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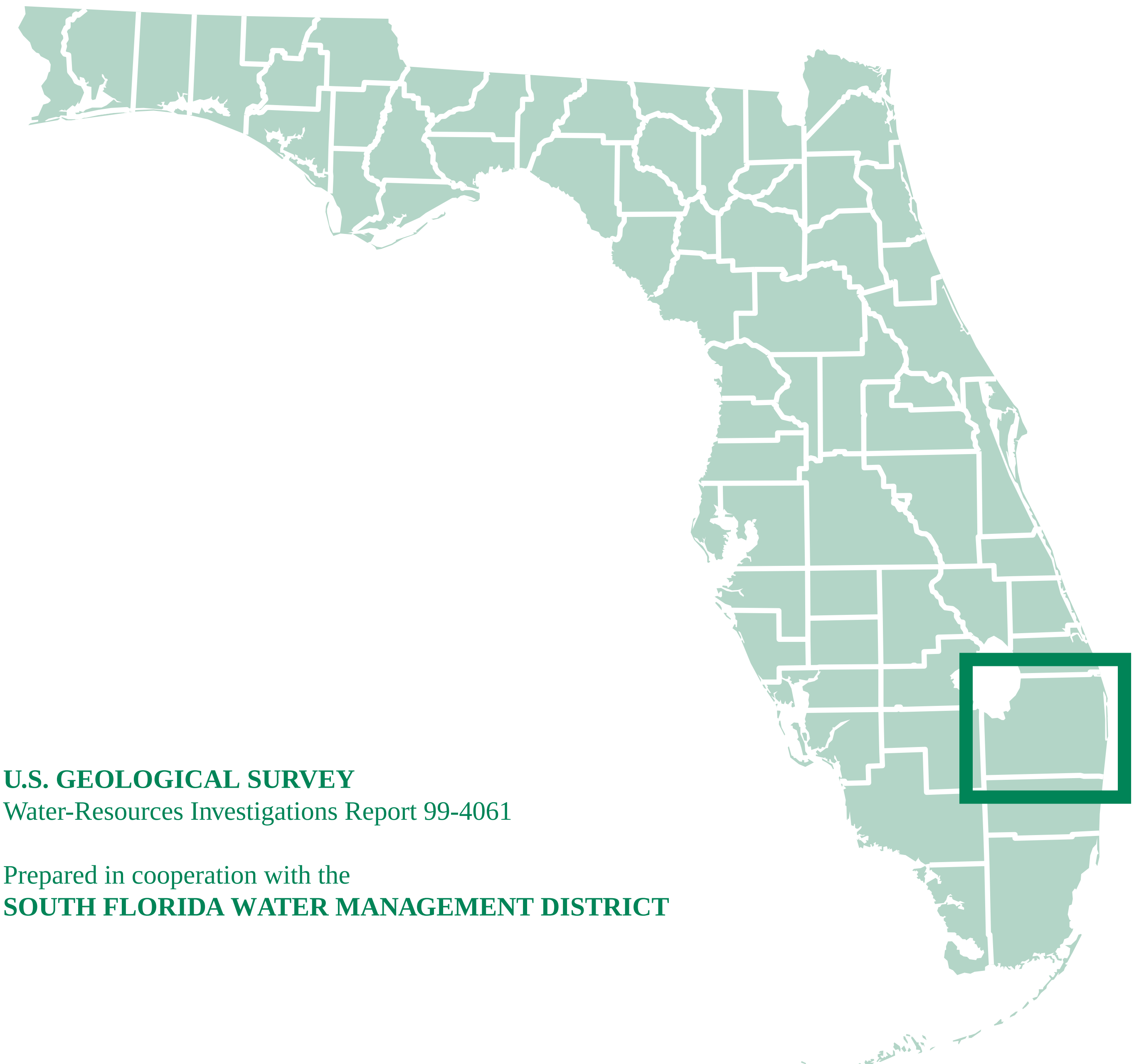
Hydrogeology and the Distribution of Salinity in the Floridan Aquifer System, Palm Beach County, Florida



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99-4061

Prepared in cooperation with the
SOUTH FLORIDA WATER MANAGEMENT DISTRICT

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By Ronald S. Reese *and* Steven J. Memberg

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Tallahassee, Florida
2000

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Hydrogeology and the Distribution of Salinity in the Floridan Aquifer System, Palm Beach County, Florida

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Abstract

The virtually untapped Floridan aquifer system is considered to be a supplemental source of water for public use in the highly populated coastal area of Palm Beach County. A recent study was conducted to delineate the distribution of salinity in relation to the local hydrogeology and assess the potential processes that might control (or have affected) the distribution of salinity in the Floridan aquifer system.

The Floridan aquifer system in the study area consists of the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer and ranges in age from Paleocene to Oligocene. Included at its top is part of a lowermost Hawthorn Group unit referred to as the basal Hawthorn unit. The thickness of this basal unit is variable, ranging from about 30 to 355 feet; areas where this unit is thick were paleotopographic lows during deposition of the unit. The uppermost permeable zones in the Upper Floridan aquifer occur in close association with an unconformity at the base of the Hawthorn Group; however, the highest of these zones can be up in the basal unit. A dolomite unit of Eocene age generally marks the top of the Lower Floridan aquifer, but the top of this dolomite unit has a considerable altitude range: from about 1,200 to 2,300 feet below sea level. Additionally, where the dolomite unit is thick, its top is high and the middle confining unit of the Floridan aquifer system, as normally defined, probably is not present.

An upper zone of brackish water and a lower zone of water with salinity similar to that of seawater (saline-water zone) are present in the Floridan aquifer system. The brackish-water and saline-water zones are separated by a transition zone (typically 100 to 200 feet thick) in which salinity rapidly increases with depth. The transition zone was defined by using a salinity of 10,000 mg/L (milligrams per liter) of dissolved-solids concentration (about 5,240 mg/L of chloride concentration) at its top and 35,000 mg/L of dissolved-solids concentration (about 18,900 mg/L of chloride concentration) at its base. The base of the brackish-water zone and the top of the saline-water zone were approximately determined mostly by means of resistivity geophysical logs. The base of the brackish-water zone in the study area ranges from about 1,600 feet below sea level near the coast to almost 2,200 feet below sea level in extreme southwestern Palm Beach County. In an area that is peripheral to Lake Okeechobee, the boundary unexpectedly rises to perhaps as shallow as 1,800 feet below sea level.

In an upper interval of the brackish-water zone within the Upper Floridan aquifer, chloride concentration of water ranges from 490 to 8,000 mg/L. Chloride concentration correlates with the altitude of the basal contact of the Hawthorn Group, with concentration increasing as the altitude of this contact decreases. Several areas of anomalous salinity where chloride concentration in this upper interval is greater than 3,000 mg/L occur near the coast. In most of these areas,

salinity was found to decrease with depth from the upper interval to a lower interval within the brackish-water zone: a reversal of the normal salinity trend within the zone. These areas are also characterized by an anomalously low altitude of the base of the brackish-water zone, and a much greater thickness of the transition zone than normal. These anomalies could be the result of seawater preferentially invading zones of higher permeability in the Upper Floridan aquifer during Pleistocene high stands of sea level and incomplete flushing of this high salinity water by the present-day flow system.

INTRODUCTION

Increasing demand for water from the surficial aquifer system in the highly populated coastal area of Palm Beach County, Fla., has prompted a need to find supplemental sources of available water for both public and agricultural use. The virtually untapped Floridan aquifer system can be used to assist in this need. Because of the brackish nature of this groundwater resource, two alternative methods of use are currently expanding: the reverse-osmosis method, and the aquifer storage and recovery (ASR) method. With the reverse-osmosis method, high pressure is applied to the water being treated, forcing it through a semipermeable membrane. This process removes the dissolved salts and produces pure water (freshwater). Because the salinity of water in the upper part of the Floridan aquifer system is considerably less than that of seawater (about 10 percent), the expense of the reverse-osmosis treatment is also less. With the ASR method, surplus freshwater from the surface or surficial aquifer system is temporarily stored in the upper part of the Floridan aquifer system, displacing the brackish water, and can be withdrawn when needed. Before the Floridan aquifer system can be used on a large scale, the hydrogeologic framework and the distribution of salinity in the Floridan aquifer system in Palm Beach County as well as all of southern Florida need to be characterized and better understood.

To address these information needs, the U.S. Geological Survey (USGS), in cooperation with the South Florida Water Management District (SFWMD), conducted a study from October 1995 through September 1997 to: (1) describe the vertical and areal variations in water quality in the Floridan aquifer system, and (2) relate these variations in water quality to the local hydrogeologic framework of southern Florida. Emphasis in this study was placed on the upper part of the Floridan aquifer system in Palm Beach County, with small portions of Hendry County to the west and Broward County to the south (fig. 1). The study area is bounded by the Atlantic Ocean on the east and Lake Okeechobee on the northwest. Land-surface elevation in the study area is less than 25 ft (feet) and generally ranges from 10 to 20 ft. Two similar studies were conducted, one to the south of the study area encompassing mainly Dade and Broward Counties (Reese, 1994), and the other to the west and southwest of the study area, encompassing mainly Collier, Lee, and Hendry Counties (Reese, 1999).

Purpose and Scope

This report delineates the distribution of salinity in relation to the local hydrogeology of Palm Beach County and assesses the potential processes that might control (or have affected) the distribution of salinity in the Floridan aquifer system. Hydrogeologic sections and maps were prepared showing the thickness, and the altitude of the top and base, of a basal Hawthorn unit in the Hawthorn Group. The base of this unit, the basal contact of the Hawthorn Group, approximately coincides with the top of the Floridan aquifer system. The altitude of the top of a thick dolomite unit that generally coincides with the top of the Lower Floridan aquifer also was mapped. Lithologic descriptions and borehole geophysical logs were used to correlate geologic units between wells. The hydrogeologic units in southern Florida (the intermediate confining unit, Upper Floridan aquifer, middle confining unit, and the Lower Floridan aquifer) are described, including their thickness, relation to geologic units, and hydraulic properties.

Because most of the water-quality data available in the study area were not comprehensive enough for a complete analysis of water quality, the analysis in this report deals only with salinity (principally chloride and dissolved-solids concentrations). The water-quality data presented in this report consist of 138 analyses, most of which were obtained from wastewater-injection-system well samples that were not collected by the USGS. Additionally, geophysical logs were used to estimate formation salinity in seven wells; either sampling for water-quality analysis in these wells was not done, or the intervals sampled did not provide adequate coverage.

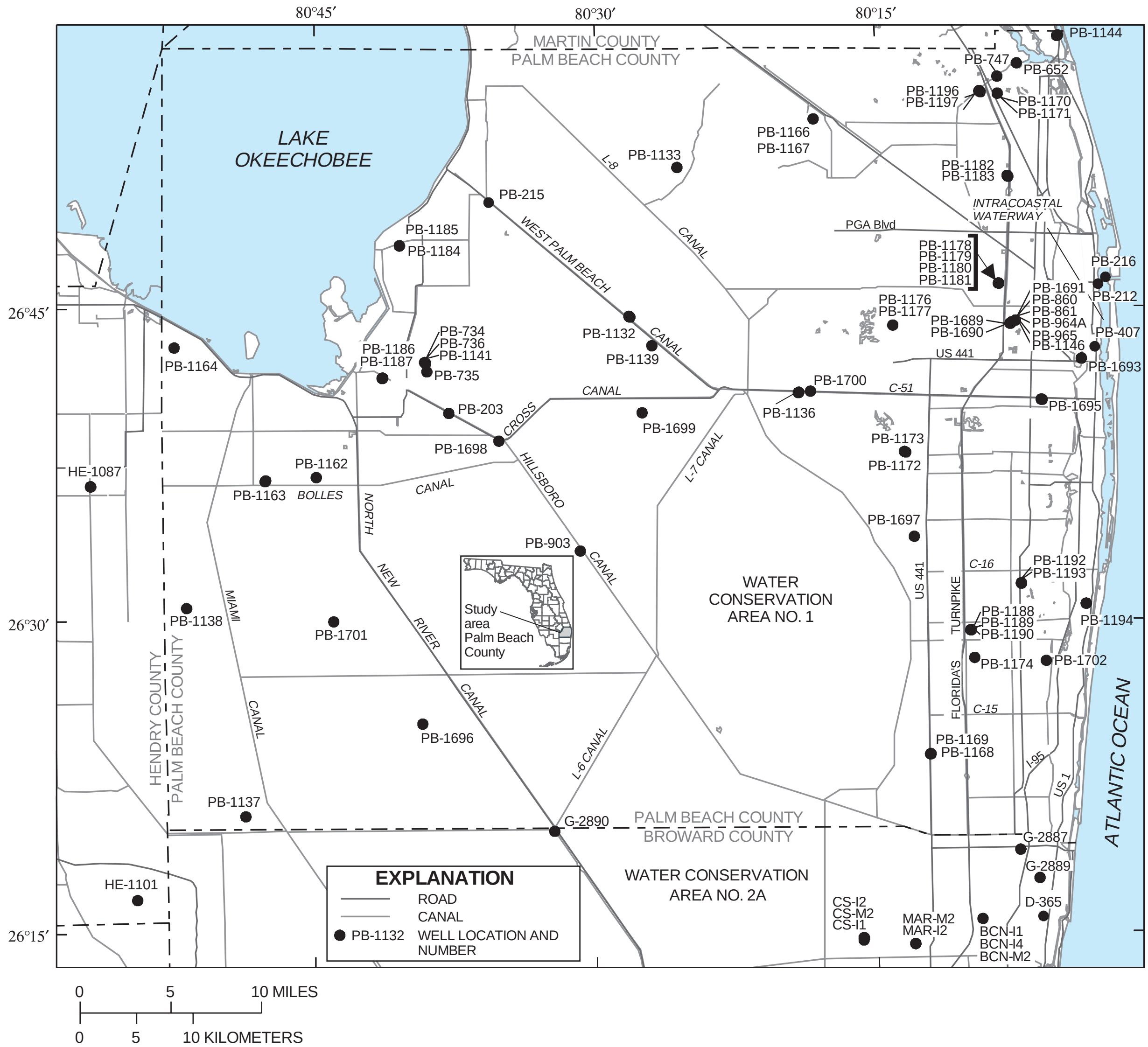


Figure 1. Location of the study area and all wells used in the study.

The Floridan aquifer system has been divided into three salinity zones. In order of increasing depth, they are the brackish-water zone, a transition zone, and the saline-water zone. The boundaries between these zones were determined principally by using borehole geophysical logs; water-quality data, with samples collected while drilling or from completed intervals, were also used. Maps were constructed that show the altitude of the base of the brackish-water zone and the distribution of salinity in the upper and lower intervals of this zone over the study area. Additionally, two plots were constructed that relate geologic data to chloride concentrations in the upper interval of the brackish-water zone, and another plot was constructed that shows the distribution of sulfate concentration relative to chloride concentration in the study area. The description and character of the brackish-water zone are emphasized in this report because of its potential use as a supplemental water-supply source. These maps and plots of the brackish-water zone were useful in determining processes that could control the distribution of salinity in the Floridan aquifer system.

Previous Studies

The Regional Aquifer System Analysis (RASA) Program of the USGS provided background information for this report. The final interpretive results of the RASA Program, which began in 1978, are presented in a series of USGS Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Several studies on the Floridan aquifer system that were conducted as part of the RASA Program (USGS Professional Paper 1403 series reports) were used for this report.

Meyer (1989) analyzed the hydrogeology, ground-water movement, and subsurface storage of liquid waste and freshwater in the Floridan aquifer system in southern Florida. Miller (1986), who studied the hydrogeologic framework of the Floridan aquifer system in the RASA study area (Florida and parts of Georgia, Alabama, and South Carolina), subdivided strata of the aquifer system into chronostratigraphic units, and constructed hydrogeologic sections, isopach maps, and structure maps. Additional studies of the same area were conducted by Bush and Johnston (1988), and Sprinkle (1989). Bush and Johnston (1988) described ground-water hydraulics, regional flow, and changes in the flow system as a result of ground-water development of the Floridan aquifer system. Sprinkle (1989) examined the geochemistry of the Floridan aquifer system, and mapped the concentrations of selected constituents in water from the Upper Floridan aquifer.

Chen (1965) studied the lithology and stratigraphy of Paleocene and Eocene strata in Florida and made paleographic interpretations. Miller (1986) confirmed that the Floridan aquifer system in southern Florida was mostly deposited during Eocene time. Puri and Winston (1974) mapped and described high transmissivity zones in southern Florida, which generally occur in the Floridan aquifer system. Scott (1988) studied the lithostratigraphy of the strata in Florida, which mostly overlie the Floridan aquifer system, and redefined the Hawthorn Formation as the Hawthorn Group.

Acknowledgments

The authors graciously thank Dr. Kevin Cunningham for his detailed description and analysis of cutting samples collected from some of the wells used in this report. The work by Dr. Cunningham, who was affiliated with the University of Miami (Rosenstiel School of Marine and Atmospheric Science, Division of Marine Geology and Geophysics), provided valuable points of control, and improved our understanding of the geologic framework of the Floridan aquifer system in southern Florida.

METHODS OF EVALUATION

The first part of this section describes the methods used in this study to classify and characterize salinity in the Floridan aquifer system. The second part describes the inventory of well data used, including the sources of wells and types of lithologic and geophysical log data available. The third part presents a discussion of the water-quality data used in this report, along with its sources, methods used in selection of previously collected data, and the methods used to collect the water samples.

Classification and Characterization of Salinity

A classification scheme for water based on dissolved-solids concentrations was used to define salinity in the Floridan aquifer system in the study area. In this scheme, which is a modification of the one by Fetter (1988, p. 368), brackish water contains dissolved-solids concentrations that range from 1,000 to 10,000 mg/L (milligrams per liter), moderately saline water contains concentrations that range from 10,000 to 35,000 mg/L, and saline water contains concentrations that range from 35,000 to 100,000 mg/L. In the scheme by Fetter (1988), saline water has a dissolved-solids concentration range from 10,000 to 100,000 mg/L, and the moderately saline water category is not used. Seawater has dissolved-solids concentrations of about 36,000 mg/L (Nordstrom and others, 1979). A well-defined relation between dissolved-solids and chloride concentrations in water from the Floridan aquifer system has been established for southeastern Florida (Reese, 1994), allowing these constituents to be interchanged in the characterization of salinity. In this report, chloride concentration is used to map the distribution of salinity.

Water in the Upper Floridan aquifer in southern Florida is brackish with chloride and dissolved-solids concentrations generally greater than 1,000 mg/L

(Sprinkle, 1989, pls. 6, 8). Most of the Lower Floridan aquifer contains water with a salinity similar to that of seawater (Meyer, 1989, fig. 3). Parts of the Floridan aquifer system where water has dissolved-solids concentrations less than 10,000 mg/L are to be protected from contamination by injected wastewater through the Underground Injection Control Program of the Safe Drinking Water Act (Fetter, 1988, p. 459). Underground injection control in Florida is regulated by the Florida Department of Environmental Protection (FDEP), formerly known as the Florida Department of Environmental Regulation (1982).

Inventory of Well Data

Data for all wells used in this study are presented in appendix I and include the following: a local well identifier, other well identifiers and/or owner, a site identification number, latitude and longitude, altitude of measuring point, well depth, bottom of casing, top and bottom of completed (open) interval, and date well construction was finished. A completed interval in a well is defined in this report as an interval open to flow regardless of the type of openings in the interval. Completed intervals are generally isolated from each other, and from other parts of the borehole, through the use of casing and cement during construction of the well.

Data from all wells used in this report are stored in the USGS Ground Water Site Inventory (GWSI) database. Some information on these wells beyond that given in appendix I, such as the land net location (section, township, and range) and drilling contractor's name, is stored in GWSI. Additional data on some wells, including site use, geophysical logs run, and a representative water-quality analysis, are presented in a publication by Smith and others (1982).

Depth in a well, as used in this report, refers to feet below the measuring point. In most cases, the altitude of the measuring point is the same as the elevation of the land surface, but in some cases, it is higher than the land surface such as the top of a drilling floor, which can be a number of feet above the land surface. If measurement of a point in a well is referenced to sea level datum in this report, the phrase "altitude, in feet below sea level" or simply "feet below sea level" will be used.

The most complete data sets from wells were collected from wastewater injection, ASR, and reverse-osmosis sites (table 1). At these sites, lithologic sample descriptions were produced and open-hole geophysical logs were run in boreholes penetrating sections of the Floridan aquifer system and above. The geophysical logs include electrical logs, dual-induction laterologs, borehole-compensated sonic logs, and natural-gamma- or gamma-ray logs. In some wells, whole-diameter cores of selected intervals in the Floridan aquifer system were taken and analyzed in a laboratory.

Many of the wells used in this study are located in close proximity to each other (fig. 1 and table 1). At most wastewater injection system sites, monitoring wells were drilled adjacent to an injection well. For example, injection wells PB-1188 and PB-1190 at the Palm Beach County Southern Region Wastewater Treatment Plant (WWTP) site are only 180 ft apart. Monitoring well PB-1189 is located halfway between the injection wells, with only 90 ft separating the monitor well from each injection well. Data collected from these and other wells drilled in close proximity at a site are considered as data collected from one well in this report.

Inventory and Collection of Water-Quality Data

Selected water-quality data that were collected from wells tapping the Floridan aquifer system are presented in appendix II. Included in the appendix are 132 water analyses taken from 56 wells, with the analyses listed alphabetically by local well identifier. Of the 132 analyses, 70 were obtained from completed intervals, 58 were obtained from open-hole intervals by a packer test, and 4 were obtained by a pumped-well test while drilling (pumped out of an open-hole section below casing). In the latter case, drilling is resumed after the pumped-well test is completed. Appendix II does not include water analyses obtained by the reverse-air rotary method while drilling, although these data at many of the sites were collected and reported by private consultants. Water analyses obtained by this method are used in this study for some wells, and a discussion of this method of drilling along with the problems associated with water samples collected by the reverse-air rotary method is presented in a publication by Reese (1994, p. 17).

Table 1. Wastewater injection, reverse-osmosis, and aquifer storage and recovery sites and identification of wells used in the study

[WWI, wastewater injection site; ASR, aquifer storage and recovery site; RO, reverse-osmosis water-supply site. Asterisk indicates injection and monitoring well pair located in close proximity to each other at same site]

Site name	Type of site	Wells used in study
Acme Improvement District	WWI	PB-1172*, PB-1173*
Belle Glade	WWI	PB-1186*, PB-1187*
Boynton Beach West Water Treatment Plant	WWI	PB-1192*, PB-1193*
Boynton Beach East Water Treatment Plant	ASR	PB-1194
Broward County North District Regional	WWI	BCN-I1, BCN-M2
Broward County No. 2A Water Treatment Plant	ASR	G-2889
Collier Manor	WWI	D-365
Coral Springs	WWI	CS-I1, CS-I2*, CS-M2*
Deerfield Beach West Water Treatment Plant	ASR	G-2887
Delray Beach North Storage Reservoir	ASR	PB-1702
Jupiter Water Systems	RO	PB-1196, PB-1197
Loxahatchee Environmental Control District	WWI	PB-1170*, PB-1171*
Margate	WWI	MAR-I2*, MAR-M2*
Pahokee	WWI	PB-1184*, PB-1185*
Palm Beach County Southern Regional	WWI	PB-1188*, PB-1189*, PB-1190
Palm Beach County System No. 3	WWI	PB-1174
Palm Beach County System No. 9 North	WWI	PB-1168*, PB-1169*
Pratt & Whitney	WWI	PB-1166*, PB-1167*
Quaker Oats Chemicals Industrial	WWI	PB-734, PB-735, PB-736, PB-1141
Royal Palm Beach	WWI	PB-1176*, PB-1177*
Seacoast Utilities Authority - Palm Beach Gardens	WWI	PB-1182*, PB-1183*
Solid Waste Authority - North County	WWI	PB-1178*, PB-1179*, PB-1180*, PB-1181*
West Palm Beach East-Central Regional	WWI	PB-860, PB-861, PB-964A, PB-965, PB-1146, PB-1689*, PB-1690*, PB-1691
West Palm Beach Water Treatment Plant	ASR	PB-1693

Several water samples (13 analyses) in appendix II were collected and analyzed by the USGS, but no USGS water samples were collected specifically for the purpose of this study. The analytical methods for determining specific conductance, and concentrations of chloride, dissolved solids, sulfate, and other constituents are described by Brown and others (1970). Data are stored in a USGS water-quality database (QWDATA). Several other water samples were collected by the SFWMD (10 analyses). However, most water-quality data (app. II), were collected from wastewater injection system wells by private consultants under contract to municipalities or county agencies – a large majority of these data were obtained from drilling and testing reports submitted by the various consultants to the FDEP following well construction. Control of water sampling and testing methods is overseen by the FDEP, originally known as the Florida Department of Environmental Regulation. According to FDEP rules (Florida Department of Environmental Regulation, 1982), the background water quality of the injection and monitoring zone(s) must be established prior to injection. FDEP permits issued to construct and operate injection well systems include specific testing requirements, one of which is pumping at least three well volumes of fluid from a monitoring well before sampling.

