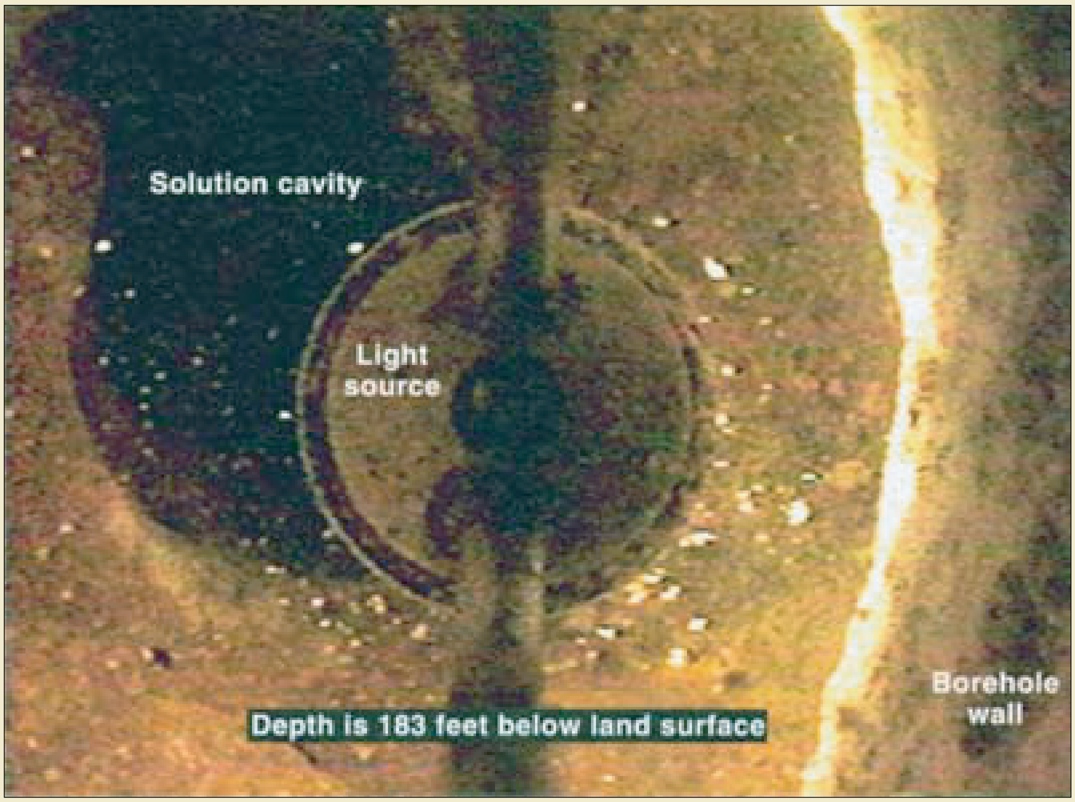
HYDROLOGIC EVALUATION OF THE UPPER FLORIDAN AQUIFER IN THE SOUTHWESTERN ALBANY AREA, GEORGIA

U.S. GEOLOGICAL SURVEY



Prepared in cooperation with the

ALBANY WATER, GAS, AND LIGHT COMMISSION

WATER-RESOURCES INVESTIGATIONS REPORT 97-4129

Cover photograph: Still from borehole video showing solution cavity 183 feet below land surface in well 12K151 completed in the Upper Floridan aquifer.

Video camera operated by John Doss and Debbie Warner, U.S. Geological Survey

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Atlanta, Georgia
1997

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS

Multiply	by	to obtain
	Length	
foot (ft)	0.3048	meter
square foot (ft^2)	0.0929	square meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
	Area	
square mile (mi^2)	2.59	square kilometer
	Volumetric rate and volume	
gallon per minute (gal/min)	6.309×10^{-5}	cubic meter per second
	2.228×10^{-3}	cubic foot per second
	0.06301	liter per second
gallon per minute per foot (gal/min/ft)	0.0124	cubic meters per minute per meter of drawdown
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

ABBREVIATIONS

USGS	U.S. Geological Survey
WGL	Albany Water, Gas, and Light Commission

VERTICAL DATUM

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

A cooperative study by the Albany Water, Gas, and Light Commission and the U.S. Geological Survey was conducted to evaluate the hydrogeology of the Upper Floridan aquifer in an area southwest of Albany and west of the Flint River in Dougherty County, Ga. The study area lies in the Dougherty Plain district of the Coastal Plain physiographic province. In this area, the Upper Floridan aquifer is comprised of the upper Eocene Ocala Limestone, confined below by the middle Eocene Lisbon Formation, and semiconfined above by the undifferentiated Quaternary overburden. The overburden ranges in thickness from about 30 to 50 feet and consists of fine to coarse quartz sand, clayey sand, sandy clay, and clay. The Upper Floridan aquifer has been subdivided into an upper water-bearing zone and a lower water-bearing zone based on differences in lithology and yield. In the study area, the upper water-bearing zone generally consists of dense, highly weathered limestone of low permeability and ranges in thickness from 40 to 80 feet. The lower water-bearing zone consists of hard, slightly weathered limestone that exhibits a high degree of secondary permeability that has developed along fractures and joints, and ranges in thickness from about 60 to 80 feet. Borehole geophysical logs and borehole video surveys indicate two areas of high permeability in the lower water-bearing zone—one near the top and one near the base of the zone.

A wellfield consisting of one production well and five observation-well clusters (one deep, intermediate, and shallow well in each cluster) was constructed for this study. Spinner flowmeter tests were conducted in the production well between the depths of 110 and 140 feet below land surface to determine the relative percentages of water contributed by selected vertical intervals of the lower water-bearing zone. Pumping rates during these tests were 1,080, 2,200, and 3,400 gallons per minute. The results of these pumping tests show that the interval between 118 and 124 feet below land surface contributes a significant percentage of the total yield to the well.

An aquifer test was conducted by pumping the production well at a constant rate of 3,300 gallons per minute for about 49 hours. Time-dependent water-level data were collected throughout the pumping and recovery phases of the test in the pumped well and the observation wells. The maximum measured drawdown in the observation wells was about 2.6 ft. At about 0.5 mile from the pumped well, there was little measurable effect from pumping. Water levels increased during the test in wells located within about 3.75 miles of the Flint River (about 0.5 miles east of the pumping well). This water-level increase correlated with a 3.5-feet increase in the stage of the Flint River.

The hydraulic characteristics of the Upper Floridan aquifer were evaluated using the Hantush-Jacob curve-matching and Jacob straight-line methods. Using the Hantush-Jacob method, values for transmissivity ranged from about 120,000 to 506,000 feet squared per day; values for storage coefficient ranged from 1.4 x 10^{-4} to 6.3 x 10^{-4}; and values for vertical hydraulic conductivity of the overlying sediments ranged from 4.9 to 6.8 feet per day. Geometric averages for these values of transmissivity, storage coefficient, and vertical hydraulic conductivity were calculated to be 248,000 feet squared per day, 2.7 x 10^{-4}, and 5.5 feet per day, respectively. If a dual porosity aquifer model (fracture flow plus matrix flow) is assumed instead of leakage, and the Jacob straight-line method is used with late time-drawdown data, the calculated transmissivity of the fractures ranged from about 233,000 to 466,000 feet squared per day; and storage coefficient of the fractures plus the matrix ranged from 5.1 x 10^{-4} to 2.9 x 10^{-2}.

INTRODUCTION

Long-term pumping from the Claiborne, Clayton, and Providence aquifers has resulted in ground-water-level declines in the Albany, Ga., area. Ground-water levels have declined more that 140 feet (ft) in the Clayton aquifer since 1940 (Hicks and others, 1987). Because of these ground-water-level declines, the Albany Water, Gas, and Light Commission (WGL) has proposed to use the shallower Upper Floridan aquifer to augment increasing municipal water demands (Hicks and others, 1987). The U.S. Geological Survey (USGS), in cooperation with the WGL, is conducting a study in an area southwest of Albany and west of the Flint River in Dougherty County to evaluate the hydrogeology of the Upper Floridan aquifer.

Purpose and Scope

This report describes the hydrogeology of the Upper Floridan aquifer in the southwestern Albany, Ga., area. Specifically, this report:

- describes the hydrogeologic framework of the geologic units that constitute the ground-water flow system comprised of the Upper Floridan aquifer and its semi-confining units;
- identifies the vertical distribution of yield within the Upper Floridan aquifer;
- quantifies fluctuations in the ground-water levels that result from pumping during the aquifer test;
- identifies cause-and-effect relations between fluctuations in ground-water levels and the stage of the Flint River; and
- presents the results of an aquifer test to quantify the hydraulic properties of the Upper Floridan aquifer.

The analyses are limited to hydrogeologic information that was obtained from a production well and 15 observation wells constructed for the project, and from water levels measured in 31 observation wells during 1995. Other hydrologic information was obtained using the following sources:

- borehole-geophysical data (natural gama, resistivity, caliper, fluid resistance, and borehole radar);
- borehole-televiewer data;
- borehole-video data;
- flowmeter analyses; and
- aquifer-test analyses using the Hantush-Jacob method, a transmissivity tensor method and the Jacob method.

Description of Study Area

The study area encompasses about 64 square miles (mi^2) and lies in the Dougherty Plain district of the Coastal Plain physiographic province in Dougherty County, about 5 miles (mi) southwest of Albany, Ga. (fig. 1) (Clark and Zisa, 1976). Topography in the study area is relatively flat and ranges in altitude from about 160 to 200 ft.

The study area, like the rest of the Dougherty Plain, is characterized by karst topography. No sink holes have been identified in the study area, but there are several depressions that seasonally contain water. Surface runoff in the study area is minimal because most of the drainage is internal. The major streams are the Flint River near the eastern boundary of the study area; and Cooleewahee Creek, a tributary to the Flint River, located near the western boundary of the study area (fig. 1).

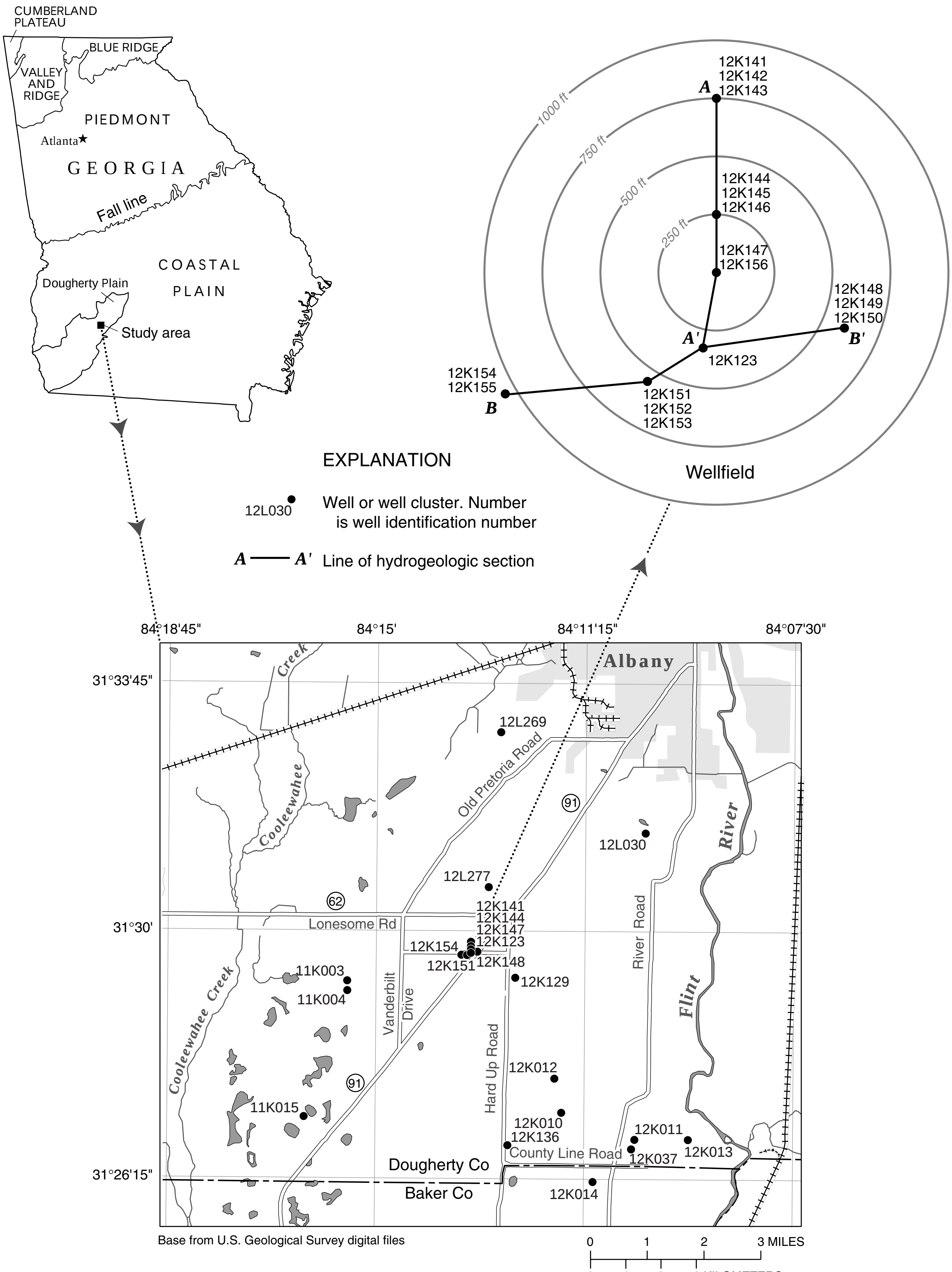

Figure 1. Location of study area and selected wells southwest of Albany, Georgia.

