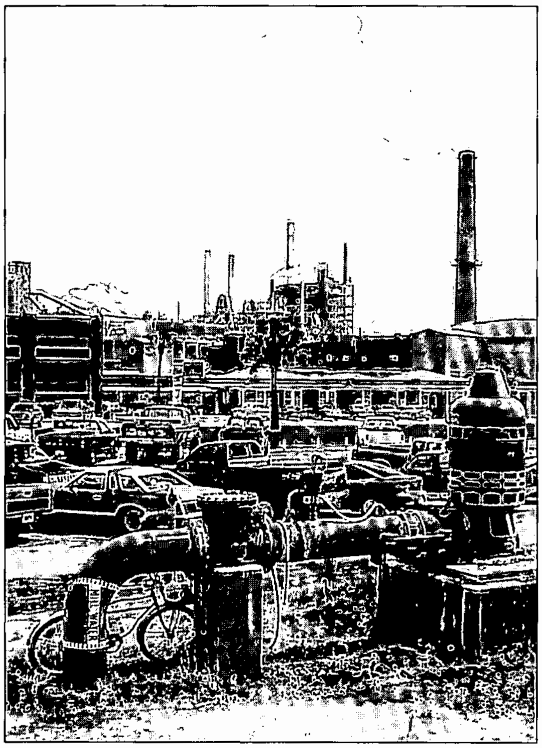
HYDRAULIC CHARACTERISTICS OF THE UPPER FLORIDAN AQUIFER IN THE SAVANNAH AND ST MARYS AREAS OF COASTAL GEORGIA

by
Debbie Warner and Brent T. Aulenbach
U.S. Geological Survey



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INFORMATION CIRCULAR 105

Cover: Production well at St Marys test site, St Marys, Georgia, July 1999.
Photograph by Alan M. Cressler, U.S. Geological Survey

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VERTICAL DATUM

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 both the United States and Canada, formerly called "Mean Sea Level of 1929."

HYDRAULIC CHARACTERISTICS OF THE UPPER FLORIDAN AQUIFER IN THE SAVANNAH AND ST MARYS AREAS OF COASTAL GEORGIA

by Debbie Warner[1] and Brent T. Aulenbach[1]

ABSTRACT

Hydraulic characteristics (transmissivity and storage coefficient) of the Upper Floridan aquifer in the Savannah and St Marys areas of coastal Georgia were evaluated by analyzing results of water-level recovery tests. Tidal corrections were applied to data from one well for the Savannah area test, and to data from the four wells for the St Marys area test. Data from one well used in the St Marys area test also were corrected for effects of nearby pumpage. Transmissivity tensor analyses were conducted to evaluate the anisotropy of the aquifer at the Savannah and St Marys test sites.

For the Savannah area, calculated transmissivity of the Upper Floridan aquifer ranges from 32,000 to 43,000 feet squared per day, and the storage coefficient ranges from 6.3×10^{-4} to 1.3×10^{-3}. Transmissivity of the aquifer has an anisotropy ratio of approximately 1.2:1 and an angle of anisotropy of approximately 108 degrees (measured counterclockwise from due east). Thus, the larger principal value of transmissivity is aligned approximately in the direction of north-northwest.

For the St Marys area, calculated transmissivity of the Upper Floridan aquifer ranges from 98,000 to 170,000 feet squared per day, and the storage coefficient ranges from 9.9×10^{-4} to 2.4×10^{-3}. Transmissivity of the aquifer has an anisotropy ratio of approximately 2.5:1 and an angle of anisotropy of approximately 64 degrees (measured counterclockwise from due east). The larger principal value of transmissivity is aligned approximately in the north-northeast direction.

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[1]Hydrologist, U.S. Geological Survey.

INTRODUCTION

Ground water is the principal source of water for the 24-county area of coastal Georgia (fig. 1), and adjacent parts of South Carolina and Florida. During 1997, about 347 million gallons per day (Mgal/d) was withdrawn in the coastal area, primarily from the Upper Floridan aquifer (Fanning, 1999). Ground-water withdrawal from the Upper Floridan aquifer has resulted in substantial water-level decline and subsequent encroachment of seawater into the aquifer at the northern end of Hilton Head Island, South Carolina, about 30 miles (mi) northeast of Savannah, Georgia; and in upward migration of deep saline water in the Brunswick, Ga., area. The U.S. Geological Survey (USGS), in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey, is conducting a technical investigation to:

- determine locations where saltwater is entering the Upper Floridan aquifer and why the saltwater is entering at those locations;
- determine the rate of saltwater movement into the Upper Floridan aquifer;
- determine other areas where saltwater contamination could occur;
- assess alternative sources of freshwater, including ground- and surface-water sources; and
- develop a monitoring-well network to assess ground-water levels and quality.

As part of these technical investigations, ground-water models are being developed to assess impacts of current and possible future pumping on ground-water levels, flow directions, and water quality in the coastal area. Better definition of hydraulic properties is needed for development of ground-water models for the area.

Purpose and Scope

This report presents results of aquifer tests by water-level-recovery methods (hereafter referred to as recovery tests) conducted during periods of reduced industrial pumpage from the Upper Floridan aquifer in the Savannah (Chatham County) area during July 13-22, 1996, and in the St Marys (Camden County) area during April 22-24, 1997 (fig. 1). The report also describes methods used to reduce interference of tidal and other influences on ground-water-level data collected during the recovery tests. The Theis curve-matching method (Theis, 1935) was used to estimate transmissivity and storage coefficient of the Upper Floridan aquifer. Transmissivity tensor analyses were conducted to provide information on directional properties and anisotropy of the aquifer. These aquifer-test analyses will contribute to a better definition of hydraulic properties of the Upper Floridan aquifer.

Methods

Recovery tests in the Savannah and St Marys areas were conducted in the area of the Union Camp Corporation and the Gilman Paper Company, respectively following a reduction in pumpage of the production wells. Flow rates at the two test sites were obtained from reported pumping records (James Baker, Union Camp Corporation, Savannah, Ga., personal commun., July 1996; and Brent Hanson, Gilman Paper Company, St Marys, Ga, personal commun., October 1998). The geographic location of the centroid of pumping was estimated based on the location of the pumping wells. Water-level data were collected using continuous recorders in observation wells.

Transmissivity and storage coefficient of the Upper Floridan aquifer was estimated from recovery-test data by using the Theis curve-matching method (Theis, 1935) for a fully penetrating well. Log-log plots of water-level change over time since the pumpage reduction were made for each observation well. Each plot was matched to the Theis type curve to obtain a match point that was used to estimate aquifer characteristics. Aquifer characteristics also were estimated in the St Marys area by using the Jacob distance-drawdown straight-line method (Jacob, 1950), using water-level recovery instead of drawdown data.

Water levels in several observation wells were influenced by tides and nearby pumping, which affected the analysis of recovery-test data by the above-mentioned methods. In the Savannah area test, water-level recovery from one well was obscured by a strong 12-hour, cyclical, tidal fluctuation. In the St Marys area test, recovery from the four observation wells was affected by tides, and data from one well also were affected by nearby pumping. Tidal affects were removed from the analysis of the Savannah area test by using only the water-level-recovery data that correspond to the mid-point of each 12-hour cycle, which reduced the amount of data used in the analysis. For the St Marys area test, an attempt was made to apply the Theis method to the

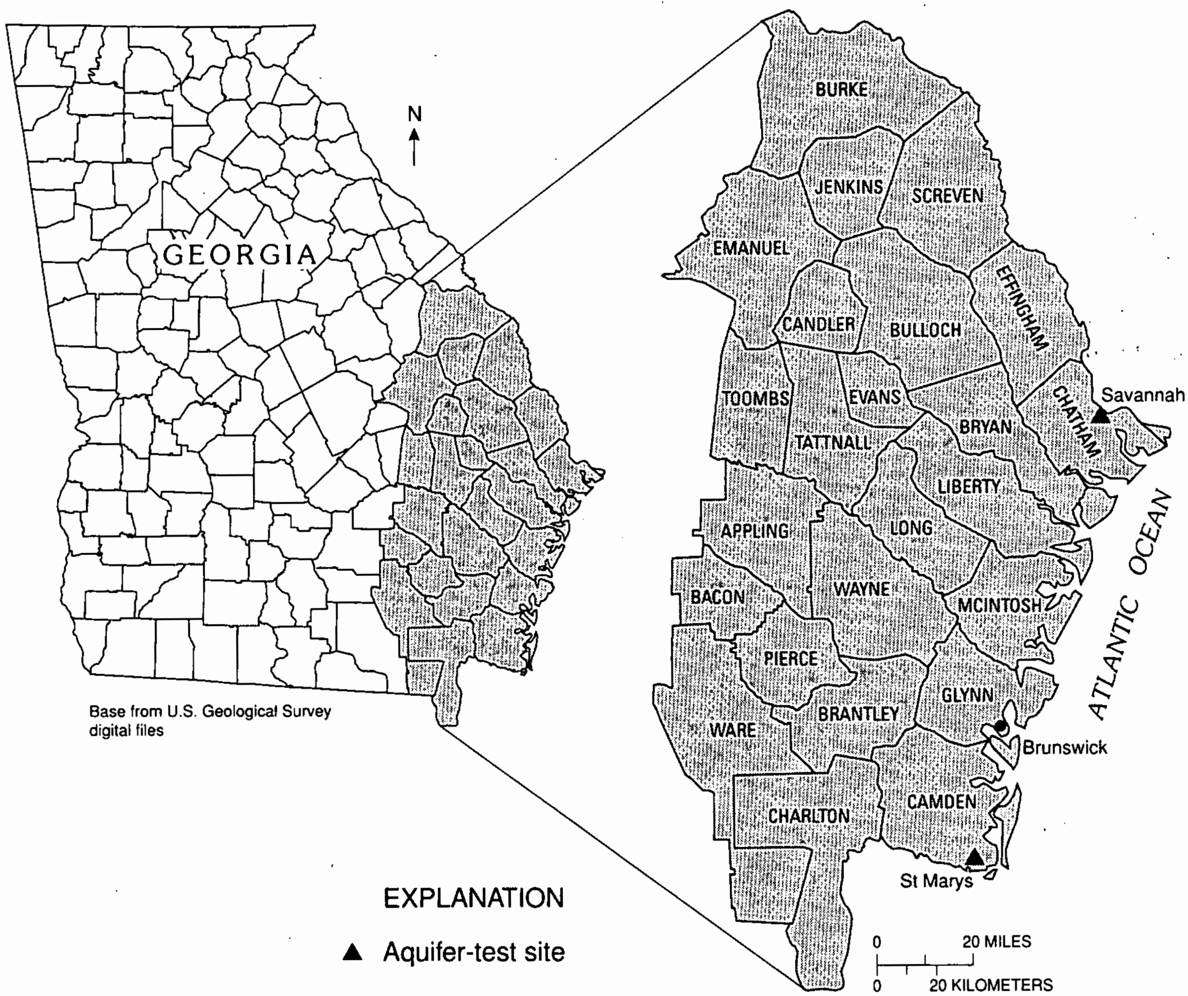


Figure 1. Location of the 24-county Georgia coastal area and aquifer-test sites.

raw recovery data from all observation wells; however, data for one well could not be fit to the Theis curve. A regression technique (described in the Appendix) then was used to effectively filter out (correct) the influence of tides and pumpage from the water-level data. The Theis method then was applied to the corrected water-level recovery data from all observation wells.

Water-level recovery data were evaluated for anisotropic transmissivity by using a method and computer program for tensor analysis (TENSOR2D; Maslia and Randolph, 1986). The tensor analysis provided the ratio and angle of anisotropy and values of transmissivity along the principal directions (principal values). Match-point values obtained from the Theis curve-matching method were used in the tensor analysis. The method of tensor analysis assumes the existence of an equivalent porous media and provides a least-squares fit of the anisotropic-diffusivity ellipse to the directional diffusivity that is calculated using the data from each observation well. Directional diffusivity is calculated as the square root of (T_d/S), where T_d is the directional transmissivity and S is the storage coefficient.