Despite the FDEP rules established for water-quality sampling, the initial sample analyzed and reported for background water quality of a completed interval may sometimes still be contaminated with drilling fluids. A slug of dense saltwater (or salt pillow), commonly used to control artesian pressure during drilling, can extensively invade the upper part of the Floridan aquifer system. Most monitoring wells are pumped or permitted to flow only on a periodic basis for sampling purposes, or the pumping or flowing rate can be low; therefore, if invasion into the formation has been extensive, the time required to return to background can be long. When a completed interval is contaminated, initial water samples generally show a change in salinity over time. Thus, an attempt was made in this study to select analyses from completed intervals after salinity had stabilized in an effort to portray uncontaminated formation water quality.

To retain an operating permit, a wastewater injection well facility is required to perform mechanical integrity testing (MIT) every 5 years after the initial permit is issued. A report is submitted to the FDEP for each test, and includes water-quality data collected during the prior 5 years from the Floridan aquifer system monitoring wells at the site. These data, collected on a weekly basis, are displayed as tables and plots in the FDEP report. This type of water-quality data was available and reviewed for all of the WWTP injection site monitoring wells completed before 1992 in the study area. In many instances, water-quality data from MIT reports were used for this study and are presented in appendix II because the data from the MIT reports indicated that the level of salinity reported in the drilling and testing reports had not yet stabilized to background level.

Open-hole packer test samples are often more contaminated than water samples from completed intervals due to the small volume of water produced before sampling and the possibility of drilling fluid leakage around the packers. Recently, barite-weighted bentonite drilling mud, in lieu of saltwater slugs, has been used to help minimize invasion and contamination of the formation during drilling. This mud in the form of wafers is placed in the hole above the zone of artesian pressure.

HYDROGEOLOGY OF THE FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system is defined as a vertically continuous sequence of permeable carbonate rocks of Tertiary age that are hydraulically connected in varying degrees, and whose permeability is generally several orders of magnitude greater than that of the rocks bounding the system above and below (Miller, 1986). This section presents a detailed description of the Floridan aquifer system in the study area, its component aquifers and confining units, and their relation to stratigraphic units.

Geologic Framework

The Floridan aquifer system in southern Florida includes, from oldest to youngest, the following: upper part of the Cedar Keys Formation of Paleocene age, Oldsmar Formation of early Eocene age, Avon Park Formation of middle Eocene age, Ocala Limestone of late Eocene age, and Suwannee Limestone of early Oligocene age (Miller, 1986). Overlying the Suwannee Limestone is the Hawthorn Group as defined by Scott (1988). The Hawthorn Group, which is divided into the Peace River Formation in the upper part and the Arcadia Formation in the lower part, was thought to be all Miocene in age (Miller, 1986; Scott, 1988); however, age-dating of core taken from a well in southwestern Florida has shown that the lowermost part of the Arcadia Formation is as old as early Oligocene in age (Wingard and others, 1994). For the present study, a lower portion of the Hawthorn Group has been defined using a marker unit and is referred to as the basal Hawthorn unit in this report. The Hawthorn Group is included in the intermediate confining unit, except for the lowermost part of the basal Hawthorn unit which is included in the Floridan aquifer system (fig. 2).

To illustrate geologic and hydrologic boundaries and spatial relations in the study area, two hydrogeologic sections were constructed (pls. 1 and 2). The locations of the east-west section (pl. 1, section A-A′) and the north-south section (pl. 2, section B-B′) are shown in figure 3. These hydrogeologic sections extend from sea level to a depth of 2,600 ft below sea level; however, some of the wells on the sections were not drilled this deep. Data presented on the sections for each well include a gamma-ray log curve and water-quality data. Geologic and salinity zone boundaries, as determined in this study, are also shown.

Lithology and Stratigraphy

The Floridan aquifer system in southern Florida is composed predominantly of limestone with dolomitic limestone and dolomite being common in the lower part of the aquifer system (fig. 2). An example of the geologic units, hydrogeologic units, lithology, and geophysical logs at a site in west-central Palm Beach County (wells PB-1186 and PB-1187) is shown in figure 4.

Delineation of the geologic units in the study area began with selected wells in which the boundaries of units were already known. Boundaries were determined using all available data including geophysical well logs and lithologic sample descriptions. The gamma-ray log was the most useful well log for determining geologic boundaries and extending boundaries by correlation between wells. The lithologic sample descriptions used in determining the geologic boundaries came from a variety of sources, including the Florida Geological Survey, the SFWMD, private consultants, individuals, and the present study. Most of the lithologic descriptions performed by the Florida Geological Survey were obtained from a computer database known as GeoSys/4G (GeoSys, Inc., 1990) in which geologic data are coded. Some of the descriptions of cuttings taken from oil wells were done by George Winston, a private geological consultant. The lithologic samples described through the present study were obtained from wells PB-903, PB-1132, PB-1133, PB-1137, PB-1139, and PB-1697 through PB-1701. Most of these sample descriptions (except those for wells PB-903, PB-1132, and PB-1139) were done at the University of Miami, Rosenstiel School of Marine and Atmospheric Science, by Dr. Kevin Cunningham (now with the USGS Miami Subdistrict). Six of these wells (PB-1137 and PB-1697 through PB-1701) were drilled by the Humble Oil and Refining Company as stratigraphic tests, and the sample interval for them was 10 ft, which provides good resolution of the geologic boundaries. A total of 55 wells were used in the delineation of geologic units in the study area; data for these wells are presented in table 2.

Eocene Group

The Oldsmar Formation, Avon Park Formation, Ocala Limestone, and Suwannee Limestone and their lateral rock equivalents are grouped, and referred to, as the Black Point Format (Winston, 1993, p. 31). In this study, these formations are also grouped together, but referred to informally, as the Eocene group, even though the Suwannee Limestone is early Oligocene in age. The occurrence of the Suwannee Limestone is interpreted to be minor in the study area in terms of both thickness and extent; it is not present in most of the study area. Demarcation of the geologic units in the Eocene group is difficult due to similarities in lithology and geophysical log response. The lithologic description for many of the wells in the study area does not include identification of microfossils that could be used to help determine boundaries. Additionally, Winston (1993; 1995) found evidence for facies changes and interfingering between these formations in southern Florida. This evidence contradicts the idea that upper boundaries of the Avon Park Formation and Ocala Limestone are represented by an unconformity with deposition of the unit restricted to a certain period of time, such as the Avon Park Formation of middle Eocene age (Miller, 1986, pl. 2). The subsequent discussion begins with the Oldsmar Formation and ascends the section.

Series	Geologic Unit	Approximate thickness (feet)	Lithology	Hydrogeologic unit	Approximate thickness (feet)
HOLOCENE	PAMLICO SAND	0-50	Quartz sand with shelly intervals	SURFICIAL AQUIFER SYSTEM	150-380
PLEISTOCENE	ANASTASIA FORMATION	0-200	Quartz sand, shell, and coquina		
	FT. THOMPSON FORMATION	0-40	Alternating marine molluscan limestone and freshwater marl		
PLIOCENE	TAMIAMI FORMATION	0-200	Sandy, shelly limestone, calcareous sandstone, quartz sand, and clayey sand		
MIOCENE AND LATE OLIGOCENE	HAWTHORN GROUP	600-800	Clay, marl, dolosilt, micritic limestone, clayey sand, silt, and phosphate grains	INTERMEDIATE CONFINING UNIT	600-700
	MARKER UNIT	90-130	Micritic limestone to marl, chert nodules, some phosphate grains		
?	BASAL HAWTHORN UNIT	30-355	Limestone, dolomite, shell, sand, sandstone, and calcareous clay or silt, abundant phosphate grains in places	FLORIDAN AQUIFER SYSTEM: LOWER HAWTHORN PRODUCING ZONE	10-180
EARLY OLIGOCENE	EOCENE GROUP: SUWANNEE LIMESTONE	0-150	Fossiliferous, calcarenitic limestone	UPPER FLORIDAN AQUIFER	500-700 ?
EOCENE: LATE	OCALA LIMESTONE	0-300	Chalky to fossiliferous, calcarenitic limestone		
EOCENE: MIDDLE	AVON PARK FORMATION ? (DOLOMITE UNIT 0-900)	900-1,200 ?	Fine-grained, micritic to fossiliferous limestone and dolomite	MIDDLE CONFINING UNIT	0?-900
EOCENE: EARLY	OLDSMAR FORMATION	1,100-1,500	Fine-grained, micritic to fossiliferous limestone, dolomitic limestone, and dense dolomite	LOWER FLORIDAN AQUIFER (BOULDER ZONE 300-650)	1,800
PALEOCENE	CEDAR KEYS FORMATION	500-600	Dolomite and dolomitic limestone		
		1,500?	Massive anhydrite beds	SUB-FLORIDAN CONFINING UNIT	1,500?

Figure 2. Generalized geology and hydrogeology of Palm Beach County.

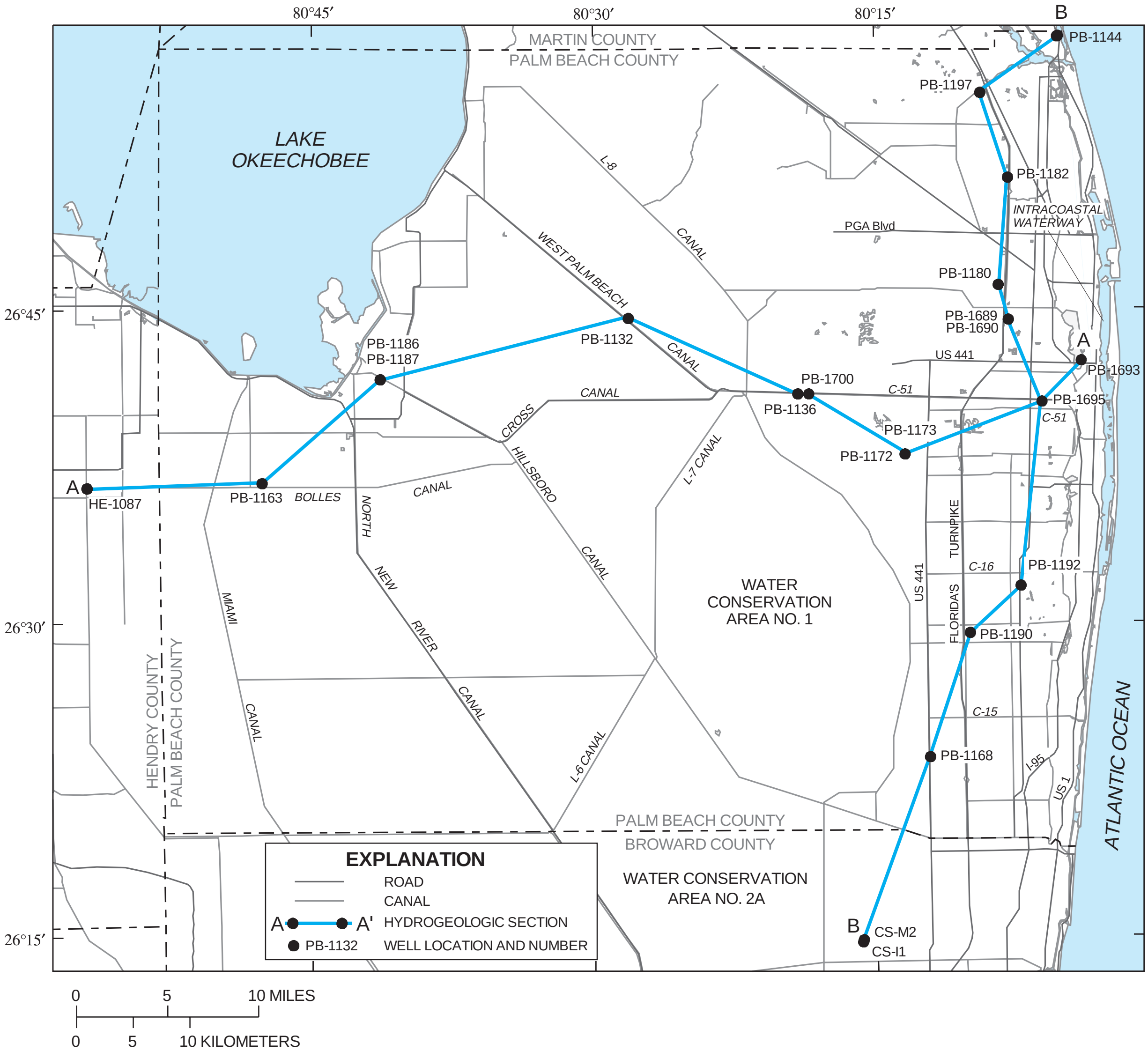
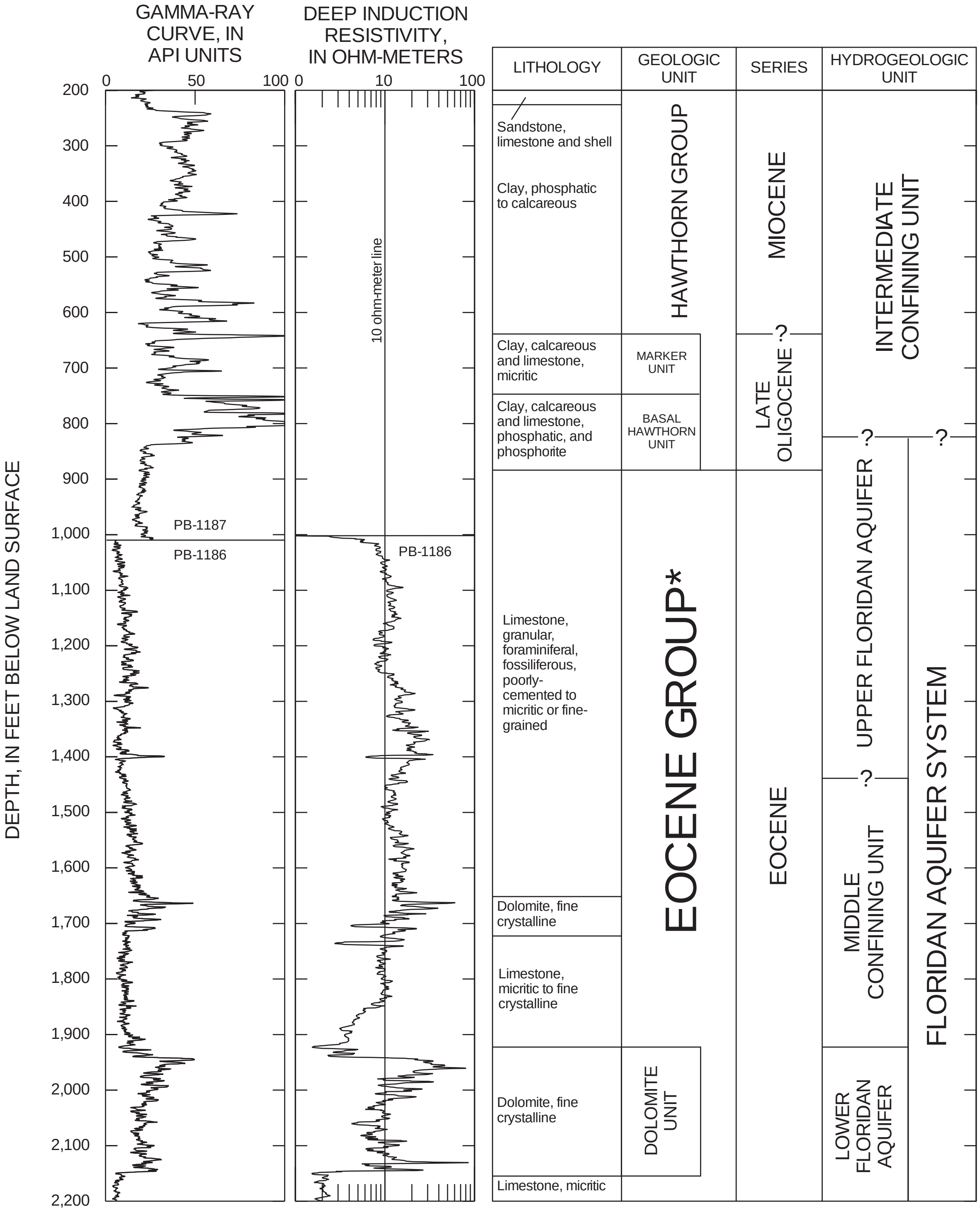


Figure 3. Traces of hydrogeologic sections A-A′ and B-B′ in the study area.

The Oldsmar Formation is about 1,100 to 1,500 ft thick in the study area (Miller, 1986, pl. 5), and its lithology is predominantly micritic limestone. The lower approximately 300- to 600-ft section of the Oldsmar Formation, locally called the Boulder Zone, is predominantly dolomite and contains massively bedded, cavernous or fractured dolomite of high permeability and dense, recrystallized dolomite of low permeability. Zones of similar lithology can also be present in the upper part of the Oldsmar Formation.

The top of the Avon Park Formation west of the study area is generally marked by a zone of thinly bedded, light-brown, finely crystalline to fossiliferous dolomite or dolomitic limestone that can be as thick as 50 ft. The Avon Park Formation predominantly consists of calcarenitic to micritic, fossiliferous limestone. In places, it consists of fine- to medium-grained carbonate sand that is moderately sorted to well sorted. Foraminifera characteristic of the Avon Park Formation are *Dictyoconus cookei* and *Dictyoconus americanus.*



EXPLANATION

API — AMERICAN PETROLEUM INSTITUTE STANDARD UNITS

? — BOUNDARY BETWEEN HYDROGEOLOGIC UNITS UNCERTAIN

* The Eocene group as informally defined in this report includes the Suwannee Limestone, Ocala Limestone, Avon Park Formation, and Oldsmar Formation. The Suwannee Limestone is interpreted to be present only in the far western portion of the study area.

Figure 4. Selected geophysical logs, stratigraphy, and hydrogeologic units for wells PB-1186 and PB-1187 in west-central Palm Beach County. Site is at the Belle Glade wastewater treatment plant.

Table 2. Boundaries of geologic units in selected wells penetrating the Floridan aquifer system as determined for this study

[Well locations are shown in figure 1. Boundaries of geologic units are shown in feet below measuring point, which usually is land surface (measuring points are presented in appendix I). Dark and medium shaded rows indicate wells are located at same site. Data used: SD, sample (lithologic) description; GL; geophysical log. Other annotations: Twin, top or base determined in adjacent well at site; >, greater than the value; --, well not deep enough or inadequate data available; NP, not present]

Local well identifier	Altitude of measuring point (feet)	Lower part of Hawthorn Group			Dolomite unit		Method used to determine boundaries
		Depth to top of Hawthorn marker unit	Depth to base of Hawthorn marker unit	Depth to basal contact of Hawthorn Group	Depth to top	Depth to base	
BCN-I1	14	790	895	1,050	1,920	2,180	SD,GL
CS-I1	13	Twin	930	1,165	2,150	2,250	SD,GL
CS-M2	13	810	935	1,100	Twin	Twin	SD,GL
G-2887	13	760	840	985	--	--	SD,GL
G-2889	17	--	850	996	--	--	SD,GL
G-2890	6	690	720	Not reached at 960 feet	--	--	SD
HE-1087	15	610	720	780	2,060	--	SD,GL
HE-1011	30	710	810	920	--	--	GL
MAR-I2	13	816	920	1,100	2,140	2,260	SD,GL
PB-203	18	680	800	910	--	--	SD
PB-216	<12	--	--	Not reached at 1,000 feet	--	--	SD
PB-652	7	765	878	1,090	--	--	GL
PB-734	15	650	742	860	--	--	GL
PB-736	15	Twin	Twin	860	Twin	Twin	SD
PB-1141	12	Twin	Twin	Twin	1,856	2,095	GL
PB-747	13	750	840	990	--	--	SD,GL
PB-903	11	790	890	1,000	--	--	SD
PB-1132	29	633	757	872	1,790	2,083	SD,GL
PB-1133	38	740	800	830	1,565	1,940	SD
PB-1136	34	--	770	920	1,410	1,950	SD,GL
PB-1137	31	707	810	932	2,330	2,500	SD,GL
PB-1138	31	666	765	865	2,170	2,451	SD,GL
PB-1139	31	600	720	930	--	--	SD
PB-1144	13	710	835	980	--	--	SD,GL
PB-1162	11	--	760	880	--	--	SD
PB-1163	12	480	720	840	--	--	SD
PB-1164	12	595	700	790	--	--	SD,GL

Table 2. Boundaries of geologic units in selected wells penetrating the Floridan aquifer system as determined for this study (Continued)

[Well locations are shown in figure 1. Boundaries of geologic units are shown in feet below measuring point, which usually is land surface (measuring points are presented in appendix I). Dark and medium shaded rows indicate wells are located at same site. Data used: SD, sample (lithologic) description; GL; geophysical log. Other annotations: Twin, top or base determined in adjacent well at site; >, greater than the value; --, well not deep enough or inadequate data available; NP, not present]

Local well identifier	Altitude of measuring point (feet)	Lower part of Hawthorn Group			Dolomite unit		Method used to determine boundaries
		Depth to top of Hawthorn marker unit	Depth to base of Hawthorn marker unit	Depth to basal contact of Hawthorn Group	Depth to top	Depth to base	
PB-1166	25	630	770	890	1,420	1,860	SD,GL
PB-1168	20	810	950	1,130	1,930	2,480	SD,GL
PB-1170	18	775	860	1,020	NP	NP	SD,GL
PB-1171	18	775	860	1,020	Twin	--	GL
PB-1172	16	Twin	Twin	Twin	Twin	2,082	SD
PB-1173	19	710	830	990	1,290	Twin	SD,GL
PB-1174	24	795	890	1,055	1,850	2,200	SD,GL
PB-1176	18	710	840	965	1,220	2,110	SD,GL
PB-1180	20	730	870	1,140	1,970	2,380	SD,GL
PB-1182	21	725	850	1,030	1,770	2,120	SD,GL
PB-1184	13	Twin	Twin	Twin	1,600	2,053	SD,GL
PB-1185	14	617	715	795	Twin	Twin	SD,GL
PB-1186	14	Twin	Twin	890	1,920	2,150	SD,GL
PB-1187	14	640	750	890	Twin	Twin	SD,GL
PB-1190	22	740	850	1,010	1,610	2,250	SD,GL
PB-1192	20	730	820	980	1,420	1,960	SD,GL
PB-1194	19	710	795	950	--	--	SD,GL
PB-1197	17	780	880	1,110	1,820	>1,900	SD,GL
PB-1689	19	Twin	Twin	1,180	NP	NP	SD,GL
PB-1690	19	695	825	1,180	Twin	--	SD,GL
PB-1693	19	675	790	1,020	--	--	SD,GL
PB-1695	15	715	820	1,050	NP	NP	SD,GL
PB-1696	11	685	725	880	1,585	>1,705	SD
PB-1697	15	670	770	960	--	--	SD
PB-1698	12	700	820	960	--	--	SD
PB-1699	13	610	770	870	--	--	SD
PB-1700	17	690	760	880	--	--	SD
PB-1701	12	720	800	890	--	--	SD
PB-1702	21	750	840	1,030	--	--	GL

A thick interval containing mostly dolomite, commonly interbedded with limestone, is usually present in either the Avon Park Formation, the upper part of the Oldsmar Formation, or both. Such a unit is present in well PB-1186, extending from a depth of 1,920 to 2,150 ft (1,906 to 2,136 ft below sea level) as shown in figure 4. The depths of the top and base of this dolomite unit, in the wells in which it could be determined, are given in table 2. Where determined, the top of the dolomite unit was as shallow as 1,200 ft below sea level (well PB-1176) and the base as deep as 2,470 ft below sea level (well PB-1137). The upper part of the dolomite unit where well PB-1176 is located, is characterized as brown, medium crystalline, sucrosic dolomite (CH_2M Hill, 1988). Although the dolomite unit was found to be as thick as 890 ft (well PB-1176), the unit generally is about 200 to 400 ft thick in the study area. A thickening of the dolomite unit usually occurs with the development of dolomite from the top of the unit upward in the stratigraphic section.