Methods of Investigation

A test hole was drilled using cable-tool techniques at a proposed site of one production well. The well was completed to a depth of 185 ft and temporarily cased with 50 ft of 14-inch diameter-surface casing and 110 ft of 8-inch-diameter formation casing. The casings were temporarily sealed with bentonite. The bottom 75 ft of the test hole was left open. Cuttings were collected and described throughout the drilling process. Few cuttings were produced from 118 to 140 ft because of a possible solution cavity. Natural gamma, resistivity, and caliper geophysical logs were run in both the test well and an existing observation well.

The test well was converted to a production well. First, the casing was removed and the hole was enlarged to a depth of 54 ft, and 30-inch-diameter pit casing was installed. The well was then enlarged to a depth of 105.5 ft and 24-inch diameter steel-formation casing was installed and sealed with cement grout. The well was then enlarged to a diameter of about 22.75 inches to a depth of 185.5 ft and left as an open hole.

Five clusters of observation wells were installed at various distances and directions from the production well (fig. 1). Four of these clusters consist of three observation wells—one deep well tapping the lower part of the Upper Floridan aquifer, one intermediate well tapping the upper part of the Upper Floridan aquifer, and one shallow well screened through the undifferentiated overburden. The fifth cluster consists of one shallow and one deep well. The deepest wells at each site were drilled using mud-rotary techniques and were constructed with 100 ft of 4-inch diameter-steel casing, followed by 100 ft of open hole into the lower part of the Upper Floridan aquifer. The intermediate-depth well at each site was constructed using mud-rotary techniques with 60 ft of 4-inch diameter-steel casing, followed by 20 ft of 3.875-inch-diameter open hole into the upper part of the Upper Floridan aquifer. The well casing was pressure grouted with cement to land surface. The shallow wells are open to the surficial aquifer; these wells were installed at each site using an 8-inch diameter hollow-stem auger and completed to a depth of about 30 ft using a 2-inch diameter polyvinyl chloride screen and riser. The screens extend from approximately 20 to 30 ft below land surface and were sand packed from 18 to 30 ft. The annulus was cemented to land surface. A pre-existing observation well was sealed with cement grout to extend the open-hole interval to a depth of 184 ft, so that its construction would be similar to the other deep observation wells. The production well and the observation wells comprise the wellfield that is referred to throughout this report (fig. 1).

After well construction, natural gamma, caliper, spontaneous potential, acoustic televiewer, and long and short-normal resistivity geophysical logs were run in the production well and each of the deep observation wells in the wellfield. Borehole radar geophysical logs were run in three of the deep wellfield observation wells. A spinner flowmeter test also was conducted in the production well during pumping at various discharge rates.

A constant-rate aquifer test (drawdown and recovery) was conducted during which the production well was pumped at a rate of 3,300 gal/min for 49 hours (hrs), and water-level fluctuations were monitored in selected wells in the study area. Pressure transducers with data loggers were used to collect water-level data from the deep and intermediate wells in the wellfield. Water-level data were collected using electric water-level indicators in the shallow wells. To ensure that the transducers were working properly, electric water-level indicators also were used to collect data in the deep wellfield observation wells during the early drawdown period. USGS data recorders with float-driven encoders were installed in three wells. Water levels were measured in 14 additional wells just prior to pumping, after about 49 hrs of pumping, and after pumping stopped. The water-level data collected during the drawdown and recovery periods from the wellfield observation wells were analyzed using the Hantush-Jacob curve-matching method (Hantush and Jacob, 1954) and the Jacob straight-line method (Jacob, 1950) to estimate the transmissivity (T) and storage coefficient (S) of the Upper Floridan aquifer and vertical hydraulic conductivity of the overlying sediments (K′). An anisotropic transmissivity tensor analysis was performed on data from three of the deep observation wells using the TENSOR2D computer program (Maslia and Randolph, 1986).

Previous Studies

Numerous hydrogeologic investigations have been conducted on the Upper Floridan aquifer in the Albany area. Wait (1960) described a sampling program designed to determine the quality of water in various aquifers in southwestern Georgia and to determine the changes in quality of ground-water that occur with time. Wait (1960) also reported the yield and water quality in the Upper Floridan aquifer (Ocala Limestone) in the Dougherty Plain. Wait (1963) provided information on the depth, thickness, areal extent, water-bearing properties, and the chemical quality of the water of the principal aquifers in Dougherty County. This report also included a description of the Ocala Limestone, and water-level fluctuations and potentiometric-surface information for the Upper Floridan aquifer.

Mitchell (1981) reported basic hydrologic and geologic data including specific capacity, transmissivity, and storage coefficient for the Upper Floridan aquifer in and adjacent to the Dougherty Plain. Mitchell (1981) also included climatologic, geologic, and hydrologic data for the Albany area. Hicks and others (1981) presented the results of an evaluation of the development potential of the ground-water resources in the Albany area and included hydrogeologic and potentiometric-surface data for the Upper Floridan aquifer. Hayes and others (1983) reported hydrologic properties for the Upper Floridan aquifer and the overburden based on aquifer-test results in the Dougherty Plain area. Hicks and others (1987) described the hydrogeology of the Albany area, assessed the chemical quality of ground water in the Upper Floridan aquifer, evaluated the development potential of the Upper Floridan aquifer, and identified the areas of greatest potential for development of ground-water resources near Albany.

Bush and Johnston (1988) described ground-water hydraulics, regional flow, and development effects on the entire Floridan aquifer system. In this report, Bush and Johnston (1988) also presented several sets of aquifer-test data.

Torak and others (1993) constructed a ground-water-flow model which indicated that the Upper Floridan aquifer could produce large quantities of ground water in much of the Albany area without creating significant areal water-level decline. Torak and others (1993) also reported values for transmissivity and hydraulic conductivity for the lower water-bearing zone of the Upper Floridan aquifer in the southwestern Albany area.

Well-Numbering System

In this report, wells are numbered using a system based on USGS topographic maps. Each 7 1/2-minute topographic quadrangle map in Georgia has been assigned a number and letter designation beginning at the southwestern corner of the State. Numbers increase eastward through 39; letters advance northward through “Z,” then double-letter designation “AA” through “PP” are used. The letters “I,” “O,” “II,” and “OO” are not used. Wells inventoried in each quadrangle are numbered sequentially beginning with “1.” Thus, the 123rd well inventoried in the Baconton North quadrangle (designated 12K) in Dougherty County is designated as well 12K123.

Acknowledgments

The author thanks the many individuals who assisted in the successful completion of this study. Special thanks goes to Mr. Lemuel Edwards, General Manager of the Albany Water, Gas, and Light Commission, for his support and assistance. Appreciation also is extended to Rowe Drilling Company, Smith Drilling Company, and Woodward-Clyde, Inc., and to the many cordial land owners who allowed access to their properties for data collection.

HYDROGEOLOGIC FRAMEWORK

In the study area, the Upper Floridan aquifer primarily is comprised of the upper Eocene Ocala Limestone. The Upper Floridan aquifer is confined below by the middle Eocene Lisbon Formation and above by the low permeability sediments of the undifferentiated Quaternary overburden (fig. 2). Regionally, the Ocala Limestone and the Lisbon Formation dip slightly and thicken to the southeast; however, in the study area the units are relatively flat (figs. 3-4).

Undifferentiated Overburden

The undifferentiated overburden is the uppermost hydrogeologic unit in the study area. The overburden ranges in thickness from about 30 to 50 ft and consists of fine to coarse quartz sand, clayey sand, sandy clay, and clay (figs. 2 and 3). At the base of the overburden, an areally extensive 10- to 15-ft thick layer of sandy

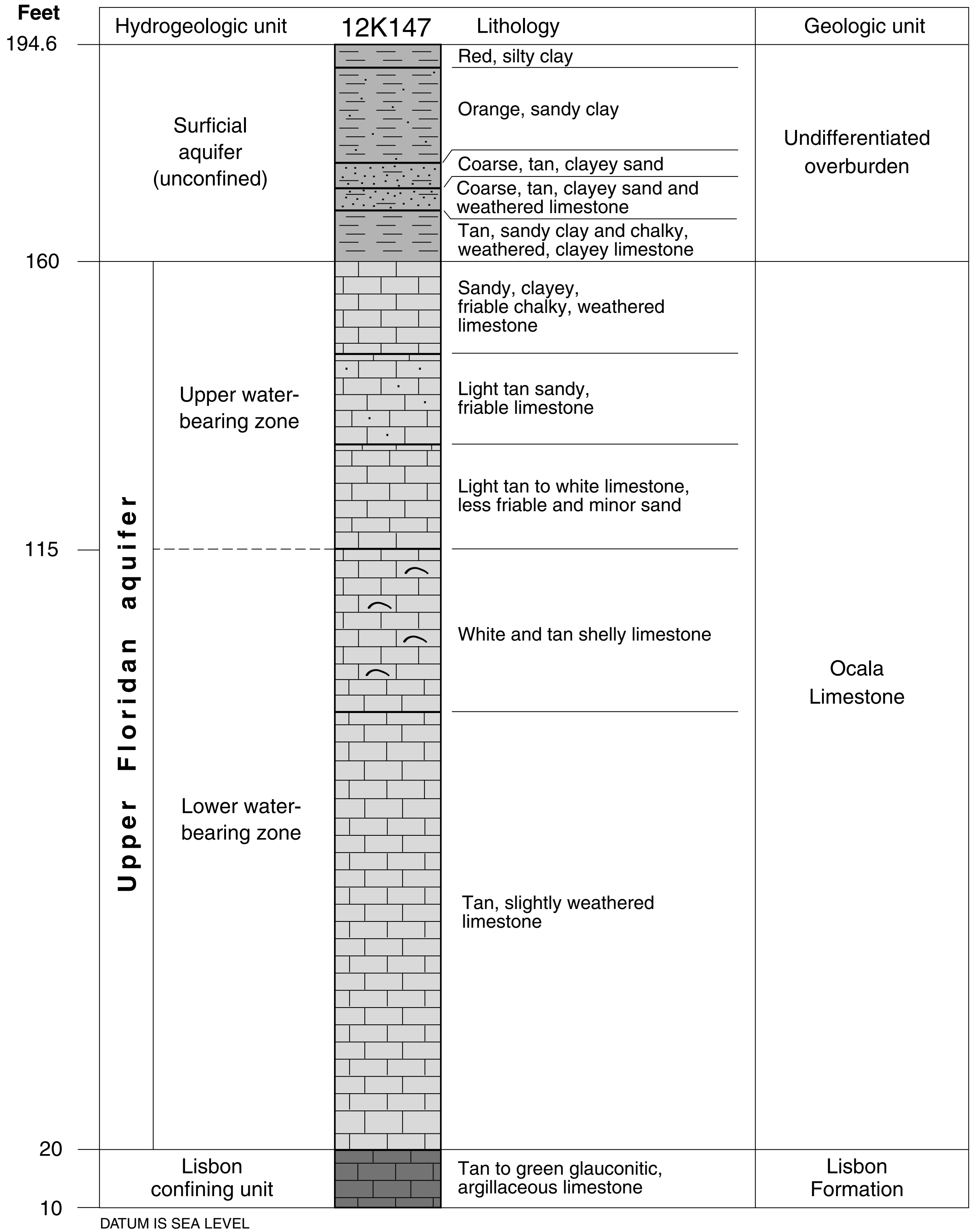

Figure 2. Lithology and hydrogeology of the undifferentiated overburden, Ocala Limestone, and Lisbon Formation (described from cuttings from well 12K147).

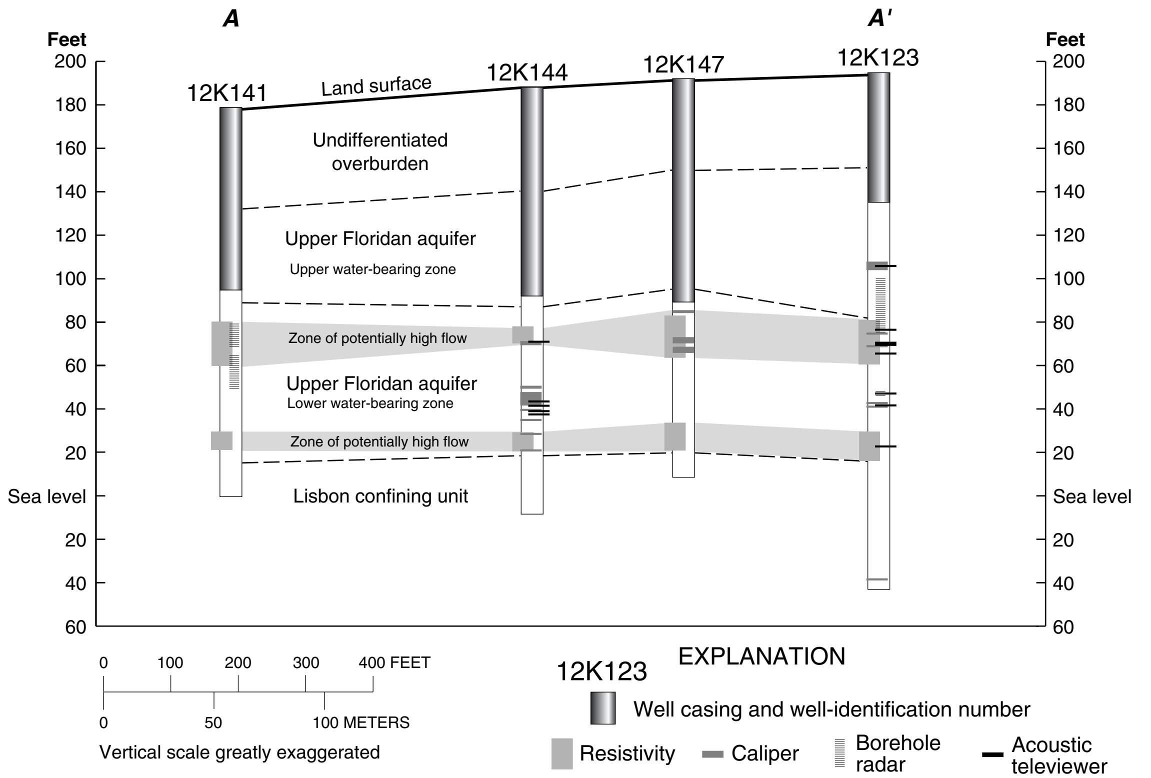

Figure 3. Hydrogeologic section A-A' showing resistivity, caliper, and borehole radar data, and voids shown on acoustic televiewer logs. Line of section is shown in figure 1.