Acknowledgments

The authors extend special thanks to the Union Camp Corporation, Savannah, Ga., and the Gilman Paper Company, St Marys for their cooperation during each of the periods of reduced pumpage. Appreciation also is extended to L. Elliott Jones of the USGS, who began the initial analysis and who provided advice during final analysis.

GENERAL HYDROGEOLOGY OF THE GEORGIA COASTAL AREA

The principal source of water in the 24-county coastal area of Georgia is the Floridan aquifer system (fig. 2) (Miller, 1986; Krause and Randolph, 1989). Secondary sources of water in the coastal area include the surficial aquifer, and the upper and lower Brunswick aquifers (fig. 2) (Clarke and others, 1990).

The Floridan aquifer system consists of interbedded clastic rocks and marl in the updip area to the northwest and massive limestone and dolomite in the downdip area to the southeast (Krause and Randolph, 1989). The Floridan aquifer system thickens from a featheredge in the northwestern outcrop area to more than 2,000 feet (ft) downdip in coastal Georgia (Krause and Randolph, 1989, plate 1). Rocks comprising the Floridan aquifer system are mainly of Paleocene, Eocene, and Oligocene age, and are connected hydraulically in various degrees. In most of the study area, the Floridan aquifer system is divided into the Upper and Lower Floridan aquifers (Krause and Randolph, 1989). In the coastal area of Georgia, the Upper Floridan aquifer mainly consists of limestone and dolomite of late Eocene and Oligocene age (Clarke and others, 1990). Generally, the uppermost part of the aquifer is the most permeable, and consists of vuggy, highly fossiliferous limestone. Use of the Lower Floridan aquifer is hindered by excessive depth, locally poor water quality, and generally low well yields.

In the Savannah area, the depth to the top of the Upper Floridan aquifer ranges from about 200 to 300 ft below sea level (Krause and Randolph, 1989), and increases toward the south (Miller, 1986). Reported estimates of transmissivity of the Upper Floridan aquifer in the Savannah area range from about 25,000 to 50,000 feet squared per day (ft^2/d) (Bush and Johnston, 1988; Krause and Randolph, 1989).

In the St Marys area, the top of the Upper Floridan aquifer ranges from about 400 ft below sea level in the west to about 600 ft below sea level in the northeast (Brown, 1984). Reported estimates of transmissivity of the Upper Floridan aquifer in the St Marys area range from about 21,000 to 43,000 ft^2/d (Krause and Randolph, 1989).

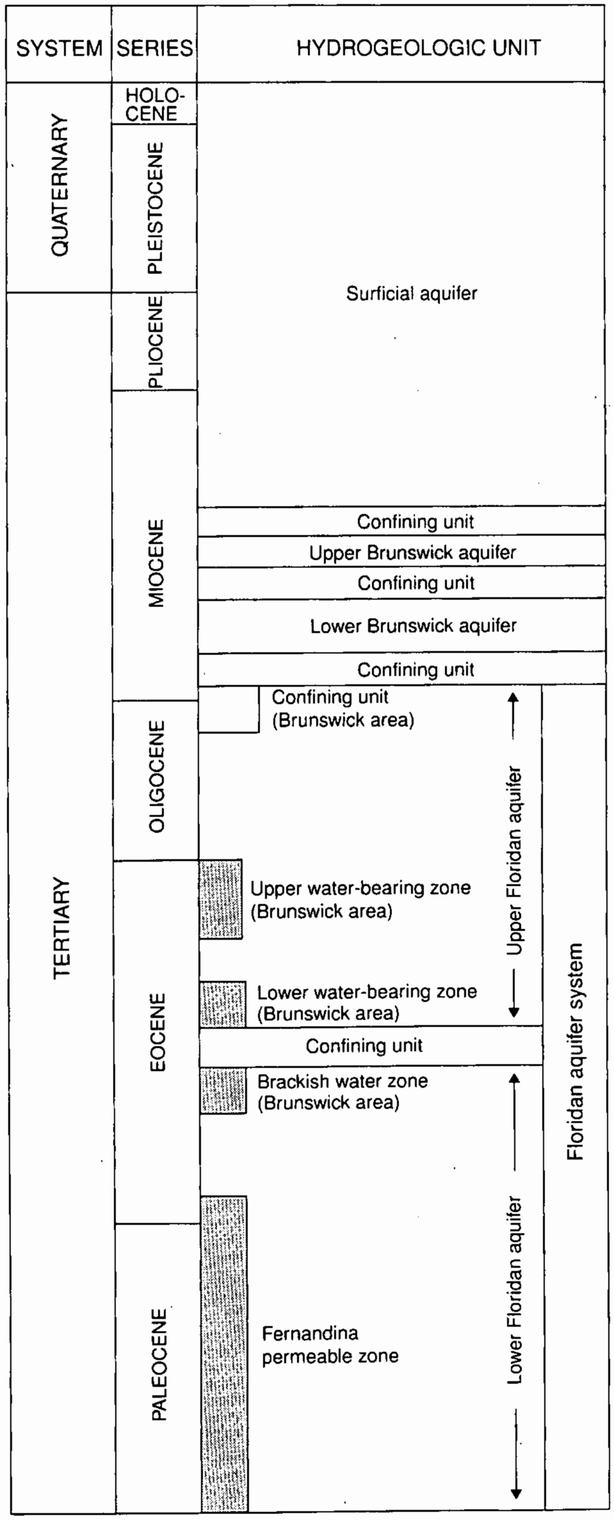


Figure 2. Generalized hydrogeologic column of the Georgia coastal area (modified from Clarke and others, 1990).

HYDRAULIC CHARACTERISTICS OF THE UPPER FLORIDAN AQUIFER

Results of recovery tests performed for this study in the Savannah and St Marys areas are presented below. Calculated hydraulic properties of the Upper Floridan aquifer in the two areas also are presented and compared in the following sections.

Savannah Area Aquifer Test

A recovery test was conducted in the Savannah, Chatham County, Ga., area at the Union Camp Corporation wellfield (figs. 1, 3). The wellfield pumps about 22 Mgal/d (15,000 gal/min, Julia L. Fanning, U.S. Geological Survey, written commun., 1998). Pumpage is periodically reduced for site maintenance. Such a shutdown occurred during July 13-22, 1996, when pumps in wells 36Q002, 37Q002, and 37Q003 (fig. 3) were shut off, and the discharge from well 36Q001 was reduced. The cumulative pumping rate was reduced by about 12,625 gal/min (18.2 Mgal/d). Pumpage from the four wells was returned to full capacity on July 22, 1996.

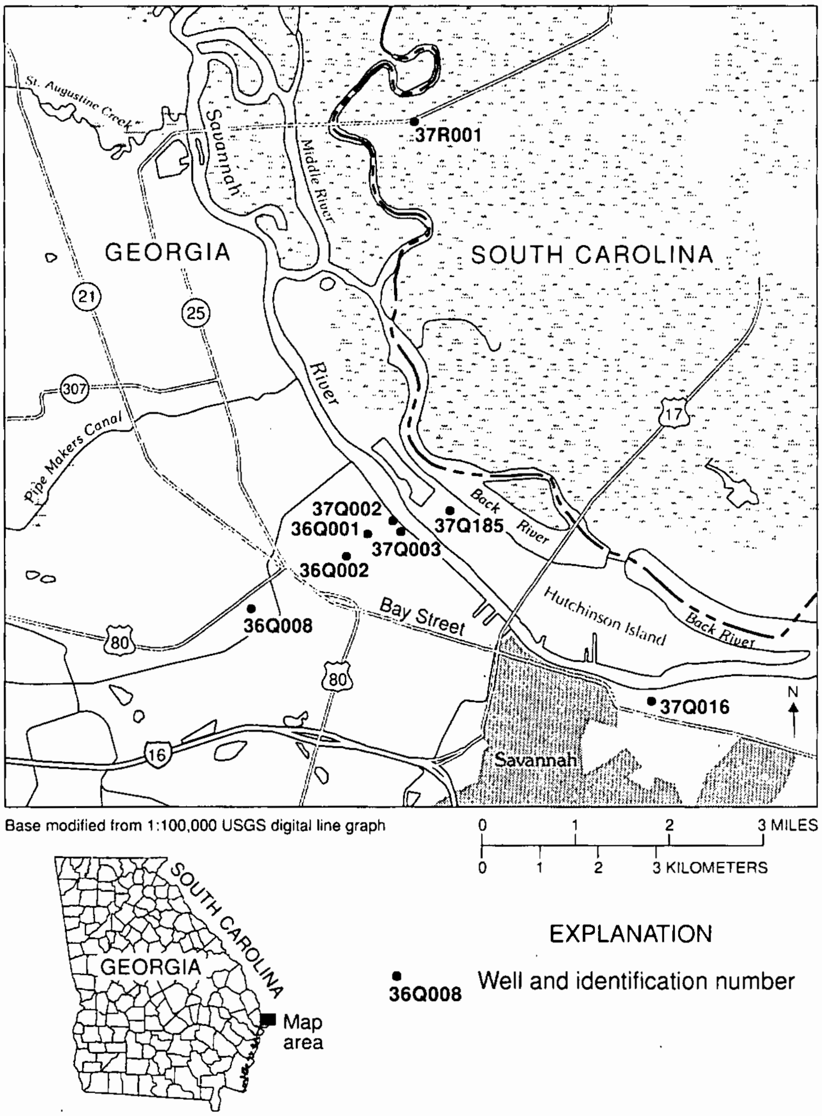


Figure 3. Location of wells used in the Savannah area aquifer test.

Water-level recovery was monitored in four observation wells (fig. 3, table 1). The observation wells are located at distances of 1.8 to 9.4 mi from the centroid of pumping, which is located approximately at latitude 32°06′09″ and longitude 81°07′26″; the latitude and longitude of the four wells in the wellfield are given in table 1, and the wells are plotted in figure 3. All production and observation wells are open to the Upper Floridan aquifer; well-location and construction data for the production and observation wells are listed in table 1. Water levels were recorded continuously in observation wells 36Q008, 37Q016, 37Q185, and 37R001 throughout the period of reduced pumpage (figs. 4-7); water-level data are not available for the production wells. Water-level data from the observation wells show a 12-hour cyclical variation, which is assumed to result from tidal fluctuations (the site is located about 0.5 mi from the Savannah River). The tidal fluctuations obscured the recovery of water level in observation well 37Q016. To compensate for tidal fluctuations in this well, only water-level measurements that correspond to the midpoints of each 12-hour cycle were used in the analysis.

Time-recovery data from the four observation wells were plotted on log-log graphs and matched to the Theis type curve (figs. 8-11). Each recorded water-level measurement was matched directly to the Theis curve, except for those measured in well 37Q016, which used measurements that corresponded to the midpoint of each 12-hour tidal cycle, to correct for tidal fluctuations. Calculated transmissivity ranges from 32,000 to 43,000 ft^2/d and has a geometric mean of 36,000 ft^2/d; these values are in good agreement with previously reported values (23,000 to 50,000 ft^2/d) of Krause and Randolph (1989). Calculated storage coefficient ranges from 6.3×10^{-4} to 1.3×10^{-3} and has a geometric mean of 7.9×10^{-4} (table 2).

