Hydrogeologic Investigation and Simulation of Ground-Water Flow in the Upper Floridan Aquifer of North-Central Florida and Southwestern Georgia and Delineation of Contributing Areas for Selected City of Tallahassee, Florida, Water-Supply Wells

By Hal Davis

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inches per year (in/yr)	2.54	centimeters per year
foot (ft)	0.3048	meter
gallon (gal)	0.003785	cubic meter
gallon (gal)	3.785	liter
mile (mi)	1.609	kilometer

Equations for temperature conversion between degrees Celsius (˚C) and degrees Fahrenheit (˚F):

$$ ^{\circ}C = 5/9\ (^{\circ}F - 32) $$
$$ ^{\circ}F = (9/5\ ^{\circ}C) + 32 $$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum 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.

ADDITIONAL ABBREVIATIONS

ft = feet
in = inch
in/yr = inches per year
gal/min = gallons per minute
Mgal/d = million gallons per day
ft/d = feet per day
ft^2/d = feet squared per day
ft^3/s = feet cubed per second

ACRONYMS

MODFLOW = USGS modular three-dimensional finite-difference ground-water flow model
MODPATH = USGS particle-tracking program
PCE = tetrachloroethylene
RASA = Regional Aquifer System Analysis
USGS = U.S. Geological Survey

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Abstract

A 4-year investigation of the Upper Floridan aquifer and ground-water flow system in Leon County, Florida, and surrounding counties of north-central Florida and southwestern Georgia began in 1990. The purpose of the investigation was to describe the ground-water flow system and to delineate the contributing areas to selected City of Tallahassee, Florida, water-supply wells. The investigation was prompted by the detection of low levels of tetrachloroethylene in ground-water samples collected from several of the city's water-supply wells.

Hydrologic data and previous studies indicate that; ground-water flow within the Upper Floridan aquifer can be considered steady-state; the Upper Floridan aquifer is a single water-bearing unit; recharge is from precipitation; and that discharge occurs as spring flow, leakage to rivers, leakage to the Gulf of Mexico, and pumpage. Measured transmissivities of the aquifer ranged from 1,300 ft^2/d (feet squared per day) to 1,300,000 ft^2/d.

Steady-state ground-water flow in the Upper Floridan aquifer was simulated using a three-dimensional ground-water flow model. Transmissivities ranging from less than 5,000 ft^2/d to greater than 11,000,000 ft^2/d were required to calibrate to observed conditions. Recharge rates used in the model ranged from 18.0 inches per year in areas where the aquifer was unconfined to less than 2 inches per year in broad areas where the aquifer was confined.

Contributing areas to five Tallahassee water-supply wells were simulated by particle-tracking techniques. Particles were seeded in model cells containing pumping wells then tracked backwards in time toward recharge areas. The contributing area for each well was simulated twice, once assuming a porosity of 25 percent and once assuming a porosity of 5 percent. A porosity of 25 percent is considered a reasonable average value for the Upper Floridan aquifer; the 5 percent porosity simulated the movement of ground-water through only solution-enhanced bedding plains and fractures. The contributing areas were generally elliptical in shape, reflecting the influence of the sloping potentiometric surface. The contributing areas delineated for a 5 percent porosity were always much larger than those determined using a 25 percent porosity. The lowest average ground-water velocity computed within a contributing area, using a 25 percent porosity, was 1.0 ft/d (foot per day) and the highest velocity was 1.6 ft/d. The lowest average ground-water velocity, determined using a 5 percent porosity, was 2.4 ft/d and the highest was 7.4 ft/d.

The contributing areas for each of the five wells was also determined analytically and

compared to the model-derived areas. The upgradient width of the simulated contributing areas were larger than the upgradient width of the analytically determined contributing areas for four of the five wells. The model could more accurately delineate contributing areas because of the ability to simulate wells as partially penetrating and by incorporating complex, three-dimensional aquifer characteristics, which the analytical method could not.

INTRODUCTION

Ground water from the Upper Floridan aquifer is the source of water-supply for Tallahassee, Fla., and for parts of the surrounding area. In most areas, the aquifer yields an ample supply of good quality water; however, in recent years low levels of tetrachloroethylene (PCE) have been detected in ground-water samples obtained from seven of the city's water-supply wells. PCE is attributed to past disposal practices of dry cleaners, service stations, and other businesses within the downtown area. The City of Tallahassee removes PCE from the water by passing it through granular-activated carbon units before distribution. This recent experience has increased the awareness of local authorities that ground-water resources need to be protected. To ensure that water-supply wells, presently free of contamination, remain clean, it is necessary to protect that portion of the aquifer from which the wells derive water. The delineation of areas contributing to supply wells requires an understanding of ground-water flow within the Upper Floridan aquifer. To gain this understanding, the U.S. Geological Survey (USGS), in cooperation with the City of Tallahassee and the Florida Department of Environmental Protection (FDEP), conducted an investigation of the Upper Floridan aquifer.

Purpose and Scope

The purpose of this report is to present the results of an investigation of that part of the Upper Floridan aquifer which underlies Tallahassee and Leon County, Fla., and the surrounding counties in north-central Florida and southwestern Georgia. The specific objectives of the investigation were to 1) determine the hydrogeologic framework of the Upper Floridan aquifer, 2) collect additional hydrogeologic data needed to characterize ground-water flow, 3) simulate ground-water flow using the USGS modular three-dimensional finite-difference ground-water flow model (MODFLOW) (McDonald and Harbaugh, 1988), 4) delineate contributing areas for selected City of Tallahassee water-supply wells, and 5) compare simulated contributing areas to analytically determined contributing areas. The contributing area of a pumping well, defined by Morrissey (1987), is the land area that has the same horizontal extent as that part of an aquifer..., from which ground-water flow is diverted to wells.