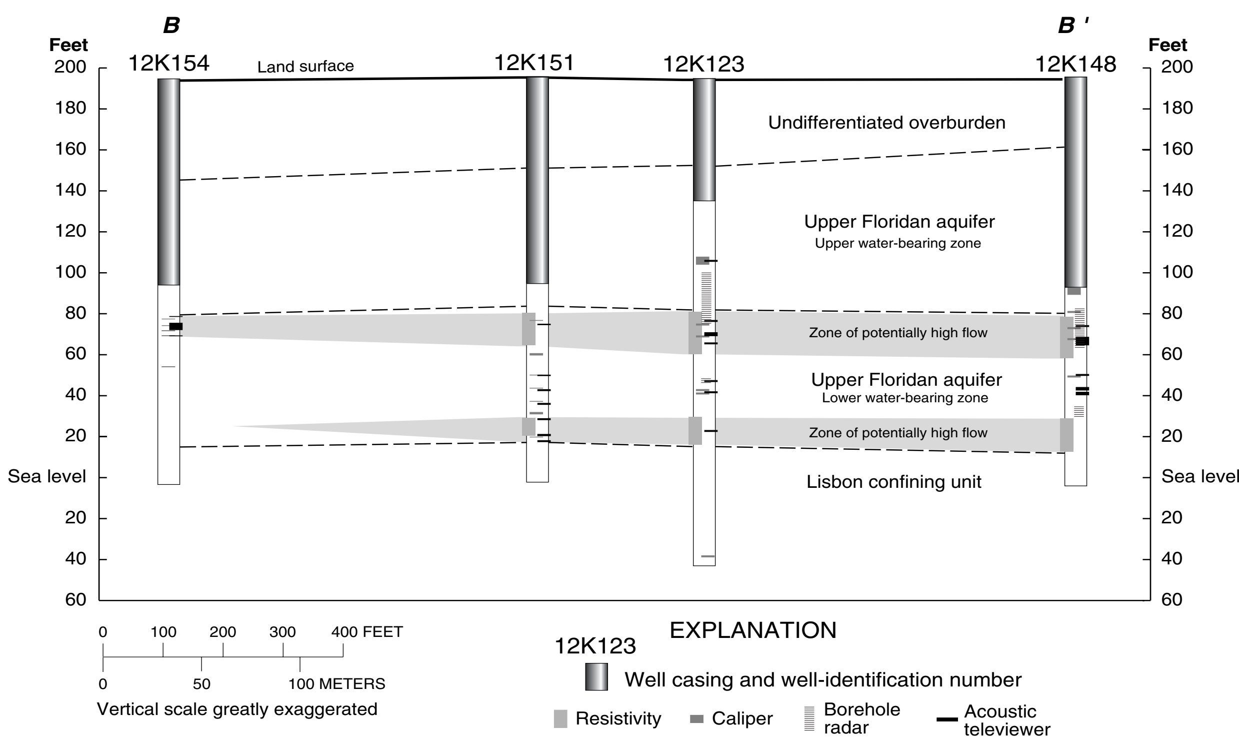

Figure 4. Hydrogeologic section B-B' showing resistivity, caliper, and borehole radar data, and voids shown on acoustic televiewer logs. Line of section is shown in figure 1.

clay and clayey limestone directly overlies the Ocala Limestone. This clayey zone probably is residuum derived from weathering of the Ocala Limestone. This zone of low-permeability material comprises the upper semiconfining unit of the Upper Floridan aquifer. At well 12K147, the upper 25 ft of overburden consists of silty clay and sandy clay, underlain by 10 ft of clayey sand, and about 10 ft of sandy clay and clay containing weathered limestone (fig. 2).

Laboratory analyses of the undifferentiated overburden indicates that the vertical hydraulic conductivity at well 12K123 ranges from 0.011 to 11.3 feet per day (ft/day) (Torak and others, 1993). The low end of the range represents a characteristic value for the clays in the semiconfining unit of the Upper Floridan aquifer, and the high end of the range is characteristic of the surficial aquifer.

The surficial aquifer comprises the higher permeability material within the undifferentiated overburden. Throughout the wellfield, the saturated thickness of the surficial aquifer ranges from about 10 to 18 ft. The sandy clay and clay below the surficial aquifer ranges from about 10 to 15 ft thick. The surficial aquifer provides recharge to the Upper Floridan aquifer; however, in the study area the semiconfining layer retards the rate of vertical infiltration into the Upper Floridan aquifer.

Upper Floridan Aquifer

In the study area, the Upper Floridan aquifer has been subdivided into an upper water-bearing zone and a lower water-bearing zone because of differing hydrologic properties (Hicks and others, 1987). Hydrogeologic sections A-A′ and B-B′ show the general position, thickness, and extent of the hydrologic units (figs. 3 and 4).

The upper water-bearing zone generally consists of dense, highly weathered limestone. In the wellfield, the upper water-bearing zone ranges in thickness from about 40 to 80 ft (figs. 3 and 4). In well 12K147, the upper 10 ft of the upper water-bearing zone consists of sandy, clayey, friable, chalky limestone, underlain by about 21 ft of sandy, friable limestone; and about 24 ft of less friable limestone and minor quartz sand (fig. 2).

The upper water-bearing zone has a lower permeability than the lower water-bearing zone (Hicks and others, 1987). This lower permeability reduces the ability of the aquifer to transmit ground water (Torak and others, 1993). The thickness of the upper water-bearing zone determines the extent to which this zone acts as a hydrologic barrier for transmitting water vertically between the undifferentiated overburden and the lower water-bearing zone (Torak and others, 1993). The upper water-bearing zone often is used for domestic supplies, but yields from these wells generally are low (Torak and others, 1993).

In the wellfield, the lower water-bearing zone ranges in thickness from about 60 to 80 ft (figs. 3 and 4). In well 12K147, the upper 20 ft of the lower water-bearing zone consists of hard, shelly limestone, underlain by 55 ft of slightly weathered limestone (fig. 2). Limestone in the lower water-bearing zone generally is harder, and therefore, more resistive than the limestone in the upper water-bearing zone; and thus, is more fractured. Fractures provide pathways for water to travel through the limestone. This process enables solution features to form within the limestone and produces the high degree of secondary permeability in this zone. The secondary permeability largely is responsible for the higher yields that are typical of wells open to the lower water-bearing zone.

Borehole geophysical and borehole video surveys were used to identify two potentially high flow zones in the lower water-bearing zone (figs. 3-5). The borehole geophysical surveys include natural gamma, electrical resistivity, caliper, and fluid resistance logs. The upper high-flow zone occurs near the contact between the upper water-bearing zone and the lower water-bearing zone and ranges in thickness from about 10 ft in well 12K144 to about 25 ft in well 12K147. The lower high-flow zone occurs near the base of the lower water-bearing zone; and ranges in thickness from about 10 ft in well 12K144 to about 20 ft in well 12K148 (figs. 3 and 4). In well 12K151, borehole resistivity is greater than 300 ohm-meters in the upper high-flow zone (between 68 and 80 ft above sea level) and above 200 ohm-meters in the lower high-flow zone (between 18 and 32 ft above sea level). There are several places within these two zones where the caliper log indicates that the borehole diameter is greater than 6 inches (fig. 5).

Because of lithologic and structural differences in the Upper Floridan aquifer, the relative yield to a well varies with depth throughout the vertical extent of the aquifer in the study area. As previously discussed, the

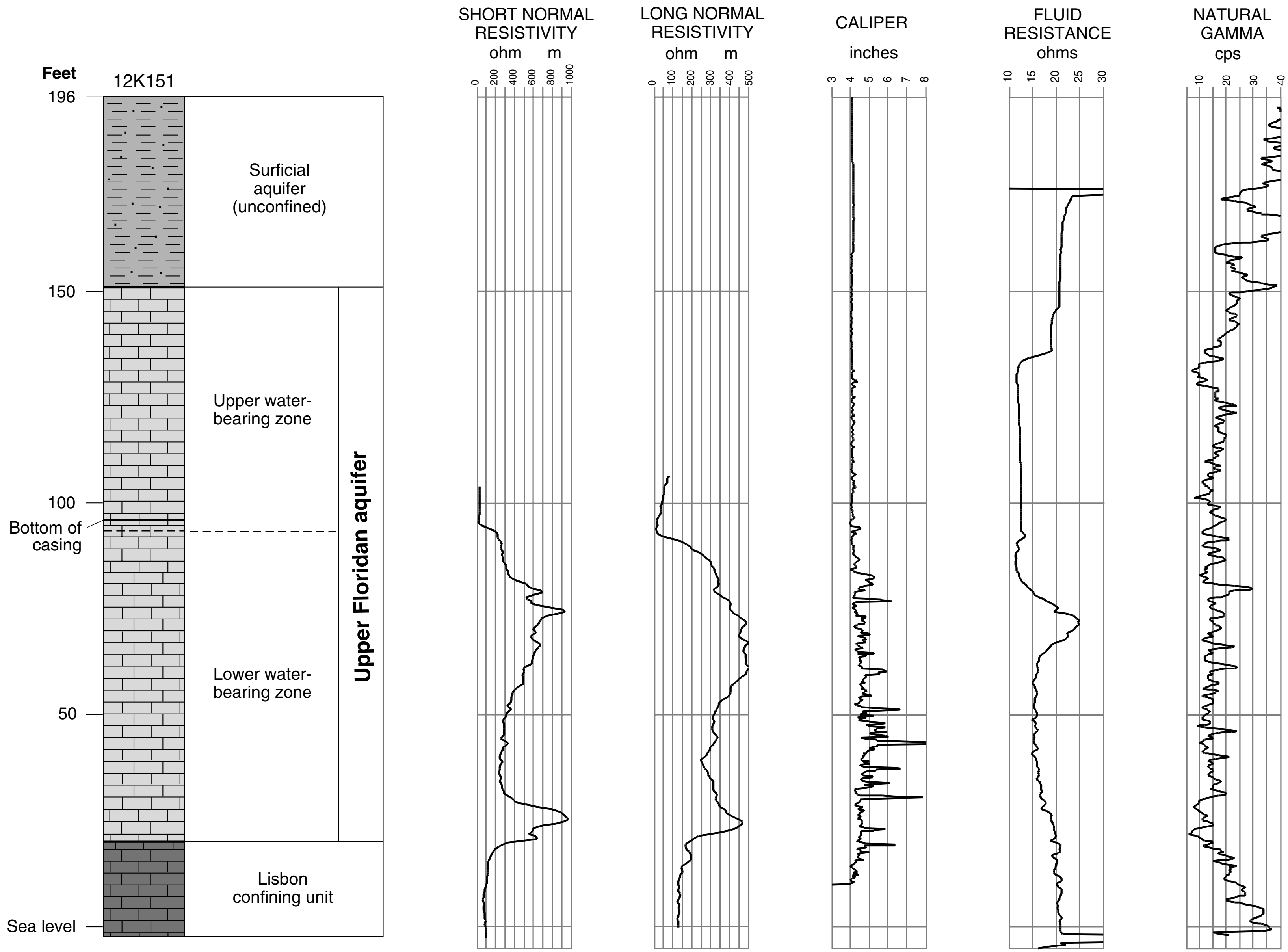

Figure 5. Hydrogeology, long and short normal resistivity, caliper, fluid resistivity, and natural gamma logs for well 12K151 (m, meters; cps, counts per second).

Upper Floridan aquifer is divided into upper and lower water-bearing zones, based on yield. The upper water-bearing zone has relatively low water-producing capability because of the low permeability; and functions mainly as a water source for the lower water-bearing zone, which provides most of the lateral ground-water flow within the Upper Floridan aquifer. The lower water-bearing zone has well-developed secondary permeability along solution-enlarged joints, bedding planes, and fractures that can significantly increase the ability of the aquifer to provide water to a well. The areas of greater permeability are vertically intermittent and may not be laterally continuous. Vertically extensive fractures were observed with the video camera in well 12K147 at depths of 116 to 123 ft below land surface. Many fractures observed with the video camera were not observed in the caliper log.

