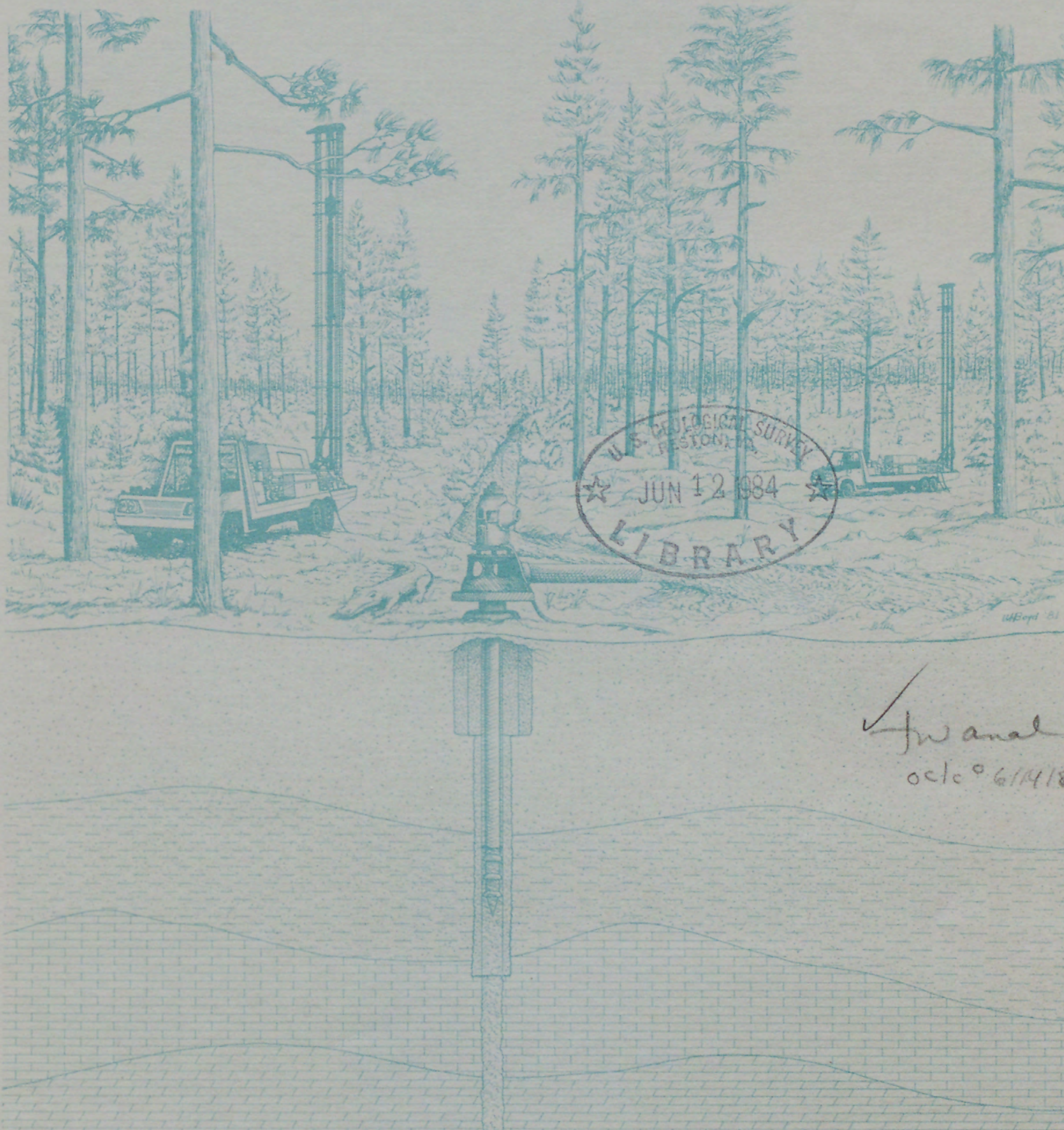
HYDROGEOLOGIC DATA FROM THE U.S. GEOLOGICAL SURVEY TEST WELLS NEAR WAYCROSS, WARE COUNTY, GEORGIA



U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS REPORT 83-4204

HYDROGEOLOGIC DATA FROM THE U.S. GEOLOGICAL SURVEY TEST WELLS NEAR WAYCROSS, WARE COUNTY, GEORGIA

By Sharon E. Matthews and Richard E. Krause

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4204

Doraville, Georgia

1984

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[Plates are in pocket]

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CONVERSION FACTORS

For use of those readers who may prefer to use SI (metric) units rather than inch-pound units, conversion factors for terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain SI (metric) unit
	Length	
inch (in.)	25.40	millimeter (mm)
inch squared (in.^{2})	6.452	centimeter squared (cm^2)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	3.785×10^{-3}	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
	43.81	liters per second (L/s)
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon per day per foot [(gal/d)/ft]	0.0124	meter squared per day (m^2/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Specific capacity	
gallon per minute per foot of drawdown [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
	Temperature	
°F = 9/5(°C) + 32		°C = 5/9(°F - 32)

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."

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ABSTRACT

Two wells were constructed near Waycross, Ware County, Georgia, from July 1980 to May 1981 to collect stratigraphic, structural, geophysical, hydrologic, hydraulic, and geochemical information for the U.S. Geological Survey Tertiary Limestone Regional Aquifer System Analysis. Data collection included geologic samples and cores, borehole geophysical logs, packer tests, water-level measurements, water-quality samples, and aquifer tests.

In the study area, the Tertiary limestone aquifer system is about 1,300 feet thick and is confined and overlain by about 600 feet of clastic sediments. The aquifer system consists of limestone, dolomite, and minor evaporites and has high porosity and permeability. A 4-day constant-discharge aquifer test was conducted, from which a transmissivity of about 1×10^6 feet squared per day and a storage coefficient of 1×10^{-4} were calculated. Water from the upper part of the aquifer is a calcium bicarbonate type. The deeper highly mineralized zone produces a sodium bicarbonate type water in which concentrations of magnesium, sulfate, chloride, sodium, and some trace metals increase with depth.

INTRODUCTION

The U.S. Geological Survey is conducting a Regional Aquifer System Analysis of the Tertiary limestone aquifer system in the Southeastern States. The study's overall objectives are as follows: (1) to describe the hydrogeologic framework and geochemistry of the limestone aquifer system, (2) to define the regional flow system, chiefly by computer simulation, and (3) to assess the effects of large withdrawals of ground water or the injection of waste into the aquifer (Johnston, 1978). A major thrust of the study is to gather data in areas where data are lacking and where other programs are unlikely to fill those data gaps.

Before 1980, the Waycross area, Ware County, in the southeastern part of the Coastal Plain of Georgia, represented a major data void with respect to the hydrogeologic framework, ground-water flow system, head relations, and water quality of the Tertiary limestone aquifer system of the Southeastern United States. The purpose of this study was to fill the data void with a drilling and testing program designed to yield a maximum of stratigraphic, structural, geophysical, hydrologic, hydraulic, and water-quality information. The intent of this report is to present the findings of that drilling and testing program.

The Waycross area is in a hydrogeologic transition zone between Brunswick (Glynn Co.), where very permeable zones exist in the lower part of the aquifer, and the Valdosta area (Lowndes Co.), where dense, impermeable dolomite and evaporites are dominant at depth. Except for a driller's log of an oil-test well drilled in 1915, about 6 1/2 mi southwest of the study area, no data existed prior to this study describing the lithology, stratigraphy, hydrology, and geochemistry of the section below the upper permeable zone of the Tertiary limestone aquifer system in the Waycross area.

Approach and Methods

During the period July 1980 to May 1981, two test wells were drilled approximately 9 mi southeast of Waycross in the Dixon Memorial State Forest (fig. 1). Test well 1 (TW 1) was used as the production or pumping well during aquifer tests, and test well 2 (TW 2) was used as an observation well. Both wells were drilled by the standard mud-rotary method to the top of the Tertiary limestone aquifer, and were cased and grouted into the top of that aquifer at a depth of 635 ft in TW 1 and 636 ft in TW 2 (fig. 2). Test well 1 was cased with 14-inch casing and test well 2 was cased with 12-inch casing. The wells were then deepened by the reverse-air rotary method to a depth of 1,970 ft in TW 1 and 1,966 ft in TW 2. The wells, each 9-7/8 inches in diameter, were completed as open holes completely through the limestone aquifer.

Drill cuttings were collected from both wells at about 10-foot intervals or at noticeable changes in lithology. Ten cores totaling 112 ft were taken by the conventional coring technique from selected intervals in TW 2, with an average core recovery of 74 percent. The cores were analyzed for lithology, paleontology, and hydraulic characteristics such as porosity, and vertical and horizontal permeability (table 1).

Geophysical logs were made in the wells at various stages of construction to determine the density, resistivity, porosity, and other characteristics of the water-bearing rocks (plates 1-3).

In May 1981, a zone at the bottom of TW 2 (1,901 to 1,966 ft) containing highly mineralized water was isolated by an inflatable-retrievable packer to measure the head and collect water-quality samples. Subsequent to packer testing, this zone was sealed with cement in both wells, thus reducing the total depth of TW 1 to 1,856 ft and TW 2 to 1,785 ft (fig. 2).

During June 1981, predetermined intervals in the open-hole part of TW 1 were isolated by two inflatable-retrievable packers to measure water levels in and above the packed intervals, and to pump the isolated intervals for water-quality sampling and analyses.

In February 1982, water-quality samples were taken at predetermined depths in the open-hole sections of TW 1 and TW 2. The results of these tests were compared with the results from the 1981 analyses, providing data as to the rate and degree of chemical stabilization of the water in the test wells.

Previous Studies

The Waycross area, Ware County, had previously been studied only as a part of general investigations of the Coastal Plain of Georgia and Florida. McCallie (1898; 1908) included one well in Ware County in a discussion of the artesian water of the Coastal Plain of Georgia.

Stephenson and Veatch (1915) included the area in a broad areal study of the geology and ground-water resources of the Coastal Plain of Georgia. Water-quality information is included in sections of that report by Dole.