Table 1. Well-location and construction data for wells used in the Savannah area aquifer test

Well number	Well name	Latitude	Longitude	Land-surface altitude (feet above sea level)	Radial distance from centroid of pumping (feet)	Diameter (inches)	Depth of casing (feet)	Well depth (feet)
				Pumped wells				
36Q001	Union Camp 03	32°06′10″	81°07′32″	11	500	30	219	947
36Q002	Union Camp 04	32°05′58″	81°07′46″	11	2,100	26	237	603
37Q002	Union Camp 05	32°06′17″	81°07′15″	10	1,200	26	215	1,000
37Q003	Union Camp 01	32°06′11″	81°07′10″	11	1,400	12	224	920
				Observation wells				
36Q008	Layne-Atlantic	32°05′30″	81°08′50″	9.91	8,200	4	250	406
37Q016	Southern Coast Line railroad docks	32°04′33″	81°04′27″	4.7	18,000	6	260	500
37Q185	Hutchinson Island TW1	32°06′22″	81°06′37″	6	4,400	4	274	344
37R001	Savannah Wildlife Refuge public-supply well	32°09′58″	81°06′54″	10	23,000	3	38	[1]119

[1]Original depth reported at 190 feet, geophysical logs indicate possible obstruction at 119 feet.

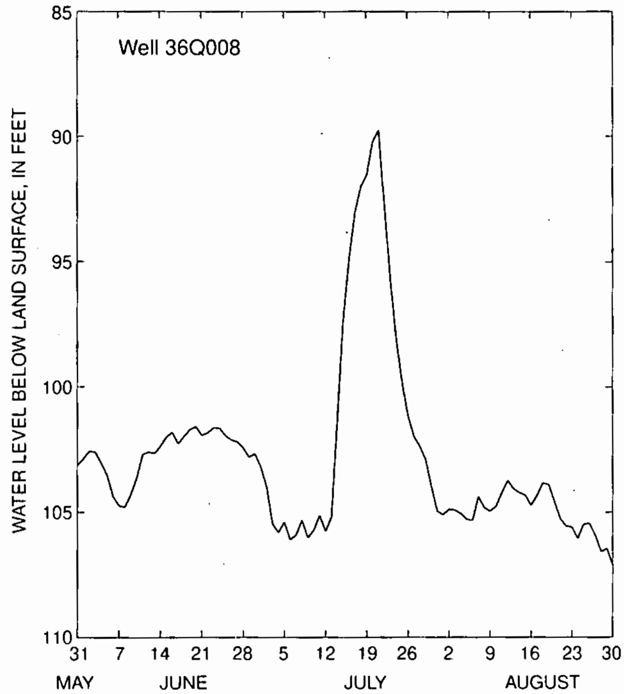


Figure 4. Water-level fluctuation in well 36Q008, June–August, 1996 (location of well shown in fig. 3).

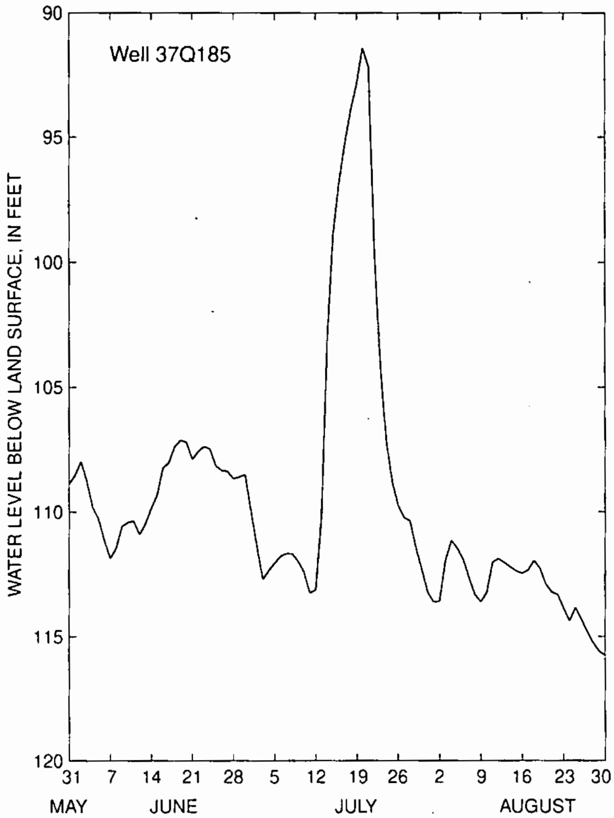


Figure 6. Water-level fluctuation in well 37Q185, June–August, 1996 (location of well shown in fig. 3).

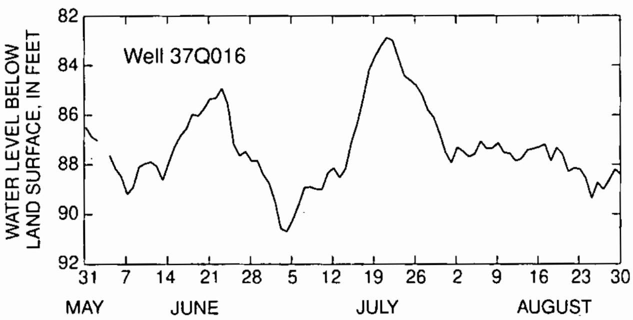


Figure 5. Water-level fluctuation in well 37Q016, June–August, 1996 (location of well shown in fig. 3).

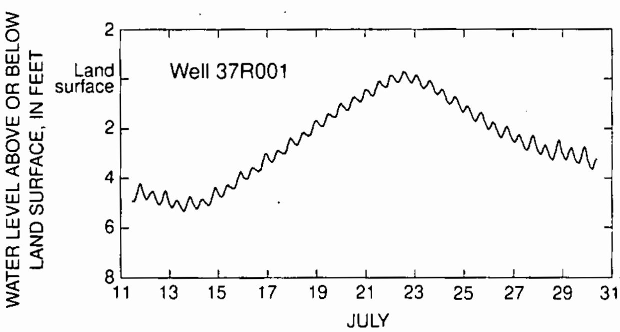


Figure 7. Water-level fluctuation in well 37R001, July 11–30, 1996 (location of well shown in fig. 3).

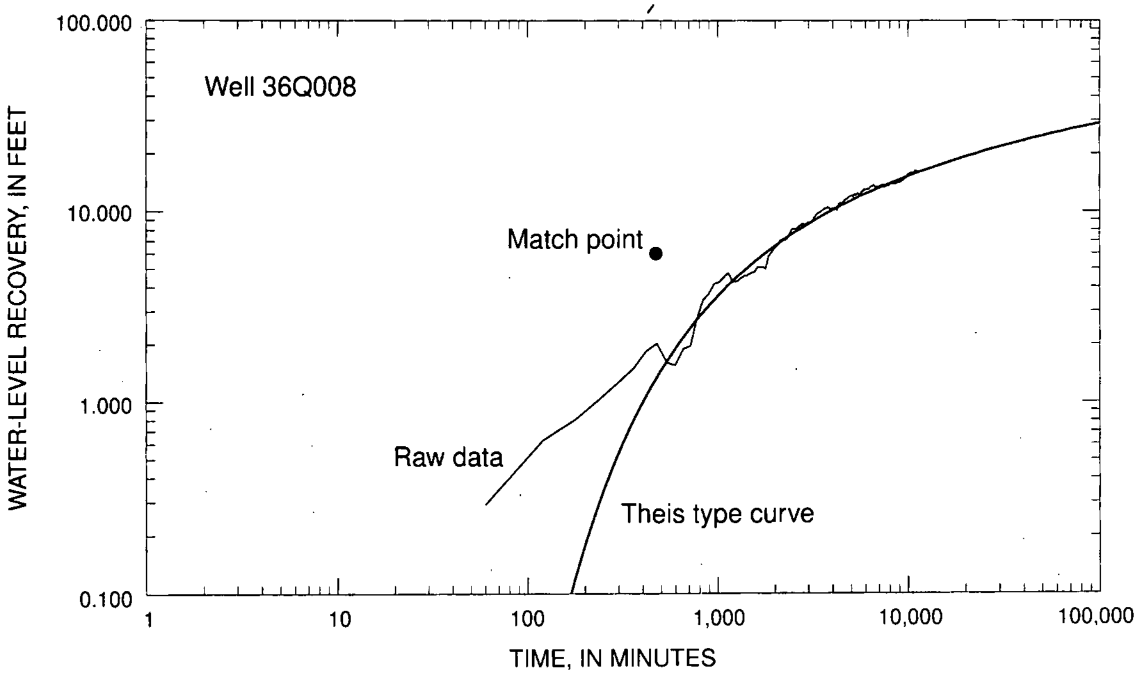


Figure 8. Log-log plot of time-recovery data for well 36Q008, July 13–22, 1996 (location of well shown in fig. 3).

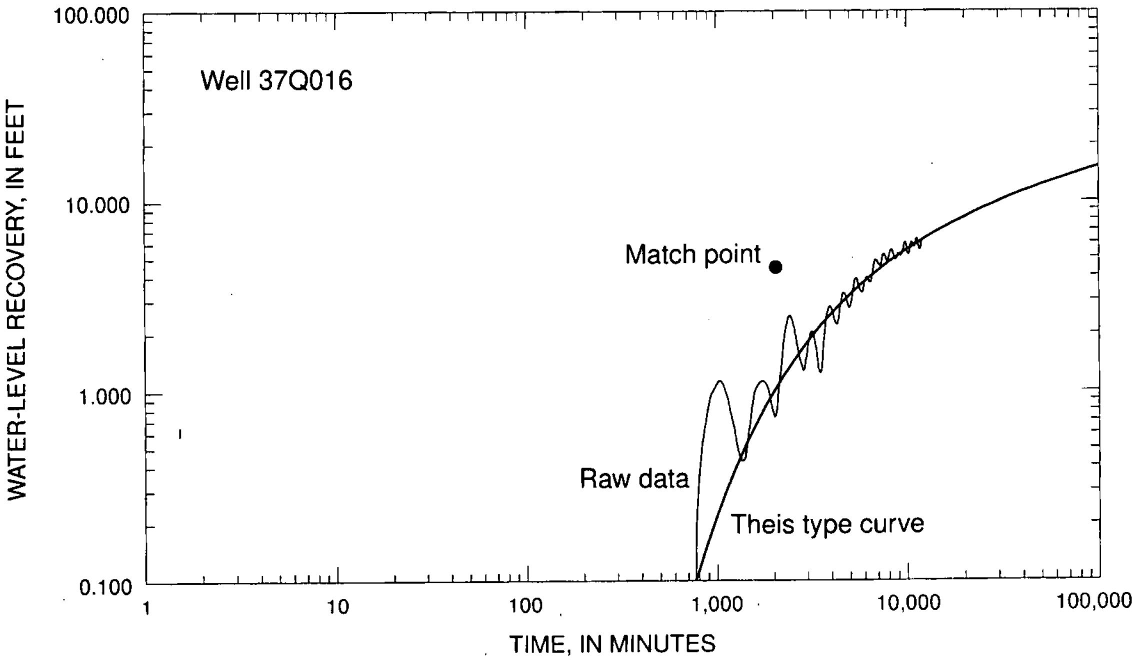


Figure 9. Log-log plot of time-recovery data for well 37Q016, July 13–22, 1996 (location of well shown in fig. 3).