This report is organized to focus on the project objectives listed above and the following items are presented: 1) a description of the general hydrogeologic framework of the Upper Floridan aquifer in north-central Florida and southwestern Georgia, 2) a potentiometric-surface map of the Upper Floridan aquifer based on water levels measured during the fall of 1991, 3) river-discharge measurements made to estimate the volume of ground water discharging from the Upper Floridan aquifer in the fall of 1991, 4) an evaluation of the transmissivity of the Upper Floridan aquifer within downtown Tallahassee, determined with a multiple-well aquifer test, 5) a conceptual model of ground-water flow within the Upper Floridan aquifer describing flow directions, hydrologic boundaries, and ground-water sources and sinks, 6) the results of computer simulations of ground-water flow using MODFLOW (McDonald and Harbaugh, 1988), 7) a delineation of contributing areas to selected Tallahassee water-supply wells using the particle-tracking program MODPATH (Pollock, 1989), and 8) a comparison of the simulated and analytically determined contributing areas.

Study Area

The study area encompasses approximately 11,000 square miles in north-central Florida and southwestern Georgia (fig.1) and is within the Coastal Plain physiographic province. The topography is characterized by rolling hills and land-surface altitudes that range from about 350 ft above sea level in the north to sea level in the south. The study area extends to the major ground-water flow boundaries in the regional ground-water flow system, and thus encompasses the entire recharge area for ground water that moves beneath Leon County, Fla. The climate is humid subtropical with relatively high rainfall. From

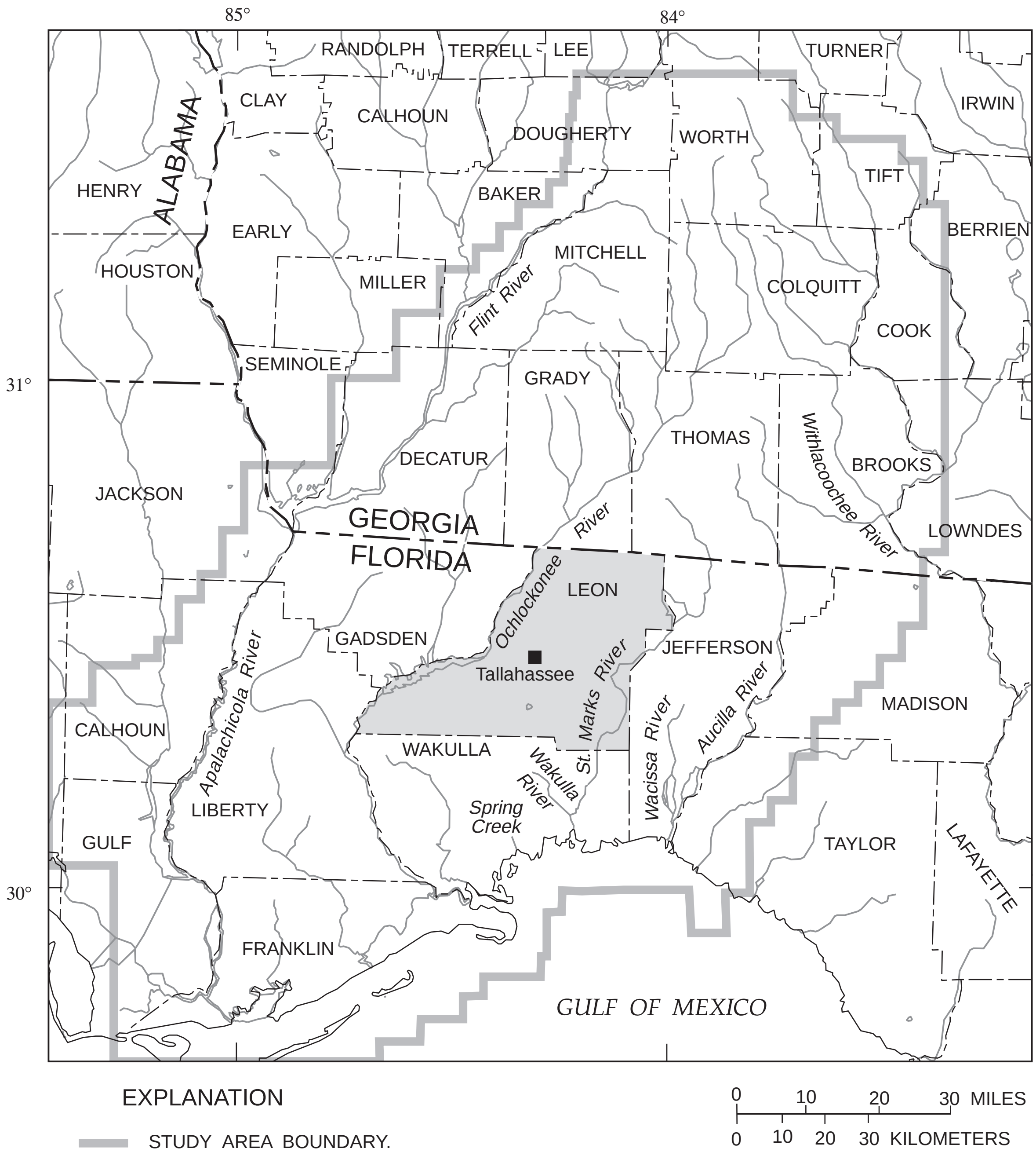


Figure 1. Study area in north-central Florida and southwestern Georgia.