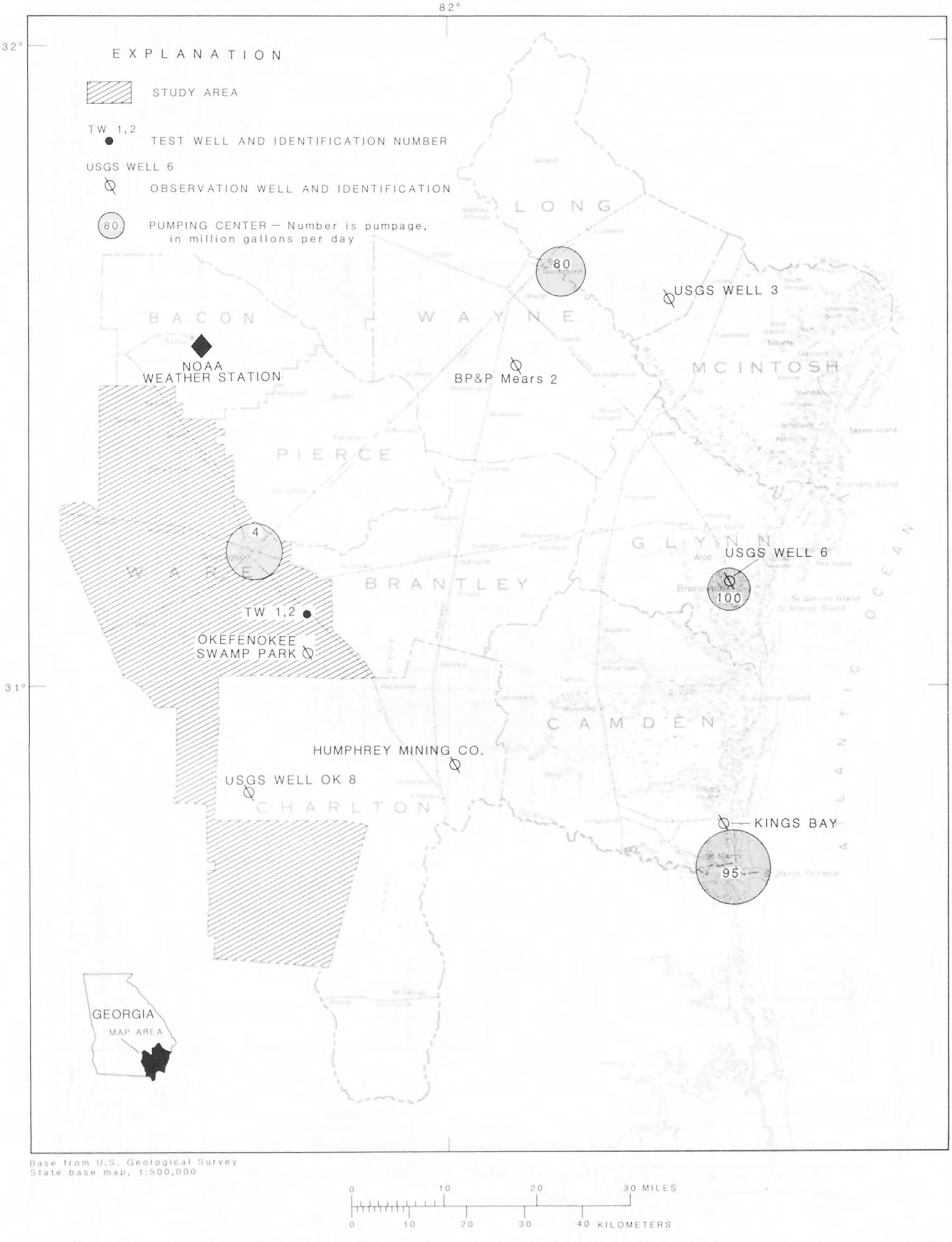

Figure 1.— Location of the study area, test wells, regional network of observation wells, and pumping centers.

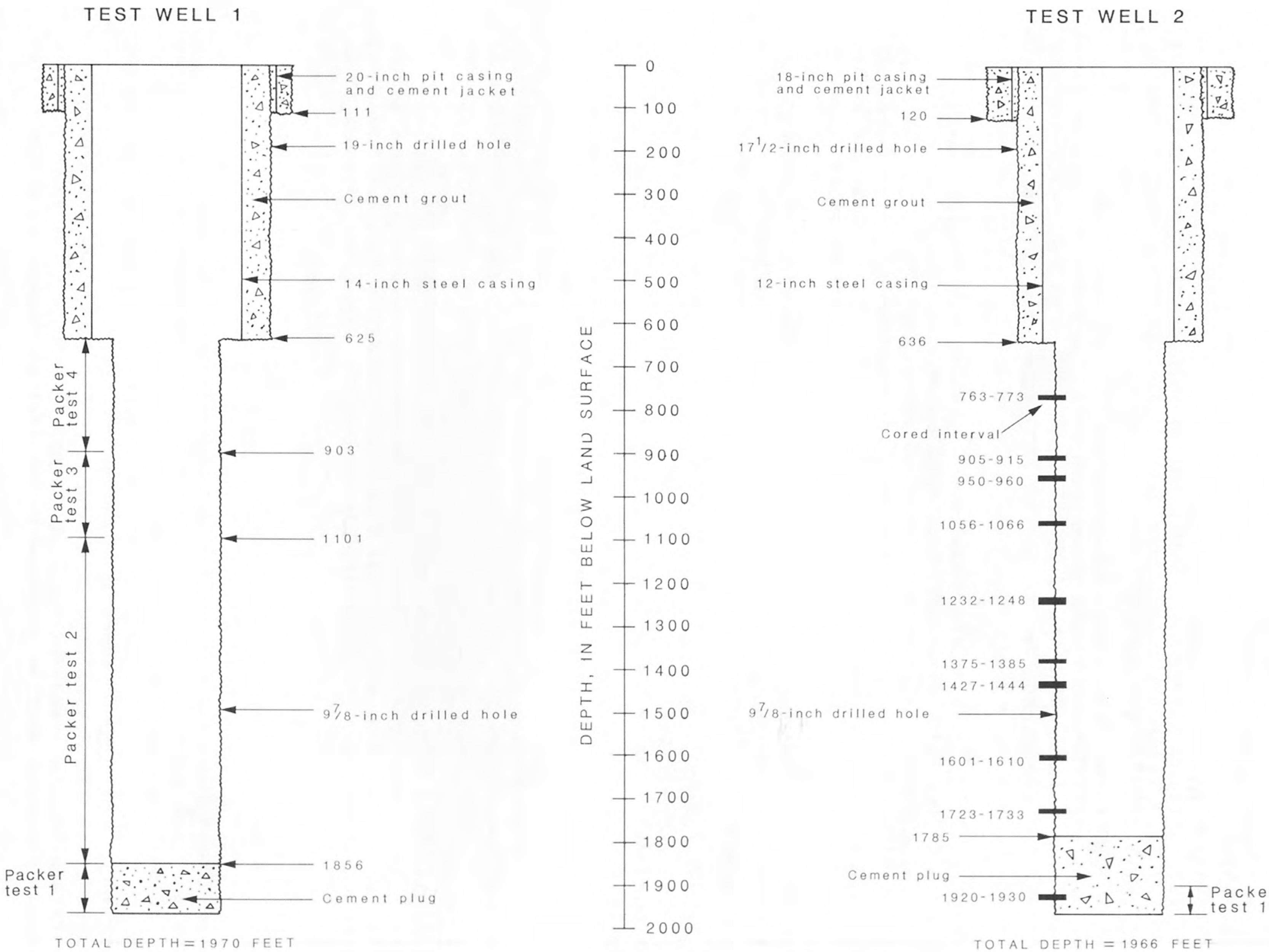

Figure 2.— Schematic diagram of the construction of test well 1 and test well 2.

Table 1.—Hydrogeologic and hydraulic characteristics of cores of test well 2

[Analyses by Core Laboratories, Inc., Tyler, Texas. Partial full diameter whole-core analyses except as indicated]

Core number	Date	Cored interval (feet below land surface)	Cored length (feet)	Recovery		Core time (mins)	Stratigraphic unit	Lithologic description	Hydraulic conductivity (ft/d for water at 60°F)				Fracture type	Porosity (percent)	Measured grain density (g/cm^3)	Bulk density (g/cm^3)
				(feet)	(percent)				Interval (feet below land surface)	Horizontal (maximum)	Horizontal (90° to maximum)	Vertical				
1	01-27-81	763-773	10	8	80	15	Ocala Limestone	Limestone, white, highly fossiliferous, highly permeable, porosity largely vuggy.	-	-	-	-	-	-	-	-
2	02-05-81	905-915	10	8.7	87	65	Avon Park and Lake City Limestones	Dolomite, dark-brown with dark-gray mottling, very-fine crystalline, hard, massive, tight. Unconnected vuggy porosity. Some fracturing.	912-913	2.4	0.044	7.3×10^{-5}	(1)	5.5	2.81	2.71
3	02-12-81	950-960	10	8.7	87	26	Avon Park and Lake City Limestones	Dolomite, light-brown with 15-20 percent fine to medium vuggy porosity as a result of selective solution of macrofossils.	954-955	6.6×10^{-4}	4.6×10^{-4}	2.4×10^{-5}	-	8.6	2.68	2.54
4	02-19-81	1,056-1,066	10	7.0	70	64	Avon Park and Lake City Limestones	Dolomite, microcrystalline, dark-brown to dark-gray, hard, dense, massive. Very little vuggy porosity. Some fracturing.	1,060-1,061	1.7×10^{-3}	1.2×10^{-4}	6.1×10^{-3}	(2)	4.1	2.86	2.78
5	03-03-81 03-04-81	1,232-1,240 1,240-1,248	8 8	3.11 4.2	39 53	10 10	Avon Park and Lake City Limestones	Limestone, off-white, chalky, highly fossiliferous, consists of 70 percent microfossils in a 30 percent micrite matrix. High porosity.	1,244-1,245	-	4.8	2.6	(3)	-	2.68	2.25
6	03-12-81	1,375-1,385	10	8.4	84	67	Avon Park and Lake City Limestones	Limestone, mottled white to gray, 60 percent weathered fossils and micritic limestone in 40 percent dark-gray glauconitic matrix. Gradational downward into dolomitic limestone, then into dark-brown vuggy dolomite with anhydrite. Low porosity.	-	-	-	-	-	-	-	-
7	03-18-81 03-18-81	1,427-1,438 1,438-1,444	11 6	4 4.3	36 72	15 32	Avon Park and Lake City Limestones	Limestone, white, soft, highly fossiliferous, about 15 percent porosity, gradational into dark-brown mottled dolomite having many anhydrite inclusions. Some fracturing.	1,443-1,444	4.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	-	10.9	2.83	2.63
8	03-31-81	1,601-1,610	9	8.7	97	68	Avon Park and Lake City Limestones	Limestone, light-gray, medium hard, consists of 60 percent microfossil material in a 40 percent chalky, hard to soft limestone matrix. Trace of vuggy porosity.	1,604-1,605	.51	.046	2.1×10^{-3}	-	17.7	2.75	2.44
9	04-09-81	1,723-1,733	10	8.8	88	66	Avon Park and Lake City Limestones	Limestone, light-gray, consists of 45 percent microfossils in 55 percent micritic limestone matrix. Inclusions of anhydrite.	1,729-1,730	.073	.073	.0244	-	26.8	2.79	2.31
10	04-22-81	1,920-1,930	10	10	100	72	Oldsmar Limestone	Limestone, cream, fossiliferous, coarsely pelletal, glauconitic, low porosity. Gradational downward into an argillaceous limestone with prominant glauconite.	1,926-1,927	2.6×10^{-3}	2.0×10^{-3}	.22	-	22.6	2.72	2.33
TOTALS			112	83.9	74											

1 Conventional plug analysis.
2 Vertical fracture permeability.
3 Horizontal fracture permeability.

This work and that of McCallie, although giving interesting information on the artesian water system, are outdated and of limited utility. Warren (1944) also included the study area in a report on the artesian water of the Coastal Plain of Georgia.