Flowmeter (spinner) tests were conducted in well 12K147 between depths of 110 and 140 ft below land surface to determine the relative percentage of water contributed by selected vertical intervals of the lower water-bearing zone at pumping rates of 1,080, 2,200, 3,400 gal/min. At the time these tests were conducted, the well bore had collapsed at a depth of about 160 ft and the second (deeper) producing zone could not be investigated. The flowmeter could not be traversed above a depth of 110 ft because the base of the pump impellers partially blocked the well bore. The tests were conducted by lowering an impeller-type flowmeter, suspended by a thin steel cable, into the well. Because the pump assembly was not removed from the well, the flowmeter centralizer could not be employed. The flowmeter was centralized in the open borehole using the caliper logging tool in the open position. This arrangement limited the data-collection method to depth specific, static readings and allowed only an upward traverse with the tool. The well was initially pumped at a constant rate of 3,400 gal/min for a period of about 1 hr, or until the water level in well 12K147 stabilized (steady-state conditions). Data collection was initiated at the bottom of the well and the flowmeter was traversed up the well while collecting point-velocity data at various intervals. This process was repeated at pumping rates of 2,200 and 1,080 gal/min, respectively.

Flowmeter techniques may not provide an accurate estimate of the average velocity of ground-water flow within the borehole, because of perturbations in the flow system caused by irregularities in the geometry of the borehole. In addition, water entering the well bore from the fractures can result in a false velocity measurement because of the vertical and horizontal components of flow passing the meter impellers. In tests conducted in well 12K147, additional errors could result from the extreme rugosity of the borehole in the flow zones dominated by secondary permeability. Turbulence created by the water entering the well bore through discrete openings also alters the velocity profile that would ideally be developed in a smooth borehole tapping a homogeneous aquifer where turbulence is minimal. Under ideal borehole-flow conditions, the minimum flow velocity occurs near the borehole wall and the maximum velocity occurs near the center of the well bore; where the flowmeter is positioned by the caliper arms. However, in well 12K147, the extreme rugosity of the borehole wall likely creates a flow situation in which, within specific vertical intervals, the maximum turbulence is greatest near the borehole wall and the centralized flowmeter may not have measured an average flow velocity (Keys, 1989). For these reasons, flow rates from specific borehole intervals are considered to be estimates to be used for comparison only. The reader should not use these data as an indicator of expected yield from discrete aquifer intervals.

Yield from each data-collection interval was computed using the measured flow velocity (flowmeter data) and the approximate borehole diameter (caliper data) for each of the three pumping rates. A graph was prepared showing the distribution of yield in the open borehole interval of well 12K147 at each pumping rate (fig. 6). At a pumping rate of 3,400 gal/min, measurable flow was not detected in the well below a depth of about 134 ft. A flow rate of about 680 gal/min was measured at a depth of 134 ft. The flow rate progressively increased to about 2,000 gal/min at a depth of 128 ft. This flow rate held fairly constant until a significant flow increase of about 1,000 gal/min was measured in the highly fractured interval between depths of 124 and 118 ft. Little additional flow contribution was measured in the interval of 118 ft to the upper limit of the traverse at a depth of 110 ft. At depths of about 122 and 118 ft, the calculated discharge, based on the measured velocity, greatly exceeds the cumulative discharge rate of 3,400 gal/min. It is hypothesized that the very high velocity observed is anomalous and is a result of the combined vertical and horizontal components of flow occurring in these zones where the vertical fractures are present.

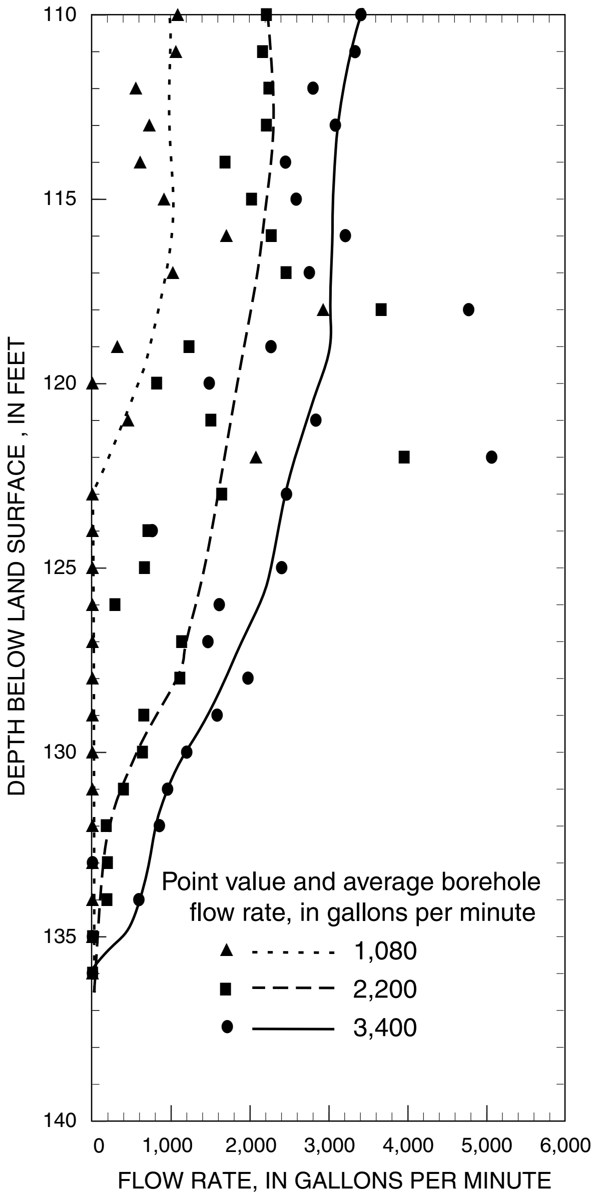

Figure 6. Vertical distribution of flow in well 12K147 at pumping rates of 1,080, 2,200, and 3,400 gallons per minute.

A sustained pumping rate of 2,200 gal/min produced a yield profile that is very similar to that produced by pumping the well at 3,400 gal/min (fig. 6). Measurable flow was not detected below a depth of about 134 ft; a flow of about 150 gal/min was measured at this depth. Flow progressively increased from a depth of 132 to 127 ft and was measured at about 1,100 gal/min at a depth of 127 ft. As observed during the 3,400 gal/min test, the apparent flow rate increased significantly in the depth interval between 124 and 118 ft. Anomalously high velocities again were observed at depths of 122 and 118 ft.

The yield profile produced by pumping the well at a constant rate of 1,080 gal/min was somewhat different than that observed during both higher-rate tests (fig. 6). Flow was not observed below a depth of 123 ft, above which an average rate of about 600 gal/min was measured. The anomalously high rate of flow again was observed at depths of 122 and 118 ft.

The results of these three flow tests suggest that the highly fractured borehole interval between 124 and 118 ft contributes a significant portion of the total yield to the well. In addition, at those discharges and that pump depth, the yield profile appears very similar at each pumping rate. However, at a pumping rate of 1,080 gal/min, the borehole interval above a depth of 122 ft supplies all of the water to the well. Only the upper part of the open borehole interval is stressed at this lower pumping rate.

Lisbon Confining Unit

The Lisbon Formation is the lower confining unit of the Upper Floridan aquifer. It consists of tan to green glauconitic, argillaceous limestone. The Lisbon confining unit acts as a nearly impermeable boundary to the Upper Floridan aquifer; and significant leakage does not occur through this zone in the Albany area (Torak and others, 1993).

AQUIFER TEST

An aquifer test was designed to evaluate the hydraulic characteristics of the Upper Floridan aquifer using wells in the study area. Ground-water levels were measured to describe a regional trend and to analyze the effects of pumping within the study area.

Design of Test and Collection of Data

A wellfield (fig. 1) consisting of 16 observation wells (12K123, 12K141–146, and 12K148–156) and the pumping well (12K147) was designed to gain hydrologic information about the Upper Floridan aquifer. Well-construction data for the study area wells are listed in table 1. Well 12K147 is completed as a 24-inch diameter well that is 185-ft deep and open to the lower water-bearing zone of the Upper Floridan aquifer (fig. 7). The observation wells were installed in five sets (five locations), each set consisting of three wells—one shallow well tapping the undifferentiated overburden, one intermediate well open to the upper water-bearing zone of the Upper Floridan aquifer, and one deep well open to the lower water-bearing zone of the Upper Floridan aquifer (fig. 8). The well cluster located in the southwestern corner of the wellfield consists of only two wells—one intermediate and one deep well. Well 12K123 is an existing well in which the lower portion was filled with cement so that it was open only to the Upper Floridan aquifer. This enabled well 12K123 to be used as an additional observation well. Interpretation of borehole geophysical logs indicates that many of the deep wells in the wellfield are open to part of the upper water-bearing zone in addition to the entire lower water-bearing zone. Each set of observation wells (fig. 1) was placed at varying distances and orientations from well 12K147 (the pumped well) to define the cone of depression resulting from pumping.

The aquifer test was designed so that well 12K147 would be pumped at a constant rate of 3,300 gal/min for 72 hrs in order to stress the aquifer. The discharge water was piped from well 12K147 to a holding pond that was constructed about 0.5 mi to the southeast. After 24 hrs of pumping, it became apparent that the pond was underdesigned and would not hold the volume of water that would be pumped in a 72-hr period. Although the dam confining the pond was improved, pumping was terminated after 49 hrs.

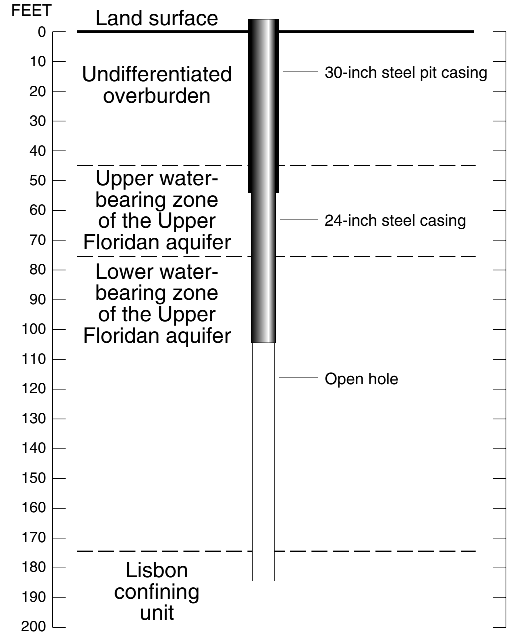

Figure 7. Well construction of pumped well 12K147.

Water-level fluctuations were monitored throughout the aquifer test in the wells within the wellfield and in wells 11K015, 12L269 and 12L277 (see figure 1). Pressure transducers and data recorders were installed on each of the deep and intermediate wells in the wellfield, and time-dependent water-level data were recorded. Time-dependent water-level data were collected using electric water-level meters or steel tapes in the shallow wells within the wellfield. Data recorders with float-driven encoders were used to collect time-dependent water-level data from wells 11K015, 12L269, and 12L277. A set of water-level measurements was collected using electric water-level meters or steel tapes from each well shown on figure 1 before pumping began, after about 49 hrs of pumping, and after pumping stopped.

Table 1. Well-construction data for selected wells in the study area
[PVC, polyvinylchloride; do, ditto; —, data not available]

Well number	Altitude of land surface (feet)	Total depth (feet below land surface)	Casing			Water-bearing zone	Type of open interval
			Depth (feet)	Diameter (inches)	Material		
12L030	180	180	84	4	steel	lower water-bearing zone	open hole
12L269	194	164	100	4	do.	do.	do.
12L277	186	203		4	do.	do.	do.
11K003	201	150	63	4	do.	upper water-bearing zone/ lower water-bearing zone	do.
11K004	201	150	60	4	do.	do.	do.
11K015	175	177	74	4	do.	do.	do.
12K010	198	200	108	12	do.	lower water-bearing zone	do.
12K011	185	200	85	12	do.	do.	do.
12K012	192	195	60	12	do.	upper water-bearing zone/ lower water-bearing zone	do.
12K013	185	200	90	12	do.	lower water-bearing zone	do.
12K014	183	137	69	—	—	upper water-bearing zone/ lower water-bearing zone	—
12K037	178	200	69	8	steel	do.	open hole
12K123	196.91	185	55	4	do.	do.	do.
12K129	196	211	122	4	do.	lower water-bearing zone	do.
12K136	194	215	135	4	do.	do.	do.
12K141	195.02	198	100	4	do.	do.	do.
12K142	195	80	60	4	do.	upper water-bearing zone	do.
12K143	195	30	20	2	PVC	surficial aquifer	screened
12K144	192.16	200	100	4	steel	lower water-bearing zone	open hole
12K145	192	80	60	4	do.	upper water-bearing zone	do.
12K146	192	30	20	2	PVC	surficial aquifer	screened
12K147	194.62	185	105	24	steel	lower water-bearing zone	open hole
12K148	193.12	197	100	4	do.	do.	do.
12K149	193	80	60	4	do.	upper water-bearing zone	do.
12K150	193	30	20	2	PVC	surficial aquifer	screened
12K151	195.80	198	100	4	steel	lower water-bearing zone	open hole
12K152	196	80	60	4	do.	upper water-bearing zone	do.
12K153	195	30	20	2	PVC	surficial aquifer	screened
12K154	195	198	100	4	steel	lower water-bearing zone	open hole
12K155	196	80	60	4	do.	upper water-bearing zone	do.
12K156	194	30	20	2	PVC	surficial aquifer	screened

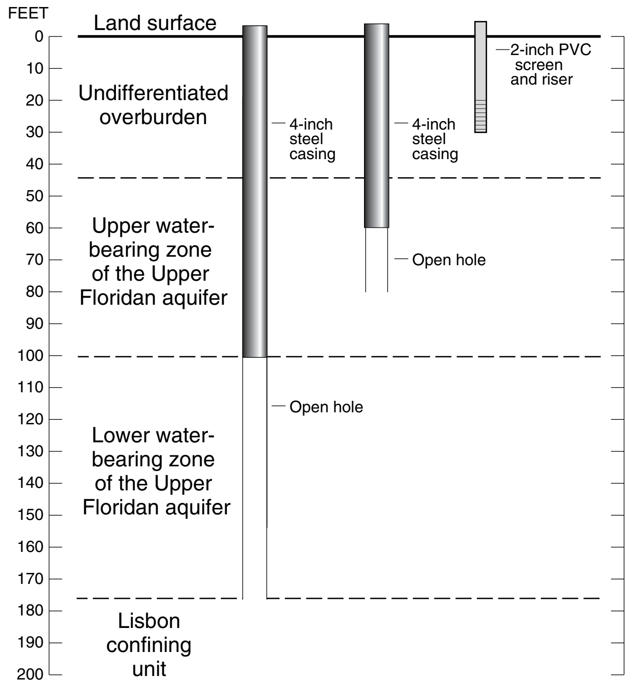

Figure 8. Well construction of a typical cluster of observation wells.