The lithology of the Ocala Limestone varies from micritic or chalky limestone, to a medium-grained calcarenitic limestone, to a coquinoid limestone. The Ocala Limestone is characterized by abundant larger benthic foraminifera, such as *Operculinoides sp., Camerina sp.,* and *Lepidocyclina sp.* (Peacock, 1983). The presence of these foraminifera aids in distinguishing this geologic unit from the overlying Suwannee Limestone (if present) and the underlying Avon Park Formation.

Suwannee Limestone

The Suwannee Limestone of early Oligocene age is interpreted to be present only in the far western Palm Beach County and Hendry County portions of the study area. In well PB-1138 in southwestern Palm Beach County, the Suwannee Limestone extends from a depth of 865 to 956 ft (Miller, 1986). The dominant lithology of the Suwannee Limestone west of the study area is pale-orange to tan, fossiliferous, medium-grained calcarenite with minor amounts of quartz sand. Phosphatic mineral grains are rare to absent. Miller (1986, pl. 11) interprets that rocks of Oligocene age (Suwannee Limestone) are not present in eastern and northern Palm Beach County and northeastern Broward County.

Hawthorn Group

The Hawthorn Group consists of an interbedded sequence of widely varying lithologies and components that include limestone, dolomite, dolosilt, shell, quartz sand, clay, phosphate grains and mixtures of these materials (fig. 2). The characteristics that distinguish the Hawthorn Group from underlying units are its high and variable siliciclastic and phosphatic content; its color, which can be green, olive-gray, or light gray; and its gamma-ray log response (fig. 4 and pls. 1 and 2). Intervals high in phosphate sand or gravel (as thick as 30 ft) are present in places and have high gamma-ray activity, with peaks of 100 to 200 American Petroleum Institute (API) standard units or more. Phosphate grain content as high as 15 percent is common.

The basal contact of the Hawthorn Group often coincides with a change from the lower gamma-ray activity of the Eocene group (generally less than 20 API units) to the higher activity in the Hawthorn Group. However, to make an accurate determination of the depth of the basal contact, both gamma-ray log responses and lithologic descriptions need to be used. For example, if only the gamma-ray curve were used, the basal contact would have been placed 50 ft higher (at 840 ft instead of 890 ft) in well PB-1187 (fig. 4). Lithologic changes that occur upward at this contact include the following: (1) the introduction of common to abundant quartz sand, clay, phosphate grains, or a mixture of these materials; (2) a change in the most common fossil types from benthic foraminifera such as *Dictyoconus sp.* to shell material derived from bivalves; (3) a change (usually) in color from pale-orange or pinkish-gray below to white or light-gray to yellowish-gray above; and (4) a change in the dominant grain size from medium or coarse grained below to fine grained or finer above.

The basal Hawthorn unit underlies the marker unit as shown in figure 4. Gamma-ray log responses indicate that the basal Hawthorn unit can usually be divided into two intervals: a lower interval that has activity similar to (but still usually higher than) the low activity in the Eocene group that underlies the basal Hawthorn unit, and an upper interval that has high activity. The lithology of the basal Hawthorn unit is highly variable, consisting of calcareous clay or silt; sandy, fossiliferous limestone; calcareous, fine-grained, quartzose sand or sandstone; dolomite; shell material; and phosphate sand. Phosphate grains can be abundant in all of these lithologies. Generally, the lower interval has more limestone, dolomite, and sand or sandstone; whereas the upper interval has more clay, silt, and phosphate grains.

The marker unit of the Hawthorn Group is present throughout the study area and correlates with a marker unit west of the study area in Lee, Hendry, and Collier Counties (Reese, 1999). The thickness and characteristic pattern of the marker unit shown by gamma-ray logs remain consistent over large portions of the study area (pls. 1 and 2). Thin beds having higher gamma-ray activity within and at the upper and lower boundaries of the marker unit could be synchronous in their deposition over large areas. The lithology of the marker unit varies from micritic limestone to marl and has been described as being arenaceous and containing chert nodules in eastern Palm Beach County. The lithology generally differs from the overlying and underlying beds, in that the marker unit has lower phosphate grain content, fewer shell fragments, and is finer grained. The marker unit corresponds relatively well with H-2: a unit defined in the Hawthorn Formation in southern Collier County to the southwest of the study area, in which the benthic foraminifera *Miogypsina sp.* was found (Peacock, 1983, p. 17).

Unconformity

The basal contact of the Hawthorn Group coincides with an important unconformity in the study area, and this unconformity corresponds with an unconformity that is present at the top of the rocks of Eocene age in southeastern Florida (Reese, 1994, fig. 6). Although some previous investigators have identified the Suwannee Limestone to be present above the top of rocks of Eocene age in southeastern Florida, it is possible that the Suwannee Limestone is not present in most of this area (Reese, 1994, p. 6). The Suwannee Limestone is present and well developed to the west of the study area in southwestern Florida. Using geophysical logs, correlation of the marker unit and the basal Hawthorn unit westward from southeastern Florida (Palm Beach County and the counties to the south) to southwestern Florida places the Suwannee Limestone in southwestern Florida subjacent to this unconformity (Reese, 1999).

The unconformity at the base of the Hawthorn Group (top of Eocene-aged rocks) in southeastern Florida has subsurface relief of at least as much as 100 ft (Reese. 1994, fig. 5). This relief could be caused by erosion and solution of the underlying carbonate rock. Continuous core taken from a well at Long Key in the Florida Keys, about 80 mi (miles) south of Palm Beach County, shows that a subaerial erosion surface is present at the contact between the Hawthorn Group and the Suwannee Limestone, and that this contact represents a depositional sequence boundary (Cunningham and Rupert, 1996). This boundary and the associated erosion could have formed as a result of a major low stand in sea level that occurred between early and late Oligocene time (Haq and others, 1988) and could be correlative to the contact between the Eocene group and the Hawthorn Group where the Suwannee Limestone is absent.

Structure

Three subsurface geologic contour maps were constructed that describe the basal Hawthorn unit. They show the altitude of the top of the unit, altitude of the base (basal contact of the Hawthorn Group), and thickness of the unit in the study area. Another map was constructed showing the altitude of the top of the dolomite unit in the Eocene group. The basal Hawthorn unit is emphasized because of its hydrologic significance as will be shown later in this report.

The altitude of the top of the basal Hawthorn unit, which also is the base of the overlying marker unit, ranges from about 690 to 930 ft below sea level in the study area (fig. 5). The persistent gamma-ray log pattern and continuity of the marker unit suggest that variations in the altitude of its base are due to structural movements or subsidence occurring after deposition, rather than paleotopography created prior to or during deposition. Two low areas are present in the study area—one to the east that parallels and lies between 5 and 10 mi from the coast, and the other passes through south-central Palm Beach County, trending northwest-southeast.

The altitude of the basal contact of the Hawthorn Group ranges from about 765 to 1,165 ft below sea level in the study area (fig. 6). Three low areas are present along the coast, all trending northeast-southwest. One area is in extreme northeastern Palm Beach County centered around wells PB-1197 and PB-652, the second area is in northeastern Palm Beach County centered around wells PB-1180 and PB-1690, and the third area is in northeastern Broward County to southeastern Palm Beach County centered around wells CS-I2 and PB-1168. A low area is also present in south-central Palm Beach County near well PB-903, trending northwest-southeast.

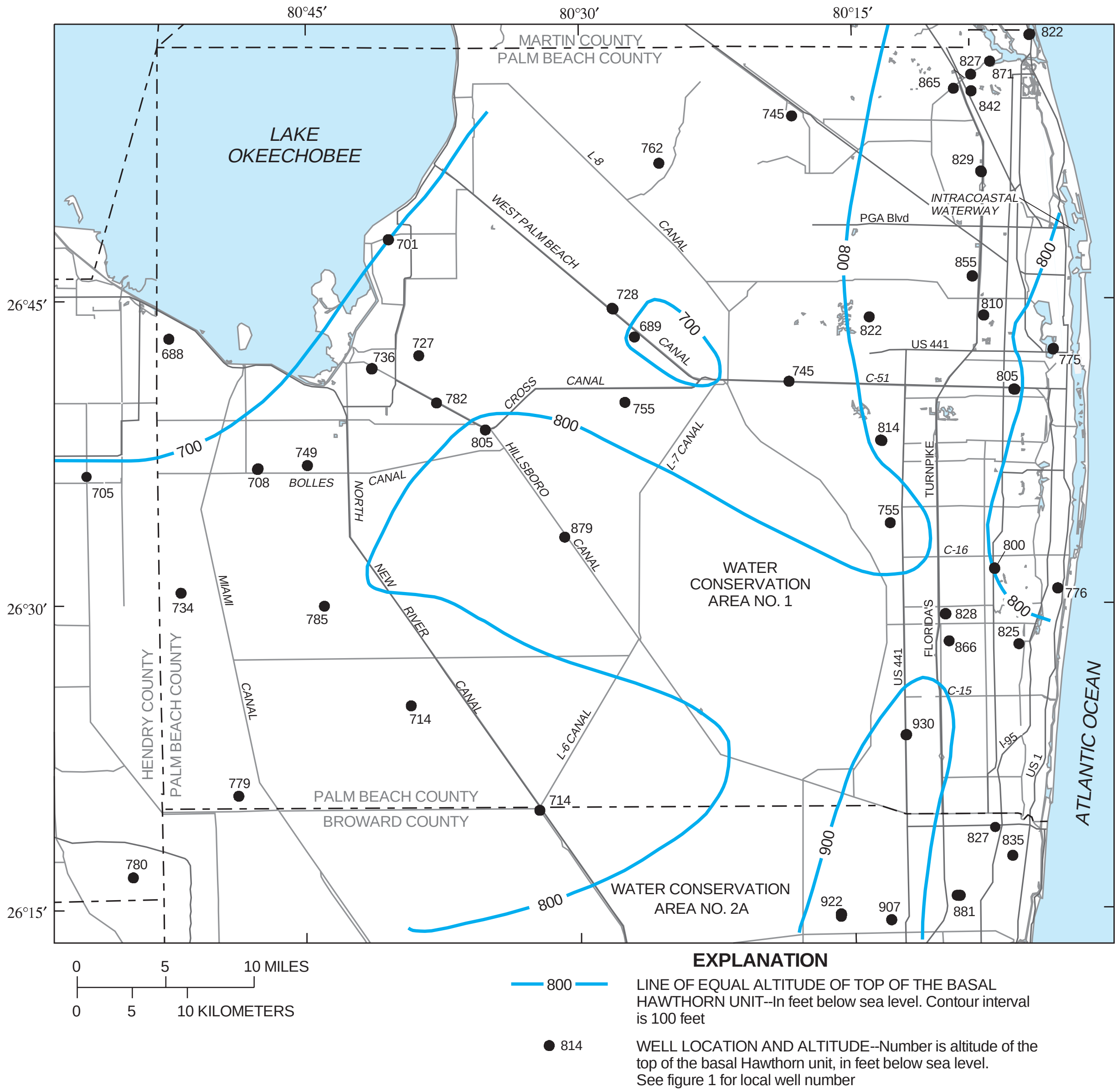


Figure 5. Altitude of the top of the basal Hawthorn unit in Palm Beach and northern Broward Counties.

Some structural features present at the basal contact of the Hawthorn Group (fig. 6) coincide with those present at the top of the basal Hawthorn unit (fig. 5). Both maps indicate a general dip to the southeast, a low area trending northwest-southeast in south-central Palm Beach County, and low areas close to the coast. These similarities suggest that much of the relief present on the basal contact surface is the result of consistent structural movements or subsidence during and after deposition of the basal Hawthorn unit. However, variations in thickness of this unit indicate that vertical movements were not the same in all areas, or that some of the relief present on the basal contact has a different origin.

The thickness of the basal Hawthorn unit is highly variable, ranging from 30 to 355 ft (fig. 7). The areas where the interval is thickest generally coincide with the three areas of low altitude at the basal contact of the Hawthorn Group that are in eastern Palm Beach County and that trend northeast-

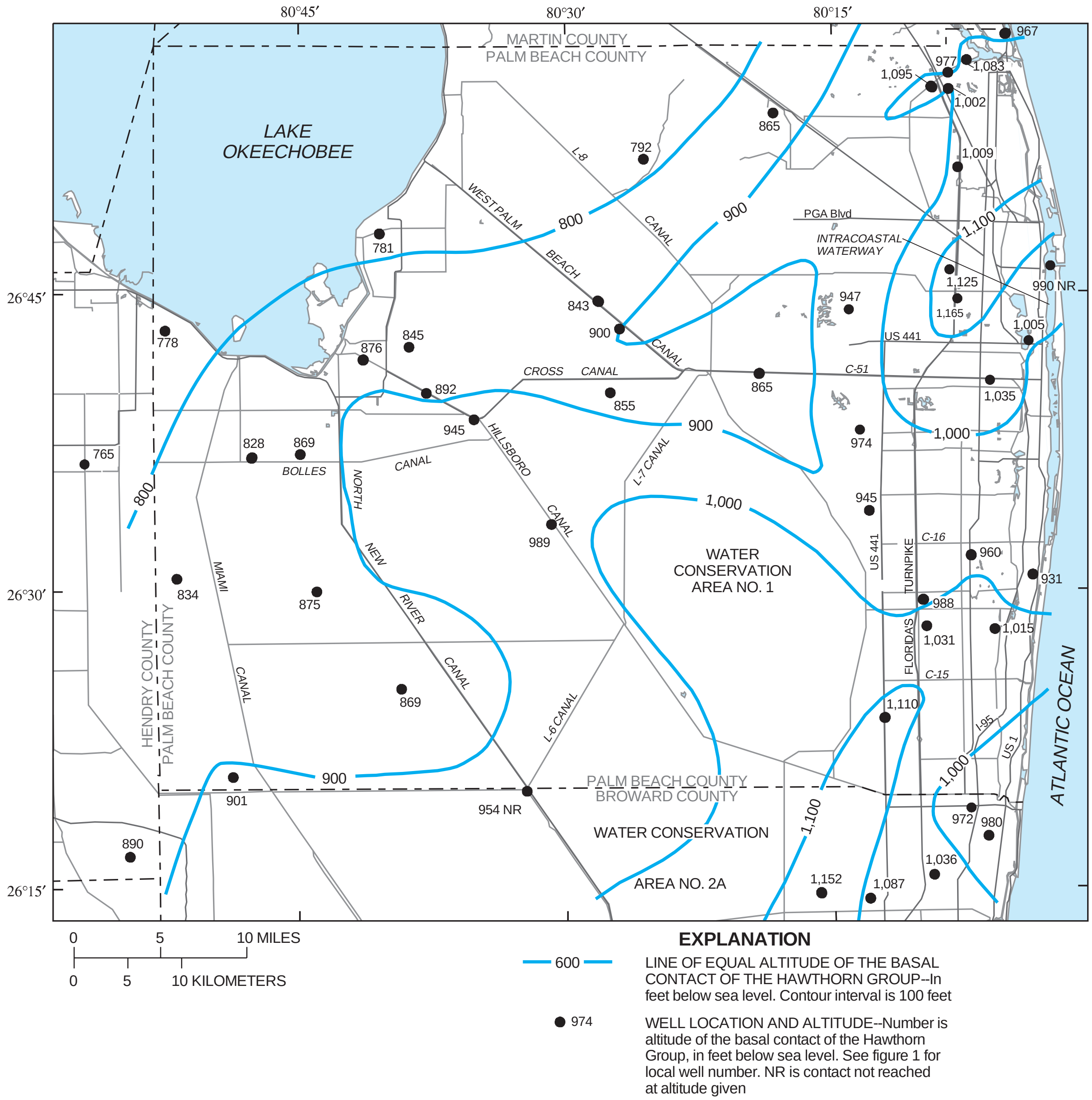


Figure 6. Altitude of the basal contact of the Hawthorn Group in Palm Beach and northern Broward Counties.

southwest (fig. 6). In parts of these low areas, the thickness exceeds 200 ft; however, in one of the low areas in northeastern Palm Beach County, the thickness is as much as 355 ft (well PB-1690).

Variations in the thickness of the basal Hawthorn unit (fig. 7) suggest that there was paleotopography present just before or during deposition of this unit. According to this interpretation, areas where the basal Hawthorn unit is thick represent paleotopographic lows and areas where the unit is thin represent paleotopographic highs. The extreme thickness of the unit in the three areas in eastern Palm Beach County of low altitude at the basal contact of the Hawthorn Group indicates that the areas were topographic lows during deposition of the unit and were filled in by this deposition. The origin of these paleotopographic low areas could be explained by two possible theories: (1) erosion after deposition of the Eocene group during a period of low sea level associated with the unconformity at the basal contact of the Hawthorn Group, or (2) differential

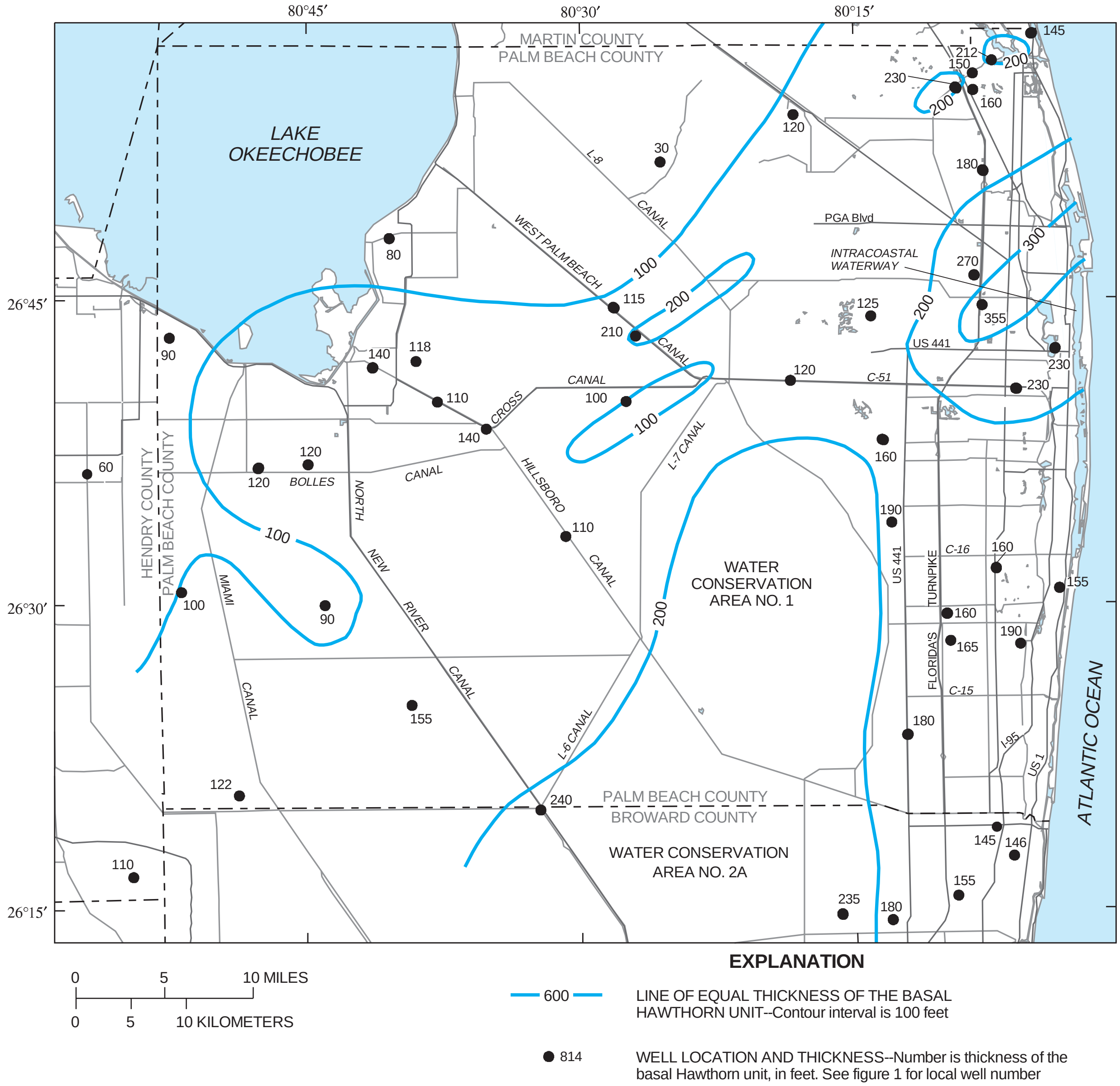


Figure 7. Thickness of the basal Hawthorn unit in Palm Beach and northern Broward Counties.

subsidence during deposition of the basal Hawthorn unit with a higher rate of subsidence in the low areas. This differential subsidence could have been caused by continuous movement of deep-seated faults bordering the low areas. Some evidence was found in favor of the latter theory; gamma-ray logs were used for stratigraphic correlation between wells in the low areas and nearby wells outside the low areas. Results indicated that substantial thickening of the upper part of the Eocene group as well as the basal Hawthorn unit occurred in some low areas.

