, PB–1723, PB–1816, and PB–1818S). Data from many of the wells indicated other formation factors (fig. 6*B*, wells G–3602, G–3605, and G–3609), and the data from some wells did not appear to correspond to any specific formation factor (fig. 6*B*, wells G–2478 and G–3250).

Most of the wells used for these analyses were screened at the bottom of the well. In these wells, the tip of the probe tended to reach the bottom of the well before a full response could be recorded for the full screened interval. New wells installed as part of the project documented in Prinos and others (2014) and in the years after this project were generally designed with sumps below the screens that allowed recording of a full response within the screened interval of the well. This new design may help improve determinations of formation factors.

Logging Equipment

Currently (2016), a Mount Sopris 2PIA–1000 EM39 induction probe, a 4305–1000–120 mini winch, and a 5MXA–1000–120 Matrix logging console operated using Matrix logging software are used to collect EMI logs; the equipment and software are described in Mount Sopris Instrument Co., Inc. (2002). Prinos and others (2014) describe the changes in induction logging systems and software used for collection of the logs during 1995–2014. Although different probes have been used to collect the EMI logs described in this report, all of the probes that have been used were "based on the Geonics EM–39 slimline induction tool" (Mount Sopris Instrument Co., Inc., 2002). The EM39 unit has three conductivity ranges to select from: 0 to 100 mS/m, 0 to 1,000 mS/m, and 0 to 10,000 mS/m. An internal jumper within the probe can be positioned to allow the selection of two of these three conductivity ranges from the surface through the probe's control box (Mount Sopris Instrument Co., Inc., 2002).

The probe has a small transmitter coil, a single centrally located focusing coil, and a receiver coil (McNeil and others, 1990). The transmitter coil emits a continuous-wave, 39.2-kilohertz (kHz) electromagnetic signal, which produces a primary field in the formation surrounding the borehole, and a secondary field that is sensed by the receiver coil (Taylor and others, 1989). The spacing between the transmitter coil and the receiver coil is 19.7 in. (McNeil and others, 1990; Mount Sopris Instrument Co. Inc., 2002). McNeil and others (1990) determined that this intercoil spacing combined with the focusing coil results in appreciable sensitivity in a donut-shaped area extending 7.9 to 39 in. from the well axis, and minimum sensitivity to the fluid inside the well bore (fig. 7). Mount Sopris Instrument Co. Inc. (2002) denotes an 11-in. radius of maximum sensitivity and a 3.9-in. radius of minimum sensitivity. Because most of the wells logged during this project had a diameter of 2 in., electrical conductivity of the fluid in these boreholes should not have affected the logs. Design of monitoring wells used for TSEMIL dataset collection is described by Prinos and others (2014). If caliper or borehole image logs collected prior to well installation indicate large cavities or highly porous rock layers, these layers can be filled with sand or pea gravel to prevent filling of void spaces by cement or grout from the annular seal. Seals like those installed above the filter pack can be installed. Centralizers can be used to keep the well centered in the borehole; however, metal screws or centralizers should not be used, because metal interferes with EMI logging.

The vertical resolution of the tool is defined as the "vertical distance where the response is more than half the maximum response to an infinitely thin bed," which is 2.1 ft for the probe that was used (McNeill, 1986; Mount Sopris Instrument Co., Inc., 2002). The measurement resolution, repeatability, and accuracy are reported by the manufacturer as 0.02, 2, and 5 percent of full scale, respectively (Mount Sopris Instrument Co., Inc., 2002). Over the full scale of 1,000 mS/m, an individual log repeatability is about ±20 mS/m for temperature changes less than 10 degrees Celsius, and the accuracy of an individual log is about ±50 mS/m; however, the time series of logs described in this report generally indicate much better accuracy.

Calibration of Equipment and Data Collection Procedures

Data collection steps include calibration of the EMI probe, collection of the EMI log, and collection of a chloride sample. During logging, the Matrix logging software records the depth of the probe and a corresponding probe reading in counts per second (cps), which is automatically converted to bulk conductivity through a linear relationship determined by a two-point calibration process. Factory-prescribed calibration procedures (Mount Sopris Instrument Co., Inc., 2002) that adhere to ASTM International guidelines (ASTM International, 2007) are used to calibrate the logging probe. This calibration process is usually performed at a well having minimal electromagnetic interference. The probe is calibrated

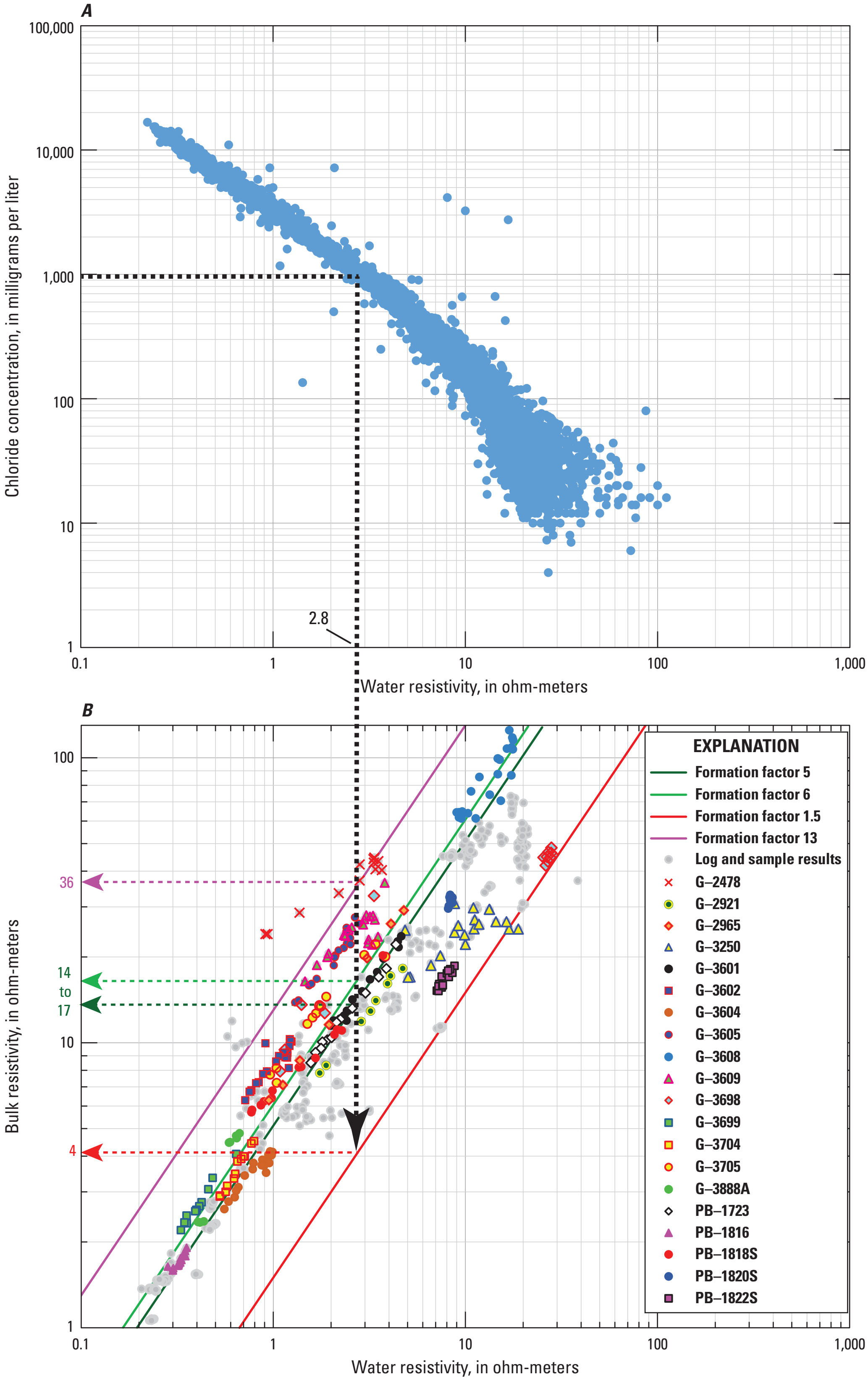


Figure 6. Relations between, *A*, chloride concentration and water resistivity and, *B*, water resistivity and bulk resistivity, in water samples and induction logs from monitoring wells in the surficial aquifer system or the Biscayne aquifer within the study area. Locations of wells named in the explanation are shown in figure 2.