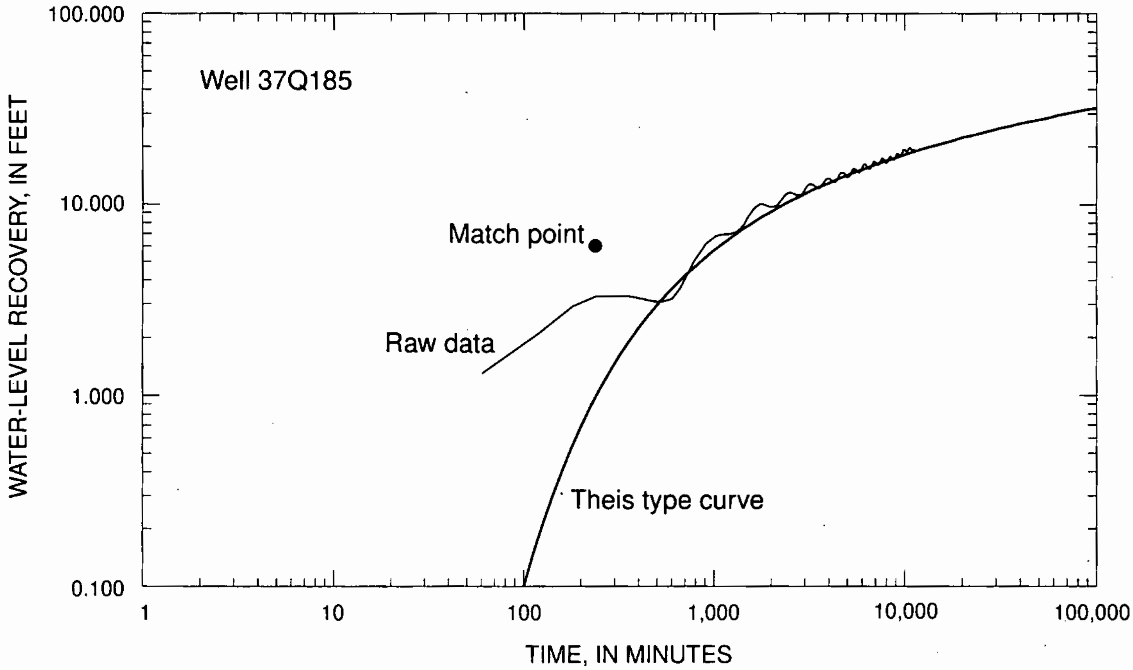


Figure 10. Log-log plot of time-recovery data for well 37Q185, July 13–22, 1996 (location of well shown in fig. 3).

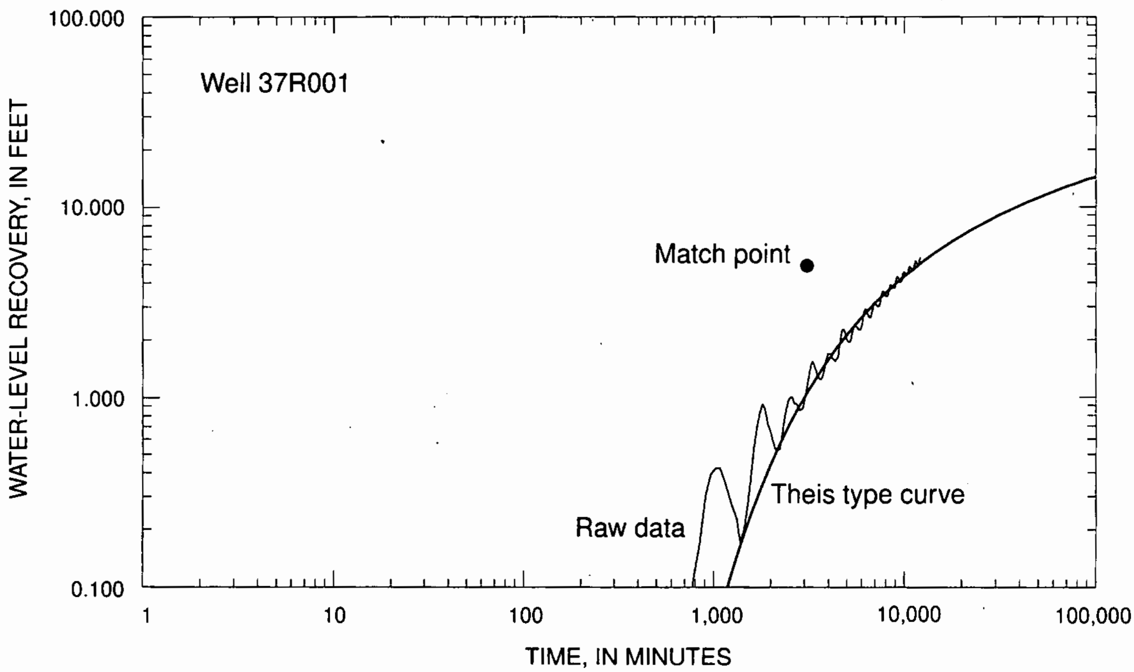


Figure 11. Log-log plot of time-recovery data for well 37R001, July 13–22, 1996 (location of well shown in fig. 3).

Table 2. Hydraulic properties of the Upper Floridan aquifer in the Savannah area, estimated using the Theis[1] curve-matching method
[ft²/d; feet squared per day]

Well number	Local name	Transmissivity (ft²/d)	Storage coefficient
36Q008	Layne-Atlantic	32,000	6.3×10^{-4}
37Q016	Southern Coast Line railroad docks	43,000	7.4×10^{-4}
37Q185	Hutchinson Island TW1	32,000	1.3×10^{-3}
37R001	Savannah Wildlife Refuge	39,000	6.3×10^{-4}
	Geometric Mean	**36,000**	$\mathbf{7.9 \times 10^{-4}}$

[1]Theis (1935).

Estimates of the anisotropic components of transmissivity tensor and of aquifer storage coefficient were obtained by applying the computer model TENSOR2D (Maslia and Randolph, 1986) to match-point data derived from the Theis analysis of water-level recovery measured in the four observation wells of the Savannah area test. Computed values of directional diffusivity were fitted to an ellipse having an angle of anisotropy of 108 degrees (measured counterclockwise from due east (fig. 12)) and ratio of anisotropy of 1.2:1.

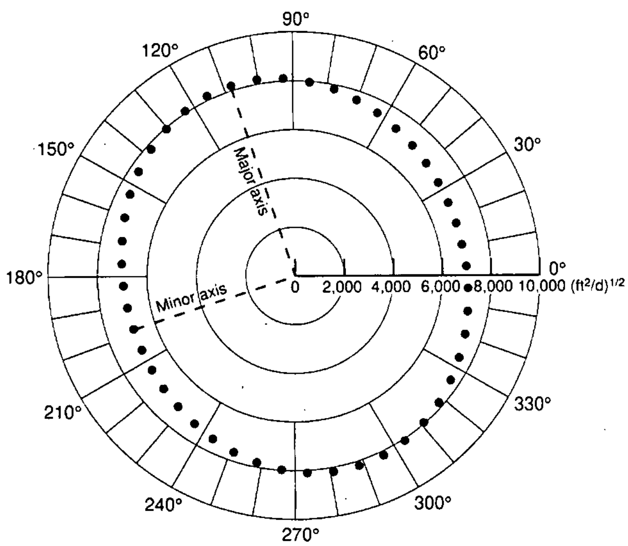


Figure 12. Diffusivity ellipse from TENSOR2D (Maslia and Randolph, 1986) analysis using data from wells 36Q008, 37Q016, 37Q185, and 37R001.

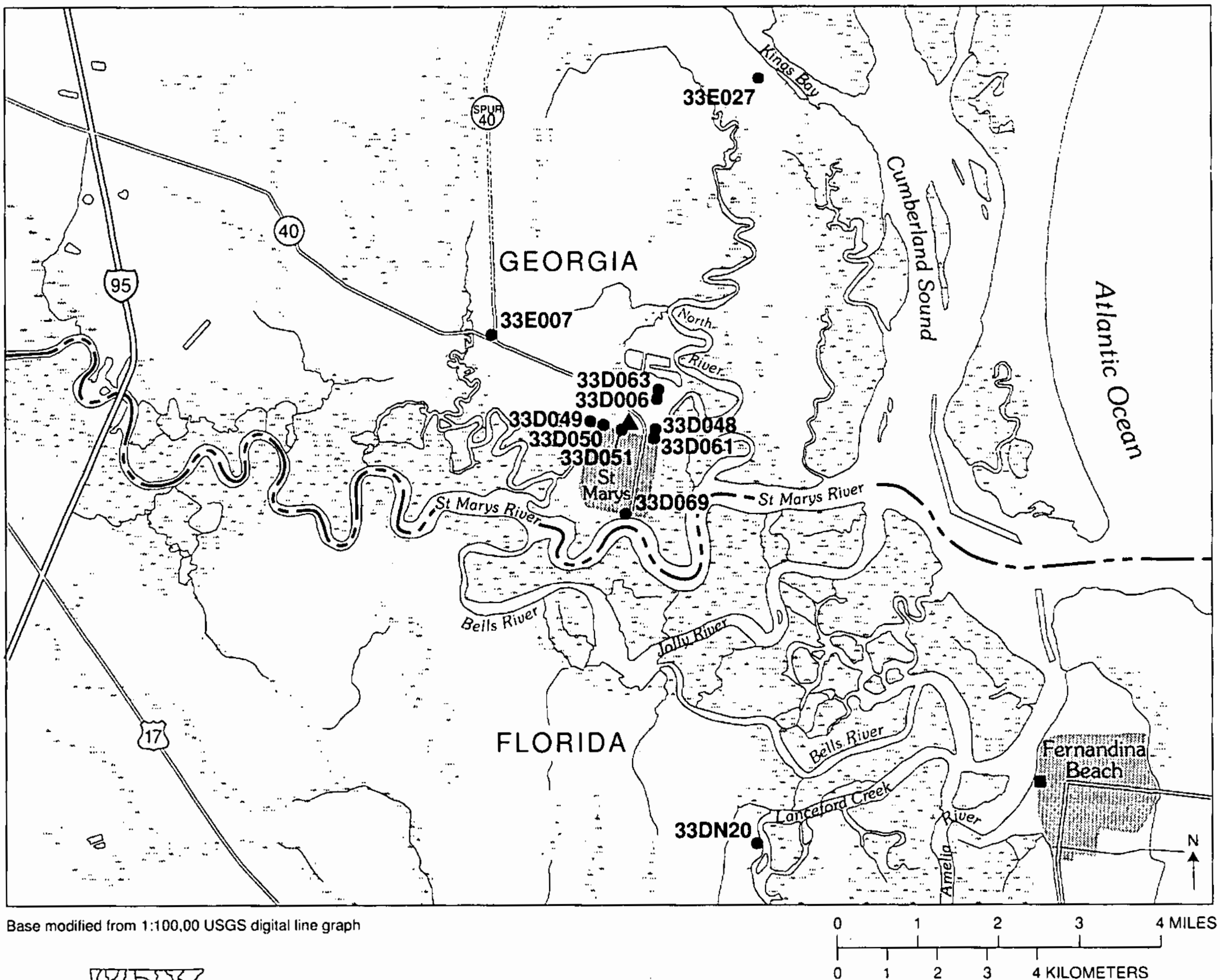
The maximum value of transmissivity, which is in the direction of the major axis of the transmissivity ellipse, approximately north-northwest, is 40,000 ft²/d. The minimum value of transmissivity, which is in the direction of the minor axis of the transmissivity ellipse, perpendicular to the major axis, is 34,000 ft²/d. The ratio of the major axis to the minor axis is 1.2:1. Geometric mean of the principal transmissivity from the tensor analysis is 37,000 ft²/d and is in good agreement with the geometric mean of values obtained from the Theis analysis (36,000 ft²/d). Storage coefficient is 6.4×10^{-4}, which also is in good agreement with the geometric mean obtained from the Theis analysis (7.9×10^{-4}).

St Marys Area Aquifer Test

A recovery test was conducted in the St Marys, Camden County, Ga., area at the Gilman Paper Company wellfield (figs. 1, 13). The wellfield pumps about 34 Mgal/d (23,800 gal/min, Julia L. Fanning, U.S. Geological Survey, written commun., 1998). Pumpage periodically is shut down for site maintenance—such a shutdown was scheduled during April 22-24, 1997, when pumps in wells 33D006, 33D048, 33D049, 33D050, 33D051, 33D061, and 33D063 (fig. 13) were shut off. Pumpage from the wells was returned to full capacity on April 24, 1997.

