GEOHYDROLOGY AND EVALUATION OF WATER-RESOURCE POTENTIAL OF THE UPPER FLORIDAN AQUIFER IN THE ALBANY AREA, SOUTHWESTERN GEORGIA

U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the

CITY OF ALBANY
WATER, GAS, AND LIGHT COMMISSION

Open-File Report 91-52

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Doraville, Georgia

1991

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
6481 Peachtree Industrial Blvd.
Suite B
Doraville, GA 30360

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply inch-pound units	by	to obtain metric units
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	43.81	liter per second (L/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Concentration	
part per million (ppm)	1,000	microgram per liter ($\mu g/L$)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

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

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ABSTRACT

In the Albany area of southwestern Georgia, the Upper Floridan aquifer lies entirely within the Dougherty Plain district of the Coastal Plain physiographic province, and consists of the Ocala Limestone of late Eocene age. The aquifer is divided throughout most of the study area into an upper and a lower lithologic unit, which creates an upper and a lower water-bearing zone. The lower water-bearing zone consists of alternating layers of sandy limestone and medium-brown, recrystallized dolomitic limestone, and ranges in thickness from about 50 to 100 feet. It is highly fractured, and exhibits well-developed permeability by solution features that are responsible for transmitting most of the ground water in the aquifer. Transmissivity of the lower water-bearing zone ranges from about 90,000 to 178,000 feet squared per day. The upper water-bearing zone is a finely crystallized-to-oolitic, locally dolomitic limestone having an average thickness of about 60 feet. Transmissivities in the upper water-bearing zone are considerably less than those in the lower water-bearing zone. The Upper Floridan aquifer is overlain by about 20 to 120 feet of undifferentiated overburden consisting of fine-to-coarse quartz sand and noncalcareous clay. A clay zone about 10 to 30 feet thick may be continuous throughout the southwestern part of the Albany area, and where present, causes confinement of the Upper Floridan aquifer and creates perched ground water after periods of heavy rainfall. The Upper Floridan aquifer is confined below by the Lisbon Formation, a mostly dolomitic limestone that contains trace amounts of glauconite. The Lisbon Formation is at least 50 feet thick in the study area, and acts as an impermeable base to the Upper Floridan aquifer. The quality of ground-water in the Upper Floridan aquifer is suitable for most uses; wells generally yield water of the hard, calcium-bicarbonate type that generally meets the U.S. Environmental Protection Agency's Primary or Secondary Drinking Water Regulations.

The water-resource potential of the Upper Floridan aquifer was evaluated by compiling results of test drilling and aquifer testing in the study area, and by conducting computer simulations of the ground-water-flow system under the seasonal-low conditions of November 1985, and under conditions of pumping within a 12-square-mile area located southwest of Albany. Results of test drilling, aquifer testing, and water-quality analyses indicate that, in the area southwest of Albany, geohydrologic conditions in the Upper Floridan aquifer, undifferentiated overburden, and Lisbon Formation were favorable for the aquifer to provide a large quantity of water without having adverse effects on the ground-water sytem. The confinement of the Upper Floridan aquifer by the undifferentiated overburden and the rural setting of the area of potential devleopment decreases the likelihood that chemical constitutents will enter the aquifer during development of the ground-water resources.

Computer simulations of ground-water flow in the Upper Floridan aquifer, incorporating conditions for regional flow across model boundaries, leakage from rivers and other surface-water features, and vertical leakage from the undifferentiated overburden, were conducted by using a finite-element model for ground-water flow in two dimensions. Comparison of computed and measured water levels in the Upper Floridan aquifer for November 1985 at 74 locations indicated that computed water levels generally were within 5 feet of the measured values, which is the accuracy to which measured water levels were known. Water-level altitudes ranged from about 260 feet to 130 feet above sea level in the study area during calibration. Aquifer discharge to the Flint River downstream from the Lake Worth dam was computed by the calibrated model to be about 1 billion gallons per day; about 300 million gallons per day greater than was measured for similar low-flow conditions. The excess computed discharge was attributed partially to stream withdrawals for industrial use, non-reported use, and channel evaporation, but mostly to increased gradients and increased flow from the aquifer to the river than existed during calibration.

Results from the calibrated finite-element model indicate that ground-water flow is dominated by inflow from regional-flow components to the west, north, and east of the study area, and by outflow to the Flint River downstream from the Lake Worth dam. Simulation results indicated that directions of ground-water flow were not changed appreciably by pumping at the November 1985 rates. However, vertical leakage from the undifferentiated overburden caused local deviations in the regional flow pattern.

A sensitivity analysis that was performed on 18 hydrologic factors affecting the flow system in the Upper Floridan aquifer showed that computed water levels changed the most (were the most sensitive) in response to changes in hydraulic conductivity of the aquifer, vertical leakage coefficient and water level in the undifferentiated overburden, and stage of the Flint River downstream from the Lake Worth dam. Computed water levels were least sensitive to changes in well pumpage, flow across the northern boundary and from Lake Worth, the boundary coefficient for the Flint River downstream from the Lake Worth dam, and flow from Cooleewahee Creek.

Simulations of six pumping scenarios in the area of potential development southwest of Albany showed that the Upper Floridan aquifer is capable of providing at least 72 million gallons per day from five locations (14.4 million gallons per day each) within this area without causing adverse affects on the flow system. The 72-million-gallon-per-day scenario yielded a maximum drawdown of about 9.4 feet, which placed the water level in the Upper Floridan aquifer about 50 feet above the top of the lower water-bearing zone. Hence, the likelihood of aquifer dewatering, well interference, or sinkhole development from pumping as much as 72 million gallons per day from within the area of potential development is small. All pumping scenarios showed that about 81 percent of the ground-water pumpage was derived from regional flow that would have discharged to the Flint River downstream from the Lake Worth dam. The dominant ground-water-flow direction toward the Flint River was not changed and no induced recharge from the Flint River entered the potential-development area. Induced recharge from the undifferentiated overburden contributed to about 1.5 percent of the total volume pumped during the simulations.

INTRODUCTION

Water-level declines in the Albany area of southwestern Georgia caused by heavy pumping from wells completed in deep aquifers of the Eocene Claiborne Group, Paleocene Clayton Formation, and Upper Cretaceous rocks that underlie the Upper Floridan aquifer have caused concern for local and State resource managers and raised questions about the ability of the deep aquifers to continue to meet increasing ground-water demands. The Albany Water, Gas, and Light Commission (WG&L) is considering using the Upper Floridan aquifer as an alternative municipal ground-water source.

A study of the hydrogeology, chemical quality, and availability of ground water in the Upper Floridan aquifer (Hicks and others, 1987) indicated that spatial variability in the hydraulic characteristics of the Upper Floridan aquifer could significantly affect water-resource development in the Albany area. Although that study identified several areas having the greatest ground-water development potential (Hicks and others, 1987, p. 38), most of these areas are not as suitable for water-resource development as the area selected for further investigation by this study. Wells may penetrate major ground-water conduits in some areas, permitting contamination from distant sources to reach municipal-supply wells quickly and virtually unattenuated. In other areas, the confining unit is absent or very "leaky"; thus, contamination from sources directly above the Upper Floridan aquifer could occur by percolation through the undifferentiated overburden. In still other areas, the undifferentiated overburden may be thin or absent, thus offering little delay in the percolation of any contaminants to the aquifer from the surface. Considering these factors, the area located west of the Flint River in Dougherty County (fig. 1), identified by Hicks and others (1987), can be considered as having the greatest potential for development of ground-water resources.

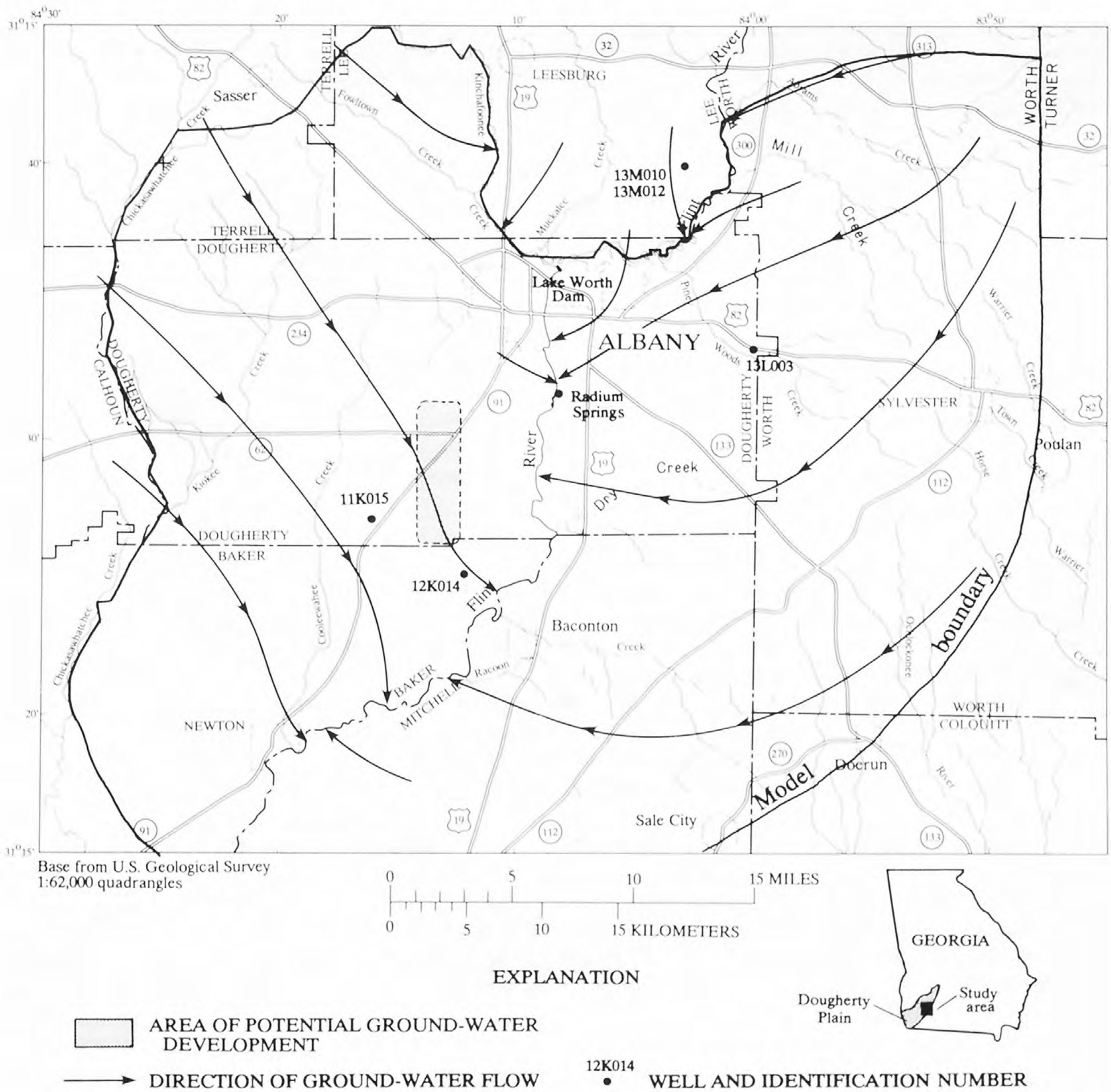


Figure 1.--Locations of study area, area of potential development, and conceptualized ground-water-flow directions in Upper Floridan aquifer.

In 1987, as part of an ongoing cooperative program with WG&L, the U.S. Geological Survey (USGS) began an investigation to evaluate the ground-water resources of the Upper Floridan aquifer in the Albany area, with particular interest in the area identified as having the greatest potential for development (fig. 1). The complex hydrologic processes associated with karst terrane, regional flow, and the relation of ground-water to surface-water flow, as described by Hicks and others (1987), required that numerical simulation be used to represent the flow system of the Upper Floridan aquifer for this evaluation. Historical data along with geohydrologic data from more recent test drilling and aquifer testing in the area of potential development were compiled and incorporated into the computer model.

This report extends the work of Hicks and others (1981, 1987); first, by reviewing and updating information on the geohydrologic characteristics of the Upper Floridan aquifer in the Albany area; and second, by evaluating the hydrologic components of the ground- and surface-water-flow systems. The effects on the flow system of developing the ground-water resource by pumping are determined by analyzing simulation results, which are used to quantify components of the flow system, determine directions of ground-water movement, and evaluate the potential for sinkhole development and for water-quality changes.

Purpose and Scope

The objectives of this report are to describe briefly the geohydrologic system of the Upper Floridan aquifer and to evaluate the water-resource potential of the aquifer by determining the effects of ground-water development in an area near Albany, Ga. (fig. 1), on the ground- and surface-water-flow system. The hydrologic significance of the various lithologies within geologic units that affect ground-water flow in the Upper Floridan aquifer is explained as it pertains to the evaluation. The evaluation uses results of test drilling and aquifer testing in the area of potential ground-water development (fig. 1), and compiles available hydrologic information to determine the factors that control ground-water flow in the Upper Floridan aquifer. The effects of these factors are represented in a finite-element model of ground-water flow in two (areal) dimensions, and results of simulations are used to aid in evaluating the water-resource potential of the Upper Floridan aquifer. Sensitivity analyses were conducted, in which simulation is used to determine which factors, among 18 controlling ground-water flow, affect the flow system most, and hence require accurate definition in the system.

The effects of ground-water development on the Upper Floridan aquifer and on the surface-water features were determined by simulating the hydrologic conditions that existed during a period of low flow and low-water level (November, 1985), and by simulating pumped wells located in an area of potential ground-water development. Six development scenarios were analyzed with regard to the effects of pumping on water levels and with regard to the hydrologic factors that affect ground-water flow in the Upper Floridan aquifer. The response of the flow system to pumping was analyzed by evaluating the following factors: aquifer drawdown, changes to water-budget components and to directions of ground-water flow, aquifer dewatering (which contributes to sinkhole formation), water-quality changes, and induced leakage from the Flint River (plate 1).

Area of Study

The Albany study area lies almost entirely within the Dougherty Plain district (Clark and Zisa, 1976) of the Coastal Plain physiographic province of Georgia, and covers an area of about 1,500 mi^2 in the southwestern part of the State (fig. 1). The area of potential ground-water development (area of potential development) occupies about 12 mi^2 of the southwestern part of the study area (fig. 1). The Dougherty Plain slopes from an altitude of about 300 ft in the northern part of the area to about 150 ft at the southeastern border. Details about the physiography of the Dougherty Plain and surrounding districts were summarized by Hicks and others (1987).

Methods of Investigation

Methods used to describe the geohydrology and to evaluate the water-resource potential of the Upper Floridan aquifer were test drilling, aquifer testing, analysis of ground- and surface-water data, and numerical simulation. Nine test wells were drilled by S & ME, Inc.,[1/] (formerly Soil and Material Engineers, Inc.) during February 1988 for WG&L. Five of the wells fully penetrated the Upper Floridan aquifer and four wells were completed in the material overlying the aquifer (undifferentiated overburden) (figs. 2, 3). Drill cuttings and 23 undisturbed core samples were collected during well installation, and all wells were cased and developed.

Permeability, bulk density, clay content, and percent moisture were determined for 16 of the 23 undisturbed core samples by S & ME, Inc. Saturated permeability was determined by the constant-head, controlled-gradient method by using a triaxial testing device, as described by the U.S. Army Corps of Engineers' triaxial test EM 1110-2-1906, Appendix VII, in accordance with the American Society for Testing Materials (ASTM) standard D 2850.

Core and drill cuttings from the nine test wells were correlated with borehole-geophysical logs, including electrical resistivity, spontaneous potential, natural gamma, and caliper logs. Lithologic data and geophysical logs from nine other wells also were used to identify and correlate stratigraphic and hydrologic units.

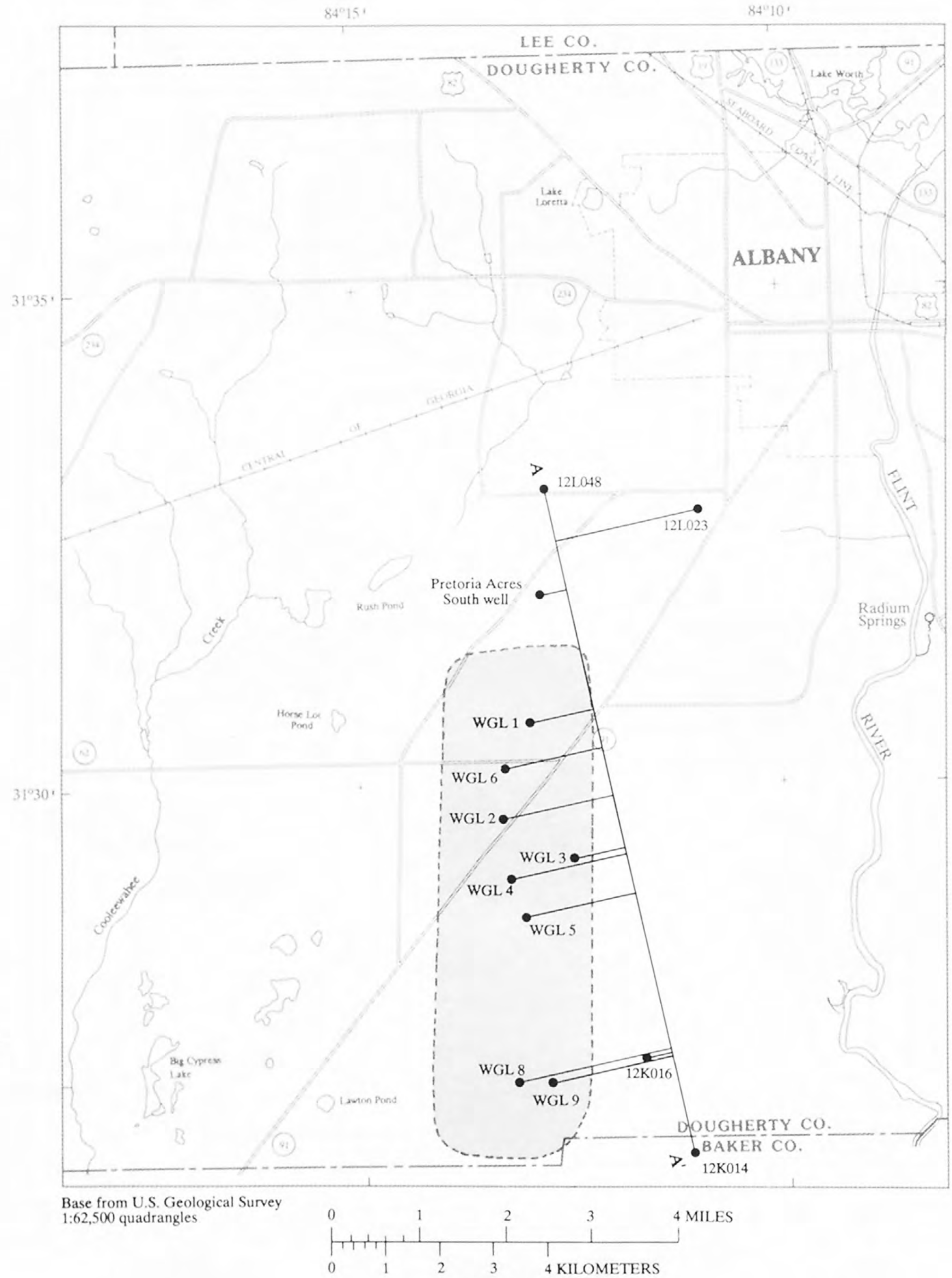
Water-level data from a network of 51 wells in the southwestern Albany area were used to construct a detailed map of the potentiometric surface for the Upper Floridan aquifer. Continuous water-level data from recorders that were installed on six wells provided information on water-level fluctuations in the area of potential development.

Stream-discharge measurements were made in the Albany area in an attempt to relate changes in the base flow of streams to the ground-water level and stream stage. Continuous-streamflow and gage-height data were collected on the Flint River at Albany. Base-flow measurements were made on selected streams during the low-flow period of November 27 and 28, 1984, so that estimates of the volume of ground water discharged by the Upper Floridan aquifer into area streams could be made (Hicks and others, 1987, p. 32).

Results of aquifer tests conducted during the previous investigation by Hicks and others (1987) at two locations in the study area also aided in the water-resource evaluation. Water-level data from drawdown and recovery tests at the pumped wells and at observation wells were used to compute transmissivity for the Upper Floridan aquifer.

The USGS's MODular Finite-Element model (MODFE) of two-dimensional ground-water flow, (Richard L. Cooley, U.S. Geological Survey, written commun., 1990; and Torak, 1990), was used to simulate flow in the Upper Floridan aquifer. The model used mathematical representations for the hydrologic factors that are conceptualized as controlling ground-water flow in the Upper Floridan aquifer. Evaluation of the water-resource potential of the aquifer was made based on results of simulations conducted to represent historical, current, and "potential" future ground-water conditions in the Upper Floridan aquifer.

[1/] Use of firm names in this report is for identification purposes only, and does not constitute endorsement by the U.S. Geological Survey.



EXPLANATION

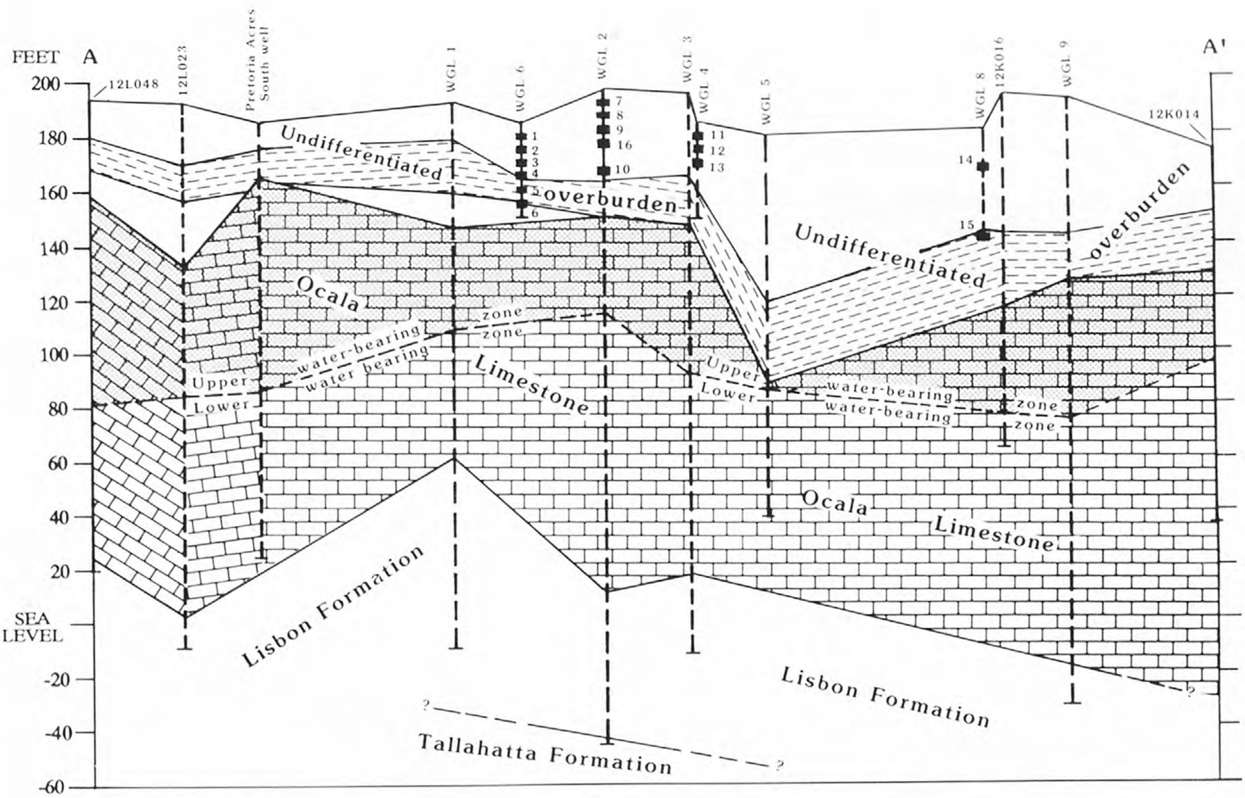
AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

A—A' LINE OF SECTION

WELLS USED TO CONSTRUCT SECTION A-A'

- 12L048 Scheduled by U.S. Geological Survey
- WGL 1 Albany Water, Gas, and Light Commission well

Figure 2.--Locations of wells used to construct section A-A'.



CORE NO.	VERTICAL HYDRAULIC CONDUCTIVITY, IN FEET PER DAY
1	8.22
2	22.7
3	11.3
4	0.001
5	.088
6	.85
7	.011
8	1.93
9	2.32
10	11.3
11	0.88
12	4.88
13	5.67
14	0.001
15	.0004
16	11.3

EXPLANATION

CLAYEY MATERIAL--
From geophysical logs

UPPER FLORIDAN AQUIFER

Upper water-bearing zone

Lower water-bearing zone

5 CORE SAMPLE AND IDENTIFICATION NUMBER

0 1 2 MILES

0 1 2 KILOMETERS

VERTICAL SCALE GREATLY EXAGGERATED

Figure 3.--Generalized geohydrologic section A-A'.

Well-Numbering System

In this report, wells are numbered using a system based on U.S. Geological Survey topographic maps. Each 7 1/2-minute topographic quadrangle map in Georgia has been given a number and letter designation beginning at the southwest corner of the State. Numbers increase eastward through 39; letters advance northward through "Z", then double-letter designations "AA" through "PP" are used. The letters "I," "O," "II," and "OO" are not used. Wells inventoried in each quadrangle are numbered sequentially beginning with "1". Thus, the forty-eighth well inventoried in the Albany West quadrangle (designated 12L) in Dougherty County is designated as well 12L048. Wells numbered by S & ME, Inc., contain the prefix "WGL" followed by sequential digits, such as WGL1, WGL2, and so forth. Some wells are not numbered and are defined by name, such as "Pretoria Acres South well."

GEOHYDROLOGY

The study area is underlain by Coastal Plain sediments of pre-Cretaceous to Quaternary age that consist of alternating units of sand, clay, sandstone, dolomite, and limestone that dip gently to the southeast and generally thicken in that direction (Hicks and others, 1987). Only those geologic units pertinent to the functioning of the Upper Floridan aquifer were investigated in this study. Those units include middle-late-Eocene age and younger sediments, and are, in ascending order, the Lisbon Formation, the Ocala Limestone, and undifferentiated overburden (fig. 3).

Karst topography characterizes the study area, which is marked by numerous shallow, flat-bottomed or rounded depressions that may be remnants of ancient sinkholes. The depressions range in depth from only a few feet to more than 25 ft, and usually are filled with sediment of low hydraulic conductivity. Many of these depressions hold water throughout much of the year.

The Lisbon Formation is thick and dense and acts as an impermeable base of the Upper Floridan aquifer. The lower part of the Ocala Limestone has well developed permeability along solution-enlarged joints, bedding planes, and fractures. The lower part of the Ocala Limestone contains most of the lateral ground-water flow in the Upper Floridan aquifer. The upper part of the Ocala Limestone is dense in most places and functions primarily to supply water to the lower part of the Ocala. Together the upper and lower parts of the Ocala Limestone compose the Upper Floridan aquifer. The undifferentiated overburden consists of alternating layers of sand, silt, and clay. Where present, the upper, sandy part may contain a water-table aquifer, which acts as a source of recharge to or receives discharge from the Upper Floridan aquifer. The lower, clayey part of the undifferentiated overburden confines the underlying Upper Floridan aquifer. For a more complete description of the geology of the area, the reader is referred to Hicks and others (1987, p. 9-12).

Hydrologic Characteristics

Undifferentiated overburden

Results of laboratory analyses of core samples indicate that the sand and clay content of the undifferentiated overburden is the dominant lithologic factor in controlling the vertical hydraulic conductivity of these sediments. Laboratory analyses of 16 undisturbed core samples that were collected from wells WGL2, WGL4, WGL6, and WGL8 (C.A. Turner, S & ME, Inc., written commun., 1988) indicate that the vertical hydraulic conductivity of sediments in the overburden ranges from about 0.0004 ft/d for a silty clay to about 23 ft/d for a fine-to-medium sand (fig. 3).

Thickness data for the undifferentiated overburden in the Albany area collected by Hicks and others (1987) were compiled for this study. Thickness of the overburden ranges from about 20 ft at the Pretoria Acres South well to about 94 ft at well WGL5 (fig. 3); however, locally, the thickness may exceed 120 ft (Hicks and others, 1987, plate 2). Although most layers of similar lithology within the undifferentiated overburden are discontinuous and can be traced only for short distances, a layer of clay in the lower half of the overburden may be continuous throughout the southwestern part of the Albany area (fig. 3). Thickness of this clay ranges from about 10 ft at well 12L048 in the northern part of the study area to about 29 ft at well WGL5, and averages about 20 feet. Zones of equal thickness for the predominantly clayey sediments in the lower half of the overburden were defined from these data (fig. 4), and were used to determine values of vertical hydraulic conductance (vertical hydraulic conductivity divided by thickness) for input to the finite-element model (see section on "Simulation of Ground-Water Flow"). The element sides of the finite-element mesh were used as zone boundaries (plate 1).

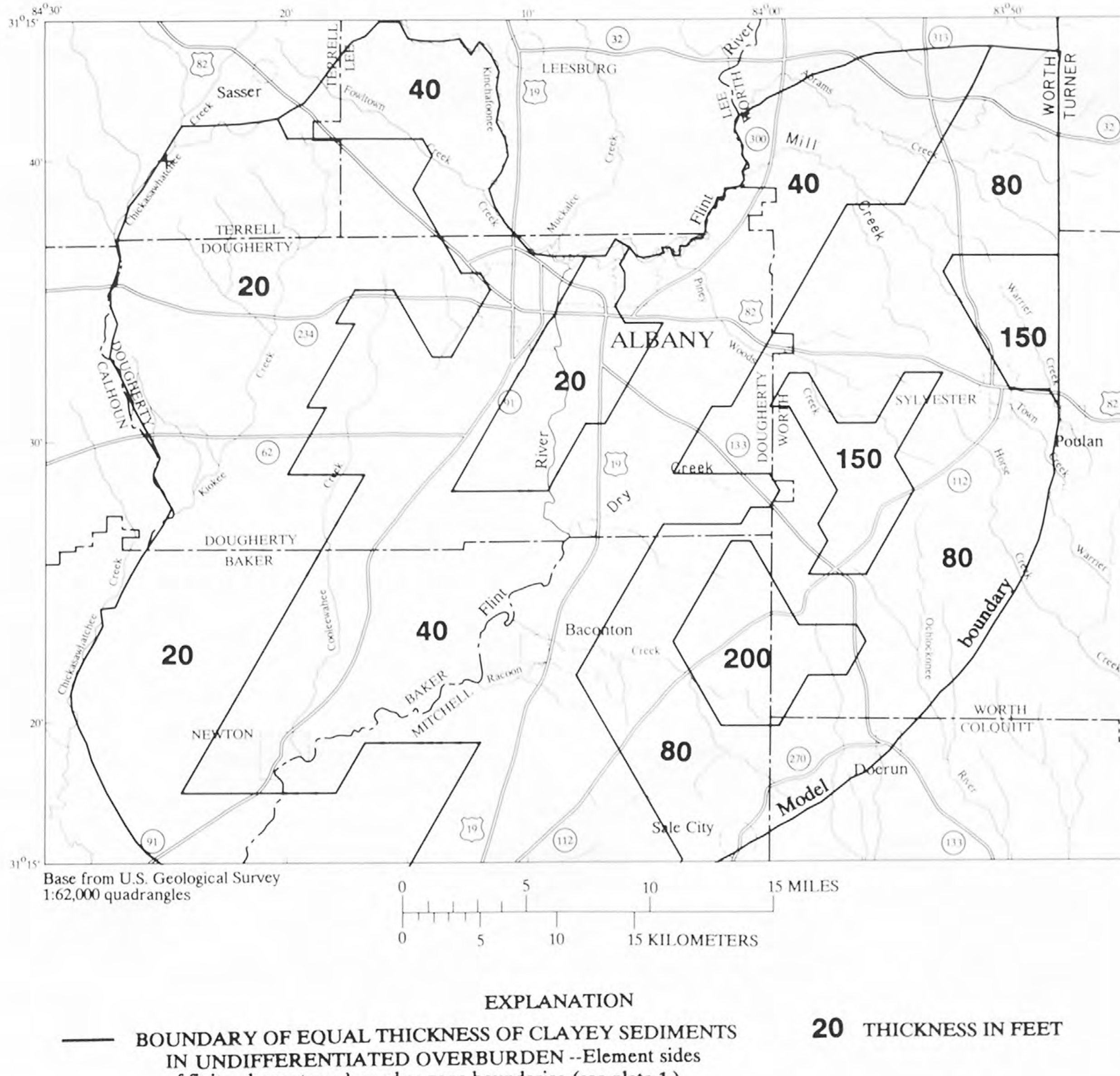


Figure 4.--Zones of thickness of predominantly clayey sediments in lower half of undifferentiated overburden.

The vertical hydraulic conductivity and thickness of the laterally continuous clay layer within the undifferentiated overburden in the Albany area create a hydrologic barrier to the vertical flow of ground water to, and from, the Upper Floridan aquifer. The clay layer can have the following effects on ground-water flow in the Upper Floridan aquifer system (1) it can cause perched ground-water conditions in the overburden following periods of heavy rainfall; (2) it can decrease the amount of ground-water recharge to the Upper Floridan aquifer from infiltration of precipitation; and (3) it can control the rate of infiltration of surface-applied chemicals, which could contaminate the ground-water supply in the aquifer.

Upper Floridan aquifer

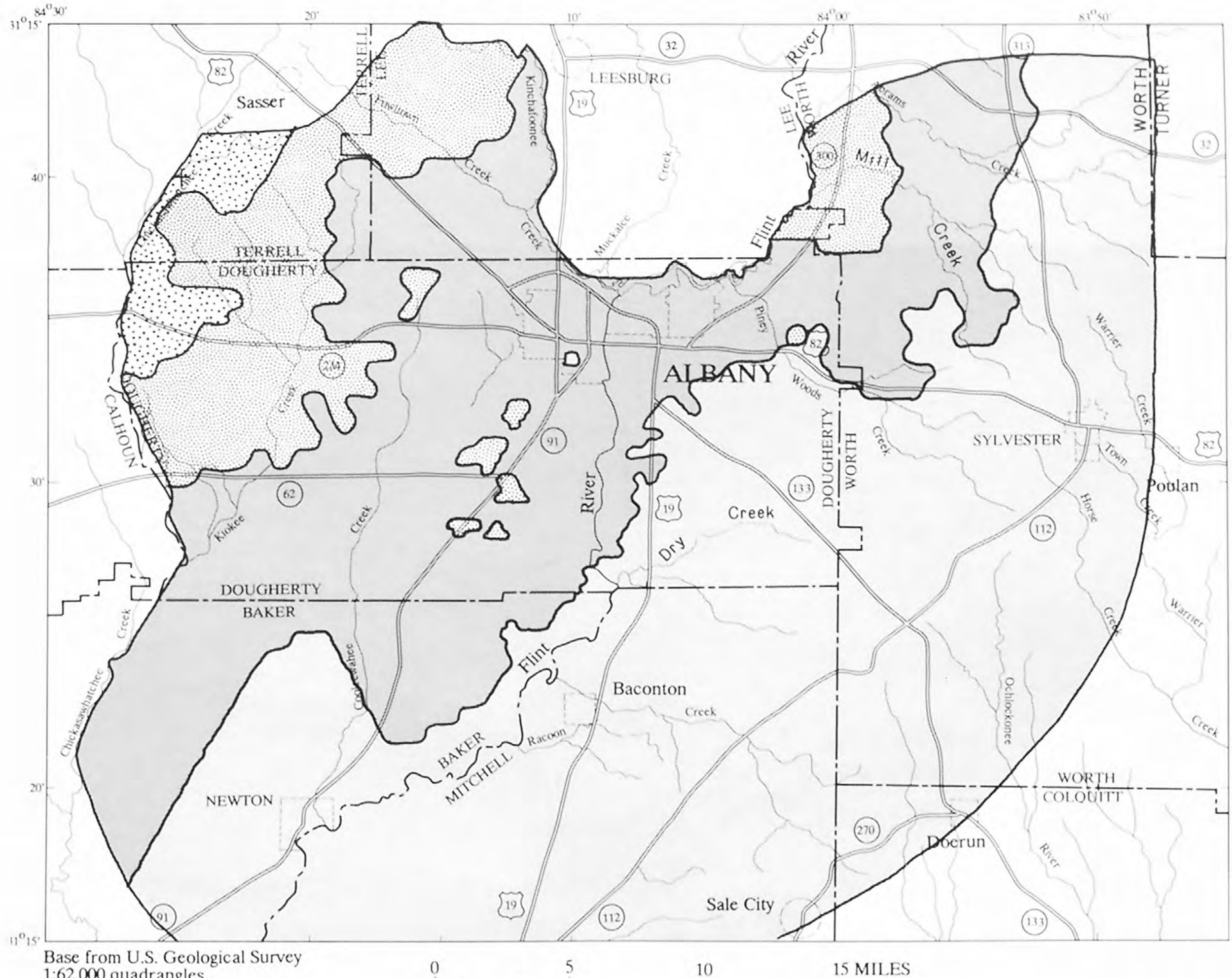
The Upper Floridan aquifer in the Albany area consists of the Ocala Limestone. The aquifer varies in thickness throughout the Albany area from about 25 ft in the northwestern part of the study area to about 270 ft in southeast Dougherty County (fig. 5). In the area of potential development, the aquifer ranges in thickness from about 77 ft at well WGL5 to about 145 ft at well WGL9 (fig. 3).

The Upper Floridan aquifer is divided into upper and lower water-bearing zones having different hydraulic properties. The relatively low permeability in the upper water-bearing zone greatly reduces its ability to transmit large quantities of ground water. Although no aquifer tests were available to give values of transmissivity or hydraulic conductivity, yields from domestic wells that were completed in the upper water-bearing zone generally are low. Well records provided by the Dougherty County Health Department indicate that the majority of domestic supplies are obtained from the upper water-bearing zone.

Thickness variations in the upper water-bearing zone determine the extent to which this zone acts as a hydrologic barrier for transmitting water vertically between the lower water-bearing zone and the undifferentiated overburden. In the northern part of the area of potential development, the lower water-bearing zone is separated from the undifferentiated overburden by about 50 to 65 ft of the upper water-bearing zone (compare altitudes in figures 6 and 7). The average thickness of the upper water-bearing zone in the study area is about 40 ft (fig. 3). In the area of potential development, thickness of the upper unit ranges from about 2 ft at well WGL5 to about 77 ft at well 12L048 (fig. 3).

Areal differences in hydraulic conductivity and in saturated thickness within the lower water-bearing zone create a variable distribution of aquifer transmissivity. Aquifer tests at wells 12L048 and 12K016 in the northern and southern parts of the area of potential development, respectively, indicated that the transmissivity of the lower water-bearing zone ranged from about 90,000 ft^2/d at well 12L048 to about 178,000 ft^2/d at well 12K016. Using thicknesses for the lower water-bearing zone of about 58 ft at well 12L048 and about 88 ft at well 12K016 and these estimates of transmissivity, the hydraulic conductivity of the lower water-bearing zone was estimated to range from about 1,500 ft/d at well 12L048 to about 2,000 ft/d at well 12K016.