Herrick (1961) included four wells in the study area in a report listing several lithologic and paleontologic well logs of the Coastal Plain. None of the wells penetrate the entire section of water-bearing limestones of the Tertiary aquifer system.

Herrick and Vorhis (1963) interpreted and used data from Herrick (1961) in their report on the subsurface geology of the Coastal Plain of Georgia. They mapped the stratigraphy (presented as a series of isopach and structure contour maps) and showed geologic sections of formations of Cretaceous through Holocene age, with emphasis on the Tertiary formations.

Stringfield (1966) is the most comprehensive reference on the artesian water from Tertiary limestone in the Southeastern States. The current study area is included in his report on the geology, artesian water, and ground water-surface water relations of the Southeastern States.

Acknowledgments

The writers wish to thank Zack L. Seymour and employees of the Waycross State Forest Branch of the Georgia Forestry Commission for their assistance and logistical support. Acknowledgment is also given Charles Burnett of the Waycross Water Plant and Christine Brown of the Federal Aviation Administration at Alma for supplying data helpful in analyzing the aquifer test. In particular, special thanks are given Rowe Drilling Co. of Tallahassee, Fla., represented by John Morrill and Sam Painter, who constructed the wells and provided data and assistance throughout the drilling and testing.

GEOLOGY

The Coastal Plain sediments underlying the Waycross study area range in age from Cretaceous to Holocene and consist chiefly of alternating units of sand, limestone, and dolomite interbedded with minor amounts of clay, shale, and evaporites (plate 1). Lithologic logs from an oil-test well drilled in 1915, about 6 1/2 mi southwest of the present study area, show that limestone and dolomite units alternate to a depth of about 2,250 ft. Below that, sand containing minor limestone and dolomite becomes the dominant lithology to a depth of 3,022 ft.

Stratigraphy

Lower Eocene

The lower 65 ft of both test wells penetrated the lower Eocene Oldsmar Limestone, which represents the upper part of the Sabinian Stage (table 2). The Oldsmar Limestone consists of off-white to light-gray limestone containing foraminifera suspended in a micritic (microcrystalline limestone) matrix (plate 1). Tan, fine-crystalline dolomite makes up about 15 to 20 percent of the rock. Very fine-grained, dark-green galuconite is visibly prominent and constitutes 5 to 10 percent of most samples.

Table 2.--Generalized stratigraphy of the Waycross study area

Erathem	System	Series		Gulf Coast Stage	Stratigraphic unit	Thickness, in feet TW 1	TW 2
Cenozoic	Quaternary	Pleistocene			Alluvium and terrace deposits, undifferentiated	105	110
	Tertiary	Pliocene(?)					
		Miocene			Hawthorn Formation	504	499
		Oligocene		Vicksburgian	Suwannee Limestone	53	61
		Eocene	Upper	Jacksonian	Ocala Limestone	208	199
			Middle	Claibornian	Avon Park Limestone and Lake City Limestone, undifferentiated	1,032	1,033
			Lower	Sabinian	Oldsmar Limestone	68+	64+

Middle Eocene

In the study area, the middle Eocene Claibornian Stage overlies the Oldsmar Limestone and is about 1,030 ft thick (table 2). The Claibornian includes the Lake City Limestone and the overlying Avon Park Limestone. These stratigraphic units are difficult to differentiate because they both consist of alternating layers of lithologically similar crystalline dolomite and fossiliferous limestone (plate 1). The dolomite is light- to dark-brown mottled, fine to coarse crystalline, dense, generally massive but locally vuggy and recrystallized, and has relatively low porosity. The dolomite contains rare inclusions and stringers of clear to milky gypsum and minor amounts of nearly black, altered glauconite. Carbonaceous shale that smolders and gives off a strong hydrocarbon odor when heated is present as very thin seams within the dolomite in both wells: in TW 1 at about 1,378, 1,398, and 1,754 ft, and in TW 2 at about 1,389 and 1,753 ft. The limestone is offwhite to light gray, micritic, pelletal, chalky, and locally recrystallized. The pellets are composed of large foraminiferal remains. Microfauna, identified by James A. Miller, U.S. Geological Survey, include:

Lepidocyclina sp.
Lepidocyclina gardnerae
Amphistegina lessoni
Pseudorbitolina cubensis
Amphistegina lopeztrigoni
Quinqueloculina sp.
Amphistegina pinarensis cosdeni
Gyroidina nassauensis
Cibicides mississippiensis ocalanus

The latter three species are of Jacksonian age and probably represent contamination from higher levels in the well. The limestone also rarely contains white algal balls and traces of glauconite.

Upper Eocene

The upper Eocene Ocala Limestone in the study area overlies the Avon Park and Lake City Limestones, undifferentiated (table 2). The Ocala is about 205 ft thick and consists of white to cream-colored, pelletal, moderately to highly porous fossiliferous limestone (plate 1). Some of the limestone is a coquina composed of bryozoan fragments, foraminifera, and mollusk shell material in a fine, locally recrystallized matrix. Microfauna, identified by James A. Miller, U.S. Geological Survey, include:

Lepidocyclina sp.
Discocyclina sp.
Echinocythereis okeechobensis
Cibicides mississippiensis ocalanus
Lepidocyclina ocalana
Heterostegina ocalana
Asterocyclina sp.
Sphaerogypsina globula

Oligocene

The Suwannee Limestone of Oligocene age overlies the Ocala Limestone and is about 55 ft thick in the study area (table 2). The Suwannee consists of white, pelletal, recrystallized, fossiliferous limestone (plate 1).

It is composed mainly of broken foraminiferal material and is very porous. Dictyoconus sp. is the most common microfossil in this section, and occurs with molds of gastropods and mollusks.

Miocene

The Hawthorn Formation of Miocene age overlies the Suwannee Limestone and is about 500 ft thick in the study area (table 2). The basal unit of the Hawthorn Formation is buff to dark-brown, coarsely crystalline, highly sandy and phosphatic dolomite that is slightly porous (plate 1). The middle unit of the Hawthorn consists of clear to frosted, subrounded to angular, fine to coarse, well-sorted sand interlayered with cream-colored fossiliferous limestone containing black, well-rounded phosphate nodules. The upper part of the Hawthorn Formation consists of very sticky, cohesive, greenish-blue clay that confines the underlying limestone aquifer.

Pliocene(?) and Pleistocene

The Waycross study area is covered by about 105 ft of unconsolidated sediment, alluvium, and terrace deposits of Pliocene(?) and Pleistocene age (table 2) that consist mainly of clear to light-brown, fine to coarse, subrounded to angular, well-sorted sand (plate 1). Traces of black nodular phosphate are also present in this part of the section.

HYDROGEOLOGY

Water supply for the Waycross area is obtained primarily from the permeable upper part of the Tertiary limestone aquifer system. This prolific ground-water system is called the principal artesian aquifer in Georgia, and the Floridan aquifer in Florida. The aquifer system includes, from oldest to youngest, undifferentiated Lake City and Avon Park Limestones, the Ocala Limestone, and the Suwannee Limestone. The principal artesian aquifer is about 1,300 ft thick in the study area and lies at a depth of about 600 ft below land surface. The aquifer is confined above by low-permeability rocks of the Hawthorn Formation of Miocene age and below by low permeability, saline-water-bearing carbonates of the Oldsmar Limestone of early Eocene age.

The aquifer has excellent water-bearing properties. The most productive part of the aquifer system is the Ocala Limestone, which supplies most of the water used in southeast Georgia. The Ocala Limestone has some primary porosity, but the formation's greatest porosity is secondary in origin. Ground water circulating through the aquifer has dissolved calcium carbonate along joints and bedding planes, thus enlarging primary flow channels, forming large solution cavities, and increasing porosity and permeability. Large cavities penetrated in the limestone during test drilling are examples of this secondary porosity. TW 1 penetrated a 7-foot cavity (754 to 761 ft) and TW 2 passed through a 9-foot opening (807 to 816 ft). Waycross city well 3 penetrated a 39-foot cavity (676 to 715 ft) in the Ocala Limestone.

High porosity and hydraulic conductivity allow the movement of large quantities of ground water in the aquifer. Waycross city wells 1, 2, and 3 were reported to yield 1,750, 2,220, and 3,900 gal/min, respectively (Charles Burnett, Waycross Water Plant, oral commun., June 1981). The specific capacity, an indication of a well's yield capability, was estimated to be 455 (gal/min)/ft. Test pumping Waycross city well 3 at the rate of 5,000 gal/min produced a drawdown of 11 ft.

Although the aquifer in this area exhibits excellent water-bearing properties as indicated by its high permeability, specific capacity, and transmissivity, the hydraulic characteristics of the selected cores from the aquifer shown in table 1 are low. This is because the sample of cored material analyzed is so small that the analysis shows only primary porosity and permeability. In contrast, the excellent water-bearing characteristics of the aquifer as a whole are attributed largely to the development of secondary porosity and permeability.

Water-level measurements made during test drilling indicate that head differences within the Tertiary limestone aquifer in the study area could not be differentiated. Water levels in TW 1 and TW 2 generally remained at about 99 ft below land surface. Deepening the wells to 1,970 and 1,966 ft, respectively, had little effect on the water levels. Immediate rises in the water levels of a few tenths of a foot did, however, follow periods of increased precipitation and were probably the result of loading of the overburden and confining bed or other environmental effects. Long periods of decreased or no precipitation caused declines in water levels of a few tenths of a foot. Water levels in the test wells did not show any response to changes in pumpage in the southeast Georgia area during the short time of observation.