The altitude of the top of the dolomite unit within the Eocene group varies considerably, ranging from about 1,200 to 2,300 ft below sea level (fig. 8). A low area extends from southeastern Palm Beach County to the northwest toward Lake Okeechobee. This low area could be structural in nature because it approximately coincides with an area of low altitude at

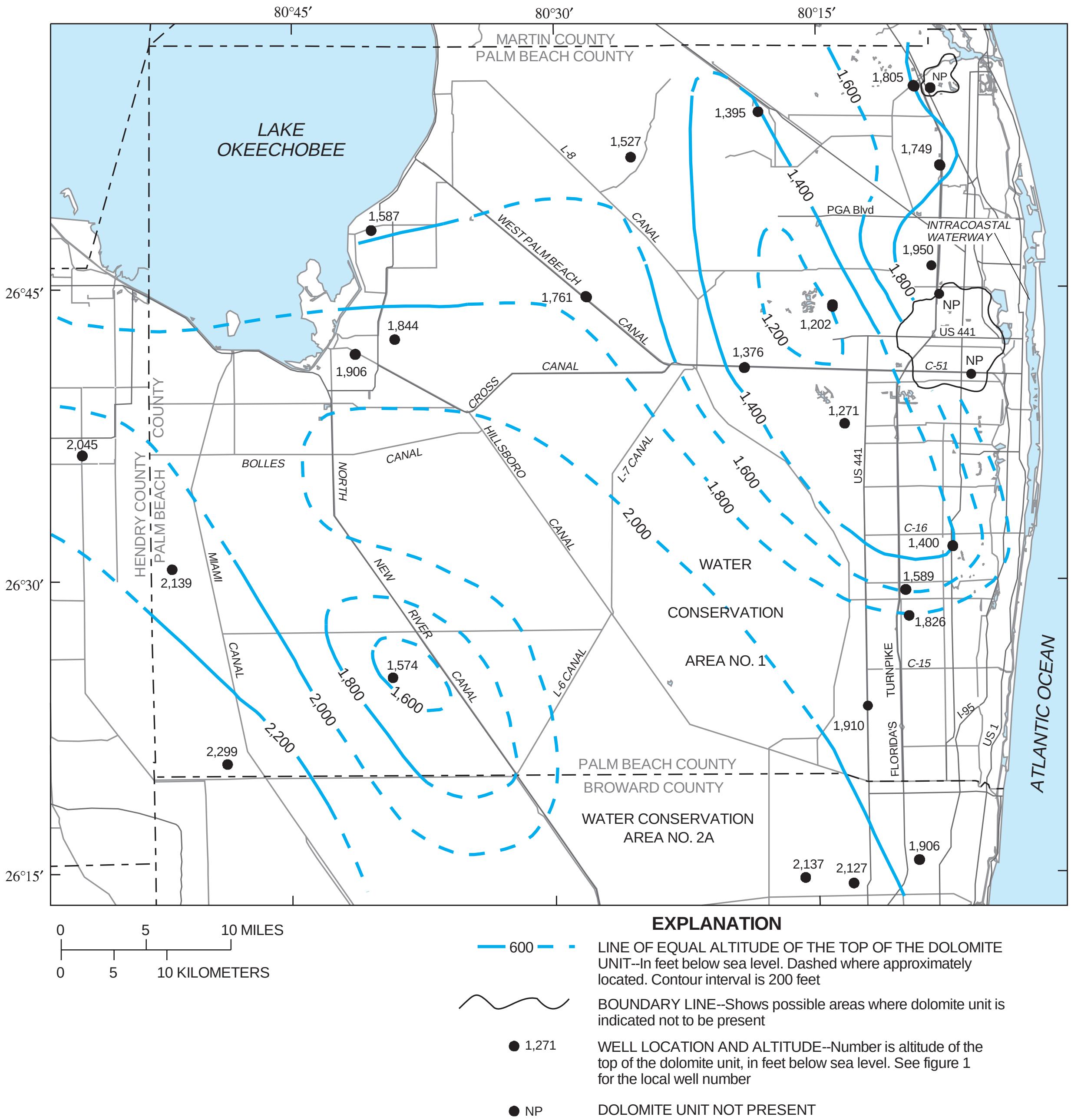


Figure 8. Altitude of the top of the Eocene group dolomite unit in the Floridan aquifer system in Palm Beach and northern Broward Counties.

the top and base of the basal Hawthorn unit (figs. 5 and 6). A high area is present in northeastern Palm Beach County, trending to the north-northwest, where the altitude is as high as 1,200 ft below sea level. This high area does not coincide with areas of high altitude at the top or base of the basal Hawthorn unit (figs. 5 and 6), and its origin could be related to depositional changes or diagenetic events that caused the development of dolomite higher in the Eocene group here than in adjacent areas. The dolomite unit is not present in one area in east-central Palm Beach County (fig. 8, wells PB-1689 and PB-1695) and in another area located in extreme northeastern Palm Beach County (fig. 8, well PB-1170).

Hydrogeologic Units

The Floridan aquifer system is divided into three hydrogeologic units: the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer (fig. 2). Overlying the Upper Floridan aquifer is a confining unit referred to as the intermediate confining unit (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). The surficial aquifer system lies between the intermediate confining unit and the land surface. Hydrogeologic units in the study area are discussed in subsequent sections of this report, beginning with the intermediate confining unit.

Intermediate Confining Unit

The intermediate confining unit extends from the base of the surficial aquifer system to the top of the Floridan aquifer system in southeastern Florida. However, in southwestern Florida, the confining unit contains a group of aquifers and is referred to as the intermediate aquifer system (Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986). The intermediate confining unit contains the Hawthorn Group of Miocene to late Oligocene age, except for the lowermost permeable part of the basal Hawthorn unit (fig. 2). The lithology of the intermediate confining unit is variable and includes fine-grained sediments, such as clay, marl, and micritic limestone, which provide confinement. The altitude of the top of the intermediate confining unit ranges from 140 ft below sea level in some inland areas to as much as 360 ft below sea level in some coastal areas (Miller, 1987).

Upper Floridan Aquifer

The Upper Floridan aquifer is generally 500 to 600 ft thick in southeastern Florida and consists of several thin water-bearing zones of high permeability interlayered with thick zones of low permeability (Reese, 1994, p. 14). The lower part of the basal Hawthorn unit and the upper part of the Eocene group are contained within the Upper Floridan aquifer in Palm Beach County (fig. 2). The potentiometric surface of the Upper Floridan aquifer ranges from about 40 ft above sea level in coastal southeastern Palm Beach County to about 60 ft above sea level in the far western part of the county and dips from west to east (Bush and Johnston, 1988, pl. 5).

The Upper Floridan aquifer is delineated on the basis of permeability characteristics. Thus, neither the top nor the base of the Upper Floridan aquifer necessarily conforms to formation or time-stratigraphic boundaries. The aquifer exists under flowing artesian conditions, so its permeable zones (or flow zones) can be defined in a well by using flowmeter and temperature logs.

The uppermost permeable zones of the Upper Floridan aquifer occur in close association with the unconformity at the top of the Eocene group, and this geologic contact is close to the top of the Upper Floridan aquifer. However, the top of the uppermost permeable zone can occur significantly above this contact. For example, in a well that was drilled in southeastern Broward County, Reese (1994, p. 14) determined that the top of this zone is 40 ft above the top of the rocks of Eocene age. Based on the position of the top of the uppermost permeable zone determined in wells with adequate data and gamma-ray logs in other wells, the approximate top of the Upper Floridan aquifer was determined for the wells on the two hydrogeologic sections (pls. 1 and 2). The lowermost part of the basal Hawthorn unit that contains flow zones is referred to as the lower Hawthorn producing zone and is estimated to range in thickness from 10 to 180 ft (fig. 2).

The depth to the base of the Upper Floridan aquifer is variable and difficult to determine because of the following: (1) much of the aquifer can consist of thick intervals of relatively low permeability, and (2) the decrease in permeability with depth in the aquifer can be gradual. The altitude of the low-permeability rocks that mark the base of the Upper Floridan aquifer ranges from 1,000 ft below sea level in northwestern Palm Beach County to 1,400 ft below sea level in northeastern Palm Beach County (Miller, 1986, pl. 29). For the present study, the base of the Upper Floridan aquifer is placed at a depth greater than 1,400 ft based on lithologic and geophysical data collected from wastewater-injection wells and various other wells in the study area. For example, in wastewater injection well PB-1168 in southeastern Palm Beach County, the base of the Upper Floridan aquifer was placed at 1,780 ft below sea level (CH_2M Hill, 1986).

The highest flow zone of the Upper Floridan aquifer occurs 90 ft above the basal contact of the Hawthorn Group in well PB-1197 in northeastern Palm Beach County; the top of the Upper Floridan aquifer was placed at the top of this flow zone at a depth of 1,020 ft (fig. 9). The base of the Upper

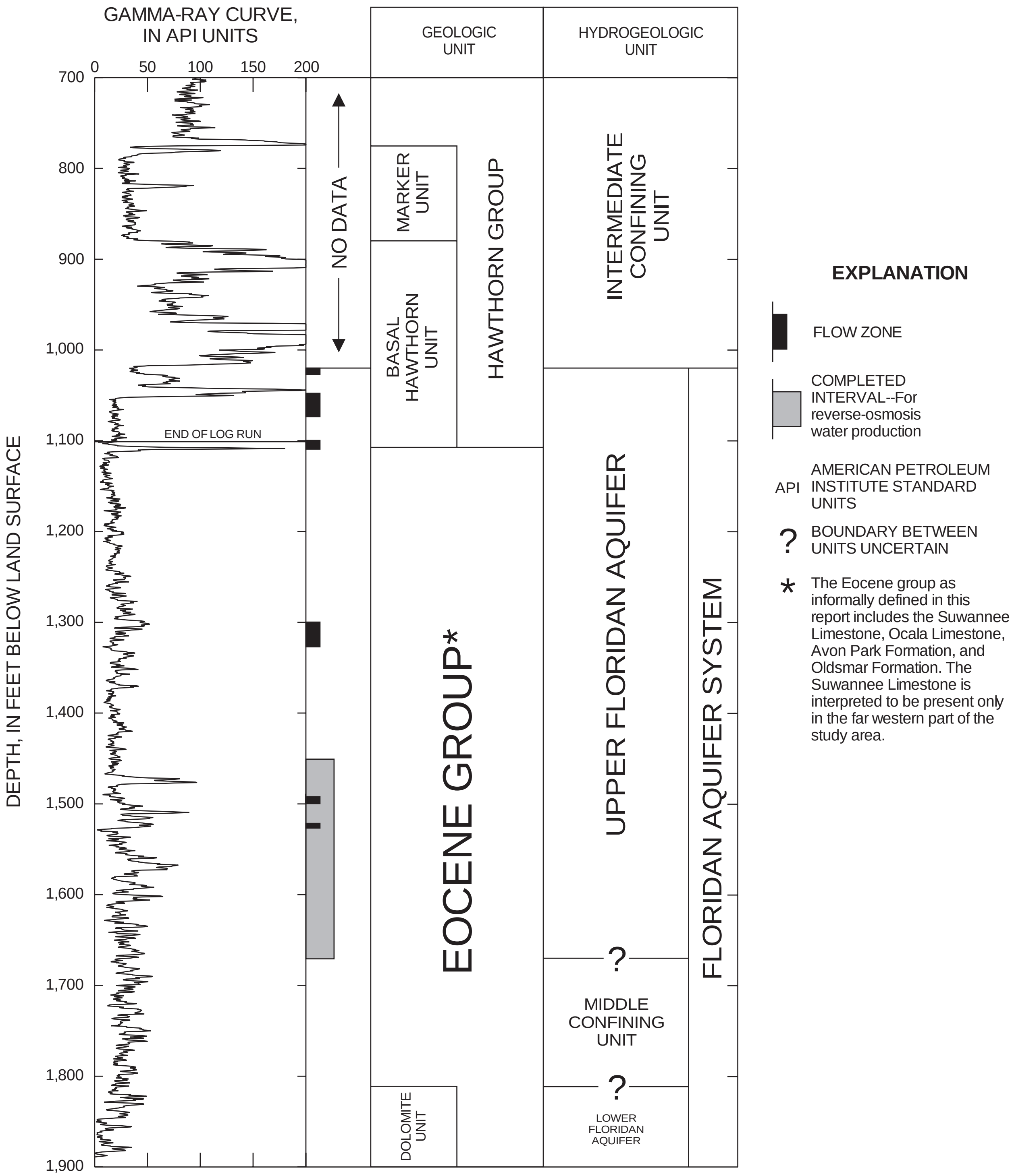


Figure 9. Gamma-ray geophysical log, flow zones below 1,020 feet, geologic units, and hydrogeologic units for well PB-1197 in northeastern Palm Beach County. Flow zones determined from flowmeter and temperature logs and flow measurements while drilling. Site is at the Jupiter water systems plant.

Floridan aquifer is placed at 1,665 ft deep in well PB-1197 and coincides with the bottom of an interval of interbedded limestone and dolomite that contains two flow zones and extends up to a depth of 1,475 ft. The top of the dolomite unit of the Eocene group is placed at 1,820 ft deep in well PB-1197 (fig. 9 and table 2). Thick intervals composed mostly of dolomite were first encountered at this depth; however, it is not known whether these deeper intervals of dolomite are permeable. A flowmeter log from well G-2887 in northeastern Broward County indicates that a flow zone is present just above the basal contact of the Hawthorn Group, which is at a depth of 985 ft (fig. 10). The gamma-ray log from well G-2887 indicates that permeable limestone could be present at a depth as shallow as 920 ft in the basal Hawthorn unit (fig. 10).

The Upper Floridan aquifer could include the dolomite unit of the Eocene group in some areas of Palm Beach County where the top of the unit is high, such as in eastern Palm Beach County (fig. 8), and this could considerably extend the base of the aquifer. For example, the dolomite unit ranges from 1,202 to 2,092 ft below sea level in well PB-1176 in northeastern Palm Beach County. Because the top of the dolomite unit is high in this well (fig. 8), the Upper Floridan aquifer probably extends down into the dolomite unit. CH_2M Hill (1988, fig. 3-1) places the top of the middle confining unit of the Floridan aquifer system at 2,082 ft below sea level in well PB-1176. High permeability can be present in dolomite beds because of their potential for development of extensive secondary porosity and fracturing.

The transmissivity of the Upper Floridan aquifer in Palm Beach is estimated to range from 10,000 to 100,000 ft^2/d (feet squared per day) according to Bush and Johnston (1988). Transmissivity was determined in well PB-1197 in northeastern Palm Beach County by a multiple-well aquifer test to have a range from about 32,000 to 132,000 ft^2/d (ViroGroup, 1994). The completed open interval in the pumped well (PB-1197) is 214 ft long and extends from a depth of 1,451 to 1,665 ft (fig. 9). Aquifer tests of the flow zones above this interval, including those in the basal Hawthorn unit, were not performed in well PB-1197. Transmissivity was also determined in well G-2887 in far northeastern Broward County by a multiple-well aquifer test and was estimated to be 24,000 ft^2/d (Camp, Dresser and McKee, 1993). The completed interval open in the pumped well (G-2887) is 168 ft long, but only 25 ft of this interval is above the basal contact of the Hawthorn Group in the well (fig. 10). In well PB-1695 in east-central Palm Beach County (fig. 1, pls. 1 and 2), a packer test of the 140-ft interval from 1,035 to 1,175 ft below sea level indicated a transmissivity of about 64,800 ft^2/d; a packer test of the 140-ft interval from 1,345 to 1,485 ft below sea level in the same well indicated a transmissivity of about 49,100 ft^2/d (John Lukasiewicz, South Florida Water Management District, written commun., 1996). The interval from 1,235 to 1,485 ft below sea level is referred to by the SFWMD as the "middle Floridan aquifer," an informal unit not used in this report. Temperature and flowmeter logs run in this well show no indication of flow zones between 1,485 and 2,385 ft below sea level.

The above data indicate that transmissivity of the Upper Floridan aquifer could be related to the thickness of the basal Hawthorn unit (fig. 7). The thickness of the basal Hawthorn unit in wells PB-1197 and PB-1695 in northeastern Palm Beach County is 230 ft, and the transmissivity in both wells was determined to be high. In comparison, the thickness of the basal Hawthorn unit is only 145 ft in well G-2887 in northeastern Broward County, and the transmissivity in this well was determined to be significantly lower than in wells PB-1197 and PB-1695. In wells CS-I1 and CS-I2 (fig. 1) in northeastern Broward County, the thickness of the basal Hawthorn unit is 235 ft thick in well CS-I1, and based on drilling characteristics and water-quality data, there were indications of high permeability in the Upper Floridan aquifer at the site (Reese, 1994, p. 44). Some correlation of higher transmissivity and increasing thickness is to be expected. The transmissivity, at least of the basal Hawthorn unit, should be higher because where thickening of the unit occurs, there is a greater thickness of limestone, and possibly dolomite, in the lower part of the unit; additionally, these lithologies are permeable or have flow zones developed within them.

Middle Confining Unit

The middle confining unit of the Floridan aquifer system in the study area is included in the middle to lower part of the Eocene group (fig. 2), and principally consists of micritic fossiliferous limestone of low permeability. The base of the middle confining unit is placed at the top of the shallowest zone of high permeability dolomite (dolostone) occurring in the Oldsmar Formation (Meyer, 1989). In most of the study area, the top of this first dolomite zone is the top

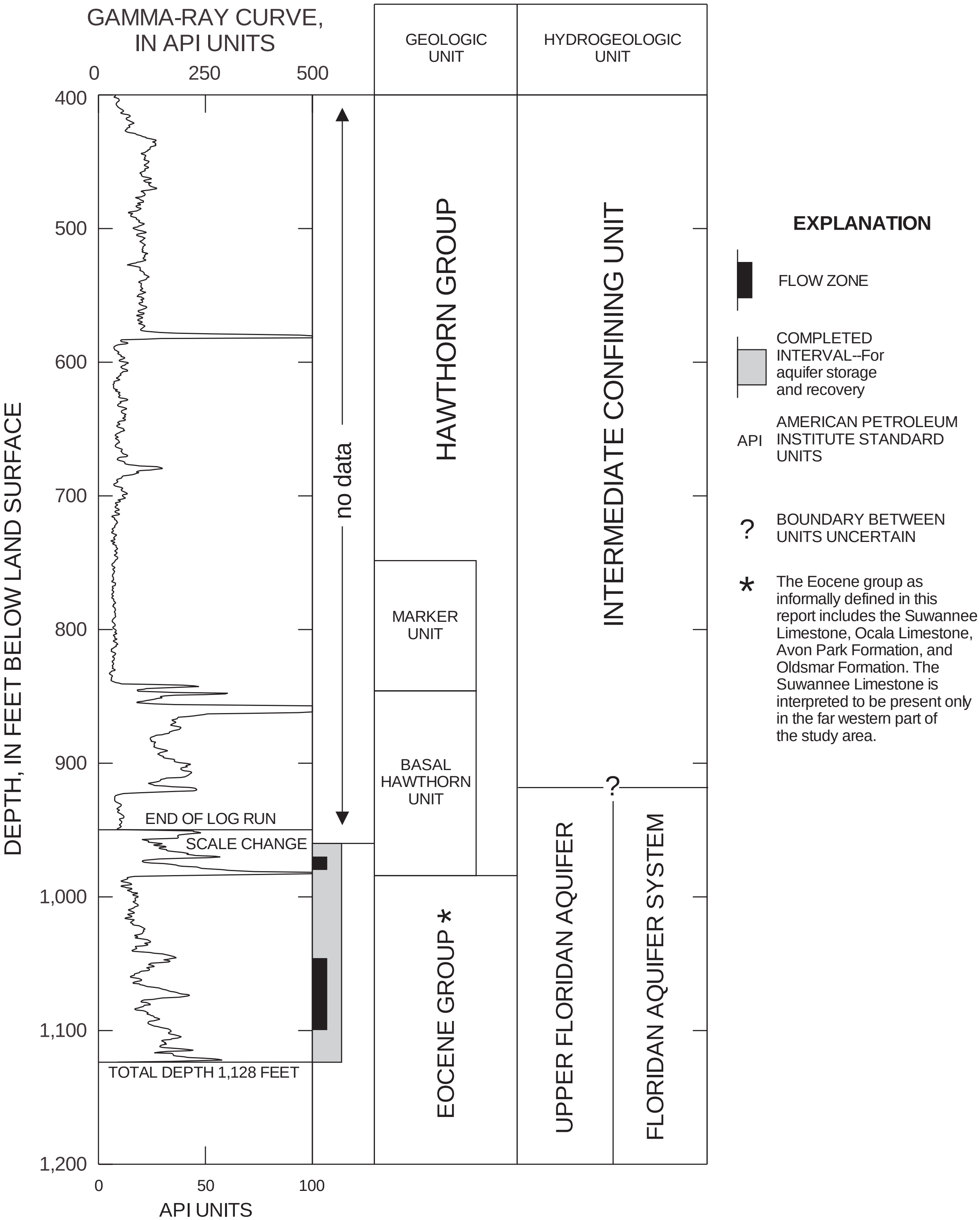


Figure 10. Gamma-ray geophysical log, flow zones below 960 feet, geologic units, and hydrogeologic units for well G-2887 in northeastern Broward County. Flow zones determined by using flowmeter log. Site is at the Deerfield Beach West water treatment plant.

of the dolomite unit (figs. 4 and 8). However, where the top of the dolomite unit is high, such as in well PB-1172 (pl. 1 and fig. 8), the middle confining unit could be absent.

The lithology of the middle confining unit is similar to the lithology of a confining unit in the upper part of the Lower Floridan aquifer. The hydraulic conductivity of this confining unit in the Lower Floridan aquifer is indicated to be very low in comparison to that in the Upper Floridan aquifer. The hydraulic conductivity of this lower confining unit was measured at most of the wastewater injection sites in the study area through core sample analysis. The vertical conductivity measured in nine core samples at a depth of between 2,217 and 2,777 ft in well PB-1176 (fig. 1) in northeastern Palm Beach County ranged from about 2×10^{-2} to 2×10^{-5} ft/d (feet per day) according to CH_2M Hill (1988). These results are comparable to an analysis of eight core samples made at an injection well site in eastern Broward County (2,149-2,808 ft deep), where the vertical conductivity was as low as 1.3×10^{-4} ft/d (Camp, Dresser and McKee, 1987).

Lower Floridan Aquifer

The top of the Lower Floridan aquifer in southern Florida is marked by the shallowest zone of highly transmissive dolomite in the Oldsmar or Avon Park Formations. Thick confining units between this permeable zone and the Boulder Zone may exist (Miller, 1986, pl. 17). The lithology of these confining units is similar to the lithology of the middle confining unit of the Floridan aquifer system.

The top of the Lower Floridan aquifer is placed at the top of a dolomite unit in the Avon Park Formation in Martin County, which is north of Palm Beach County (Lukasiewicz, 1992). The upper 400 ft of this unit contains permeable zones of cavernous dolomite and is referred to as the upper permeable portion of the Lower Floridan aquifer. The top of this dolomite unit varies from 1,150 to 1,400 ft below sea level in Martin County (Lukasiewicz, 1992, fig. 10). The interval containing permeable dolomite that has its top at 1,458 ft below sea level (1,475 ft deep) in well PB-1197 in northeastern Palm Beach County (fig. 9) could be equivalent to this upper permeable interval of the Lower Floridan aquifer in Martin County.

The highly transmissive Boulder Zone, predominantly composed of dolomite, is located in the middle to lower part of the Lower Floridan aquifer. Its thickness is variable and ranges from about 300 to 400 ft in western Palm Beach County (Miller, 1986, pl. 17) and is about 650 ft in eastern Broward County (Meyer, 1989, fig. 6). The top of the Boulder Zone extends from 2,500 to 3,100 ft below sea level in the study area according to Miller (1986, fig. 23). However, evaluation of all the WWTP injection wells (table 1) and their completed intervals (app. I) indicates that the top of the Boulder Zone is no shallower than about 2,700 ft below sea level. The base of the Lower Floridan aquifer is 500 to 600 ft below the base of the Boulder Zone in southern Florida (Miller, 1986, pl. 17). This lower section consists of permeable dolomite or dolomitic limestone of the Cedar Keys Formation (fig. 2). The high permeability in the Boulder Zone is due to the cavernous porosity and extensive fracturing present. The transmissivity of the Boulder Zone is very high, ranging from about 3.2×10^6 ft^2/d (Meyer, 1974) to 24.6×10^6 ft^2/d (Singh and others, 1983).

DISTRIBUTION OF SALINITY IN THE FLORIDAN AQUIFER SYSTEM

An investigation of the distribution of salinity in the Floridan aquifer system in Palm Beach County indicated that the system could be divided, based on geophysical log responses, as were used in earlier studies of southeastern Florida (Reese, 1994, p. 30) and southwestern Florida (Reese, 1999). These zones, in order of increasing depth, are a brackish-water zone, a transition zone containing slightly saline water, and a saline-water zone. Salinity increases rapidly with depth in the transition zone. The transition zone was defined using a salinity of 10,000 mg/L of dissolved-solids concentration (about 5,240 mg/L of chloride concentration) at its top and 35,000 mg/L of dissolved-solids concentration (about 18,900 mg/L of chloride concentration) at its base. The concentration used at its base is a salinity value similar to that of seawater. The boundaries of these three zones and the distribution of salinity are determined for all wells in the study area having adequate geophysical log, adequate water-quality data, or both. This section describes the procedure used to determine formation salinity using geophysical logs and compares log-derived salinity and water sample analyses at two sites. The term “formation” in this report refers to the bulk rock or sediment, including the contained water under ambient conditions, and “formation water” is equivalent to the term “ground water.”