The highly permeable nature of the lower water-bearing zone of the Upper Floridan aquifer is the result of well-developed permeability caused by dissolution of limestone by ground water circulating along bedding planes and fractures (Hicks and others, 1987). The permeability of the lower water-bearing zone is imparted by interconnected conduits or solution openings. A system of major solution conduits has developed in areas near the Flint River (fig. 8). These major conduits transport large quantities of ground water from the Upper Floridan aquifer to springs, such as Radium Springs, which discharge water to the Flint River. Although the cross-sectional area that contributes ground water to the Flint River from the solution conduits is small in comparison with the cross-sectional area across which ground water enters the River from the entire aquifer, the solution conduits conduct a major part of the ground-water flow and contribute greatly to shaping the potentiometric surface of the aquifer (Hayes and others, 1983, p. 46). Consequently, the distribution of solution openings and fractures were used to define, in a qualitative sense, zones of high and low hydraulic conductivity for the digital model of the aquifer.

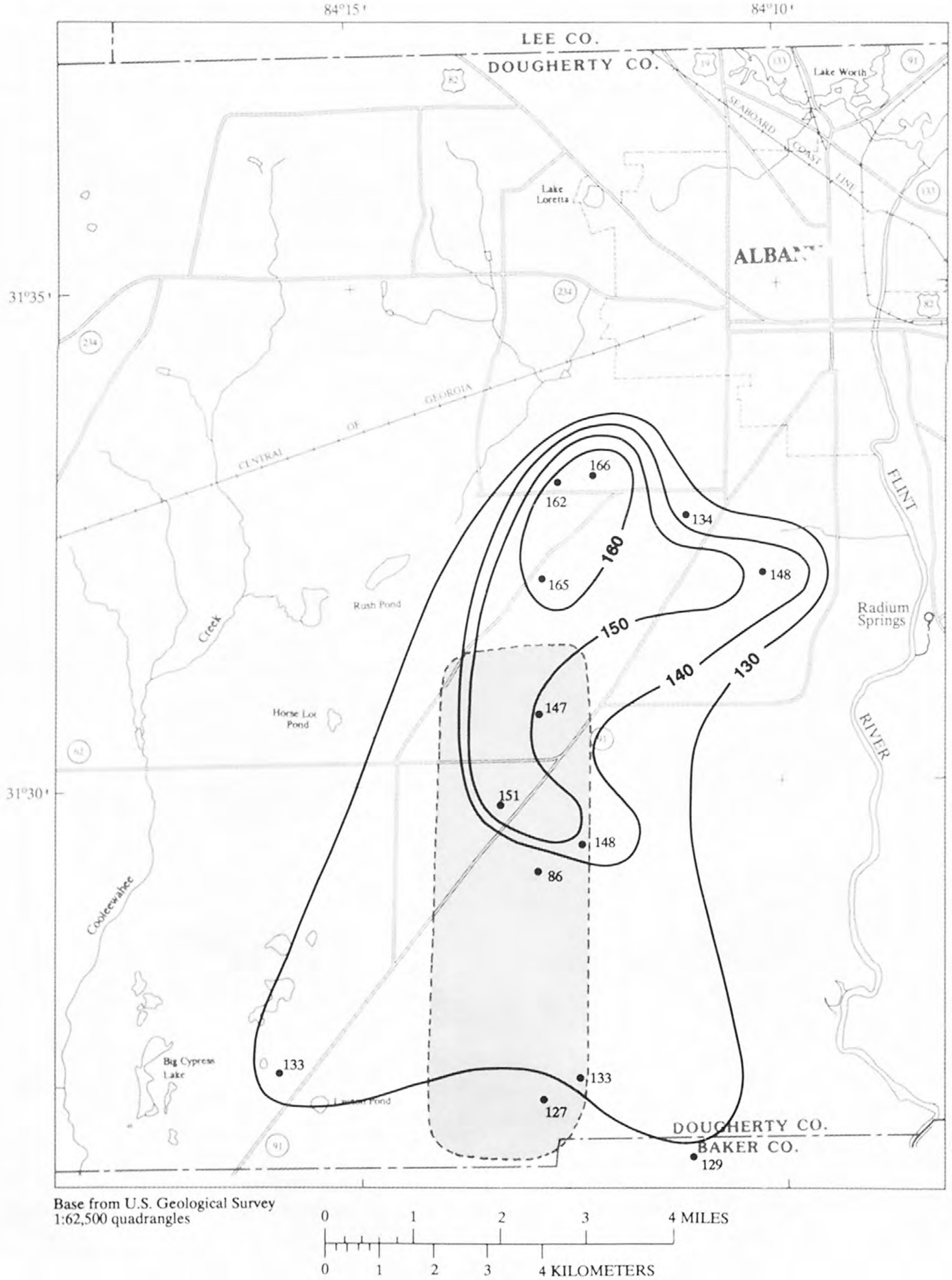


EXPLANATION

AQUIFER THICKNESS AT NODAL LOCATION, IN FINITE-ELEMENT MESH, INDICATED BY PATTERNS
AQUIFER THICKNESS, IN FEET

- Less than 50
- 50 to 100
- 100 to 200
- Greater than 200

Figure 5.--Thickness of Upper Floridan aquifer.



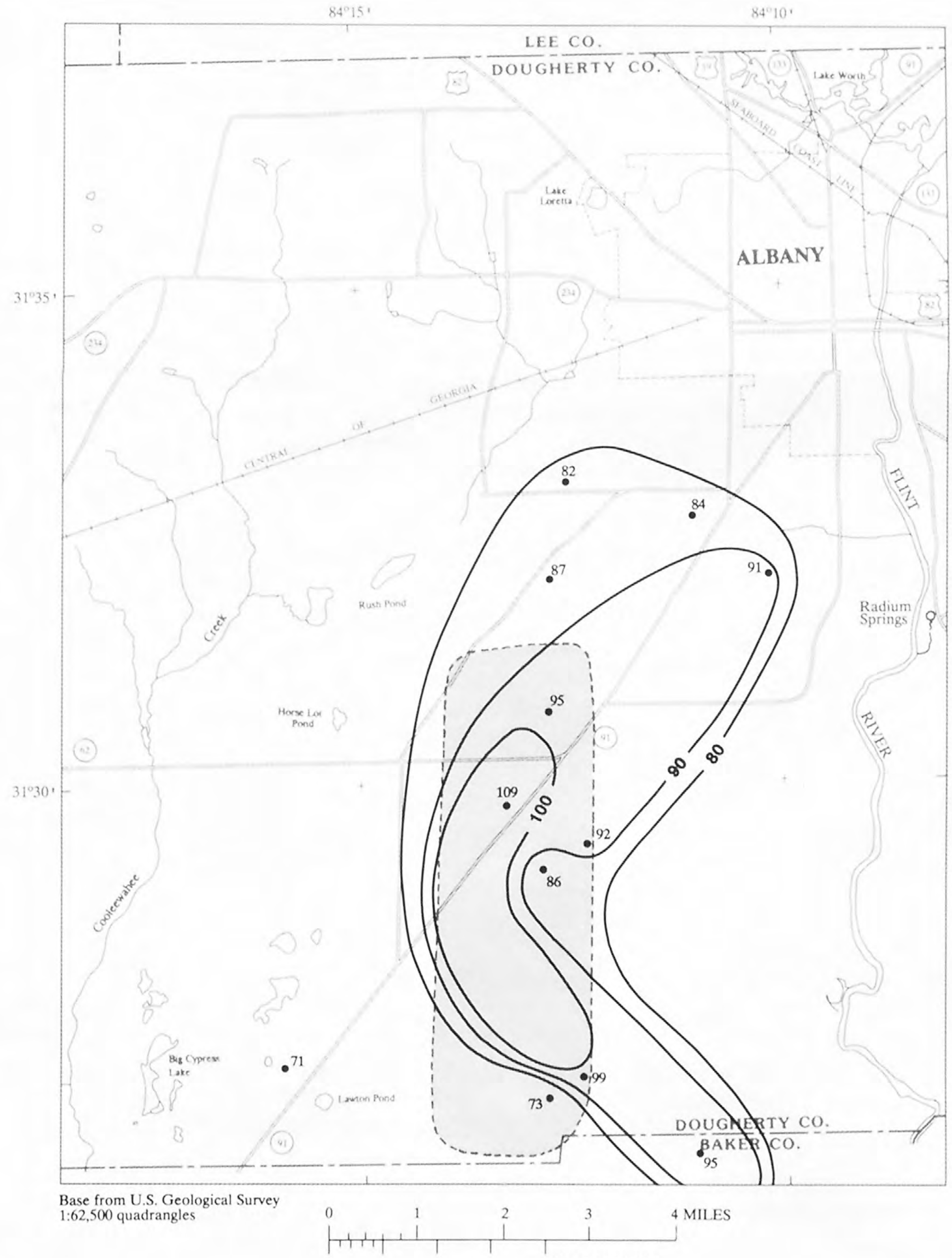
EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

—140— TOP-OF-AQUIFER CONTOUR--Shows altitude of top of upper water-bearing zone. Contour interval 10 feet. Datum is sea level

133 • WELL--Number indicates altitude of top of upper water-bearing zone, in feet above sea level

Figure 6--Altitude of top of upper water-bearing zone of Upper Floridan aquifer in area of potential development, southwest of Albany, Georgia.



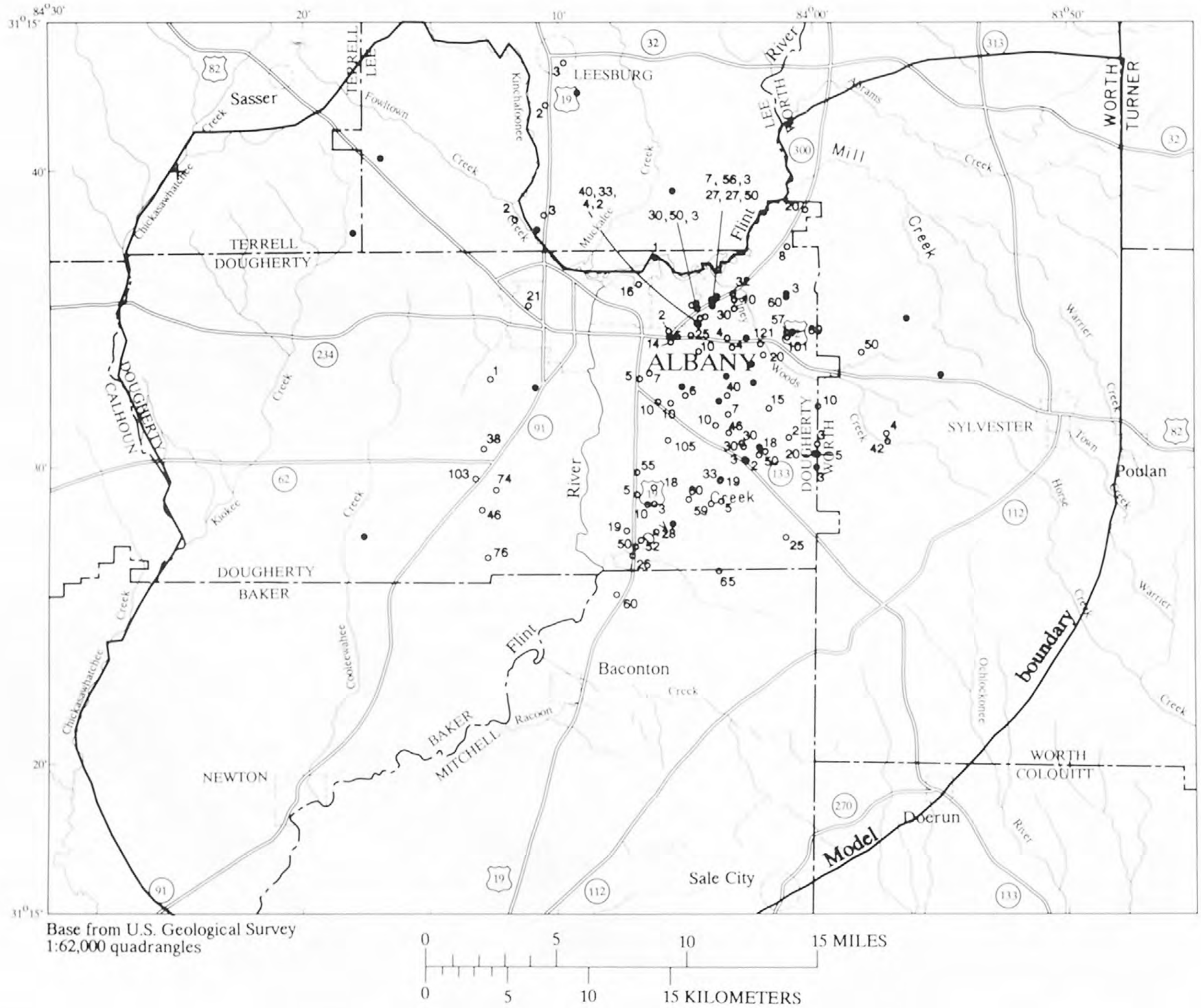
EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

—80— TOP-OF-AQUIFER CONTOUR-- Shows altitude of top of upper water-bearing zone. Contour interval 10 feet. Datum is sea level

73
● WELL--Number indicates altitude of top of lower water-bearing zone, in feet above sea level

Figure 7.--Altitude of top of lower water-bearing zone of Upper Floridan aquifer in area of potential development, southwest of Albany, Georgia.



EXPLANATION

WELLS USED TO DEFINE HYDRAULIC-CONDUCTIVITY

• **Dense, hard limestone, with no solution openings or fracture**

60 o **Solution openings or fractures. Number indicates thickness of feature, in feet**

Figure 8.--Wells used to define hydraulic conductivity in Upper Floridan aquifer.

Thickness of the lower water-bearing zone ranges from about 46 ft at Albany to about 85 ft northeast of Albany, and to about 58 ft to the southwest (Hicks and others, 1987, p. 11). In the area of potential development, thickness of the lower unit ranges from about 48 ft at well WGL1 to about 104 ft at well WGL2 (fig. 3). The altitude of the top of the lower water-bearing zone (fig. 7) is hydrologically significant, as water-level declines below the top of the lower water-bearing zone will increase the potential for sinkhole formation (Hicks and others, 1987, p. 40).

Lisbon Formation

The hard, well-cemented, and clayey nature of the limestone comprising the Lisbon Formation in the study area gives this unit a distinctly lower water-yielding capability when compared with the Upper Floridan aquifer, causing it to act as an impermeable base to the Upper Floridan aquifer (Hayes and others, 1983). Because of the relatively low transmissivity compared with the Upper Floridan aquifer (Watson, 1981), wells yield only a few gallons per minute from this unit, although southeast of the study area, domestic supplies of water may be obtained from the Lisbon Formation (Hayes and others, 1983).

Results of a regional ground-water-flow analysis that included the Upper Floridan aquifer and the Lisbon Formation indicate that the Lisbon Formation acts as an impermeable base to the Upper Floridan aquifer in the study area (Robert E. Faye and Gregory C. Mayer, U.S. Geological Survey, written commun., November, 1990). These results indicate that recharge by vertical leakage to the Upper Floridan aquifer across the Lisbon Formation occurs north of the study area at a rate of about 10 ft^3/s, and that discharge from the Upper Floridan aquifer through the Lisbon Formation occurs south of the study area at a rate of about 5 ft^3/s, with no leakage occurring in the Albany area. With a total lateral-flow component through the aquifer of about 4,000 ft^3/s (Robert E. Faye and Gregory C. Mayer, written commun., November, 1990), the Lisbon Formation is an effective impermeable lower boundary to the Upper Floridan aquifer.

Ground-Water Levels

Ground-water levels in the transmissive parts of the undifferentiated overburden and in the Upper Floridan aquifer respond positively (increase) to recharge and negatively (decrease) to discharge. Water levels generally are higher in areas where the aquifer and the overburden are recharged and are lower in areas where ground water discharges naturally to streams, or in areas of heavy pumping. In the undifferentiated overburden, water levels respond relatively quickly to precipitation and drought. However, in the Upper Floridan aquifer, neither the response time nor the magnitude of water-level changes resulting from precipitation or drought is predictable; it varies areally and can be either nearly instantaneous or very slow, or, either large or barely perceptible.

Seasonal fluctuations

The ground-water level in the Upper Floridan aquifer generally is at a maximum during February through April, declines through summer, and is at a minimum during November and December. During years of normal precipitation, seasonal fluctuations in the water level ranges from about 2 ft in the eastern part of the study area, to about 30 ft near Albany. Near major agricultural and industrial pumping centers, seasonal water-level fluctuations probably exceed 30 ft. However, unlike water-level fluctuations in the deeper aquifers, these fluctuations (declines) do not result in the formation of distinct cones of depression in the potentiometric surface of the Upper Floridan aquifer (Hicks and others, 1987). In the area of potential ground-water development, annual water-level fluctuations range from about 7 to 18 ft.

The water level in the undifferentiated overburden is highest during February through April, declines during the summer and fall, and is at a minimum during November through January (fig. 9). Beginning in late December and continuing through January, water levels in wells experience a rapid increase in response to recharge by infiltration of precipitation. Monthly water levels in 22 wells tapping the undifferentiated overburden ranged from about 1 to 22 ft below land surface for the period April 1982 through December 1984 (Sandra C. Cooper, U.S. Geological Survey, oral commun., 1984). Maximum annual-water-level fluctuations in individual wells ranged from about 10 to 16 ft.

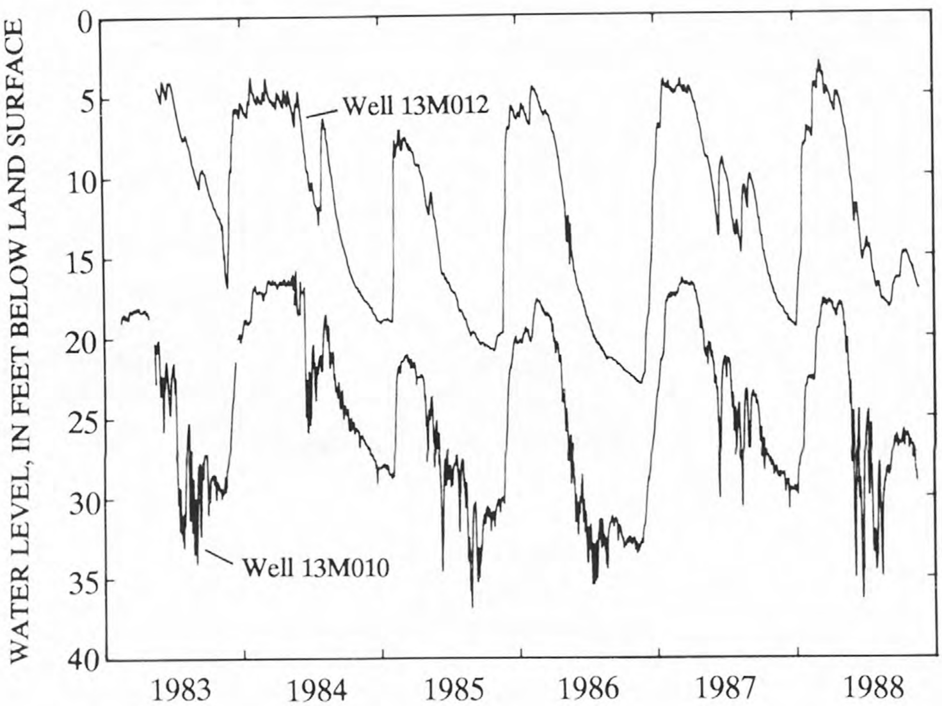


Figure 9.--Water-level fluctuations in wells 13M010 and 13M012, in undifferentiated overburden, 1983-88 (see fig. 1 for location).

Long-term effects of drought conditions and pumping

The water level in the Upper Floridan aquifer in the Albany area has not shown long-term declines from drought conditions. A typical response to drought conditions in the Upper Floridan aquifer is shown by the water-level hydrograph of well 13L003 (fig. 10), which is located near the Dougherty-Worth County line. During the droughts of the early and late 1960's, 1980-81, and 1986, the water level in well 13L003 declined to record or near-record lows, but recovered to predrought levels with the return of normal precipitation (Hicks and others, 1987). During the drought of 1986, water levels in wells 11K015, 12L028, and 12K014 declined to record lows, but with the return of normal precipitation during the next season, they recovered to predrought levels (figs. 11-13).

The potentiometric surface of the Upper Floridan aquifer for conditions that existed prior to development (1957) (Wait, 1963) was compared with the potentiometric surface for November 1985 (Hicks and others, 1987, plate 1). Similarities between the two surfaces show that 28 years of pumping at an average rate of about 66 Mgal/d from the Upper Floridan aquifer has not produced a long-term decline in the ground-water level. Thus, the ground-water-flow system of the Upper Floridan aquifer remains in equilibrium; recharge received from normal, annual rainfall is approximately equal to the combined effects of natural and man-induced discharge (Hicks and others, 1987, p. 22).

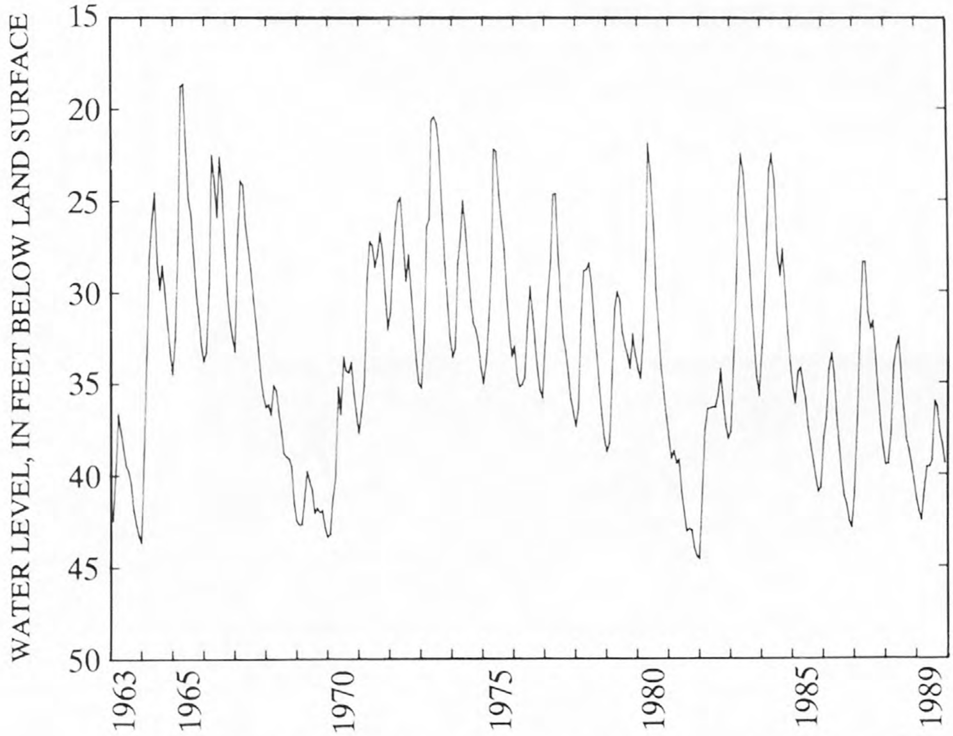


Figure 10.--Water-level fluctuations in well 13L003 in Upper Floridan aquifer, 1963-89 (see fig. 1 for location).

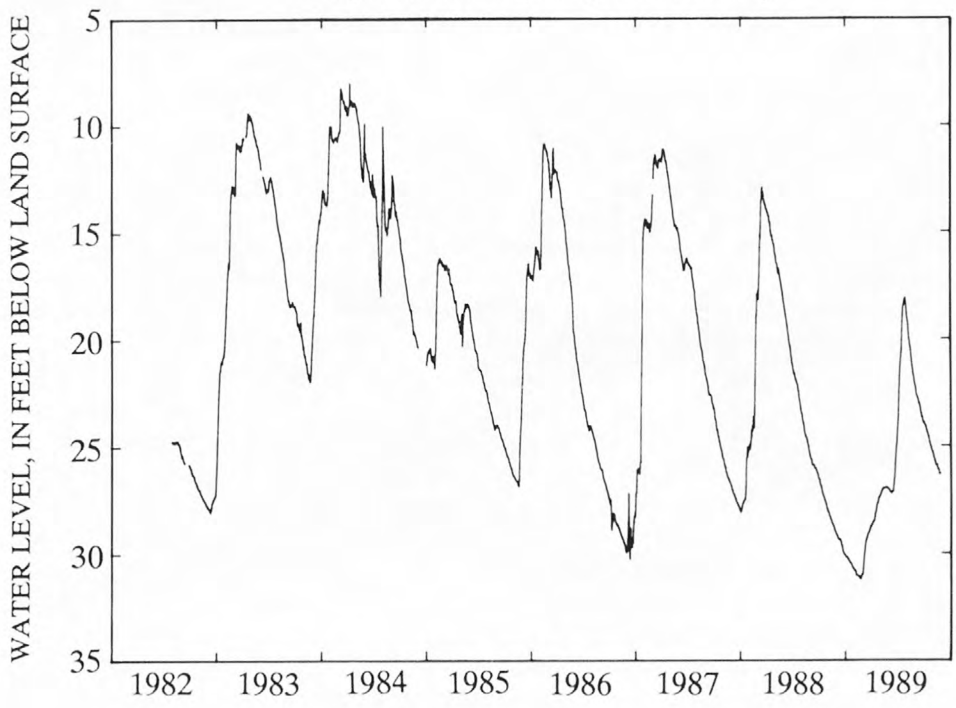


Figure 11.--Water-level fluctuations in well 11K015 in Upper Floridan aquifer, 1982-89 (see fig. 1 for location).

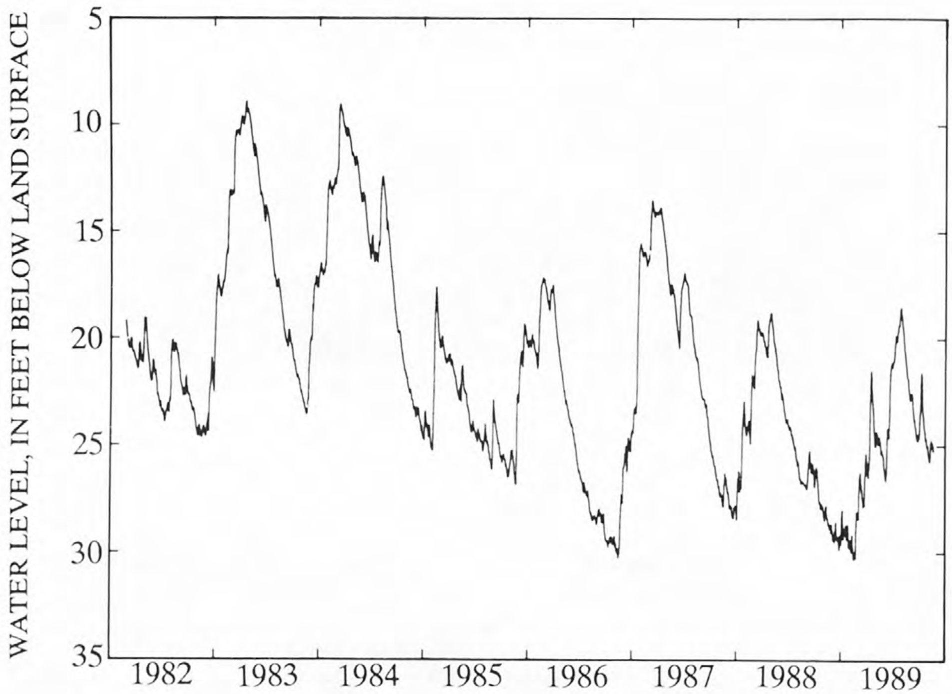


Figure 12.--Water-level fluctuations in well 12L028 in Upper Floridan aquifer, 1982-89 (see fig. 1 for location).

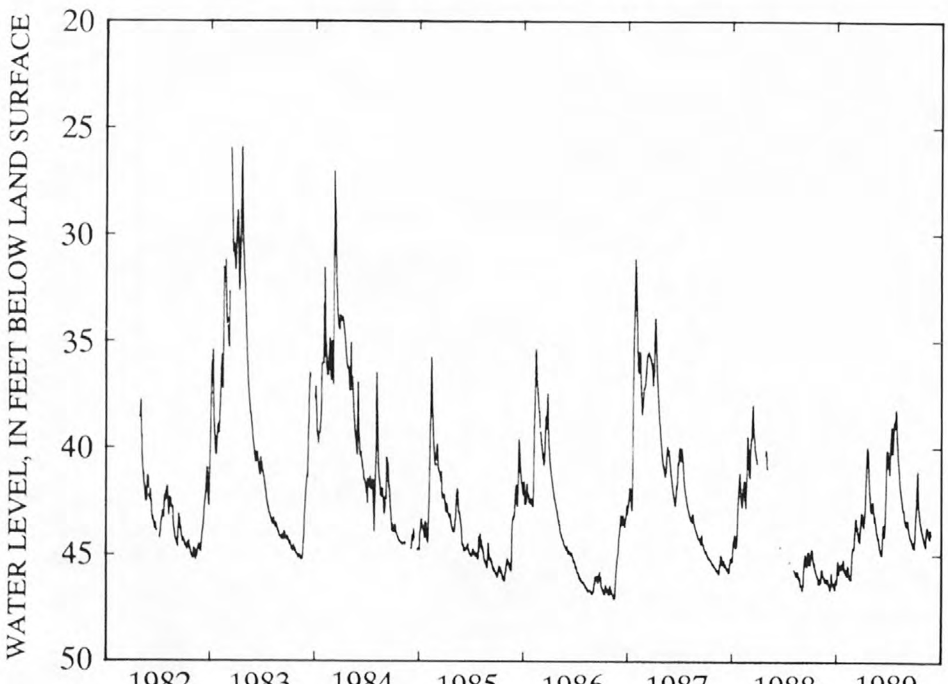


Figure 13.--Water-level fluctuations in well 12K014 in Upper Floridan aquifer, 1982-89 (see fig. 1 for location).

Ground-Water Quality

Water in the Upper Floridan aquifer is of good quality and generally does not contain constituent concentrations that exceed the maximum contaminant levels established for drinking water by the Georgia Department of Natural Resources (1977) and the U.S. Environmental Protection Agency's (EPA) Primary or Secondary Drinking-Water Regulations (1986 a,b). The water generally is a hard, calcium-bicarbonate type and is less mineralized than water in deeper aquifers (Hicks and others, 1981).

Water-quality samples from the Upper Floridan aquifer and from the Flint River at Newton were collected as part of a previous investigation by Hicks and others (1987); no sampling of water in the Upper Floridan aquifer was conducted for this water-resource evaluation. The analyses by Hicks and others (1987, p. 33-36) indicated that the general quality of water in the Upper Floridan aquifer is suitable for most purposes, although trace concentrations of certain organic compounds were detected in some wells. However, as stated by Hicks and others (1987, p. 35), the samples indicated a one-time concentration of these contituents in the aquifer at specific locations, and flushing (transport) or dilution at these locations may have precluded detection at a later time. In addition, water samples from wells in rural areas and in the area of potential development did not contain these constituents.

Water from a well completed in the Upper Floridan aquifer in an urban area of Albany contained higher concentrations of trace metals and was more acidic than samples collected in rural or agricultural areas (Hicks and others, 1987, table 2). Water from another well in an urban area of Albany contained a trace amount of chlordane, the use of which is restricted by the EPA to subsurface injection for termite control and two volatile organic compounds (VOC), which are used as industrial degreasers: tetrachloroethylene (5.9 μg/L) and trans-1,2-dicloroethylene (16 μg/L). Organic compounds such as aldicarb, a nematicide, its degredation products sulfoxide and sulfone, and the insecticide dieldrin occurred in some of the water samples from wells tapping the Upper Floridan aquifer for agricultural supply. These compounds probably entered the Upper Floridan aquifer as vertical recharge from the undifferentiated overburden, as they generally are applied to the soil as agricultural pesticides. However, analyses of samples collected from the same wells six months later showed no detectable concentrations of these constituents (Hicks and others, 1987, p. 33).

Ground-Water and Surface-Water Relations

In the study area, the base flow of the Flint River and its tributaries is maintained by discharge from the Upper Floridan aquifer. Discharge to the streams is at a maximum during winter and early spring when ground-water levels are at a maximum, but as ground-water levels decline in late spring and summer, the volume of ground-water discharge decreases. Base-flow measurements that were made for the Flint River and its tributaries during the low-flow period October 27 and 28, 1986, indicated that the Flint River received about 1,079 ft^3/s of ground-water discharge in the river reach between Albany and Newton (fig. 1). Major solution conduits emerging in or near the Flint River transmitted large volumes of water from the Upper Floridan aquifer to the river.

Although the lithology and the degree of solutioning of the Upper Floridan aquifer near the Flint River indicates good hydraulic connection between the aquifer and the river, sudden changes in river stage for short durations of time do not necessarily cause a corresponding water-level change in the aquifer. From February 21 to March 4, 1987, the stage of the Flint River at Albany rose more than 12 ft in response to heavy rainfall in the northern part of the State. However, the water level in well 12K014, less than 2 mi from the Flint River (fig. 1), increased by less than 2 ft during the same period (fig. 14).

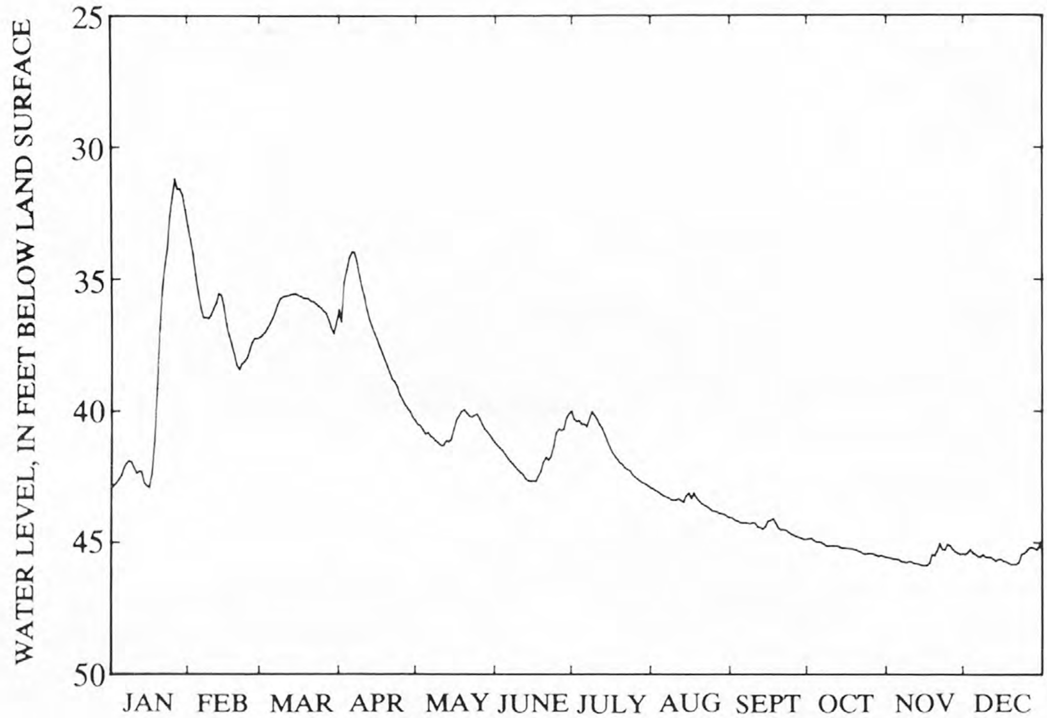


Figure 14.--Water-level fluctuations in well 12K014 in Upper Floridan aquifer, 1987 (see fig. 1 for location).

EVALUATION OF WATER-RESOURCE POTENTIAL OF THE UPPER FLORIDAN AQUIFER

Water-resource potential of the Upper Floridan aquifer is defined as the ability of the aquifer to provide an additional supply of water over that which is presently being pumped, without causing adverse hydrologic effects on the ground-water and surface-water systems. Adverse effects that might occur generally are the result of excessive water-level declines near pumped wells, which could cause hydraulic gradients from the Upper Floridan aquifer toward surface-water features and toward the undifferentiated overburden to be reversed, increase the potential for sinkhole development due to aquifer dewatering, and degrade the quality of water. The implications of these possible adverse hydrologic effects on the flow system include contamination of the Upper Floridan aquifer by induced recharge from the overlying undifferentiated overburden or from the Flint River, decreased well yields, increased power consumption to sustain well yields, or lowering of well-pump intakes.

Interpretation of Results of Test Drilling, Aquifer Testing, and Data Analysis

Test drilling, aquifer testing, and data analysis of the Upper Floridan aquifer in the area of potential development indicated that large quantities of water could be withdrawn from the aquifer without causing adverse hydrologic effects on the flow system. Fractures and solution openings that were observed in wells tapping the aquifer also suggested that large quantities of water can move through the Upper Floridan aquifer under conditions that approach conduit flow; thus, drawdown and well-interference effects in the area of potential development would be minimal. This concept was verified by testing wells 12K016 and 12L048 at rates of 5.8 Mgal/d and 3.6 Mgal/d, respectively, and observing drawdowns in the aquifer (David W. Hicks, U.S. Geological Survey, written commun., April, 1988).

Interpretation and analysis of hydrologic data indicate that the Upper Floridan aquifer is capable of establishing equilibrium or steady-state conditions quickly during the mid-to-late fall months. Results of pumping tests in the Albany area on file at the District Office of the U.S. Geological Survey, 6481-B Peachtree Industrial Blvd., Doraville, Ga., indicate that ground-water levels are restored to prepumping conditions within about 4 days after the stress is removed. Water-levels in wells that are completed in the aquifer and in the undifferentiated overburden (figs. 9-14) appear to be constant during this period; these units receive little or no recharge by infiltration of precipitation during the fall months, and irrigation pumpage has decreased with the end of the growing season. The rapid increase in water levels in late December and early January caused by recharge to the Upper Floridan aquifer by infiltration of precipitation verifies the short duration of time needed for the aquifer to respond to stress and for equilibration to steady-state conditions. Therefore, it is reasonable to assume that the aquifer exhibits steady-state conditions during the low-flow period of November 1985.

The following implications about the water-resource potential of the Upper Floridan aquifer were developed from interpreting results of test drilling, aquifer testing, and data analysis:

- the aquifer exhibited equilibrium or steady-state conditions for the November 1985 period, which coincided with seasonal-low ground-water levels and streamflow conditions in the Albany area;

- the large positive hydraulic gradients that extend through the aquifer to the Flint River downstream from the Lake Worth dam indicate that a large component of aquifer discharge to the River occurs in this area;

- the relation between aquifer head and river stage indicates that large withdrawals from the aquifer would not reverse the hydraulic gradient to the Flint River; and therefore, not induce leakage from the River;

- the relatively thick clay and silty-clay layers within the undifferentiated overburden, and the massive, recrystallized and dolomitized limestone of the Lisbon Formation beneath the aquifer indicate that the Upper Floridan aquifer is confined along its upper and lower boundaries in the vicinity of the area of potential development; and thus,

- vertical leakage across either boundary would be small in response to increased pumping from the aquifer.