1961 - 1990, the average annual temperature in Tallahassee was 67^{o} F and the average precipitation was 66 in/yr (National Oceanic and Atmospheric Administration, oral commun., 1995).

The major physiographic features of the study area, delineated and described by Clark and Zisa (1976) for Georgia and by Brooks (1981) for Florida, were the Dougherty Plain District, Tifton Upland District, Apalachicola Delta District, and Ocala Uplift District (fig. 2). The topography of the Dougherty Plain District consists of gently rolling hills that are interrupted by numerous sinkholes. Karst topography prevails with many sinkholes still forming. The altitude within the Tifton Upland District ranges from about 480 ft in the north to 150 ft in the southeast, resulting in a gentle slope. This district contains a well

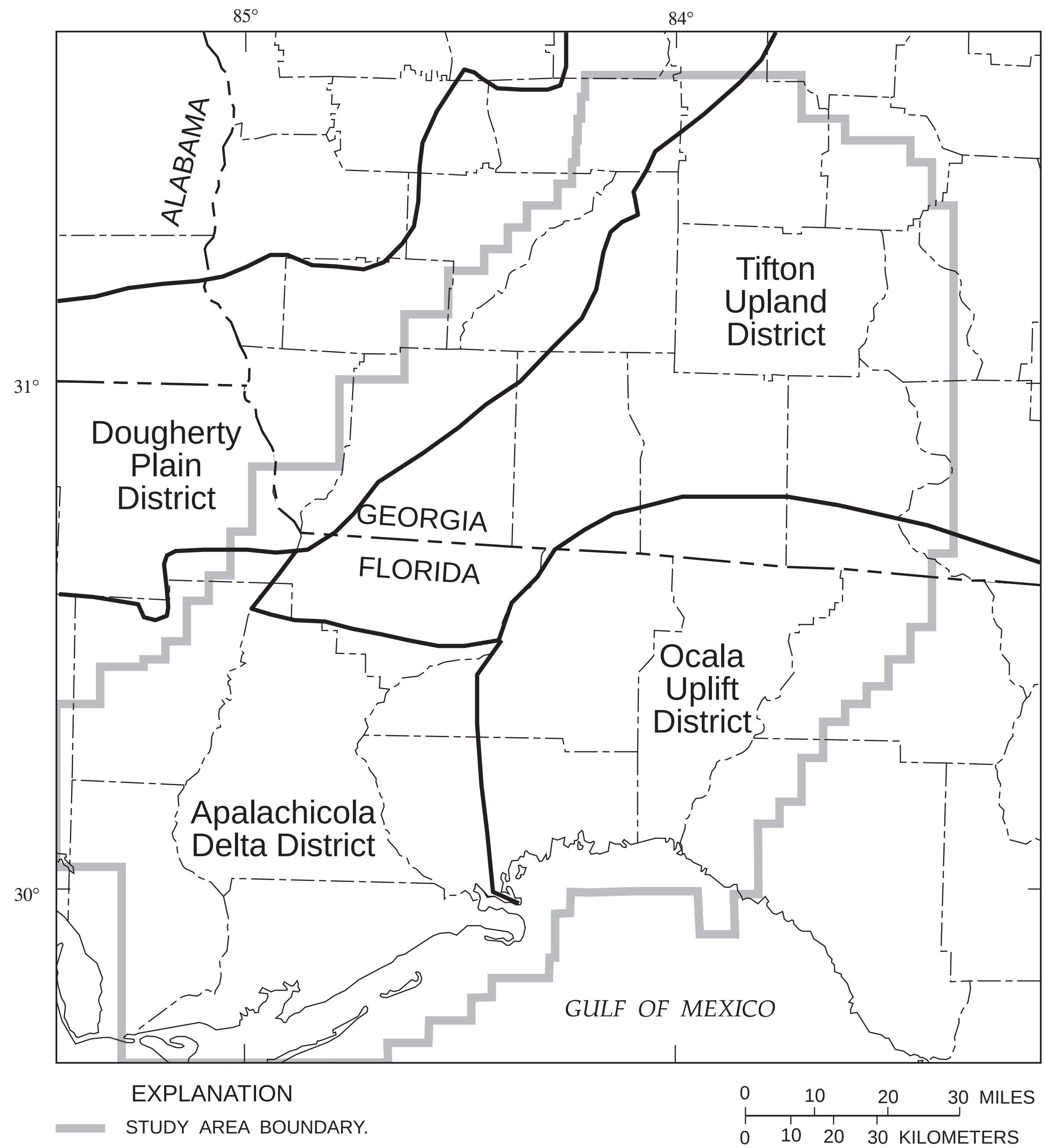


Figure 2. Major physiographic features in north-central Florida and southwestern Georgia (modified from Clark and Zisa, 1976, and Brooks, 1981).

developed dendritic drainage system. The Apalachicola Delta District contains river terraces and deltas, past and present, of the Apalachicola River and is a clastic terrain with no karst features. The topography of the Ocala Uplift District consists of gently rolling hills and in many places limestone occurs at or near land surface. The southward draining streams are continually modified by solution of the underlying limestones.