Evaluation of Formation Water Salinity

Geophysical log evaluation of formation water salinity was performed in the study area. The formation resistivity (R_o) for limestone was computed (Archie, 1942) for the two threshold salinity values cited above for expected ranges in porosity, cementation factor *m*, and formation temperature. The top and base of the transition zone in the study area were determined using values of R_o obtained by assuming expected values for porosity (30-35 percent), cementation factor (m = 2.0), and formation temperature (80 degrees Fahrenheit). These average R_o values are 6 ohm-m (ohm-meters) for a salinity of 10,000 mg/L of dissolved-solids concentration and 2 ohm-m for a salinity of 35,000 mg/L of dissolved-solids concentration. The methodology and relations used in this evaluation were developed by Reese (1994), and the assumptions made are believed to hold for all of southern Florida in the Floridan aquifer system.

Geophysical logs were used to determine formation water salinity for selected limestone intervals in seven wells in the Upper Floridan aquifer (table 3). A borehole-compensated neutron-density log from a well to the southwest of the study area (Reese, 1994, fig. 8) was used to estimate porosity. For the depth interval of 930 to 1,340 ft, which includes the selected depth intervals analyzed in table 3, the log-derived porosity averaged about 40 percent with a variation around this average of about 5 percentage units. This average porosity value was used in the calculations of salinity as chloride concentration given in table 3. Formation temperature was assumed to be 77 degrees Fahrenheit, and the cementation factor used was 1.8. The cementation factor, *m*, was previously measured using limestone core samples collected from several Floridan aquifer system wells in southern Florida and was found to increase with depth, probably because of increasing compaction and cementation (Reese, 1994; 1999).

Often, the greatest error in calculating salinity from geophysical logs results from an uncertainty in the value used for porosity, and a sensitivity analysis was performed for porosity keeping the other parameters constant. Starting with a porosity of 40 percent, calculations using two chloride concentration values, 1,000 and 4,000 mg/L, were made; then porosity was varied by 5 percentage units, from 35 to 45 percent. The resulting errors in the calculated chloride concentration ranged from 21 to 37 percent. The greatest error was for a porosity of 35 percent and a chloride concentration of 1,000 mg/L.

Good correlation was found between log-derived salinity values (table 3) and water sample salinity values (app. II) at two sites (table 1): the West Palm Beach East-Central Regional WWTP site

Table 3. Salinity data calculated by using geophysical logs for selected limestone intervals in the Floridan aquifer system

[Well locations are shown in figure 1. Depth of sample intervals are given in feet below measuring point, which usually is land surface (measuring points are presented in appendix I). Type of resistivity log used: E, conventional electrical log (normal and lateral devices); DIL, dual induction log (deep induction, medium induction, and shallow focusing electrode devices)]

Local well identifier	Depth interval analyzed (feet)	Chloride (milligrams per liter)	Specific conductance (microsiemens per centimeter)	Type of resistivity log used
PB-1136	1,000 - 1,100	800	3,500	E
PB-1137	930 - 1,010	900	3,700	E
PB-1138	956 - 1,050	1,400	5,200	DIL
PB-1146	1,280 - 1,340	4,000	13,000	DIL
PB-1173	1,010 - 1,040	1,600	5,800	DIL
PB-1174	1,060 - 1,100	1,600	5,800	DIL
PB-1178	1,230 - 1,280	2,600	8,700	DIL

(WPB site), and the Solid Waste Authority—North County WWTP site (SWA site). At the WPB site, the log-derived chloride concentration of 4,000 mg/L for well PB-1146 (1,280-1,340 ft deep) compares well with the water sample value of 3,870 mg/L chloride concentration in well PB-1690 (1,000-1,080 ft deep). At the SWA site, the log-derived chloride concentration of 2,600 mg/L in well PB-1178 (1,230-1,280 ft deep) also compares well with the water sample value of 2,300-mg/L chloride concentration in well PB-1179 (1,020-1,111 ft deep). Depth intervals compared at both well sites are located in the upper part of the Upper Floridan aquifer where the salinity would be expected to be similar.

Determination of Salinity Zone Boundaries

In the study area, salinity zone boundaries were determined using geophysical logs, water-quality data collected from known intervals (completed and packer test), and water-quality data collected while drilling by the reverse-air rotary method. A total of 25 wells are presented in table 4; however, one well (PB-1197) was not drilled deeply enough to determine the depth of any salinity zone boundary.

The depths of the salinity zone boundaries in the Floridan aquifer system were determined principally using resistivity geophysical logs. The dual-induction resistivity log was used in 16 wells; it was the most important data source in 14 of these wells (table 4). Three resistivity curves recorded on this geophysical log are from the deep induction, medium induction, and shallow penetrating focusing electrode devices. These devices have different depths of investigation away from the borehole and record deep, medium, and shallow measurements of resistivity of the formation, respectively. In a deep injection well in southeastern Florida where invasion of the formation from salty drilling fluid had not occurred, calculations of true formation resistivity using the three resistivity curves and correction charts for borehole and invasion effects were made (Reese, 1994, p. 28). These calculations showed that the correction between true formation resistivity and the deep induction resistivity values was small; therefore, deep induction resistivity is assumed to approximate the true formation resistivity in a well.

Water-quality data principally were used in six wells to determine the boundaries of the salinity zones in the study area (table 4). Use of water-quality data alone is often not as accurate as using geophysical logs to determine a salinity zone boundary in a well because of sampled intervals that are very thick, limited in number, or both. Additionally, for water-quality data collected during drilling by the reverse-air rotary method, the depth determined for a boundary should be considered the maximum depth. This is because an increase in formation water salinity with depth can go undetected if the formation being drilled has low permeability.

Invasion of the formation with drilling fluids or injected wastewater can affect the placement of salinity-zone boundaries using geophysical logs. In two wells in which the dual-induction log principally was used to determine the salinity zone boundaries, the log indicated that salty drilling fluid had invaded the formation. The base of the brackish-water zone determined in these two wells, PB-1170 and PB-1174, is somewhat uncertain because of this contamination (table 4). However, these depths are meaningful because relative changes in resistivity readings at this boundary are still present. The base of the brackish-water zone in well PB-1141 is also somewhat uncertain because of possible contamination of the formation (table 4). The source for this contamination, if present, was injected wastewater into nearby well PB-736 at a depth below the base of the brackish-water zone (injection interval from 1,938 to 2,242 ft deep) at the site. This injection occurred during the 5 years prior to the drilling of well PB-1141 (Kaufman and McKenzie, 1975).

Finally, determination of salinity zone boundaries in intervals where dolomite beds are present (table 4) can be subjective because the threshold formation resistivity values used to determine salinity zone boundaries do not apply in dolomite. If dolomite interbeds are present, the boundary can be placed at a greater depth than where it actually occurs because the porosity of dolomite usually is much lower than that of limestone, resulting in a higher overall formation resistivity. A dual-induction log of well PB-1186 provides an example of the uncertainty in determining the top of the saline-water zone caused by the presence of the dolomite unit (fig. 11).

Table 4. Depths to salinity zone boundaries in the Floridan aquifer system as determined for this study

[Depths are given in feet below measuring point, which usually is land surface (measuring points are presented in appendix I). Methods: DIL, dual induction log (deep and medium induction and shallow focusing electrode devices); E, conventional electrical log (normal and lateral devices); QW, water-quality data (samples from known intervals); DQW, water-quality data (samples collected while drilling by reverse-air rotary method). Methods are listed in order of importance in determining boundaries for each well. Other annotations: ?, depth of boundary or thickness of zone is uncertain; *, depth of boundary is uncertain because of dolomite beds; --, no data; >, greater than the value]

Well identification	Depth to base of brackish-water zone (feet)	Depth to top of saline-water zone (feet)	Thickness of transition zone (feet)	Method
BCN-I1	1,623	1,880	257	DIL
CS-I2	2,017	2,180	163	DIL
HE-1087	2,070?	--	--	DIL (bottom at 2,082 feet), QW
MAR-M2	1,770	--	--	E, QW
PB-1133	2,080	2,230	150	E
PB-1136	1,990	2,140	150	E
PB-1137	2,220	2,540?*	320?	E
PB-1138	2,030	2,160	130	DIL
PB-1141	1,830?	2,090?*	260?	DIL (possible contamination), QW
PB-1146	1,920	2,240	320	DIL, QW
PB-1166	1,830?	2,010	180?	DQW, E, QW
PB-1168	1,730?	--	--	QW, E
PB-1170	2,040?	>2,800	>760?	DIL (contamination), QW
PB-1173	1,830	1,950	120	DIL
PB-1174	1,825?	1,885?*	60?	DIL (contamination)
PB-1176	1,900?	--	--	DQW, QW
PB-1178	1,970	2,760	790	DIL, QW
PB-1180	1,990	--	--	DIL
PB-1182	1,880	2,550	670	QW, DIL (Top at 2,020 feet)
PB-1184	1,850?*	2,050	200?	QW, DIL
PB-1186	1,855	2,150?*	295?	DIL
PB-1190	1,780?*	1,880?*	100?	DIL, DQW
PB-1192	1,620	1,910?*	290?	DIL, QW
PB-1197	Not reached at 1,900 feet			DQW
PB-1695	1,645	1,790	145	E

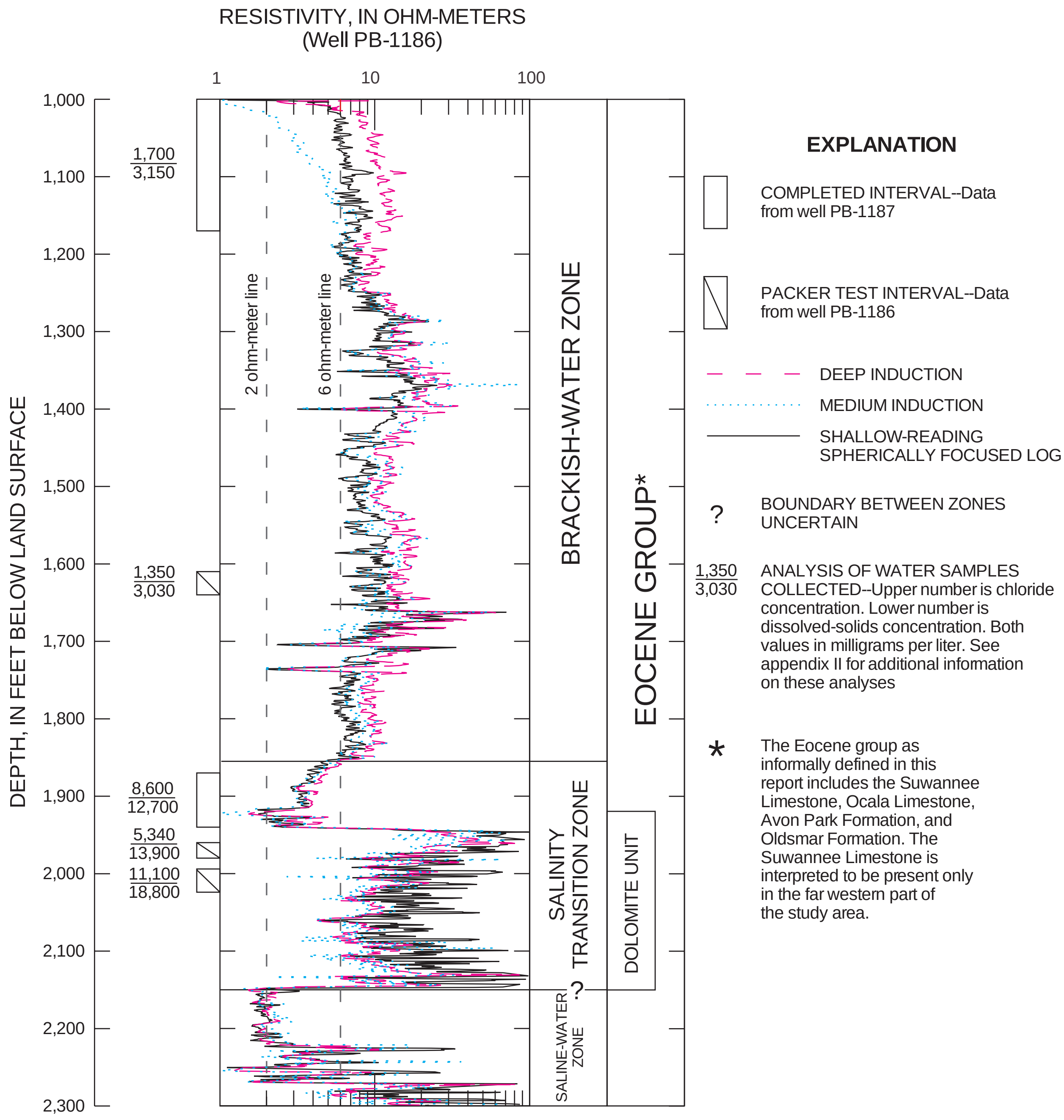


Figure 11. Resistivity geophysical log, water-quality data, salinity zones, and geologic units for wells PB-1186 and PB-1187 in west-central Palm Beach County. Site is at the Belle Glade wastewater treatment plant.

Distribution of Salinity by Zone

In this section, the distribution of salinity in the Floridan aquifer system is discussed for the three zones: the brackish-water zone, a transition zone, and the saline-water zone. The brackish-water zone (chloride concentration of less than 5,240 mg/L) is emphasized because of its potential use as a supplemental water-supply source. Development of the Floridan aquifer system in the study area, as in the rest of southern Florida, has been minor. Decline of the estimated predevelopment potentiometric surface of the Upper Floridan aquifer in all of southern Florida was less than 10 ft as observed in May 1980 (Bush and Johnston, 1988, pl. 6). It is assumed that water quality in the Floridan aquifer system is still representative of predevelopment conditions.

Brackish-Water Zone

The approximate depth of the base of the brackish-water zone was determined in each well in the study area where adequate data were available (table 4). A map showing the altitude of the base of the brackish-water zone in the study area is discussed herein. Also discussed are the variations of salinity (chloride concentration) in the brackish-water zone, which is divided into upper and lower intervals.

The altitude of the base of the brackish-water zone in the study area (fig. 12) is similar to that mapped in Dade and Broward Counties (Reese, 1994, fig. 15). The mapped surface generally dips inland, with contours that parallel the coast. The direction of the dip to the west is as expected, given the downgradient direction to the east shown by the Upper Floridan aquifer potentiometric surface in Palm Beach County (Bush and Johnston, 1988, pl. 5). The base of the brackish-water zone ranges from about 1,600 ft below sea level near the coast (well PB-1192) to almost 2,200 ft below sea level in extreme southwestern Palm Beach County (well PB-1137). The boundary is higher than expected in an area that is peripheral to Lake Okeechobee, and could be as shallow as 1,800 ft below sea level (wells PB-1141, PB-1184, and PB-1186). The west dip of the base of the brackish-water zone in eastern Palm Beach County also is shown on plate 1.

The base of the brackish-water zone in several wells (CS-I2, PB-1146, PB-1170, PB-1178, PB-1180, PB-1182, and PB-1197) located near the coast in Palm Beach and northern Broward Counties is deeper than expected by several hundred feet based on their distance from the coast. The base of this zone is deepest near the coast in well PB-1170 where it is 2,022 ft below sea level. The depression of this boundary in some of the above-mentioned wells is shown by the north-south hydrogeologic section (pl. 2). The base of the brackish-water zone in well CS-I2 is also deeper than expected, in comparison to its depth at the same distance inland farther south in Broward County (Reese, 1994, fig. 15).

The altitude of the base of the brackish-water zone (fig. 12) is related to the altitude of the basal contact of the Hawthorn Group (fig. 6) and the thickness of the basal Hawthorn unit (fig. 7) in the anomalous areas along the coast where the altitude of the base of the brackish-water zone is deeper than expected. In these areas, the basal contact of the Hawthorn Group is also deep (close to or greater than 1,100 ft below sea level) and the thickness of the basal Hawthorn unit is 200 ft or more thick.

For the purpose of describing salinity variations, the brackish-water zone has been divided into upper and lower intervals. The upper interval extends from the top of the Floridan aquifer system to a depth generally not exceeding 1,300 ft. The lower interval generally ranges in depth from about 1,400 to 1,600 ft. Both of these intervals are included in the Upper Floridan aquifer in this report. The lower interval has approximately the same depths as what has been informally referred to as the middle Floridan aquifer in southeastern Florida (John Lukasiewicz, South Florida Water Management District, written commun., 1999).

Lines of equal chloride concentration in ground water from the upper interval of the brackish-water zone are shown in figure 13. The chloride data for selected wells in the upper interval and the lower interval (when measured) are shown in figure 13, and their respective sample intervals are given in table 3 and appendix II. Chloride concentrations in the upper interval range from 490 mg/L in eastern Hendry County (well HE-1087) to 8,000 mg/L in extreme northeastern Palm Beach County (well PB-652). Areas where chloride concentrations exceed 1,500 mg/L are along the coast, in an area that is peripheral to Lake Okeechobee, and probably in the region that extends northwest-southeast across central Palm Beach County (from the southern end of Lake Okeechobee to southeastern Palm Beach County). The latter of these three areas of high chloride concentration approximately coincides with another area of

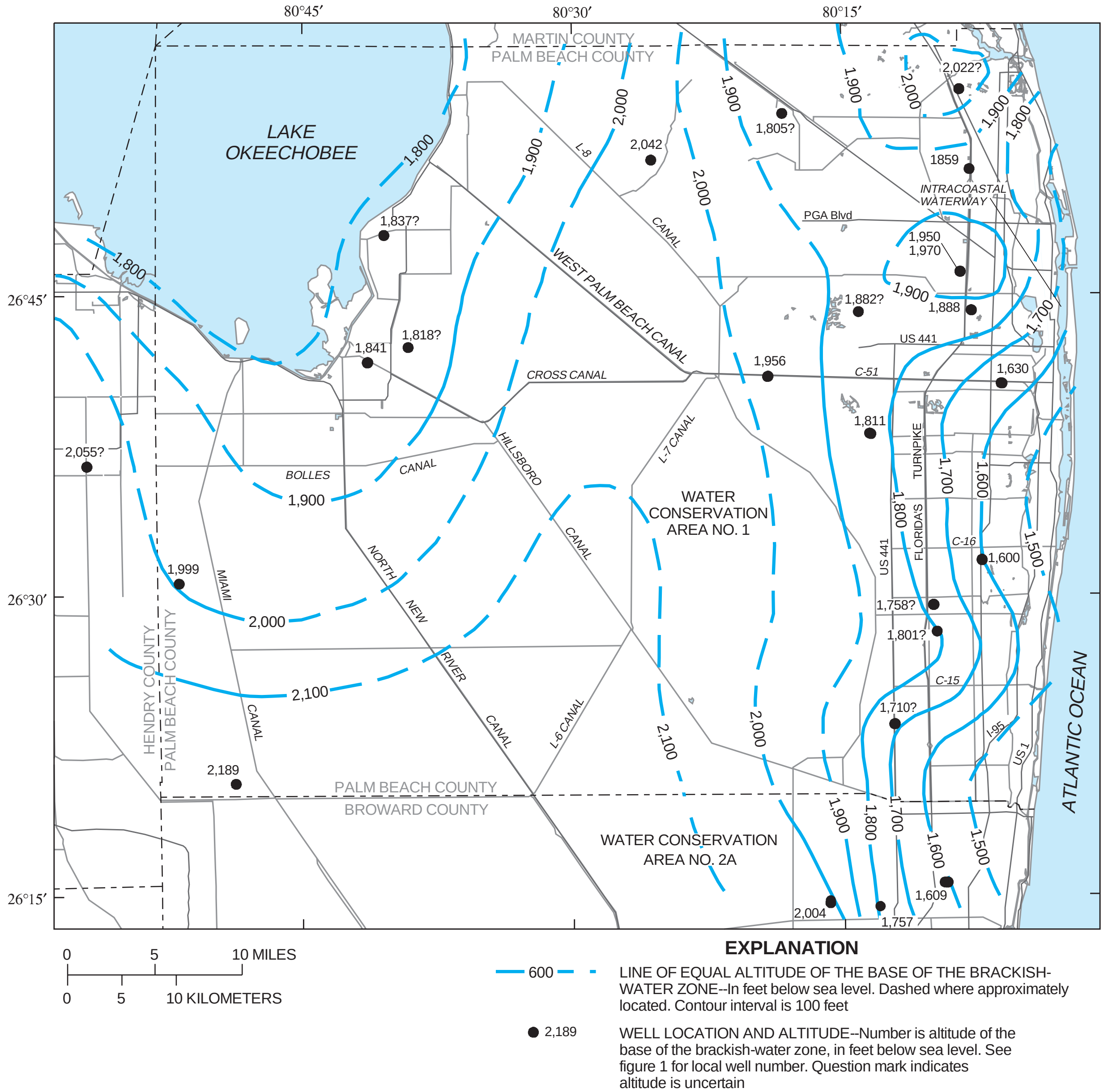


Figure 12. Altitude of the base of the brackish-water zone in Palm Beach and northern Broward Counties.

high chloride concentration (greater than 500 mg/L) in the surficial aquifer system, extending from the southern end of Lake Okeechobee to south-central Palm Beach County (Parker and others, 1955, fig. 221).

Chloride concentration in the upper interval of the brackish-water zone exceeds 3,000 mg/L in four areas of eastern Palm Beach and Broward Counties along the coast (figs. 1 and 13). The wells in these areas, from north to south, are: PB-652 (8,000 mg/L), PB-1196 (4,000 mg/L), PB-1183 (3,020 mg/L), PB-1690 (3,870 mg/L), CS-I1 (5,640 mg/L), and MAR-M2 (3,510). These anomalous areas, except in the vicinity of well PB-1183, show a reversal in salinity, with higher chloride concentration in the upper interval than in the lower interval of the brackish-water zone (fig. 13). Salinity in the brackish-water zone would normally be expected to increase with depth or not vary greatly.

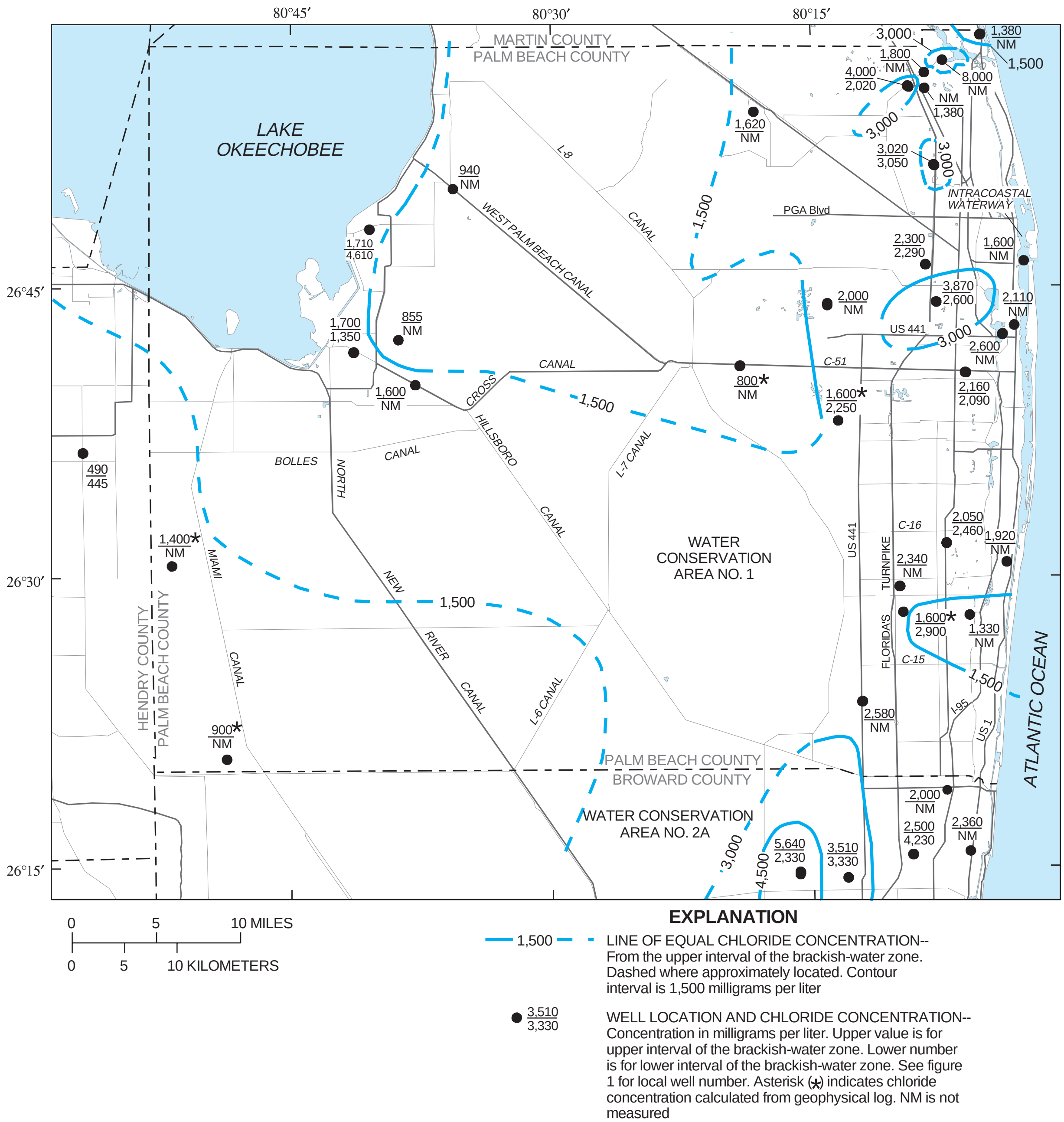


Figure 13. Chloride concentrations in ground water from the upper and lower intervals of the brackish-water zone in Palm Beach and northern Broward Counties. The depth intervals for the upper and lower intervals generally are as follows: upper, from the top of the Floridan aquifer system to 1,300 feet; lower, from 1,400 to 1,600 feet.