The effects of the development of water from in the Upper Floridan aquifer and of these aspects of the flow system--vertical leakage from the undifferentiated overburden, regional flow to and induced recharge from the Flint River, well interference, and the potential for sinkhole formation--were analyzed by using a finite-element model that simulated ground-water flow in the aquifer, and are discussed in the following sections of this report.

Simulation of Ground-Water Flow

A two-dimensional, finite-element model of steady-state ground-water flow was used to simulate the flow system of the Upper Floridan aquifer as it existed in November 1985, and to aid in evaluating the water-resource potential in a part of the study area located southwest of Albany. Simulation was used to test our conceptual models of the ground-water- and surface-water-flow system, which were based on interpretations of data and on results of test drilling and aquifer-test analysis. Complexities in the ground-water- and surface-water-flow system, in aquifer geometry, and in lateral and vertical boundary conditions required that numerical simulation be used to incorporate as many of these complexities into the water-resource evaluation as possible. The ability of the finite-element model to accurately represent these complexities was essential for providing definitive results that could be used to evaluate the water resources of the Upper Floridan aquifer and to define flow-system response to potential development.

Certain disadvantages and limitations to using a steady-state approach in the water-resources evaluation of the Upper Floridan aquifer need to be addressed and understood before discussing the evaluation and its results. Conversely, a steady-state approach to evaluating the water-resources potential of the Upper Floridan aquifer has distinct advantages over a nonsteady-state approach. The water manager must be able to weigh the advantages, disadvantages, and limitations of the steady-state approach used in this evaluation before making long-term decisions about developing the ground-water resources of the Upper Floridan aquifer.

Disadvantages and limitations of a steady-state approach

Because steady-state ground-water flow is neither time dependent nor time variant, transient effects of releasing water from, or taking water into, storage within the Upper Floridan aquifer and within the undifferentiated overburden are not addressed by the steady-state approach. These transient effects are manifested in the leakage of water across the boundary between the Upper Floridan aquifer and undifferentiated overburden and in a decrease in water-level changes as the aquifer responds to changes in stress on the system. Thus, a disadvantage or limitation to using a steady-state approach to evaluate the water-resource potential of the Upper Floridan aquifer is that transient responses within the aquifer and overlying semiconfining unit are not represented when changes in stress are applied to the flow system. These transient responses cause a time delay for the aquifer to equilibrate to the new, long-term, steady-state condition that reflects long-term, flow-system response to changes in stress (such as changes in pumping rates, river stage, or recharge from infiltration of precipitation).

Although transient responses in the aquifer and semiconfining unit eventually dissipate with time, these responses might represent an important source (or sink) of water to be released from (or taken into) storage before they dissipate completely, leaving only steady-state and steady-leakage conditions. Hence, a limitation of a steady-state approach to the evaluation is that there is no mechanism to account for water that is taken up or released by storage within the Upper Floridan aquifer and undifferentiated overburden during initiation of stresses on the system. A further limitation is that values for aquifer storage coefficient and specific storage of the undifferentiated overburden--the hydrologic properties that directly affect transient response--cannot be derived from this evaluation.

Advantages of a steady-state approach

Steady-state simulation of low-flow and low-water-level conditions in the evaluation of an aquifer system provides conservative estimates (worst-case conditions) of the long-term effects of additional ground-water development on the system. Imposing additional stress on an aquifer that already exhibits low-flow and low-water-level conditions causes the aquifer to be stressed beyond conditions that actually might occur within the study area during normal periods of seasonal precipitation. Sustaining the additional stress until new steady-state conditions are established in the aquifer and undifferentiated overburden provides conservative estimates of the water-resource potential of the aquifer and allows evaluation of the increased potential for sinkhole development during water-level conditions that are most conducive to their formation. Transient effects in the aquifer and overlying semi-confining unit will create a time delay in achieving worst-case conditions of maximum water-level declines in response to increased pumpage. The water-resource potential and the increased potential for sinkhole development can be evaluated only under worst-case conditions, which are attained through a steady-state approach during low-water-level conditions. Periods of drought or an extended period of unusually low precipitation, such as in November 1985 and in two other periods during the last decade, exacerbate an already low water-level condition. This situation, coupled with a rapid response time of the aquifer to adjust to stress, renders the timing of transient effects within the Upper Floridan aquifer and the undifferentiated overburden irrelevant to the water-resource evaluation.

By adopting a steady-state approach to the water-resource evaluation, the temporal, short-term (transient) responses of the undifferentiated overburden to contribute water to the Upper Floridan aquifer are eliminated. These responses tend to create smaller water-level declines in the aquifer than would occur under steady-state conditions. Transient responses also delay the establishment of a flow-through (steady) component of leakage; therefore, delaying the migration of water on the land surface, and hence, any contaminants from entering the Upper Floridan aquifer. By eliminating transient effects, steady leakage from (or flow through) the undifferentiated overburden is permitted to occur at the instant that the additional stress is applied, thereby giving a long-term, worse-case estimate of the rate at which surface contaminants can enter the aquifer in response to additional pumping. Thus, in keeping with the objectives of this report, the water-resource potential of the Upper Floridan aquifer, the potential for increased sinkhole development due to dewatering, and the likelihood of infiltration of contaminants, are evaluated by considering those hydrologic conditions that are not only plausible in nature, but yield the most water-level decline--the conditions of steady state and low flow.

Conceptualization of the flow system

Conceptualization of the flow system of the Upper Floridan aquifer was based on interpretation of available hydrologic data given in the preceeding sections. This conceptualization was a prelude to forming a working hypothesis of the flow system, from which conceptual models were developed and tested by using simulation.

The ground-water- and surface-water-flow system was in equilibrium for the November 1985 conditions. Water levels in wells that were completed in the Upper Floridan aquifer were near seasonal lows, and the aquifer had not received any recharge (infiltration from precipitation) that would significantly affect water levels.

The Upper Floridan aquifer is semiconfined above by undifferentiated overburden and effectively confined below by the Lisbon Formation (fig. 15). The principal recharge mechanism to the aquifer is vertical leakage from perched, water-bearing zones within the undifferentiated overburden. The variable thickness and content of sand and clay in the overburden (Hayes and others, 1983) result in zones of locally large and small leakage rates to and from the overburden.

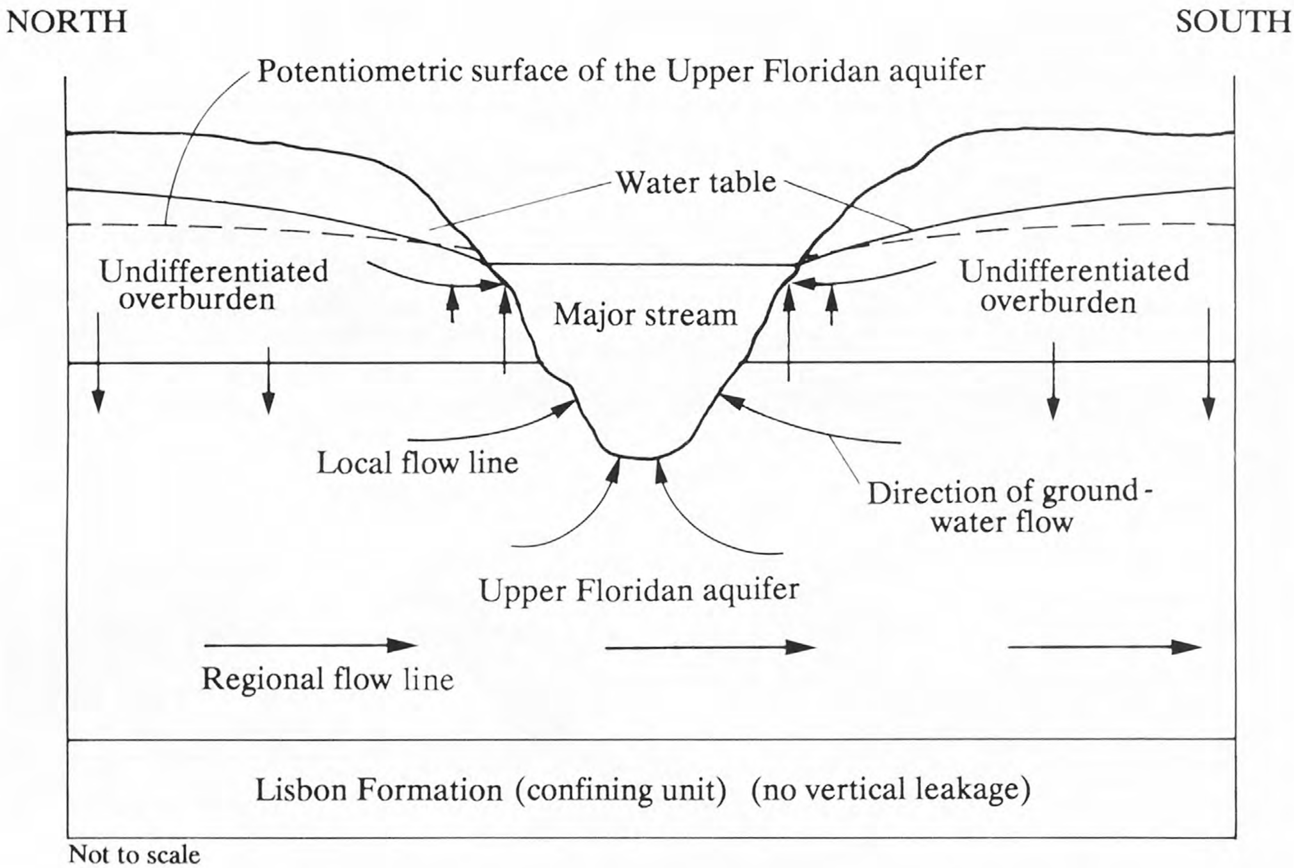


Figure 15.--Conceptual flow model of Upper Floridan aquifer (modified from Hayes and others,1983).

In the study area, the flow system of the Upper Floridan aquifer is dominated by regional inflow across most of the boundaries and by discharge to the Flint River (fig. 1). Some regional outflow occurs along the eastern boundary near Sylvester and, along the southern boundary, flow is generally east to west until it discharges to the Flint River (fig. 1). Other surface-water features, such as creeks and streams, reservoirs, lakes, and solution features that are typical of karst areas, have minor effects on shaping the potentiometric surface of the Upper Floridan aquifer.

The Upper Floridan aquifer was conceptualized as a single, isotropic, water-bearing unit of variable thickness and hydraulic conductivity. Horizontal and vertical variations in hydraulic properties caused by changes in lithology and in the extent of solution openings and fractures contribute to the lateral nonhomogeneity of the aquifer. Depending on the relative altitudes of the water level in the aquifer and the top of the aquifer, water in the aquifer was either unconfined (water-table) or confined (artesian).

Mathematical model

The mathematical model used to simulate ground-water flow in the Upper Floridan aquifer consists of partial-differential equations that are assumed to describe the physics of fluid flow in porous media, subject to certain boundary conditions (Richard L. Cooley, U.S. Geological Survey, written commun., 1990). Variants of the governing equation and boundary conditions are presented as they apply to flow in the Upper Floridan aquifer.

Governing Equation

Ground-water flow in the Upper Floridan aquifer within the boundaries of any discontinuities in transmissivity or within external boundaries is assumed to be governed by the following two-dimensional, steady-state-flow equation

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x} + T_{xy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x} + T_{yy}\frac{\partial h}{\partial y}\right) + R(H-h) + W + P = 0; \qquad (1)$$

where

(x,y) = Cartesian coordinate directions [length];

$h(x,y)$ = hydraulic head in the aquifer [length];

$H(x,y)$ = hydraulic head in the source layer [length];

$\begin{bmatrix} T_{xx}(x,y) & T_{xy}(x,y) \\ T_{yx}(x,y) & T_{yy}(x,y) \end{bmatrix}$ = symmetric transmissivity tensor written in matrix form [length^2/time]

$R(x,y)$ = vertical hydraulic conductance (vertical hydraulic conductivity divided by thickness) of a confining bed [time^{-1}];

$W(x,y)$ = unit areal recharge or discharge rate (positive for recharge) [length/time];

$P(x,y) = \sum_{j=1}^{p} \delta(x-a_j)\,\delta(y-b_j)\,Q_j$ = Dirac-delta designation for p point sources or sinks, each of strength Q_j [length/time] and located at (a_j, b_j). Q_j is positive for injection.

Boundary and Initial Conditions

Equation (1) is subject to the following boundary and initial conditions:

(1) At a discontinuity in transmissivity (an internal boundary) the normal component of ground-water flow and the hydraulic head are unchanged as the discontinuity is crossed. Thus, at a discontinuity in transmissivity between aquifer zones a and b (fig. 16), the normal component of flow at the zone boundary is given as $q_n \big|_*$, where $*$ = a,b, and

$$q_n \big|_a = q_n \big|_b$$

or

$$\left[n_x \left(T_{xx}\frac{\partial h}{\partial x} + T_{xy}\frac{\partial h}{\partial y}\right) + n_y \left(T_{yx}\frac{\partial h}{\partial x} + T_{yy}\frac{\partial h}{\partial y}\right)\right] \Big|_a$$

$$= \left[n_x \left(T_{xx}\frac{\partial h}{\partial x} + T_{xy}\frac{\partial h}{\partial y}\right) + n_y \left(T_{yx}\frac{\partial h}{\partial x} + T_{yy}\frac{\partial h}{\partial y}\right)\right] \Big|_b ; \qquad (2)$$

where (n_x,n_y) is a unit outward-pointing vector along a boundary; and,

$$h \Big|_a = h \Big|_b; \qquad (3)$$

(2) the normal component of flow, q_n (fig. 16) at a hydrologic boundary is given by the sum of a specified component, q_B , and a head-dependent component, $\alpha(h_B - h)$, or

$$n_x \left(T_{xx}\frac{\partial h}{\partial x} + T_{xy}\frac{\partial h}{\partial y}\right) + n_y \left(T_{yx}\frac{\partial h}{\partial x} + T_{yy}\frac{\partial h}{\partial y}\right); \qquad (4)$$

$$= q_B + \alpha(h_B - h);$$

where

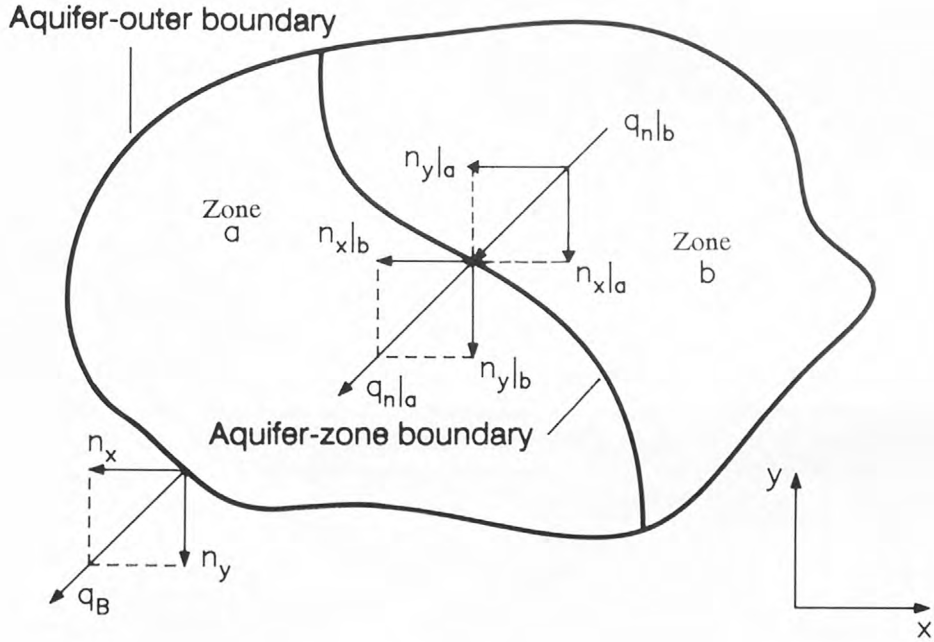
$\alpha(x,y)$ = a parameter equal to "infinity" for a specified-head (Dirichlet) condition and to zero for a specified-flux (Neumann) condition. A general (Cauchy) boundary condition is specified by a finite and positive α (Cooley, 1983);

$q_B(x,y)$ = specified component of flux normal to a boundary [length^2/time];

$h_B(x,y)$ = specified head at a boundary [length];

(3) the hydraulic head is known everywhere for the steady-state period, or $h = h_o$; (5)

where $h_o(x,y)$ is the initial head [length] (required as transmissivity is a function of hydraulic head for water-table conditions.



EXPLANATION

$q_n|_a$, $q_n|_b$ --NORMAL COMPONENT OF GROUND-WATER FLUX ENTERING OR LEAVING ZONES a AND b, RESPECTIVELY

$n_x|_a$, $n_x|_b$ --UNIT VECTOR IN x DIRECTION ASSOCIATED WITH $q_n|_a$ AND $q_n|_b$, RESPECTIVELY

$n_y|_a$, $n_y|_b$ --UNIT VECTOR IN y DIRECTION ASSOCIATED WITH $q_n|_a$ AND $q_n|_b$, RESPECTIVELY

q_B --SPECIFIED COMPONENT OF GROUND-WATER FLUX NORMAL TO A BOUNDARY

n_x , n_y --UNIT OUTWARD-POINTING VECTORS IN x AND y DIRECTIONS, RESPECTIVELY, ASSOCIATED WITH q_B

x , y --CARTESIAN COORDINATE DIRECTIONS

Figure 16.--**Boundary fluxes,** q_n , across aquifer-zone boundary, and q_B, across aquifer-outer boundary.

Both artesian (linear) and water-table (nonlinear) conditions, which exist in the Upper Floridan aquifer, are represented by equation (1). Ground-water flow under artesian conditions is linear (having linear boundary conditions), as terms in equation (1) that multiply either hydraulic head h(x,y) or derivatives of head are not functionally dependent on head. Under water-table or semiconfined conditions, equation (1) contains terms that are functionally dependent on head; transmissivity is a function of aquifer thickness, which in turn is a function of hydraulic head, and the steady-leakage term R(H-h) is a function of the difference between the head in the undifferentiated overburden and the altitude of the top of the aquifer. The latter condition is nonlinear because the form of the expression for the leakage rate changes as a function of the position of the aquifer head relative to the top of the aquifer. The linear case of steady vertical leakage is shown in equation (1) as the hydraulic conductance R is multiplied by the head difference (H-h).

The bracketed terms in equation (2) are unit discharges across the aquifer-zone boundary. Likewise, the sum of the first two terms in equation (4) are unit discharges across and normal to the aquifer-outer boundary, and are positive for inflow. For convenience, specified and head-dependent components of equation (4) are termed Cauchy-type boundaries as each component represents a special case of the Cauchy-boundary condition (Norrie and deVries, 1973; and Cooley, 1983). Linear and nonlinear forms of equation (4) are used to represent boundary conditions in the study area. Details of specific applications are given in the following sections.

Numerical model MODFE

The numerical model used to simulate ground-water flow in the Upper Floridan aquifer is the MODular Finite-Element model (MODFE) of the U.S. Geological Survey (Richard L. Cooley, U.S. Geological Survey, written commun., 1990; and Torak, 1990). The governing equation and boundary conditions are approximated in MODFE by using the extended Galerkin finite-element method with triangular elements and linear coordinate (basis) functions in space (Cooley, 1983; and Zienkiewicz, 1977, chapter 3). Approximate solutions to the governing equation are obtained at the intersections of element sides, which are called nodes.

Finite-Element Mesh

A finite-element mesh consisting of 3,061 triangular elements and 2,962 nodes was used to represent the variability in hydraulic properties, boundary geometry, surface-water features, and hydraulic head within the study area (plate 1). The general pattern of ground-water movement and of ground-water and surface-water interaction that was shown in figure 1 aided in defining the model boundaries shown on plate 1. In general, the mesh was comprised of equilateral triangles of two sizes, 2,083 and 4,167 ft on a side; however, element sizes were adjusted by moving nodes where specific flow-system geometries needed to be represented, such as along stream reaches or along the external-model boundary. For these cases, the size of element sides ranged from about 1,100 ft along parts of streams to about 4,750 ft along part of the external-model boundary. Part of the study area southwest of Albany was represented by using the smaller-sized elements, as the model in this area was used in evaluating the water-resource potential of the aquifer in the area of potential development. The smaller elements permitted details in computed hydraulic head and in aquifer-property variability to be represented more accurately than those in the larger elements in order to evaluate the effects of increased pumpage on the water level in the Upper Floridan aquifer.

Selection of the sizes and shapes of elements used in this study was the result of preliminary simulations that tested the ability of various element sizes and shapes to accurately represent changes in aquifer properties, boundary geometry, and hydraulic head. The finite-element mesh used here was designed to accomodate more complex features in the potentiometric surface than actually existed for the period of November 1985, such as distinct cones of depression caused by pumping, or large changes in hydraulic gradient over relatively short distances.

Boundary Conditions

Hydrologic boundaries to the study area of regional flow and leakage to and from surface-water features were represented in MODFE by the head-dependent part of a Cauchy-type boundary (Torak, 1990). The exception to this representation is for the Flint River downstream from the Lake Worth dam, which was represented as a nonlinear, head-dependent (Cauchy-type) boundary (Torak, 1990) because of the potential for the water level in the Upper Floridan aquifer to drop below the bottom of the river-bed sediments during simulations of water-resource development. Leakage to and from the undifferentiated overburden was represented in MODFE as a nonlinear, vertical-leakage function (Torak, 1990). Specified-head boundaries were not used to represent any of the hydrologic boundaries; although, the head-dependent parts of the Cauchy-type boundary and the nonlinear Cauchy-type boundary represent weak forms of the specified-head condition.

Regional flow.--

Regional inflow and outflow across external model boundaries were represented in MODFE by the head-dependent part of a Cauchy-type boundary (Torak, 1990). This boundary condition linearly relates the volumetric-flow rate across the boundary to a head difference. The general form of the boundary condition is given as the right side of equation (4) having q_B set to zero. For representing regional flow, the controlling head h_B is located in the aquifer but external to the model area. The controlling head is situated transverse to and at a distance L from the boundary (or element) side so that it is unaffected by water-level changes within the study (model) area (fig. 17). Each node on an element side that defines a Cauchy-type boundary has an external head associated with it. Thus, for node i on an element side defined by nodes k and l, where i = k or l, the volumetric-flow rate across the boundary is expressed as

$$Q_B = (1/2)\alpha L_{kl} (h_{Bi} - h_i) ; \qquad (6)$$

where

$$\alpha = \frac{K\,b}{L} , \qquad (7)$$

for which K and b are defined as the average hydraulic conductivity and thickness, respectively, of the aquifer within the distance L from the external model boundary. The term L_{kl} in equation (6) is the length of the element side. A distance of about 3 mi was used for L in equation (7) for computing the boundary coefficient, α, and for determining the external head h_{Bi}. Values of h_{Bi} for each node i on a Cauchy-type boundary that represents regional flow were interpolated from a map of the potentiometric surface for November 1985 (Hicks and others, 1987).

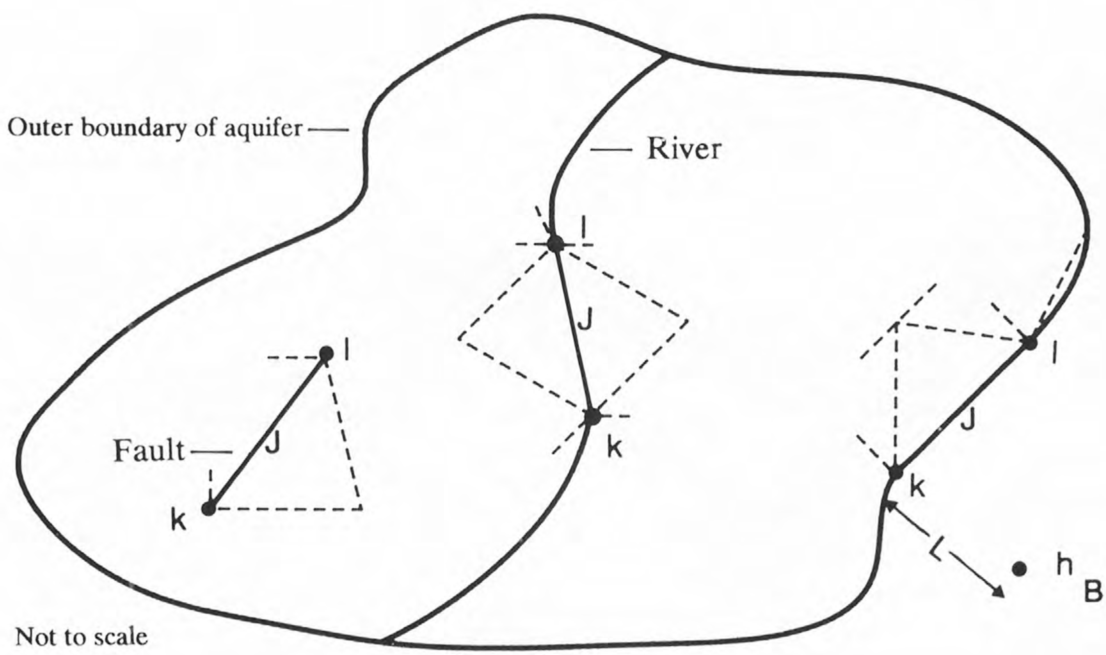


Figure 17.--Applications of head-dependent Cauchy-type boundary along element-side j bounded by nodes k and l. Boundary head, h_B, is located at distance L from aquifer-outer boundary.

Element sides that were used to simulate regional flow as Cauchy-type boundaries were grouped into zones (plate 1) according to the a values that were calculated by equation (7). Of a total of 18 boundary zones, 17 were used to represent regional flow (table 1). Where some zones were situated along surface-water features, the effects of the surface-water features and regional flow were distinguished within the zone by using different α values for each element side (table 1). Zonation of these boundary conditions facilitated data input to MODFE, calibration of the model, and the sensitivity-analysis procedure.

Table 1.--*Cauchy-type boundaries by zone*

[Boundary-coefficient values obtained from calibrated model]

Zone	Number of element sides	Boundary coefficient, α (feet/day)	Description
1	18	10	Northern model boundary; Kinchafoonee Creek
2	3	200	Northern model boundary; Lake Worth and regional flow
3	24	0.05	Cooleewahee Creek
4	15	60	Western model boundary; regional flow
5	8	0	do.
6	13	24.2 to 63.1	do.
7	6	160	Eastern model boundary; regional flow
8	2	90	do.
9	8	105	do.
10	6	135	do.
11	9	12	Northern model boundary; Flint River and regional flow
12	23	18.0 to 69.2	Northern model boundary; Lake Worth, reservoir, and regional flow
13	3	70	Eastern model boundary; regional flow
14	2	80	do.
15	3	120	do.
16	15	120	do.
17	12	200	do.
18	13	17.4 to 55.5	Western model boundary; regional flow.

Surface-water features--

Leakage to and from streams, lakes, and reservoirs was represented in MODFE as the head-dependent part of a Cauchy-type boundary (Torak, 1990) in a manner similar to that in which regional-flow-boundary conditions were represented. For surface-water features, terms contained in equations (6) and (7) were defined as follows. (The nonlinear Cauchy-type boundary that represented the Flint River downstream from the Lake Worth dam (plate 1) is an extension of the head-dependent part of a Cauchy-type boundary, and is described after the general description is given.) The boundary coefficient becomes

$$\alpha = \frac{K_r W_r}{b_r}, \tag{8}$$

where K_r is the vertical hydraulic conductivity of the surface-water sediments, W_r is the width of the surface-water feature, and b_r is the thickness of the sediments (fig. 18a). Values for α are specified either by reach or by zone, where a zone is a collection of reaches that contain the same hydraulic properties (see table 1 and plate 1). The controlling head h_{Bi} in equation (6) is the surface-water level, such as stream stage or lake level, associated with node i. Nodes are aligned along the stream reach, or other surface-water feature, and the width, W_r, is the average width of the surface-water feature, measured transverse to the element side (fig. 18c).

Initial values for the leakage coefficient α were obtained from a previous study by Hayes and others (1983) in the Dougherty Plain, which encompasses the Albany area. These values were adjusted during the calibration procedure to account for differences in the numerical approximation of surface-water features that occur between the finite-difference model used by Hayes and others (1983), and the finite-element model MODFE. Because the leakage coefficient combines three physical properties of the surface-water feature--hydraulic conductivity, width, and sediment thickness--into one term (α), variations in any of these properties cause variations in α. Values for the boundary coefficient that were used in the calibrated model are listed in table 1 by zone.

The representation of surface-water features in MODFE requires that a controlling head, h_B, be input at every node on a reach. Therefore, surface-water levels were interpolated between measurements to obtain these data inputs for MODFE. An extension to the general description of the head-dependent Cauchy-type boundary causes a nonlinear condition that limits leakage from the surface-water feature into the aquifer to a maximum rate when the aquifer head, h, drops below the bottom elevation of the surface-water sediments, z_r (fig. 18a). This condition is termed a nonlinear, head-dependent, Cauchy-type boundary because the form of the leakage expression is dependent on the relative positions of the aquifer head and the altitude of the bottom of the river-bed sediments. For node i on an element side representing a nonlinear, head-dependent, Cauchy-type boundary, the leakage expressions are given as

$$Q_{ri} = \begin{cases} C_{ri}\,(h_{ri} - h_i), & \text{where } h_i > z_{ri}; \text{ and} \\ C_{ri}\,(h_{ri} - z_{ri}), & \text{where } h_i \leq z_{ri}; \end{cases} \tag{9}$$

where Q_{ri} is the volumetric flow rate [length^3/time] at node i, and C_{ri} is the nodal coefficient given as $(1/2)\alpha L_{kl}$, and i is either k or l (Torak, 1990). The boundary coefficient, α, contained in C_{ri} is defined by equation (8).

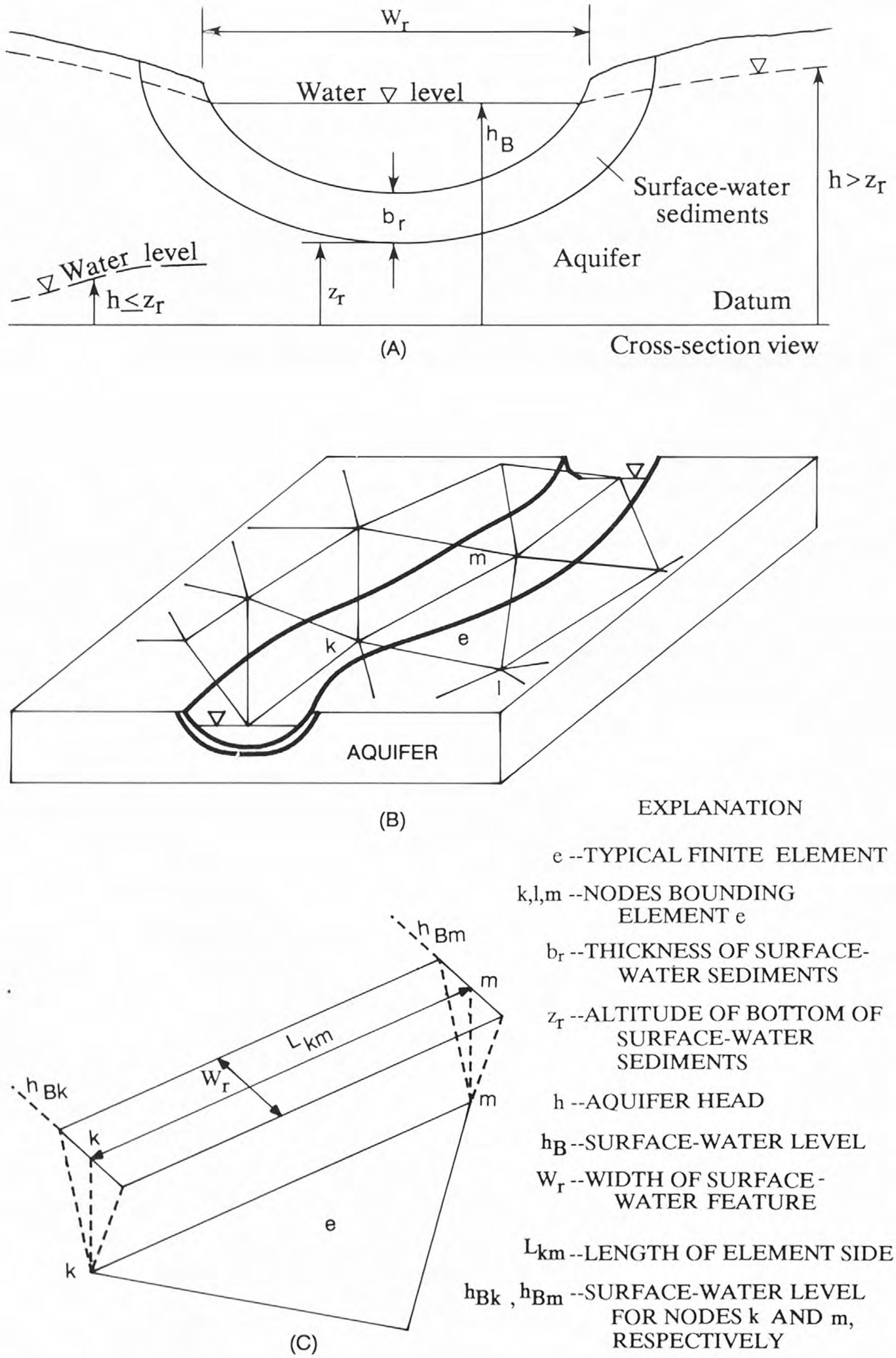


Figure 18.--Surface-water features represented as linear and nonlinear Cauchy-type boundaries.

The Flint River downstream from the Lake Worth dam was represented in MODFE as a nonlinear, head-dependent, Cauchy-type boundary (plate 1). This representation of the Flint River was preferred over the linear, head-dependent, Cauchy-type boundary, described earlier, because the potential existed, during simulations of pumping, for computed water levels in the Upper Floridan aquifer to fall below the altitude of the bottom of the river-bed sediments. Computed water levels in the vicinity of the other surface-water features were not expected to be below the bottom of the surface-water sediments; therefore, the nonlinear boundary condition was not used to represent these features.

Stage for the Flint River downstream from the Lake Worth dam was interpolated between measured values and was input to MODFE by node in the same manner as that described above for the linear head-dependent, Cauchy-type boundaries. Although the simulation was of November 1985 conditions, recharge by way of precipitation and runoff early in the month caused a rise in the stage of the Flint River of about 2 to 5 ft above a typical, low-flow condition, which occurred the following year. Therefore, river stages for November 1986, were used in the calibrated model. The effects of using November 1986 river stages on the water budget for the Upper Floridan aquifer is discussed in the section "Water-Budget Components". The sensitivity of computed water levels in the Upper Foridan aquifer to changes in river stage is discussed in the section "Sensitivity Analysis".

Values of boundary coefficient, α, and stage of the Flint River were obtained in the same manner as that in which similar values were obtained for the other surface-water features. The Flint River downstream from the Lake Worth dam was divided into six zones of nonlinear Cauchy-type boundaries (plate 1), based on the grouping of river reaches that contain the same value of α. The α values used in the calibrated model are listed in table 2. Note in table 2 that zone 1 contains one element side representing the reach where the Lake Worth dam is located (plate 1).

Table 2.--*Nonlinear Cauchy-type boundaries by zone representing the Flint River downstream from the Lake Worth dam*

[Boundary-coefficient values obtained from calibrated model]

Zone	Number of element sides	Boundary coefficient, α (feet/day)
1	1	120
2	10	2,000
3	21	300
4	34	800
5	5	260
6	37	200

Vertical leakage.--

Vertical leakage into and out of the undifferentiated overburden was represented in MODFE by using a nonlinear, vertical-leakage function (Torak, 1990). This representation is an extension to the term R(H-h) in equation (1) for steady-vertical leakage, in that the rate of recharge to the aquifer by leakage is limited to a maximum value when the aquifer head drops below the top of the aquifer (fig. 19). Discharge to the undifferentiated overburden from the Upper Floridan aquifer is not limited by the nonlinear, vertical-leakage function. Expressions for the volumetric-flow rate, Q_{ai}, across the vertical boundary between the Upper Floridan aquifer and the undifferentiated overburden are given for node i as

$$Q_{ai} = \begin{cases} C_{ai}\,(H-h_i) & \text{where } h_i > z_{ti}; \text{ and} \\ C_{ai}\,(H-z_{ti}), & \text{where } h_i \leq z_{ti}; \text{ and} \end{cases}; \qquad (10)$$

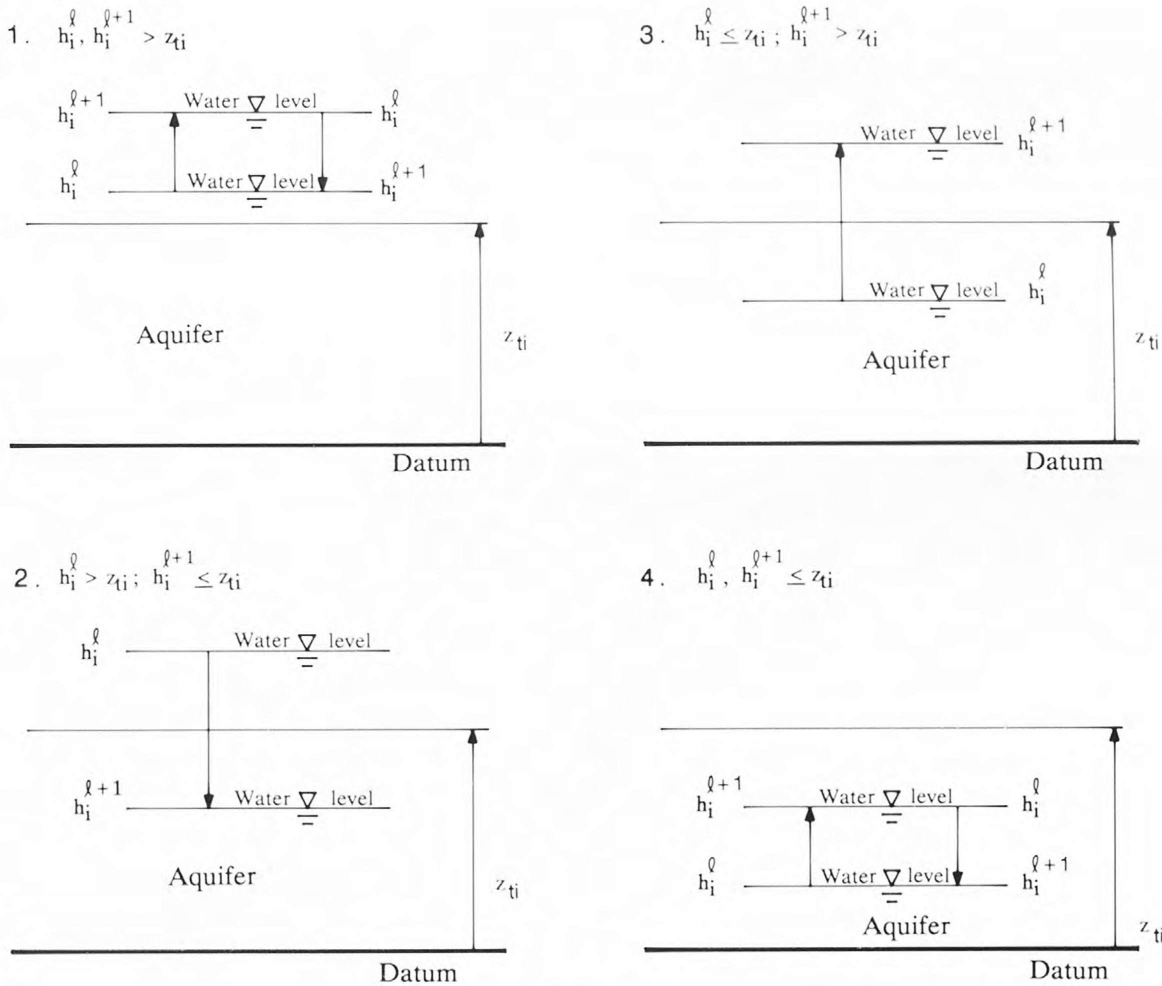
(Richard L. Cooley, U.S. Geological Survey, written commun., 1990) where z_{ti} is the altitude of the top of the aquifer. The term C_{ai} is a leakage coefficient, which is defined for node i as

$$C_{ai} = (1/3)\ R^e \Delta^e ; \qquad (11)$$

where R^e is the hydraulic conductance of the undifferentiated overburden in element e and Δ^e is the area of element e.