Water levels in individual zones were determined by packer tests in TW 1 and TW 2. In May 1981, the low-permeability zone containing highly mineralized water (Oldsmar Limestone) at the bottom of TW 2 was isolated by an inflatable-retrievable packer set at 1,900 ft and connected to the surface by a 4-inch drop pipe (fig. 2). A 3-inch submersible pump was installed in the drop pipe at a depth of about 270 ft. Pumping steadily lowered the water level from 107.27 ft below land surface to a depth of about 195 ft, producing a drawdown of about 88 ft over a 2-hour period. Correcting for density gives a value of 64.43 ft below land surface for the equivalent freshwater head at 1,970 ft. Discharge ranged from 5 gal/min to less than 1 gal/min for the lower confining zone. Following the test, the zone was sealed off with cement.

In June 1981, predetermined intervals in the open-hole part of TW 1 were isolated by inflatable-retrievable packers in order to measure water levels in and above the packed intervals, and to pump the isolated intervals for water-quality sampling. For the first packer test (test 2, fig. 2), a single packer was set and inflated at 1,101 ft and a 3-inch submersible pump was installed in a 4-inch drop pipe to sample water from the interval 1,101 to 1,856 ft. The static water level in the packed interval was 102.15 ft. Correcting for density, head for this zone was determined to be 101.75 ft. A pumping rate averaging 8 gal/min produced no observable drawdown. For the second packer test (test 3, fig. 2), the packers were set to straddle the interval between 903 and 1,103 ft. The static water level prior to pumping was 101.40 ft and remained unchanged during the test in which the zone was pumped at 8 gal/min. As the water in this interval had a density of 0.998, no correction for density was made. Again, water-quality samples were collected from the isolated interval. The pump was then moved outside the drop pipe (test 4, fig. 2) and water-quality samples were collected from the interval 903 ft to the bottom of casing (635 ft). An oily scum developed on the water surface and prevented accurate water-level measurements of this interval.

In order to determine the relative yield of individual water-bearing zones within the aquifer, a flow-meter traverse was made in TW 1 while pumping the well at 1,900 gal/min. The rate of flow in the well was calculated by converting the revolutions of the flow-meter spinner per 100 seconds to feet per minute. The rate of vertical borehole flow at selected depths was calculated by the equation,

$$Q = 5.88\ d^2v,$$

where

Q is rate of vertical borehole flow in gallons per minute,

d is the diameter of the hole in feet,

and

v is the velocity of the water in feet per minute.

The flow meter was traversed up the hole and held static at 10-foot intervals from 1,100 ft, the deepest part of the well having vertical borehole flow, to the bottom of the casing (635 ft). The hole diameter below the casing was determined from the caliper log, which is a record of the average diameter of the drill hole (plate 2). The increase or decrease in the rate of flow for each interval indicated the quantity of water that entered or left the well within that interval. The flowmeter also was traversed and held stationary inside the cased interval to aid in checking calibration, as both the casing diameter and discharge at the surface were known.

The flow-meter traverse for TW 1 showed that water enters the well at different intervals corresponding to highly permeable zones in the aquifer. The interval between 1,070 and 1,090 ft, the deepest permeable zone in the well, produced 240 gal/min. This interval consists of fine-crystalline, dense dolomite and has low to moderate permeability. The interval from 940 to 970 ft, consisting of porous interbedded dolomite and limestone, yielded 60 gal/min. The interval between about 750 and 900 ft, from the top of the middle Eocene into the upper Eocene Ocala Limestone, produced 500 gal/min. The lithology of this interval ranges from vuggy dolomite of the middle Eocene to fossiliferous limestone of the Ocala. The interval between 635 and 750 ft, which includes the upper Eocene Ocala Limestone and the Oligocene Suwannee Limestone, yielded 1,100 gal/min.

Aquifer-Test Analysis

An aquifer test was conducted June 16-19, 1981, 9 mi southeast of Waycross, Ga., using two recently drilled wells tapping the Tertiary limestone aquifer system. (See fig. 1 for location.) TW 1 was used as the control (pumping) well, and TW 2, 154 ft distant, as an observation well. (See fig. 2 and plate 1 for well construction and lithology.) In addition, water levels from a recently drilled well at the Okefenokee Swamp Park (4.1 mi from TW 1) and an unused well at the Humphrey Mining Co. (23 mi from TW 1), each tapping the Tertiary limestone aquifer system, were used in the aquifer-test analysis. (See fig. 1 for locations.)

The aquifer test involved pumping TW 1 at an uninterrupted, nearly constant rate of 2,040 gal/min for 47 hrs 10 min while measuring drawdown in TW 2. The pumping well was equipped with a 10- by 8-inch orifice for measuring discharge. Each observation well was equipped with a float-actuated continuous water-level monitor that recorded water-level data before, during, and after pumping.

An attempt was made to measure the water level in the pumping well by the wetted-tape and electric-tape methods, but a wet pump column and lubricating oil on the water surface prevented accurate measurements. An air line installed in the well did not have the sensitivity needed to record the small changes in water level.

Barometric pressure and pumpage data were collected to evaluate factors that could have influenced water levels in the observation wells, and thus have affected the aquifer-test analysis. Uncalibrated barometric pressure was recorded on-site with a continuous-recording barograph. Hourly barometric pressure for 17 continuous hours per day was also obtained from a National Oceanic and Atmospheric Administration weather station at Alma, 33 mi north-northeast of the test site. Pumpage data for the city of Waycross supply wells, the only significant discharge in the immediate area, also were obtained. In addition, continuous water-level records from observation wells throughout the area were examined for anomalous fluctuations and trends that would indicate changes in withdrawal rates at the major pumping areas of Brunswick, Jesup, and St. Marys, Ga., and Fernandina Beach, Fla. See figure 1 for pumping centers and withdrawal rates.

Assumptions

The aquifer-test analysis presented here is based on the assumption that the karstic limestone aquifer acts as a porous medium over the area of influence of the test. The most general model, the Theis non-leaky artesian equation, was used to analyze the test data. Note that the Theis equation makes the following assumptions:
(1) the aquifer is horizontal and infinite in areal extent,
(2) the aquifer is confined by less permeable beds above and below,
(3) the aquifer parameters are uniform in space and time,
(4) flow is laminar, and
(5) water is released from storage instantaneously with a decline in head.
In addition, the Theis equation assumes constant discharge from a fully penetrating well of negligible diameter in a nonleaky aquifer, the discharge being derived exclusively from storage in the aquifer.

The application of the Theis equation at the Waycross site is justified for these reasons:
(1) a thick, nearly impermeable clayey confining bed overlies a highly permeable limestone aquifer suggesting non-leaky or nearly non-leaky confined conditions,
(2) head differences within the limestone aquifer are immeasureable (See previous section.) suggesting hydraulic interconnection throughout the limestone,
(3) both the pumping well (TW 1) and the observation well (TW 2) fully penetrated the limestone aquifer, and
(4) as discussed later, there is a close match between the time-drawdown data and the Theis type curve.

Adjustment to Drawdown Data

An examination of the barometric pressure recorded at Alma indicates that some relation exists between it and the water level in TW 2 (fig. 3). For example, gradual pressure rises during June 10-13, 23-24, and 26-29, probably caused the water-level declines in TW 2 during those same periods. The relation between pressure declines and water-level rises is present but not easily discerned, probably because of the small magnitude of the pressure declines and the seasonal water-level decline shown in TW 2, and in other wells in the area. That seasonal decline was more than 1 ft during June 1981 in USGS test well OK 8, and the Humphrey Mining Co. and Okefenokee Swamp Park observation wells. (See fig. 1 for locations.)

During the drawdown period of the aquifer test, from 0930 hr on June 16 to 0840 hr on June 18, barometric pressure declined about 0.05 in. of mercury, or 0.06 ft of water (fig. 4). This decrease in pressure should have caused water levels in the confined aquifer to rise. However, the water level in the Okefenokee Swamp Park observation well, nearest to TW 2, declined during this period. The water-level decline, beginning on June 16, also occurred in TW 2 and continued after the test in it and the Okefenokee well (fig. 4). In effect, the water-level decline indicated a net response opposing that which should be caused by barometric effects. Because the water level in TW 2, as supported by that in the Okefenokee Swamp Park observation well, showed a net response other than that which the barometric pressure would have caused, the drawdown data were not corrected for barometric effects.

Although diurnal fluctuations in barometric pressure and water level in the observation wells appear to have a causal relation, the fluctuations are not time synchronous (fig. 4). The fluctuations in the water level are probably a result of earth tides, and are not easily corrected for. Indeed, they are not eliminated from the drawdown data, as a best-fit line or curve can be superposed through the data.

Adjustments to the drawdown data for the seasonal water-level decline were based on the water level in the nearby Okefenokee Swamp Park well. The water level in the Okefenokee Swamp Park well, 4.1 mi south of the test site, showed a flat trend before the test and began to decline at about the beginning of the drawdown period, at a rate of about 0.003 ft/hr, or 0.14 ft for the 48-hour drawdown period (figs. 3 and 4). This deline continued after the pumping well was shut off, but at a slightly lesser rate (fig. 4).

The trend in TW 2, with the exception of the pumping-induced drawdown, was almost identical to that in the Okefenokee Swamp Park well (fig. 4). Analyses were made using both unadjusted data, and that corrected for the decline of 0.003 ft/hr.

Analysis

Data from the aquifer test were plotted as elapsed time (t) since pumping began versus drawdown (s) in the observation well, on logarithmic-scale graph paper. The data curve was superposed on a Theis (1935) type curve plotted from the well function W(u) and the reciprocal of the variable of integration (1/u), on graph paper of the same scale. W(u) and 1/u are dimensionless variables related to the aquifer characteristics transmissivity (T) and storage coefficient (S); and to the aquifer test data, including