At one of these anomalous areas, the one in which well PB-1690 is located (WPB site), the vertical distribution of salinity in the brackish-water zone is well defined by resistivity log measurements and water-quality data from wells PB-1146, PB-1690, and PB-1691 (fig. 14). These data indicate an anomalous interval of higher salinity at depths between 1,000 and 1,430 ft. Deep-induction resistivity readings of as low as 4 ohm-m were obtained in this interval in well PB-1146, and the chloride concentration calculated from this geophysical log is 4,000 mg/L at a depth interval from 1,280 to 1,340 ft in the well (fig. 14 and table 3). Salinity is lower deeper in the brackish-water zone, with a chloride concentration of 2,600 mg/L in well PB-1691 at a depth interval from 1,559 to 1,600 ft (fig. 14). In the anomalous area in northeastern

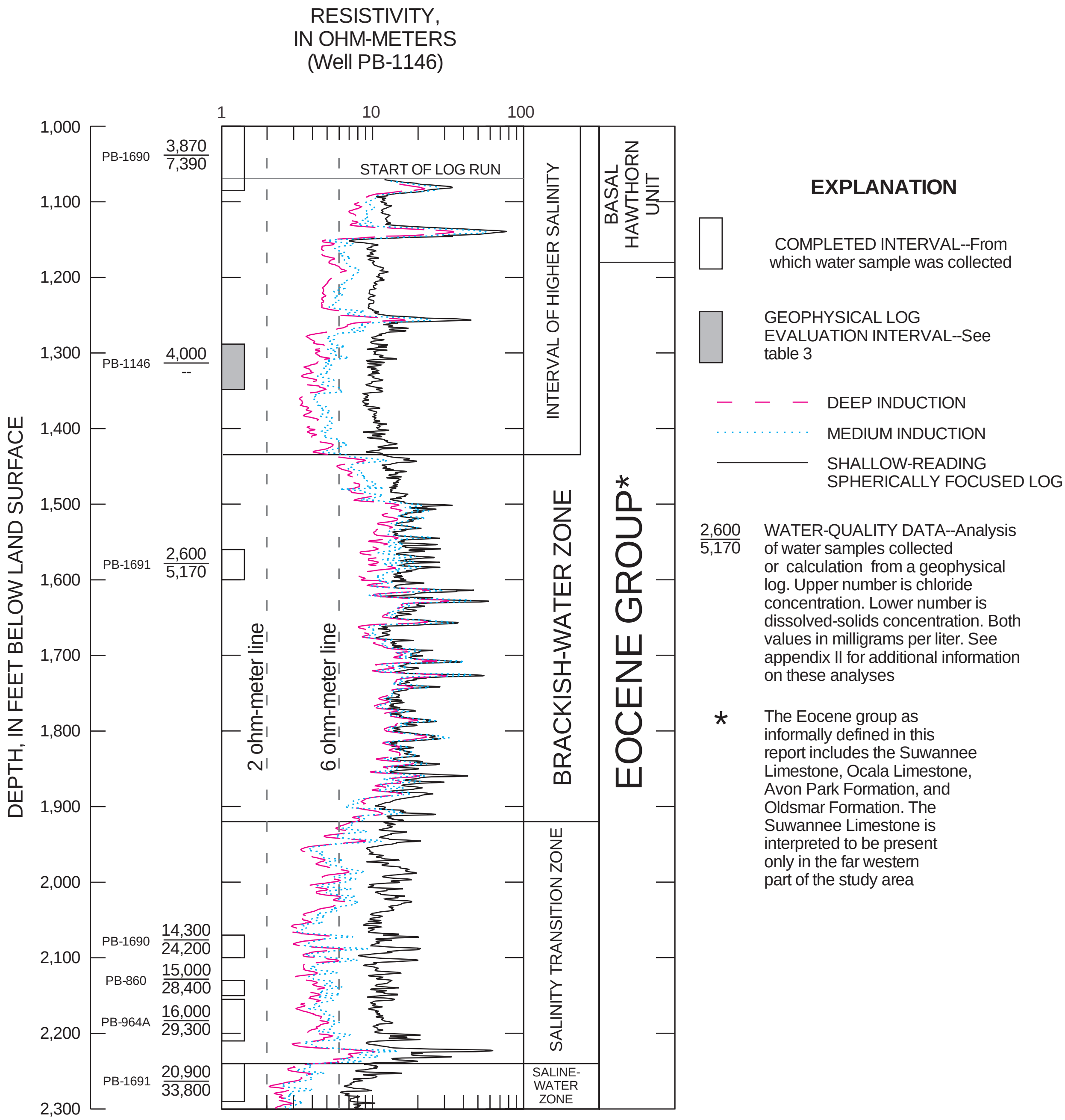


Figure 14. Resistivity geophysical log, water-quality data, salinity zones, and geologic units for selected wells in eastern Palm Beach County. The resistivity log and salinity zone boundaries are from well PB-1146. Completed intervals and geophysical log evaluation intervals are from selected wells as noted. Site is at the West Palm Beach East-Central Regional wastewater treatment plant.

Broward County that includes wells CS-I1 and MAR-M2, a similar distribution of salinity exists (Reese, 1994, fig. 14). The vertical distribution of salinity as shown by a dual-induction resistivity log run in well CS-I2 (Reese, 1994, fig. 14) seems very similar to that shown by the same type of log run in well PB-1146 at the WPB site (fig. 14).

Transition Zone

The transition zone is a salinity interface that forms when equilibrium exists between two water masses of contrasting density. The increase in salinity with depth in the transition zone suggests mixing or diffusion associated with a brackish-water/saline-water interface. The thickness of the transition zone in the study area is 150 ft or less in 7 of 19 wells (table 4); however, south of the study area in Dade and Broward Counties, the thickness of the transition zone is 124 ft or less in 10 of 18 wells (Reese, 1994, p. 40). This could indicate that lithology is more uniform and generally more permeable in Dade and Broward Counties than in Palm Beach County. Unlike in Dade and Broward Counties, dolomite (in the dolomite unit) commonly occurs in the brackish-water zone and transition zone in Palm Beach County.

The transition zone is very thick (greater than 300 ft) in wells PB-1137, PB-1146, PB-1170, PB-1178, and PB-1182 (table 4). Except for well PB-1137, all of these wells are located near the coast and are wells where the base of the brackish-water zone is deeper than expected. The thickness of the transition zone in well PB-1178 (790 ft) is exceptionally thick.

Some correlation between the occurrences of the transition zone and dolomite unit is evident as shown by the two hydrogeologic sections (pls. 1 and 2). Either a portion of the dolomite unit occurs within the transition zone or the unit lies close to and approximately parallels the transition zone. Geochemical studies of the Floridan aquifer system have concluded that some of the dolomite present in the system formed in the brackish-water mixing zone associated with a saltwater interface (Hanshaw and others, 1971; Randazzo and Hickey, 1978; Cander, 1991). The variable position of the dolomite unit could have resulted from vertical movements of the transition zone through geologic time as a result of sea level changes.

Saline-Water Zone

Although the salinity of water in the saline-water zone is generally similar to that of seawater, which has a chloride concentration of 19,800 mg/L (Nordstrom and others, 1979), there is some variability in the study area. In appendix II, 19 water sample analyses were determined to be from depth intervals entirely within the saline-water zone. Chloride concentrations from completed intervals in the saline-water zone (6 analyses) ranged from 17,700 to 20,900 mg/L, and chloride concentrations from packer-test intervals (13 analyses) ranged from 15,000 to 21,800 mg/L. Analyses of water samples collected from the Boulder Zone of the Lower Floridan aquifer were not used in this study; however, in an earlier study (Reese, 1994, p. 40), the average dissolved-solids concentration of Boulder Zone water from several wells in Dade and Broward Counties was 37,000 mg/L. This value is slightly higher than that normally measured in seawater.

Areas of Anomalous Salinity

This section discusses the areas of anomalous salinity in the Floridan aquifer system that occur in the study area and processes that could control the depth of the base of the brackish-water zone. For these purposes, three plots were constructed that relate water-quality data to geologic and salinity zone boundaries.

A plot was constructed that relates chloride concentration in the upper interval of the brackish-water zone to the altitude of the basal contact of the Hawthorn Group (fig. 15). A linear correlation (correlation coefficient = 0.62) was found in which the log of

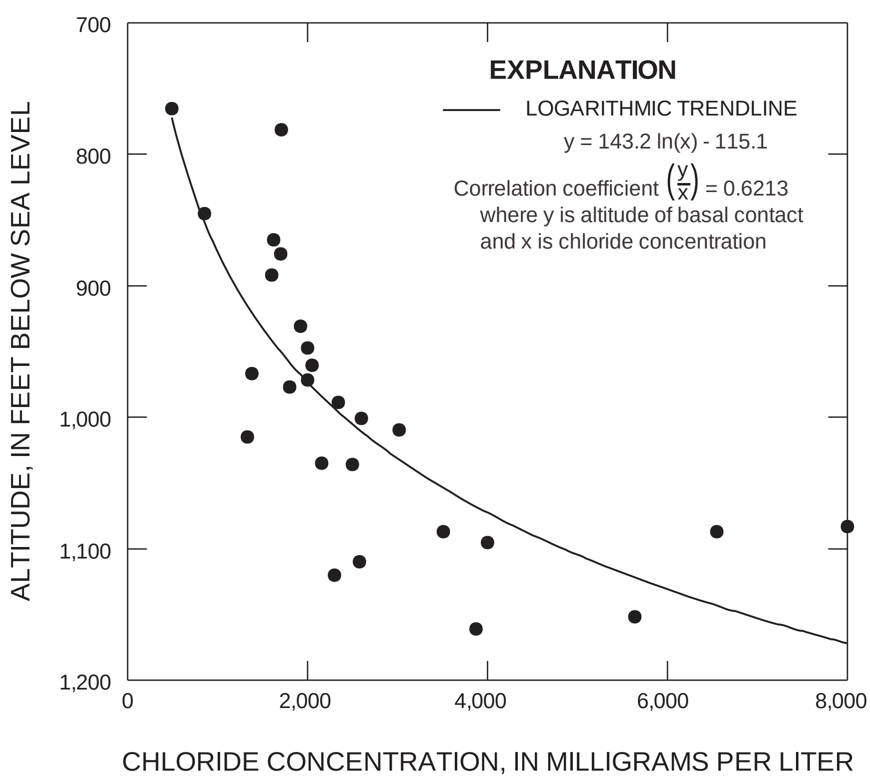


Figure 15. Chloride concentrations in water from the upper interval of the brackish-water zone showing relation to the altitude of the basal contact of the Hawthorn Group. Each sample comes from a different well.

chloride concentration increases as the altitude of this contact decreases. The correlation between these two parameters is also shown by comparison of the contours on the map of the altitude of basal contact of the Hawthorn Group (fig. 6) with those on the map of chloride concentrations from the upper and lower intervals of the brackish-water zone (fig. 13). Areas of high salinity in the upper interval of the brackish-water zone that are present along the coast in the study area could have resulted from the influx of seawater into the Upper Floridan aquifer during high sea-level stands in the Pleistocene Epoch (Stringfield, 1966, p. 72). According to this theory, flushing of this saline water by the present freshwater flow system has been incomplete (Reese, 1994, p. 45). As discussed earlier, flow zones are associated with the base of the basal Hawthorn unit; where the altitude of this contact is low, the basal Hawthorn unit is thick and the transmissivity of the Upper Floridan aquifer is high. Thus, areas where the altitude of this contact is low could have been the first and most heavily invaded during a rise in sea level.

As sea level rose, the freshwater-saltwater interface in the Floridan aquifer system would also have risen in an attempt to seek a new equilibrium position. As the new equilibrium position for the interface rose above the basal contact of the Hawthorn Group, invasion of seawater could have been more rapid because of the higher permeability associated with this contact. Even if the transmissivity of the Upper Floridan aquifer is not higher in areas where the contact is lower, these areas could have been more heavily invaded because they were more likely to have been exposed to invasion and for longer periods.

Of significance are the processes that could be controlling the depth of the base of the brackish-water zone. A plot was constructed, relating chloride concentration in the upper interval of the brackish-water zone to the altitude of the base of the brackish-water zone (fig. 16). The data on the plot suggests a trend in which chloride concentrations increase as the altitude of the base of the brackish-water zone becomes shallower. A theoretical mixing line was drawn on the plot that assumes dilution of water at the top of the brackish-water zone at a rate proportional to the increase in the depth of the base of the brackish-water zone, and this line coincides with the trend of data points. The mixing line is drawn through two end-member points (chloride concentration values), which are estimated where the base of the brackish-water zone is at its deepest (eastern Hendry County—about 2,200 ft below sea level) and shallowest (top of the Floridan aquifer system along the coast—about 1,000 ft below sea level) in the study area. The chloride concentration values used for these two end-member points in the study area are 500 and 5,240 mg/L,

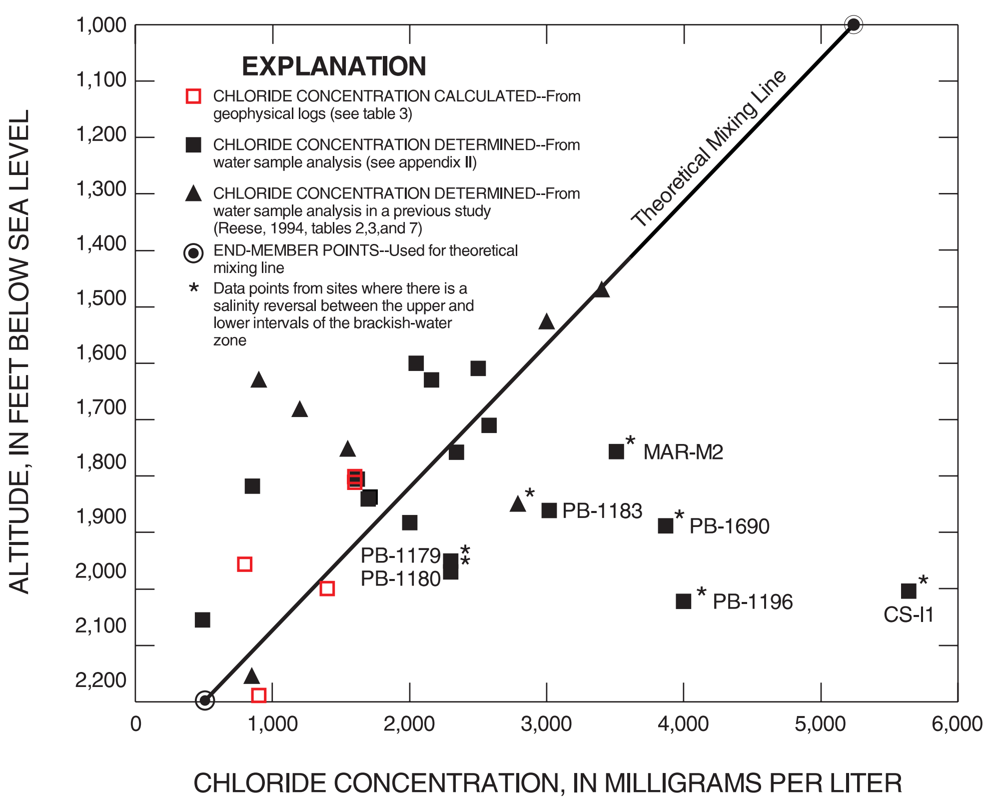


Figure 16. Chloride concentrations in water from the upper interval of the brackish-water zone showing relation to the altitude of the base of the brackish-water zone.

respectively. The 5,240-mg/L end-member point is the calculated chloride concentration value that corresponds with the 10,000 mg/L dissolved-solids concentration value used to define the base of the brackish-water zone. Eight data points plot in an anomalous position in relation to the theoretical mixing line. These data are in an area on the plot where the base of the brackish-water zone is deeper than expected given their chloride concentration. All of these anomalous data points, except for one (well PB-1183) are from wells where there is a salinity reversal between the upper and lower intervals of the brackish-water zone. However, the salinity reversals in wells MAR-M2 and PB-1179 are slight. A salinity reversal probably is present in well PB-1183; however, the locations of sampled intervals in the lower interval of the brackish-water zone at the site are close to the base of the brackish-water zone, where salinity would be expected to be higher (pl. 2 and app. II, well PB-1182).

To better understand the areas of anomalous salinity in the Floridan aquifer system, a plot was constructed that relates chloride concentration to sulfate concentration in the study area (fig. 17). A pure water-seawater mixing line was drawn on this plot, consisting of 80 water sample analyses given in appendix II. Data show some grouping relative to this line by salinity zone. Many data points fall below this line, of which 6 data points are from the lower interval of the brackish-water zone and 19 data points are from the underlying transition zone. Additionally, 4 of these 6 data points in the brackish-water zone and 10 of these 19 data points in the transition zone are from the anomalous areas where there is a salinity reversal in the brackish-water zone. The data points that fall significantly below the pure water-seawater mixing line (fig. 17) indicate depletion of sulfate that probably results from a geochemical transformation known as sulfate reduction. A similar plot of the same constituents (sulfate and chloride) also was constructed for

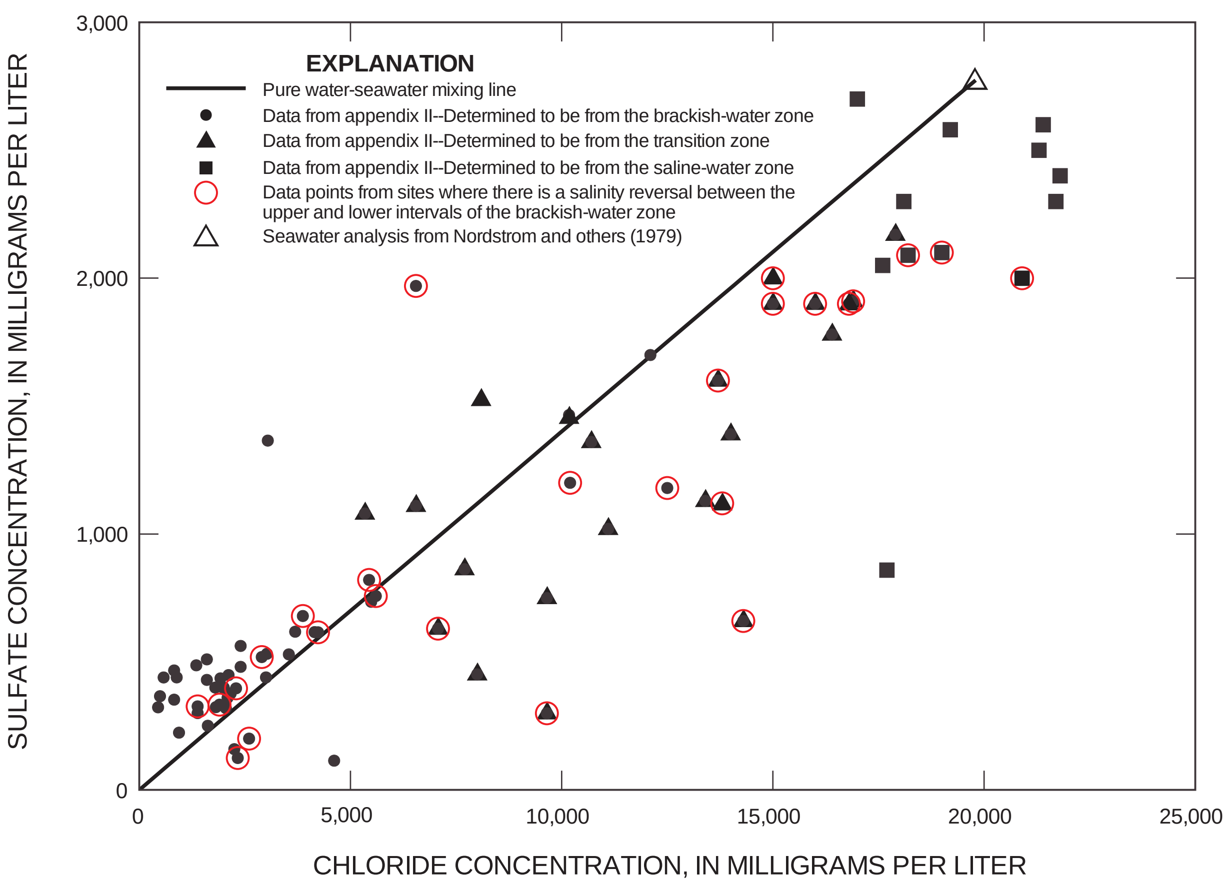


Figure 17. Chloride and sulfate concentrations in water from the Floridan aquifer system showing relation to a pure water-seawater mixing line. Data show grouping relative to mixing line by salinity zone.

southwestern Florida and indicated the prevalence of sulfate reduction in the transition zone, but virtually no reduction of sulfate was found in the brackish-water zone (Reese, 1999).

The areas of anomalous salinity in the Floridan aquifer system have common characteristics and generally occur: (1) near the coast where the basal Hawthorn unit is thick and the depth of the basal contact of the Hawthorn Group is deep, and correspondingly where the transmissivity of the Upper Floridan aquifer is high; and (2) where the dolomite unit is not present or where the top of the dolomite unit is deep and the thickness of the unit is slight. The vertical distribution of salinity in these areas is characterized as follows:

- A salinity reversal occurs in the brackish-water zone with a wedge of higher salinity water occupying the upper interval of the zone.
- The base of the brackish-water zone is much deeper than expected (100–300 ft deeper), given the location of the areas relative to the coast and the salinity that is present in the upper interval of the brackish-water zone.
- A thickness of the transition zone that is much greater than normal, which could indicate lower vertical permeability than usual in this zone.
- The sulfate concentrations in the lower interval of the brackish-water zone and in the transition zone in these anomalous areas can be severely depleted.

SUMMARY AND CONCLUSIONS

The Floridan aquifer system is considered to be a valuable supplemental source for public water supply in Palm Beach County, in spite of its brackish nature in this area. This report describes the distribution of salinity in this thick and complex aquifer system and relates the distribution to the local hydrogeology, thereby allowing for some understanding of processes that might control (or have affected) this distribution.