Initial values of vertical hydraulic conductance, R^e, that were input to MODFE were computed from a value of 0.0001 ft/d for vertical hydraulic conductivity given by Hayes and others (1983, p. 34), and from values of clay thickness within the lower half of the undifferentiated overburden. A hydraulic conductivity of 0.0001 ft/d is typical of the clay and clay-sized sediment that is in the lower half of the undifferentiated overburden. As discussed by Hayes and others (1983), the presence of more clay and less sand in the lower half of the undifferentiated overburden (termed residuum in their report) than in the upper half makes the lower half of these sediments less conductive than the upper half. Thus, it was reasonable to assume that only the thickness of sediments in the lower half of the undifferentiated overburden, specifically the clay thickness, was acting as a confining bed to the Upper Floridan aquifer.

Clay thicknesses were established from data that were collected in the Albany area during the study by Hicks and others (1987). These data consist of drillers' logs and lithologic descriptions of well-bore sediments, and were partitioned into zones of equal thickness. The element sides of the finite-element mesh were used as zone boundaries (fig. 4). Zones having a zero value for vertical hydraulic conductance were established where the overburden was absent, had a total thickness less than 10 ft, or where the clay thickness was zero, as it was assumed that the overburden could neither supply enough water nor act as a confining bed in these areas to affect the flow system. The distribution of vertical hydraulic conductance used in the calibrated model is shown in figure 20, and the corresponding zonal values are given in table 3.



EXPLANATION

h_i --HYDRAULIC HEAD IN AQUIFER

z_{ti} --ALTITUDE OF TOP OF AQUIFER

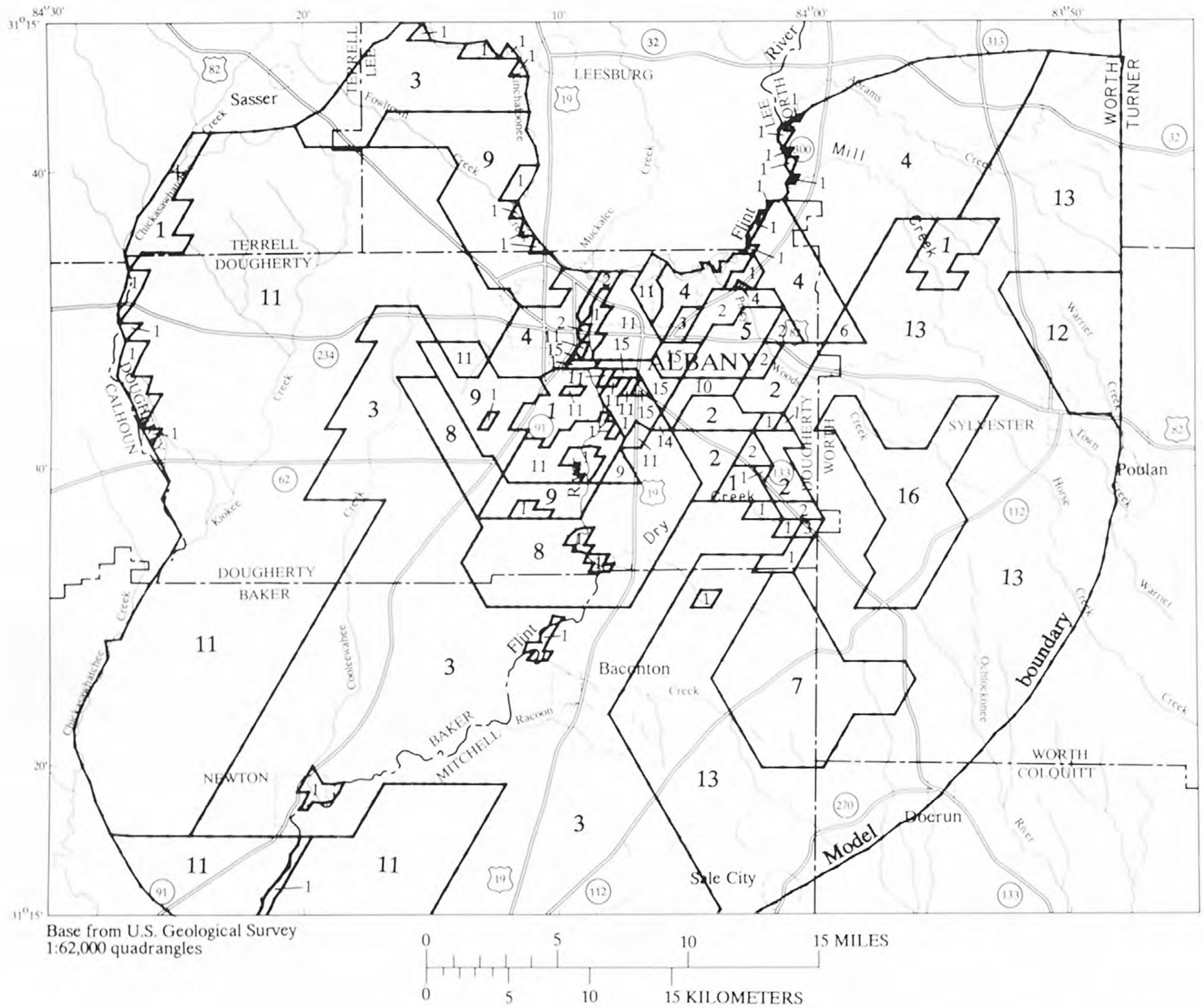
ℓ AND $\ell+1$ -- ITERATION LEVEL

Figure 19.--Four cases of possible head changes during simulation that cause nonlinear, steady vertical leakage from undifferentiated overburden.

Table 3.--*Vertical hydraulic conductance values by zone*

Zone number	Vertical hydraulic conductance (day^{-1})	Zone number	Vertical hydraulic conductance (day^{-1})
1	[1]/0.	9	$1.25(10^{-5})$
2	$1.(10^{-9})$	10	$2.(10^{-5})$
3	$1.(10^{-8})$	11	$2.5(10^{-5})$
4	$3.125(10^{-7})$	12	$5.(10^{-5})$
5	$8.(10^{-7})$	13	$5.5(10^{-5})$
6	$6.25(10^{-6})$	14	$8.(10^{-5})$
7	$3.13(10^{-6})$	15	$2.5(10^{-4})$
8	$1.(10^{-5})$	16	$1.(10^{-3})$

[1]/Clay thickness is zero or undifferentiated overburden thickness is less than 10 feet.



EXPLANATION

3 — BOUNDARY OF VERTICAL HYDRAULIC CONDUCTANCE ZONE AND IDENTIFICATION NUMBER

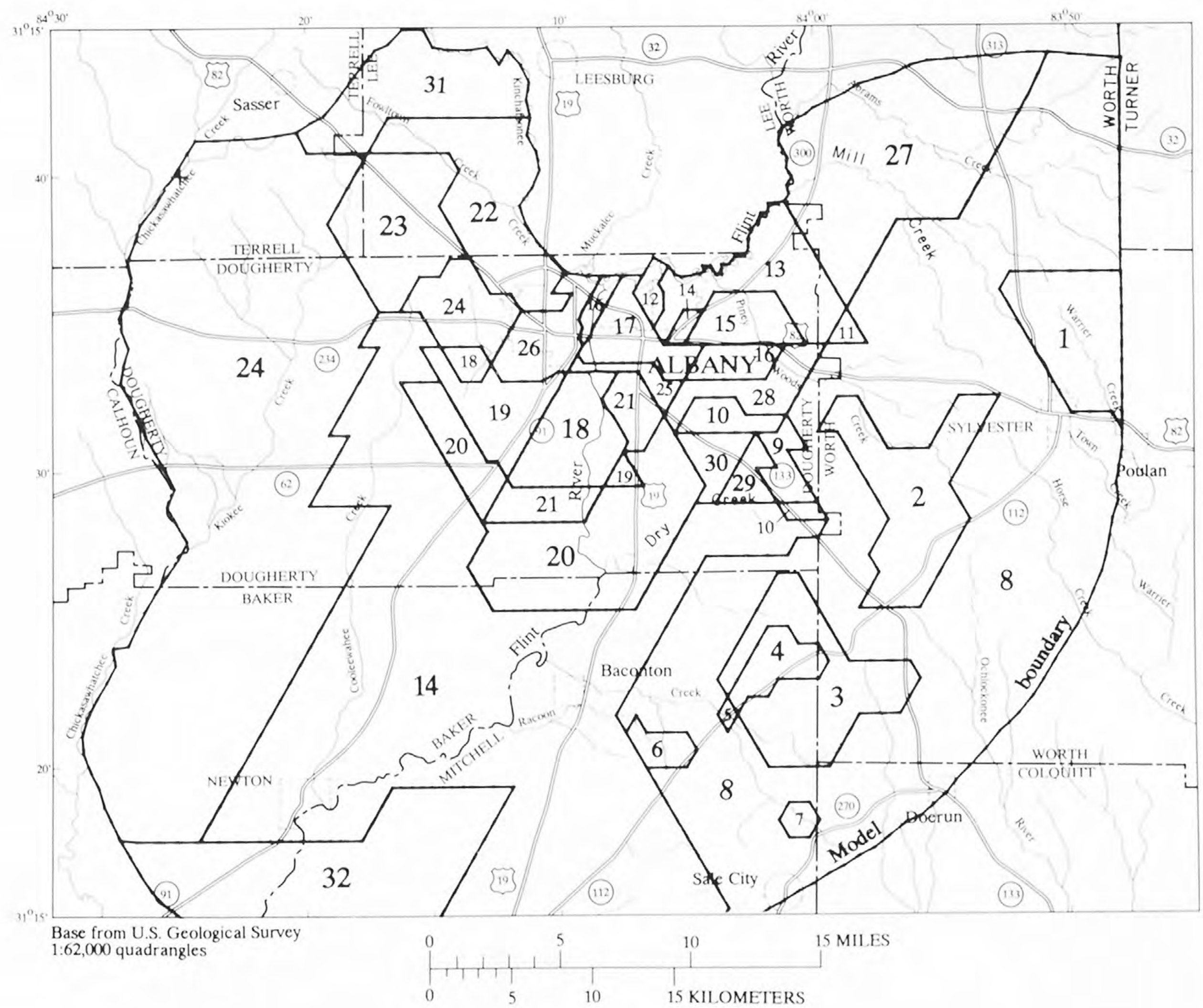
1-Element sides of finite-element mesh used as zone boundaries

Figure 20.--Zones of vertical hydraulic conductance of undifferentiated overburden.

Values for the source-layer head, H, were input to MODFE as the water level above the confining sediments in the undifferentiated overburden. Because the water level in the undifferentiated overburden is at or near seasonal low during November-January (Hayes and others, 1983), it was assumed that, for November 1985 conditions, only the clay within the lower half of the overburden was saturated. Thus, source-layer heads were computed as being the altitude of the top of the clay within the lower half of the overburden, and were input to MODFE by node. The effects on simulation results of estimating the head in the undifferentiated overburden in this manner are discussed in the section "Sensitivity Analysis".

Hydraulic-Property Zones

Areal variations in hydraulic properties that affect ground-water flow in the Upper Floridan aquifer and through the undifferentiated overburden were represented in MODFE by using hydraulic-property zones. Each zone consists of a group of elements containing a unique combination of values for the hydraulic conductivity of the Upper Floridan aquifer and for the vertical hydraulic conductance of the undifferentiated overburden. Variations in the vertical hydraulic conductivity and thickness of the undifferentiated overburden cause variations in zonal values of vertical hydraulic conductance, which were discussed in the previous section. Variations in the hydraulic conductivity of the Upper Floridan aquifer were determined from transmissivity and thickness data that were compiled in the Albany area by Hicks and others (1983), and from an areal representation of well-bore data that describe the occurrence and extent of fractures and solution openings (fig. 8). These data led to the establishment of 32 hydraulic-property zones for the study area (fig. 21). Values for hydraulic conductivity used in the calibrated model are listed in table 4 by hydraulic-property zone.



EXPLANATION

32 HYDRAULIC-PROPERTY-ZONE BOUNDARY AND IDENTIFICATION NUMBER
--Element sides of finite-element mesh used as zone boundaries

Figure 21.--Distribution of hydraulic-property zones.

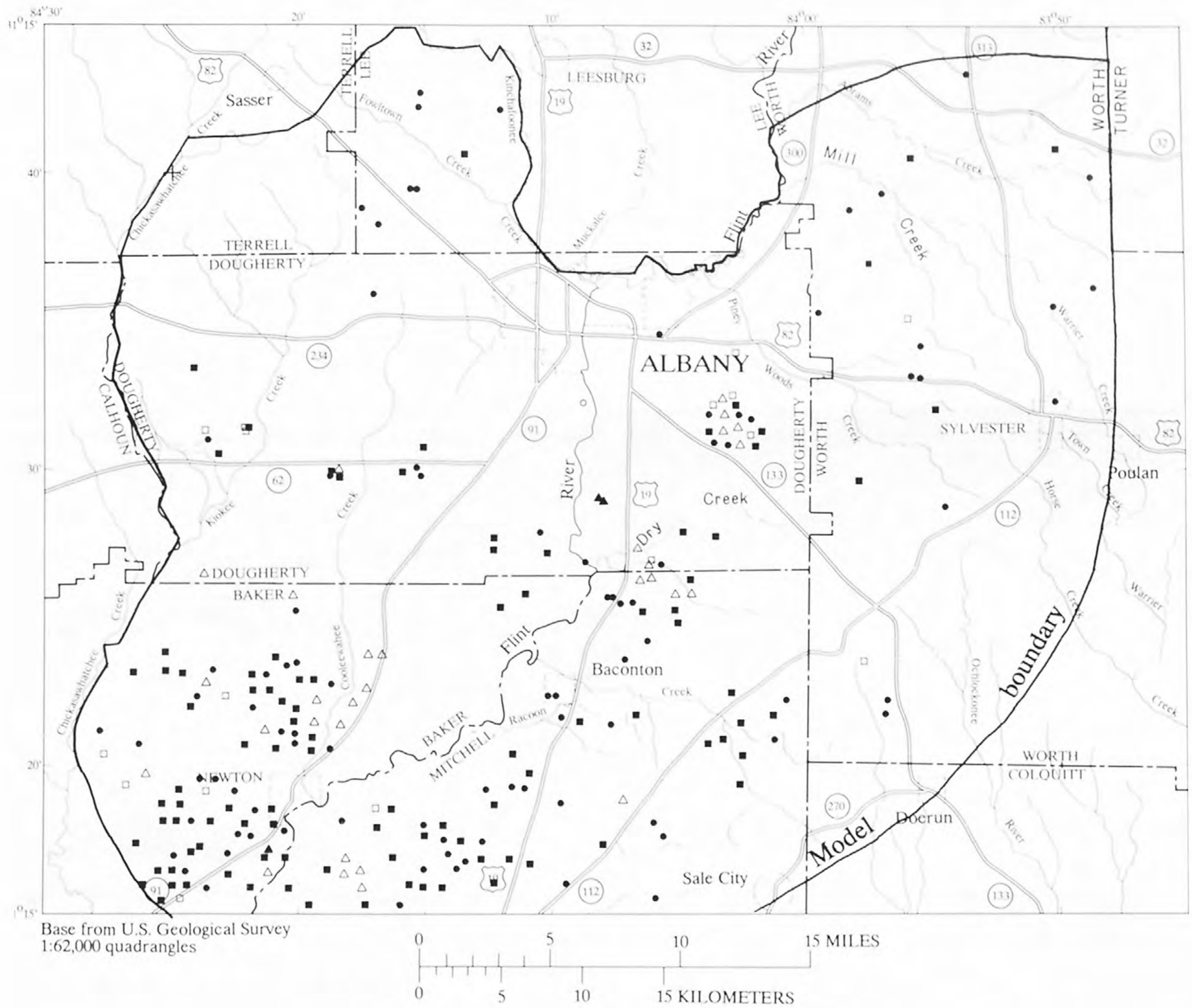
Table 4.--*Hydraulic conductivity values by zone*

Zone number	Number of elements	Hydraulic conductivity (feet/day)	Zone number	Number of elements	Hydraulic conductivity (feet/day)
1	44	1,350	17	43	19,500
2	53	2,100	18	110	250
3	53	1,800	19	78	900
4	13	1,000	20	257	8,000
5	2	1,000	21	71	8,500
6	8	500	22	56	350
7	4	600	23	45	2,900
8	520	1,120	24	400	3,200
9	12	5,500	25	13	21,000
10	11	9,500	26	36	1,150
11	3	130	27	133	900
12	7	300	28	15	2,000
13	77	130	29	8	9,000
14	737	1,600	30	10	10,500
15	16	15,000	31	46	2,800
16	20	19,500	32	160	2,200

Distribution of Well Pumpage

The locations and pumping rates of municipal, industrial, and irrigation wells in the study area for November 1985 were obtained from files at the U.S. Geological Survey, 6481-B Peachtree Industrial Blvd., Doraville, GA 30360. Reports from the Georgia Irrigation Reporting System (GIRS) provided average monthly pumping rates for municipal and industrial wells. Locations of irrigation wells were obtained from data collected for the State Irrigation Well Survey of 1980 and from other miscellaneous files that updated the 1980 data. The GIRS indicated that pumping rates for irrigation wells during November 1985 were about one fifth of the rates reported during the spring growing season. Therefore, pumping rates for all irrigation wells were input to the model as one fifth of the spring growing-season rates. The estimated November 1985 pumpage from irrigation wells was about 77 Mgal/d, and the estimated municipal and industrial pumpage was about 30.5 Mgal/d. The distribution of well pumpage in the Albany area is shown in figure 22.

Pumping rates from wells in the Upper Floridan aquifer were represented as point withdrawals at the nodes in the finite-element mesh nearest to the wells. This procedure distributed the pumping rates from the locations shown in figure 22 to 583 nodes (fig. 23). The element sizes used in the mesh permitted well pumpage to be represented at nodes that were either at or within 2,000 ft of the actual well locations. The absence of distinct drawdown cones from the November 1985 potentiometric surface shown by Hicks and others (1987) indicated that well pumpage has an aggregate rather than an individual effect on shaping the potentiometric surface of the Upper Floridan aquifer. Therefore, representing well-pumping rates in MODFE as point withdrawals at the nearest nodes to the well locations was assumed to have little effect on the accuracy of simulating the potentiometric surface of November 1985. This assumption seems to be valid as computed water levels for the Upper Floridan aquifer were relatively insensitive to changes in well-pumping rates (see "Sensitivity Analysis" section).

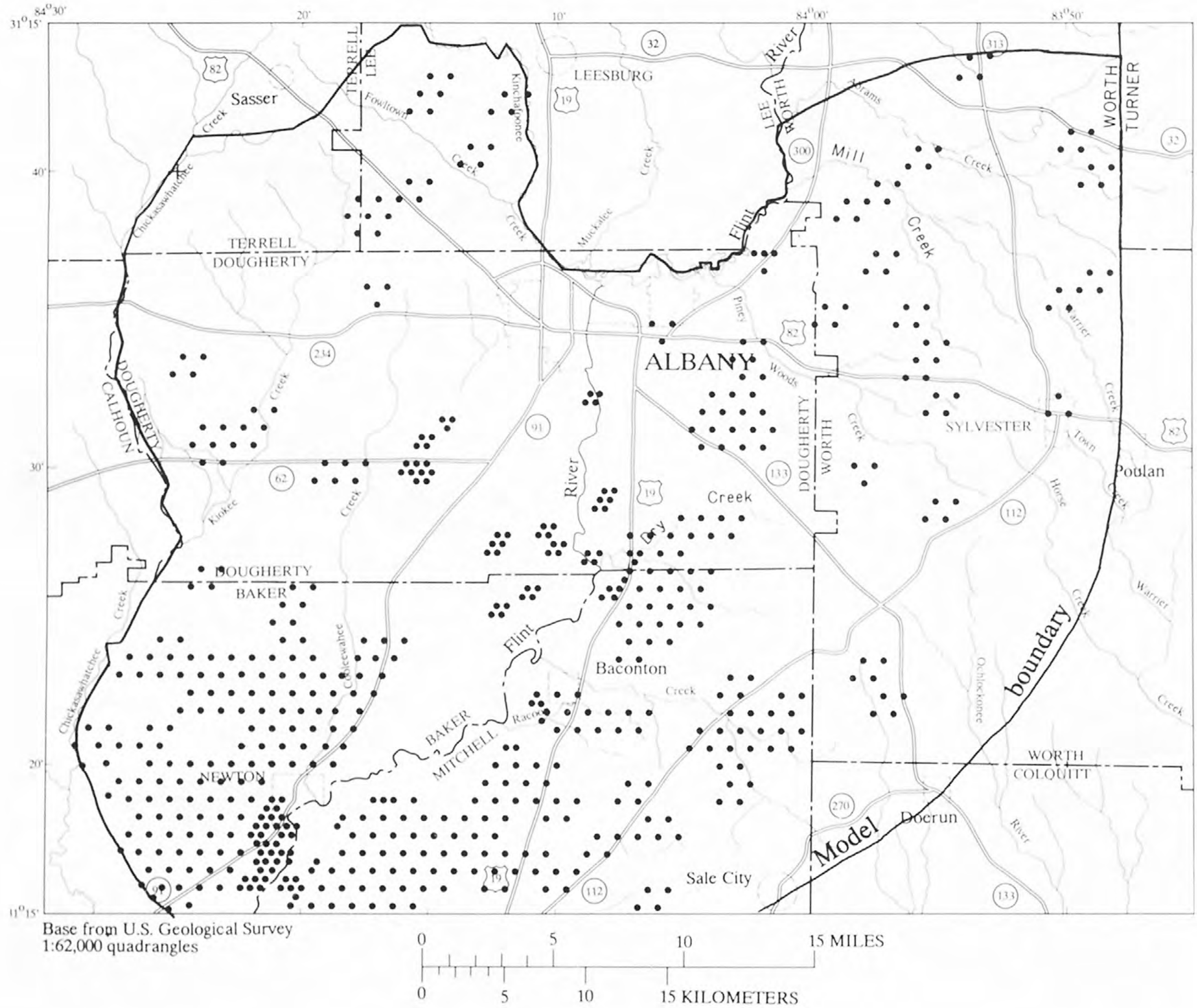


EXPLANATION

PUMPING RATE, IN THOUSANDS OF CUBIC FEET PER DAY

- ○ Less than 3 (one well)
- □ 10 to 100
- • 100 to 200
- ■ 200 to 250
- △ 250 to 450
- ▲ Greater than 450

Figure 22.--Locations of pumped wells in the study area, November 1985.



EXPLANATION

• NODE INDICATING LOCATION OF SIMULATED PUMPING

Figure 23.--Locations of nodes simulating pumping in November 1985.

Calibration

The acceptance of model results for evaluating the water-resources potential of the Upper Floridan aquifer depends on the accuracy of the model to represent the ground-water-flow system that existed during an historical period for which suitable hydrologic data exist. The process of adjusting the data inputs of hydraulic properties, within plausible limits, to produce a computed solution that is within an acceptable level of error with respect to the historical period is termed calibration. The objective of calibration in the Albany area was to represent the ground-water-flow system of the Upper Floridan aquifer for the November 1985 conditions with the computed results from MODFE.

Procedure

The calibration procedure involved trial-and-error adjustments to hydraulic properties that affected computed water levels from MODFE and comparisons of computed water levels with measured values at discrete points (wells). Adjustments to the following hydraulic properties were made within plausible limits to effect calibration:

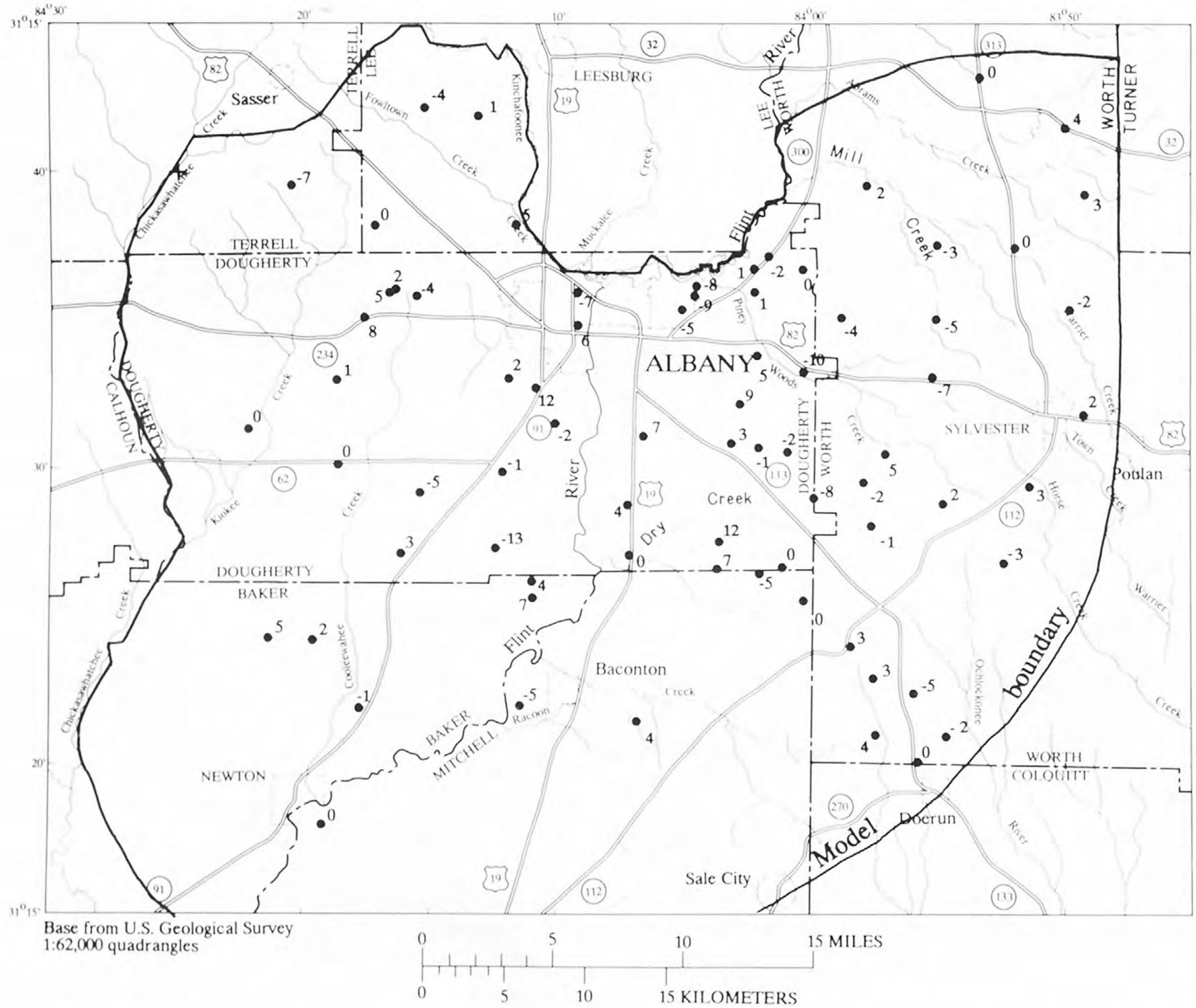
- hydraulic conductivity of the Upper Floridan aquifer,
- vertical hydraulic conductance of the undifferentiated overburden,
- head in the undifferentiated overburden,
- leakage coefficients for Cauchy-type boundaries that represent boundary conditions and surface-water features,
- controlling heads to boundary conditions and surface-water features.

Well-pumping rates were not adjusted for the calibration; however, the effects of changing pumping rates on computed water levels is discussed in the "Sensitivity Analysis" section.

An acceptance criterion of 5 ft was established for comparing computed water levels with measured values. Water-level residuals (computed minus measured water levels) were calculated and were compared with the acceptance criterion. To achieve a successful calibration, water-level residuals were required, on the average, to satisfy the acceptance criterion. This criterion represents the accuracy to which altitudes of land surface were known at wells where water-levels had been measured. Thus, computed water levels were not expected to be more accurate than the well altitudes. In addition to satisfying the acceptance criterion, the distribution of water-level residuals was analyzed after each simulation, and changes to hydraulic properties were made in an attempt to obtain a random distribution of residuals in magnitude and in sign.

Water-Level Residuals

Differences between computed and measured water levels, or water-level residuals, were determined during calibration at 74 well locations within the Albany area (fig. 24). Water levels were computed at the locations of wells where measurements were made by applying the finite-element concept of linear variation (of head) within an element (Zienkiewicz, 1977, p. 93-95). The water-level residuals from the calibrated model are given in table 5.



EXPLANATION

• 0 WELL--Number indicates water-level residual (simulated values minus measured values), in feet

Figure 24.--Locations of water-level measurements for November 1985 and values of water-level residuals.

The plot of water-level residuals over the study area (fig. 24) shows that the distribution of signs and magnitudes of the values was nearly random, with two exceptions. A cluster of three wells having negative residuals (computed water levels were less than measured values) was located along the northern model boundary east of the Lake Worth dam and the reservoir. Another area of negative residuals was located east of the Dougherty-Worth County line, in the east-central part of the study area. Reasonable changes to hydraulic properties that affect ground-water flow in these areas were not able to change the water-level residuals so that they would be either randomly distributed or within the acceptability criterion. The effects of changing hydraulic properties on ground-water levels is discussed in the "Sensitivity Analysis" section.

Table 5.--*Water-level residuals from calibrated model*

Well number	$h_{i\,model}^{*}$ Computed water-level altitude (feet)	$h_{i\,obs.}^{*}$ Measured water-level altitude (feet)	Water-level residual (feet)
11J020	132.0	132.6	-0.6
11K017	147.3	145.2	2.1
11K016	148.3	143.3	5.0
12K014	140.4	136.4	4.0
12K009	143.0	136.3	6.7
11K015	151.6	148.2	3.5
12K016	139.5	152.1	-12.6
11K003	158.8	163.5	-4.7
12K015	152.9	154.3	-1.4
11L019	167.1	166.8	0.3
11L014	181.3	181.8	-0.5
11L020	184.2	183.5	0.7
11L021	196.5	191.7	4.9
11L022	195.4	187.9	7.5
11L017	196.0	193.8	2.2
11L018	192.5	196.5	-4.0
12L028	164.6	162.4	2.2
12L023	159.6	147.9	11.6
12L030	151.2	152.9	-1.7
13K014	148.5	148.9	-0.5
13K019	149.1	145.2	3.9
13K017	165.6	158.5	7.1
13K011	163.6	151.5	12.1
14K009	182.5	190.6	-8.1
13K018	179.5	179.6	-0.1
13L048	173.8	175.5	-1.7
13L033	165.0	161.8	3.1
13L028	168.0	168.8	-0.8
13L012	156.5	149.9	6.6
13L032	164.7	156.1	8.7
13L003	173.6	183.7	-10.1
13L057	164.8	159.6	5.1
13L058	163.8	162.9	0.8
13L047	199.1	199.4	-0.3
13L055	184.1	185.9	-1.8
13L054	178.7	177.5	1.2
13L052	173.0	181.2	-8.2
13L014	168.5	177.5	-9.1
13L049	161.7	166.8	-5.2
12L044	164.6	171.4	-6.8

See footnote at end of table.

Table 5.--*Water-level residuals from calibrated model--Continued*

Well number	$h_{i_{model}}$* Computed water-level altitude (feet)	$h_{i_{obs.}}$* Measured water-level altitude (feet)	Water-level residual (feet)
12L029	154.5	149.0	5.5
11M017	228.7	232.7	-4.0
11M010	211.8	211.7	0.1
12M027	211.1	210.5	0.6
12M015	187.4	182.9	4.5
11J012	116.8	116.9	-0.1
13J004	150.4	146.7	3.7
12J003	128.7	133.7	-5.0
13K021	175.0	180.4	-5.4
13K022	184.5	184.0	0.4
11M007	233.1	240.2	-7.1
14J021	185.4	185.8	-0.4
14J020	190.9	192.6	-1.7
14J018	184.9	181.1	3.7
14J022	192.9	197.4	-4.5
14K007	190.5	187.3	3.2
14K008	192.7	189.4	3.3
15K009	218.4	215.4	3.0
14K011	210.1	210.7	-0.7
14K006	211.2	213.2	-2.1
14K012	224.3	222.3	2.0
14L013	215.8	211.2	4.6
15K010	213.0	216.2	-3.3
15L020	221.2	219.4	1.8
14L012	224.5	231.4	-6.9
14L011	206.6	210.7	-4.1
14L009	229.8	234.5	-4.7
15L022	240.1	241.7	-1.7
14L014	235.4	238.0	-2.7
15L023	246.6	246.4	0.1
14M009	226.7	225.1	1.6
15M005	259.0	255.8	3.2
15M004	264.9	260.8	4.1
14M008	253.3	253.1	0.2

*Average residual $= \frac{1}{N} \sum_{i=1}^{N} (h_{i_{model}} - h_{i_{obs.}}) = 0.2$ ft; N = 74

The water-level residuals (table 5) indicate that the acceptability criterion was met, and that calibration of the model was successful for the ground-water conditions in the Upper Floridan aquifer for November 1985. Water-level residuals were evaluated with regard to the acceptability criterion by computing the root-mean square residual (RMSE), given as

$$\text{RMSE} = \left[\frac{1}{N} \sum_{i=1}^{N} (h_{i\,model} - h_{i\,obs.})^2 \right]^{1/2}$$

where

N is the number of residuals (74), and hi_{model} and $hi_{obs.}$ are the computed and measured hydraulic head, respectively, for the ith residual. The RMSE value that satisfied the acceptability criterion was computed as 4.8 ft. The arithmetic average of the water-level residuals was computed as 0.2 ft. Changes in the RMSE and sum of squares during the calibration process are discussed in the "Statistics" section. Of the 74 water-level residuals, 53 values were within ± 5 ft, four values were greater than ± 10 ft, and no water-level residual was larger than 12.6 ft. A frequency distribution of water-level residuals was produced, using 5-ft intervals, to illustrate the distribution of residuals for the calibrated model (fig. 25).

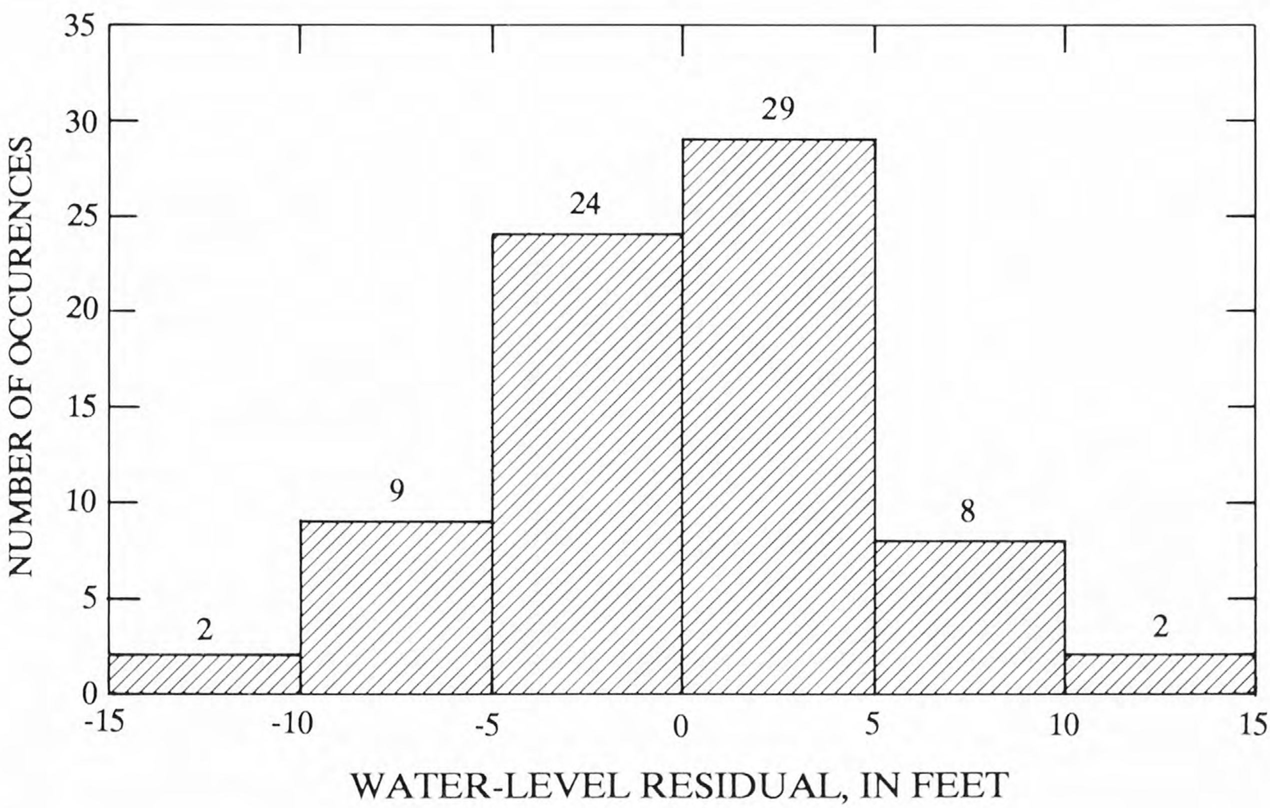


Figure 25.--Frequency distribution of water-level residuals from calibration.

Statistics

Statistics of sum of squares, root-mean-square residual (RMSE), and standard deviation were computed from the water-level residuals after each simulation to assist in determining the ability of the model to represent the November 1985 ground-water levels. Seventy-eight trial-and-error changes were made to the data inputs of MODFE and subsequent simulations were performed before obtaining a computed solution that was accepted as the calibrated model. Changes in statistics that occurred during the calibration process were shown by plotting the statistical values after each simulation (fig. 26).