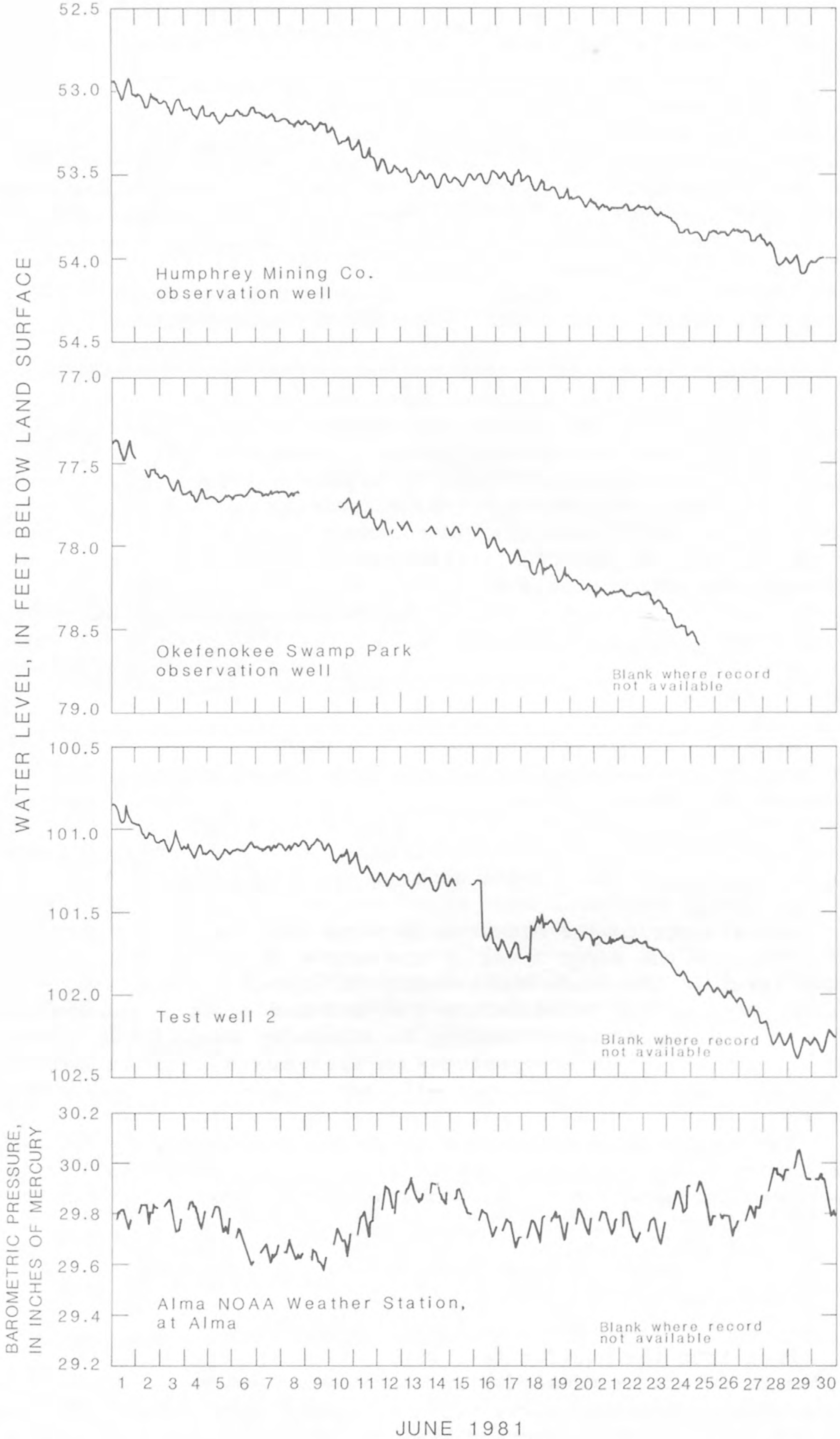

Figure 3.— Comparison of barometric pressure and water levels, June 1981.

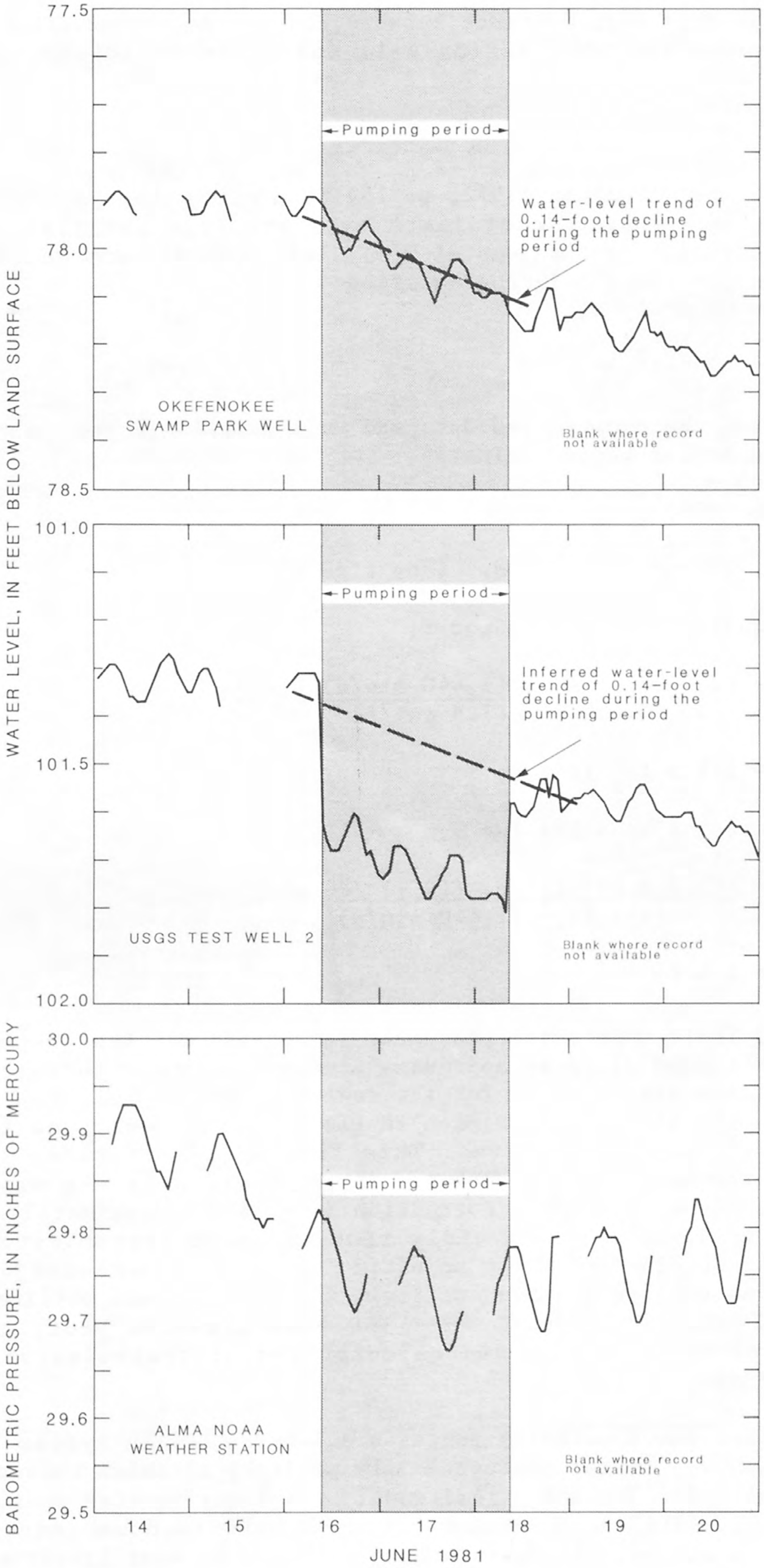

Figure 4.— Comparison of barometric pressure and water levels, June 14-20, 1981.

discharge rate (Q), distance between control and observation wells (r), and drawdown in the observation well (s). The relations are based on the equations:

$$W(u) = 4\pi Ts/Q, \qquad (1)$$

and

$$u = r^2S/4Tt, \qquad (2)$$

of C. V. Theis (Lohman, 1972, p. 15) from which the type curve was constructed. In superposing, coordinate axes are kept parallel, a common match point is chosen, and values of W(u), 1/u, s, and t are determined and used to solve for T and S in the equations:

$$T = QW(u)/4\pi s, \qquad (3)$$

and

$$S = 4Tut/r^2. \qquad (4)$$

Using the uncorrected data and well-function curve, a match point was selected having the coordinates:

$W(u) = 1.0$,
$1/u = 10^5$,
$s = 0.029$ ft, and
$t = 80$ min; 0.0555 d. (See fig. 5.)

Using equation 3 to solve for T,

$$T = \frac{(2{,}040 \text{ gal/min})\ (1{,}440 \text{ min/d})\ (1.0)}{4\pi\ (0.029 \text{ ft})\ (7.5 \text{ gal/ft}^3)}$$

$$= 1.1 \times 10^6 \text{ ft}^2\text{/d},$$

and equation 4 to solve for S,

$$S = \frac{4(1.1 \times 10^6 \text{ ft}^2\text{/d})\ (10^{-5})\ (80 \text{ min})}{(154 \text{ ft})^2\ (1{,}440 \text{ min/d})}$$

$$= 1 \times 10^{-4}.$$

The Theis type-curve placement reasonably matches the unadjusted data when positioned along an approximate median of the fluctuating data (fig. 5). If data are adjusted for the regional water-level trend of 0.003 ft/hr decline, the time-drawdown plot is flatter and lower, and provides a poor match with the Theis curve. This flatter, lower curve implies an even greater transmissivity. However, if the early data are emphasized in the curve matching, the trend correction is small (approximately 0.01 ft for the first 3 hrs), and for the early time the same transmissivity (1.1×10^6 ft^2/d) is obtained with the adjusted data as with the unadjusted (fig. 6). A somewhat smaller storage coefficient (8×10^{-5}) was obtained by using the adjusted data. See figure 6 for the time-drawdown plot, the Theis curve match and coordinates, and calculations of transmissivity and storage coefficient.

A flat curve normally suggests a leaky artesian system and a possible match with any of the Hantush family of leaky artesian curves (Lohman, 1972, p. 32, pl. 4). The analytical model of a leaky aquifer does not seem probable as the likelihood of 0.2 to 0.4 ft of drawdown inducing measurable leakage is remote. If leakage had occurred, it most likely would have come from beds within a few tens of feet above the limestone tapped by the well. It is unlikely that leakage was induced through the low-permeability beds of the Hawthorn Formation. Also, significant leakage would not have been