Ground-Water Levels

Ground-water levels were measured throughout the study area before the aquifer test was started to determine background water-level trends and pre-pumping conditions. Water levels were also measured throughout the pumping and recovery phases of the aquifer test.

Regional Trend

Water-level measurements must be corrected for regional trends during an aquifer test to remove effects of climatic changes and area pumpage. Well 11K015 was used to monitor the trend of the Upper Floridan aquifer because it is thought to be outside the influence of the test pumping and outside the influence of the Flint River. From the middle of February through the end of March 1995, water levels in the Upper Floridan aquifer declined (fig. 9A). During the pumping phase of the aquifer test, the water-level in well 11K015 declined approximately 0.2 ft (fig. 9B). Throughout the recovery phase of the test, the water-level in this well declined only slightly. The water-level decline in well 11K015 probably reflects the low precipitation prior to the aquifer test. Only about 0.2 inch of rainfall was reported within the 4 days prior to the aquifer test; and no rainfall was reported during the aquifer test in the Albany area.

Water-level measurements were made in the observation wells in the study area on the morning of February 21, 1995, just prior to the start of the aquifer test, and converted to altitudes (table 2). The pre-pumping potentiometric surface of the Upper Floridan aquifer in the study area ranged from 147.7 ft above sea level in well 12K037 to 179.1 ft above sea level in well 11K004. The general direction of ground-water flow was to the southeast.

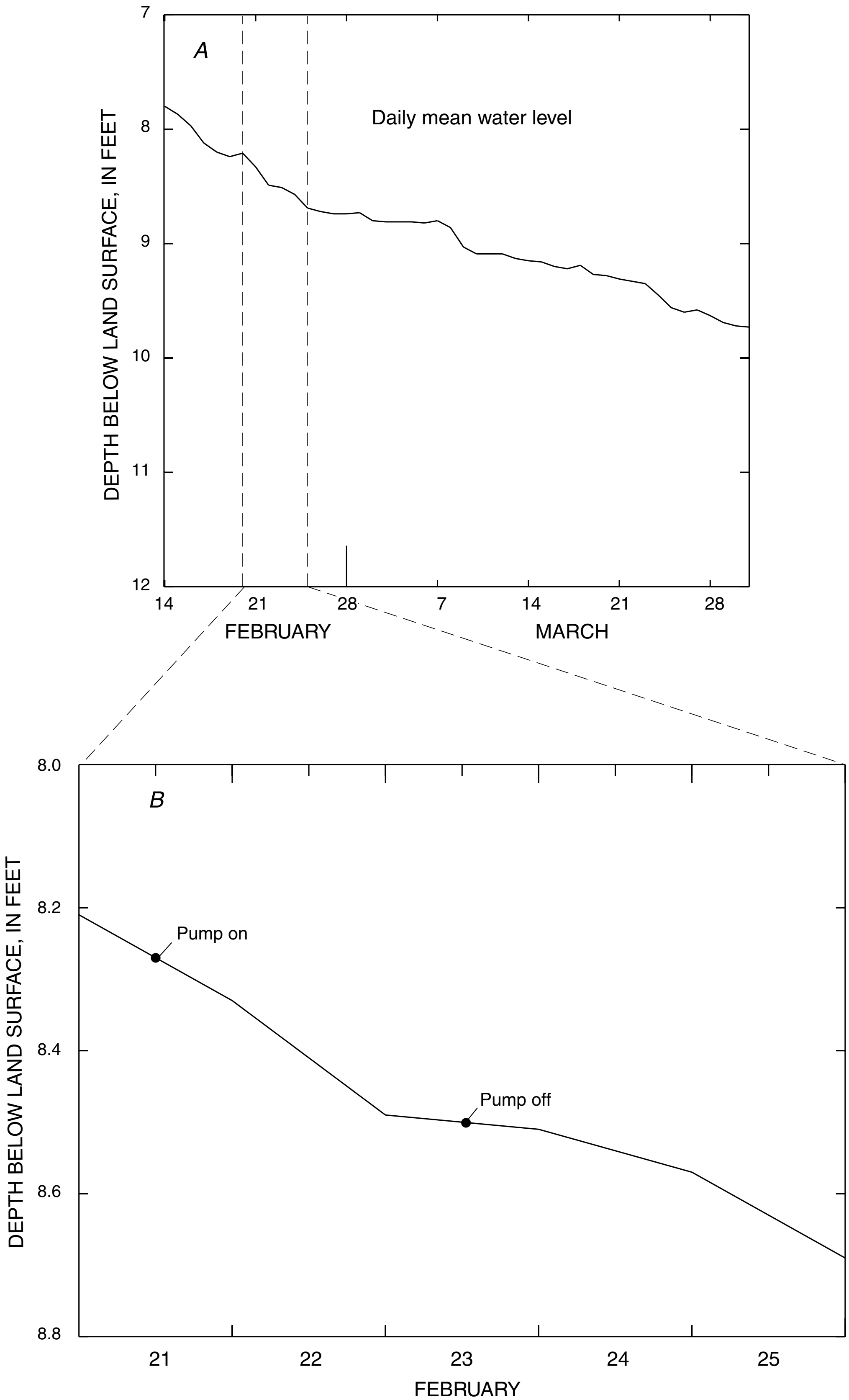

Figure 9. Water-level fluctuation in well 11K015, (*A*) February 14–March 31, 1995, and (*B*) February 21–25, 1995.

Table 2. Water-level data collected under pre-pumping conditions, after about 49 hours of pumping, and four days after pumping stopped for selected wells in the study area
[-, (minus) water-level decrease; —, data not available; do., ditto]

Well number	Water-level altitude (feet)		Water-level change (feet)		Water-level altitude (feet)	Water-bearing zone
	Pre-pumping conditions (02-21-95)	After about 49 hours of pumping) (02-23-95)	Observed	Corrected (-0.2 feet)	Four days after pumping stopped (02-27-95)	
12L030	166.6	166.8	0.2	0.4	—	lower water-bearing zone
12L269	178.4	178.1	-0.3	-0.1	—	do.
12L277	179.0	178.9	-0.1	0.1	179.0	do.
11K003	178.3	178.0	0-.3	-0.1	—	upper water-bearing zone/ lower water-bearing zone
11K004	179.1	178.8	-0.3	0.1	—	do.
11K015	166.6	166.4	-0.2	0	—	do.
12K010	164.3	165.4	1.1	10.3	—	lower water-bearing zone
12K011	155.5	158.5	3.0	3.2	—	do.
12K012	163.0	164.0	1.0	10.2	—	upper water-bearing zone/ lower water-bearing zone
12K013	166.9	169.8	2.9	3.1	—	lower water-bearing zone
12K014	155.2	156.8	1.6	1.8	—	upper water-bearing zone/ lower water-bearing zone
12K037	147.4	149.9	2.5	2.7	—	do.
12K122	174.9	174.2	-0.8	-0.6	175.0	do.
12K123	177.7	175.1	-2.6	-2.4	178.5	do.
12K129	170.9	170.9	0	0.2	171.2	lower water-bearing zone
12K136	166.0	166.1	0.1	0.3	—	do.
12K141	177.5	176.4	-1.1	-0.9	177.3	do.
12K142	177.7	176.8	-0.9	-0.7	177.4	upper water-bearing zone
12K143	177.8	176.9	-0.9	-0.7	177.3	surficial aquifer
12K144	177.7	175.7	-2.0	-1.8	177.5	lower water-bearing zone
12K145	177.7	—	—	—	—	upper water-bearing zone
12K146	177.7	176.4	-1.3	-1.1	177.0	surficial aquifer
12K147	178.1	129.1	-49.0	-48.8	178.6	lower water-bearing zone
12K148	177.7	176.3	-1.4	-1.2	177.4	do.
12K149	177.6	176.7	-0.9	-0.7	177.2	upper water-bearing zone
12K150	177.5	176.7	-0.8	-0.6	177.2	surficial aquifer
12K151	177.8	177.0	-0.8	-0.6	177.6	lower water-bearing zone
12K152	178.0	177.3	-0.7	-0.5	177.7	upper water-bearing zone
12K153	177.2	176.6	-0.6	-0.4	176.8	surficial aquifer
12K154	177.8	177.1	-0.7	-0.5	177.6	lower water-bearing zone
12K155	177.8	177.2	-0.6	-0.4	177.5	upper water-bearing zone
12K156	177.7	176.0	-1.7	-1.5	177.1	surficial aquifer

Effects of Pumping

Water-level measurements were made in the observation wells in the study area after about 49 hrs of pumping well 12K147 and converted to altitudes (table 2). The potentiometric surface of the Upper Floridan aquifer ranged from 149.9 ft above sea level in well 12K037 to 178.8 ft above sea level in well 11K004 (table 2). The general direction of flow was still to the southeast. Pumping well 12K147 at a rate of 3,300 gal/min for 49 hrs did not significantly affect the potentiometric surface of the Upper Floridan aquifer in the study area. Time-dependent water-level data were collected in the surficial aquifer and in both zones of the Upper Floridan aquifer at each cluster site in the wellfield throughout the aquifer test (figs. 10-16). Water-level decline was variable throughout the study area and ranged from a maximum of about 49 ft in well 12K147, the pumping well; to a minimum of about 0.4 ft in wells 12K153 and 12K155.

Water-level data collected before pumping and after about 49 hrs of pumping were subtracted in order to calculate water-level change in the study area. The water-level-change data then were corrected for regional trend (the 0.2 ft decline observed in well 11K015 was subtracted from each value) (table 2; fig. 17). The negative values of water-level change indicate decreases in water level, and the positive values represent increases in water level. At a distance greater than about 0.5 mi from well 12K147, there appeared to be no measurable effect from pumping. All of the wells located within about 3.75 mi of the Flint River showed an increase in water level after about 49 hrs of pumping. This water-level increase probably resulted from the 3.5 ft increase in the stage of the Flint River during the pumping phase of the aquifer test (fig. 18). The water level at well 12K011, which is located slightly greater than 1 mi from the Flint River, rose about 3.2 ft (fig. 17). The hydrograph of well 12K014 shows an increase of about 2 ft, which reflects the rise in the stage of the Flint River (fig. 18). The increase in the stage of the Flint River probably caused a decrease in the rate of natural discharge from the Upper Floridan aquifer to the Flint River and resulted in increased water levels in the wells located near the river. The hydrograph of well 11K015 shows a water-level decline (fig. 18). The Flint River appears to have had a greater impact on water-level fluctuations in the Upper Floridan aquifer than did the pumping during this test.

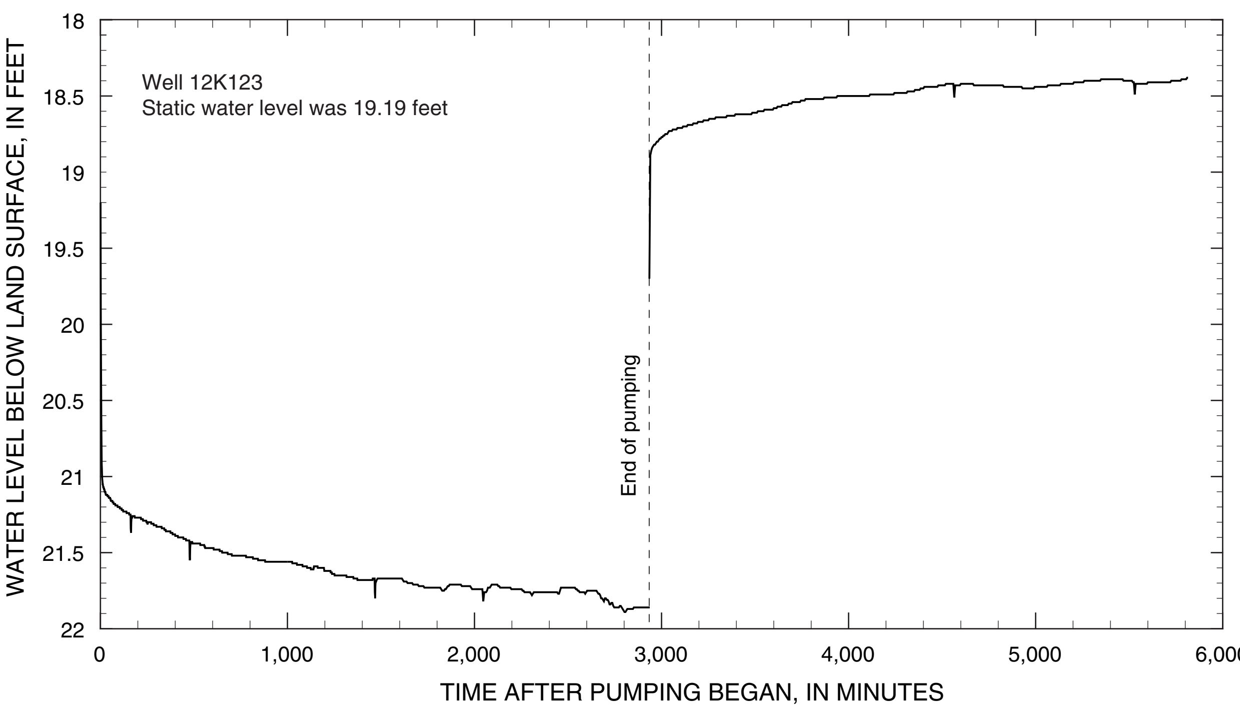

Figure 10. Water-level fluctuation in well 12K123, February 21–24, 1995.