Plots of statistical values (fig. 26) indicated improvement in the ability of the model to represent ground-water levels of November 1985 during the process of achieving calibration. Values for the sum of squares decreased from 6,853 to 1,717 ft^2, standard deviation decreased from 8.6 to 4.8 ft, and the RMSE decreased from 9.6 to 4.8 ft from the first to the last simulation in the calibration process. Statistics that were computed from the water-level residuals obtained from the calibrated model indicated that the acceptance criterion for calibration had been met (table 6.)

Predominant directions of ground-water movement

The predominant directions of ground-water movement in the Upper Floridan aquifer can be inferred from contours of the computed potentiometric surface and from flow-direction plots from the calibrated model (plate 2). These representations support the directions of ground-water movement that were described earlier for the conceptual model of the flow system. Along the external boundaries, ground water flows into the study area from the west, north, and northeast, and flows out of the study area to the east and south (plate 2). The predominant flow directions at these boundaries indicate that ground-water flow is controlled by regional components emanating from outside the study area and by surface-water features situated at the study-area (or model) boundaries. Their influence on water levels within the study area is discussed in the "Sensitivity Analysis" section. The method used to compute flow directions was obtained from M.L. Maslia (U.S. Geological Survey, written commun., 1989).

Within the study area, ground-water movement is mostly from the model boundaries, described above, toward the Flint River south of the Lake Worth dam (plate 2). The relatively steep hydraulic gradients on the potentiometric surface in the northeastern part of the study area, near the Dougherty-Worth County line, appear to be influenced by a low hydraulic-conductivity zone situated among higher hydraulic-conductivity zones in the surrounding areas (fig. 21, table 3). To the west of the low hydraulic-conductivity zone, the hydraulic gradient is relatively flat, yet ground water flows readily because relatively high hydraulic conductivities exist in the Upper Floridan aquifer in this area. These high conductivities are a result of near-conduit-flow conditions that were created by extensive fractures and solution openings within the limestone (Hicks and others, 1987).

Local irregularities in ground-water-flow directions are caused by a combination of hydrologic influences on the regional flow system (plate 2), such as nonhomegeneities in hydraulic properties for the Upper Floridan aquifer and undifferentiated overburden. In addition, local effects of pumping could cause flattening of the potentiometric surface and possibly cause slight depressions within a limited area, giving the appearance of anomalous flow patterns by the flow-direction indicators. This can be inferred by comparing the locations of nodes that were used to simulate pumping wells (fig. 23) with the flow-direction indicators. In particular, in the southeast part of the study area, there are many pumping wells to create the local effects just described. The limited extent of these local flow patterns is attested by the location and shape of the potentiometric contours; larger flow irregularities would have created closed contours around the hydrologic feature. However, in the absence of closed contours or contour shapes that would indicate flow directions other than the regional pattern described earlier, it can be inferred that the local aberrations in the regional-flow directions are not areally extensive.

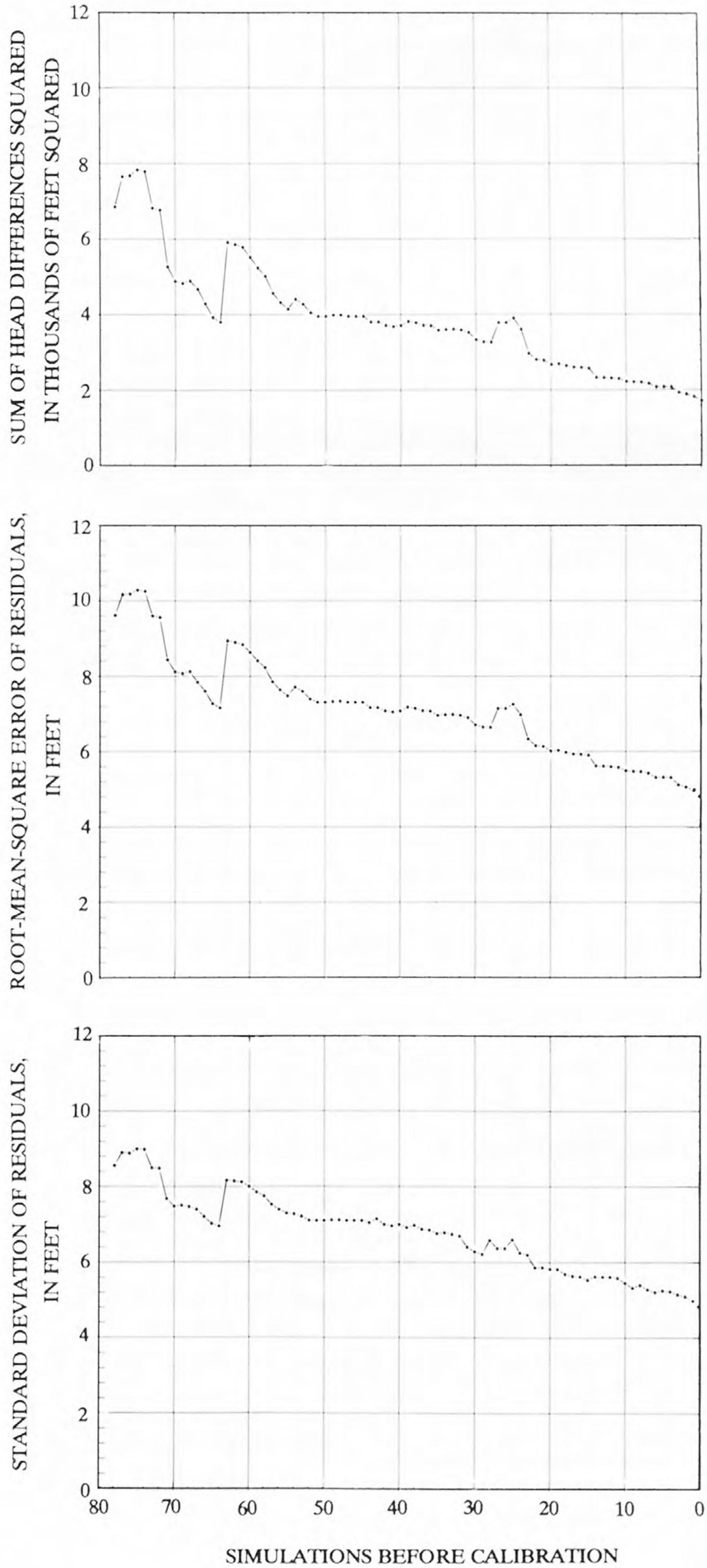


Figure 26.--Sum of head differences squared, root-mean-square residual and standard deviation of water-level residuals by simulation during calibration process.

Table 6.--*Statistics for water-level residuals from calibrated model*
[*ft^2, feet squared; ft, feet; RMSE, root-mean-square residual*]

Number of terms	=	74
Sum of squares	=	1,717 ft^2
RMSE	=	4.8 ft
Standard deviation	=	4.8 ft
Average residual	=	0.2 ft

Percent of residuals within:

1 standard deviation, 70.3
2 standard deviation, 94.6
3 standard deviation, 100

Number of water-level residuals between:

Class (feet)	Number of occurrences
-20 to -15	0
-15 to -10	2
-10 to -5	9
-5 to 0	24
0 to 5	29
5 to 10	8
10 to 15	2
15 to 20	0

Directions of ground-water movement that were influenced by vertical leakage from the undifferentiated overburden can be seen by comparing the flow directions and contours of the potentiometric surface (plate 2) with the plot of water-level differences between the Upper Floridan aquifer and the undifferentiated overburden (fig. 27). About 5 mi southeast of the Dougherty-Worth County line, the flow directions and the contours of the potentiometric surface indicate an area of high water level and diverging ground-water flow (plate 2). This area, just west of Sylvester, also has higher land-surface altitude and increased thickness of undifferentiated overburden than does the surrounding areas. The appreciable positive difference between the water-level in the undifferentiated overburden and the water level in the Upper Floridan aquifer (fig. 27) suggests that this is an area of relatively high vertical leakage from the overburden into the aquifer.

In other areas, ground-water-flow directions show subtle effects of vertical leakage to the undifferentiated overburden. This occurs just south of the area of potential development, near the Dougherty-Baker County line, and in the vicinity of the Flint River near Radium Springs (plate 2). Flow vectors in these areas show small circular, or convergent, patterns that appear to coincide with upward leakage to the undifferentiated overburden from the Upper Floridan aquifer. (Compare plate 2 with fig. 27.)

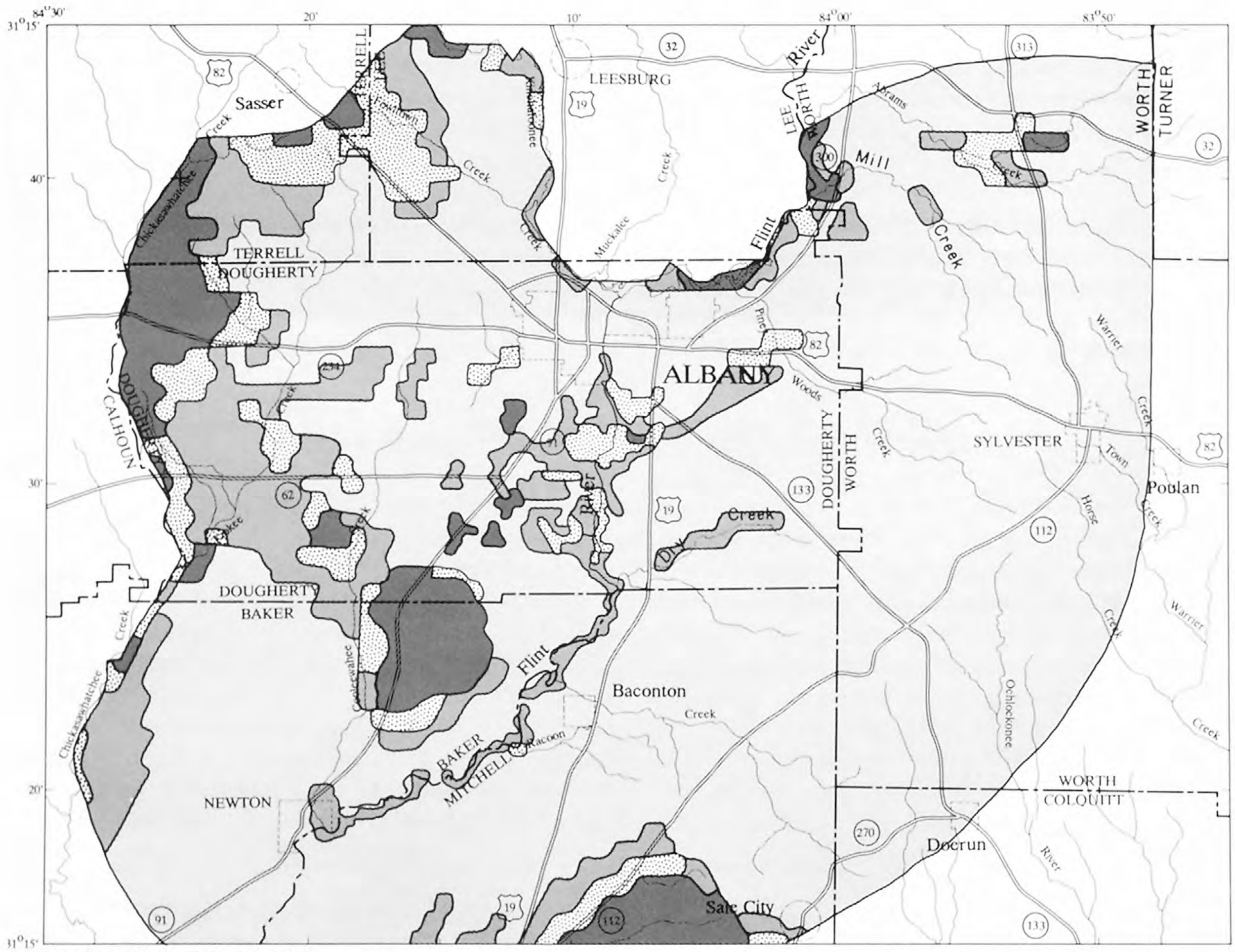
Importance of surface-water features to ground-water flow

Ground-water flow in the study area for November 1985 conditions was dominated by surface-water features, principally the Flint River south of the Lake Worth dam. Here, the Flint River acted as a drain for regional flow that entered across most of the study-area boundaries. The Flint River downstream from the Lake Worth dam caused contours in the potentiometric surface of the Upper Floridan aquifer to bend sharply upstream, indicating a large component of aquifer discharge to the River (plate 2). These contours bend sharply in the vicinity of Radium Springs, where the occurrence of solution cavities and near-conduit-flow conditions in the aquifer are intercepted by the Flint River (Hicks and others, 1987). The presence of solution openings and conduits in the aquifer northeast of Radium Springs (fig. 4) enabled ground water to flow easily toward the Flint River; thus, creating conditions in the aquifer of high ground-water flow and gentle hydraulic gradients (plate 2). Discharge rates to the Flint River and other surface-water features from the Upper Floridan aquifer were computed by the calibrated model of November 1985 conditions, and are given in the section "Water-Budget Components".

Other surface-water features appear to have less of an influence on the potentiometric surface of the Upper Floridan aquifer than does the Flint River downstream from the Lake Worth dam. Although the Chickasawhatchee, Cooleewahee, and Kinchafoonee Creeks drain the Upper Floridan aquifer, computed discharge rates from the aquifer are small compared with discharge to the Flint River, and contours of the computed potentiometric surface are hardly affected by discharges to these creeks (plate 2). Along the northern boundary of the study area, some water leaks from Lake Worth and from the reservoir that was created behind the Lake Worth dam (plate 2). However, most of the influence on ground-water flow in this area is from regional flow that enters the study area beneath the surface-water features. East of the Flint River, the surface-water features typically are creeks and streams that seem to be hydraulically connected to the undifferentiated overburden rather than to the Upper Floridan aquifer (Hicks and others, 1987).

Water-budget components

Water budgets were prepared from model output for the calibration period, November 1985, to account for inflows and outflows to the ground-water-flow system by hydrologic feature, and to assess the importance of individual hydrologic features in shaping the potentiometric surface of the Upper Floridan aquifer. Volumetric flow rates were computed and percentages of flow in the entire system, relative to the November 1985 pumping rate from wells, were determined for each water-budget component. The percentage of flow that each water-budget component contributes to the withdrawal rate from wells was computed from the results of a simulation having no pumping and the simulation of November 1985 conditions.



Base from U.S. Geological Survey
1:62,000 quadrangles

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

VERTICAL LEAKAGE BETWEEN UPPER FLORIDAN AQUIFER AND UNDIFFERENTIATED OVERBURDEN--Pattern indicates recharge to or discharge from Upper Floridan aquifer, determined from head differences (H-h): h is aquifer head; H is head in undifferentiated overburden

HEAD DIFFERENCE, IN FEET

DISCHARGE	RECHARGE
Greater than 10	Greater than -10
0 to 10	0 to-10

Figure 27.--Head differences between source-layer in undifferentiated overburden and Upper Floridan aquifer from calibrated model.

November 1985 Conditions

The volumetric flow rates and percentages of flow in the entire system, relative to the November 1985 withdrawal rates from wells, is given in table 7 for each water-budget component. These rates and percentages indicate that ground-water discharge from the Upper Floridan aquifer to the Flint River downstream from the Lake Worth dam was about an order of magnitude larger than the withdrawal rate from all wells. Recharge to the Upper Floridan aquifer by vertical leakage from the undifferentiated overburden, primarily in upgradient areas, was about 6.8 times as large as the withdrawal rate from wells. Ground-water inflow across model boundaries (regional flow) and by leakage from rivers and surface-water features other than the Flint River, was about 6.5 times as large as the withdrawal rate from wells. Recharge to the Upper Floridan aquifer from the Flint River downstream from the Lake Worth dam was about 29 percent of the withdrawal rate from wells. Ground-water discharge from the Upper Floridan aquifer to the undifferentiated overburden, primarily along the southern boundary of the study area, was about 3 percent of the withdrawal rate from wells. Discharge to regional flow, primarily along the southern and eastern model boundaries, was about 2.7 times larger than the withdrawal rate from wells.

Table 7.--*Water-budget components for calibration period, November 1985*

Budget component	Volumetric flow rate (millon gallons per day)	Percent of pumping rate
Discharge to Flint River	-1,051.0	978
Discharge to regional flow	-290.5	270
Discharge to wells	-107.5	100
Discharge to undifferentiated overburden	-3.3	3
Total discharge	-1,452.3	
Recharge from undifferentiated overburden	727.5	677
Recharge from regional flow and other rivers	694.0	646
Recharge from Flint River	31.0	29
Total recharge	1,452.5	

The largest water-budget component, and consequently the most important hydrologic feature to shape the potentiometric surface of the Upper Floridan aquifer for November 1985, was ground-water discharge to the Flint River downstream from the Lake Worth dam (table 7). About 1,050 Mgal/d was simulated as the discharge rate from the Upper Floridan aquifer to the Flint River downstream from the Lake Worth dam (fig. 1). This discharge rate compares well with base-flow measurements that were made on the Flint River at Albany and at Newton (fig. 1), which indicated that between these stations, the Flint River received ground-water discharge, mainly from the Upper Floridan aquifer, at a rate of about 1,080 ft^3/s, or about 700 Mgal/d. The excess in discharge computed by the model can be attributed partially to stream withdrawals for industrial use (22 Mgal/d), non-reported use, and channel evaporation, but mostly to greater simulated water-level differences between the Upper Floridan aquifer and the Flint River than occurred during the November 1985 period. The possible sources of error in these water-level differences and their effects on the water budget are discussed in the section "Sources and Effects of Error".

Results from a simulation that used the November 1985 boundary conditions and no ground-water pumpage were compared with results from the calibrated model (which contained pumpage) to determine the effect of pumping on water-budget components for the Upper Floridan aquifer. In effect, the comparison of simulation results indicated which water-budget components changed from predevelopment conditions as a result of pumping in the Upper Floridan aquifer and, hence, which components contributed water to the pumped wells. The volumetric-flow rates and percentages of flow that each water-budget component contributed to the November 1985 withdrawal rate are given in table 8. Of the 107.5 Mgal/d total withdrawal rate from wells in November 1985, about 79 Mgal/d, or about 74 percent, was derived from ground water that would have discharged to the Flint River under predevelopment conditions (see "Reduced discharge to Flint River; table 8). Induced recharge from regional flow and leakage from other surface-water features contributed about 16 percent of the water withdrawn by wells, and reduced discharge to these hydrologic features contributed about 7.8 percent of the withdrawal rate from wells (see table 8). About 2.3 Mgal/d, or about 2.2 percent of the withdrawal rate from wells, was derived from reduced discharge to and increased recharge from the undifferentiated overburden. Of this leakage rate, about 0.17 Mgal/d was reduced discharge from the Upper Floridan aquifer to the overburden (table 8). Induced recharge from the Flint River into the Upper Floridan aquifer contributed about 0.04 percent of the withdrawal rate from wells.

Table 8.--*Water-budget components that comprise the November 1985 pumping rates*

Budget component	Volumetric flow rate (million gallons per day)	Percent of pumping rate
Discharge to wells	-107.5	100.0
Reduced discharge to Flint River	79.2	73.7
Reduced discharge to regional flow	8.3	7.8
Reduced discharge to undifferentiated overburden	0.2	0.2
Induced recharge from regional flow and other rivers	17.6	16.4
Induced recharge from undifferentiated overburden	2.1	2.0
Induced recharge from Flint River	0.05	0.04

Sources and Effects of Error

During the simulation process, errors are introduced into the computed solution of hydraulic head that need to be evaluated with respect to their effect on results and on conclusions about the flow system. Some errors are unavoidable and, through the advancement of simulation techniques, are very small, as they originate from the physical or mathematical limitations for representing the physics that describe ground-water flow and boundary conditions. Other errors can be kept to a minimum through proper conceptualization of the flow system and application of digital models that sufficiently address the conceptual scheme. Still other, larger errors are associated with measuring and reporting physical phenomena such as hydraulic head, hydrologic characteristics, well pumping rates, and stream stage and discharge. These measurement errors need to be identified and minimized as they could obscure the true behavior of the flow system and lead to erroneous conceptualizations or conclusions about flow-system response to stresses.

Discrepancies (errors) exist between computed results from the calibrated model for the Upper Floridan aquifer and measurements of ground-water discharge to the Flint River and of altitudes of water levels in wells. The excess ground-water discharge to the Flint River from the Upper Floridan aquifer that was computed during calibration was attributed to greater computed water-level differences between the aquifer and the river than were measured during the November 1985 period. Computed ground-water levels were about 5 to 7 ft higher than measured values in areas of the Upper Floridan aquifer where solution openings would permit the most ground-water discharge to the river, in the vicinity of Radium Springs (figs. 1, 8). In addition, use of November 1986 river stages for calibration because recharge events (precipitation and runoff; see section on "Surface-Water Features") occurred during November 1985, resulted in river-stage inputs to MODFE that were from 2 to 5 ft lower than measured stages for the calibration period. The combination of these water-level differences accounted for almost 200 Mgal/d of the 332 Mgal/d excess in ground-water discharge to the Flint River that was computed by the calibrated model. This was determined by a simulation that was performed in which river stage between the Lake Worth dam and Newton (fig. 1) was input to MODFE at values that were 10 ft higher than the values used in the calibrated model. The 10-ft increase in river stage represented the combined effects of the differences between values of aquifer head (lower) and river stage (higher) that were used in the calibrated model and values that were measured during the calibration period.

In addition to errors in computed water levels for the Upper Floridan aquifer, errors in determining or reporting altitudes of land surface at wells can cause inaccuracies in measured ground-water levels that range within at least ± 5 ft of the true values. Altitude of land surface at wells is known to less than half a topographic contour interval of altitude; thus, water-level differences between the Upper Floridan aquifer and the Flint River could be smaller, or larger, than what is indicated by the measured values by as much as 5 ft. This range in accuracy of ground-water levels can account for about 100 Mgal/d of computed discharge to the Flint River from the Upper Floridan aquifer. Because other water-budget components contribute much less to the ground-water-flow system of the Upper Floridan aquifer than discharge to the Flint River, errors in measured water levels have less of an effect on assessing the importance of these components than on discharge to the Flint River.

Sensitivity analysis

The effects on computed ground-water levels of independently changing values for hydrologic factors of the flow system were determined in a sensitivity analysis involving MODFE and the data inputs for the calibrated model. The objective of the analysis was to determine which of the hydrologic factors, when changed from values used in the calibrated model, produced the most change in computed water levels in the Upper Floridan aquifer. Presumably, the hydrologic factors to which computed water levels are the most sensitive would be those physical properties of the ground-water and surface-water system that, when changed in the model, simulated the most change in the flow system and in the potentiometric surface of the Upper Floridan aquifer.

Procedure

Values for hydrologic factors that were conceptualized as having an influence on computed ground-water levels of the Upper Floridan aquifer were changed uniformly over the model area or over segments of boundaries (zones) from the values that were used in the calibrated model, and a simulation was performed. Changes were made to each hydrologic factor over a range of values, and the sum of squares of the water-level residuals was computed after each simulation. Eighteen hydrologic factors were determined to have an influence on the ground-water and surface-water system in the study area (table 9). The hydraulic conductivity of the Upper Floridan aquifer, withdrawal rates for wells, and vertical-leakage coefficient and source-layer heads for the undifferentiated overburden were each treated as single hydrologic factors that were changed over the entire model area; no changes were made to individual values in a zone or at a node for these factors. Other hydrologic factors defined aspects of the flow system that were simulated in MODFE as the zones of a Cauchy-type boundary, either the leakage coefficient or the external (or boundary) head (table 9).

Table 9.--*Hydrologic factors used in sensitivity analysis*

Aquifer and confining-bed factors

Hydraulic conductivity of Upper Floridan aquifer	Withdrawal rates for wells
Vertical leakage coefficient of undifferentiated overburden	Source-layer heads of undifferentiated overburden

Cauchy-type-boundary factors

Zone(s)	4- 6, 18	Regional flow across western model boundary; boundary coefficient.
	4- 6, 18	Regional flow across western model boundary; external head.
	7-10, 13-17	Regional flow across eastern model boundary; boundary coefficient.
	7-10, 13-17	Regional flow across eastern model boundary; external head.
	1	Kinchafoonee Creek, northern model boundary; boundary coefficient.
	1	Kinchafoonee Creek, northern model boundary; creek stage.
	2, 12	Lake Worth and reservoir, regional flow, northern model boundary; boundary coefficient.
	2, 12	Lake Worth and reservoir, regional flow, northern model boundary; external head.
	11	Flint River and regional flow, northern model boundary; boundary coefficient.
	11	Flint River and regional flow, northern model boundary; river stage and external head.
	2- 6	Flint River downstream from the Lake Worth dam; boundary coefficient.
	2- 6	Flint River downstream from the Lake Worth dam; river stage.
	3	Cooleewahee Creek (west of area of potential development); boundary coefficient.
	3	Cooleewahee Creek (west of area of potential development); creek stage.

Significance to the Ground-Water-Flow System

The significance of the hydrologic factors in table 9 to ground-water flow in the Upper Floridan aquifer is demonstrated by plots showing the relation of the sum of water-level residuals squared (termed "sum of head differences squared" in the plots) to changes in hydrologic factors for each simulation (figs. 28-45). Hydrologic factors that are influential to the flow system yielded plots that resemble a parabola having a deep trough and steeply dipping sides (figs. 28-33). The shapes of these "sensitivity curves" indicate that small changes to the values of these hydrologic factors produced large changes in computed water levels, and, hence, have a greater influence on the ground-water-flow system than hydrologic factors that produce relatively flat sensitivity curves (shown in figures 34-45). Thus, the hydrologic factors that have the most influence on water levels are the factors that are assumed to govern ground-water flow in the Upper Floridan aquifer under steady-state conditions. Consequently, these factors need to be determined with the most accuracy to ensure a meaningful analysis of the water-resource potential by using simulation.

Results of the sensitivity analysis indicate that computed water levels, and hence, steady-state ground-water flow in the Upper Floridan aquifer were influenced mostly by the following hydrologic factors:

- aquifer hydraulic conductivity,
- vertical leakage coefficient of the undifferentiated overburden,
- source-layer heads of the undifferentiated overburden,
- stage of the Flint River downstream from the Lake Worth dam, and
- boundary heads along the eastern and western model boundaries.

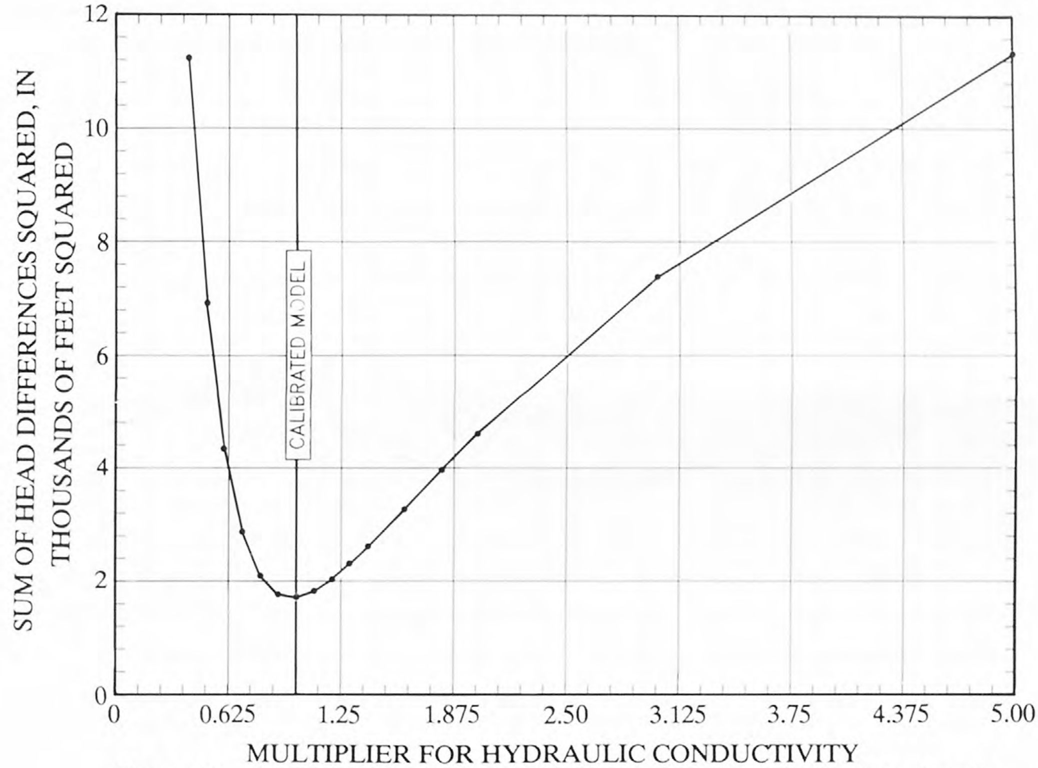


Figure 28.--Changes in sum of head differences squared with respect to changes in aquifer hydraulic conductivity.

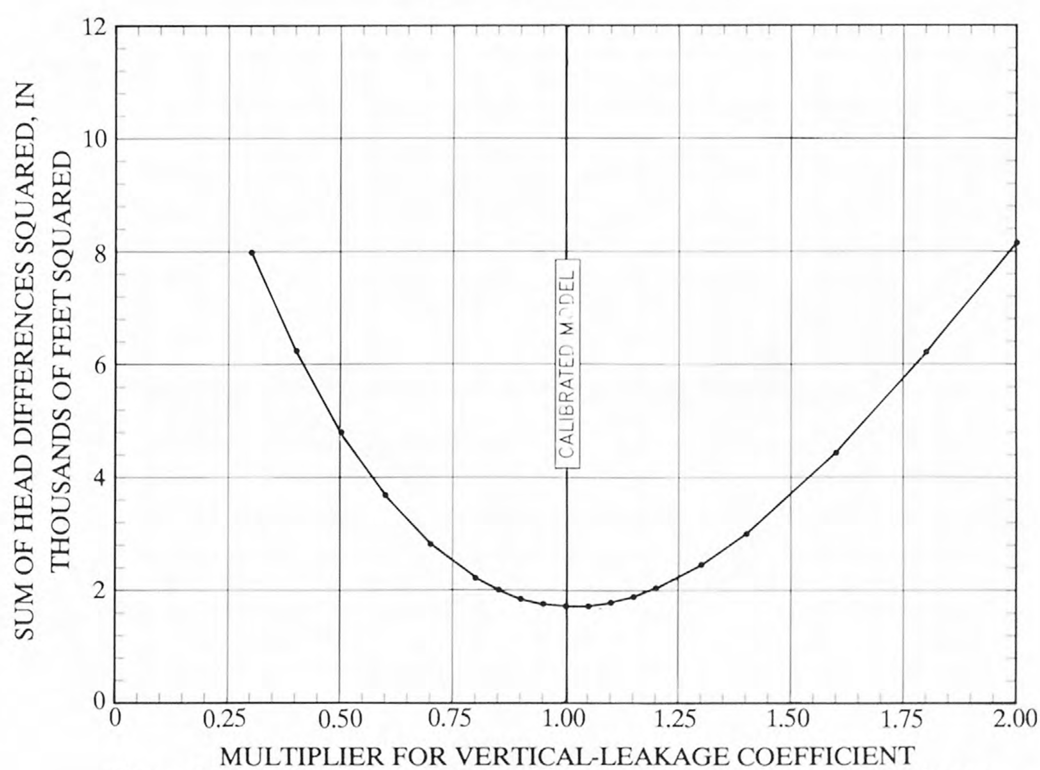


Figure 29.--Changes in sum of head differences squared with respect to changes in vertical-leakage coefficient of undifferentiated overburden.

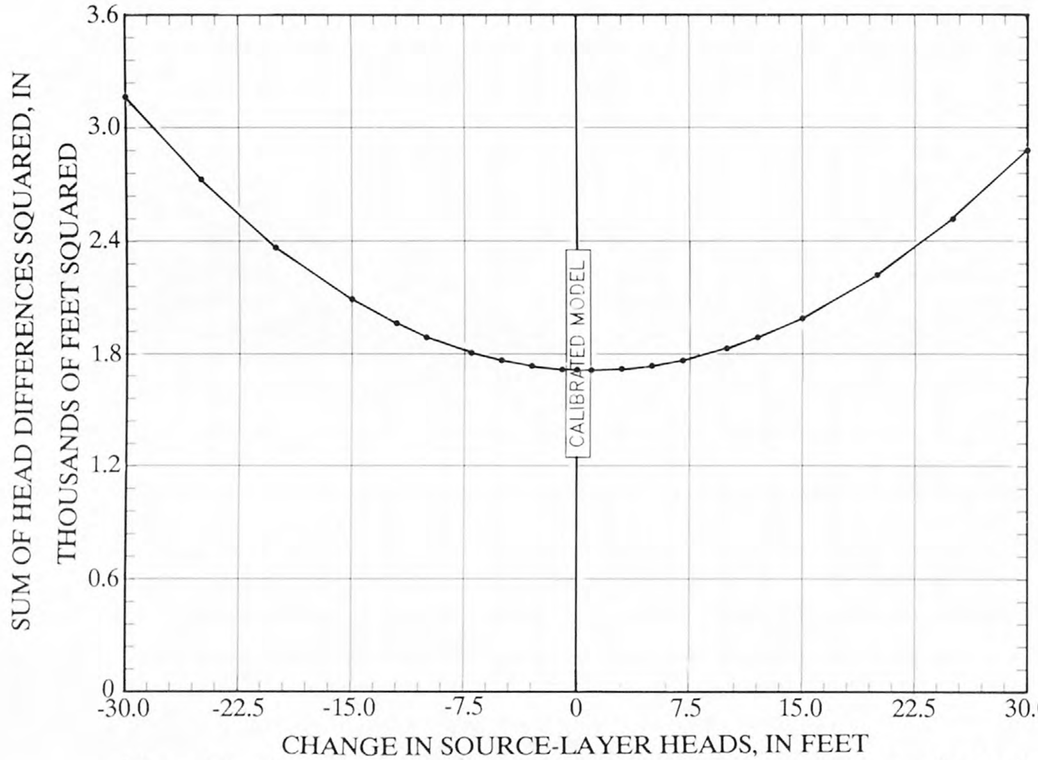


Figure 30.--Changes in sum of head differences squared with respect to changes in source-layer heads in undifferentiated overburden.

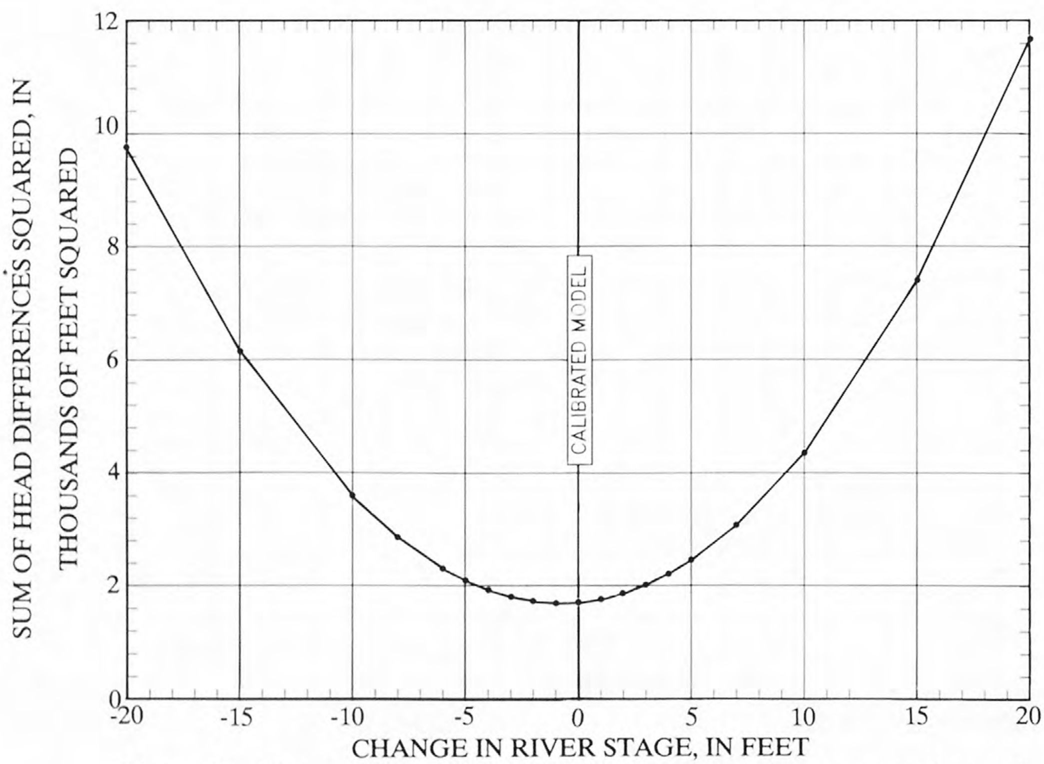


Figure 31.--Changes in sum of head differences squared with respect to changes in stage of Flint River downstream from the Lake Worth dam.

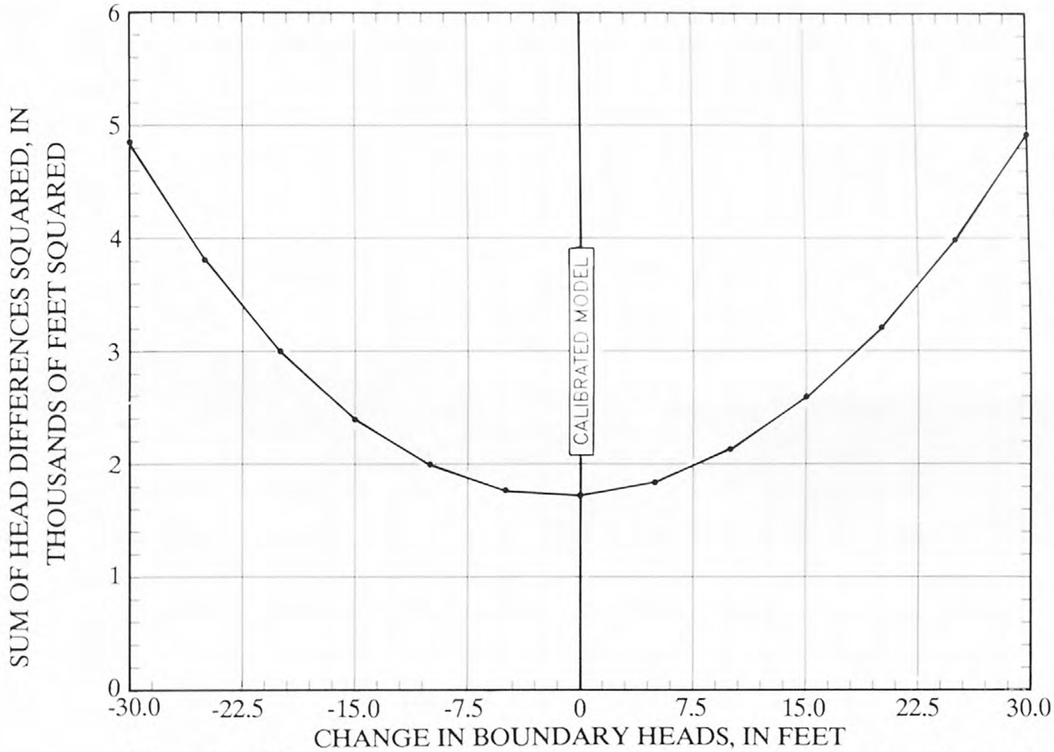


Figure 32.--Changes in sum of head differences squared with respect to changes in boundary heads along western model boundary.