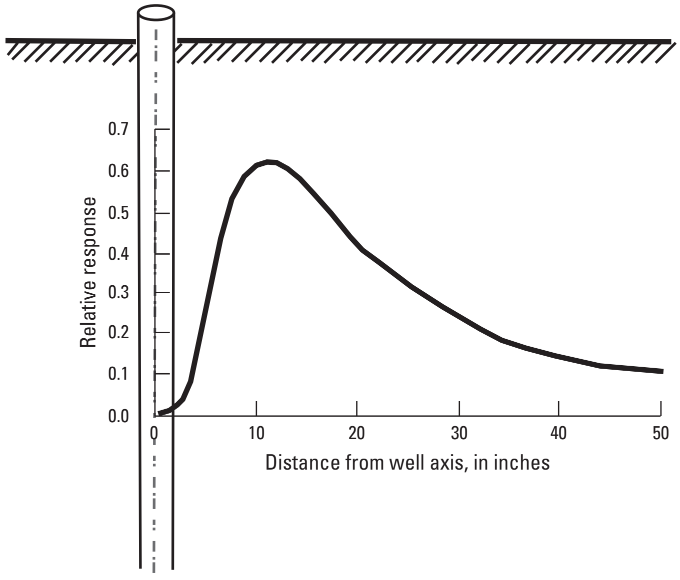


Figure 7. Relative response with radial distance from the borehole axis. Modified from McNeill and others (1990).

at a distance of at least 10 ft from any metallic object, including the logging unit itself, and is held so that the tip of the probe is at least 10 ft in the air (Mount Sopris Instrument Co., Inc., 2002).

The probe is set to the 0- to 1,000-mS/m range for calibration and logging of all wells, including those that currently yield freshwater. The 0- to 1,000-mS/m range is currently the preferred setting because many of the wells already yield saltwater or might begin to yield saltwater in the future. Using this range at all wells avoids any changes in the time series of logs that could potentially be introduced by a change in the range for which the probe is being calibrated. Calibration procedures, however, have varied over the years since the EMI logs were first collected. In some years and at some sites, logs were collected with the probe set and calibrated in the 0- to 100-mS/m and 0- to 10,000-mS/m ranges. This is discussed in greater detail in the "Corrections to Individual Electromagnetic-Induction Logs" section of this report.

A substantial difference between the temperature of the induction probe and the temperature of water in the borehole might cause an inaccurate calibration (Mount Sopris Instrument Co., Inc., 2002); therefore, prior to calibration, the probe is allowed to equilibrate with the water in the well for at least 15 to 30 minutes at a water depth of about 20 ft until the bulk conductivity readings stabilize. The probe is then removed from the well, and the calibration is performed as quickly as possible to ensure the probe temperature is as close to the well water temperature as possible during calibration.

The probe is calibrated using a factory-manufactured calibration coil that provides four known bulk conductivity values selected by using a switch on the coil. The calibration values for the coil currently being used are 0, 91, 460, and 1,704 mS/m. The calibration is performed using the 0- and 460-mS/m calibration coil settings, and the calibrated EMI probe is then checked at the 91- and 1,704-mS/m settings. Once completed, the calibration is generally used for the duration of the logging field trip, and check measurements of the calibration are performed as needed.

Prior to collection of the EMI log in each well, the probe is lowered to a depth of about 20 ft below water surface and allowed to equilibrate with the water in the well until readings have stabilized. In 2002, the amount of time that the probe is allowed to equilibrate with the water in the well was increased from 10 to 15 minutes to a minimum of 15 to 30 minutes. After the probe temperature has stabilized, EMI logs are collected. The probe is raised until the joint where the cable head connects with the probe is aligned with the top of the well casing or a specified reference point. A down-hole log is collected as the probe is lowered to the bottom of the well. This log is called a down-hole log. The software automatically references the displayed depths to the tip of the probe. An up-hole log is collected as the probe is raised from the bottom of the well to the well reference point. Another set of down-hole and up-hole logs are collected, and all of these logs are compared determine if the data are consistent. Generally, the up-hole logs are considered to be better than the down-hole logs because, in tight wells, for example, the probe might become temporarily stuck in the well during down-hole logging while additional cable is played out by the winch. This can cause a temporary discontinuity between the actual depth of the probe and the depth recorded by the winch. In addition, if the probe temperature continues to change during logging, the down-hole and up-hole log will differ because of drift. Beginning in 2009, two up-hole logs and two down-hole logs were collected in each well. The final up-hole log is the preferred log for the TSEMIL dataset, because the extended time in the well ensures adequate time for the probe to equilibrate to the temperature of the water in the well, and because the cable is under constant tension during up-hole logging, which ensures accurate log depths.

Corrections to Individual Electromagnetic-Induction Logs

Corrections have been applied to individual induction logs to compensate for (1) small errors in vertical alignments, (2) differences in calibration and calibration coil issues, (3) differences in probe range settings, and (4) anomalous values in probe readings. These corrections are described in greater detail in subsequent sections of this report.

Correcting for Small Errors in Vertical Alignment

The recorded depths of identifiable features in a log, such as prominent peaks, might differ slightly from log to log because of small differences in setting up the starting depth of each log. These differences are minimized by selecting a specific point on the induction logging tool that is aligned with the top of the well casing at the beginning of collection of each log. Any remaining differences can be removed by adjusting the logs vertically so that the depths of prominent features coincide. The depths of the logs are adjusted to correspond with depth bls if the logs are collected on land. Logs collected from wells in Biscayne Bay (fig. 1) are adjusted to correspond with depth below the bottom of the bay. The cable used to lower the EMI probe stretches slightly, and the amount of this stretch varies depending on the thickness of the cable. An adjustment for this slight stretch has been applied to some EMI logs.

Correcting for Differences in Calibration and Calibration Coil Issues

Prinos and others (2014) describe the calibration settings and methods used during 1995–2013 in detail. In 1995, the probe was not calibrated using a calibration coil. Readings in counts per second were converted to bulk conductivity using the manufacturer's recommended conversion. This method is described by Mount Sopris Instruments (2008) and is the same method that was used for "the first version of the tool when no calibration ring was available" (Paul Staples, Mount Sopris Instruments, written commun., November 30, 2015). A calibration coil was used in January 1996, but the probe was not recalibrated for the logs collected in May 1996 and in 1997. In all subsequent years, a calibration coil was used to calibrate the probe at the beginning of each field trip. Two calibration coils have been used: the first was used from 1996 to 2007 and had coil settings of 0, 81, 345, and 1,301 mS/m, and the second coil has been used from 2008 to present and has coil settings of 0, 91, 460, and 1,704 mS/m.

In 2008, a discrepancy between the two coils was discovered and both coils were sent back to the manufacturer for testing. Through comparison with a master calibration coil, the manufacturer determined that two of the coil settings on the first coil had been mislabeled. The coil settings of 81 and 345 mS/m should have been labeled 92 and 460 mS/m, respectively. The 0- and 1,301-mS/m calibration coil settings were correct. The incorrect 345-mS/m calibration coil setting was used for all logs collected in 1998, in the spring of 2002, and from 2002 to 2007. A 1,301-mS/m calibration coil setting was used for all other logs collected between 1996 and 2002. A 1.333 multiplier has been applied to the logs collected using the incorrectly labeled 345-mS/m calibration coil setting. No correction was needed for the logs collected using the 1,301-mS/m calibration.

In 2002, before determining that the calibration coil had been incorrectly labeled, an observed difference between the logs calibrated using the 345- and 1,301-mS/m calibration coil settings was considered to be the result of saturation of the probe response to readings above 1,000 mS/m, and a 0.7686 multiplier had been applied to all logs calibrated using the 1,301-mS/m calibration coil setting. This correction was in error because the incorrectly labeled 345-mS/m coil setting had caused the observed difference between the logs. After the calibration coil mislabeling issue was identified, the 0.7686 multiplier was removed, and the previously described correction was applied to those logs collected using the incorrectly labeled coil setting. After the necessary corrections were applied to the slope of the affected logs, only minor (±15 mS/m) offsets remained between any of the logs.