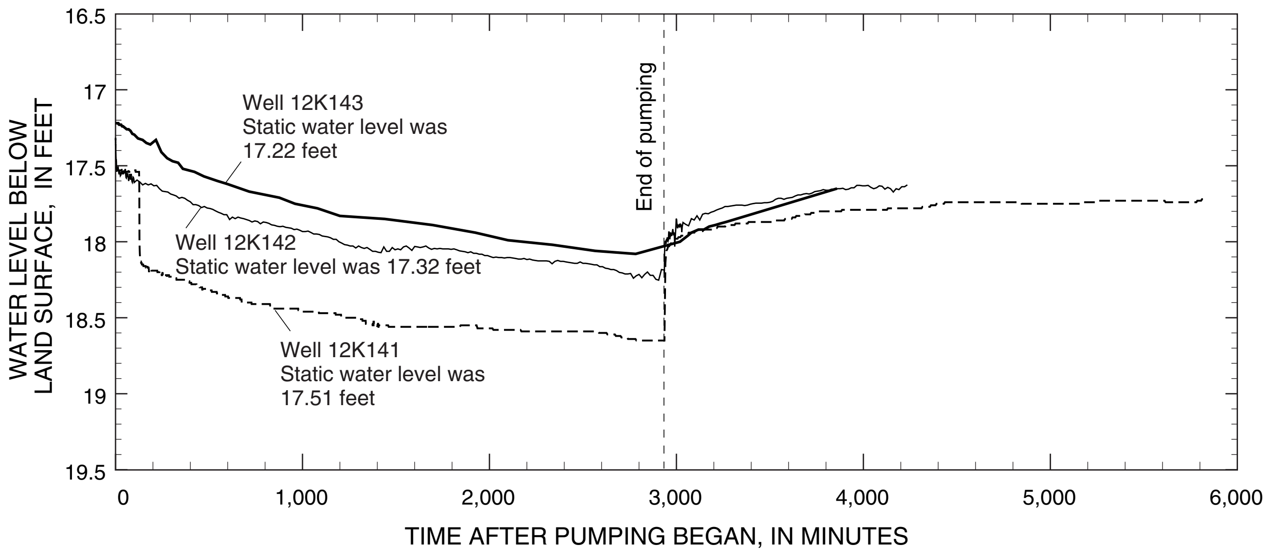

Figure 11. Water-level fluctuations in wells 12K141, 12K142, and 12K143, February 21–24, 1995.

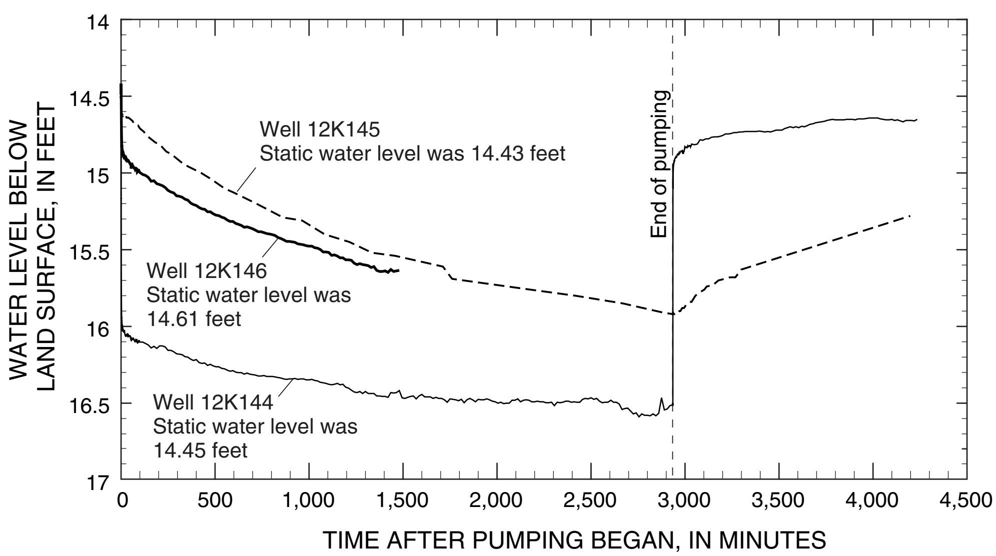

Figure 12. Water-level fluctuations in wells 12K144, 12K145, and 12K146, February 21–24, 1995.

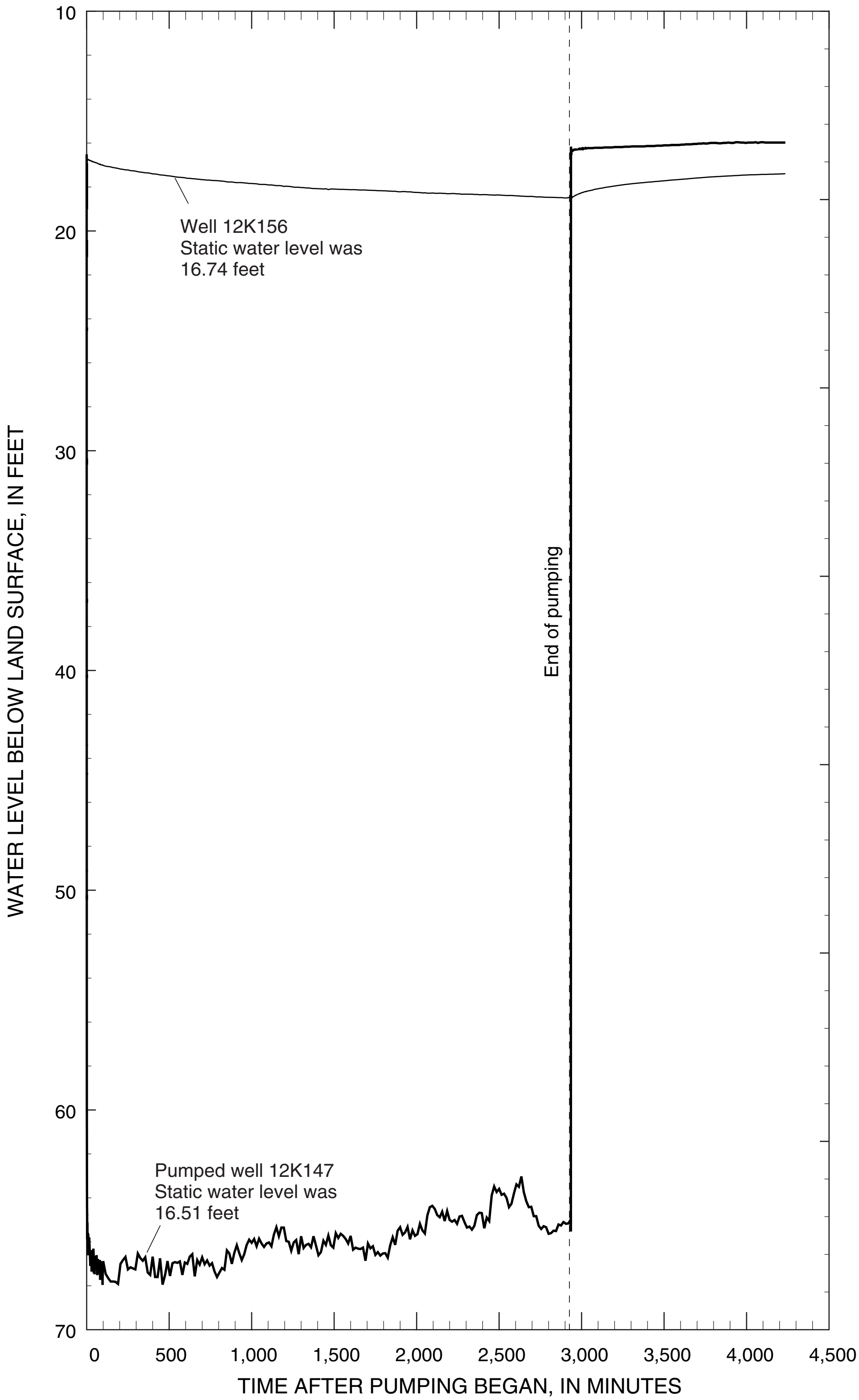

Figure 13. Water-level fluctuations in wells 12K147 (pumped well) and 12K156, February 21–24, 1995.

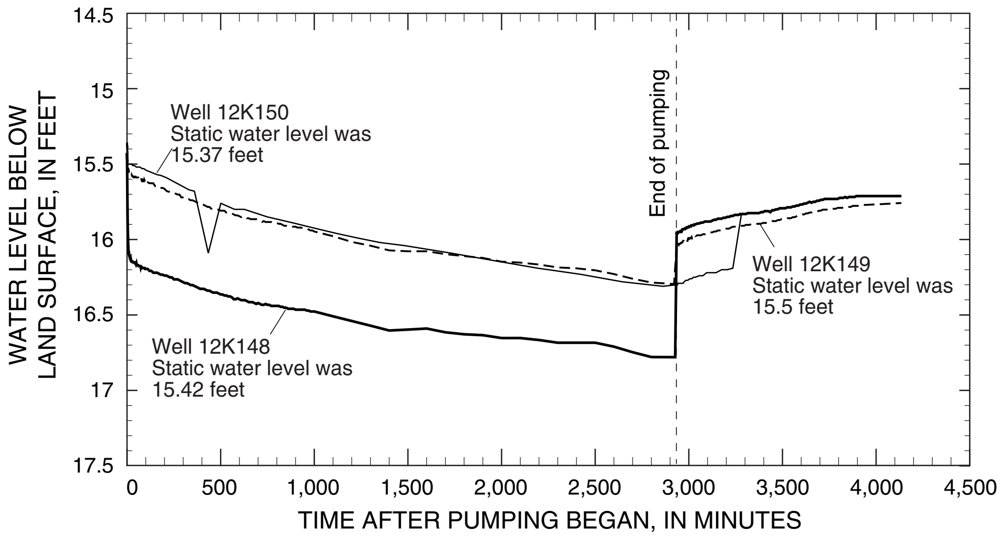

Figure 14. Water-level fluctuations in wells 12K148, 12K149, and 12K150, February 21–24, 1995.

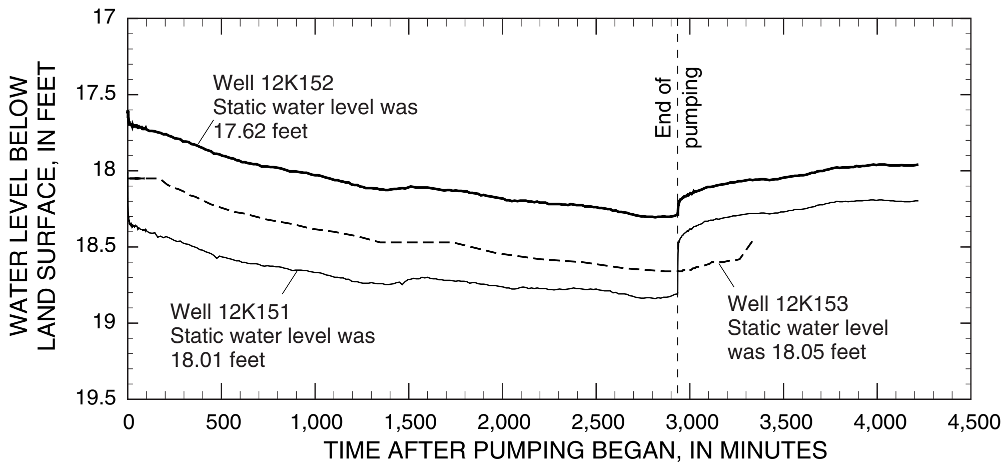

Figure 15. Water-level fluctuations in wells 12K151, 12K152, and 12K153, February 21–24, 1995.

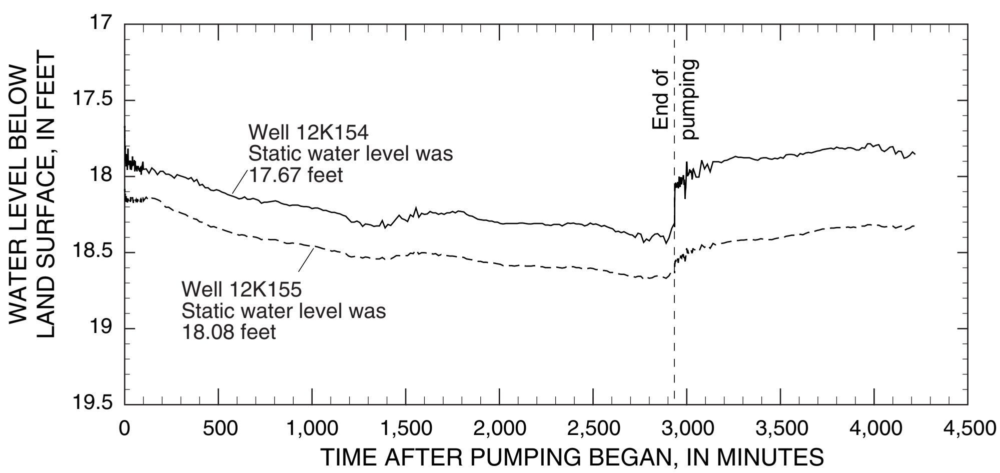

Figure 16. Water-level fluctuations in wells 12K154 and 12K155, February 21–24, 1995.