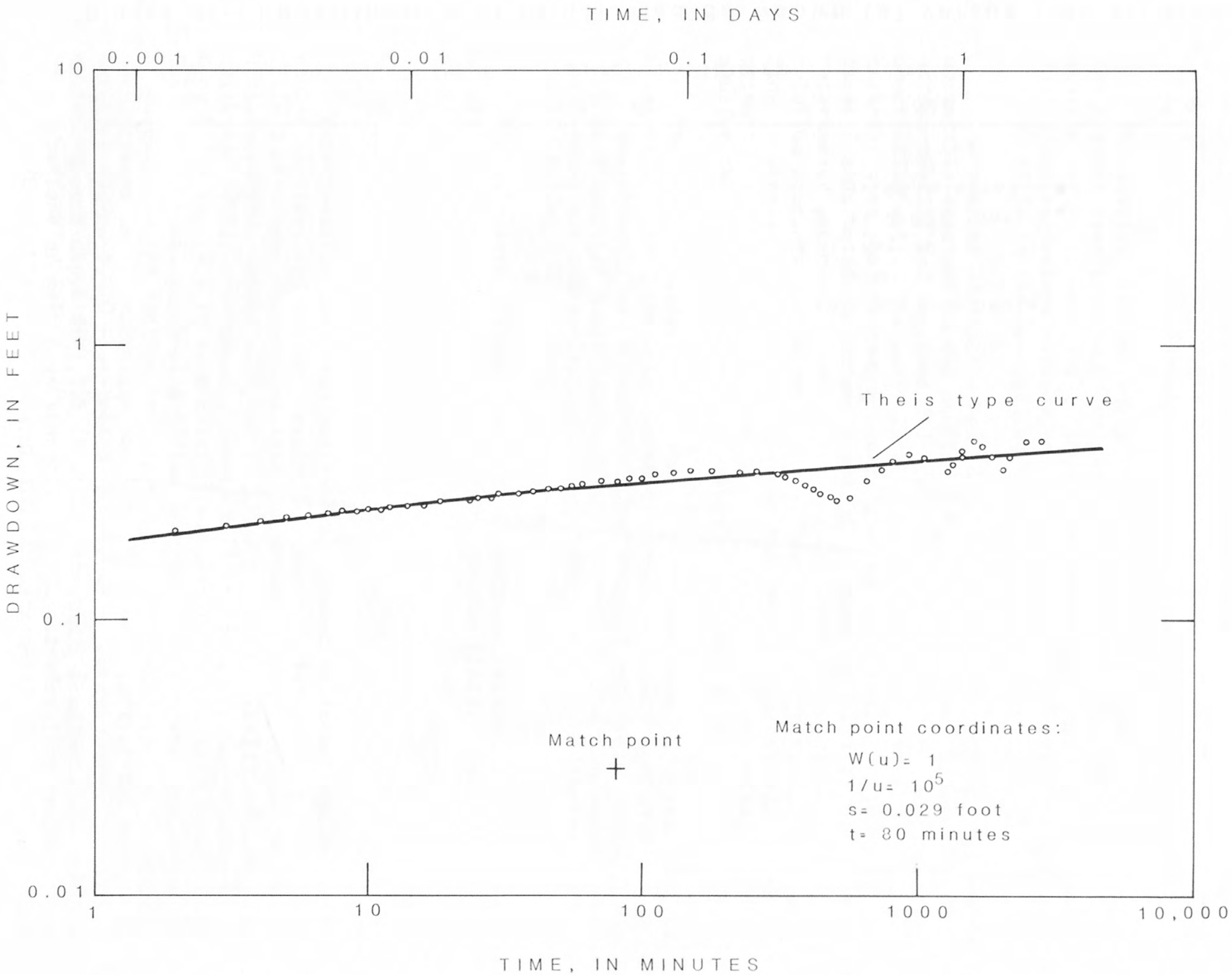

Figure 5.— Logarithmic plot of drawdown (s) versus time (t) from the Waycross aquifer test, superposed on the Theis type curve (nonleaky, artesian).

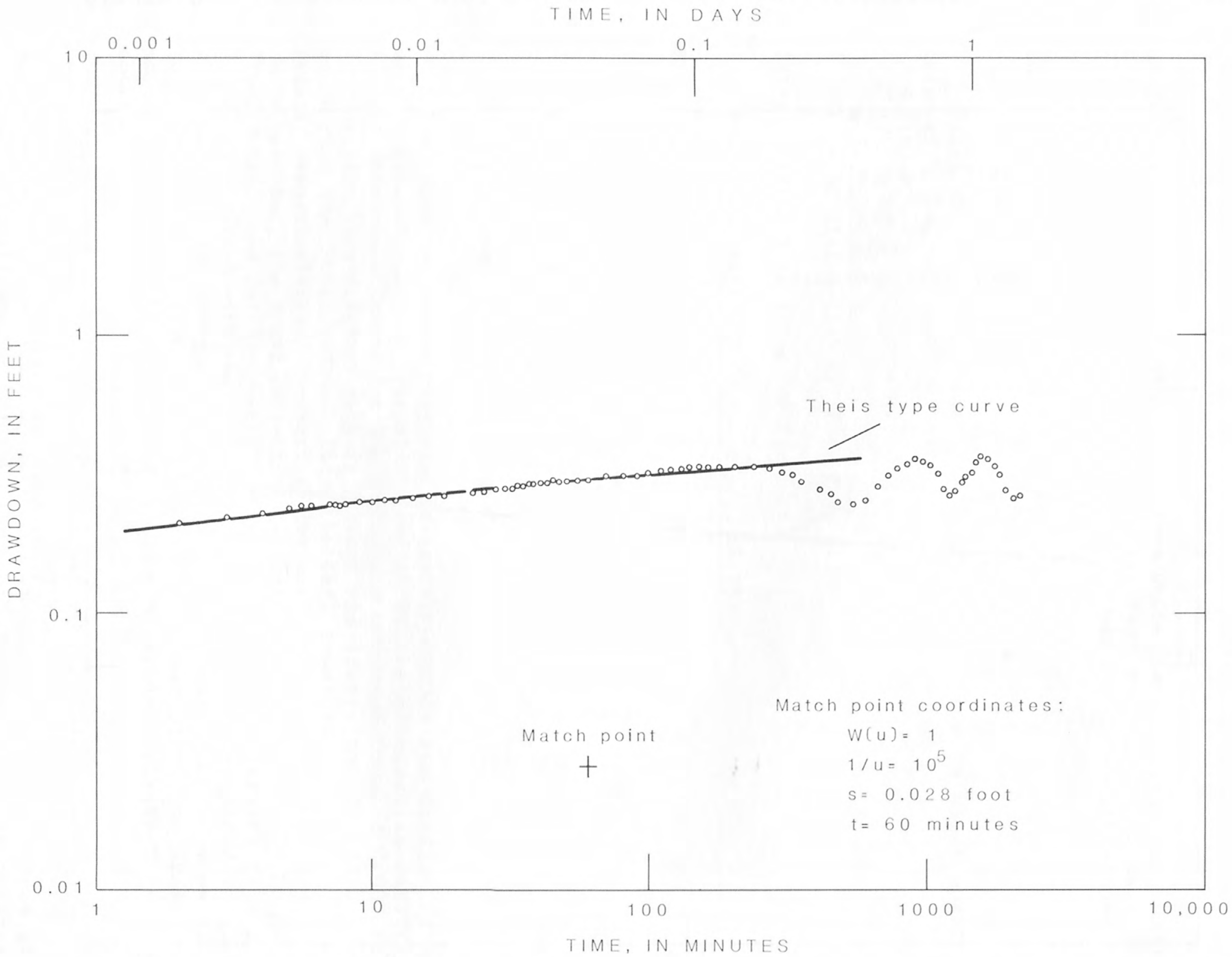

Figure 6.— Logarithmic plot of adjusted drawdown (s) versus time (t) from the Waycross aquifer test, superposed on the Theis type curve (nonleaky, artesian).

likely from underlying formations, because a flow-meter survey made during the pumping of TW 1 at a rate of 1,900 gal/min did not induce measurable yield from any part of the aquifer below about 1,090 ft.

Summary of Aquifer-Test Analysis

The aquifer test obviously indicates a large value of transmissivity, the highest ever reported for an aquifer test of the Tertiary limestone aquifer system in Georgia. Although not accurately determined because of environmental factors already mentioned, the transmissivity is approximately 1 x 10^6 ft^2/d in the area of the test site.

The pumping of about 3 Mgal/d from the aquifer system caused nearly immeasurable drawdown in the aquifer system at a distance of only 154 ft. The stress applied and released did produce the waterhammer phenomenon in the observation well. The water level in the observation well (TW 2) fluctuated markedly when pumping ceased, oscillating more than 15 times during the first 7 min, having a maximum amplitude of more than 1.5 ft (fig. 7). The waterhammer phenomenon, caused by pressure waves being transmitted through solution openings in the aquifer, has been defined primarily for unsteady flow in pipes. The occurrence of the phenomenon suggests that flow occurs primarily in large, solution-derived conduits in the aquifer, giving the aquifer the high transmissivity determined in this test.

The regional hydrology in the Waycross area also supports high transmissivity. First, the area is characterized by a very flat gradient in both the predevelopment and modern-day potentiometric surfaces. Second, calibration of a computer model of the aquifer system in this area under both predevelopment and modern-day conditions requires a transmissivity of about 1 x 10^6 ft^3/d.

The calculated value of storage coefficient (about 1 x 10^{-4}) is less accurate because of the imprecise match of the field plots and type curve along the horizontal axis.

GROUND-WATER QUALITY

Water-quality data from analyses of samples collected during drilling, packer testing, and aquifer testing are shown in tables 3, 4, 5, 6, and 7. Table 3 shows the chemical analyses of water from TW 1 collected through the drill stem from depths of 1,445 to 1,970 ft during air-lift reverse rotary drilling. Water from about 1,445 to 1,785 ft is a calcium bicarbonate type; from 1,785 to 1,816 ft is a calcium magnesium bicarbonate type; and from 1,816 ft to total depth is a sodium magnesium bicarbonate type. The amount of dolomite in the section increases with depth and this would account for the increase in the magnesium content. The lower part of the hole, approximately 1,900 to 1,970 ft, yielded highly mineralized water. Two samples collected at a depth of 1,965 ft with a downhole sampler gave the highest concentrations of most constituents. The dissolved-solids concentration was 19,000 mg/L at this depth, compared to an average of 900 mg/L at shallower depths.