Correcting for Differences in Probe Range Settings

As described in the "Calibration of Equipment and Collection Procedures" section of this report, the probe was set and calibrated for the 0- to 1,000-mS/m range for most of the collected logs. Some of the logs collected near the Florida Power & Light Company cooling canal system (fig. 1) indicate maximum bulk conductivities greater than 1,000 mS/m; however, the 0- to 1,000-mS/m range was generally selected for these logs because much of the data is at or below 1,000 mS/m, and the 10,000-mS/m maximum greatly exceeded the maximum bulk conductivity for even the most saline wells. In 2013, however, EMI logs were collected from some of the wells near the Florida Power & Light Company cooling canal system using the 0- to 10,000-mS/m range. This resulted in large offsets from the bulk conductivities of logs collected in other years. To make the 2013 logs comparable with the logs of other years for the TSEMIL datasets, the offsets for the 2013 logs were adjusted horizontally to align with the logs of other years.

Addressing Anomalous Values in Probe Readings

Beginning in August 2012 and extending through 2013, a software update caused an increase in the measurement noise of EMI logs above that of preceding or subsequent logs (fig. 8*A*). This increase was relatively small and was most evident in logs having bulk conductivities less than 50 mS/m. In 2014, this issue was avoided by using a previous software version for logging. However, in 2015, the problematic version of the software was used, which again resulted in increased measurement noise. Logs affected by the noise were smoothed by applying a 5- to 7-point moving average (fig. 8*B*).

Metal objects interfere with EMI logging, and if a steel or galvanized iron casing extends partially down a well, the EMI probe cannot sense the materials outside of the metallic casing. As the probe is lowered down the well and past the influence of a metallic casing, a spike is created in the data. Metal well centralizers or metal screws used to attach the well centralizers can cause very large spikes in the data at the depths where the centralizers are installed. These spikes are not reflective of the bulk conductivity caused by natural lithologic or pore water variations and have been removed from the EMI logs where necessary.

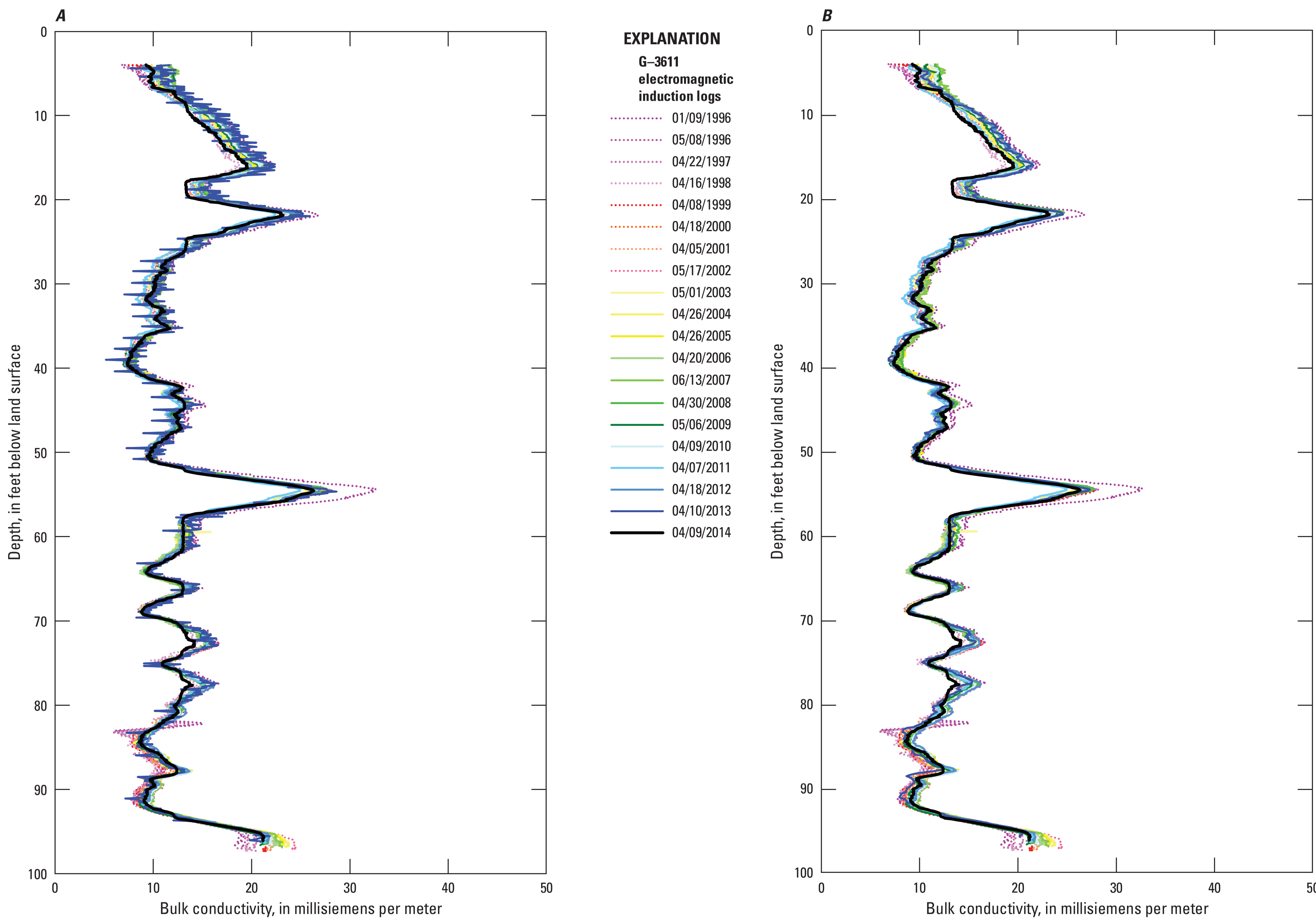


Figure 8. Comparison of the time-series electromagnetic induction log datasets from well G–3611: *A*, before application of a 6-point moving average to the 2013 log to correct for increased measurement noise and, *B*, after application of the correction. Location of well shown in figure 2.

Processing of Time-Series Electromagnetic-Induction Log Datasets

A TSEMIL dataset is created by processing individual EMI logs to remove the minor offsets between logs caused by differences in calibration resulting from variations in temperature, humidity, and time required to calibrate the probe (fig. 9*A*) so that actual changes in aquifer salinity are more readily apparent (fig. 9*B*). With the exception of small and generally uniform offsets in bulk conductivity between the logs collected on different dates, individual EMI logs collected from a given well, in general, are nearly identical throughout the depth interval where the aquifer is saturated with freshwater (fig. 9*A*). Each log is typically within about ±15 mS/m of the mean of the dataset at any given depth, which is within the stated resolution, repeatability, and accuracy specifications of the probe. Although the offsets are small (±15 mS/m), they obscure the ability to identify small but real changes in bulk conductivity resulting from changes in aquifer salinity. Once these offsets have been removed, changes from year to year due to saltwater movement are easier to identify (fig. 9*B*). TSEMIL dataset processing and quality assurance involves (1) establishing an initial baseline based on available logs, (2) validating the baseline using additional information, (3) evaluating temporal changes in the baseline, and (4) evaluating the stability of the baseline. Some of the most commonly observed temporal changes are (1) variations in bulk conductivity near the water table where water saturation of pore spaces might vary, and water temperature might be more variable; (2) dissipation of conductive water in high porosity rock layers, which might have entered these layers during drilling; and (3) changes associated with saltwater intrusion.

Establishing an Initial Baseline

An initial baseline is established by adjusting two or more logs to align with the mean or median bulk conductivity of the logs at a selected depth. The most important part of this procedure is selecting a depth at which there are no temporal changes in the electrical conductivity of water in the aquifer. If there are any such changes at the alignment depth, the corrections might be invalid. Generally, a depth in the freshwater saturated part of the aquifer well below the water table is selected, because changes in aquifer-water conductivity are rarely observed at these depths.

Once an alignment depth is selected, the logs are aligned by (1) determining the mean or median bulk conductivity measured by the time series of EMI logs at the selected depth, (2) determining the difference between this value and the bulk conductivity measured at this same depth for each individual log of the set, (3) subtracting this difference from each bulk conductivity measurement of that individual log, and (4) repeating this process for all logs in the set until all logs are adjusted to the mean or median bulk conductivity at the selected depth (fig. 9*B*). Some logs might be excluded from the computation of the mean or median because of known calibration issues with these logs. If there are many years with no changes at the alignment depth and then a change occurs at this depth, it might still be possible to align the affected log with the previous logs by considering other alignment depths.