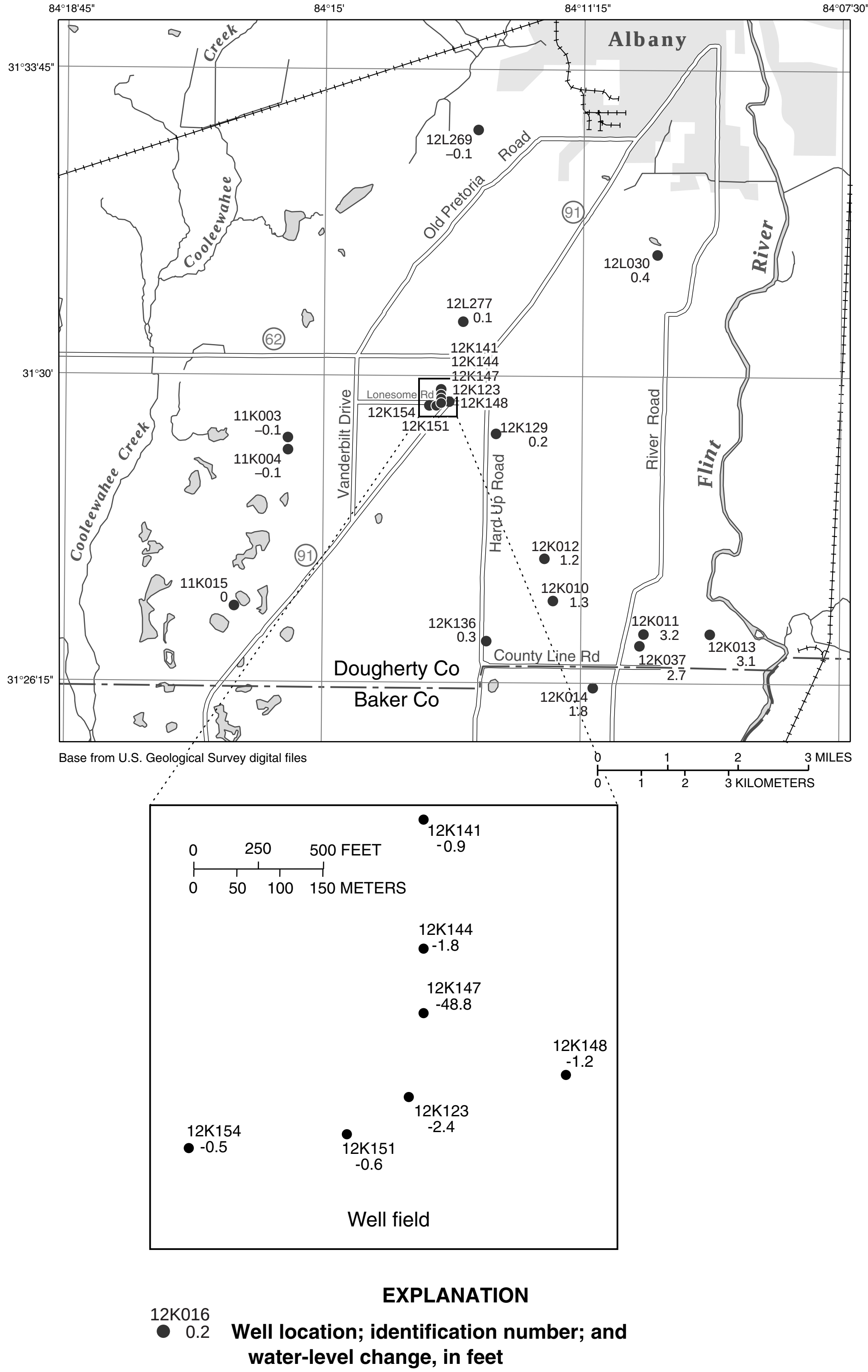

Figure 17. Water-level change in selected wells in the study area, February 21–23, 1995 (data corrected for regional trend).

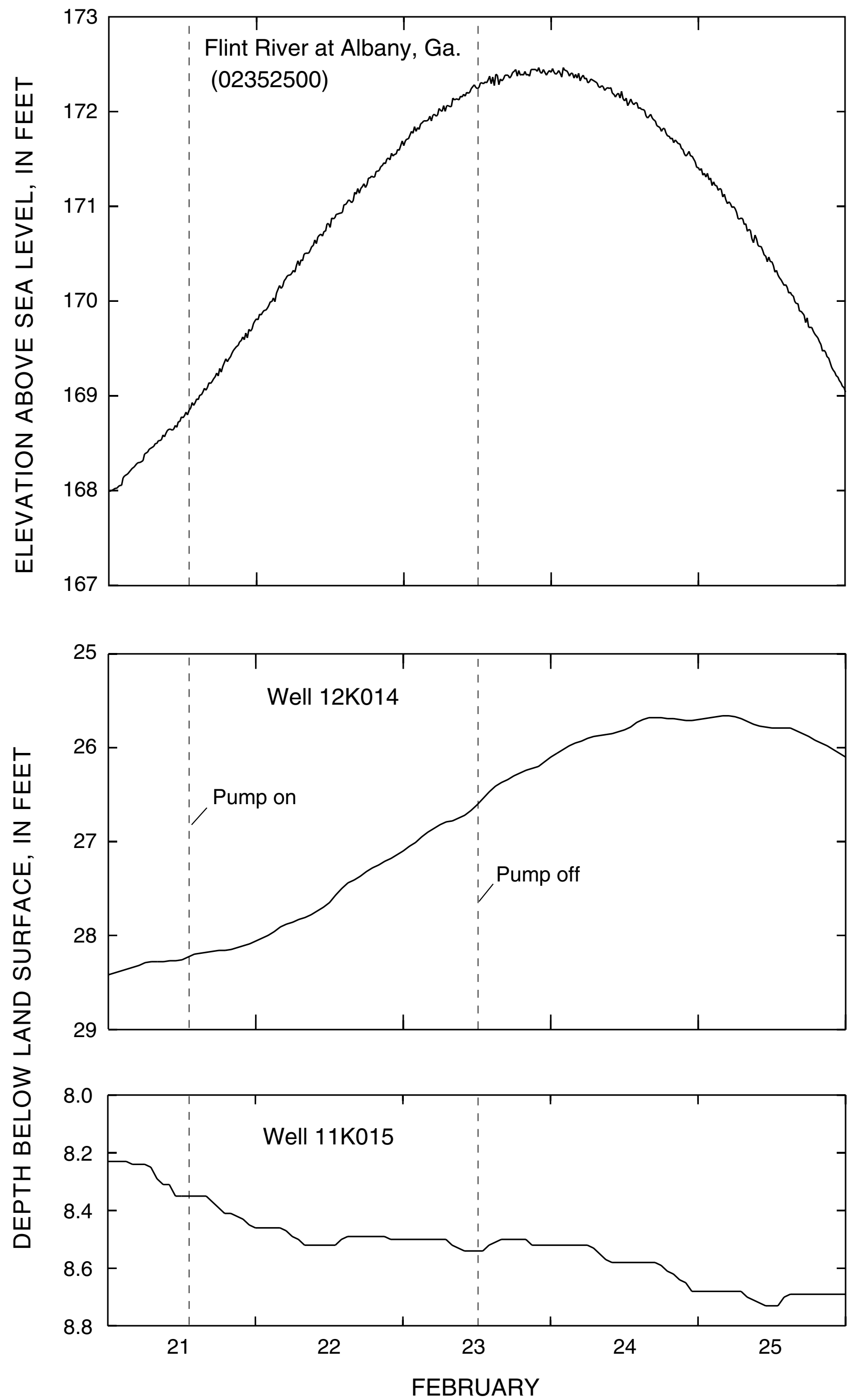

Figure 18. Water-level fluctuations in the Flint River at Albany (stream-gaging station 02352500), and in wells 12K014 and 11K015, February 21–25, 1995**.**

Pumping stress exerted on the lower water-bearing zone at well 12K147 resulted in a slight water-level decline in the observation wells throughout the wellfield area in the surficial aquifer and the upper water-bearing zone and lower water-bearing zone of the Upper Floridan aquifer (table 2). Water-level declines in the surficial aquifer ranged from about 1.5 ft in well 12K156, located about 10 ft from the pumping well to about 0.4 ft in well 12K153, located about 555 ft from the pumping well in the southwestern part of the wellfield. Water-level declines in the upper water-bearing zone were similar to those observed in the surficial aquifer and ranged from about 0.4 ft in well 12K155, located 1,040 ft from the pumping well; to 0.7 ft in wells 12K142 and 12K149 located 750 and 610 ft from the pumping well, respectively. However, water levels were not measured in well 12K145, located 250 ft from the pumping well; and it is likely that the water-level decline in this well would have been greater than 0.7 ft. Water-level declines in the lower water-bearing zone (excluding those measured in well 12K147) ranged from 2.4 ft in well 12K123, located 330 ft from the pumping well; to 0.5 ft in well 12K154, located about 1,040 ft from the pumping well (fig. 17).

Water levels were measured for the entire recovery period in the pumped well and the observation wells completed in the lower water-bearing zone. Within a few minutes after cessation of pumping, water levels in wells tapping the lower water-bearing zone recovered to within 10 percent of their static levels (figs. 10-16). After a few hours, water levels had recovered to background levels.

The large drawdown (48.8 ft) in the production well, relative to the drawdowns measured (2.4 ft and less) in the observation wells indicates significant well loss in the production well. The low efficiency of the production well probably is a result of turbulence in the Upper Floridan aquifer around the well bore.

Analyses of Aquifer-Test Data

Based on the hydrogeologic data collected prior to and during this study, the Upper Floridan aquifer is best described as a leaky, fracture-flow system. Most of the water in the aquifer is believed to be laterally transported through the fracture system in the lower water-bearing zone. During the aquifer test, water initially was drawn from the fractures. As pumping continued, the hydraulic potential along the fracture boundaries changed, and the aquifer matrix began to contribute recharge to the fractures. Because of the complexity of this karst system, only estimates of transmissivity (T) and storage coefficient (S) of the Upper Floridan aquifer; and vertical hydraulic conductivity (K′) of the overlying sediments, could be obtained from the aquifer-test analyses. The Hantush-Jacob curve matching method, a transmissivity tensor method, and the Jacob straight-line method were used to analyze the aquifer-test data.

The time-drawdown data were fitted to Hantush-Jacob type curves for analyzing test data from aquifers receiving leakage across confining units (Hantush and Jacob, 1954). Previous investigators also used this method of analysis for aquifer tests conducted in the study area (for example, Mitchell, 1981). An example of time-drawdown data collected at observation well 12K151 fitted to a Hantush-Jacob curve is shown in figure 19. Using the Hantush-Jacob method, the calculated T at the deep observation wells in the wellfield (with the exception of well 12K123) ranged from 120,000 to 506,000 ft^2/d; the calculated S ranged from 1.4×10^{-4} to $6.3 \times 1\ 0^{-4}$ (table 3); and the calculated K′ ranged from 4.9 to 6.8 ft/d. The time-drawdown data from well 12K123 did not fit a Hantush-Jacob type curve. Geometric averages for these ranges of values for T, S, and K′ were calculated to be about 248,000 ft^2/d, 2.7×10^{-4}, and 5.5 ft/d, respectively. Torak and others (1993) reported a value of 178,000 ft^2/d for T in the lower water-bearing zone of the Upper Floridan aquifer from an aquifer test conducted at a site located about 9 mi south of Albany. This value of T is similar to the geometric average of the T calculated using the Hantush-Jacob method for this study. Torak and others (1993) also reported a range for K′ of 0.011 to 11.3 ft/day for the undifferentiated overburden at well 12K123 from laboratory analyses. The geometric average of K′ values calculated using the Hantush-Jacob method for this study is within the range reported by Torak and others (1993).