Recovery of water levels was monitored in four observation wells (fig. 13, table 3). The observation wells are located at distances of 1.1 to 5.8 mi from the centroid of pumping, which is located at latitude 30°44'13" and longitude 81°32'55"; the latitude and longitude of the four wells in the wellfield are given in table 3, and the wells are plotted in figure 13. The site is located about 0.5 mi west of the North River, a tidally influenced stream. All production and observation wells are open to the Upper Floridan aquifer; well-location and construction data for the production and observation wells are listed in table 3. Water levels were recorded continuously in observation wells 33D069, 33E007, 33E027, and 33DN20 throughout the period of reduced pumpage (figs. 14-17); water-level data are not available for the production wells.

Water levels in the observation wells show cyclical fluctuations, resulting from both a strong tidal influence and nearby pumping. These effects obscured water-level recovery in the observation wells. To compensate for tidal and pumping effects, a regression technique was used to correct the water-level recovery data. This technique is described in detail in the Appendix.



Base modified from 1:100,00 USGS digital line graph

EXPLANATION

▲ Approximate centroid of pumpage

33DN20● Well and identification number

■ Fernandina Beach Tidal Reference Station

Figure 13. Location of wells used in the St Marys area aquifer test.

Table 3. Well-location and construction data for wells used in the St Marys area aquifer test
[na, data not available]

Well number	Well name	Latitude	Longitude	Land-surface altitude (feet)	Radial distance from centroid of pumping (feet)	Diameter (inches)	Depth of casing (feet)	Well depth (feet)
				Pumped wells				
33D006	Gilman Paper Company 8	30°44′16″	81°32′36″	9	2,500	24	560	1,199
33D048	Gilman Paper Company 9	30°44′06″	81°32′35″	10	1,900	26	530	1,164
33D049	Gilman Paper Company 6	30°44′06″	81°33′25″	15	3,000	17.5	520	1,259
330050	Gilman Paper Company 5	30°44′11″	81°33′19″	15	1,900	20	529	1,215
33D051	Gilman Paper Company 4	30°44′07″	81°32′57″	10	600	20	519	1,220
33D061	Gilman Paper Company 11	30°44′01″	81°32′36″	10	2,000	26	550	1,088
33D063	Gilman Paper Company 10	30°44′32″	81°32′30″	10	2,800	26	560	1,099
				Observation wells				
33D069	National Park Service CI	30°43′13″	81°33′00″	8	6,000	4	467	575
33E007	Huntley Jiffey (Davis)	30°45′12″	81°34′36″	18	10,800	3	552	760
33E027	U.S.Navy Kings Bay TW1	30°47′56″	81°31′11″	10.42	23,800	8	555	990
33DN20	unnamed well in Florida	30°39′39″	81°31′26″	na	30,400	na	na	na

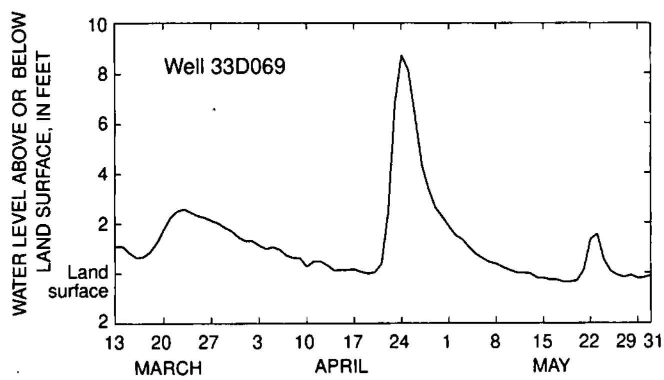


Figure 14. Water-level fluctuation in well 33D069, March 13–May 31, 1997 (location of well shown in fig. 13).

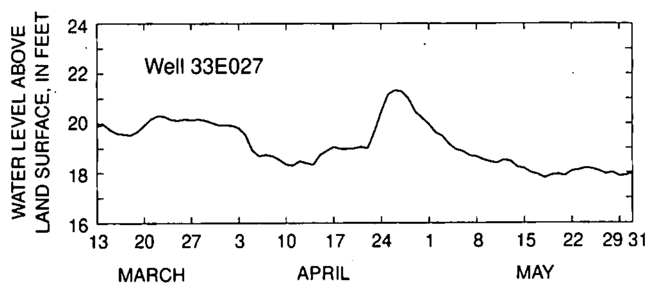


Figure 16. Water-level fluctuation in well 33E027, March 13–May 31, 1997 (location of well shown in fig. 13).

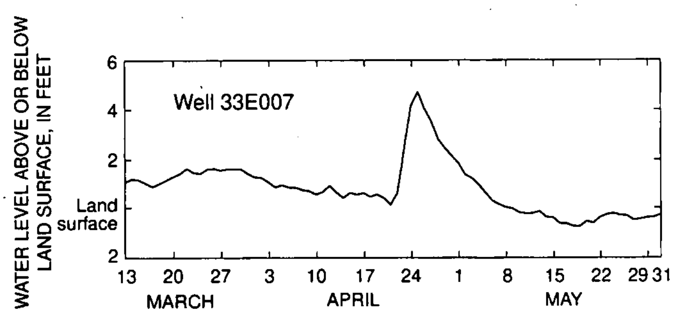


Figure 15. Water-level fluctuation in well 33E007, March 13–May 31, 1997 (location of well shown in fig. 13).

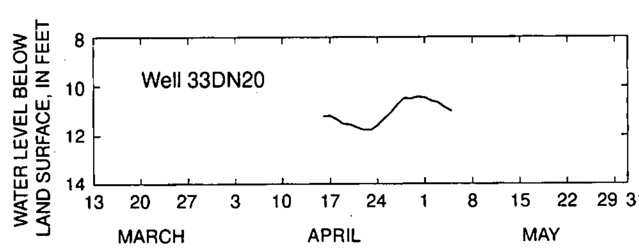


Figure 17. Water-level fluctuation in well 33DN20, April 15–May 5, 1997 (location of well shown in fig. 13).

Hydraulic properties of the Upper Floridan aquifer in the St Marys area were initially determined using the raw (uncorrected) time-recovery data from three of the four observation wells. Data from one observation well (33DN20) could not be matched to the Theis curve because of the effects of tides. The raw time-recovery data were plotted on log-log graphs (figs. 18-21) and a match to the Theis curve was obtained for three of the four wells. Calculated transmissivity ranges from 79,000 to 135,000 ft^2/d and has a geometric mean of 103,000 ft^2/d. Calculated storage coefficient ranges from 1.1×10^{-3} to 1.9×10^{-3} and has a geometric mean of 1.5×10^{-3} (table 4).

Table 4. Hydraulic properties of the Upper Floridan aquifer in the St Marys area using raw (uncorrected) data, estimated using the Theis[1] curve-matching method
[ft^2/d; feet squared per day]

Well number	Local name	Transmissivity (ft^2/d)	Storage coefficient
33D069	National Park Service	101,000	1.6×10^{-3}
33E007	Huntley Jiffey (Davis)	79,000	1.9×10^{-3}
33E027	U.S. Navy Kings Bay TW1	135,000	1.1×10^{-3}
	Geometric Mean	**103,000**	$\mathbf{1.5 \times 10^{-3}}$

[1]Theis (1935)

A second Theis analysis was performed after the raw recovery data were corrected for effects of tides and other nearby pumping wells (figs. 22-25). These corrected data provide a much better fit to the Theis curve than do the raw data and were used to estimate the transmissivity and storage coefficient for the Upper Floridan aquifer in the St Marys area (table 5). Transmissivity computed by using the corrected data is higher than estimates computed by using the raw data, and range from 98,000 to 170,000 ft^2/d, and has a geometric mean of 120,000 ft^2/d. Overall, estimates of transmissivity using the corrected data are more than four times higher than previously reported values (21,000 to 43,000 ft^2/d). Storage coefficient using the corrected data is similar to estimates computed using the raw data, and range from 9.9×10^{-4} to 2.4×10^{-3} and has a geometric mean of 1.5×10^{-3}.

Table 5. Hydraulic properties of the Upper Floridan aquifer in the St Marys area using data corrected for tidal influences, estimated using the Theis[1] curve-matching method
[ft^2/d, feet squared per day]

Well number	Well name	Transmissivity (ft^2/d)	Storage coefficient
33D069	National Park Service CI	110,000	1.4×10^{-3}
33E007	Huntley Jiffey (Davis)	98,000	1.7×10^{-3}
33E027	U.S. Navy Kings Bay TW1	130,000	9.9×10^{-4}
33DN20	unnamed well in Florida	170,000	2.4×10^{-3}
	Geometric Mean	**120,000**	$\mathbf{1.5 \times 10^{-3}}$

[1]Theis (1935).

The Jacob distance-recovery analysis (1950) was conducted using raw data from four observation wells. Estimated transmissivity is 130,000 ft^2/d and estimated storage coefficient is 1.3×10^{-3}. These values are in good agreement with the respective geometric means of 120,000 ft^2/d and 1.5×10^{-3}, calculated using corrected data using the Theis (1935) curve-matching method.

Estimates of the anisotropic components of transmissivity tensor and of aquifer storage coefficient were obtained by applying the computer model TENSOR2D (Maslia and Randolph, 1986) to match-point data derived from the Theis analysis of corrected water-level recovery in the four observation wells of the St Marys area test. Computed values of directional diffusivity were fitted to an ellipse having an angle of anisotropy of 64 degrees (measured counterclockwise from due east (fig. 26)) and anisotropy ratio of 2.5:1.

The maximum value of transmissivity, which is in the direction of the major axis of the transmissivity ellipse, approximately north-northeast, is 180,000 ft^2/d. The minimum value of transmissivity, which is the direction of the minor axis of the transmissivity ellipse and perpendicular to the major axis, is 72,000 ft^2/d. The ratio of the major axis to the minor axis is 1.2:1. Geometric mean of the principal transmissivity is 110,000 ft^2/d, which is in good agreement with the geometric mean obtained from Theis analysis of the corrected data (120,000 ft^2/d). Storage coefficient is 1.5×10^{-3}, which is the same as the geometric mean obtained from the Theis analysis of the corrected data.

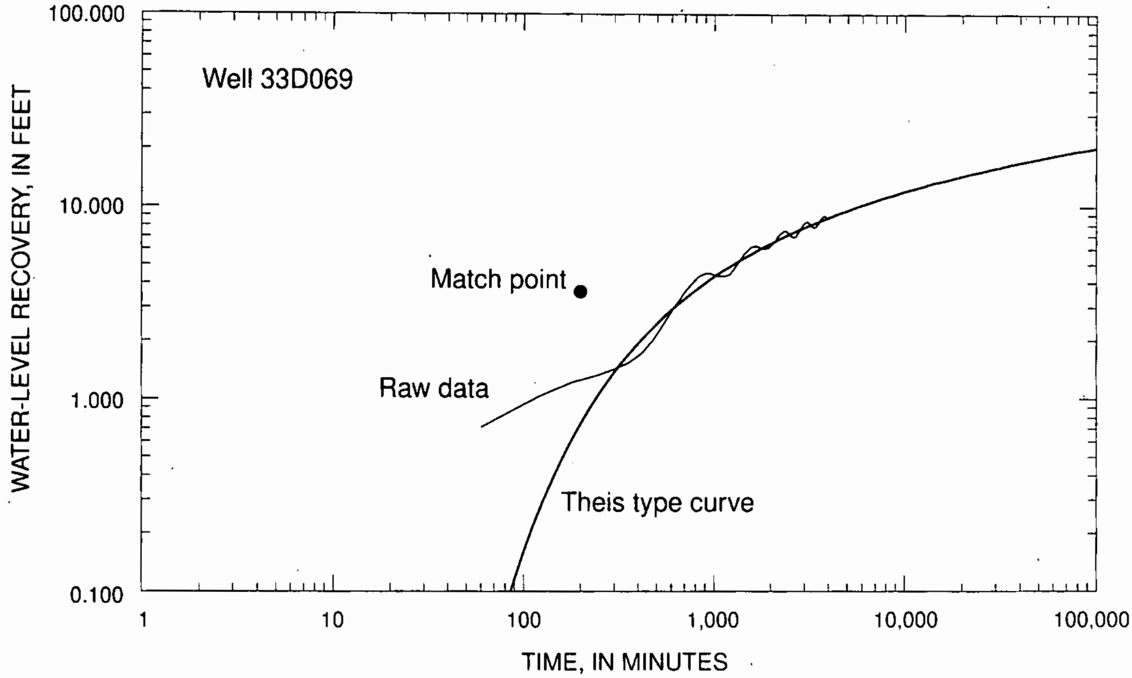


Figure 18. Log-log plot of raw (uncorrected) time-recovery data for well 33D069, April 22–24, 1997 (location of well shown in fig. 13).