If all of the logs in a dataset are adjusted to the median or the mean of the logs at the selected alignment depth, then the median or mean of the all the adjusted logs is zero. This provides a simple check to verify that the dataset has been properly adjusted. When using the correction procedures described, there is generally only about ±2 to 3 mS/m of completely irregular variation between successive logs that cannot be removed (fig. 9*B*). Even if perfect numerical alignment is achieved at one or two depths, the ±2 to 3 mS/m of random variation remains at all other depths. This variation is probably the result of random instrumentation noise but is slightly greater than the manufacturer-specified noise level of less than 0.5 mS/m (Mount Sopris Instrument Co., Inc., 2002). Equipment variation, drift, and calibration may be contributing factors. The random variation is much smaller than the change in bulk resistivity associated with saltwater entering previously freshwater-saturated materials.

Validating the Baseline

One method of validating the quality of the TSEMIL dataset baseline is to compare the chloride concentrations in samples collected from the screened interval of the well to the corresponding unadjusted and adjusted bulk conductivities from the TSEMIL dataset over the same interval. These comparisons show that TSEMIL dataset processing improves the relationship of chloride concentration in samples to the bulk-conductivity measurements (fig. 10). Monitoring well G–3611, for example, has a screened interval of 95 to 100 ft bls. A comparison of the bulk conductivity of the unadjusted EMI measurements at a depth of 96 ft bls to the chloride concentration of water samples from this well indicates a poor fit (figs. 10 and 11*A*), with a root mean squared error (RMSE) for this comparison of 17.4 mS/m. The adjusted bulk conductivities from the TSEMIL dataset improves the fit between chloride concentration and bulk conductivity, particularly after the first five logs (figs. 10 and 11*B*). The RMSE for this comparison is 1.7 mS/m. The first five logs were apparently affected by fluids associated with the drilling of the well (fig. 10).

TSEMIL dataset processing generally improves the fit between the chloride concentration of water samples and adjusted bulk conductivity at salinity levels that typically occur near the leading edge of intruding saltwater. Chloride concentrations in this area are typically in the range of 250 to 2,000 mg/L, and the associated range in bulk conductivity is generally about 50 to 130 mS/m. The fit between chloride samples and bulk conductivity is noticeably improved by TSEMIL dataset processing of logs from well G–3609, for example, although the RMSE only improved from 3.7 to 2.2 mS/m (figs. 12–15).

In some instances, the changes in the salinity of the water are so great that the offsets caused by calibration error are trivial in comparison and need not be considered. Measured bulk conductivities near the Florida Power & Light Company cooling

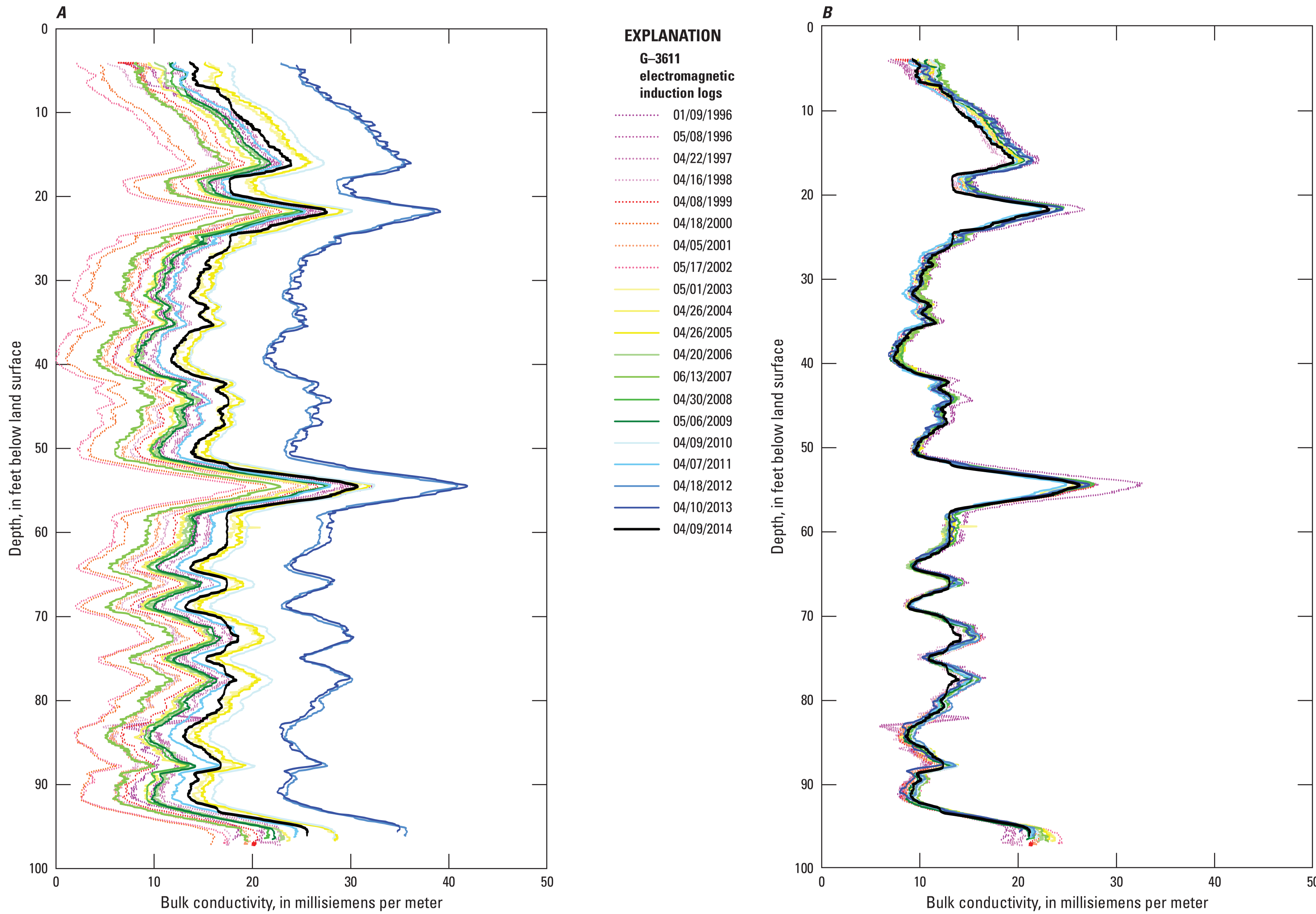


Figure 9. Electromagnetic-induction logs collected from monitoring well G–3611 from January 1996 to April 2014: *A*, prior to bulk conductivity corrections and, *B*, following corrections in bulk conductivity applied to create a time-series electromagnetic-induction log dataset, Miami-Dade County, Florida. Location of well shown in figure 2.