Previous Investigations

Hendry and Sproul (1966) investigated the geology and ground-water resources of Leon County. They described the geology and hydrology of the Upper Floridan aquifer, the overlying units, and the general water quality. Miller (1986) described the geology of the Floridan aquifer system that underlies all of Florida and parts of Georgia and South Carolina. Within the study area, Miller mapped the top, bottom, and thickness of the Upper Floridan aquifer and described the geology of the formations that comprise the aquifer. His investigation was part of the Regional Aquifer System Analysis (RASA) program of the USGS. Bush and Johnston (1988) simulated ground-water flow in the entire Floridan aquifer system using a finite-difference model as part of the RASA program. During their investigation, model-derived transmissivities were determined for the Upper Floridan aquifer in the study area, as well as rates of recharge and discharge. A relatively coarse grid with spacing of 8 by 8 mi was used for these simulations.

GEOLOGIC SETTING

The study area is underlain by sedimentary rocks of Tertiary through Quaternary age that consist of limestone, dolostone, clay, and sand of varying degrees of lithification (Miller, 1986). The geologic units from oldest to youngest are: the Clayton Formation of Paleocene age, the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, the Ocala Limestone of late Eocene age, the Suwannee Limestone of Oligocene age, the St. Marks and Chattahoochee Formations of early Miocene age, the Hawthorn Group of Miocene age, the Jackson Bluff, Miccosukee, and Citronelle Formations of Pliocene age, and the undifferentiated sediments of Pleistocene and Holocene age. A list of geologic units, their relation to the principal hydrogeologic units (aquifers and confining units), and corresponding model layers is shown in figure 3. The characteristics of the aquifers, confining units, and model layers are described in later sections. This report uses the terms St. Marks Formation, Chattahoochee Formation, and Hawthorn Group, because they are the currently accepted terminology of the Georgia and Florida Geological Surveys. The geologic descriptions in this section are based on work by Miller (1986), unless otherwise cited.

Sediments of Paleocene Age

The Paleocene-age Clayton Formation underlies the entire study area. The altitude at the top of this formation ranges from about 300 ft below sea level in the north to greater than 3,000 ft below sea level in the extreme south. The formation occurs as a massive calcareous marine clay in the southern part of the study area. Updip, it occurs as a fine- to medium-grained glauconitic sand and clayey sand with smaller amounts of medium- to dark-gray clay.

Sediments of Eocene Age

Eocene-age sediments can be subdivided into the Oldsmar and Avon Park Formations, and Ocala Limestone. The Oldsmar Formation underlies the entire study area, but consists of permeable limestones only in Wakulla, Leon, Jefferson, Taylor, and Madison Counties, Fla. Westward, the Oldsmar becomes increasingly argillaceous and less permeable as it interfingers with calcareous clastic rock. Northward, the Oldsmar grades from limestone to argillaceous limestone and calcareous clay into glauconitic calcareous sand. The altitude of the top of the permeable part of the Oldsmar Formation ranges from about 1,700 ft to greater than 2,500 ft below sea level and is approximately 500 feet thick.

The Avon Park Formation underlies the entire study area and ranges in thickness from about 300 ft in the north to about 1,200 ft in the south. The Avon Park consists of a permeable and relatively pure limestone only in parts of Wakulla, Leon, Jefferson, Taylor, and Madison Counties, Fla. Within these counties, the Avon Park Formation consists of a cream, tan, or light-brown, soft- to well-indurated limestone that is pelletal but locally micritic. To the west and north of these counties, the formation quickly grades into a low-permeability argillaceous, micritic, glauconitic limestone that, in turn, grades updip into calcareous, glauconitic, often shelly sand and clay beds. The altitude of the top of the permeable part of the Avon Park Formation ranges between 800 and 1,000 ft below sea level.

The Ocala Limestone is permeable through the entire study area and ranges in thickness from about 200 ft in the north to about 500 ft in the south. The altitude of the top of the Ocala is about 200 ft above sea level in the northwest where it outcrops in the Dougherty Plain. The Ocala slopes gently to the south, where it reaches depths of between 500 and 1,000 ft below sea level. The Ocala Limestone consists of two different rock types. The upper portion is a white, generally soft and friable, porous coquina consisting of foraminifera, bryozoan fragments, and whole to broken echinoid remains. The lower part of the Ocala Limestone is composed of cream to white, generally fine-grained, soft to semi-indurated, micritric limestone containing abundant miliolid remains and large foraminifers (Applin and Applin, 1944).

SYS-TEM	SERIES	FORMATION	HYDROGEOLOGIC UNIT	MODEL LAYERS
QUATERNARY	HOLO-CENE	Undifferentiated Deposits	Water-table aquifer	Layer 1
	PLEIS-TOCENE	Undifferentiated terrace and shallow marine deposits		
TERTIARY	PLIO-CENE	Citronelle Formation Miccosukee Formation Jackson Bluff Formation		
	MIOCENE	Hawthorn Group	Low-permeability Miocene- and Pliocene-age sediments	Confining unit
		Chattahoochee and St. Marks Formations	Upper Floridan aquifer	Layers 2 and 3
	OLIGOCENE	Suwannee Limestone		
	EOCENE	Ocala Limestone		
		Avon Park Formation		
		Oldsmar Formation		
	PALEOCENE	Clayton Formation	Low-permeability sediments	No-flow boundary

Figure 3. Relation of geologic units, hydrogeologic units, and model layers in north-central Florida and southwestern Georgia.