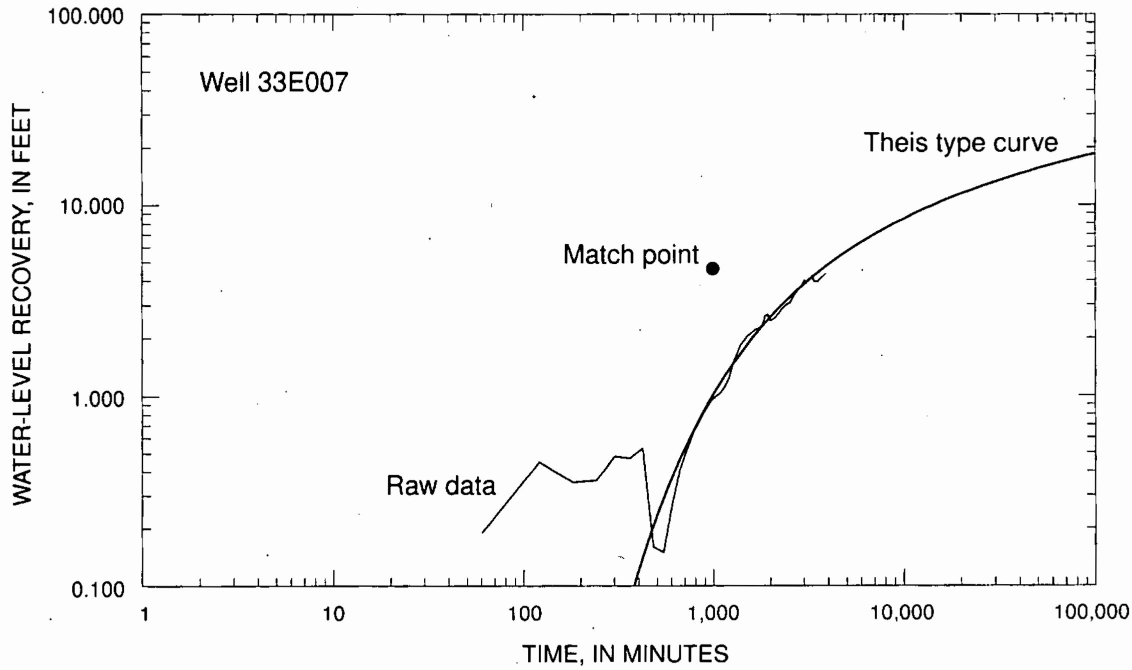


Figure 19. Log-log plot of raw (uncorrected) time-recovery data for well 33E007, April 22–24, 1997 (location of well shown in fig. 13).

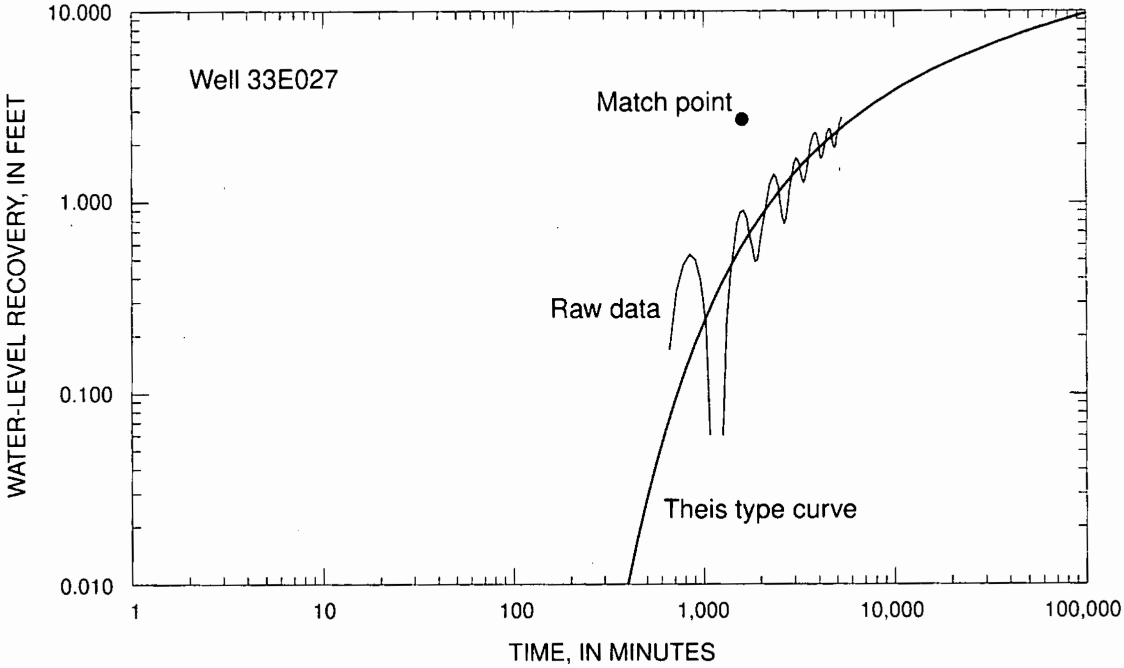


Figure 20. Log-log plot of raw (uncorrected) time-recovery data for well 33E027, April 22–24, 1997 (location of well shown in fig. 13).

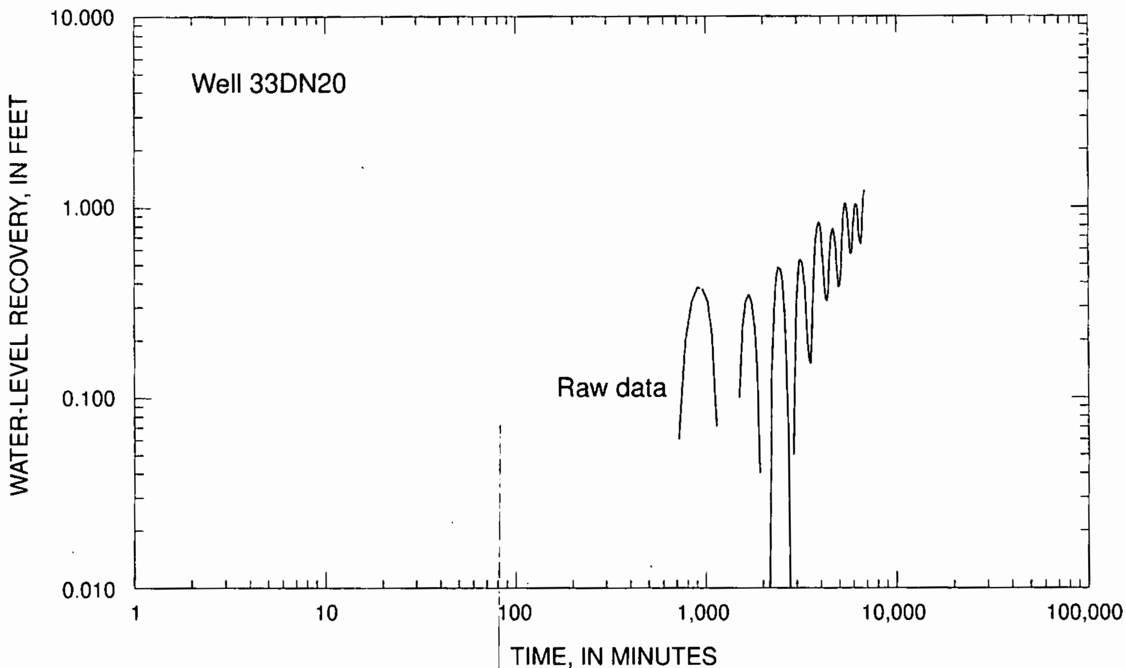


Figure 21. Log-log plot of raw (uncorrected) time-recovery data for well 33DN20, April 22–24, 1997 (location of well shown in fig. 13).

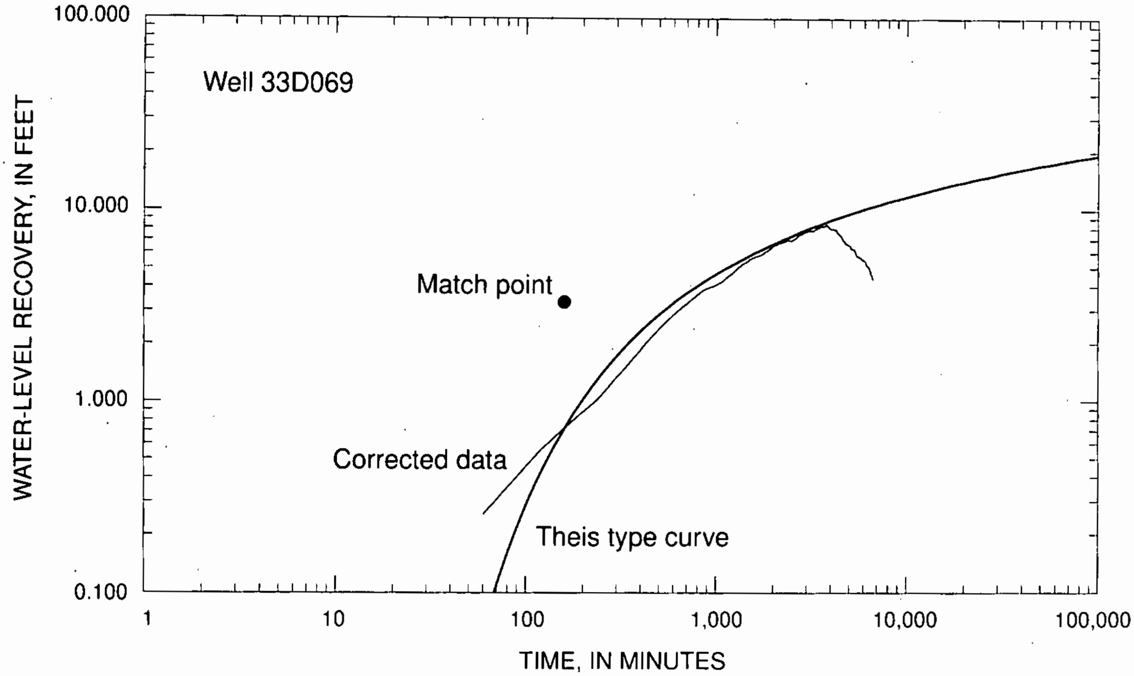


Figure 22. Log-log plot of corrected time-recovery data for well 33D069, April 22–24, 1997 (location of well shown in fig. 13).