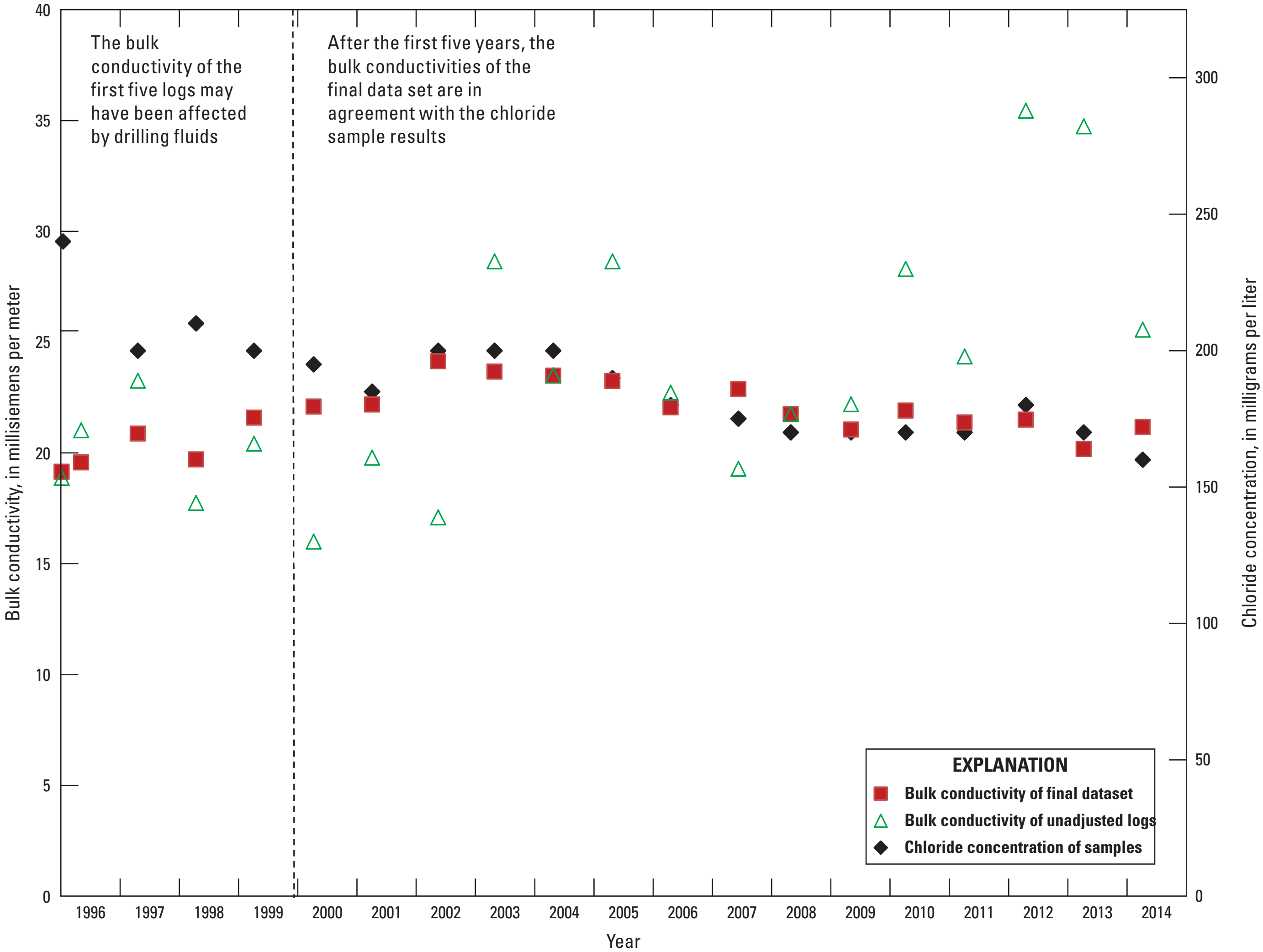


Figure 10. Comparison of adjusted and unadjusted bulk conductivities measured at 96 feet below land surface with the chloride concentration of water sample results from well G–3611, which has a screened interval of 95 to 100 feet below land surface, January 1996 to April 2014, Miami-Dade County, Florida. Location of well shown in figure 2.

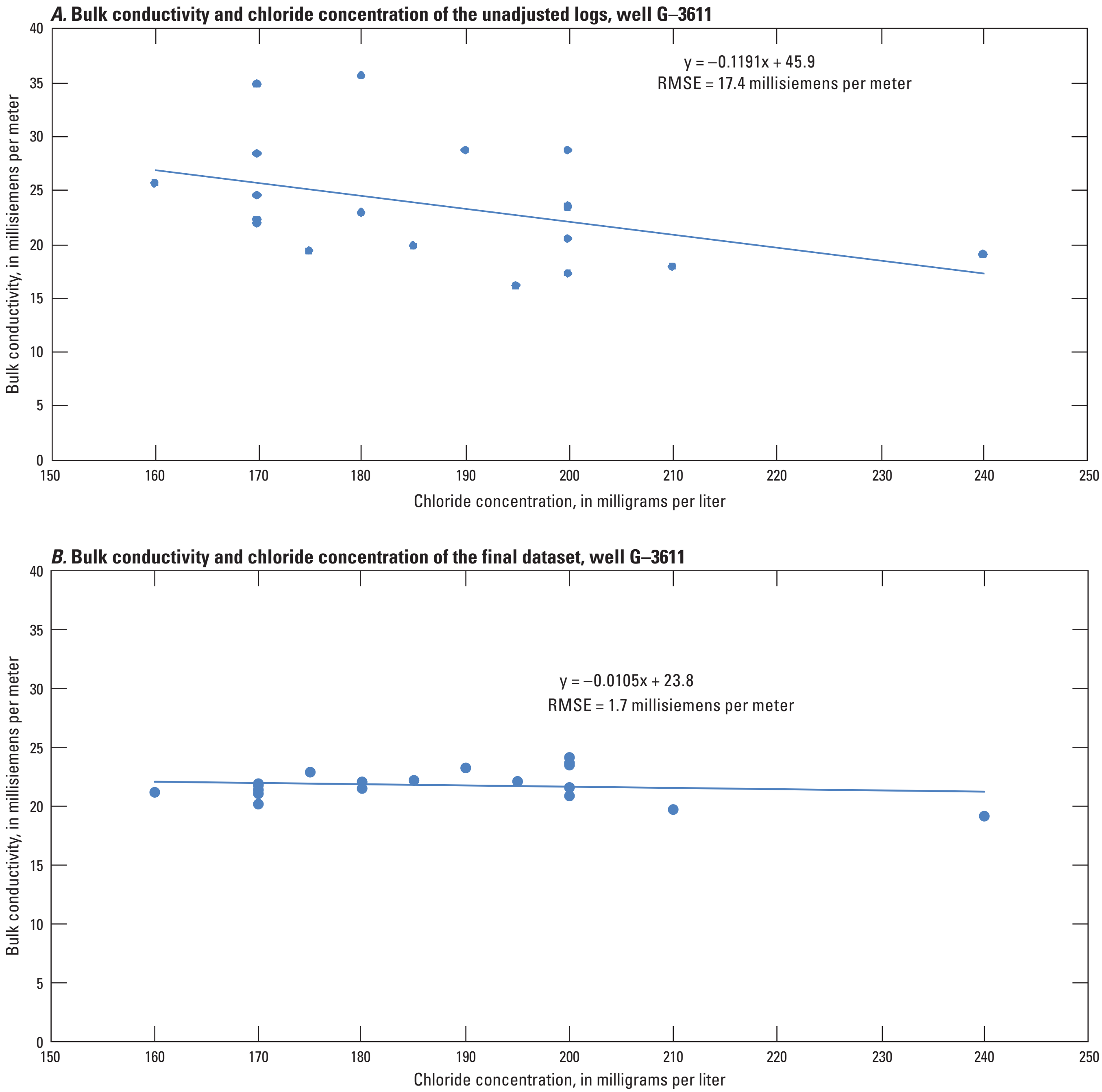


Figure 11. Linear regressions and root mean squared error (RMSE) for comparisons of, *A*, unadjusted and, *B*, adjusted bulk conductivities and chloride concentrations of water sample results from well G–3611; January 1996 to April 2014, Miami-Dade County, Florida. Location of well shown in figure 2.