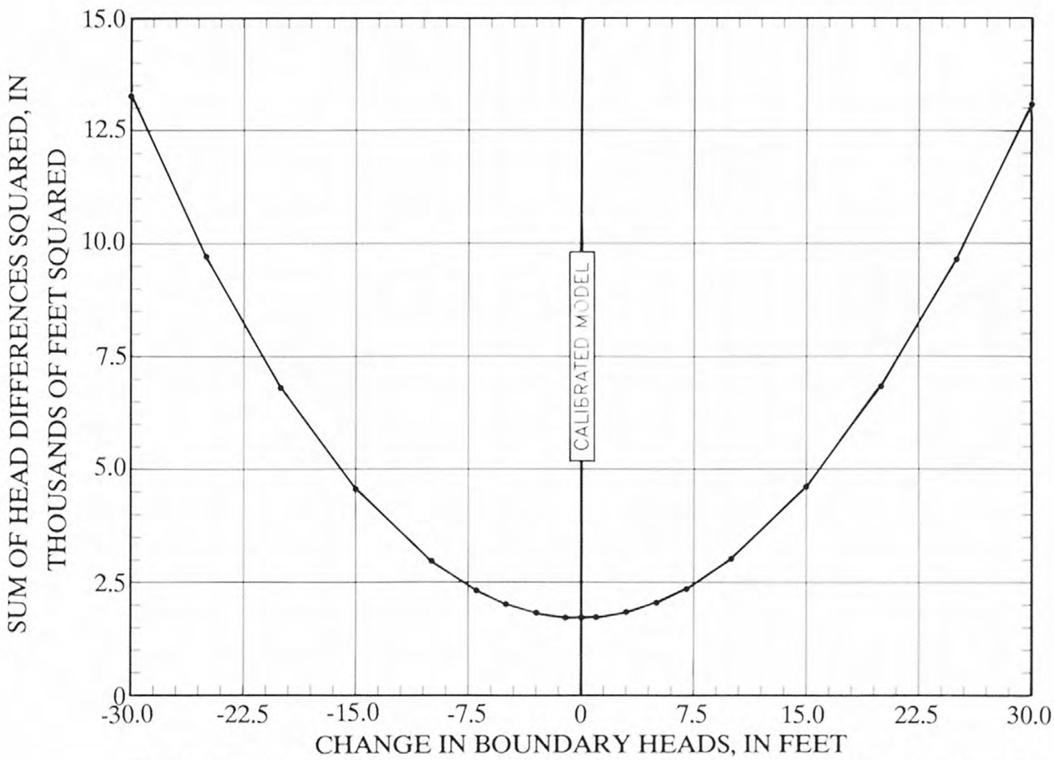


Figure 33.--Changes in sum of head differences squared with respect to changes in boundary heads along eastern model boundary.

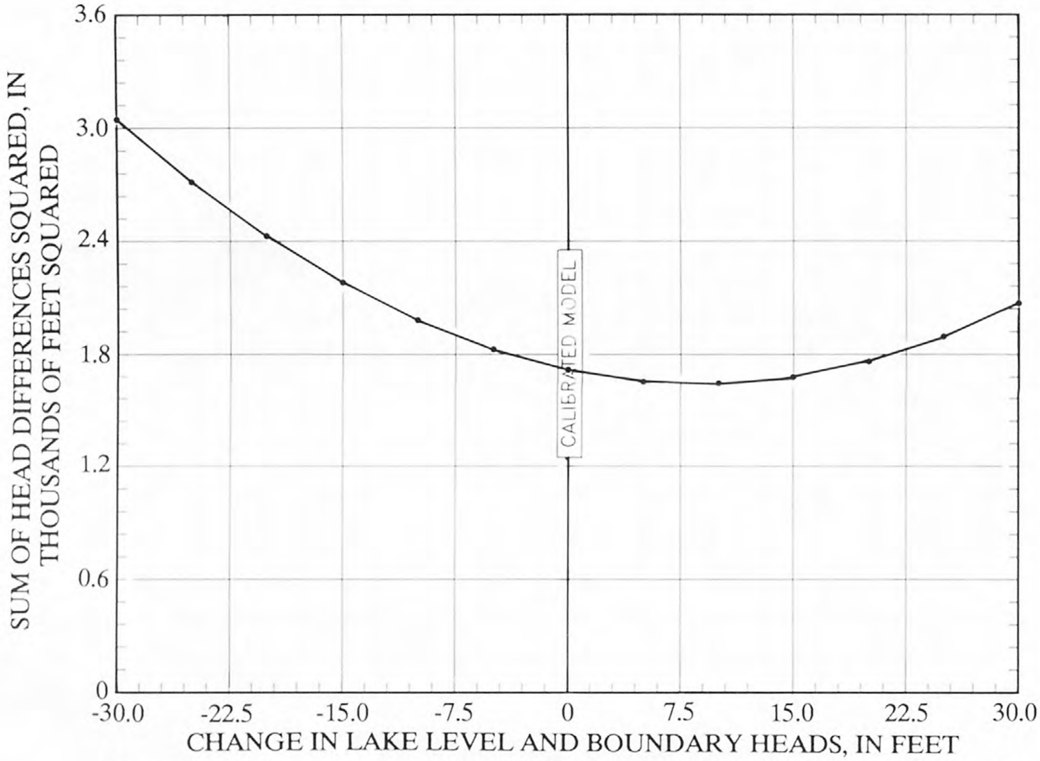


Figure 34.--Changes in sum of head differences squared with respect to changes in lake level and boundary heads, respectively, for Lake Worth and regional flow from north.

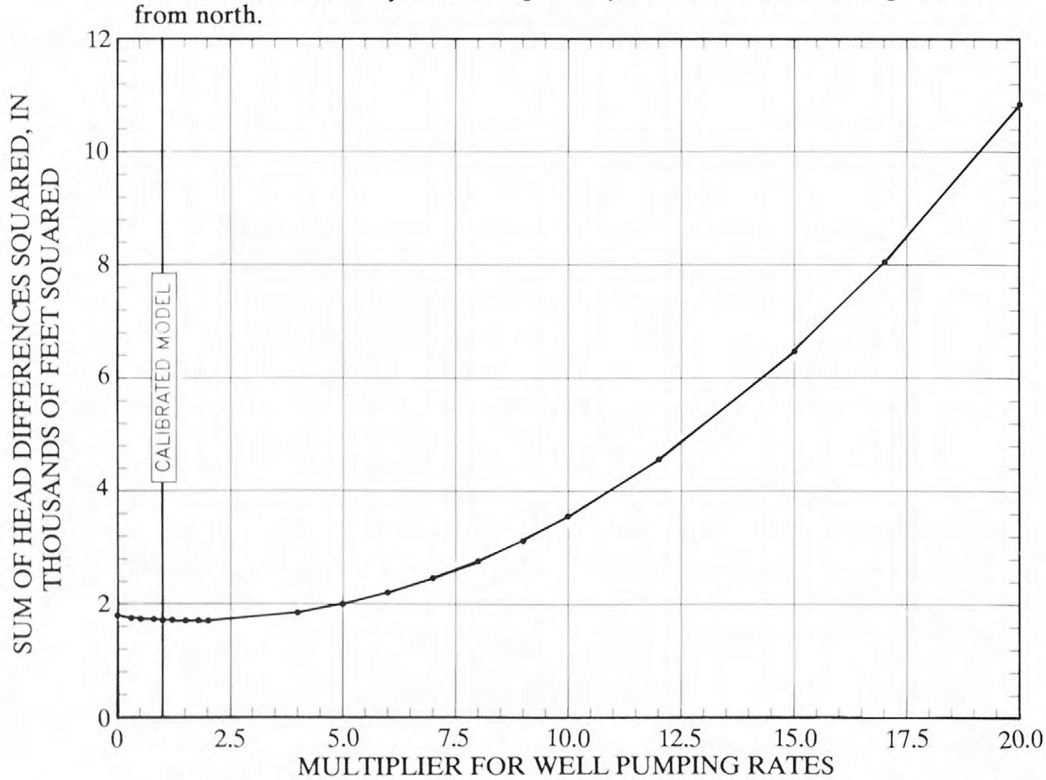


Figure 35.--Changes in sum of head differences squared with respect to changes in well-pumping rates.

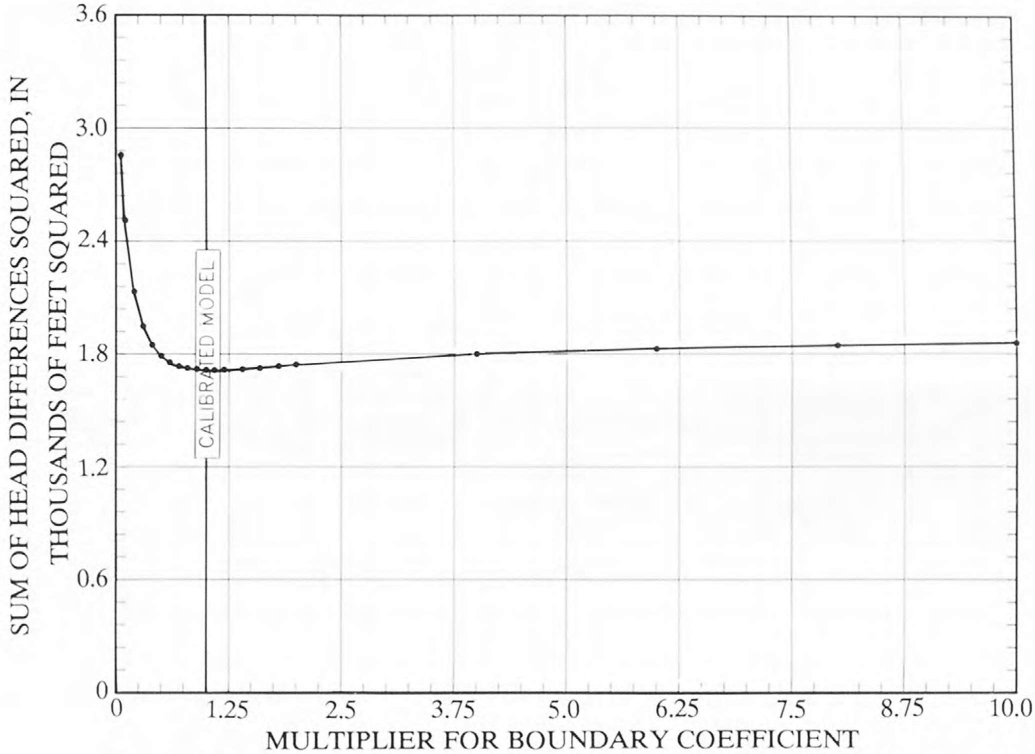


Figure 36.--Changes in sum of head differences squared with respect to changes in boundary coefficient of Kinchafoonee Creek.

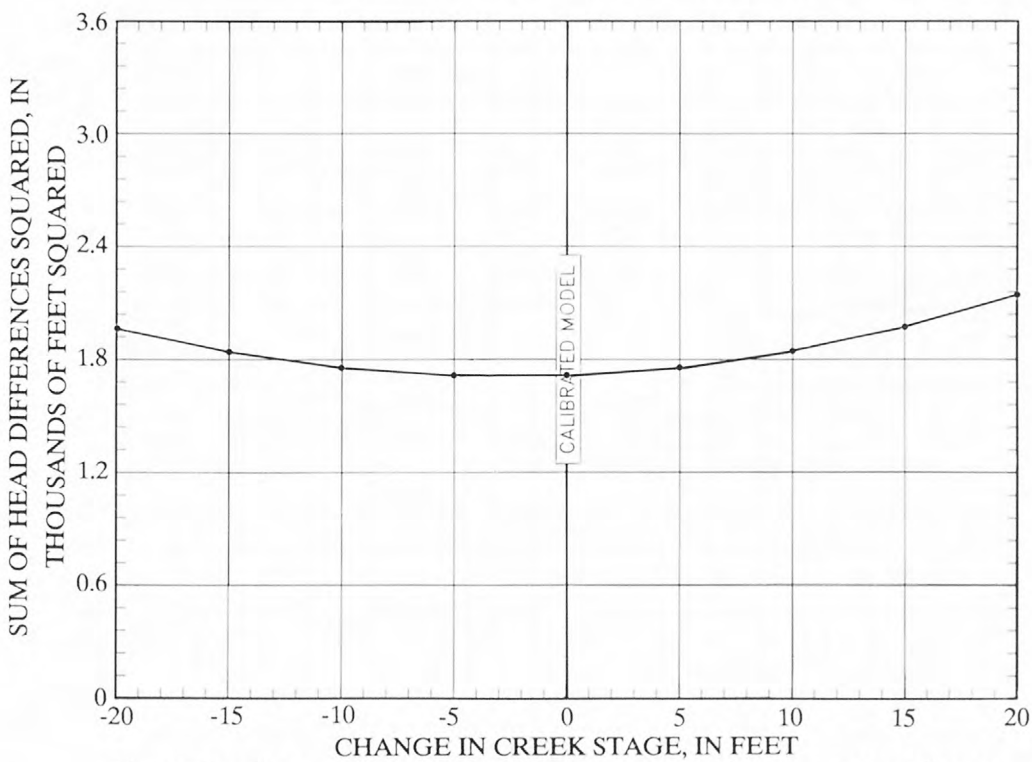


Figure 37.--Changes in sum of head differences squared with respect to changes in stage of Kinchafoonee Creek.

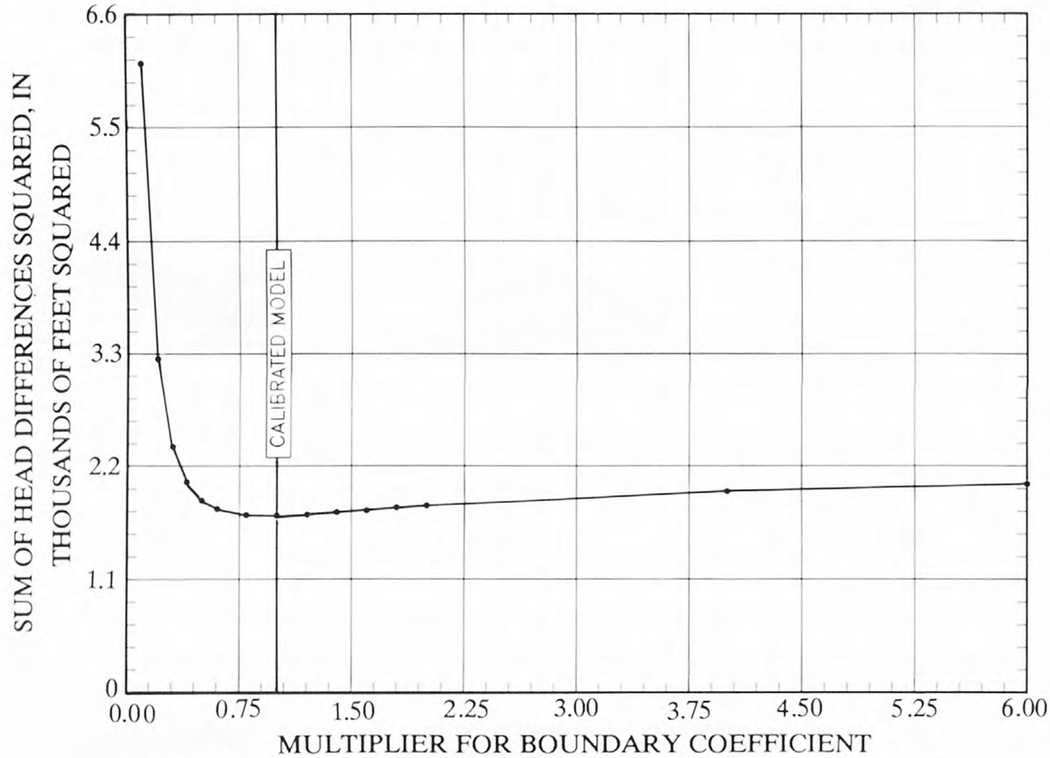


Figure 38.--Changes in sum of head differences squared with respect to changes in boundary coefficient of western model boundary.

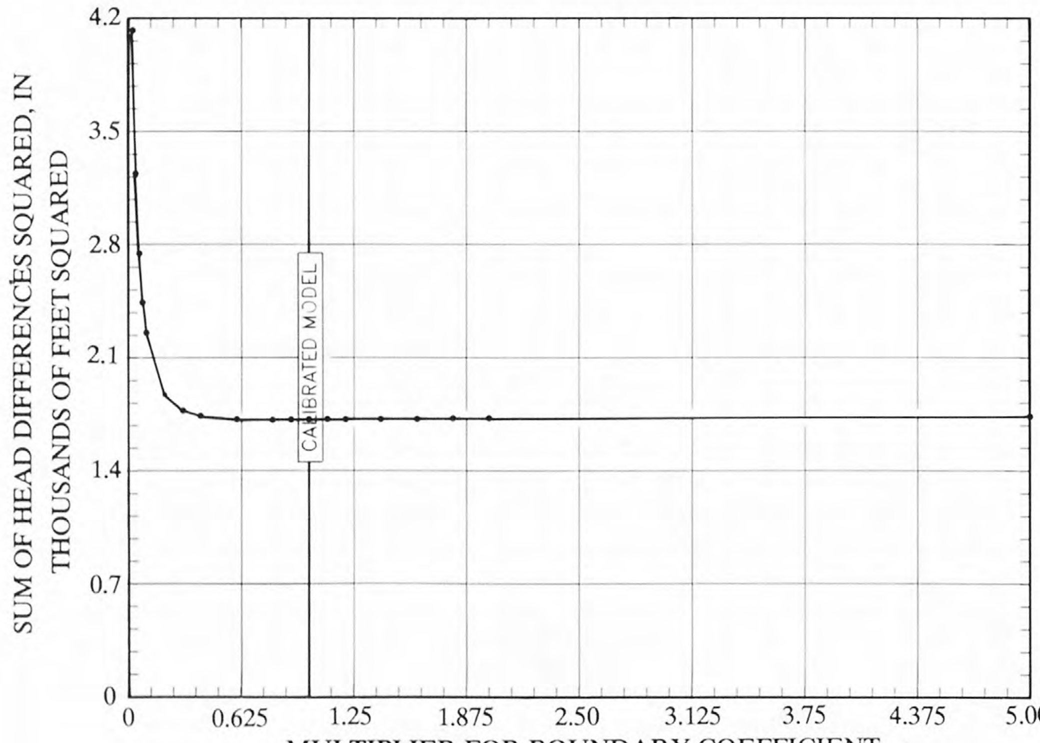


Figure 39.--Changes in sum of head differences squared with respect to changes in boundary coefficient of eastern model boundary.

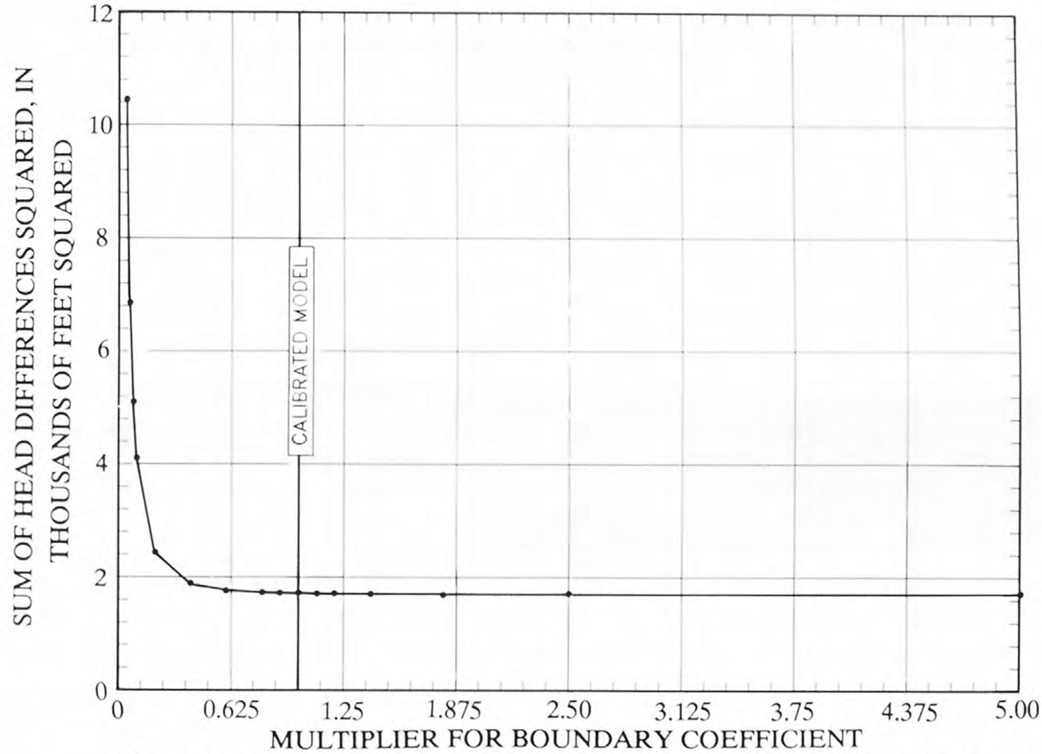


Figure 40.--Changes in sum of head differences squared with respect to changes in boundary coefficient of Flint River downstream from the Lake Worth dam.

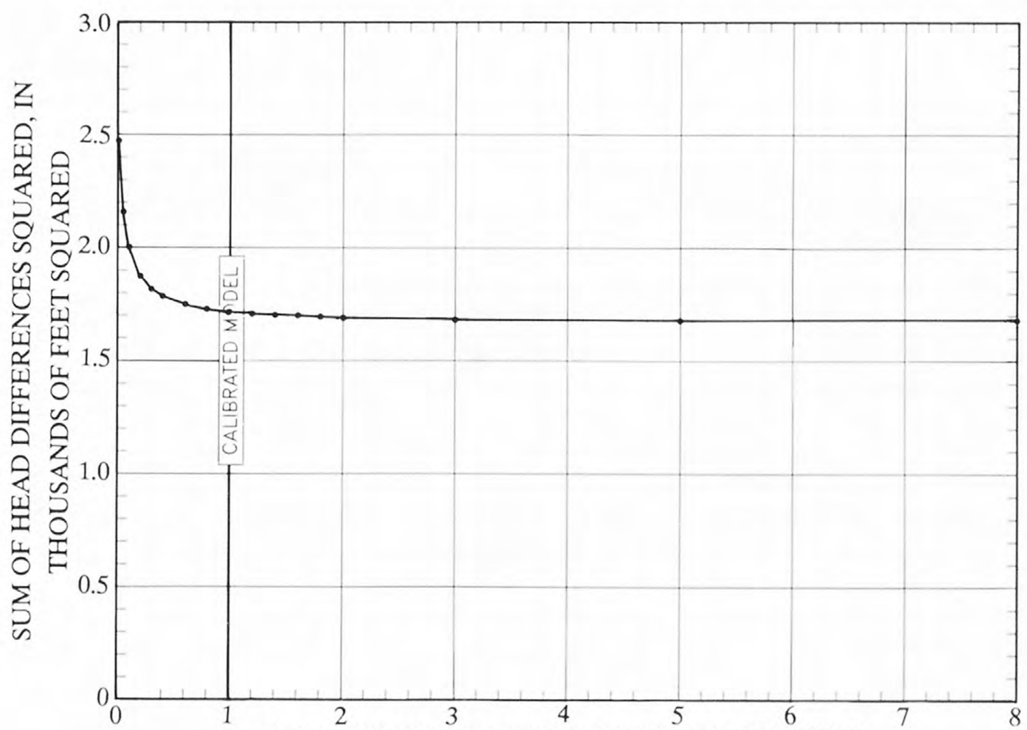


Figure 41.--Changes in sum of head differences squared with respect to changes in boundary coefficient of Lake Worth and regional flow from north.

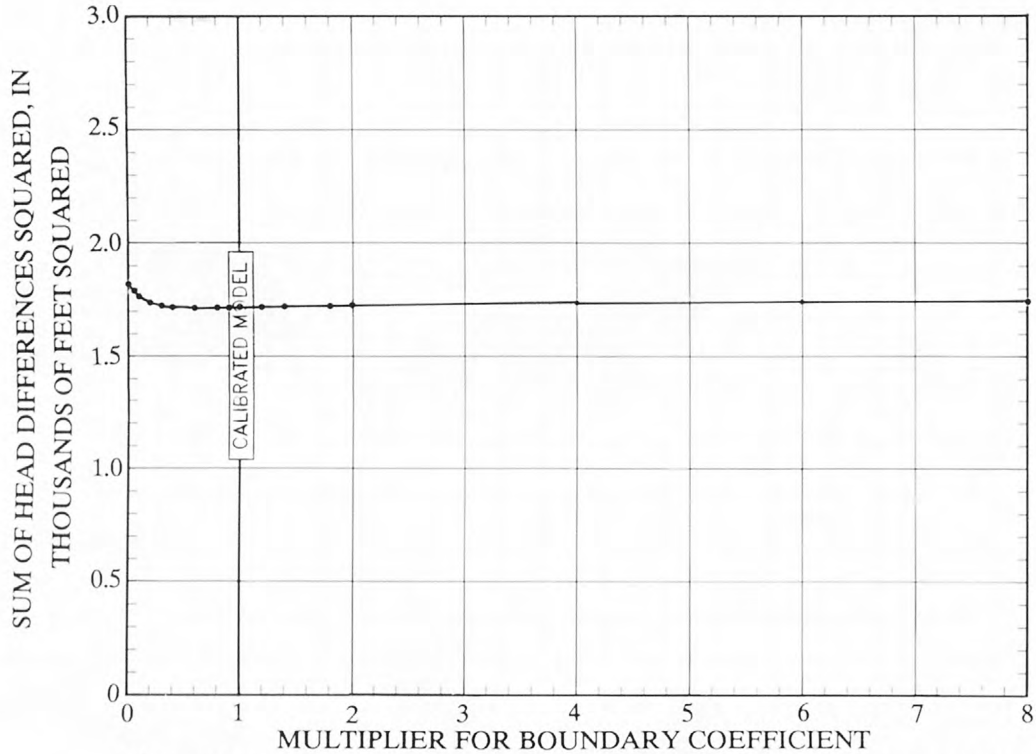


Figure 42.--Changes in sum of head differences squared with respect to changes in boundary coefficient of Flint River and regional flow from north.

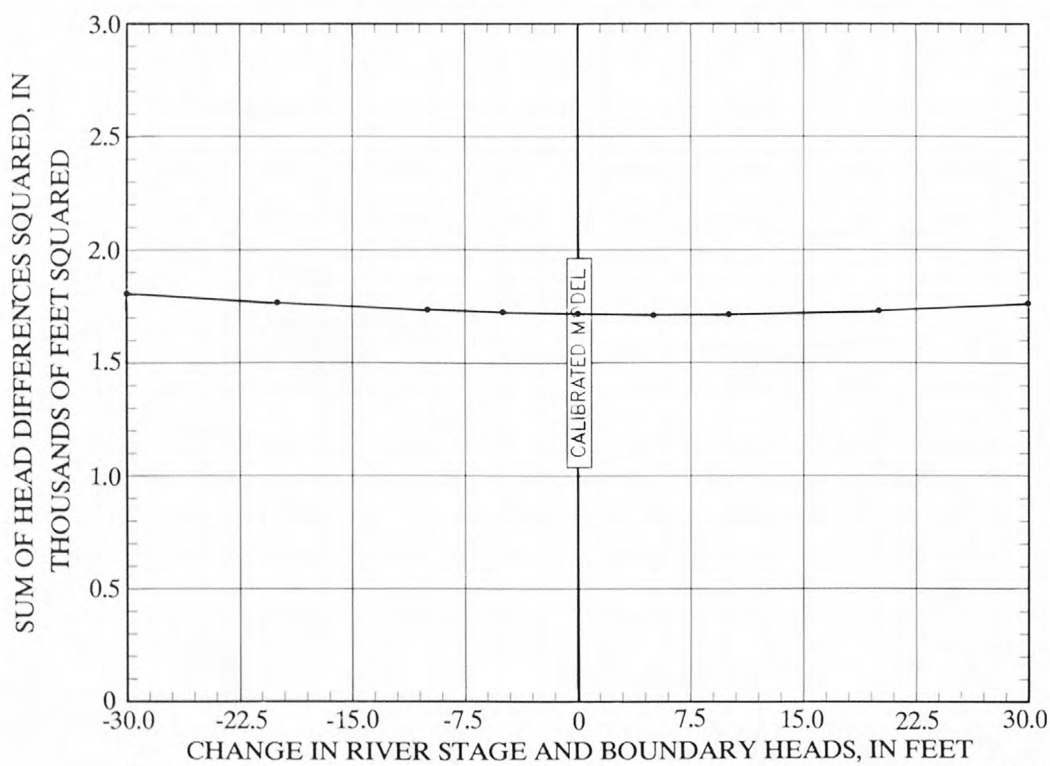


Figure 43.--Changes in sum of head differences squared with respect to changes in stage of Flint River and boundary heads to north.

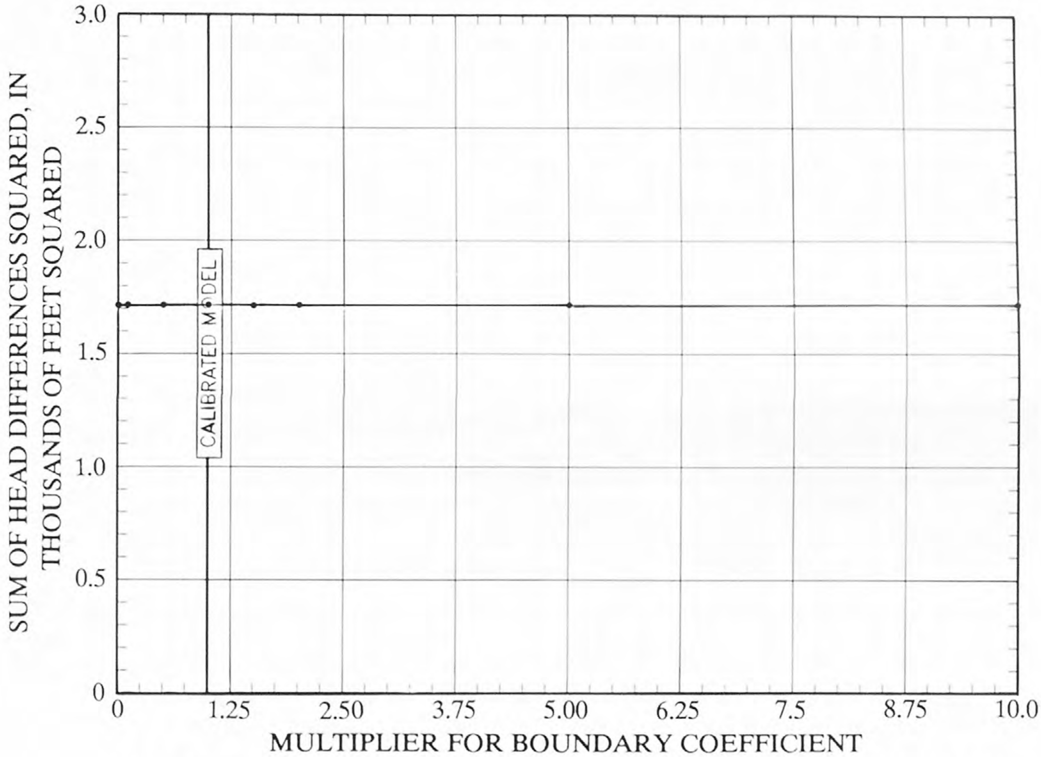


Figure 44.--Changes in sum of head differences squared with respect to changes in boundary coefficient of Cooleewahee Creek.

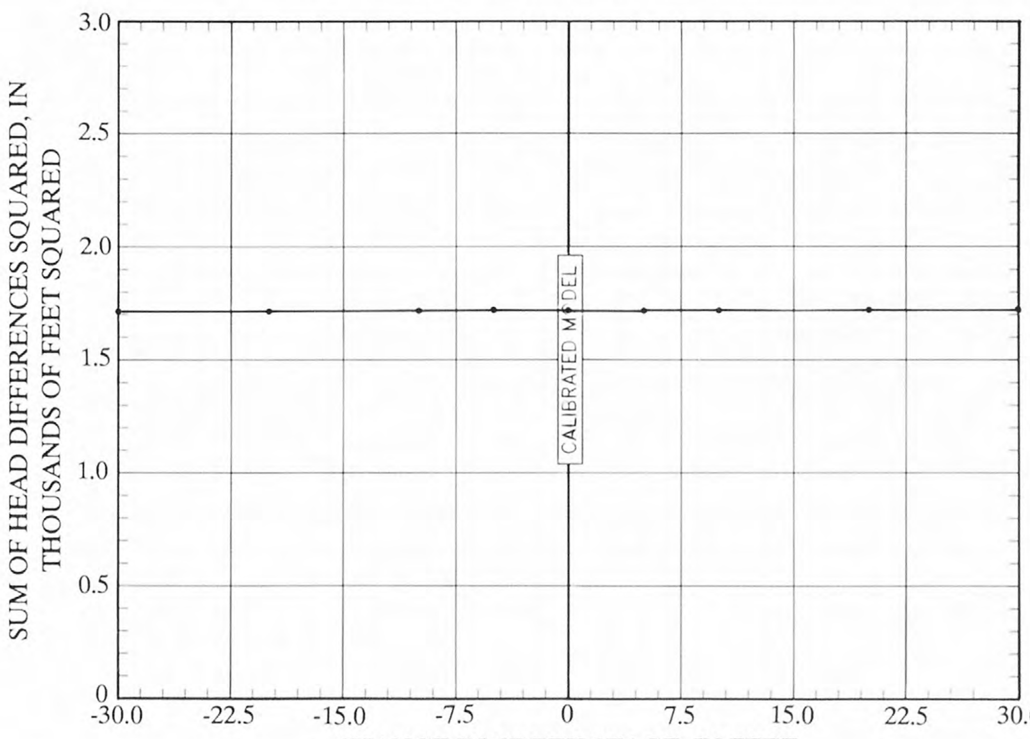


Figure 45.--Changes in sum of head differences squared with respect to changes in stage of Cooleewahee Creek.

Plots of the sensitivity curves for these hydrologic factors (figs. 28-33) show that large changes to the sum of squares occurred when relatively small changes were made to values used in the calibrated model. Although the Flint River downstream from the Lake Worth dam and the eastern and western model boundaries were not areally extensive with respect to the model area (plate 1), their importance to ground-water flow in the Upper Floridan aquifer in the entire model area was demonstrated by the magnitude of changes in the sum of squares that was observed in the sensitivity curves (figs. 31-33).

Other hydrologic factors from table 9 yielded sensitivity curves that indicate that they were not as influential to ground-water flow in the Upper Floridan aquifer as the factors whose curves were plotted in figures 28-33. The sensitivity analysis demonstrated that ground-water levels were affected very little by changes in well-pumping rates that were less than about a five-fold increase in the rates for November 1985 (fig. 35). Small differences in the sum of squares were realized between the calibrated model and the sensitivity simulation that had no pumpage from the Upper Floridan aquifer (fig. 35), indicating that ground-water withdrawal from wells in the Upper Floridan aquifer had a minor effect on shaping the potentiometric surface for November 1985. Of lesser importance than well pumpage in affecting ground-water flow in the Upper Floridan aquifer were the following hydrologic factors: the northern model boundary, Kinchafoonee Creek, boundary coefficients for the eastern and western model boundaries, and Cooleewahee Creek. Sensitivity curves for these hydrologic factors were relatively flat (figs. 34, 35-39, 44-45), indicating that large changes to values that were used in the calibrated model produced small changes in computed water levels.

The significance of the apparent insensitivity of ground-water flow to values for the hydrologic factors depicted in figures 34-45 is that these hydrologic factors initially were conceptualized as being important to the ground-water-flow system (see earlier section on "Conceptualization of the Flow System"). The fairly uniform distribution of wells having water-level measurements and the proximity of the measurements to these hydrologic factors (plates 1 and 2) precludes the possibility that sensitivity of computed water levels to these hydrologic factors was obscured by a sparse set of water-level measurements. Although leakage coefficients for surface-water features and the eastern and western model boundaries yielded sensitivity curves that were relatively flat (figs. 36, 38-42, 44), sensitivity curves for boundary heads and surface-water levels indicated that these heads and water levels influence ground-water flow in the Upper Floridan aquifer more than do the boundary coefficients (figs. 31-34, 37). The greater sensitivity of computed water levels to boundary heads and to surface-water levels than to boundary coefficients indicates that the ground-water-flow system was influenced by heads along the boundaries and surface-water features in a manner similar to that in which the flow system would be influenced by specified-head boundaries if such boundaries were present in the model area. Therefore, the accuracy of water-level measurements along model boundaries and at surface-water features plays an important part in the accuracy of computed water levels within the model area.

The plot of sensitivity curves for Cooleewahee Creek indicated that ground-water flow in the Upper Floridan aquifer essentially is unaffected by changes in the leakage coefficient and creek stage (figs. 44, 45). This is important to ground-water flow in the Upper Floridan aquifer as Cooleewahee Creek is within a few miles of the area of potential development that was evaluated by simulating pumped wells in that area. The response of the ground-water-flow system to well pumpage is discussed in the following section.

Flow-system response to pumpage

Pumpage within the area of potential development located south of Albany (fig. 46), was simulated by MODFE to evaluate the water-resource potential of the Upper Floridan aquifer in that area. Six scenarios of pumping were simulated by adding wells to the calibrated model at the nodal locations (fig. 46) and by computing the steady-state solution. In the first three scenarios, the pumping rate was 7.2 Mgal/d at one well (node) at three different locations; in the next scenario, 21.6 Mgal/d was withdrawn from three wells (7.2 Mgal/d each); and in the last two scenarios, 36 and 72 Mgal/d was withdrawn from 5 wells (7.2 and 14.4 Mgal/d each, respectively). The water-resource potential of the Upper Floridan aquifer was evaluated by determining the effects of pumping on the ground-water and surface-water system. These effects were expressed as aquifer drawdown, changes to water-budget components and to directions of ground-water movement, and the increased potential for sinkhole development or water-quality impairment.