Table 4 shows the chemical analyses of water collected from TW 2. The samples from 701 to 1,877 ft were collected, as in TW 1, through the drill stem during air-lift reverse rotary drilling. As in TW 1, water from the

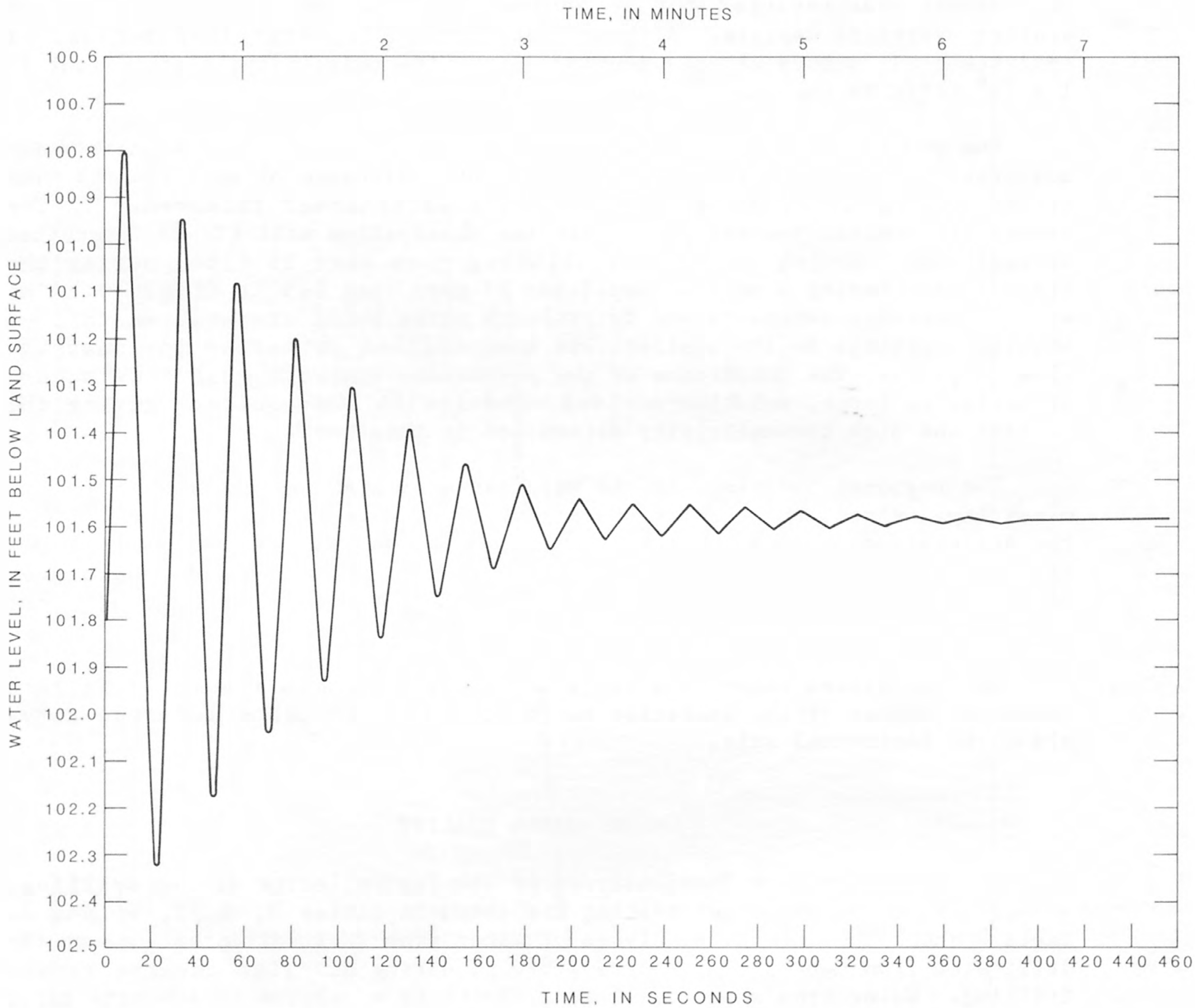

Figure 7.— Water level in test well 2 reconstructed from analog chart showing recovery and the waterhammer phenomenon, Waycross aquifer test.

Table 3.--Chemical analyses of water from test well 1 sampled from the drill pipe during air-lift reverse rotary drilling

[Analyses by U.S. Geological Survey]

Sample depth (ft below land surface)	Date sampled	Milligrams per liter													Specific conductance, in micromhos at 25°C	pH	Temperature, in degrees Celsius	Micrograms per liter			
													Hardness								
		Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Alkalinity, as $CaCO_3$	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrogen, as NO_2+NO_3	Dissolved solids, sum of constituents	Calcium, magnesium (Ca,Mg)	Noncarbonate				Barium (Ba)	Iron (Fe)	Manganese (Mn)	Strontium (Sr)
1,445	11-10-80	45	56	25	16	1.8	140	120	16	0.6	0.01	365	240	100	480	8.0	24.8	70	70	20	520
1,474	11-10-80	45	64	24	16	1.8	140	130	16	.6	.10	383	260	120	525	8.0	24.0	70	80	10	490
1,508	11-12-80	41	68	33	20	2.1	130	160	18	.6	.78	425	310	180	676	8.0	23.0	60	80	10	870
1,539	11-12-80	43	71	35	22	2.1	170	200	21	.7	.03	498	320	150	657	7.9	22.0	60	40	10	890
1/ 1,569	12-01-80	7.8	340	180	75	4.7	44	1,700	160	5.3	.00	2,510	1,600	1,600	454	8.0	22.5	10	690	30	10,000
1,600	12-01-80	24	49	22	11	1.1	63	220	24	.6	.03	390	210	150	810	8.0	25.0	40	60	10	660
1,630	12-02-80	15	43	23	11	1.0	80	260	33	.7	.03	435	200	120	830	8.1	25.0	30	20	7	460
1,692	12-03-80	11	45	24	16	1.2	69	280	58	.7	.01	478	210	140	980	8.0	25.0	20	20	6	390
1,723	12-04-80	13	48	25	18	1.0	48	310	46	.7	.01	491	220	180	960	8.0	25.0	20	20	10	430
1,754	12-05-80	28	63	38	48	2.3	48	330	97	.8	.01	637	320	270	1,200	8.0	25.0	50	110	10	950
1,785	12-08-80	40	120	61	98	4.5	140	490	150	.9	.04	1,050	550	410	1,570	8.0	24.5	60	90	30	1,800
1,816	12-09-80	38	100	61	150	6.1	140	400	220	.9	.02	1,060	500	360	1,720	7.9	26.0	70	120	30	1,700
1,847	12-10-80	35	110	65	230	8.2	140	480	340	1.0	.00	1,360	540	400	2,240	8.0	26.0	60	130	30	2,000
1,878	12-10-80	36	130	84	310	10.0	140	660	460	1.1	.07	1,780	670	530	2,720	8.0	26.0	60	140	30	2,300
1,902	12-11-80	37	120	80	300	10.0	140	530	430	1.1	.02	1,590	630	490	2,600	8.0	25.0	60	140	30	2,200
1,938	12-15-80	37	130	86	360	11.0	140	600	480	1.1	.07	1,790	680	540	2,740	7.7	26.0	60	60	30	2,200
1,970	12-16-80	38	110	77	330	10.0	120	500	430	1.0	.04	1,570	590	470	2,450	7.8	25.0	60	50	20	1,900
2/ 1,965	12-18-80	27	600	600	5,800	140.0	91	3,300	9,100	3.2	.04	19,600	4,000	3,900	28,620	7.5	21.0	100	310	70	8,000
2/ 1,965	12-18-80	27	600	600	5,600	150.0	87	3,500	9,000	3.2	.53	19,500	4,000	3,900	31,301	7.7	19.0	100	320	60	8,300

1/ Water had been uncirculated for 4 days, and more closely represents undiluted formation water at the 1,569-ft depth.
2/ Samples collected with a downhole sampler.

Table 4.--Chemical analyses of water from test well 2 sampled from the drill pipe during air-lift reverse rotary drilling

[Analyses by U.S. Geological Survey; <, less than]

Sample depth (ft below land surface)	Date sampled	Milligrams per liter											Hardness		Specific conductance, in micromhos at 25°C	pH	Temperature, in degrees Celsius	Micrograms per liter			
		Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Alkalinity, as $CaCO_3$	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrogen, as NO_2+NO_3	Dissolved solids, sum of constituents	Calcium, magnesium (Ca,Mg)	Noncarbonate				Barium (Ba)	Iron (Fe)	Manganese (Mn)	Strontium (Sr)
701	01-21-81	42	35	12	13	3.8	130	37	12	0.6	0.01	234	140	7	338	8.1	21.0	50	<10	3	230
763	01-22-81	45	38	16	13	2.4	140	40	12	.5	.01	251	160	21	379	8.1	23.0	60	10	6	240
810	01-29-81	28	28	11	9.6	3.0	74	44	12	.4	.09	181	120	41	400	8.1	23.0	50	<10	4	170
945	02-11-81	27	25	9.9	8.6	3.9	84	28	10	.4	.03	164	100	19	400	7.8	23.5	40	<10	4	140
1,009	02-17-81	43	35	15	13	2.5	130	34	12	.5	.53	236	150	19	345	7.9	23.5	60	<10	7	210
1,056	02-18-81	44	34	14	13	2.7	140	27	11	.5	.25	232	140	3	322	8.0	22.0	50	10	8	190
1,113	02-25-81	42	34	14	13	2.5	130	31	11	.5	.19	227	140	13	335	8.0	22.0	60	20	9	190
1,232	03-02-81	38	35	14	12	2.3	130	47	11	.5	.02	238	150	15	382	8.2	24.0	50	<10	7	220
1,352	03-10-81	37	38	14	11	2.3	130	39	10	.5	.01	230	150	23	355	8.3	24.0	50	20	6	190
1,427	03-17-81	32	40	12	12	2.3	140	41	10	.6	.04	234	150	10	375	8.3	24.0	40	30	4	160
1,491	03-24-81	43	45	19	14	2.7	130	73	12	.6	.05	288	190	61	415	8.0	24.0	0	0	0	320
1,580	03-27-81	42	100	39	16	3.2	130	440	14	.8	.02	664	410	400	670	8.0	24.0	50	20	20	960
1,753	04-13-81	47	60	25	39	3.2	140	130	50	.6	.07	440	250	110	720	8.0	25.0	60	30	10	480
1,877	04-16-81	45	83	49	210	7.8	140	300	310	.8	.04	1,090	410	270	1,550	8.0	24.5	60	130	20	1,000

upper zone of the aquifer is a calcium bicarbonate type. The concentrations of magnesium generally increase downhole. Water from the lower part of the section in TW 2 was highly mineralized.

Table 5 shows the chemical analyses of water collected from TW 2 with a downhole sampler prior to plugging the bottom of the well. These analyses are more representative of water from the lower part of the well than are samples taken from the drill stem, because the downhole sampler permitted less mixing with water from above. The water ranges in specific conductance from 352 umhos at 25°C in the upper permeable zone to 42,000 umhos in the highly mineralized lower zone. Chloride concentrations increase markedly from 2,200 mg/L at 1,620 ft to 16,000 mg/L at 1,965 ft.

Table 6 shows the chemical analyses of water sampled during packer testing of TW 1 and TW 2. The packer test in TW 2 isolated the mineralized water-bearing zone (1,901 to 1,966 ft). Water from this zone is a sodium magnesium bicarbonate type, also containing high concentrations of calcium, sulfate, strontium, iron, and zinc. The occurrence of poor quality water in this zone is probably due to the dissolution of evaporites found in the dolomite of the Oldsmar Limestone. The dissolution of gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$), and probably celestite ($SrSO_4$) would contribute calcium, sulfate, and strontium to the ground water. In addition, the presence of poor quality water may be due, in part, to incomplete flushing of residual seawater. The high concentration of iron may be due to the presence of glauconite. The source of high zinc concentrations is not known.