The Floridan aquifer system in Palm Beach County includes the upper part of the Cedar Keys Formation, Oldsmar Formation, Avon Park Formation, Ocala Limestone, Suwannee Limestone, and a lower portion of the Hawthorn Group. However, the Suwannee Limestone is interpreted to be present only in the far western portion of the study area. A thick dolomite unit is usually present in the Avon Park Formation and upper part of the Oldsmar Formation. The Oldsmar Formation, Avon Park Formation, Ocala Limestone, and Suwannee Limestone are grouped together and referred to informally as the Eocene group. Overlying the Eocene group is the Hawthorn Group, the lower part of which includes the basal Hawthorn unit and a marker unit.

Geophysical logs and lithologic descriptions of wells penetrating the Floridan aquifer system were used to produce detailed subsurface maps of the top of the basal Hawthorn unit, basal contact of the Hawthorn Group, top of the dolomite unit, and thickness of the basal Hawthorn unit. The altitude of the top of the basal Hawthorn unit, which coincides with the base of the overlying marker unit, ranges from about 690 to 930 ft below sea level. The altitude of the basal contact of the Hawthorn Group ranges from 765 to 1,165 ft below sea level. The altitude of the top of the dolomite unit within the Eocene group varies considerably, ranging from about 1,200 to 2,300 ft below sea level. A low area is present at the top of the dolomite unit, extending from southeastern Palm Beach County to the northwest toward Lake Okeechobee. This low area coincides with areas of low altitude at the top of the basal Hawthorn unit at the basal contact of the Hawthorn Group.

The thickness of the basal Hawthorn unit is variable, ranging from about 30 to 355 ft. Areas of the basal Hawthorn unit where the interval is thick probably represent paleotopographic lows, which were present just before or during deposition of the basal Hawthorn unit. Some of the relief present in these paleotopographic lows could be explained by an unconformity at the basal contact of the Hawthorn Group. This major unconformity, which corresponds with an unconformity at the top of the rocks of Eocene age in southeastern Florida, is characterized by relief of at least as much as 100 ft that could be largely related to erosion and solution of the underlying carbonate rocks. An alternate interpretation is that the paleotopographic lows resulted from differential subsidence during deposition of the basal Hawthorn unit caused by movement along deep-seated faults. This interpretation probably explains the majority of the relief.

The Floridan aquifer system consists of the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer. Overlying the Upper Floridan aquifer is the intermediate confining unit. The Upper Floridan aquifer generally is 500 to 600 ft thick in southeastern Florida and consists of several thin water-bearing zones of high permeability interlayered with thick zones of low permeability. The lower part of the basal Hawthorn unit and the upper part of the Eocene group are contained within the Upper Floridan aquifer in the study area. The uppermost permeable zones of the Upper Floridan aquifer occur in close association with the unconformity at the basal contact of the Hawthorn Group, and this contact is considered to approximate the top of the Upper Floridan aquifer. However, the highest permeable zone can occur significantly above this contact. The Upper Floridan aquifer is delineated on the basis of permeability characteristics, and thus, neither the top nor the base of this aquifer necessarily conforms to formation or time-stratigraphic boundaries.

Measured transmissivity values for the Upper Floridan aquifer range from 24,000 to 132,000 ft^2/d. Based on available data, the transmissivity of the Upper Floridan aquifer could be related to the thickness of the basal Hawthorn unit. Results suggest that transmissivity is high where the basal Hawthorn unit is thick. The correlation of transmissivity and thickness should not be unexpected. The transmissivity should be higher, at least in the basal Hawthorn unit, because of the corresponding thickening of the lower part of the unit where permeable limestone and possibly dolomite are present.

In most of the study area, the top of the dolomite unit, generally considered to be of high permeability, marks the top of the Lower Floridan aquifer. However, where the dolomite unit is thick and its top is high, such as occurs in northeastern Palm Beach County, the middle confining unit, defined as being above the dolomite unit, is probably absent. The Upper Floridan aquifer could be considered to extend to the base of the dolomite unit in these areas. Alternatively, the Upper and Lower Floridan aquifers could be hydraulically well connected by the dolomite unit in these areas.

The Floridan aquifer system can be divided into three salinity zones: the brackish-water zone, a transition zone, and the saline-water zone. Salinity increases rapidly with depth in the transition zone. The transition zone was defined by using a salinity of 10,000 mg/L of dissolved-solids concentration (about 5,240 mg/L of chloride concentration) at its top and 35,000 mg/L of dissolved-solids concentration (about 18,900 mg/L of chloride concentration) at its base. The concentration used at its base is a salinity value similar to that of seawater. The base of the brackish-water zone in the study area ranges from about 1,600 ft below sea level near the coast to almost 2,200 ft below sea level in extreme southwestern Palm Beach County. The boundary unexpectedly rises in an area that is peripheral to Lake Okeechobee, to perhaps as shallow as 1,800 ft below sea level.

For the purpose of describing salinity variations, the brackish-water zone was divided into an upper interval that extends from the top of the Floridan aquifer system to a depth of about 1,300 ft, and a lower interval that ranges in depth from 1,400 to 1,600 ft. Chloride concentrations in the upper interval ranged from 490 mg/L in eastern Hendry County to 8,000 mg/L in extreme northeastern Palm Beach County. Areas where chloride concentrations exceeded 1,500 mg/L are located along the coast, near Lake Okeechobee, and probably in a region extending northwest-southeast across central Palm Beach County. Chloride concentrations in the upper interval were found to be related to the altitude of the basal contact of the Hawthorn Group, with the concentration increasing as the contact becomes deeper.

Chloride concentrations in the upper interval of the brackish-water zone exceeded 3,000 mg/L in several areas along the coast. In these anomalous coastal areas, the base of the brackish-water zone was found to be 100 to 300 ft deeper than expected. Other characteristics of these anomalous areas include the following: (1) the altitude of the basal contact of the Hawthorn Group is deep and the basal Hawthorn unit is thick; (2) the dolomite unit is either not present, or its top is deep and its thickness is small; (3) the vertical distribution of salinity within the brackish-water zone is characterized by a decrease in salinity with depth from the upper interval to the lower interval (a salinity reversal); (4) a much greater thickness of the transition zone than normal, which could indicate poor vertical mixing; and (5) at least in some areas a severely depleted concentration of sulfate relative to chloride concentration in the lower part of the brackish-water zone and the transition zone.

The anomalous areas along the coast in the study area could have resulted from the preferential encroachment of seawater into areas of higher permeability in the Upper Floridan aquifer during Pleistocene high sea-level stands. The most permeable part of the Upper Floridan aquifer is low in these areas, and this could have also made these areas more prone to lateral invasion. These anomalies then persisted because of incomplete flushing of the high salinity water by the present flow system.

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Appendix I
Inventory of Wells from the Study Area

APPENDIX I. INVENTORY OF WELLS IN THE STUDY AREA

[Location of wells are shown in figure 1. The site identification number should not be used for the latitude-longitude location of a well. This number is assigned by the U.S. Geological Survey for identification purposes in the Ground-Water Site Inventory System. Depths are given in feet below measuring point, which usually is land surface. Dashes indicate no data]

Local well number	Other well identifier and/or owner	Site identification number (land-net location)	Latitude	Longitude	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Top/bottom of completed interval (feet)	Date at end of con-struction
BCN-I1	IW-1, Broward County North District Regional	261538080092801 (SW SE S21 T48S R42E)	261538	800928	14.35	3,512	160 1,000 1,950 2,990	2,990/3,512 --/-- --/-- --/--	03-28-90 -- -- --
BCN-I4	IW-4, Broward County North District Regional	261538080091801 (SE SE S21 T48S R42E)	261538	800918	14.42	3,500	160 1,000 1,949 2,950	2,950/3,500 --/-- --/-- --/--	11-25-90 -- -- --
BCN-M2	MW-2, Broward County North District Regional	261538080092001 (SE SE S21 T48S R42E)	261538	800920	14.75	2,079	160 1,000 2,000	1,000/1,130 2,000/2,079 --/--	10-31-90 -- --
CS-I1	IW-1, Coral Springs	261438080154801 (SW SW S28 T48S R41E)	261438	801548	13	3,500	125 995 2,300 3,006	1,193/1,222 2,153/2,183 3,006/3,500 --/--	05-29-85 -- -- --
CS-I2	IW-2, Coral Springs	261445080154801 (SW SW S28 T48S R41E)	261445	801548	13	3,500	170 1,001 1,800 2,900	2,900/3,500 --/-- --/-- --/--	11-29-89 -- -- --
CS-M2	MW-2, Coral Springs	261445080154802 (SW SW S28 T48S R41E)	261445	801548	13	1,650	170 1,000 1,510	1,000/1,110 1,510/1,650 --/--	11-01-89 -- --
D-365	IW-1, Broward Utilities, Collier Manor, W-5144	261548080060201 (SW NE S19 T48S R43E)	261548	800602	14.70	1,150	-- 1,004	--/-- 1,004/1,150	05-01-59 05-04-79
G-2887	IW-1, Deerfield Beach ASR	261857080072601 (SE NE S02 T48S R42E)	261857	800726	13.17	1,128	400 960	960/1,128 --/--	10-92 --
G-2889	IW-1, Broward County Office of Environmental Services, ASR	261735080062501 (SE S12 T48S R42E)	261735	800625	16.6	1,017	400 995	995/1,017 --/--	-- --
G-2890	W-9958	261955080321501	261955	803215	6	950	--	--/--	--
HE-1087	L2-TW, South Florida Water Management District	263630080565801 (NW NW S04 T45S R34E)	263630	805658	15	2,235	120 742 1,400	1,400/1,810 --/-- --/--	01-28-94 -- --

Local well number	Other well identifier and/or owner	Site identification number (land-net location)	Latitude	Longitude	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Top/bottom of completed interval (feet)	Date at end of con-struction
HE-1101	P-903, Houston Oil & Minerals Corporation	261638080542801 (NE SW S26 T48S R34E)	261638	805428	13.9	11,633	3,817	--/--	12-13-77
MAR-I2	IW-2, Margate	261427080130301 (NW NW S36 T48S R41E)	261427	801303	12.6	3,204	230 925 1,800 2,552	2,552/3,200 --/-- --/-- --/--	06-19-84 -- -- --
MAR-M2	MW-2, Margate	261427080130302 (NW NW S36 T48S R41E)	261427	801303	12.6	1,850	230 1,029 1,600 1,810	1,029/1,093 1,600/1,650 --/-- 1,810/1,850	06-19-84 -- -- 11-05-93
PB-203	S-353, University of Florida	264000080375001 (S03 T44S R37E)	264002	803758	17.64	1,332	957	--/--	03-17-27
PB-212	S-382, Florida Power & Light	264552080030601 (S21 T43S R43E)	264244	800323	22.5	1,080	108 977	--/-- --/--	-- 1923
PB-215	S-399, Field 11, U.S. Sugar	265008080353801 (S12 T42S R37E)	265008	803542	18	958	850	--/--	--
PB-216	S-400, U.S. Coast Guard	264618080024501 (S34 T42S R43E)	264618	800245	11.5	1,000	--	--/--	04-37
PB-407	S-1184, Royal Palm Ice	264259080032001 (S21 T43S R43E)	264259	800320	18	1,035	--	--/--	1924
PB-652	Wilson	265642080072301 (S35 T40S R42E)	265642	800723	7	1,385	826	--/--	1939
PB-734	Shallow MW-1, Quaker Oats Chemicals	264200080390001 (S28 T43S R37E)	264228	803905	15	1,400	648	--/--	1966
PB-735	Deep MW-2/IW-2, Quaker Oats Chemicals	264200080390002 (S28 T43S R37E)	264222	803857	15	2,067	1,490	1,490/--	1966
PB-736	IW-1, Quaker Oats Chemicals, PB-600, PB-505, PB-493, PB-546	264227080390701 (S28 T43S R37E)	264229	803905	15	2,242	228 684 1,496 1,938	--/-- --/-- --/-- --/--	-- -- -- 10-65
PB-747	PB-733, South Florida Water Management District	265604080082601 (S03 T41S R42E)	265604	800826	13	1,280	400 990	--/-- --/--	-- 06-74
PB-860	Test Monitor, West Palm Beach	264421080073204 (S11 T43S R42E)	264421	800732	12	2,150	2,130	2,130/2,150	1975
PB-861	Test Monitor, West Palm Beach	264421080073205 (S11 T43S R42E)	264421	800732	12	2,171	2,150	2,150/2,171	1975
PB-903	W-9112	263322080305001	263322	803050	11	1,200	--	--	--

Local well number	Other well identifier and/or owner	Site identification number (land-net location)	Latitude	Longitude	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Top/bottom of completed interval (feet)	Date at end of con-struction
PB-964A	DW1A, West Palm Beach, W-13012	264416080074401 (S11 T43S R42E)	264416	800745	19	3,632	114 404 1,018 3,026	2,154/2,166 2,194/2,208 -- --	-- -- -- 07-29-77
PB-965	DW2, West Palm Beach, W-13690	264413080074801	264412	800748	19	3,680	115 392 1,030 3,024	2,228/2,238 2,270/2,277 -- --	-- -- -- 11-76
PB-1132	Hughes & Hughes	264438080281101 (S08 T43S R39E)	264438	802811	28.6	11,002	4,002	--/--	06-79
PB-1133	Permit 235, Amerada	265146080253501 (S34 T41S R39E)	265152	802513	38	11,010	1,032 4,219	--/-- --/--	-- 09-01-55
PB-1136	Permit 47, Humble Oil, W-1471	264056080190901 (S02 T48S R35E)	264056	801909	34	13,375	149 849 5,639	--/-- --/-- --/--	-- -- 07-13-47
PB-1137	Permit 265, Humble Oil, W-4661	262039080484201 (S02 T48S R35E)	262013	804841	31	12,810	276 1,988 4,602	--/-- --/-- --/--	-- -- 02-02-57
PB-1138	Permit 740, Shell Oil	263039080515101 (S07 T46S R35E)	263003	805227	31.06	16,848	302 1,672 4,198	--/-- --/-- --/--	-- -- 02-06-75
PB-1139	Permit 385, Amerada, W-8322	264313080265801 (S21 T43S R39E)	264322	802652	31	10,903	4,015	--/--	03-24-68
PB-1141	IW-3, Quaker Oats Chemicals	264224080390401 (S28 T43S R37E)	264224	803904	12	3,163	235 790 1,613 2,890 2,910	--/-- --/-- --/-- --/-- --/--	-- -- -- 08-77 --
PB-1144	PBF-1, Broadview Condominiums	265800080051301 (S30 T40S R43E)	265811	800513	19	1,038	1,020	--/--	--
PB-1146	DW1, West Palm Beach	264416080074502 (S11 T43S R42E)	264416	800745	19	2,974	1,064 2,463	--/-- --/--	-- 1976
PB-1162	W-10079	263656080445501	263656	804455	11	1,150	--	--/--	--
PB-1163	W-10080	263657080473701	263647	804737	12	1,120	--	--/--	--
PB-1164	W-10213	264310080523001	265310	805230	12	840	--	--/--	--
PB-1166	IW-1, Pratt & Whitney	265404080181701 (SE S14 T41S R40E)	265404	801817	25	3,310	165 970 1,865 2,728	2,728/-- --/-- --/-- --/--	04-23-85 -- -- --

Local well number	Other well identifier and/or owner	Site identification number (land-net location)	Latitude	Longitude	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Top/bottom of completed interval (feet)	Date at end of con-struction
PB-1167	MW-1, Pratt & Whitney	265404080181702 (SE S14 T41S R40E)	265404	801817	25	2,050	165 1,000 1,958	1,000/1,237 1,958/2,050 --/--	04-25-85 -- --
PB-1168	IW-1, Palm Beach County System 9 North	262333080121201 (NW S07 T47S R42E)	262333	801212	20	3,300	250 970 1,800 2,640	2,640/3,300 --/-- --/-- --/--	09-09-85 -- -- --
PB-1169	MW-1, Palm Beach County System 9 North	262333080121202 (NW S07 T47S R42E)	262333	801212	20	1,800	250 970 1,700	970/1,105 1,700/1,800 --/--	10-18-85 -- --
PB-1170	IW-1, Loxahatchee ENCON	265515080082501 (NW S10 T41S R42E)	265528	800827	18	3,505	115 923 1,997 2,839	1,501/1,532 1,840/1,870 2,839/3,505 --/--	01-18-86 -- -- --
PB-1171	MW-1, Loxahatchee ENCON	265515080082502 (NW S10 T41S R42E)	265528	800827	18	2,107	60 1,040 2,062	2,062/2,107 --/-- --/--	04-11-94 -- --
PB-1172	IW-1, ACME Improvement District	263805080133001 (NW S23 T44S R41E)	263805	801300	16	3,389	120 995 2,027 2,756	1,428/1,958 1,958/1,990 2,756/3,389 --/--	07-14-86 -- -- --
PB-1173	MW-1, ACME Improvement District	263805080130002 (NW NW S23 T44S R41E)	263805	801300	19	2,010	118 1,538 1,938	1,538/1,622 1,938/2,010 --/--	09-19-96 -- --
PB-1174	IW-1, Palm Beach County System 3	262810080094901 (SE S09 T46S R42E)	262810	800949	23.97	3,495	120 1,000 2,035 2,964	1,488/1,528 1,920/1,920 2,694/3,495 --/--	11-10-86 -- -- --
PB-1176	IW-1, Royal Palm Beach	264409080140501 (NE S15 T43S R41E)	264403	801405	17.83	3,300	45 190 890 1,900 2,716	2,716/3,300 --/-- --/-- --/-- --/--	02-13-88 -- -- -- --
PB-1177	MW-1, Royal Palm Beach	264403080140502 (NE S15 T43S R41E)	264403	801405	18.69	2,050	45 200 930 2,000	930/1,080 2,000/2,050 --/-- --/--	02-11-88 -- -- --

Local well number	Other well identifier and/or owner	Site identification number (land-net location)	Latitude	Longitude	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Top/bottom of completed interval (feet)	Date at end of con-struction
PB-1178	IW-1, Solid Waste Authority - North County	264608080082501 (SE S34 T42S R42E)	264608	800825	20	3,512	50 200 1,000 2,000 3,000	3,000/3,512 --/-- --/-- --/-- --/--	04-10-88 -- -- -- --
PB-1179	MW-1, Solid Waste Authority - North County	264608080082503 (SE S34 T42S R42E)	264608	800825	20	1,871	30 200 1,020 1,817	1,020/1,111 1,817/1,871 --/-- --/--	03-23-88 -- -- --
PB-1180	IW-2, Solid Waste Authority - North County	264608080082502 (SE S34 T42S R42E)	264608	800825	20	3,501	50 200 1,000 2,000 3,000	3,000/3,501 --/-- --/-- --/-- --/--	04-09-88 -- -- -- --
PB-1181	MW-2, Solid WasteAuthority - North County	264608080082504 (SE S34 T42S R42E)	264608	800825	20	2,161	1,025 2,110	--/-- --/--	-- --
PB-1182	IW-1, Seacoast Utilities Authority	265118080075501 (SW S34 T41S R42E)	265118	800755	20.52	3,320	200 990 2,020 2,750	2,750/3,320 --/-- --/-- --/--	09-29-88 -- -- --
PB-1183	MW-1, Seacoast Utilities Authority	265118080075502 (SW S34 T41S R42E)	265118	800755	20.23	2,020	200 995 1,965	995/1,103 1,870/1,890 1,965/2,020 --/--	09-29-88 05-07-96 -- --
PB-1184	IW-1, Pahokee	264803080402701 (SW S19 T42S R37E)	264803	804027	13.03	3,510	193 996 2,000 2,650	2,650/3,510 --/-- --/-- --/--	10-17-89 -- -- --
PB-1185	MW-1, Pahokee	264803080402702 (SW S19 T42S R37E)	264803	804027	13.82	2,008	192 996 1,915	996/1,147 1,915/2,008 --/--	08-04-89 -- --
PB-1186	IW-1, Belle Glade	264142080412301 (S36 T43S R36E)	264142	804123	14.1	3,505	163 999 2,100 2,850	2,850/3,505 --/-- --/-- --/--	06-10-90 -- -- --
PB-1187	MW-1, Belle Glade	264141080412301 (S36 T43S R36E)	264141	804123	14.1	1,940	173 1,001 1,871	1,001/1,169 1,871/1,940 --/--	06-10-90 -- --

Local well number	Other well identifier and/or owner	Site identification number (land-net location)	Latitude	Longitude	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Top/bottom of completed interval (feet)	Date at end of con-struction
PB-1188	IW-1, Palm Beach County Southern Regional	262930080100101 (NW S04 T46S R42E)	262930	801001	21.38	3,311	50 260 1,000 1,890 2,660	2,600/3,311 --/-- --/-- --/-- --/--	11-14-90 -- -- -- --
PB-1189	MW-1, Palm Beach County Southern Regional	262930080100001 (NW S04 T46S R42E)	262930	801000	21.5	1,984	260 1,000 1,900	1,000/1,096 1,900/1,984 --/--	09-07-90 -- --
PB-1190	IW-2, Palm Beach County Southern Regional	262930080095901 (NW S04 T46S R42E)	262930	800959	21.5	3,450	25 260 1,000 1,890 2,645	2,645/3,450 --/-- --/-- --/-- --/--	11-13-90 -- -- -- --
PB-1192	IW-1, Boynton Beach RO Reject	263143080071801 (S23 T45S R42E)	263143	800718	19.56	3,312	48 345 970 2,000 2,780	2,780/3,310 --/-- --/-- --/-- --/--	12-23-91 -- -- -- --
PB-1193	MW-1, Boynton Beach RO Reject	263143080071802 (S23 T45S R42E)	263143	800718	20.25	1,855	345 970 1,800	970/1,084 1,800/1,855 --/--	04-21-92 -- --
PB-1194	IW-1, Boynton Beach ASR	263044080035101 (NE S33 T45S R43E)	263044	800351	19.05	909	38 399 804	804/909 --/-- --/--	04-13-92 -- --
PB-1196	DZMW, Jupiter RO Production	265522080092401 (NW S09 T41S R42E)	265522	800924	--	1,609	300 1,137 1,549	1,137/1,155 1,549/1,609 --/--	08-12-94 -- --
PB-1197	RO-5, Jupiter RO Production	265523080092301 (NW S09 T41S R42E)	265523	800923	17	1,665	150 1,024 1,451	1,451/1,665 --/-- --/--	08-12-94 -- --
PB-1689	IW-6, West Palm Beach	264440080075901 (SW S11 T43S R42E)	264408	800805	19	3,378	120 1,000 1,994 2,950 2,950	2,950/3,378 --/-- --/-- --/-- --/--	09-16-86 -- -- -- --
PB-1690	MW-1 at IW-6, West Palm Beach	264440080075902 (SW S11 T43S R42E)	264408	800805	19	2,059	72 120 1,000 2,059	1,000/1,080 2,042/2,059 --/-- --/--	09-16-86 -- -- --

Local well number	Other well identifier and/or owner	Site identification number (land-net location)	Latitude	Longitude	Altitude of measuring point (feet)	Well depth (feet)	Bottom of casing (feet)	Top/bottom of completed interval (feet)	Date at end of con-struction
PB-1691	MW-2, West Palm Beach	264412080074803 (SW S11 T43S R42E)	264412	800748	19	2,289	40 261 1,559 2,240	1,559/1,600 2,240/2,289 --/-- --/--	05-05-93 -- -- --
PB-1693	MW-1, West Palm Beach ASR	264232080040001 (NW S21 T43S R43E)	264232	800400	18.97	1,191	379 975	975/1,191 --/--	11-96 --
PB-1695	PBF-3,4,5, TZMW, South Florida Water Management District	264033080061101 (NW S06 T44S R43E)	264033	800611	15	2,490	320 1,050 1,360 2,340	1,050/1,252 1,360/1,510 2,340/2,490 --/--	02-01-96 -- -- --
PB-1696	W-7500, Sugar Cane Growers Coop	262505080391601 (NW NW S28 T46S R37E)	262505	803916	11	1,705	--	--/--	1965
PB-1697	W-9104, HOR CT	263400080130001 (NW S12 T45S R41E)	263400	801300	15	984	--	--/--	--
PB-1698	W-9110, Humble	263840080351001	263840	803510	12	1,045	--	--/--	--
PB-1699	W-9113, HOR CT	264000080273001 (S04 T44S R39E)	264000	802730	13	1,064	--	--/--	--
PB-1700	W-9114, HOR CT	264100080183001	264100	801830	17	1,028	--	--/--	--
PB-1701	W-10102, Humble SCT	263000080440001 (NW S10 T46S R36E)	263000	804400	12	935	--	--/--	--
PB-1702	Test Well, Delray Beach ASR	262800080060001	262800	800600	21.2	1,201	400 1,017	--/-- --/--	-- --