Sediments of Oligocene Age

The thickness of the Suwannee Limestone reaches a maximum of about 600 ft in the southwestern part of the study area and thins to less than 100 ft in the southeast, where it outcrops. The Suwannee also outcrops along the southern and western edge of the Dougherty Plain, but has been removed by erosion from most of the interior of the Dougherty Plain. The altitude of the top of the Suwannee ranges from just over 200 ft in the north to greater than 500 below sea level in the southwest. The Suwannee usually consists of two permeable rock types: 1) cream to tan, crystalline, highly vuggy limestone containing prominent gastropod and pelecypod casts and molds and 2) white to cream, finely pelletal limestone containing small foraminifers and pellets of micrite bound to a finely crystalline limestone matrix.The two facies are interbedded and cannot be recognized at all locations.

Sediments of Miocene Age

The Miocene-age sediments can be subdivided into the St. Marks Formation, Chattahoochee Formation, and the Hawthorn Group. The St. Marks outcrops, or subcrops at shallow depths, in the western part of the Ocala Uplift Physiographic District. Northward, the St. Marks grades laterally into the Chattahoochee Formation. The Chattahoochee is not present in the Dougherty Plain due to lack of deposition or removal by erosion. The St. Marks is a predominantly fine- to medium-grained, partially recrystallized, silty to sandy limestone that has undergone degrees of secondary dolomitization (Hendry and Sproul, 1966). The Chattahoochee is primarily a dolostone containing quartz sand, clay, calcite, limestone, chert, mica, heavy minerals, phosphate, and fossils (Huddlestun, 1988). The permeability of the St. Marks and Chattahoochee Formations ranges from very permeable to relatively impermeable.

The Hawthorn Group is thin or absent in the Dougherty Plain and in parts of the Ocala Uplift due to lack of deposition or later removal by erosion. The group is thickest in the Apalachicola Delta Physiographic District and within the Tifton Uplands, where the thickness can exceed several hundred feet. The Hawthorn is predominantly sand and clay; subordinate components include dolomite, dolostone, calcite, limestone, phosphorite, phosphate, silica in the forms of claystone, chert, and siliceous microfossils, feldspar, heavy minerals, carbonaceous material and lignite, zeolites, and fossils (Huddlestun, 1988). Locally, in beds and lenses, dolostone, limestone, phosphorite, clay, or claystone can make up the dominant lithologies.

Sediments of Pliocene Age

The Pliocene-age sediments can be subdivided into several formations including the Jackson Bluff Formation, the Miccosukee Formation, and the Citronelle Formation. The Jackson Bluff and Citronelle Formations occur only in the southwestern part of the study area. The Jackson Bluff is composed of clayey sands and sandy clays that are very macrofossilferous; the Miccosukee Formation is composed of interbedded and cross-bedded clays, silts, sands and gravels of varying coarseness and mixtures (Hendry and Sproul, 1966). The Citronelle Formation is composed of medium to coarse sand containing many stringers of gravel and a few thin clay beds. Similar in distribution to the Hawthorn Group, the Pliocene-age sediments are thin or absent in the Dougherty Plain and parts of the Ocala Uplift, and Tifton Uplands due to lack of deposition or later removal by erosion. Sediments of the Hawthorn Group and the clay, silts, and sandy clays of the Miccosukee and Jackson Bluff Formations form a continuous low-permeability unit that is referred to in this report as the low-permeability Miocene- and Pliocene-age sediments (fig. 3).

Sediments of Pleistocene and Holocene Age

Pleistocene-age sediments consist of medium- to coarse-grained, tan, white, and brown sand that locally contains trace amounts of carbonaceous material and shell fragments. The Holocene deposits include thin sand and gravel accumulations deposited mostly adjacent to streams, estuaries, and lagoons.

HYDROLOGIC SETTING

Aquifers in the study area include the water-table aquifer and Upper Floridan aquifer, which are separated by low-permeability Miocene- and Pliocene-age sediments (figs. 3 and 4). The water-table aquifer yields only small amounts of water when pumped and generally is not utilized. Some water, usually for domestic supply, is produced from the sandy units within the low-permeability Miocene- and Pliocene-age sediments. The Upper Floridan aquifer is utilized for municipal, industrial, agricultural, and domestic water supply. The transmissivity of the Upper Floridan aquifer ranges over several orders of magnitude within the study area. Where transmissivities are high, the Upper Floridan aquifer generally yields large quantities of good-quality water.

Water-Table Aquifer

The water-table aquifer lies within the shallow sediments exposed at land surface. The age of these sediments ranges from Holocene to Pliocene. The transmissivity ranges from very low where the