Drawdown

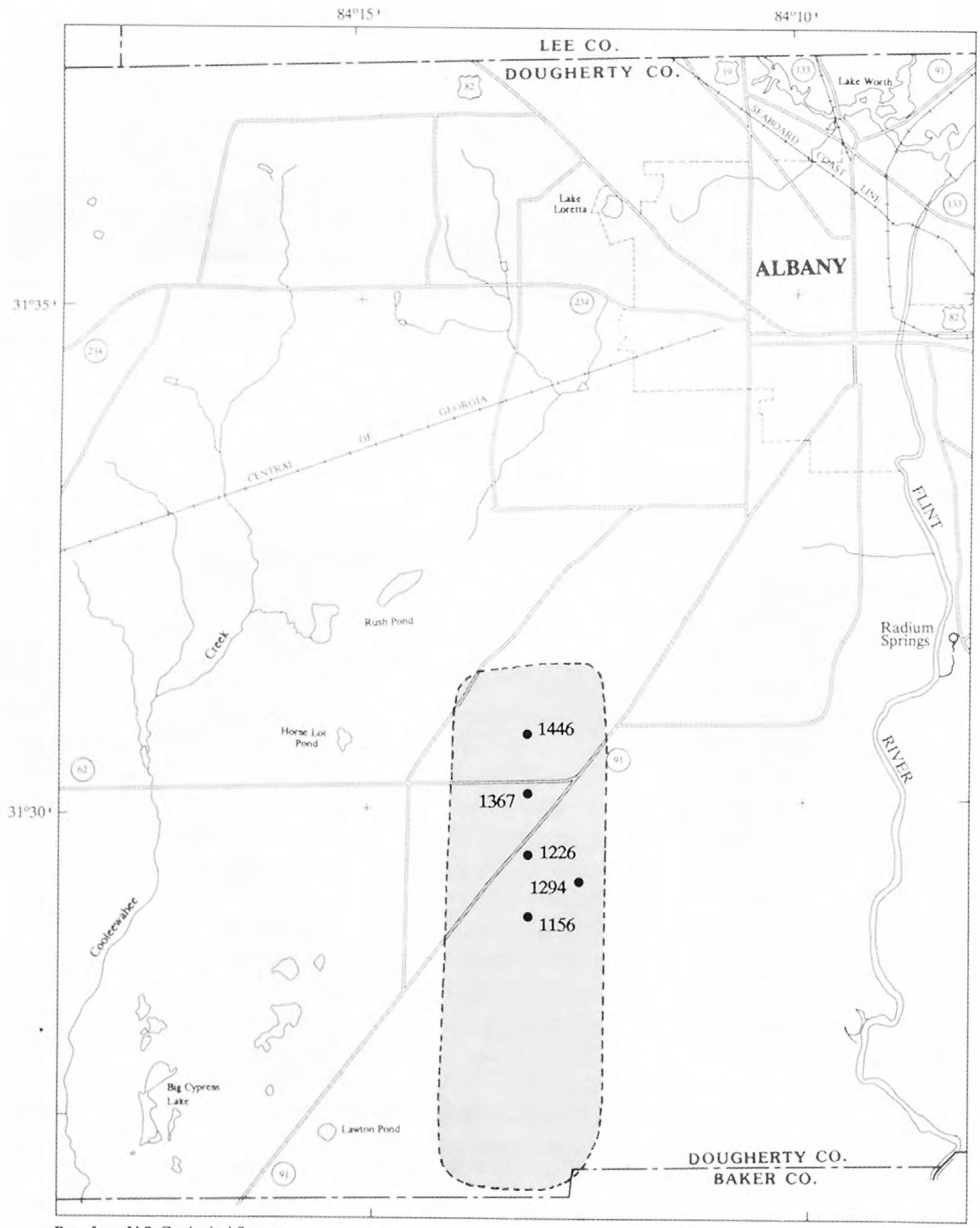
Water-level drawdown in the Upper Floridan aquifer in response to pumping within the area of potential development was determined by simulating pumping for the six scenarios described previously and by subtracting the resulting computed water levels from water levels that were obtained from the calibrated model of November 1985 conditions. Drawdown values from the six pumping scenarios were obtained at all nodes in the finite-element mesh. The drawdowns represent point (nodal) values at the intersections of elements in the finite-element mesh, and are distinct values that can be compared with the actual drawdowns that would occur in wells under steady-state conditions. Lines of equal drawdown were contoured on a map of the potential-development area (figs. 47-52) to show the areal extent of drawdown in the Upper Floridan aquifer that resulted from pumping. Maximum drawdowns occurred at the nodes where pumping wells were simulated.

The drawdown resulting from each of the six scenarios of pumping (table 10) indicated that the Upper Floridan aquifer was minimally affected by increased ground-water withdrawal over the November 1985 rates. Of the three simulations that involved pumping 7.2 Mgal/d at different nodal locations, pumping at node 1446 caused the most drawdown, about 1.9 ft, to occur (table 10). The plot showing lines of equal drawdown for this simulation (fig. 47) showed a fairly symmetric pattern around the pumping node, having a slight elongation of drawdown to the northwest. This elongation may result from thinning of the aquifer toward the northwest, which results in lower aquifer transmissivity in that area. The effect of pumping on the Flint River downstream from the Lake Worth dam appeared to be minimal, as the 0.1-ft line of equal drawdown was west of the river. Plots of computed drawdown for the other two scenarios of 7.2 Mgal/d pumping (figs. 48, 49) showed a smaller area of influence from the pumped well than from the simulation of pumpage at node 1446 (fig. 47). This probably was caused by the Upper Floridan aquifer being thicker toward the southeast, which results in higher aquifer transmissivity there, and by the occurrence of more solution openings in the vicinity of the southernmost wells (fig. 8).

Table 10.--*Maximum drawdown due to simulated pumping in area of potential development*

[--, pumping not simulated at node]

	Drawdown, in feet					
Simulation	Node 1226	Node 1294	Node 1446	Node 1367	Node 1156	Pumping rate (million gallons per day)
1	1.16	--	--	--	--	7.2
2	--	1.10	--	--	--	7.2
3	--	--	1.85	--	--	7.2
4	2.58	2.29	3.14	--	--	21.6
5	4.15	3.53	4.70	4.38	3.77	36
6	8.35	7.12	9.44	8.81	7.33	72



Base from U.S. Geological Survey
1:62,500 quadrangles

0 1 2 3 4 MILES

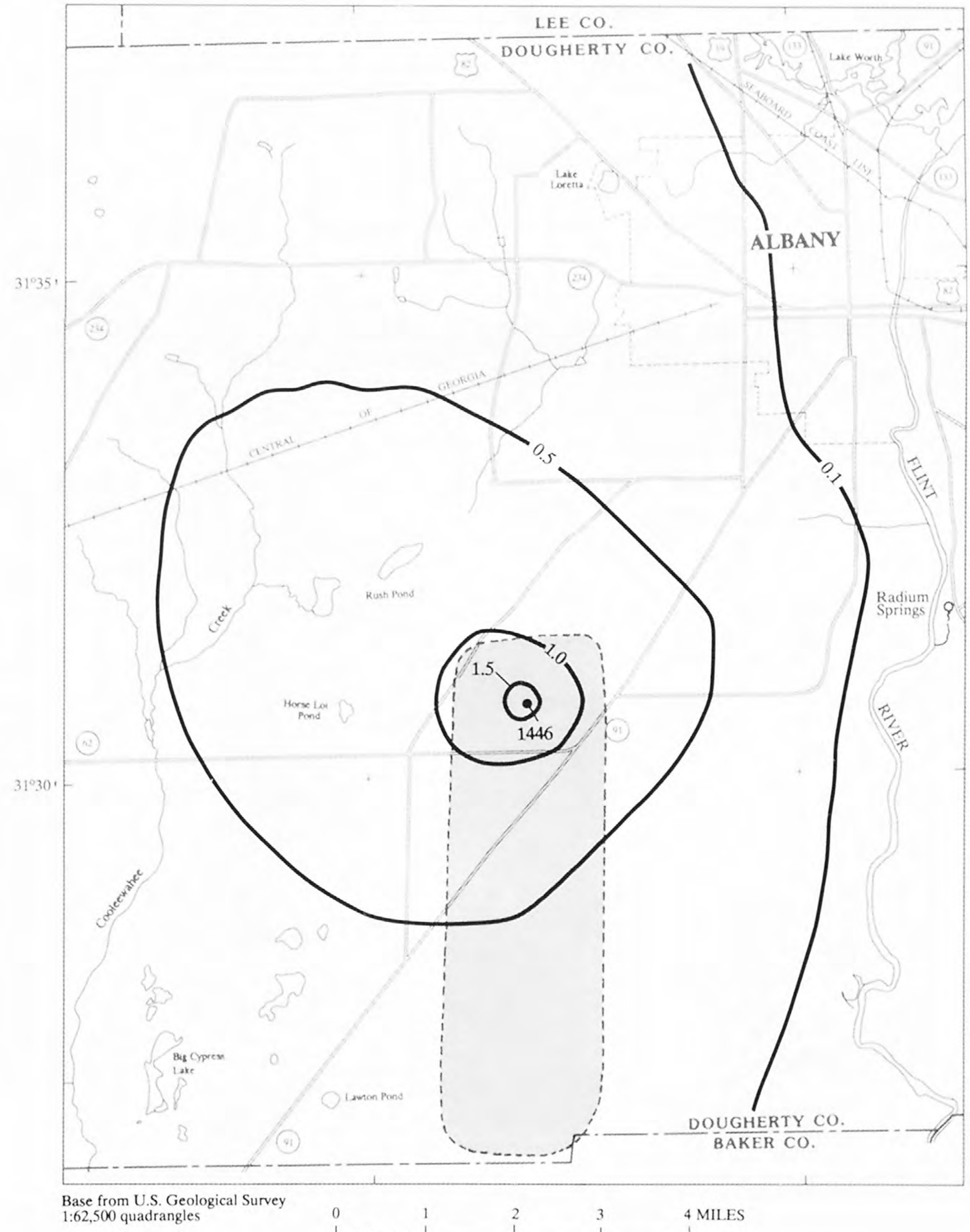
0 1 2 3 4 KILOMETERS

EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

1156 • PUMPED WELL--Number indicates node in finite-element mesh

Figure 46.--Locations of area of potential development and nodes used to simulate pumping in MODular Finite-Element model (MODFE).



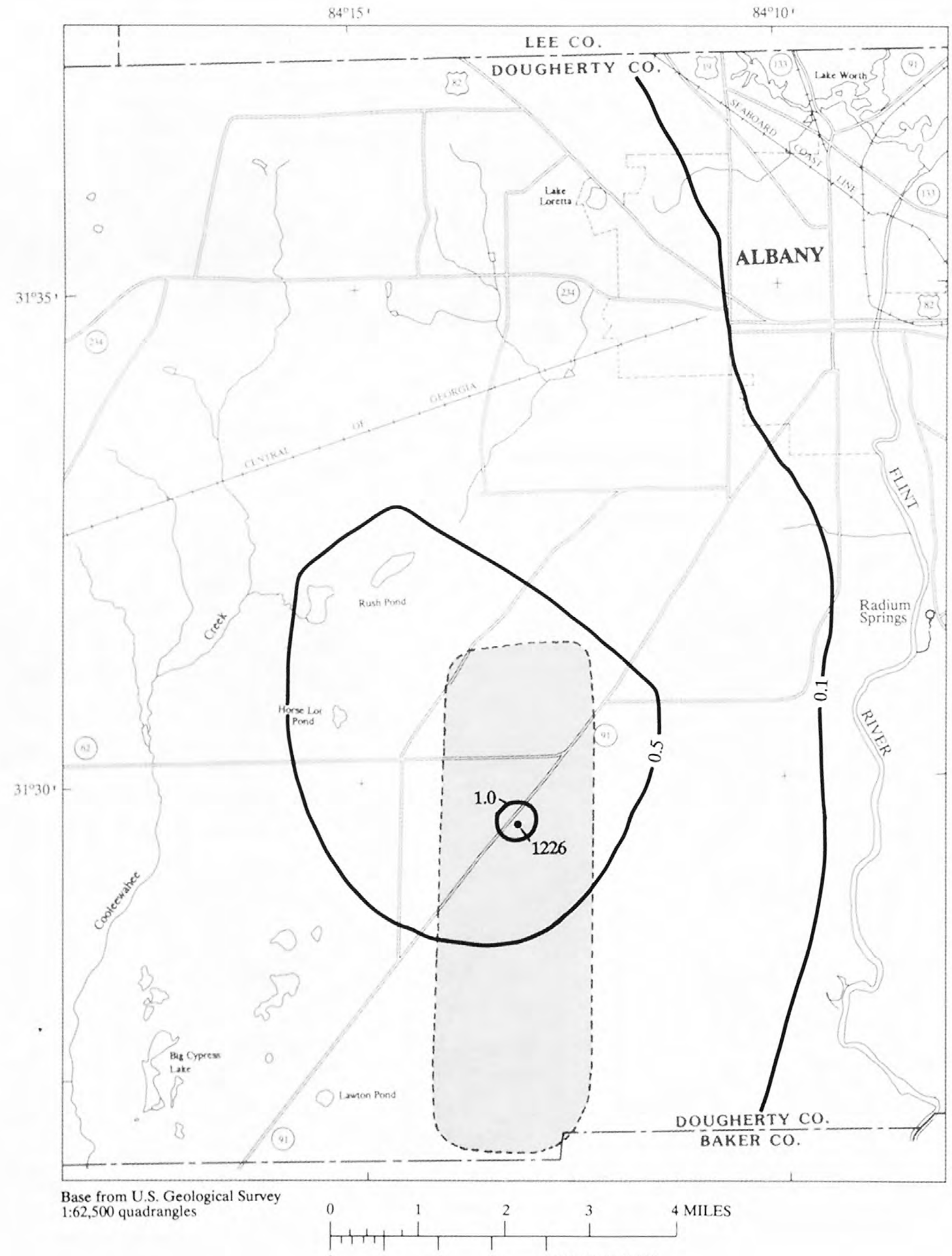
EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

1446 PUMPED WELL--Number indicates node in finite-element mesh

1.0 LINE OF EQUAL DRAWDOWN--Interval varies, in feet

Figure 47.--Lines of equal computed drawdown in Upper Floridan aquifer from simulated pumping rate of 7.2 million gallons per day at node 1446.



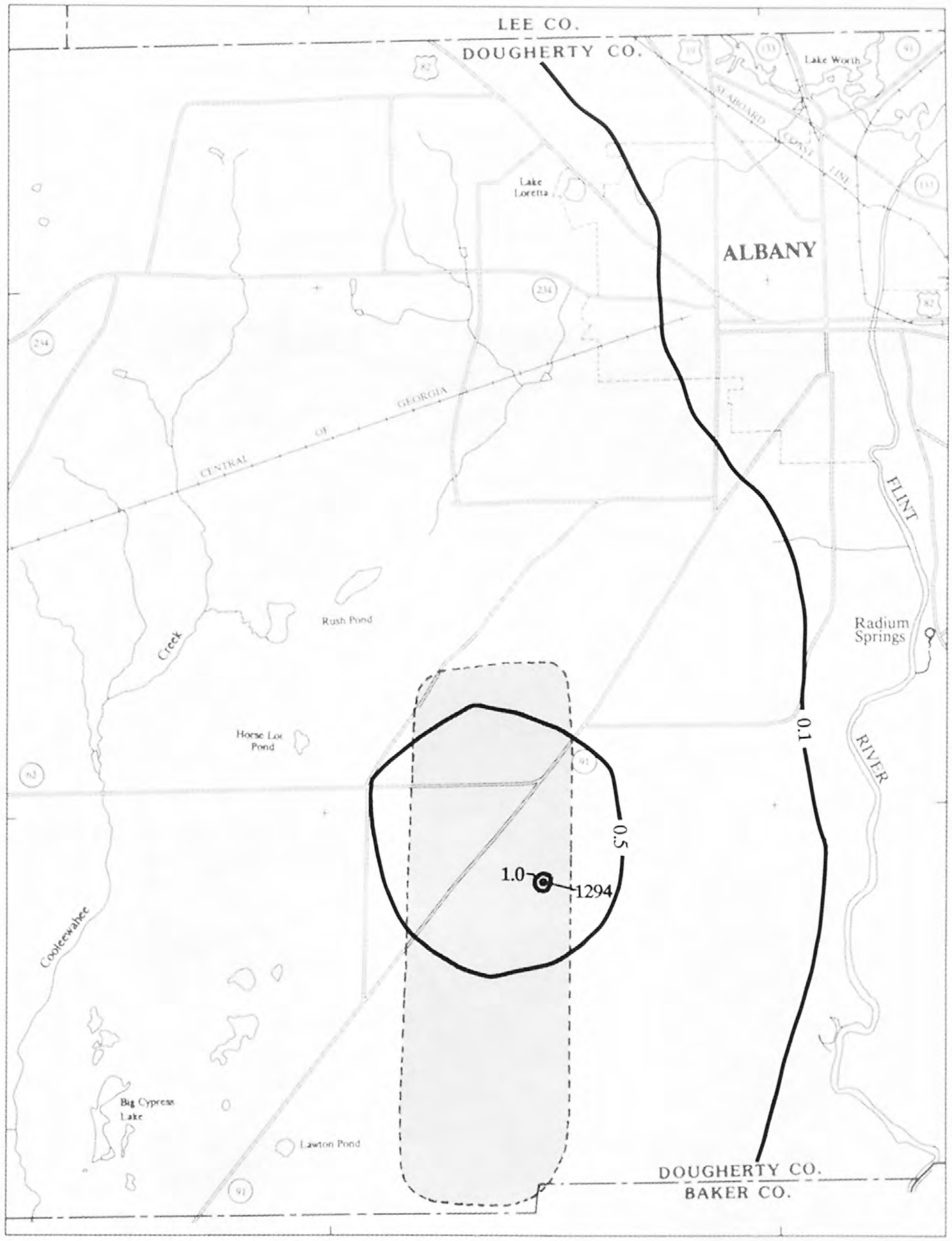
EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

— 0.5 — LINE OF EQUAL DRAWDOWN--Interval varies, in feet

1226 • PUMPED WELL--Number indicates node in finite-element mesh

Figure 48.--Lines of equal computed drawdown in Upper Floridan aquifer from simulated pumping rate of 7.2 million gallons per day at node 1226.



Base from U.S. Geological Survey
1:62,500 quadrangles

0 1 2 3 4 MILES
0 1 2 3 4 KILOMETERS

EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

1294 • PUMPED WELL--Number indicates node in finite-element mesh

0.1 LINE OF EQUAL DRAWDOWN--Interval varies, in feet

Figure 49.--Lines of equal computed drawdown in Upper Floridan aquifer from simulated pumping rate of 7.2 million gallons per day at node 1294.

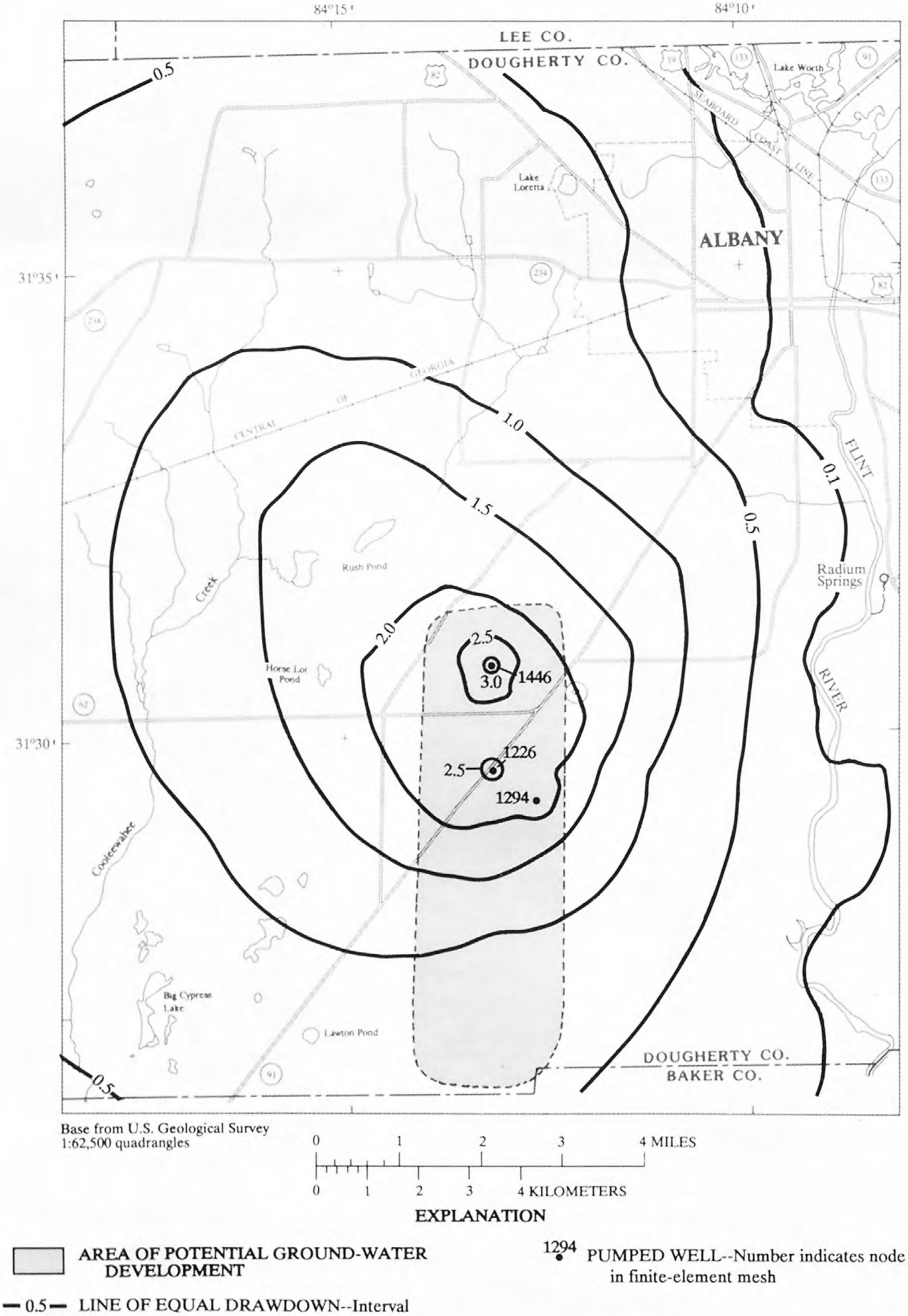


Figure 50.--Lines of equal computed drawdown in Upper Floridan aquifer from simulated pumping rate of 21.6 million gallons per day at nodes 1226, 1294, and 1446.

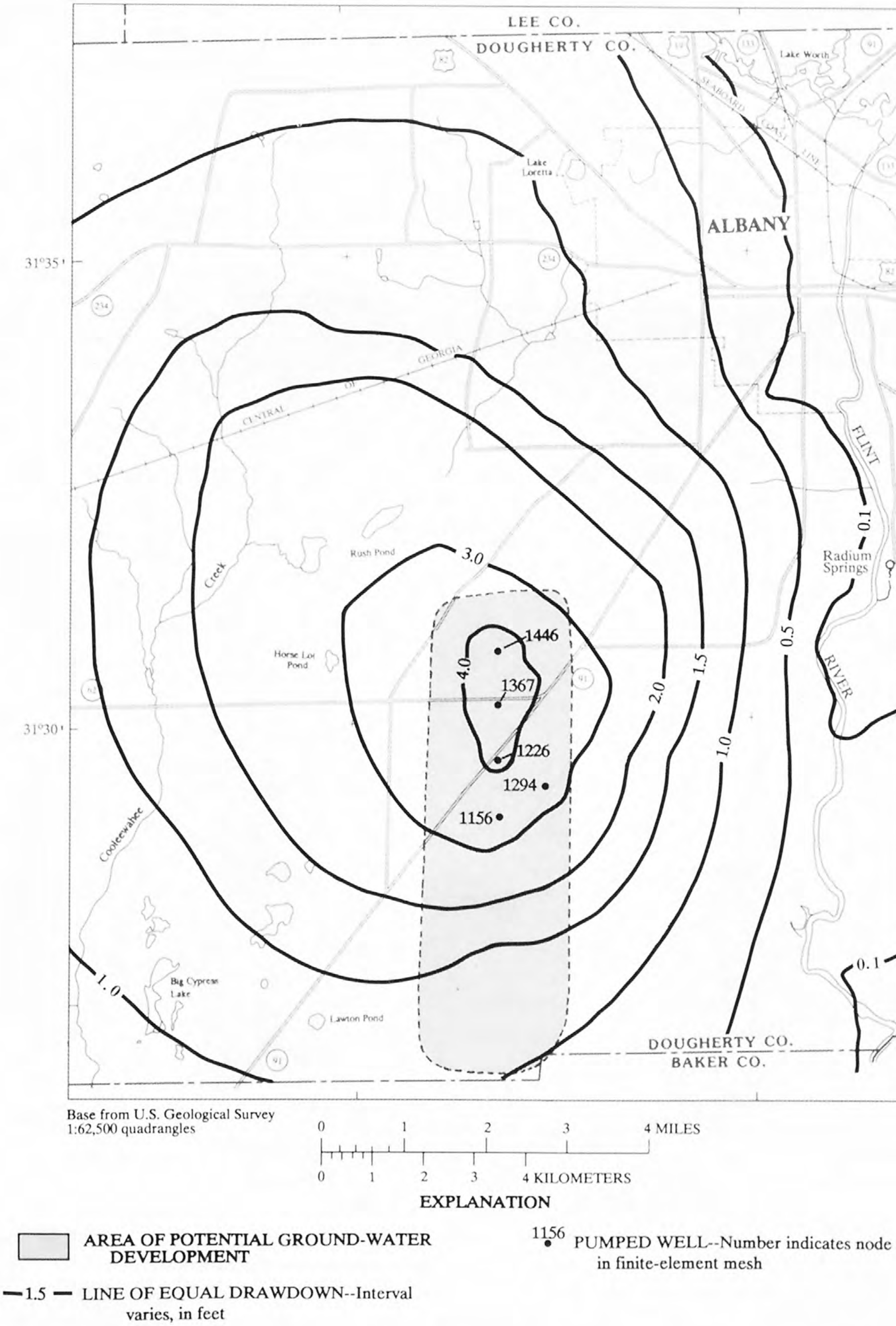
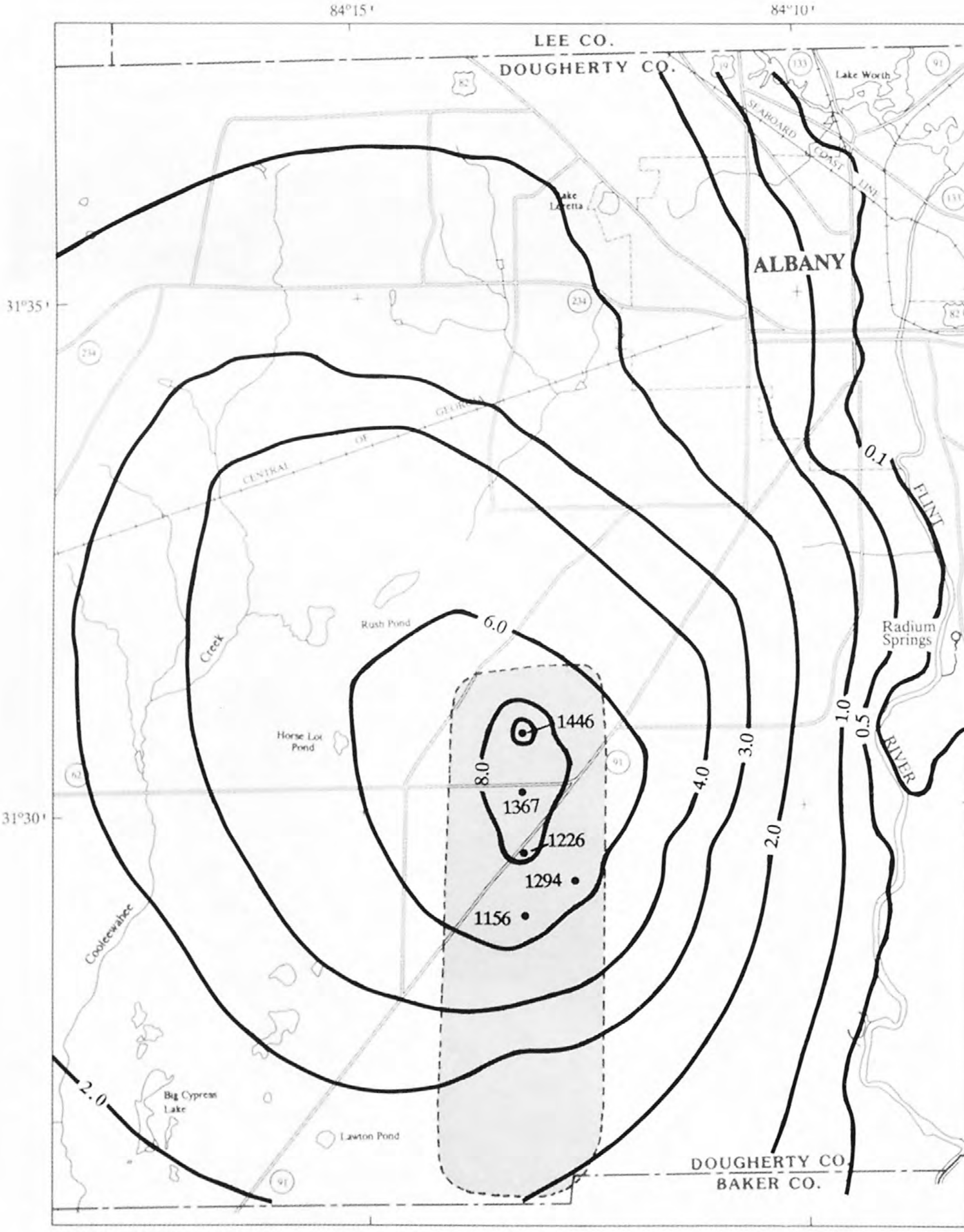


Figure 51.--Lines of equal computed drawdown in Upper Floridan aquifer from simulated pumping rate of 36 million gallons per day at nodes 1156, 1226, 1294, 1367, and 1446.



Base from U.S. Geological Survey
1:62,500 quadrangles

0 1 2 3 4 MILES

0 1 2 3 4 KILOMETERS

EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

1156 • PUMPED WELL--Number indicates node in finite-element mesh

—3.0— LINE OF EQUAL DRAWDOWN--Interval varies, in feet

Figure 52.--Lines of equal computed drawdown in Upper Floridan aquifer from simulated pumping rate of 72 million gallons per day at nodes 1156, 1226, 1294, 1367, and 1446.

The plot of computed drawdown from the simulation of pumping 21.6 Mgal/d at three nodes (7.2 Mgal/d each from nodes 1226, 1294, and 1446) in the area of potential development (fig. 50) showed how possible variations in hydraulic conductivity and in aquifer thickness (that is, variations in transmissivity) affect ground-water flow in the Upper Floridan aquifer. Maximum drawdown varied among the three nodes from about 2.3 ft at node 1294, to about 3.1 ft at node 1446. As discussed previously, the aquifer is thicker and more transmissive in the vicinity of nodes 1226 and 1294 and contains more solution openings than in the vicinity of node 1446 (fig. 8).

The effect on the Flint River downstream from the Lake Worth dam of withdrawing a total of 21.6 Mgal/d at three locations within the proposed well field appears to be minimal, according to the drawdown plot (fig. 50). The 0.1-ft line of equal drawdown crosses the river east of the area of potential development and remains on the east side of the river for about two miles. Most of the 2-ft line of equal drawdown lies within the area of potential development, and the 1-ft line of equal drawdown extends a maximum of about 4 mi from the area of potential development in the northwesterly direction (fig. 50).

Plots of computed drawdown in the water level of the Upper Floridan aquifer (figs. 51, 52) understandably indicated a greater effect on the aquifer of pumping in the area of potential development for the scenarios involving 36 and 72 Mgal/d than for the scenarios involving less pumpage (table 10). The maximum drawdowns ranged from about 3.5 ft at node 1294, to about 4.7 ft at node 1446, for the scenario of withdrawing a total of 36 Mgal/d from 5 wells. For the scenario involving withdrawal of 72-Mgal/d from the aquifer, maximum drawdowns were about double the values that were obtained from the 36-Mgal/d scenario. For the 36-Mgal/d-withdrawal rate, most of the 3-ft line of equal drawdown was contained within the area of potential development, but the 1-ft line of equal drawdown extended from the well field a maximum of about 6 mi (fig. 51). The shape of the equal-drawdown lines for the 72-Mgal/d-withrawal rate was identical to the shape of lines that were plotted for the 36-Mgal/d withdrawal rate (figs. 51, 52), except the magnitude of drawdown for the 72-Mgal/d scenario was double the values that were obtained from the 36-Mgal/d scenario; the 6-ft line of equal drawdown for the 72-Mgal/d scenario coincided with the 3-ft line of equal drawdown for the 36-Mgal/d scenario, and so forth.

Changes to Water-Budget Components

Changes in volumetric flow rates and in relative percentages that each water-budget component contributed to pumping the additional quantities in the area of potential development were determined by comparing water-budget components from the calibrated model for November 1985 conditions with similar components from the six scenarios of pumping. Values for the volumetric-flow rates of water-budget components that were obtained from simulating the six scenarios were subtracted from values of similar components obtained from the calibrated model of November 1985 conditions. The effects of pumping within the area of potential development on the water resources in the Upper Floridan aquifer were analyzed in terms of changes to water-budget components that were caused by the pumping, and in terms of percentages that each component contributed to the pumping rate. Results of these computations are listed in table 11.

The three scenarios of pumping 7.2 Mgal/d from different locations within the area of potential development created different effects on water-budget components of the ground-water-flow system in the Upper Floridan aquifer. The amount of regional ground-water flow that would have discharged to the Flint River but was intercepted by pumping is listed in table 11 as "Reduced discharge to Flint River". The average volumetric flow rate of ground water that was intercepted by the 7.2 Mgal/d pumpage was about 81 percent of the pumping rate, or about 5.9 Mgal/d. The volumetric flow rates and percentages of the pumping rate that this water-budget component contributed to the pumped well varied by about 0.7 Mgal/d, or by about 10 percent of the pumping rate, among the three 7.2 Mgal/d scenarios, depending on hydrologic factors described previously, and on the proximity of the pumping node to the Flint River. The closest well location to the River, node 1294, intercepted the most water from regional flow; that is, it had the largest volumetric flow rate and percentage of the pumping rate as discharge to the Flint River of the three 7.2 Mgal/d scenarios. The farthest location, node 1446, intercepted the least water from regional flow and, consequently had the smallest rate and percentage of discharge from the Flint River of the three 7.2 Mgal/d scenarios (see table 11; figs. 47-49).

Table 11.--Water-budget components from various pumping scenarios in area of potential development

Component	Node 1446	Node 1294	Node 1226	Nodes 1446, 1294, and 1226	Nodes 1156, 1226, 1294, 1367, and 1446	Nodes 1156, 1226, 1294, 1367, and 1446
	Volumetric rates for indicated pumping scenarios (gallons per day)					
Discharge to wells	-7,200,000	-7,200,000	-7,200,000	-21,600,000	-36,000,000	-72,000,000
Reduced discharge to Flint River	5,494,530	6,196,180	5,880,430	17,574,720	29,384,650	58,826,870
Reduced discharge to regional flow	169,670	108,450	131,490	408,820	668,260	1,330,240
Reduced discharge to undifferentiated overburden	38,360	23,890	30,360	90,370	145,850	280,150
Induced recharge from regional flow and other rivers	1,357,470	781,740	1,045,430	3,183,080	5,236,220	10,446,110
Induced recharge from undifferentiated overburden	139,210	88,100	110,600	340,060	558,500	1,102,520
Induced recharge from the Flint River	1,680	1,230	1,380	4,350	7,070	14,140
	Percentage of pumping rates					
Discharge to wells	100.00	100.00	100.00	100.00	100.00	100.00
Reduced discharge to Flint River	86.10	81.70	81.40	81.60	81.60	81.70
Reduced discharge to regional flow and other rivers	1.50	1.80	1.90	1.90	1.90	1.90
Reduced discharge to undifferentiated overburden	0.30	0.40	0.40	0.40	0.40	0.40
Induced recharge from regional flow and other rivers	10.90	14.50	14.70	14.60	14.60	14.50
Induced recharge from undifferentiated overburden	1.20	1.50	1.60	1.60	1.60	1.50
Induced recharge from Flint River	0.02	0.02	0.02	0.02	0.02	0.02

Commensurate with the decrease in ground-water discharge to the Flint River caused by pumping in the area of potential development was the increase in recharge from regional flow and other rivers over the November 1985 conditions (see "Induced recharge from regional flow and other rivers", table 11). Recharge to the Upper Floridan aquifer across model boundaries (including river reaches) located mostly to the north and west of the potential-development area varied with each pumping scenario of 7.2 Mgal/d according to the proximity of the pumping node to the model boundaries. Of the three pumping scenarios of 7.2 Mgal/d, the closest pumping node to the model boundaries, node 1446, yielded the highest volumetric flow rate and percentage of well pumpage derived from the boundary, and the most distant node to these boundaries, node 1294, yielded the lowest flow rate and percentage of well pumpage from the boundary (table 11). Although the flow rates and percentages from this water-budget component represented the increase in ground-water flow across all model boundaries and in leakage from all rivers other than the Flint River downstream from the Lake Worth dam, the effects of pumping in the area of potential development did not extend far enough to the east of the Flint River downstream from the Lake Worth dam to cause other boundary conditions or river reaches to be affected. Thus, changes in volumetric flow rates and percentages of the pumping rate for this water-budget component were considered to be caused by the influence of the pumping on flow across model boundaries and from river reaches that are located west of the Flint River downstream from the Lake Worth dam.

Water-budget components other than reduced discharge to the Flint River and induced recharge from regional flow and other rivers had minor effects on supplying water to wells that simulated a 7.2 Mgal/d pumping rate in the area of potential development. The interception of ground-water discharge across model boundaries (regional flow) and to rivers other than the Flint River downstream from the Lake Worth dam contributed between 1.5 and 1.9 percent of the 7.2 Mgal/d pumping rate to the wells (table 11). Induced recharge from the undifferentiated overburden accounted for about 1.2 to 1.6 percent of the pumping, and interception of discharge to the undifferentiated overburden from the Upper Floridan aquifer contributed about 0.3 to 0.4 percent of the pumping within the area of potential development (table 11).

The water-budget component that changed the least from the November 1985 conditions in response to pumping 7.2 Mgal/d within the area of potential development is leakage (induced recharge) to the Upper Floridan aquifer from the Flint River downstream from the Lake Worth dam. This water-budget component results from lowered water levels in the aquifer near the river in response to the pumping. About 0.02 percent of the 7.2 Mgal/d pumping rate, or between about 1,200 and 1,700 gal/day, was computed as the rate of induced recharge to the Upper Floridan aquifer from this water-budget component. However, because hydraulic gradients in the Upper Floridan aquifer west of the Flint River were toward the River and away from the potential-development area for all pumping scenarios, the water identified as recharge from the Flint River would not flow into the potential-development area to supply water to the pumped wells. Analyses of ground-water movement by using plots of flow directions (discussed in the section "Directions of Ground-Water Movement") indicate that ground-water-flow directions in the aquifer were changed slightly near the Flint River because of pumping in the potential-development area. The increased recharge to the aquifer from the Flint River occurs in a narrow band to the southeast of the potential-development area, just beneath and west of the River, where recharge also was occurring during November 1985 conditions. The recharging water is limited to this area because the regional flow of ground water is from the northwest towards the River. Thus, the regional hydraulic gradient in the Upper Floridan aquifer remained as the dominant hydrologic factor in determining ground-water-flow for all six pumping scenarios, and prevented water that might have recharged the aquifer from the Flint River to flow westward toward the area of potential development.