Three zones were isolated by packers in TW 1. The first zone was from 1,101 ft to total depth (1,856 ft). [Note: The highly mineralized lower zone in TW 1 had been plugged back to 1,856 ft prior to the packer tests.] Water from this zone is a calcium magnesium bicarbonate type also having high concentrations of sodium, chloride, sulfate, and strontium. The specific conductance of water from this zone was about 5,700 umhos at 25°C and the dissolved-solids concentration was about 5,500 mg/L. The high concentration of strontium and iron is probably due to the presence of celestite and glauconite, respectively.

The second packer test isolated the zone between 903 and 1,103 ft. Water from this zone is a calcium bicarbonate type having a high concentration of sulfate. The concentration of sodium and chloride is very low in this interval compared to the zone below. Specific conductance was about 450 umhos at 25°C and dissolved-solids concentration was about 310 mg/L.

The last packer test in TW 1 sampled water from the interval between 650 and 900 ft. This water was also a calcium bicarbonate type having a specific conductance of 375 umhos at 25°C and a dissolved-solids concentration of about 250 mg/L.

Table 7 gives the chemical analyses of water from TW 1 and TW 2 collected with a downhole sampler after both wells were allowed to stabilize for about 8 months after initial testing. The concentrations shown in table 7 are probably more representative of native water from individual zones, because (1) the downhole sampler permitted little mixing with water from above and (2) the 8-month stabilization period allowed the water in both wells to approach equilibrium with the rock. The water in the upper part of the wells is a calcium bicarbonate type, grading into a sodium magnesium bicarbonate type in the lower or more mineralized zones. In TW 1 the specific conductance ranged from 450 umhos at 25°C in the upper permeable

Table 5.--Chemical analyses of water from test well 2 collected with a downhole sampler

[Analyses by U.S. Geological Survey]

Sample depth (feet below land surface)	Date sampled	Milligrams per liter					Specific conductance, in micromhos at 25°C	pH	Density, at 20°C (g/mL)
		Alkalinity, as $CaCO_3$	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids				
					Residue, at 180°C	Volatile			
650	05-04-81	130	89	210	653	104	1,020	8.2	1.000
800	05-04-81	130	39	33	307	64	440	8.1	.998
1,100	05-04-81	140	32	10	249	45	352	7.0	.999
1,140	05-04-81	120	64	29	330	72	468	8.0	.998
1,180	05-04-81	130	880	91	1,670	208	1,900	8.1	1.000
1,320	05-04-81	170	990	240	2,980	472	3,160	8.0	1.001
1,345	05-04-81	150	1,800	130	3,080	422	3,080	7.9	1.002
1,520	05-04-81	120	1,900	430	3,880	652	4,100	8.0	1.002
1,570	05-04-81	130	1,400	1,200	4,390	700	5,620	7.6	1.002
1,620	05-04-81	130	1,900	2,200	6,570	1,070	8,400	8.1	1.003
1,650	05-04-81	130	3,400	4,700	12,200	1,080	15,600	7.7	1.009
1,850	05-04-81	110	4,000	10,000	22,200	2,580	28,300	7.5	1.016
1,930	05-04-81	160	5,000	14,000	31,300	2,210	40,500	7.8	1.022
1,930	05-04-81	72	4,900	14,000	31,100	2,980	40,000	7.6	1.021
1,965	05-04-81	67	5,100	16,000	33,100	2,580	42,000	8.0	1.022
1,965	05-04-81	120	4,700	16,000	32,700	3,350	41,600	7.5	1.022

Table 6.--Chemical analyses of water from test wells 1 and 2 collected during packer tests

[Analyses by U.S. Geological Survey]

		Milligrams per liter																				Micrograms per liter												
													Dissolved solids		Hardness																			
Well and sample depth (ft below land surface)	Date sampled	Silica (SiO_2)	Bromide (Br)	Calcium (Ca)	Carbon (C)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Alkalinity, as $CaCO_3$	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Residue at 180°C	Residue of dissolved calcium	Calcium, magnesium (Ca,Mg)	Noncarbonate	Specific conductance, in micromhos at 25°C	pH	Temperature, in degrees Celsius	Color, in platinum-cobalt units	Density, at 20° Celsius (g/mL)	Aluminum (Al)	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Selenium (Se)	Strontium (Sr)	Zinc (Zn)
TW 2 1,901 to 1,966	05-08-81	16	66	990	3.4	840	7,600	240	74	5,200	14,000	5.7	31,600	29,400	5,600	5,500	41,200	8.1	22.5	5	1.023	100	0	0	50	1	2	1,800	1	390	0	0	18,000	6,500
TW 1 packer set at 1,101 well depth 1,856	06-08-81	21	4.8	560	0	400	470	19	140	2,800	680	7.9	5,520	4,960	3,100	2,900	5,700	7.2	23.8	8	1.004	50	0	0	30	0	0	950	0	90	0	0	9,300	80
TW 1 straddle pack 903 to 1,103	06-09-81	44	.3	45	0	19	17	2.2	140	59	18	.5	312	290	190	51	435	7.7	24.5	5	.998	10	0	1	20	0	1	110	0	20	0	0	310	6
TW 1 650 to 900	06-10-81	30	.3	38	0	17	15	2.4	140	37	15	.4	250	242	170	25	375	8.2	23.5	10	.997	10	0	0	10	2	0	1,700	1	80	0	0	250	140

Table 7.--Chemical analyses of water samples collected from test wells 1 and 2 with a downhole sampler

[Analyses by U.S. Geological Survey]

Test well	Sample depth (feet below land surface)	Date sampled	Milligrams per liter: Alkalinity, as $CaCO_3$	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids: Residue, at 180°C	Volatile	Specific conductance, in micromhos at 25°C	pH	Density, at 20°C (g/mL)
1	650	02-03-82	140	55	26	308	53	450	7.9	0.999
1	780	02-03-82	140	45	14	280	49	404	7.9	.999
1	820	02-03-82	140	44	13	273	52	396	7.9	.999
1	860	02-03-82	140	41	12	262	52	394	8.1	1.000
1	1,020	02-03-82	140	54	18	275	41	397	8.1	.999
1	1,080	02-03-82	140	54	17	280	39	405	7.9	.999
1	1,140	02-03-82	140	92	27	355	61	510	7.9	.999
1	1,300	02-03-82	140	960	140	1,800	300	2,110	7.8	1.001
1	1,660	02-03-82	140	1,000	140	1,920	296	2,250	8.0	1.000
1	1,710	02-03-82	140	4,200	5,100	14,100	1,320	15,300	7.6	1.010
1	1,845	02-03-82	120	5,200	8,500	20,700	1,390	25,600	7.8	1.015
2	640	02-03-82	130	2.7	8.3	179	19	253	7.9	.999
2	700	02-03-82	130	10	7.4	192	29	276	8.0	.999
2	800	02-03-82	130	25	9.9	224	36	324	7.9	1.000
2	1,180	02-03-82	40	39	16	242	66	350	8.0	.999
2	1,420	02-03-82	130	440	45	901	137	1,130	8.0	1.001
2	1,560	02-03-82	130	590	52	1,160	172	1,370	8.1	1.001
2	1,585	02-03-82	130	800	79	1,410	204	1,660	7.8	.996
2	1,620	02-03-82	130	1,100	99	1,970	276	2,150	7.8	1.001
2	1,690	02-03-82	140	3,900	3,100	11,400	1,360	11,500	7.6	1.008
2	1,730	02-03-82	130	5,300	6,100	16,700	1,390	16,900	7.6	1.013
2	1,777	02-03-82	43	5,200	8,200	20,100	1,280	23,800	--	1.015

zone to 25,600 umhos in the highly mineralized zone. In TW 2 specific conductance ranged from 253 umhos at 25°C in the upper permeable zone to 23,800 umhos in the highly mineralized zone. Chloride concentrations increased from 140 mg/L at 1,660 ft in TW 1 to 8,500 mg/L at 1,845 ft. In TW 2 the chloride concentration was 99 mg/L at 1,620 ft and 8,200 mg/L at 1,777 ft.

In general, water in the principal artesian aquifer in the study area is a calcium bicarbonate type grading into a sodium bicarbonate type at a depth of about 1,800 ft. Concentrations of magnesium, sulfate, chloride, and some trace metals increase with depth. Constituent concentrations in water from the upper permeable zone are within the limits set for drinking water by the U.S. Environmental Protection Agency (1977) and the Georgia Department of Natural Resources, Environmental Protection Division (1977). However, highly mineralized water from the lower zone would not be suitable for human consumption.

SUMMARY

Before 1980, the Waycross area, Ware County, Ga., represented a major data void with respect to the hydrogeologic framework, ground-water flow system, head relations, and water quality of the Tertiary limestone aquifer system of the Southeastern United States. Two wells drilled near Waycross as part of the U.S. Geological Survey's Tertiary Limestone Regional Aquifer System Analysis provided geologic, hydrologic, and geochemical data to fill this data gap. Drilling, coring and testing were designed to yield a maximum of stratigraphic, structural, geophysical, and hydrologic information.

Test well 1 was used as a pumping well and test well 2 was used as an observation well for a fully-penetrating aquifer test. Both wells were cased and grouted into the top of the limestone aquifer. Each well was left as an open hole completely through the limestone aquifer.

Drill cuttings and water samples were collected from both test wells. Ten cores were taken by the conventional coring technique in test well 2. Geophysical logs were run in both test wells to determine the density, resistivity, and porosity of the water-bearing rocks.

The Coastal Plain sediments underlying the Waycross study area range in age from Cretaceous to Holocene and consist chiefly of units of sand, limestone, and dolomite, interbedded with minor clay layers. The Tertiary limestone aquifer system in this area is about 1,300 ft thick and is overlain by about 600 ft of clastic sediments. The aquifer includes undifferentiated Lake City and Avon Park Limestones, the Ocala Limestone, and the Suwannee Limestone, known as the principal artesian aquifer in Georgia and the Floridan aquifer in Florida.

A 4-day constant-discharge aquifer test was conducted to obtain transmissivity and storage coefficient values. Using the Theis type curve (nonleaky), a transmissivity of about 1×10^6 ft^2/d and a storage coefficient of about 1×10^{-4} were calculated. The transmissivity is larger than any other reported for an aquifer test in the aquifer system in Georgia, but the storage coefficient is similar to values reported for the confined part of the aquifer system.

Water quality was determined from samples collected (1) through the drill stem during drilling, (2) with a downhole sampler subsequent to well completion, and (3) during packer tests. The water from the upper part of the principal artesian aquifer in the study area is a calcium bicarbonate type. The deeper highly mineralized zone produces a sodium bicarbonate type water in which the concentrations of magnesium, sulfate, sodium, chloride, and some trace metals increase with depth.

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