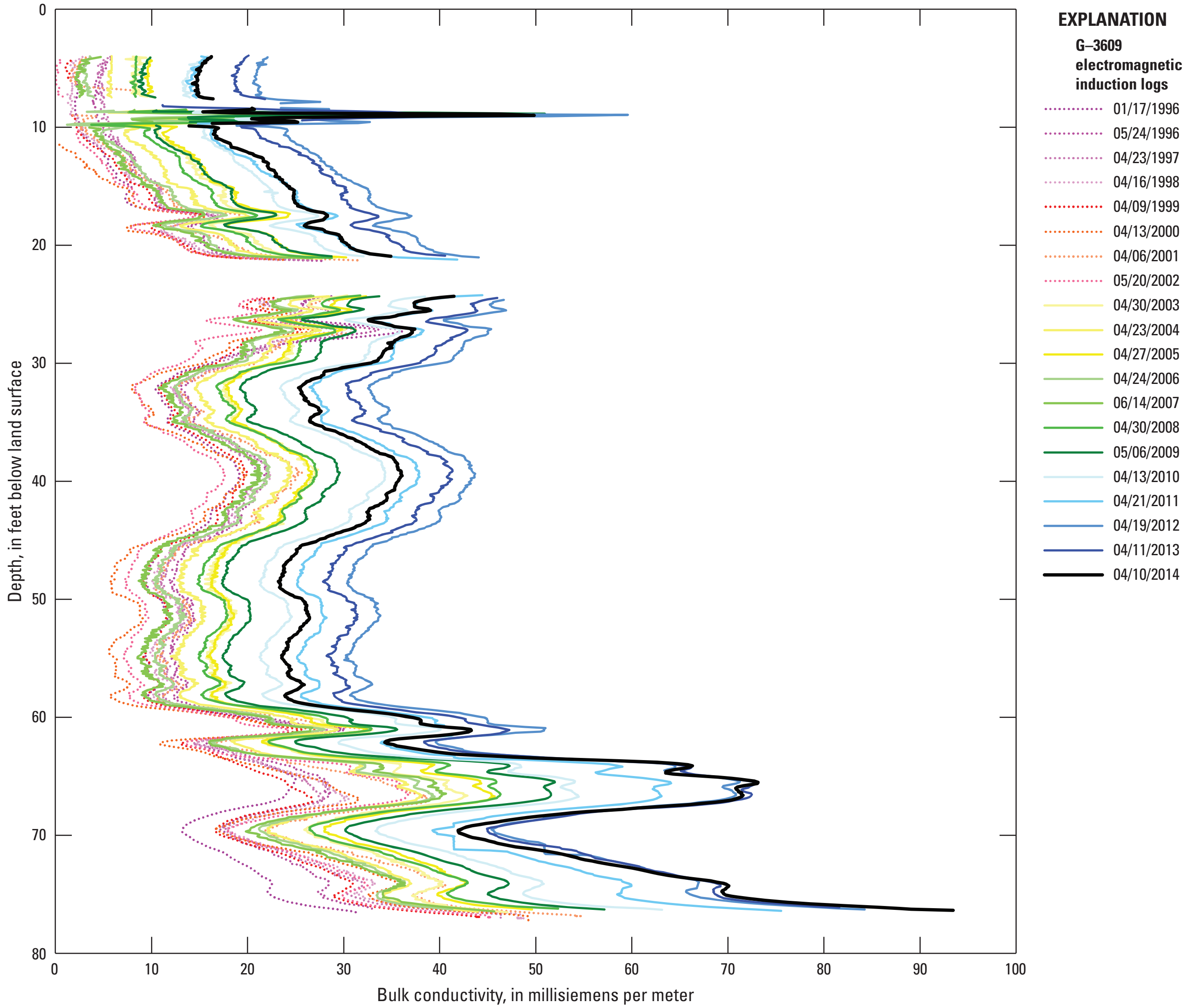


Figure 12. Electromagnetic-induction logs collected from monitoring well G–3609 from January 1996 to April 2014 prior to bulk conductivity corrections, Miami-Dade County, Florida. Location of well shown in figure 2.

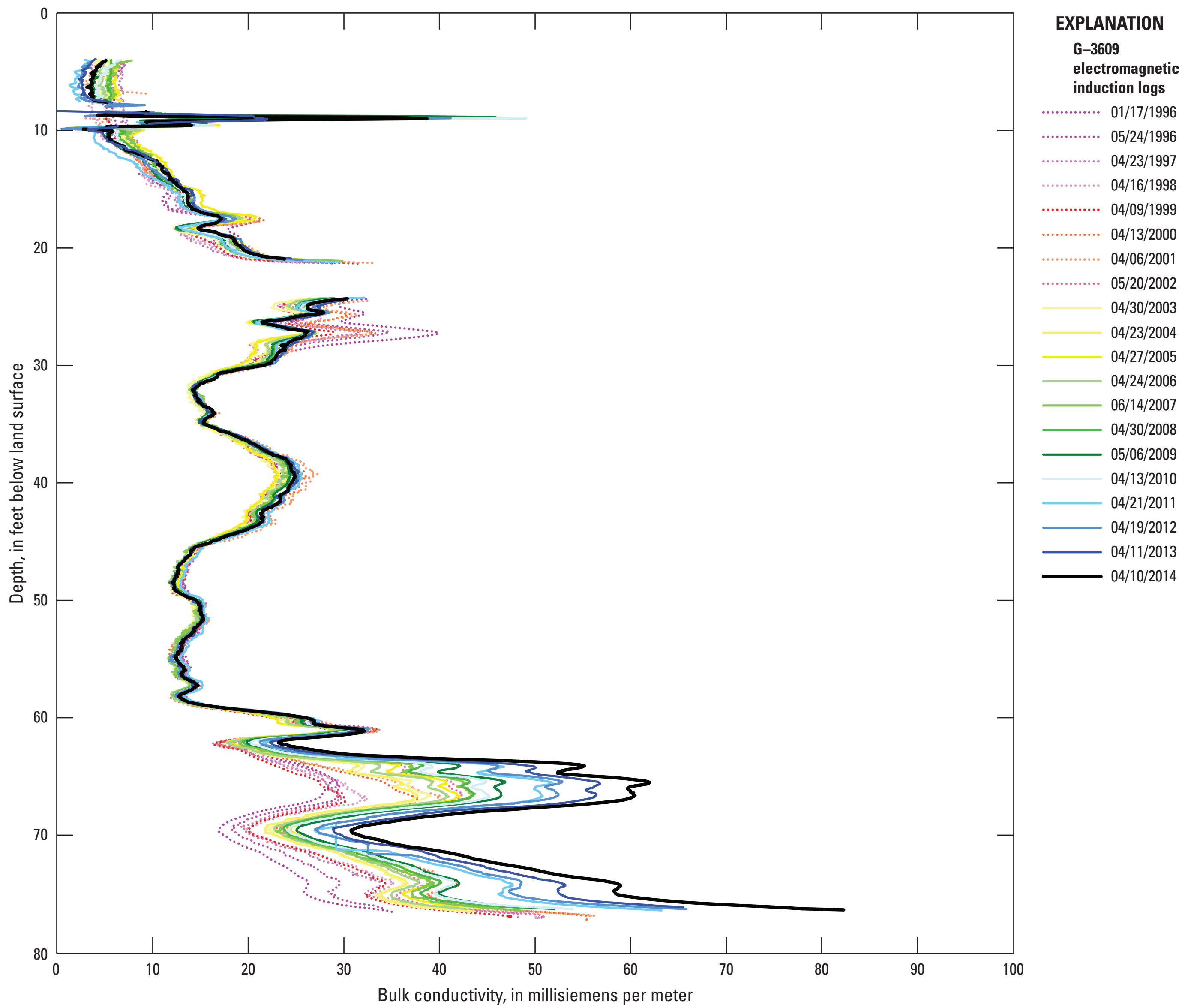


Figure 13. Time-series electromagnetic-induction log dataset that results from correction of errors in the calibration slope and offset. Monitoring well G–3609, January 1996 to April 2014, Miami-Dade County, Florida. Location of well shown in figure 2.