Appendix II

Selected Water-Quality Data Collected from Known Intervals in Wells from the Floridan Aquifer System

APPENDIX II. SELECTED WATER-QUALITY DATA COLLECTED FROM KNOWN INTERVALS IN WELLS FROM THE FLORIDAN AQUIFER SYSTEM

[Not all of the wells were used in the study; those wells used are shown in figure 1. Depths are given in feet below measuring point, which usually is land surface (measuring points are presented in appendix I). Source of water sample: packer, data from open-hole interval by packer test; completed, data from completed interval; pumped, data obtained by pumped-well test while drilling (pumped out of open hole below casing); USGS, U.S. Geological Survey data; SFWMD, South Florida Water Management District data. Other annotations: ft, feet; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; --, not determined; ?, depth to top of sample interval is uncertain; >, greater than the value; *, chloride calculated from specific conductance in wells PB-652 and PB-1702]

Local well identifier	Source of water sample	Sampling date	Depth to top of sample interval (ft)	Depth to bottom of sample interval (ft)	Chloride (mg/L)	Dissolved solids (mg/L)	Specific conductance (µS/cm)	Sulfate (mg/L)
BCN-I1	Packer	01-04-90	1,500	1,520	4,230	5,550	10,100	616
	Packer	01-05-90	1,640	1,660	6,550	10,800	17,600	1,110
	Packer	01-03-90	1,690	1,710	9,650	14,600	29,600	750
BCN-I4	Packer	08-05-90	1,756	1,806	7,250	12,000	28,900	--
	Packer	08-05-90	1,963	2,013	18,700	29,800	68,800	--
BCN-M2	Completed	11-15-90	1,000	1,130	2,500	5,480	--	--
	Completed	11-15-90	2,000	2,079	18,600	37,500	--	--
CS-I1	Completed	05-01-87	1,193	1,222	5,640	--	--	--
	Completed	05-01-87	2,153	2,183	15,100	--	--	--
	Packer	01-26-85	2,451	2,498	15,000	28,300	43,200	--
CS-I2	Packer	09-07-89	1,090	1,130	5,400	9,370	15,200	--
	Packer	09-05-89	1,180	1,220	5,800	10,700	16,800	--
	Packer	10-11-89	2,300	2,340	17,500	30,000	6,810	--
	Packer	10-12-89	2,450	2,490	19,800	34,800	7,890	--
	Packer	10-13-89	2,600	2,640	16,900	39,400	6,930	--
CS-M2	Completed	03-15-90	1,000	1,110	6,550	11,500	--	1,970
	Completed	03-15-90	1,510	1,650	2,330	4,430	--	124
D-365	Completed-USGS	06-02-59	989	1,150	2,360	5,120	7,870	--
G-2887	Completed	09-30-92	960	1,128	2,000	3,800	5,400	400
HE-1087	Packer-SFWMD	01-01-94	1,266	1,284	490	1,370	2,240	366
	Packer-SFWMD	01-01-94	1,442	1,494	445	1,370	2,230	322
	Packer-SFWMD	01-01-94	1,652	1,704	882	2,160	--	440
	Packer-SFWMD	01-01-94	1,890	1,908	3,080	5,550	9,990	1,360
	Packer-SFWMD	01-01-94	2,072	2,124	10,700	19,100	30,800	1,360
MAR-M2	Completed	JAN 1988	1,029	1,093	3,510	--	10,000	--
	Completed	JAN 1988	1,600	1,650	3,330	--	9,890	--
	Packer	07-15-93	1,720	1,750	4,000	8,110	10,500	--
	Packer	07-17-93	1,770	1,800	5,850	11,700	16,700	--
	Completed	07-28-94	1,810	1,850	6,200	12,700	17,400	--
PB-203	Completed-USGS	02-11-75	957	1,332	1,600	3,670	5,700	510
PB-212	Completed-USGS	10-28-40	977	1,080	2,400	--	--	481
PB-215	Completed-USGS	09-12-41	850	958	940	--	3,590	223
PB-216	Completed-USGS	07-15-74	?	1,000	1,600	3,360	5,100	430
PB-407	Completed-USGS	09-09-41	?	1,035	2,110	--	7,260	449
PB-652*	Completed	02-23-73	826	1,385	8,000	--	21,500	--
PB-734	Completed	03-14-66	650	1,400	855	--	--	364
	Completed-USGS	04-11-75	650	1,400	960	3,630	4,700	110
PB-735	Completed	02-14-67	1,490	2,067	10,400	--	--	1,500

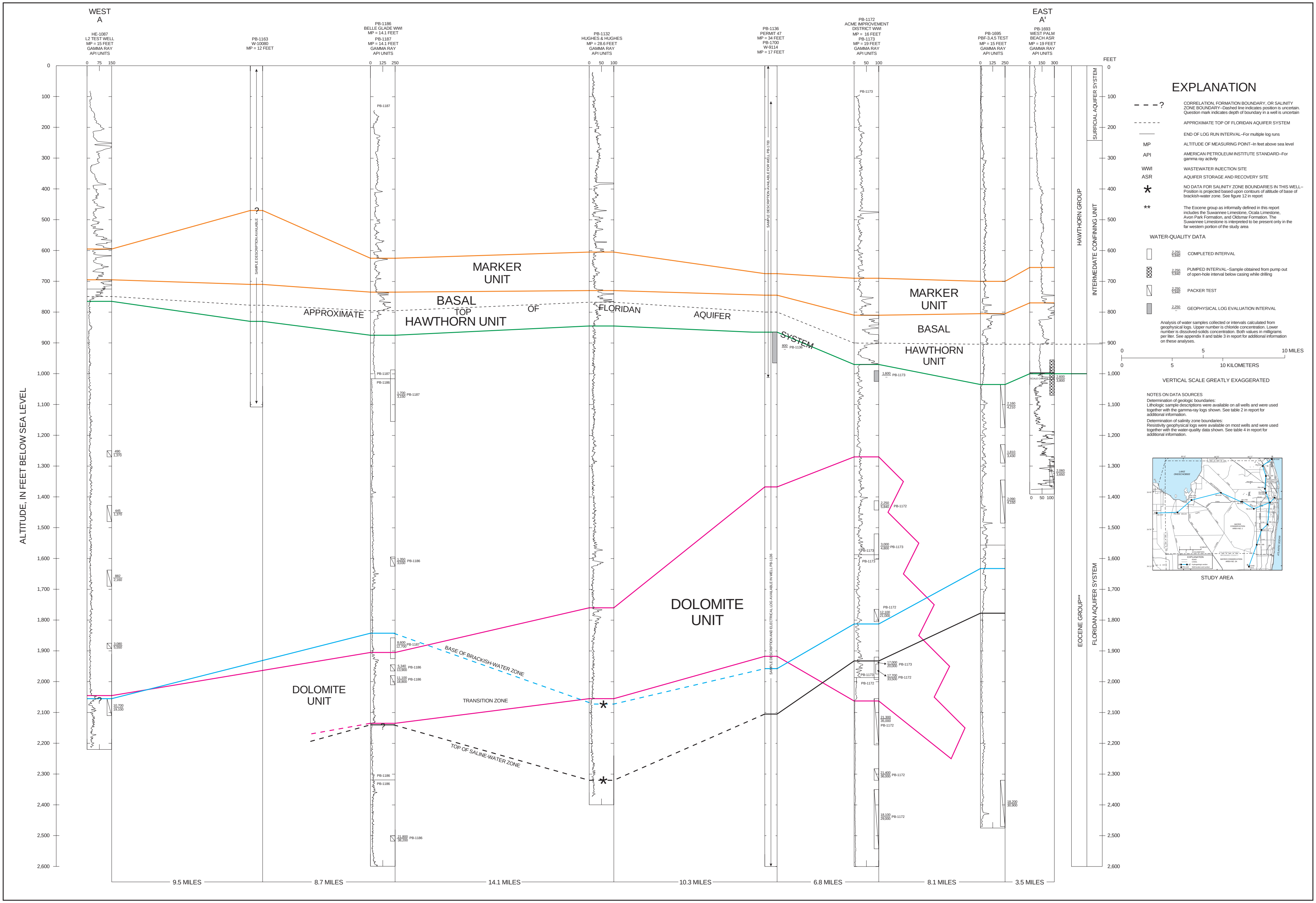
Local well identifier	Source of water sample	Sampling date	Depth to top of sample interval (ft)	Depth to bottom of sample interval (ft)	Chloride (mg/L)	Dissolved solids (mg/L)	Specific conductance (µS/cm)	Sulfate (mg/L)
PB-736	Pumped	09-14-65	687	1,105	1,160	--	--	515
	Pumped	09-18-65	687	1,320	690	--	--	415
	Completed-USGS	01-06-72	1,938	2,242	8,000	--	26,000	452
PB-747	Completed-USGS	06-19-74	990	1,280	1,800	4,060	6,400	400
PB-860	Completed-USGS	08-17-78	2,130	2,150	15,000	28,400	38,800	2,000
PB-861	Completed-USGS	07-21-75	2,150	2,171	15,000	28,600	40,600	1,900
PB-964A	Completed-USGS	08-15-78	2,154	2,208	16,000	29,300	42,900	1,900
PB-965	Completed-USGS	08-16-78	2,228	2,277	19,000	33,600	45,700	2,100
PB-1144	Completed-SFWMD	12-05-77	1,020	1,038	1,380	3,180	4,370	300
PB-1167	Completed	05-13-85	1,000	1,237	1,760	3,220	5,300	--
	Completed	12-07-94	1,000	1,237	1,620	2,990	--	250
	Completed	05-13-85	1,958	2,050	17,900	29,200	37,000	--
	Completed	12-07-94	1,958	2,050	17,900	30,500	--	2,170
PB-1169	Completed	05-10-95	970	1,105	2,580	5,170	8,420	--
	Completed	05-10-95	1,699	1,800	9,340	17,500	26,300	--
PB-1170	Packer	11-12-85	1,405	1,455	5,440	9,250	9,800	821
	Completed	09-08-94	1,501	1,532	1,380	2,790	5,130	326
	Packer	11-12-85	1,810	1,840	5,600	9,700	9,900	758
	Completed	09-08-94	1,840	1,870	1,900	3,610	5,800	333
	Packer	11-12-85	2,280	2,330	16,900	29,000	23,800	1,910
	Packer	11-12-85	2,360	2,570	13,700	23,100	20,000	1,600
	Packer	11-12-85	2,568	2,709	16,800	28,300	23,200	1,900
PB-1171	Completed	09-15-94	2,062	2,107	9,650	15,100	26,800	299
PB-1172	Completed	07-02-86	1,428	1,459	2,250	5,840	10,000	159
	Packer	10-15-85	1,780	1,820	12,100	21,000	>20,000	1,700
	Completed	07-30-86	1,958	1,990	17,700	33,500	45,700	859
	Packer	10-16-85	1,960	2,000	17,600	26,000	>20,000	2,050
	Packer	10-19-85	2,070	2,220	21,300	35,000	>20,000	2,500
	Packer	10-21-85	2,295	2,335	21,400	36,000	>20,000	2,600
	Packer	10-18-95	2,365	2,558	18,100	29,000	>20,000	2,300
PB-1173	Completed	09-18-96	1,538	1,622	3,000	4,800	--	440
	Completed	09-18-96	1,938	2,010	17,000	20,000	--	2,700
PB-1174	Completed	10-15-86	1,488	1,528	3,540	8,000	12,000	530
	Completed	APR 1991	1,488	1,528	2,900	5,360	9,430	--
	Packer	02-14-86	1,498	1,548	3,690	8,970	9,100	618
	Packer	02-14-86	1,917	1,968	21,700	40,500	28,000	2,300
	Completed	10-15-86	1,920	1,950	19,200	35,600	47,000	2,580
	Completed	APR 1991	1,920	1,950	17,800	30,000	43,100	--
PB-1176	Pumped	11-08-97	1,900	1,917	9,840	16,500	26,000	--
PB-1177	Completed	05-13-88	930	1,018	2,000	4,000	--	398
	Completed	05-13-88	2,000	2,050	16,400	28,500	--	1,780
PB-1178	Packer	01-17-88	1,630	1,670	2,290	4,980	5,860	397
	Packer	01-14-88	1,745	1,785	2,900	5,940	6,300	519
	Packer	01-16-88	1,840	1,880	10,200	21,000	20,200	1,200
PB-1179	Completed	03-05-93	1,020	1,111	2,300	4,500	7,900	--
	Completed	04-30-93	1,817	1,871	3,950	7,050	10,900	--
PB-1180	Packer	02-04-88	1,785	1,825	12,500	19,400	24,500	1,180
	Packer	02-04-88	1,860	1,890	4,150	7,920	10,900	617
PB-1181	Packer	11-15-96	2,105	2,161	13,800	29,700	30,300	1,120

Local well identifier	Source of water sample	Sampling date	Depth to top of sample interval (ft)	Depth to bottom of sample interval (ft)	Chloride (mg/L)	Dissolved solids (mg/L)	Specific conductance (µS/cm)	Sulfate (mg/L)
PB-1182	Packer	1988	1,814	1,837	3,050	5,950	8,500	--
	Packer	1988	1,857	1,880	3,570	5,950	8,500	--
	Packer	1988	1,876	1,899	4,350	8,040	11,500	--
	Packer	1988	1,917	1,940	5,500	10,100	14,500	--
	Packer	1988	1,948	1,984	6,820	11,900	17,000	--
PB-1183	Completed	09-29-88	995	1,103	3,020	6,280	--	532
	Completed	05-15-96	1,870	1,890	5,490	9,880	--	735
	Completed	09-29-88	1,965	2,020	7,070	12,900	--	630
PB-1184	Packer	06-08-89	1,776	1,821	4,610	8,500	10,400	114
	Packer	06-12-89	1,890	1,935	7,700	16,200	18,900	863
PB-1185	Completed	09-27-89	996	1,147	2,400	5,000	7,030	563
	Completed	01-26-91	996	1,147	1,710	3,950	6,100	--
	Completed	09-27-89	1,915	2,008	13,400	19,620	25,300	1,130
	Completed	01-26-91	1,915	2,008	9,430	17,000	24,400	--
PB-1186	Packer	02-10-90	1,610	1,640	1,350	3,030	4,070	487
	Packer	02-05-90	1,960	1,980	5,340	13,900	17,000	1,080
	Packer	02-08-90	1,994	2,024	11,100	18,800	21,900	1,020
	Packer	06-12-90	2,513	2,531	21,800	38,200	3,150	2,400
PB-1187	Completed	MAY 1993	1,001	1,169	1,700	3,150	--	--
	Completed	MAY 1993	1,871	1,940	8,600	12,700	--	--
PB-1188	Packer	06-07-90	1,882	1,950	20,800	36,500	48,000	--
PB-1189	Completed	09-15-94	1,000	1,096	2,340	5,260	8,520	--
	Completed	03-05-92	1,900	1,984	19,800	31,900	47,500	--
PB-1192	Packer	06-08-91	1,428	1,449	2,460	4,880	8,450	--
	Packer	06-07-91	1,608	1,629	5,810	11,400	18,200	--
	Packer	06-07-91	1,708	1,729	7,440	14,400	22,900	--
	Packer	06-06-91	1,737	1,759	7,710	14,300	24,000	--
PB-1193	Completed	04-21-92	970	1,084	2,050	3,800	--	319
	Completed	04-21-92	1,800	1,855	14,000	28,300	--	1,390
PB-1194	Completed	05-21-92	804	909	1,920	3,910	6,670	436
PB-1196	Completed	09-24-93	1,137	1,155	4,000	--	--	--
	Completed	09-24-93	1,549	1,609	2,020	--	--	--
PB-1197	Completed	08-06-94	1,451	1,665	1,900	--	--	--
PB-1690	Completed	10-15-86	1,000	1,080	3,870	7,390	11,000	680
	Completed	10-15-86	2,070	2,100	14,300	24,200	32,000	660
PB-1691	Completed	01-03-97	1,559	1,600	2,600	5,170	6,500	200
	Completed	01-03-97	2,240	2,289	20,900	33,800	35,000	2,000
PB-1693	Pumped	08-29-96	975	1,090	2,600	3,800	7,700	--
	Packer	09-14-96	1,304	1,384	2,060	3,650	6,850	--
PB-1695	Packer-SFWMD	02-12-96	1,050	1,190	2,160	4,210	7,460	377
	Packer-SFWMD	01-04-96	1,246	1,304	1,810	3,430	6,110	323
	Packer-SFWMD	02-09-96	1,360	1,500	2,090	4,150	7,170	360
	Packer-SFWMD	02-06-96	2,340	2,485	18,200	30,900	46,300	2,090
PB-1702*	Packer	06-14-96	974	1,020	--	--	6,000	--
	Completed	09-16-96	1,020	1,210	1,330	--	5,000	--

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

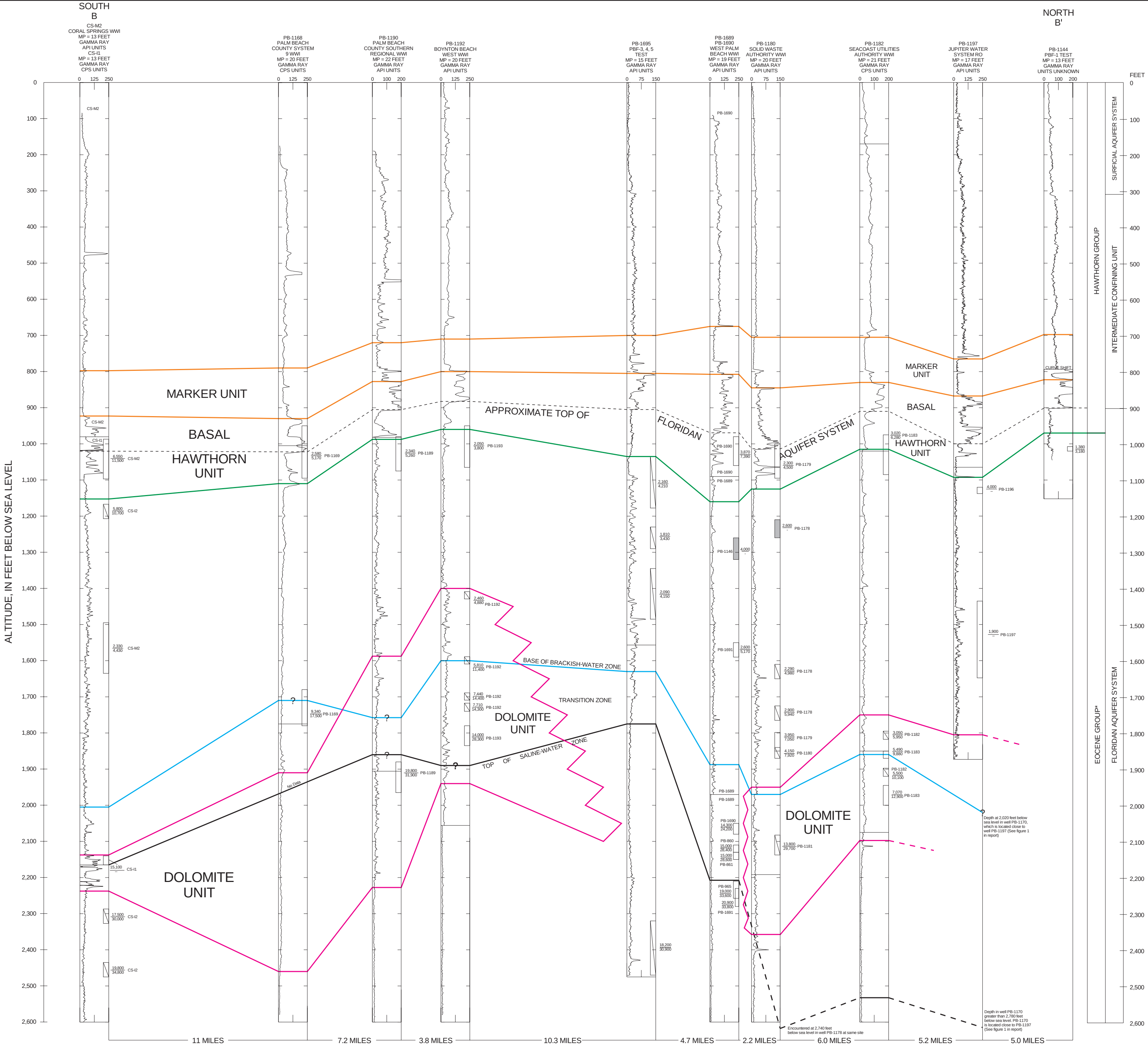
PREPARED IN COOPERATION WITH THE
SOUTH FLORIDA WATER MANAGEMENT DISTRICT

WATER-RESOURCES INVESTIGATIONS REPORT 99-4061
Hydrogeologic Section *A-A'* PLATE 1
Reese, R.S., Memberg, S.J.,. 1999, Hydrogeology and the Distribution of Salinity in the Floridan Aquifer System, Palm Beach County, Florida



HYDROGEOLOGIC SECTION *A-A'*

By
Ron S. Reese and Steven J. Memberg
1999



EXPLANATION

- – – ? CORRELATION, FORMATION BOUNDARY, OR SALINITY ZONE BOUNDARY--Dashed line indicates position is uncertain. Question mark indicates depth of boundary in a well is uncertain
- - - - - - APPROXIMATE TOP OF FLORIDAN AQUIFER SYSTEM
- ——— END OF LOG RUN INTERVAL--For multiple log runs
- MP ALTITUDE OF MEASURING POINT--In feet above sea level
- CPS COUNTS PER SECOND
- API AMERICAN PETROLEUM INSTITUTE STANDARD--For gamma ray activity
- WWI WASTEWATER INJECTION SITE
- RO REVERSE-OSMOSIS WATER-SUPPLY SITE
- * The Eocene group as informally defined in this report includes the Suwannee Limestone, Ocala Limestone, Avon Park Formation, and Oldsmar Formation. The Suwannee Limestone is interpreted to be present only in the far western portion of the study area

WATER-QUALITY DATA

- 2,250 / 5,840 COMPLETED INTERVAL
- 2,250 / 5,840 PACKER TEST
- 2,250 / -- GEOPHYSICAL LOG EVALUATION INTERVAL

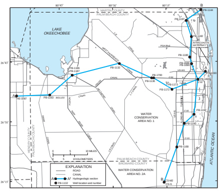
Analysis of water samples collected or intervals calculated from geophysical logs. Upper number is chloride concentration. Lower number is dissolved-solids concentration. Both values in milligrams per liter. See appendix II and table 3 in report for additional information on these analyses.

0 5 10 MILES
0 5 10 KILOMETERS
VERTICAL SCALE GREATLY EXAGGERATED

NOTES ON DATA SOURCES

Determination of geologic boundaries:
Lithologic sample descriptions were available on all wells and were used together with the gamma-ray logs shown. See table 2 in report for additional information.

Determination of salinity zone boundaries:
Resistivity geophysical logs were available on most wells and were used together with the water-quality data shown. See table 4 in report for additional information.



STUDY AREA

HYDROGEOLOGIC SECTION *B-B'*

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