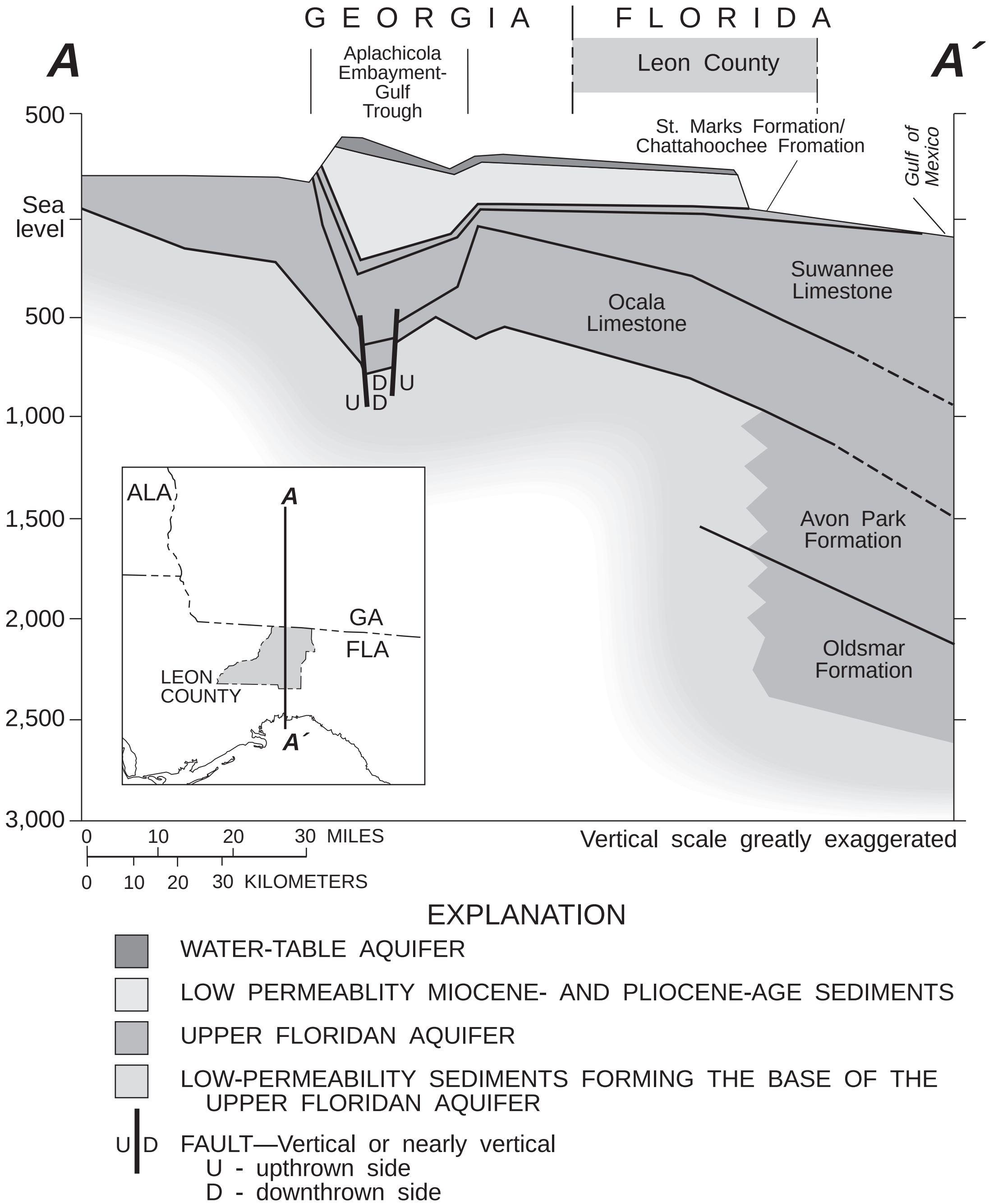


Figure 4. Generalized hydrogeologic section showing aquifers and geologic formations of the Upper Floridan aquifer in north-central Florida and southwestern Georgia.

sediments are fine grained, to moderately high where significant thicknesses of sand and gravel are present. The water-table aquifer is present through most of the study area and generally is less than 50 ft thick. It is generally absent from the Dougherty Plain and parts of the Ocala Uplift. In areas where the water-table aquifer is absent, the water table lies within the Upper Floridan aquifer.

Low-Permeability Miocene- and Pliocene-Age Sediments

The low-permeability Miocene- and Pliocene-age sediments overlie and in some areas confine the Upper Floridan aquifer. These sediments are several hundred feet thick in the Apalachicola Embayment-Gulf Trough feature (figs. 4 and 5). This feature has