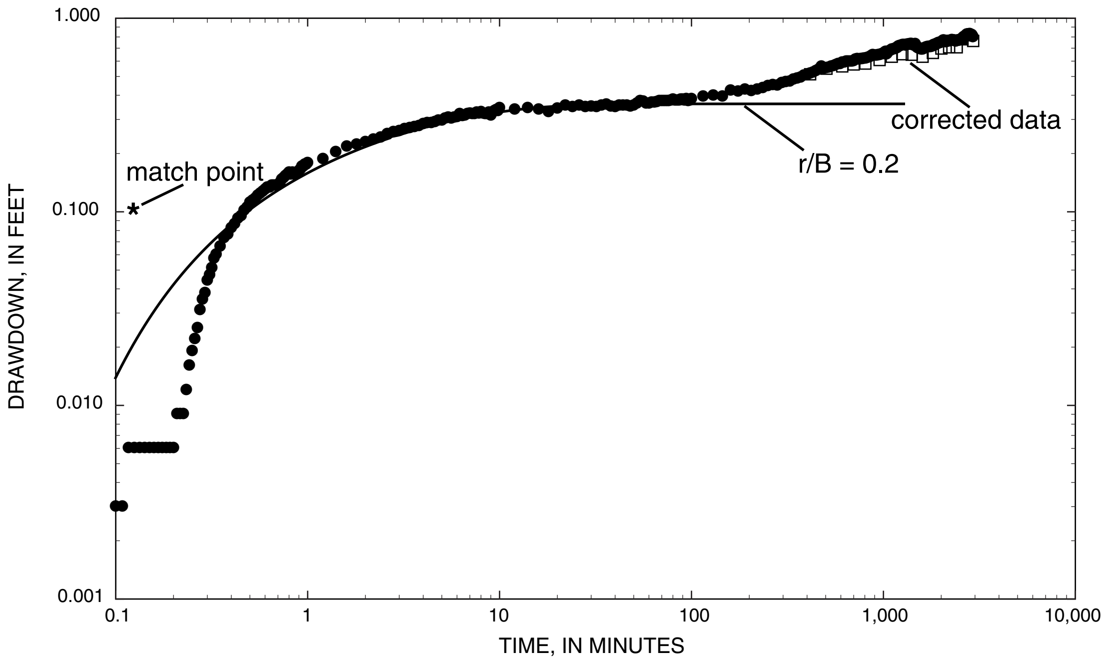

Figure 19. Log-log plot of time-drawdown data and matching Hantush-Jacob type curve of r/B = 0.2 for well 12K151, February 21-23, 1995.

Table 3. Estimated transmissivity and storage coefficient for the lower water-bearing zone of the Upper Floridan aquifer, using data from selected wells in the wellfield southwest of Albany, Georgia, February 1995

Well number	Transmissivity (feet squared per day)	Storage coefficient
12K141	181,000	1.7×10^{-4}
12K144	120,000	1.7×10^{-4}
12K148	187,000	6.3×10^{-4}
12K151	506,000	5.5×10^{-4}
12K154	460,000	1.4×10^{-4}

The match-point data from the Hantush-Jacob method (Hantush and Jacob, 1954) were used to estimate the anisotropic transmissivity tensor components of ground-water flow in the Upper Floridan aquifer in the study area. The method and computer program (TENSOR2D) used for the tensor analysis are documented in Maslia and Randolph (1986). The tensor analysis is an equivalent porous media approach that uses least squares to fit the anisotropic diffusivity ellipse to the directional diffusivity for each observation well.

The observation wells—12K141, 12K144, 12K148, 12K151, and 12K154—are referenced to an arbitrary x-y coordinate system whose origin is located at well 12K147 (the pumped well) and whose x-axis is oriented east-west. Wells 12K141 and 12K144 could not both be used for this analysis because they are radially aligned with the pumped well (Maslia and Randolph, 1986). A polar plot of directional diffusivity [square root of (T_d/S) where T_d is the directional transmissivity] for the five observation wells is shown in figure 20. Well 12K154 is an outlier which indicates that at the scale that includes this well, the Upper Floridan aquifer does not behave as an equivalent porous media. A possible explanation is that well 12K154 taps a fracture that controls the flow.

The tensor analysis was performed using wells 12K144, 12K148, and 12K151. Computed values of directional diffusivity can be fitted to an ellipse whose angle of anisotropy is 64.8 degrees and ratio of anisotropy is 3.8:1 (fig. 21). The geometric mean of principal transmissivity is 319,000 ft^2/d and the storage coefficient is 5.8×10^{-4}.

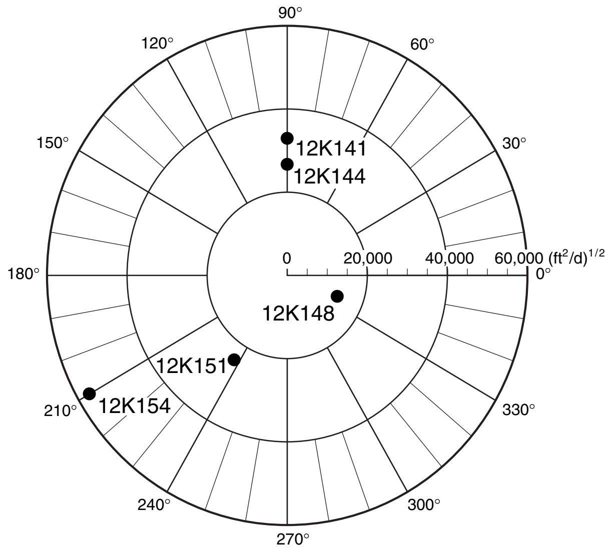

Figure 20. Directional diffusivity [square root of (T_d/S)] for wells 12K141, 12K144, 12K148, 12K151, and 12K154.

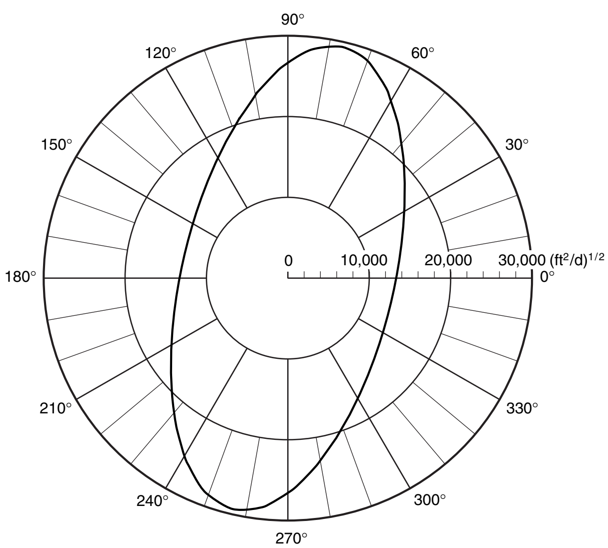

Figure 21. Diffusivity ellipse from TENSOR2D (Maslia and Randolph,1986) analysis using wells 12K144, 12K148, and 12K151.

The time-drawdown data from the observation wells (such as that shown in figure 19) and the borehole geophysical data suggest that the hydrogeology of the Upper Floridan aquifer in the wellfield area is complex. The time-drawdown data from the observation wells deviate from the Theis curve and flatten out soon after pumping began (from about 1 to 3 minutes). According to the Hantush-Jacob analyses (Hantush and Jacob, 1954), this early deviation and flattening suggests that the aquifer receives leakage from confining units. Results of this method may be misleading, however, suggesting more leakage than actually occurs if the flattening of the time-drawdown curves is caused by some other factor. Another explanation of the deviation from the Theis curve is fracture flow, resulting in a dual-porosity response. The time-drawdown data for well 12K151 (fig. 19) deviate from the Theis curve at about 3 minutes, then indicate an increase in drawdown from about 100 minutes until the end of pumping. Data shown in figure 19 can be divided into three groups—early time that fits the Theis curve (about 0.3 to 3 minutes); intermediate time that flattens out from the Theis curve (about 3 to 100 minutes); and late time that shows a second increase in drawdown (greater than 100 minutes). The three response intervals are evident on a semi-log plot of time-drawdown data (fig. 22) as three different slopes. In this dual-porosity model, the first slope represents flow from the fractures; the second slope represents a time when the aquifer is in a period of transition; and the third slope (later time data) represents a combination of fracture and matrix flow (Kruseman and de Ridder, 1990). During the transition period, the hydraulic potential along the fracture boundaries changes, and the aquifer matrix begins to contribute recharge to the fractures.

The late time/drawdown data, which indicate a secondary increase in drawdown, suggest that the system may be responding to dual porosity. As an alternative to the Hantush-Jacob approach for leaky aquifers, the Jacob straight-line method (Jacob, 1950) was used with the late time/drawdown data (greater than about 100 minutes on figure 22). Using late time/drawdown data, the transmissivity of the fracture system, and the storage coefficient of the fracture system plus that of the aquifer matrix were computed (Kruseman and de Ridder, 1990). Applying this approach to the aquifer-test data from the deep observation wells at the test site, values for T of the fracture system ranged from 233,000 to 466,000 ft^2/d and values for S of the fractures plus the matrix ranged from 5.1×10^{-4} to 2.9×10^{-2}.

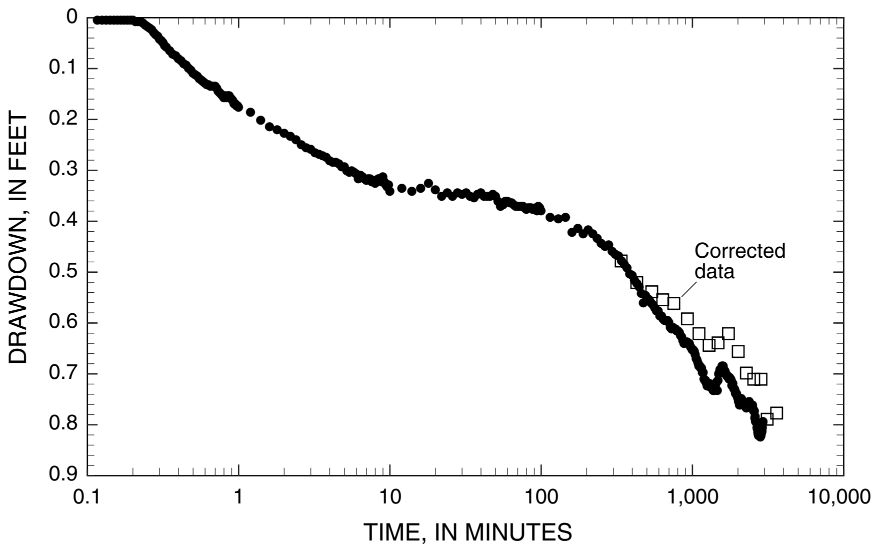

Figure 22. Semi-log plot of time versus drawdown data for well 12K151, February 21-23, 1995.

SUMMARY

Large withdrawals of ground water in the Albany area of southwestern Georgia have lowered the water levels in deep aquifers as much as 140 feet (ft) since the 1950's. Due to these declines, the Albany Water, Gas, and Light Commission has proposed to use the shallow Upper Floridan aquifer to augment their current municipal water supply. A cooperative study by the Albany Water, Gas, and Light Commission and the U.S. Geological Survey was conducted to evaluate the hydrogeology of the Upper Floridan aquifer in an area southwest of Albany and west of the Flint River in Dougherty County, Ga. The study area lies in the Dougherty Plain district of the Coastal Plain physiographic province. The Upper Floridan aquifer in the study area is composed of the Eocene Ocala Limestone. The aquifer is confined below by the middle Eocene Lisbon Formation and semiconfined above by the undifferentiated Quaternary overburden.

The Upper Floridan aquifer has been subdivided into an upper water-bearing zone and a much higher permeability lower water-bearing zone. The upper water-bearing zone consists of friable, weathered limestone and the lower water-bearing zone consists of harder, fractured limestone. In the study area, the upper water-bearing zone ranges in thickness from 40 to 80 ft, and the lower water-bearing zone ranges in thickness from 60 to 80 ft. Secondary permeability largely is responsible for higher yields that are typical of wells open to the lower water-bearing zone.

Wells were installed and borehole geophysical, borehole video, and flowmeter data were collected. Borehole geophysical and borehole video surveys were used to identify two potentially high flow zones in the lower water-bearing zone. A spinner flowmeter test indicated that the highly fractured borehole interval between 118 and 124 ft contributed a significant portion of total yield to the production well.

A constant-rate drawdown and recovery aquifer test, in which the production well was pumped at 3,300 gallons per minute for 49 hours, indicated that water-level declines from pumping were variable throughout the wellfield area. Water-level declines in the surficial aquifer ranged from about 1.5 ft near the pumped well, to about 0.4 ft in a well located in the southwestern part of the test site. Water-level declines in the upper water-bearing zone were similar to those observed in the surficial aquifer and ranged from about 0.4 to 0.7 ft. Water-level declines in the lower water-bearing zone at the wellfield ranged from about 0.5 to about 2.4 ft. At distances greater than about 0.5 mile from the pumped well, there were no measurable effects from pumping. After pumping ceased, the water levels returned to 10 percent of the static levels within a few minutes and continued to recover slowly for the next several hours.

The wells located within about 3.75 miles of the Flint River showed an increase in water levels during the test resulting from a rise in the river stage of 3.5 ft. The rise in river stage probably caused a decrease in the natural discharge from the Upper Floridan aquifer to the river. The Flint River appears to have had a much greater effect on the regional potentiometric surface of the Upper Floridan aquifer than did the pumping test.

Analyses of the aquifer-test data provide estimates for transmissivity (T) and storage coefficient (S) for the lower water-bearing zone of the Upper Floridan aquifer and for vertical hydraulic conductivity (K′) of the overlying sediments. Estimates of T using the Hantush-Jacob method for aquifers receiving leakage across confining units, ranged from 120,000 to 506,000 feet squared per day (ft^2/d), estimates of S ranged from 1.4×10^{-4} to 6.3×10^{-4}, and estimates of K′ ranged from 4.9 to 6.8 feet per day (ft/d). Geometric averages for these ranges of T, S, and K′ were calculated to be 248,000 ft^2/d, 2.7×10^{-4}, and 5.5 ft/d, respectively. A tensor analysis was performed using the program TENSOR2D. The program calculated the geometric mean of principal T to be 319,000 ft^2/d and the S to be 5.8×10^{-4}. Assuming a dual-porosity aquifer model, the Jacob straight-line method and late time/drawdown data, T of the fractures was calculated to range from 233,000 to 466,000 ft^2/d and estimates of S of the fractures plus the matrix ranged from 5.1×10^{-4} to 2.9×10^{-2}.

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