The volumetric flow rates of all water-budget components increased for the pumping scenarios of 21.6, 36, and 72 Mgal/d within the area of potential development and the percent of ground-water flow that each component contributed to the pumping rates remained nearly constant and about equal to the percentages that were computed for the 7.2 Mgal/d withdrawal from node 1226. For all pumping scenarios, reduced discharge to the Flint River from regional flow accounted for about 82 percent of the pumping rates. Induced recharge from ground-water flow across the northern and western model boundaries and leakage from other rivers besides the Flint River contributed about 15 percent to the pumping rates. The remaining 3 to 4 percent of the pumping rates was contributed by reduced discharge to regional flow (about 2 percent), induced recharge from the undifferentiated overburden (about 1.5 percent), reduced discharge to the undifferentiated overburden (about 0.4 percent), and induced recharge from the Flint River downstream from the Lake Worth dam (about

0.02 percent). The effects of these pumping scenarios on ground-water flow in the Upper Floridan aquifer and on leakage from the Flint River downstream from the Lake Worth dam into the aquifer are evaluated by using plots that indicate directions of ground-water movement in the area of potential development and near the Flint River; and are discussed in the following section.

Directions of Ground-Water Movement

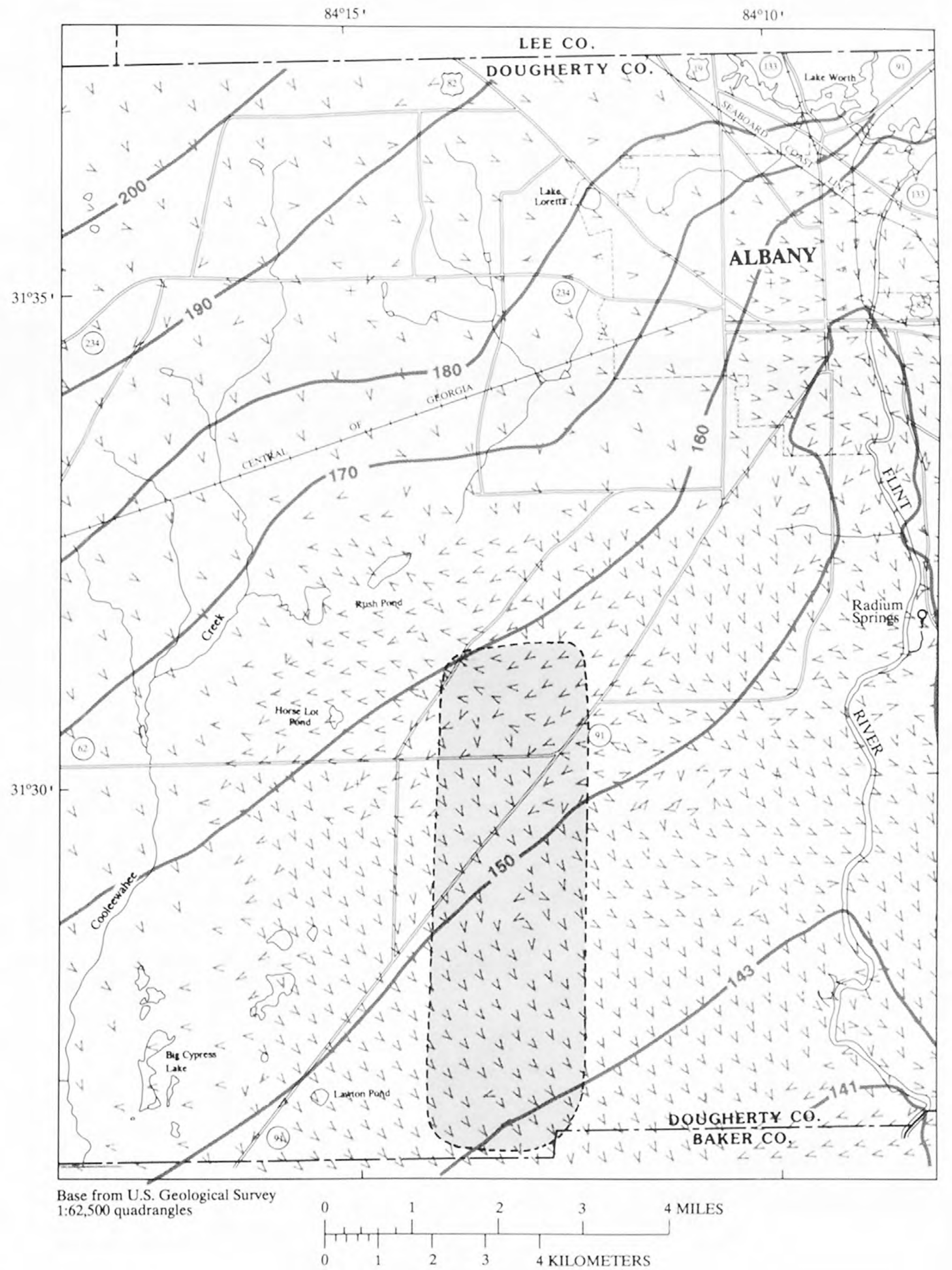
Directions of ground-water movement in the Upper Floridan aquifer near the area of potential development and near the Flint River downstream from the Lake Worth dam were analyzed for the scenarios of proposed pumping to aid in evaluating the water-resource potential of the aquifer. Of particular importance to the evaluation were changes to ground-water-flow directions in response to pumping that might cause leakage from the Flint River into the potential-development area. Flow-direction plots, similar to the plot used in an earlier section (plate 2), were created from results of simulating the six scenarios of pumping, and were compared with a similar plot for the November 1985 conditions (figs. 53-59).

Changes in ground-water-flow directions in the Upper Floridan aquifer in response to pumping 7.2 Mgal/d within the area of potential development were imperceptible when flow-direction plots for these scenarios were compared to a similar plot that was made from simulating the November 1985 conditions (figs. 53-56). Directions of ground-water flow in the Upper Floridan aquifer, as discussed earlier, appear to be dominated by regional flow from the northwest and by vertical flow into and out of the undifferentiated overburden, to the extent that pumping 7.2 Mgal/d from the aquifer has little effect on lateral ground-water-flow directions. Consequently, ground-water-flow directions in the area of potential development and near the Flint River were virtually the same as the November 1985 flow directions for the scenarios of pumping 7.2 Mgal/d.

The plot of ground-water-flow directions in the Upper Floridan aquifer that resulted from simulating 21.6 Mgal/d pumping from three locations in the potential-development area (fig. 57) showed no change in flow directions from the November 1985 conditions (fig. 53) in this area. The direction of ground-water flow is changed slightly beneath the Flint River between the 141- and 143-ft contours of water levels in the aquifer; however, ground water flows toward the River and beyond it, away from the area of potential development, in a southeasterly direction (figs. 53-57).

The slight changes in the ground-water-flow directions that occurred in the scenario of pumping 21.6 Mgal/d from three wells in the area of potential development continued to occur in the scenario of pumping 36 Mgal/d from five wells (fig. 58). Flow directions at a few locations near the pumping nodes were changed slightly from the directions shown in the previous plots (figs. 53-57). However, ground water continued to flow through the area of potential development from the northwest toward the Flint River with no significant change in direction from the November 1985 conditions (fig. 53).

Flow directions from the scenario of pumping 72 Mgal/d from five locations in the area of potential development (fig. 59) showed the most change of all pumping scenarios, although none of the changes to flow directions induced flow from the Flint River into the potential-development area. Ground-water-flow directions were altered in the vicinity of the potential-development area, and about 1 mi east of this area (fig. 59), plots of about seven flow-direction indicators changed from the southeasterly direction that occurred under November 1985 conditions (fig. 53) to a north-south orientation parallel to the area of potential development. This change in the ground-water-flow direction probably was caused by changes in vertical leakage rates to or from the undifferentiated overburden, which was caused by lower water levels in the Upper Floridan aquifer for this pumping scenario than for the November 1985 conditions. Even with the changes to ground-water-flow directions that occurred in response to pumping 72 Mgal/d, most of the flow-directions that were plotted between the area of potential development and the Flint River were unchanged from the November 1985 conditions, and the regional direction of ground-water movement was virtually unaffected by this pumping rate.



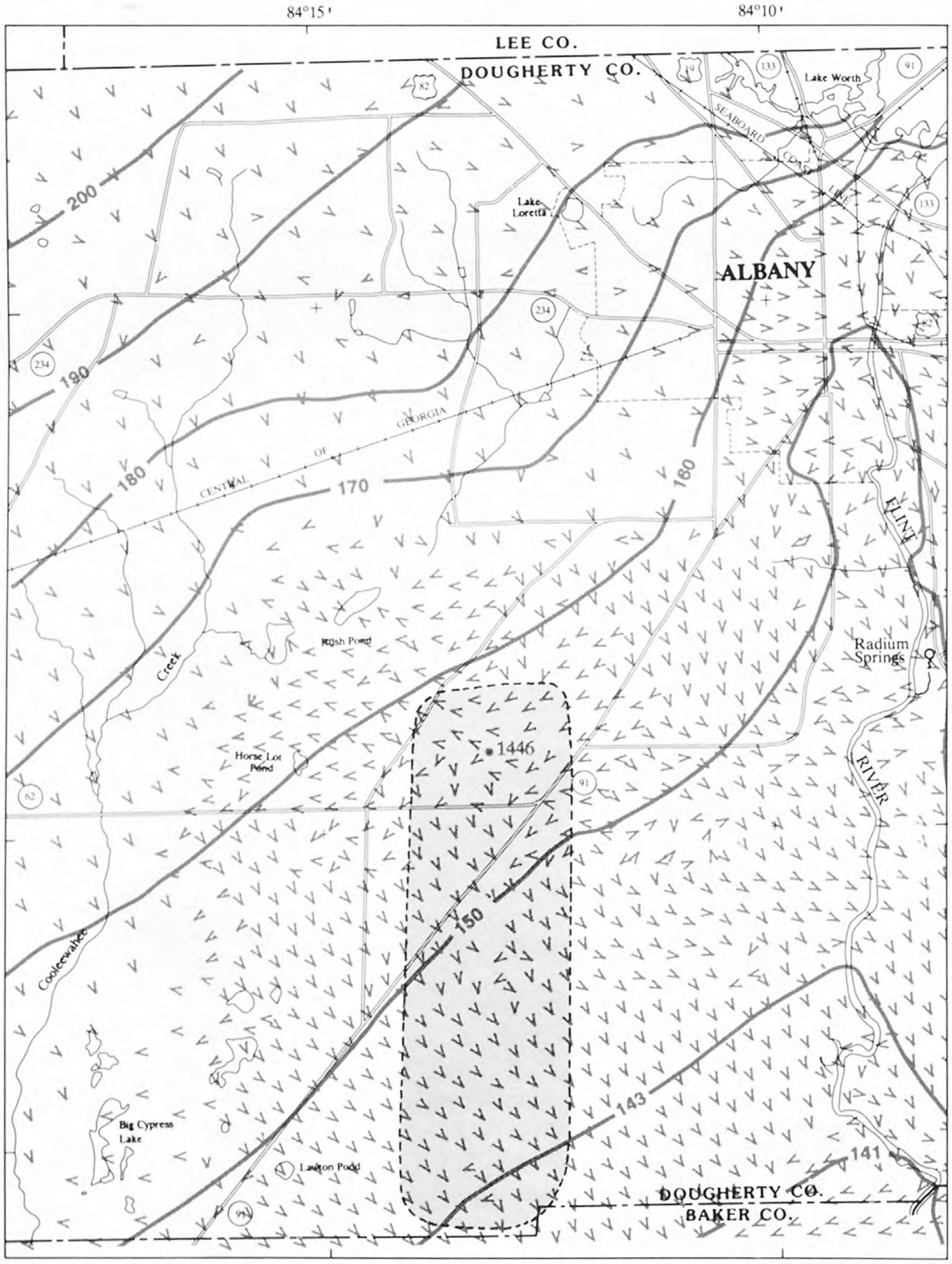
EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

150 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval varies, in feet. Datum is sea level

< FLOW-DIRECTION INDICATOR--Indicates direction of ground water movement, computed at center of element

Figure 53.--Computed potentiometric surface and directions of ground-water movement in Upper Floridan aquifer in simulation of November 1985 conditions.



Base from U.S. Geological Survey
1:62,500 quadrangles

0 1 2 3 4 MILES

0 1 2 3 4 KILOMETERS

EXPLANATION

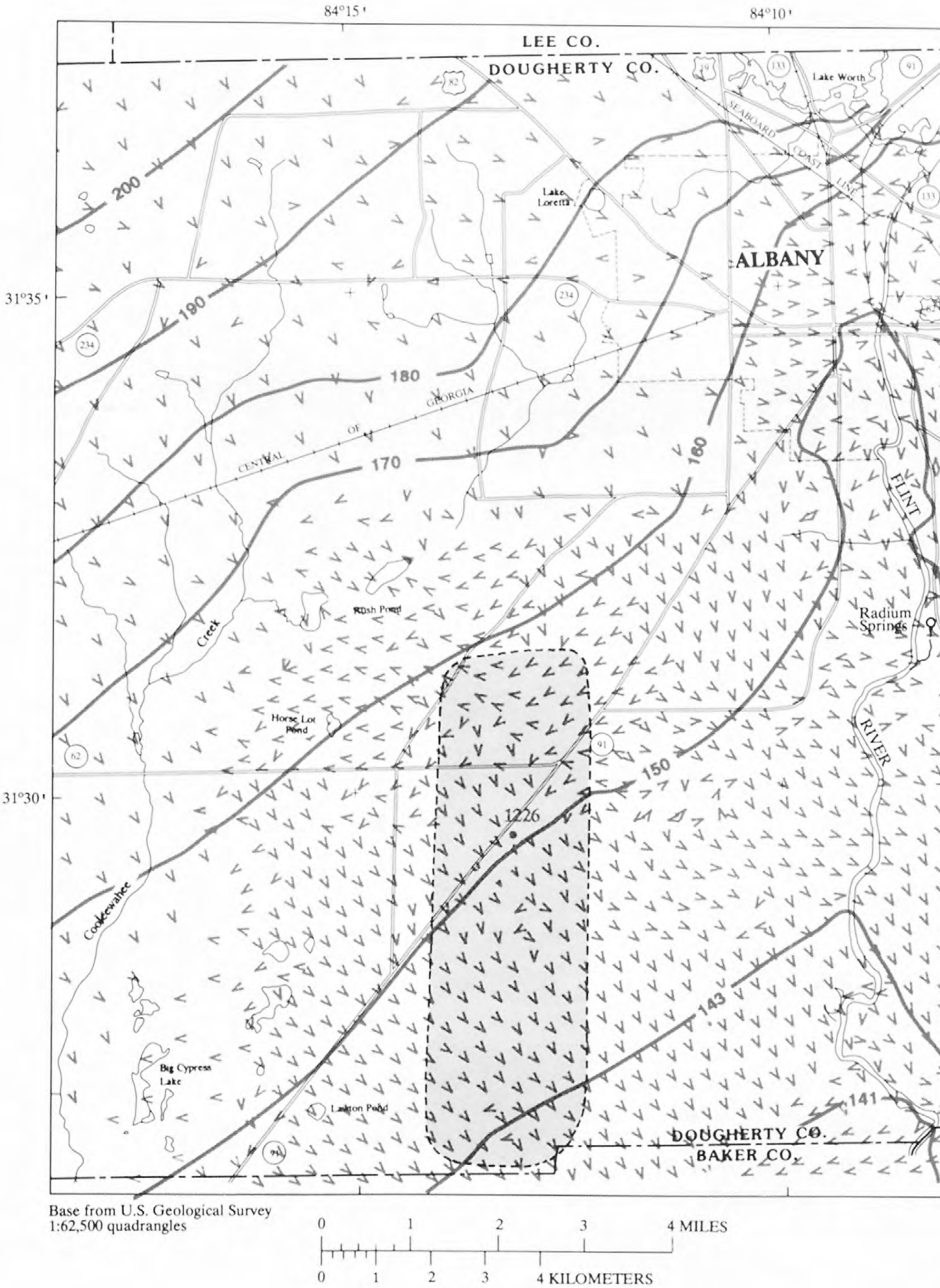
AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

< FLOW-DIRECTION INDICATOR--Indicates direction of ground water movement, computed at center of element

— 150 — SIMULATED POTENTIOMETRIC CONTOUR-- Shows altitude at which water level would have stood in tightly cased wells. Contour interval varies, in feet. Datum is sea level

1446 • PUMPED WELL--Number indicates node in finite-element mesh

Figure 54.--Computed potentiometric surface and directions of ground-water movement in Upper Floridan aquifer in simulation of pumpage of 7.2 million gallons per day at node 1446.



EXPLANATION

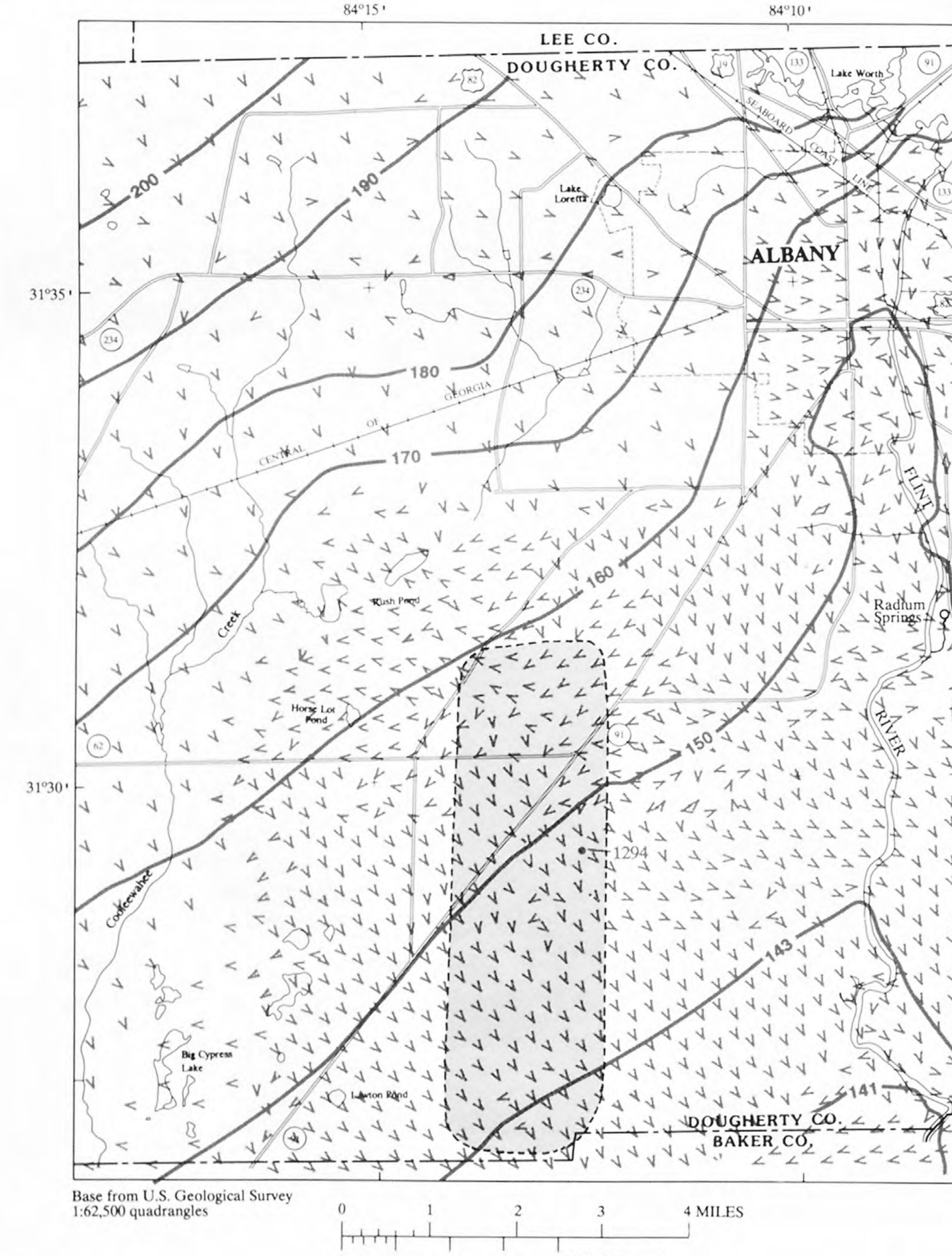
AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

— 150 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval varies, in feet. Datum is sea level

< FLOW-DIRECTION INDICATOR--Indicates direction of ground water movement, computed at center of element

1226 • PUMPED WELL--Number indicates node in finite-element mesh

Figure 55.--Computed potentiometric surface and directions of ground-water movement in Upper Floridan aquifer in simulation of pumpage of 7.2 million gallons per day at node 1226.



EXPLANATION

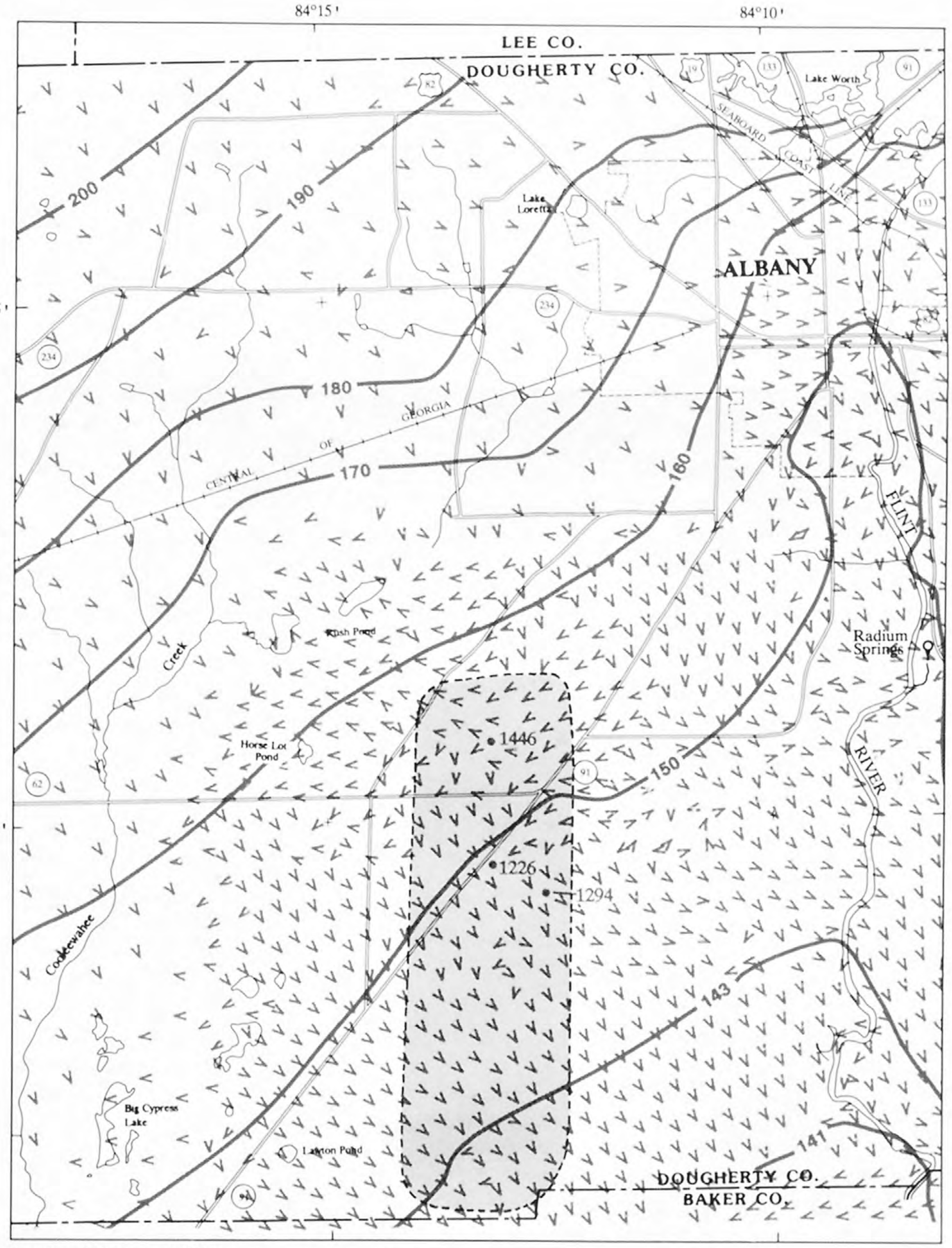
AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

— 150 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval varies, in feet. Datum is sea level

< FLOW-DIRECTION INDICATOR--Indicates direction of ground water movement, computed at center of element

1294 • PUMPED WELL--Number indicates node in finite-element mesh

Figure 56.--Computed potentiometric surface and directions of ground-water movement in Upper Floridan aquifer in simulation of pumpage of 7.2 million gallons per day at node 1294.



Base from U.S. Geological Survey
1:62,500 quadrangles

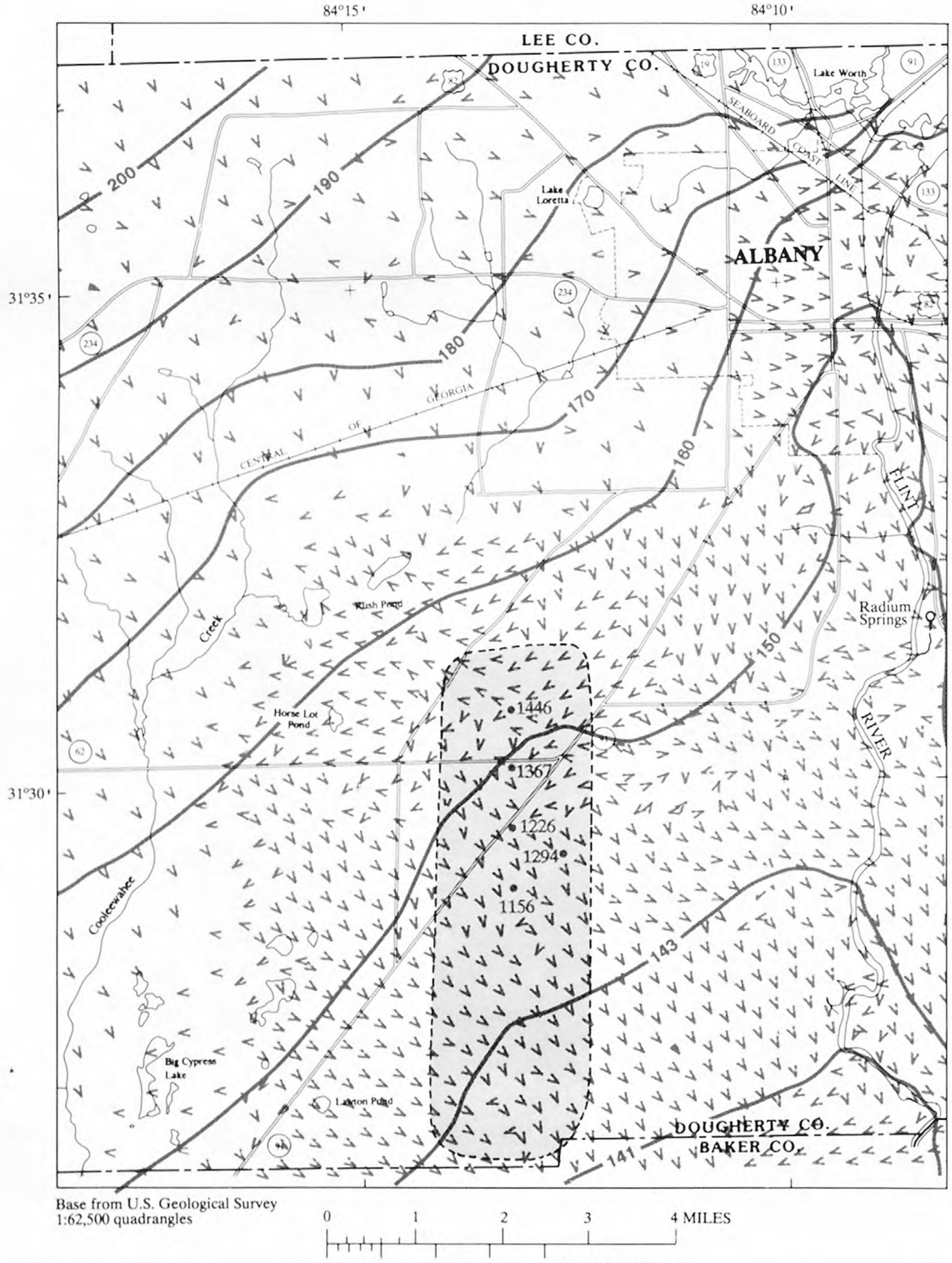
0 1 2 3 4 MILES

0 1 2 3 4 KILOMETERS

EXPLANATION

▭	**AREA OF POTENTIAL GROUND-WATER DEVELOPMENT**
—143—	SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval varies, in feet. Datum is sea level
<	FLOW-DIRECTION INDICATOR--Indicates direction of ground water movement, computed at center of element
1294 •	PUMPED WELL--Number indicates node in finite-element mesh

Figure 57.--Computed potentiometric surface and directions of ground-water movement in Upper Floridan aquifer in simulation of pumpage of 21.6 million gallons per day at nodes 1226, 1294, and 1446.



EXPLANATION

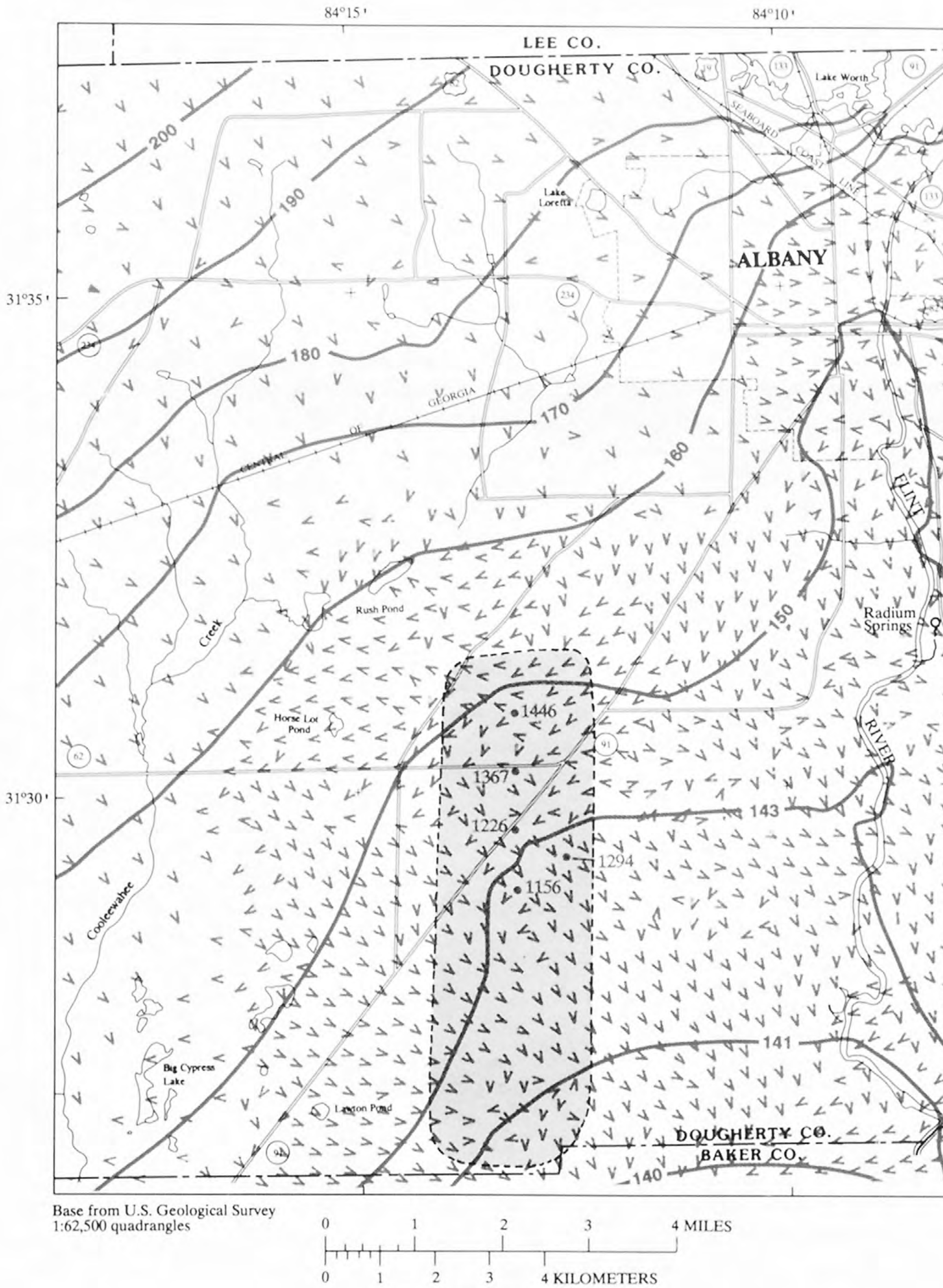
AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

< FLOW-DIRECTION INDICATOR--Indicates direction of ground water movement, computed at center of element

—143— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval varies, in feet. Datum is sea level

1156 • PUMPED WELL--Number indicates node in finite-element mesh

Figure 58.--Computed potentiometric surface and directions of ground-water movement in Upper Floridan aquifer in simulation of pumpage of 36 million gallons per day at nodes 1156, 1226, 1294, 1367, and 1446.



EXPLANATION

AREA OF POTENTIAL GROUND-WATER DEVELOPMENT

— 143 — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval varies, in feet. Datum is sea level

< FLOW DIRECTION INDICATOR--Indicates direction of ground water movement, computed at center of element

1156 • PUMPED WELL--Number indicates node in finite-element mesh

Figure 59.--Computed potentiometric surface and directions of ground-water movement in Upper Floridan aquifer in simulation of pumpage of 72 million gallons per day at nodes 1156, 1226, 1294, 1367, and 1446.

Potential for Sinkhole Development

The potential for dewatering the Upper Floridan aquifer, and thus, increasing the potential for sinkhole development, caused by developing the ground-water resources was analyzed by using simulated water levels from the 36 and 72 Mgal/d pumping scenarios and maps showing altitudes of the water-bearing zones of the aquifer. Aquifer dewatering occurs when the water level is below the altitude of the top of the aquifer. This condition is hazardous geologically, and hydrologically, in that the rock matrix comprising the aquifer may actually collapse from the removal of hydraulic pressure when the potentiometric surface is lowered excessively by pumping. Sinkhole development may cause damage to overlying structures, such as utility lines, buildings, and roads, and may change the topography by creating circular depressions or similar collapse features.

The potential for aquifer dewatering was determined by comparing the water-level surface of the Upper Floridan aquifer that resulted from the 72 Mgal/d (worst-case) pumping scenario (fig. 59) with the altitude of the top of the the lower, principal water-bearing zone in the aquifer (fig. 7). The massive and unfractured nature of the upper water-bearing zone in the area of potential development indicates that it would be less prone to structural collapse than the lower water-bearing zone if dewatered. The existence of fractures and solution features in the lower water-bearing zone makes this zone susceptible to sinkhole formation if water levels were to drop below the top of this zone. A comparison of maps showing altitudes of the top of the lower water-bearing zone and of the top of the Upper Floridan aquifer (figs. 6, 7) with the water level in the aquifer that resulted from the 72 Mgal/d scenario (fig. 59) showed that the water level in the vicinity of pumping nodes 1226, 1367, and 1446, was about 5 ft below the top of the Upper Floridan aquifer, but about 50 ft above the top of the lower water-bearing zone. Because the water level in the Upper Floridan aquifer was above the fractures and solution features of the lower water-bearing zone for all of the pumping scenarios, the potential for aquifer dewatering and increased potential for sinkhole development was determined to be negligible.

Potential for Changes in Water Quality

Possible changes in the chemical quality of water in the Upper Floridan aquifer resulting from developing the ground-water resources were analyzed by evaluating the changes to the hydraulic mechanisms that control water quality in the aquifer. These mechanisms are the direction of ground-water flow, vertical leakage from the undifferentiated overburden, and leakage from the Flint River downstream from the Lake Worth dam. Based on the analyses described in earlier sections, none of these hydraulic mechanisms were changed enough by the proposed pumping to affect the quality of ground water in the Upper Floridan aquifer. Ground water continued to flow towards the Flint River from the area of potential development during all pumping scenarios; thus, no water from the Flint River downstream from the Lake Worth dam entered the potential-development area, and all water removed from the Upper Floridan aquifer during the simulated pumping scenarios was derived from the aquifer. The amount of water that was supplied to the area of potential development by vertical leakage from the undifferentiated overburden was small (table 11) in comparison with the vertical leakage rate and the percentage of the pumping rate that this water-budget component comprised of the total budget for the November 1985 calibration period (table 7). Therefore, because changes to the mechanisms that were assumed to govern ground-water quality in the Upper Floridan aquifer were affected very little by pumping in the area of potential development, it was assumed that water-quality changes in the aquifer would be negligible as a result of developing the ground-water resources in this area.

CONCLUSIONS

The ability of the Upper Floridan aquifer to transmit large amounts of water as regional flow from the west, north, and east of the study area to be discharged to the Flint River downstream from the Lake Worth dam, and the relatively minor effects of ground-water pumping on water quality and water levels in the aquifer, gives the Upper Floridan aquifer a potential for large water-resource development in the area of potential development near Albany, Georgia. The hydrologic conditions of large regional-flow components, low vertical leakage from the undifferentiated overburden, small drawdowns, and a low potential for sinkhole development, make the area located in Dougherty County to the west of the Flint River and downstream from the Lake Worth dam a suitable location for developing the Upper Floridan aquifer. Because hydraulic gradients and directions of ground-water flow in the Upper Floridan aquifer were affected only slightly by pumping scenarios that withdrew as much as 72 Mgal/d from within this area, and because computed water levels remained at least 50 ft above fractures and solution features of the lower water-bearing zone of the aquifer for the 72-Mgal/d scenario, withdrawals of as much as 72 Mgal/d from the area appear to be possible without adversely affecting the ground-water- and surface-water-flow system of the Upper Floridan aquifer.

Although results of the simulations show a large potential for developing the water resources of the Upper Floridan aquifer in the study area, and a high degree of accuracy when compared to measured values, a more accurate evaluation of the water-resource potential of the Upper Floridan aquifer would be possible by decreasing the uncertainty in measured ground- and surface-water levels and in the definition of hydrologic factors that govern flow in the aquifer. Results from sensitivity analyses indicate that computed water levels are most sensitive to changes in the hydraulic conductivity of the Upper Floridan aquifer and in the vertical-leakage coefficient (or, vertical-hydraulic conductance) of the undifferentiated overburden. The hydrologic factors to which computed water levels are the next most sensitive are source-layer heads in the undifferentiated overburden and river stages in the Flint River downstream from the Lake Worth dam. Because measured water levels in the aquifer and in the overburden are known only to within 5 ft of their true values, many combinations of values for these, and other, hydrologic factors would provide an acceptable computed solution for the calibration period. However, computed results for the pumping scenarios would vary for each combination of hydrologic factors. The amount of variation in computed results can be decreased by minimizing innaccuracies in measured water levels and in better defining hydrologic factors of the flow system, thereby providing a more accurate water-resource evaluation.

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