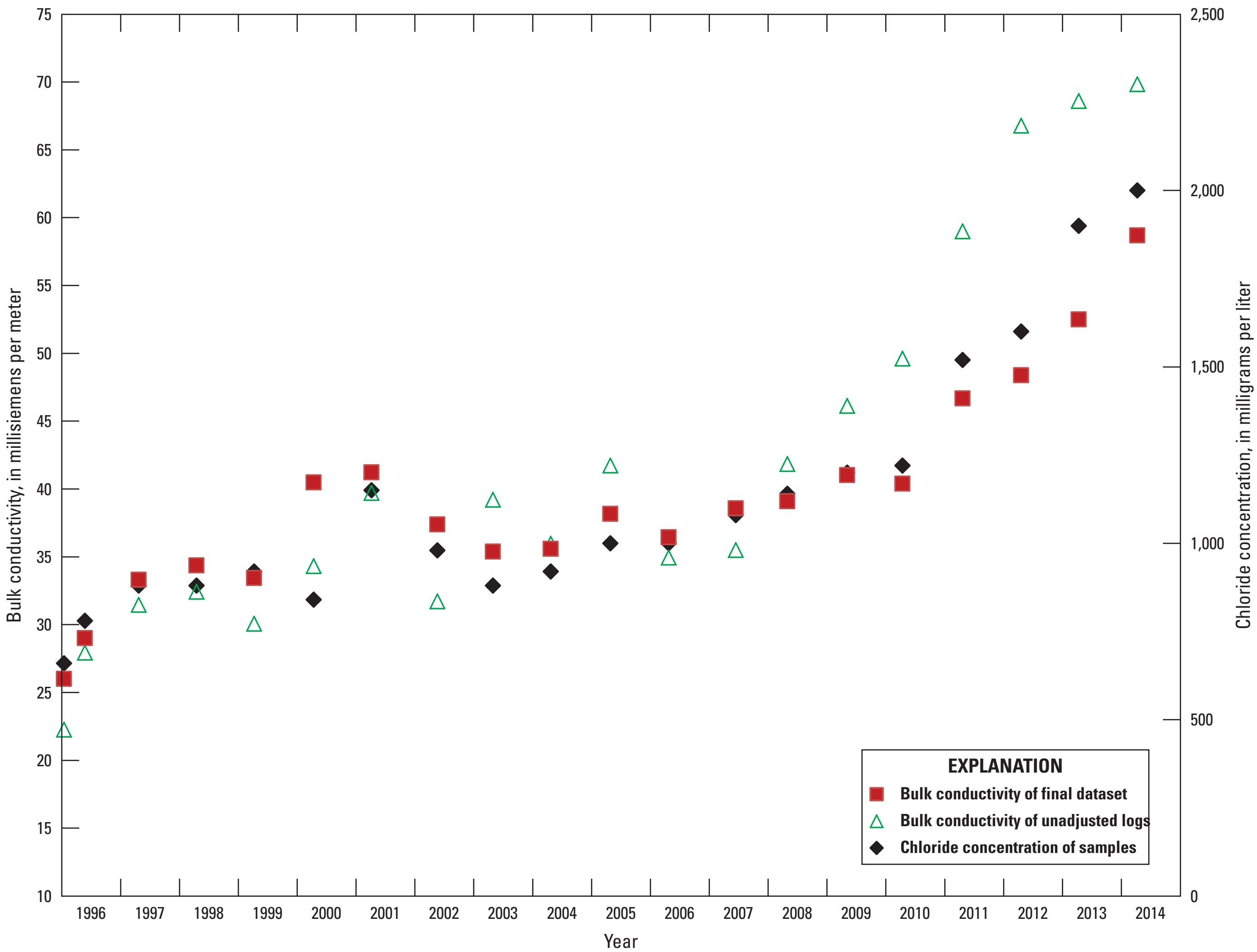


Figure 14. Comparison of adjusted and unadjusted bulk conductivities measured at 74.5 feet below land surface with the chloride concentration of water sample results from well G–3609, which has a screened interval of 80 to 85 feet below land surface; January 1996 to April 2014, Miami-Dade County, Florida. Location of well shown in figure 2.

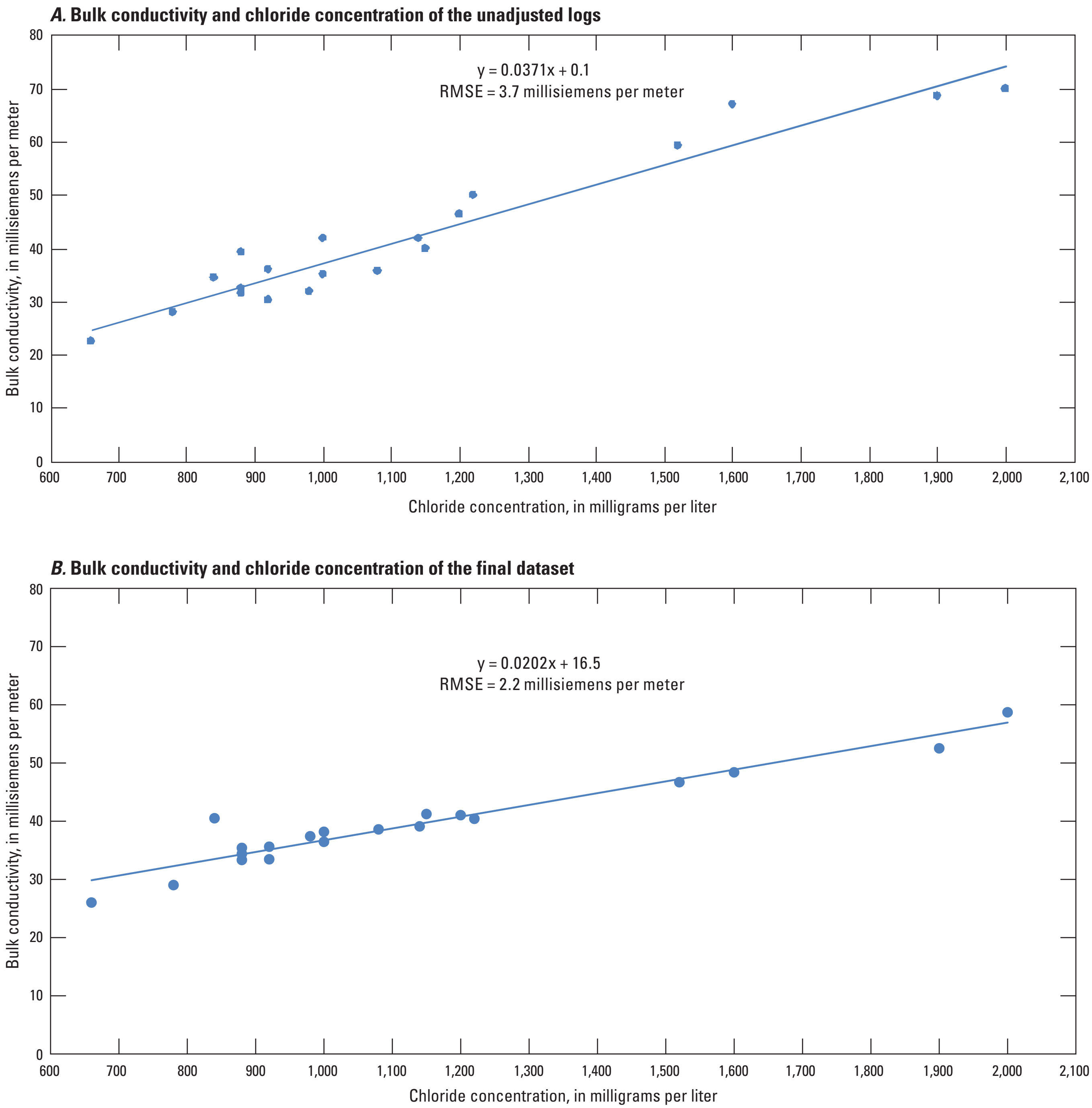


Figure 15. Linear regressions and root mean squared error (RMSE) for comparisons of, *A*, unadjusted and, *B*, adjusted bulk conductivities and chloride concentrations of water sample results from well G–3609; January 1996 to April 2014, Miami-Dade County, Florida. Location of well shown in figure 2.

canal system, for example, can be up to 2,500 mS/m. The offsets between these logs, with the exception of those collected using different calibration settings, are generally less than 20 mS/m. As such, these offsets are negligible and do not require removal prior to identification of temporal changes in water conductivity.

Considering the magnitude of corrections that have been applied and the manufacturer-specified measurement accuracy of 5 percent of full scale, or 50 mS/m for a full scale setting of 1,000 mS/m, the correlations observed between chloride concentration and bulk conductivity indicate that the TSEMIL dataset processing method produces useful results. Factors that could potentially create differences between the chloride concentration in water samples and measured bulk conductivity include: (1) differences between the EMI-log measured depth and the depth of the screened interval, caused by the probe encountering the bottom of a well before a full response can be measured at the open interval; (2) the number of different EMI logging instruments and calibration methods that have been used; (3) the potential for chloride concentrations in water samples to change rapidly if samples are drawn from well-connected pore spaces while EMI logs would also measure water trapped in finer pores that diffuses more slowly; and (4) the potential for water to be drawn in from outside the radius of investigation of the EMI logging equipment during water sampling. Although these factors could create differences between the chloride concentration in water samples and measured bulk conductivity, the preceding examples demonstrate that agreement is generally better than it would be without the corrections.

Evaluating Temporal Changes in the Baseline

As new logs are added to an existing TSEMIL dataset, they can be corrected to align with the initial baseline; however, the new mean or median of the corrections to the logs might not be zero. Rather than adjusting the baseline when every new log is added, the baseline of the TSEMIL dataset is not updated unless the mean or median of all corrections is more than ±15 percent of the range of the corrections that have been applied. For example, if the range of corrections at the alignment depth is 20 mS/m, the baseline would not be adjusted until the mean or median of all of the corrections is more than ±3 mS/m from zero. Once enough logs have been collected, the mean or median of the dataset at the selected alignment depth should become stable and adjustments to the baseline should be unnecessary. If the mean or median does not stabilize, there might be actual changes in bulk conductivity at the alignment depth, and a different alignment depth should be selected, if possible.

Evaluating Baseline Stabilization

Existing TSEMIL datasets were analyzed to determine the minimum number of logs required for the baseline to stabilize to within ±2 mS/m. TSEMIL datasets from 11 wells at which a minimum of 19 logs had been collected were used in this analysis. Starting with the first log collected, new baselines were determined for each log added to the dataset, and the difference between each baseline and the final baseline of the dataset was determined (fig. 16*A*–*B*). The analysis indicated that up to 16 logs were needed before all of the 11 log datasets had stabilized to within ±2 mS/m of the final median of the dataset, whereas up to 18 logs were needed before all of the log datasets had stabilized to within ±2 mS/m of the final mean of the dataset (fig. 16*A*–*B*). Given this analysis, logs were adjusted to the median of the dataset, rather than the mean, at the selected alignment depth. This decision was also made because the median is typically less sensitive to outliers than the mean.