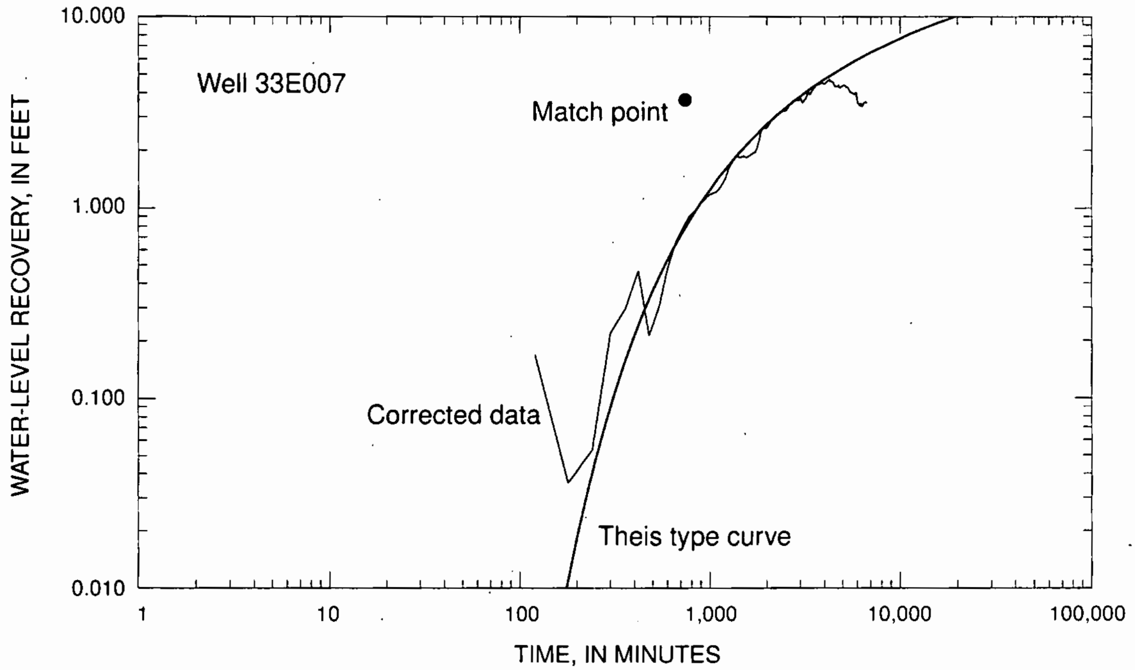


Figure 23. Log-log plot of corrected time-recovery data for well 33E007, April 22–24, 1997 (location of well shown in fig. 13).

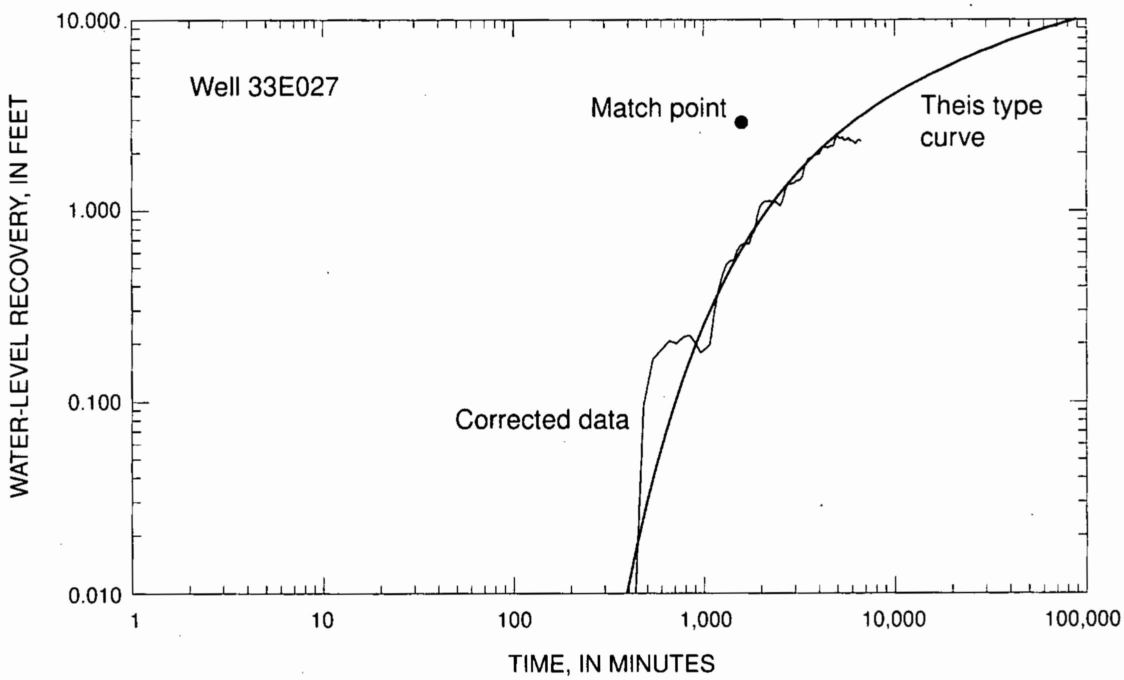


Figure 24. Log-log plot of corrected time-recovery data for well 33E027, April 22–24, 1997 (location of well shown in fig. 13).

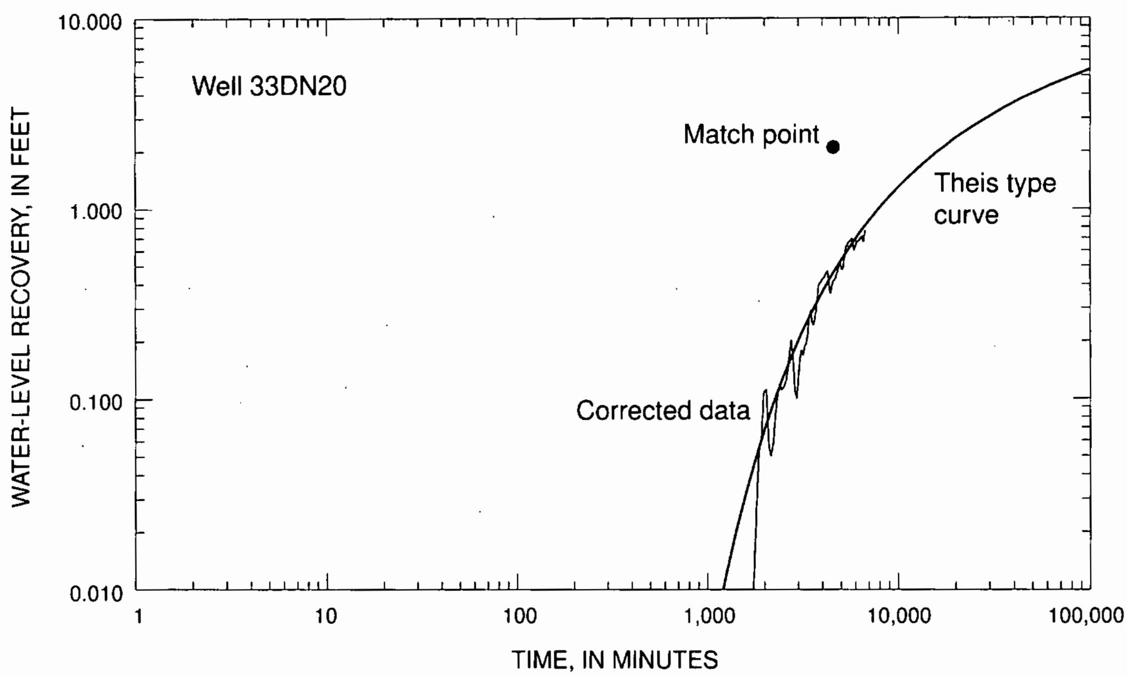


Figure 25. Log-log plot of corrected time-recovery data for well 33DN20, April 22–24, 1997 (location of well shown in fig.13).

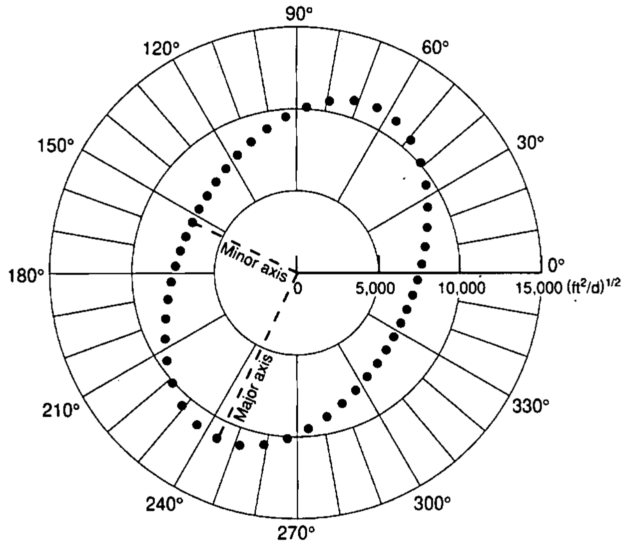


Figure 26. Diffusivity ellipse from TENSOR2D (Maslia and Randolph, 1986) analysis using corrected data from wells 33D069, 33E007, 33E027, 33DN20.

Comparison of Aquifer-Test Results

Analysis of the two aquifer tests suggests that the Upper Floridan aquifer in the St Marys area is approximately three times more transmissive than in the Savannah area, and that the storage coefficient in the St Marys area is about one order of magnitude higher than in the Savannah area. The transmissivity tensor analysis at each site suggests that the Upper Floridan aquifer is nearly isotropic in the Savannah area (anisotropy ratio of 1.2:1), but is anisotropic in the St Marys area (anisotropy ratio of 2.5:1). The direction of the major axis of the transmissivity ellipse, which is the direction of the maximum value of transmissivity, is approximately north-northwest in the Savannah area but north-northeast in the St Marys area. The direction of the major axis is shifted 44 degrees between the two areas.

SUMMARY

As part of a cooperative study to evaluate ground-water resources of coastal Georgia, the U.S. Geological Survey in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey conducted water-level-recovery tests in the Upper Floridan aquifer in the Savannah (Chatham County) area during July 13-22, 1996, and in the St Marys (Camden County) area during April 22-24, 1997. Water-level data were analyzed for aquifer transmissivity and storage coefficient by using the Theis curve-matching method. Tidal corrections were applied to data from one observation well located in the Savannah area and to data from all four observation wells in the St Marys area. Data from one well (33E007) in the St Marys area test also were corrected for nearby pumping effects.

Analysis of water-level recovery data from the Upper Floridan aquifer in the Savannah area indicates that transmissivity ranges from 32,000 to 43,000 ft^2/d, and has a geometric mean of 36,000 ft^2/d; these values are in good agreement with those previously reported. The storage coefficient determined from the Savannah test ranges from 6.3×10^{-4} to 1.3×10^{-3} and has a geometric mean of 7.9×10^{-4}.

The St Marys area aquifer-test analysis indicates that the transmissivity ranges from 98,000 to 170,000 ft^2/d, and has a geometric mean of 120,000 ft^2/d; these values are about four times higher than previously reported values. The storage coefficient determined from the St Marys test ranges from 9.9×10^{-4} to 2.4×10^{-3}, and has a geometric mean of 1.5×10^{-3}.

The water-level recovery tests in the Savannah and St Marys areas suggest that the Upper Floridan aquifer in the St Marys area is almost three times more transmissive than in the Savannah area, and that the storage coefficient in the St Marys area is about one order of magnitude higher than in the Savannah area. Tensor analyses suggest that the Upper Floridan aquifer is nearly isotropic in the Savannah area; in the St Marys area, the aquifer exhibits anisotropy at a ratio of 2.5 to 1, and the larger principal value is oriented north-northeast.