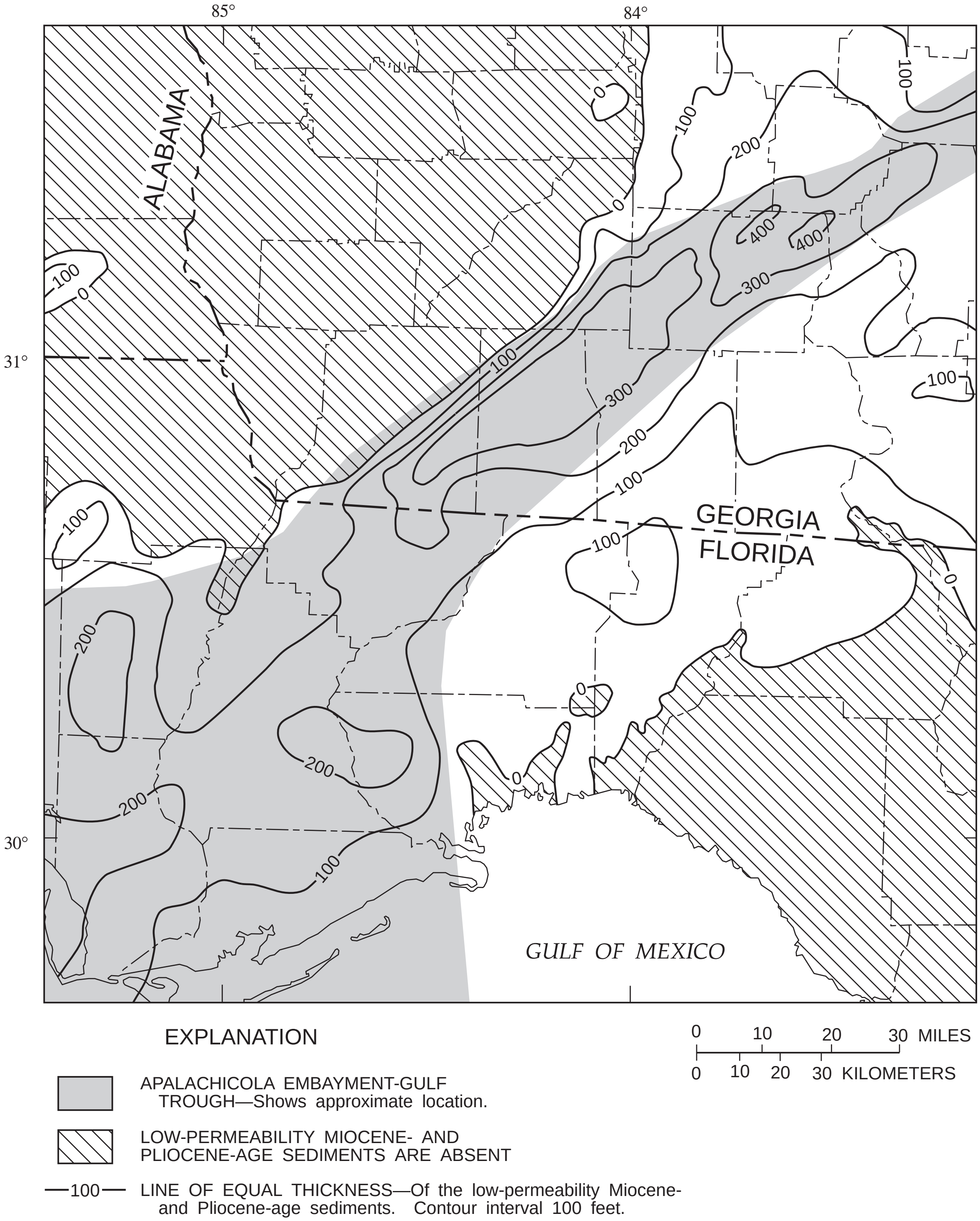


Figure 5. Thickness of low-permeability Miocene- and Pliocene-age sediments (modified from Miller, 1986).

been described as a marine channel that linked the Gulf of Mexico to the Atlantic Ocean during the early Tertiary (Huddlestun, 1988). Falling sea levels restricted circulation within this channel, allowing deposition of thick accumulations of fine grained material. The low-permeability Miocene- and Pliocene-age sediments are generally not present in the Dougherty Plain and are less than 100 ft thick in the Ocala Uplift District (fig.5) (Miller, 1986).

Upper Floridan Aquifer

The Upper Floridan aquifer is part of the Floridan aquifer system that occurs in Florida and parts of Georgia, South Carolina, and Alabama. Miller (1986) defined the Floridan aquifer system as a vertically continuous sequence of carbonate rocks of generally high permeability that are hydraulically connected in varying degrees and whose permeability is, in general, an order of magnitude to several orders of magnitude greater than those of the rocks that bound the system. Within the study area, the Upper Floridan aquifer includes all or parts of the Oldsmar Formation, Avon Park Formation, Ocala Limestone, Suwannee Limestone, St.Marks Formation, and Chattahoochee Formation (fig. 4).

Miller delineated the Upper Floridan aquifer based on the permeability characteristics of the rocks, thus neither the top nor bottom of the aquifer necessarily conforms to formation or time-stratigraphic boundaries. The altitude of the top of the Upper Floridan aquifer (fig. 6) ranges from about 200 ft above sea level in the Dougherty Plain to greater than 400 ft below sea level in parts of the Apalachicola Delta District and Tifton Uplands. The Upper Floridan aquifer is uplifted along the Barwick Arch (Sever, 1966), a subregional feature that lies southeast of the Apalachicola Embayment-Gulf Trough. The altitude of the base of the aquifer (fig. 7) ranges from 200 ft above sea level in the north, where it pinches out, to greater than 2,200 ft below sea level in the south. The aquifer thickens from about 100 ft in the north (fig. 8) to greater than 2,000 ft in the south.