The analysis also showed that the corrections made to the logs are not completely random. If they were random, the offsets would be equally distributed on the zero axis. Although calibrated using the same calibration coil, many of the logs collected using the newest EMI probe are skewed to higher bulk conductivities relative to the historical data. The skew of the offsets might be related to this difference in instrumentation or to longer probe temperature equilibration times in more recent logs.

Although the TSEMIL dataset processing of even a few logs improves evaluations of the differences between the logs that are related to changes in salinity, the analysis shows that about 16 logs are needed to estimate the bulk conductivity within ±2 mS/m. Unlike many other types of data published by the USGS, the median of TSEMIL datasets should not be considered final until 16 logs are collected and the median of the dataset is stable. Many years of data may be necessary for the baseline to stabilize, because most TSEMIL datasets consist of logs that are only collected annually. Changes in the baseline are noted in the manuscripts that are published with the TSEMIL datasets.

Presentation of Time-Series Electromagnetic-Induction Log Datasets

Individual EMI logs in the TSEMIL dataset are color coded from oldest to newest by collection date in the general color sequence of magenta, red, orange, yellow, green, blue, and indigo using various shades of these colors to differentiate each log from others. The lines colored in shades of magenta, red, and orange are dashed so that they can be further differentiated from the green and blue colored lines by those who have deuteranopia or protanopia types of colorblindness. The most recent log is black.

If all of the individual EMI logs from a well plot directly on top of each other at all depths, the water conductivity is not changing (fig. 9*B*). A monotonic increase or decrease in water conductivity through time results in a set of curves or curve segments that deviate from preceding logs and follow the above mentioned color sequence (fig. 13). Variations in bulk conductivity near the water table are common and might be influenced by temporal variations in the water saturation in the vadose zone above the depth of the water table and by incomplete submergence of the probe (Prinos and Valderrama, 2015); generally, this variation at the top of the water table is not meaningful to understanding saltwater intrusion.

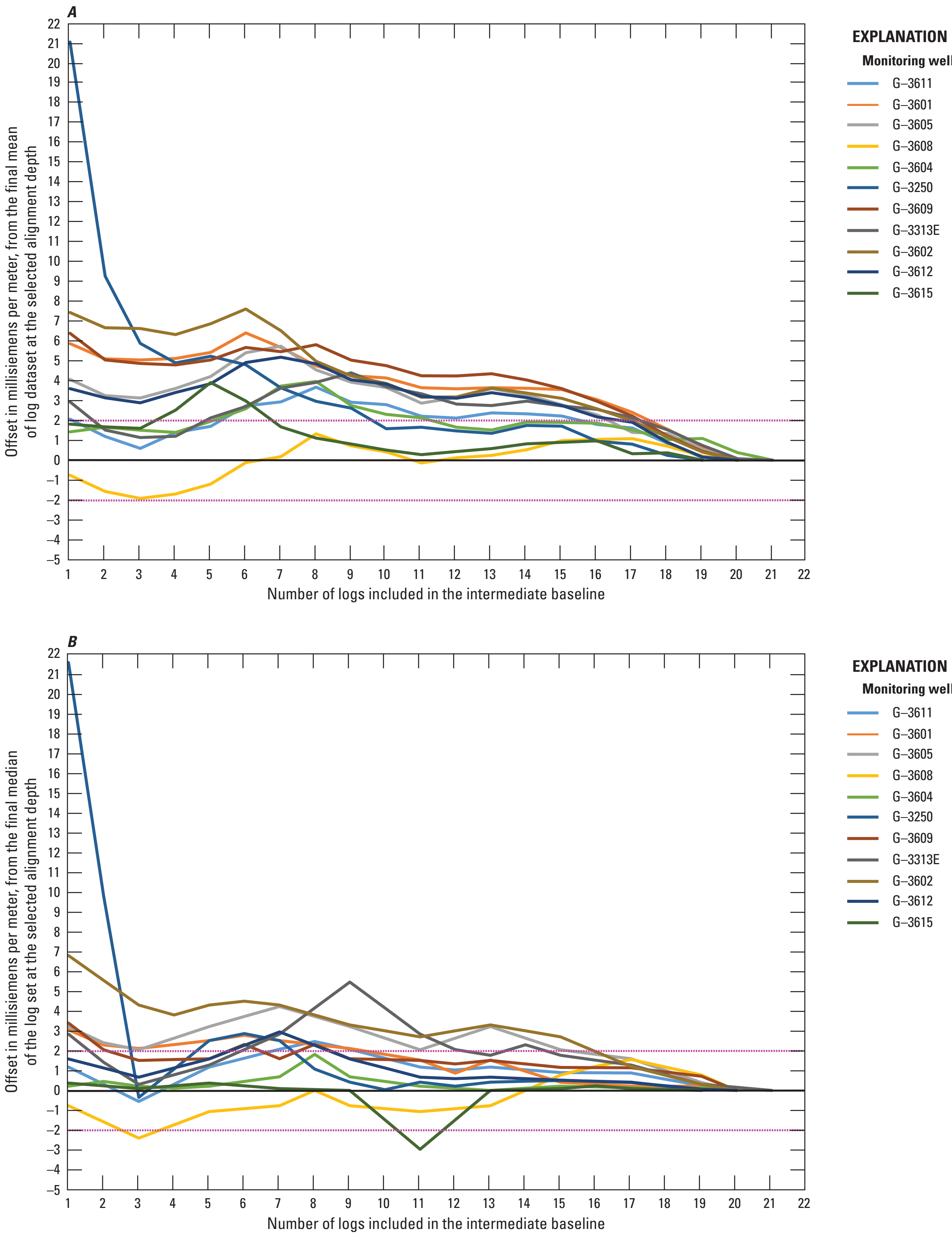


Figure 16. Offsets, in millisiemens per meter, of baselines from, *A*, the final mean and, *B*, median of the dataset. Locations of sites shown in figure 2. Stippled magenta lines depict range of ± 2 millisiemens per meter.

Summary

Time-series electromagnetic induction log (TSEMIL) datasets are used by the U.S. Geological Survey to evaluate changes in water conductivity over time in the aquifers of south Florida. These datasets are compilations of individual electromagnetic induction (EMI) logs collected from polyvinyl chloride cased or uncased monitoring wells. The EMI logs are collected using a geophysical logging tool called a "probe" that is lowered into a monitoring well. As the EMI probe passes through different layers of rock or sediment outside of a well, the different physical properties of each layer will result in variations in the recorded bulk conductivity values. Polyvinyl chloride casings do not interfere with EMI measurements. Corrections are applied to EMI logs to compensate for (1) small errors in vertical alignment of the probe, (2) differences in calibration, (3) differences in the selected probe range settings, and (4) to remove anomalous values from probe readings. Once necessary, corrections are applied to individual EMI logs collected in a monitoring well, a TSEMIL dataset is created by processing individual EMI logs to remove minor offsets between logs caused by differences in calibration resulting from variations in temperature, humidity, and time required to calibrate the probe so that actual changes in aquifer salinity are more readily apparent. TSEMIL dataset processing and quality assurance involves (1) establishing an initial baseline based on available logs, (2) validating the baseline using additional information, (3) evaluating temporal changes in the baseline, and (4) evaluating the stability of the baseline.

TSEMIL dataset processing can improve comparisons of water sample results and EMI measurements from wells. For example, this processing improved the root mean squared error of the linear regression between bulk conductivity of the EMI log measurements and the chloride concentration of water samples from 17.4 to 1.7 millisiemens per meter in well G–3611. The improvement is less, however, for TSEMIL dataset processing of EMI logs from very saline wells, because the offsets between logs can be trivial relative to changes in salinity. TSEMIL dataset processing of EMI logs from well G–3609, for example, only improved the RMSE from 3.7 to 2.2 millisiemens per meter, because the offsets between logs were much smaller than the overall changes in bulk conductivity and chloride concentration.

Although TSEMIL dataset processing of even a few logs improves the evaluations of differences between the logs that are related to changes in the salinity, the analysis shows that about 16 logs are needed to estimate the bulk conductivity within ±2 millisiemens per meter. Unlike many other types of data published by the U.S. Geological Survey, the median of TSEMIL datasets should not be considered final until 16 logs are collected and the median of the dataset is stable.

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