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APPENDIX —TECHNIQUE FOR REMOVING EFFECTS OF TIDES AND PUMPAGE FROM GROUND-WATER LEVELS MEASURED DURING AN AQUIFER-RECOVERY TEST AT ST MARYS, GEORGIA

INTRODUCTION

Observation wells used in an aquifer recovery test conducted at St Marys, Ga., in April 1997, were sensitive to tidal fluctuations and pumping. Sensitivity of ground-water levels to tidal fluctuations and pumping resulted in recovery-test data that were difficult to analyze by using the Theis curve-matching method (Theis, 1935). A regression technique described herein corrected the water-level data by effectively filtering out tidal and pumping influences, thus making estimation of aquifer hydraulic properties using the Theis curve-matching method less ambiguous than estimates obtained by using the uncorrected (raw) water-level data. In fact, raw water-level data from one observation well—33DN20— were impossible to match to the Theis curve; however, a match was obtained with the corrected data.

Tidal Data

Tidal-level data in the vicinity of the observation wells were obtained from data collected under the National Water Level Observation Program, operated by the Oceanic Products and Services Division of the National Ocean Service, which is part of the National Oceanic and Atmospheric Administration (NOAA). Data were downloaded from the NOAA world wide web site (http://www.opsd.nos.noaa.gov) on November 4, 1998.

Continuous tidal data were obtained at 6-minute intervals from the nearest tidal reference station to the recovery test, that is, at Fernandina Beach, Amelia River, Fla., (NOAA tidal reference station 8720030, fig. 13). Tides at the reference station were recorded in feet, using a tidal datum of Mean Lower Low Water (MLLW) and have been verified by NOAA for accuracy. Because the nearest tidal reference station is approximately 7 mi from the recovery test conducted at St Marys, Ga., tidal data were adjusted for differences in the timing and height of the tides between the Fernandina Beach tidal reference station and the tidal station at St Marys on the St Marys River, which does not have continuous tidal data available. Differences in the timing and height of the tides were determined by NOAA by comparing historical data between the two stations.

Tidal adjustments between the reference station and the tidal station at St Marys differ at low and high tides. Adjustments for the timing of tides are +45 minutes at low tide and +38 minutes at high tide; that is, low and high tides occur later at St Marys than at Fernandina Beach. To adjust for the height of the tides, the observed tidal heights are multiplied by 1.05 at low tide and by 0.98 at high tide. Because tidal adjustments are available only for high and low tides, estimates of tidal adjustments were required for the times during the recovery test when water levels were recorded (1-hour intervals). A sinusoidal function, rather than a linear function, was used to represent the tidal adjustments for the period between high and low tides. A sinusoidal function in phase with tidal data better simulates how tidal corrections change through time than a linear tidal adjustment. The effect of using a sinusoidal function rather than a linear function to estimate tidal corrections on the water-level recovery data is probably small because the variation in tidal adjustments is relatively small with respect to the overall variation in tides.

Regression Technique for Removing Tidal and Pumping Effects

A regression technique was used to remove tidal effects from the aquifer-test data. The first step was to determine the fluctuation in ground-water levels in the observation wells caused solely by the tides during the period not affected by the recovery test. Water-level data for the period before the recovery test were used for this purpose, from April 1, 1997 through the beginning of April 22, 1997. All four observation wells—33D069, 33E07, 33E027, and 33DN20—had declining water levels during this period. Two likely causes for the declines are pumpage exceeding recharge and seasonal declines in regional recharge to the aquifer. Removing the decreasing temporal trends in water levels in the observation wells prior to the recovery was important because these trends could result in model parameter mis-specification when performing the regression.

Water-level declines observed prior to the recovery test exhibited a nonlinear temporal trend that varied by well. Water-level declines were represented as polynomial functions in time. A third-order polynomial was sufficient to remove the decreasing temporal trend in water-level data for three of the four wells. The fourth well—33E027—had a more complex water-level decline than did the other three and required a fifth-order polynomial to remove the temporal trend. Water-level data were detrended by calculating the residuals to the models, that is, differences between actual water levels and water levels predicted from each polynomial model.

The remaining variation in the detrended water-level data was assumed to be caused by tidal fluctuations, and in one case, nearby pumping. For the observation wells that were influenced only by tides, a linear regression was used to model the remaining variation in ground-water level as a function of the adjusted tidal data for the tidal station at St Marys. Thus, it was assumed that there is a linear relation between tides and ground-water level. For observation well 33E007, a daily cycle of water-level fluctuation was more dominant than water-level fluctuation caused by tides, likely a result of pumping from a nearby well. Pumping may have been from well 33D056, a large (15-in. diameter) industrial well located about 2,000 ft from well 33E007. To account for both pumping and tidal influences, the detrended data were modeled by using a multiple linear regression, which was a function of both adjusted tidal data and pumpage. Because pumpage data from the nearby well were not available, the influence of pumping on water-level data was estimated by using a sinusoidal function having a daily period and an appropriate phase shift that was consistent with water-level fluctuation. For some of the observation wells, a time lag existed between tidal fluctuations and the response of ground-water levels. The appropriate time lag for each observation well was determined by changing the times of the adjusted tidal data used in the regression model at 10-minute intervals and choosing the time lag that maximized the coefficient of determination (R^2) of the model. The coefficient of determination, R^2 (Draper and Smith, 1981), gives a measure of the usefulness of the linear regression model to represent the tidal and pumping effects that were observed in the ground-water levels during the recovery test. It is the square of the correlation between the variation in observed ground-water levels that is attributed to tidal and pumping effects and the model-generated representation of those effects. Values of R^2 range from zero, for a model that is uncorrelated with the effects it was designed to represent, to unity (1.0), for a perfect correlation of the effects by the model. The regression model was designed to represent only the cyclic variations in ground-water level that were assumed to be attributed to tides and pumping; variations caused by natural ground-water recession have been removed previously by detrending the data.

Tidal efficiency describes the proportional effects of tidal variations on ground-water levels and is defined as the fractional change in ground-water levels as a result of the change in tidal levels (Erskine, 1991). Tidal efficiency typically is calculated as the ratio between the standard deviation of ground-water-level data and the standard deviation of tidal-level data (Erskine, 1991). For the regression technique, the tidal efficiency is equivalent to the coefficient of the tidal term in the regression model.

Coefficients from the second regression model were used to predict the effects of tides on ground-water levels during the recovery test. For this period, the predicted values were subtracted from the actual water levels in the observation wells to remove tidal effects. Note that water-level data collected from the observation wells during the recovery test were not detrended by using the polynomial relations that were developed for the declining water levels during the period prior to the recovery test for two reasons: (1) polynomial functions can be used only to predict water levels that exist within the time period—predictions outside of this time period would be highly inaccurate; and (2) declining water levels that occurred before the recovery test may have been caused by the pumped wells that were used in the recovery test itself; and therefore, the declining trend would not be present during the recovery test.

RESULTS AND DISCUSSION

The regression technique presented here adequately removed the variation in observed ground-water levels caused by tidal effects, and in one case, removed an unexplained daily cycle of ground-water-level fluctuation. Estimation of hydraulic properties by using the Theis method with the corrected water-level recovery data (figs. 22-25) was less ambiguous than similar determinations using the uncorrected data (figs. 18-21). The effects of tides on ground-water levels in well 33DN20 made matching the raw water-level-recovery data to the Theis type curve impossible. However, the regression technique effectively removed variations in the water-level-recovery data that were assumed to be caused by tides, enabling the corrected data to be matched with the Theis type curve. Hydraulic properties determined from individual observation wells varied by as much as 20 percent for transmissivity and 18 percent for the storage coefficient between raw and corrected data (tables 4, 5).

Time lags between tidal fluctuations and corresponding changes in ground-water levels generally were consistent with distance of the well from the source of tidal fluctuations (table A1, fig. 13). Water levels in wells near rivers and bays exhibited short time lags; whereas water levels in inland wells had longer time lags because of the longer distance through which the tidal signal travels in the aquifer. Wells 33D069 and 33E027, located near the St Marys River and Kings Bay, did not have time lags; whereas, well 33E007 located far from both the river and bay had a time lag of 100 minutes. Water levels in well 33DN20 were inconsistent with the lag-distance relation, exhibiting a lag of 80 minutes, despite the well's close proximity to Lanceford Creek.

Tidal efficiencies, as determined by the regression approach, range from 0.03 to 0.13 for the observation wells (table A1). Wells 33D069, 33E027, and 33DN20 are located short distances from the tidal influences of rivers or bays and showed higher tidal efficiencies (ranging from 0.082 to 0.13) than well 33E007 (0.03), which is located farther away from rivers and bays.

After removing the variation due to ground-water recession, much of the remaining variation in water levels in the three observation wells located near rivers or bays (33D069, 33E027, and 33DN20) were explained by tidal fluctuations (R^2 of 0.74 to 0.84; table A1). Data from the more inland well (33E007) had a lower R^2 (0.59); however, this well was influenced by a large daily cycle that exerted more control on the water-level variation than the tidal influence. This lower R^2 may indicate that the model that predicted daily variations may not be well posed rather than indicate inaccuracy in predicting tidal variation. Even with the low R^2, a large portion of the variation was predicted and removed from the water-level recovery data for this well to allow an improved match of the corrected data with the Theis type curve.

The regression method was a more appropriate approach than other statistical methods for removing tidal influences on ground-water levels for this data analysis. Other methods—Erskine (1991), for example—compare the standard deviation of the ground-water-level data to tidal-level data to determine a tidal efficiency. The standard-deviation method determines tidal efficiency indirectly by assuming that all the variation in ground-water level is the result of changes in tidal levels. In contrast, the regression method is a direct approach for relating tidal fluctuations to ground-water levels through time (tidal efficiency). For method comparison, tidal efficiency was calculated by both methods (table A-1). The standard-deviation method required that the ground-water-level data be detrended because the declining trend in water levels before the recovery test would increase the standard deviation of the ground-water levels; thereby overstating the tidal efficiency. The standard-deviation method resulted in higher values calculated for tidal efficiency (9 to 16 percent higher) which would result in an overcorrection of ground-water levels for tidal fluctuations. Because most of the variation in well 33E007 was the result of unexplained daily fluctuation, the tidal efficiency of this well could not be determined using the standard-deviation method. Regardless of which method is used for determining tidal efficiency, a regression approach still was necessary for determining the time lag for tidal induced ground-water-level fluctuations. Furthermore, the regression method can be expanded to filter out other factors that affect ground-water levels, such as the daily cycle appearing in well 33E007.

Table A-1. Observation wells used in the St Marys area aquifer-recovery test, tidal-time lags, tidal efficiencies, and coefficient of determination of regression models

Well number	Time lag (minutes)	Tidal efficiency (fraction, as determined from regression)	Tidal efficiency (fraction, as determined from standard deviations)	Coefficient of determination (R^2) of regression model (adjusted, after detrending)
33D069	0	0.13	0.15	0.74
[1]33E007	100	0.034	not applicable	0.59
33E027	0	0.11	0.13	0.74
33DN20	80	0.082	0.089	0.84

[1]The model used a multiple regression with daily sinusoidal variation, which had an amplitude of one foot and an efficiency of 0.28.

The method did not filter out all short-term signals observed in the observation-well data (figs. 22-25). Some of the remaining signal could be a result of daily variations in the tides between the tidal reference station and the observation wells. This is a plausible explanation because the tidal data are adjusted from a reference station using a long-term correction to give the tidal fluctuation near the wells. Also, the method did not account for ground-water withdrawal (pumpage) from other wells in the study area. Because the aquifer is at a depth of about 500 ft below land surface, precipitation should not cause significant short-term fluctuations in water levels. A potential problem with the technique is that the influence of tides may be different during the recovery phase than during the pumped phase. The range in ground-water levels in observation wells is similar during the recovery test and in the period prior to the recovery test when the regression modeling was applied. Despite the unknown causes for all water-level variations, the regression technique effectively removed a sufficient amount of the short-term variation in observed water levels that was assumed to be related to tides and nearby pumpage. Filtering out tidal effects and cyclical pumpage variations from the water levels with this technique allowed corrected time-recovery curves to have a shape similar to the Theis curve, creating a more consistent match to the theis curve than the raw data.

Cost: $875.00
Quantity: 100