Hydraulic Properties of the Upper Floridan Aquifer

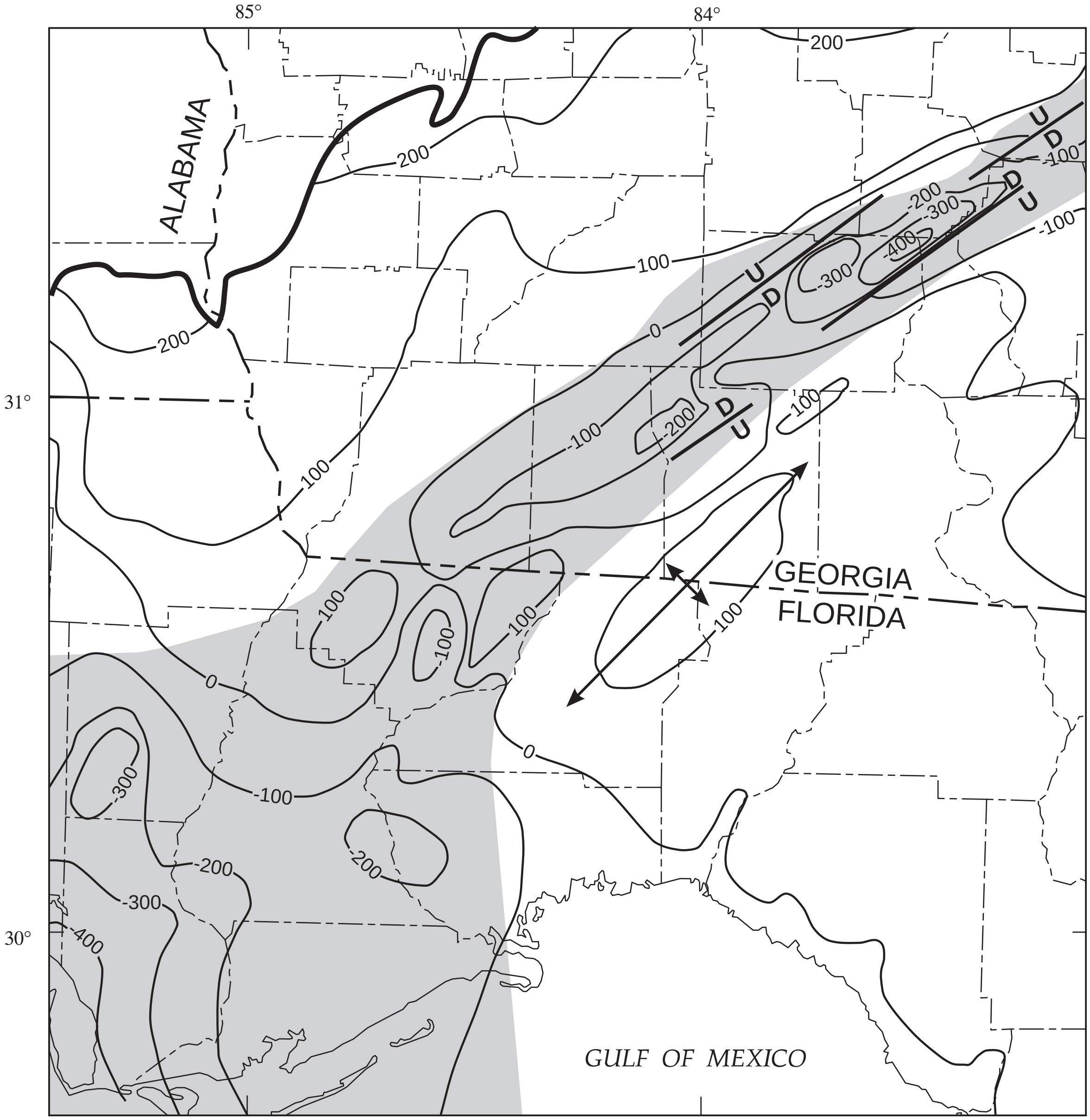
Bush and Johnston (1988) conducted an investigation of the entire Floridan aquifer system and observed that carbonate rocks are nearly always characterized by an uneven distribution of permeability. Throughout much of the area where the Upper Floridan aquifer occurs, the water-bearing openings consist of one or more of the following: 1) openings in loosely cemented fossil hashes that are similar to the interstices of sands, 2) mosaics of many fractures and solution-widened joints, and 3) solution cavities ranging in size from less than 1 in to tens of feet or more. Large solution cavities generally occur near large springs and some sinkholes where dissolution of the limestone is greatest, but these areas represent only a small part of the aquifer on a regional scale. In areas away from the large solution openings, the fist two conditions dominate. The transmissivity of the Upper Floridan aquifer is directly related to the thickness and lithology of the overlying low-permeability sediments. Thinner and more permeable overlying sediments allow greater rates of infiltration and increased dissolution of the limestones. The removal of these sediments from some areas during Pleistocene time is largely responsible for the current distribution of karst, and, therefore, the current distribution of transmissivity.

Transmissivity values determined by aquifer tests for the Upper Floridan aquifer vary greatly within the study area, ranging from 1,300 ft^2/d to 1,300,000 ft^2/d (fig. 9). The highest transmissivity values generally occur within the Dougherty Plain, Ocala Uplift, and parts of the Tifton Uplands where the overlying low-permeability sediments are thinnest or absent. The lowest transmissivity values generally occur within the Apalachicola Embayment - Gulf Trough where the overlying low-permeability sediments are thickest.

Bush and Johnston (1988) simulated ground-water flow using a finite difference model. Their investigation indicated that transmissivity values were as high as 1,000,000 ft^2/d in the Dougherty Plain, ranged between 10,000 and 50,000 ft^2/d along the axis of the Apalachicola Embayment - Gulf Trough, and were greater than 1,000,000 ft^2/d in parts of the Ocala Uplift and Tifton Uplands. Assigned transmissivities in some areas near large springs were as high as 10,000,000 ft^2/d. Kellam and Gorday (1990) also recognized that the Upper Floridan aquifer, within the Apalachicola Embayment - Gulf Trough, consisted of poorly permeability limestones. They attributed the lower permeabilities to a combination of factors: 1) the lower primary permeability of the deeper-water limestones deposited in the feature, 2) the greater thickness of overburden which limits development of secondary porosity, and 3) possibly a lack of joints and fractures to enhance ground-water movement. They further postulated that ground-water movement was sluggish in parts of the feature based on high levels of dissolved ions in the water.

Ground-Water Pumpage

Wells and water-supply systems that withdraw water from the Upper Floridan aquifer are listed in table 1 and locations are shown in figure 10. Generally, the list contains wells or systems that pump, on



EXPLANATION

APALACHICOLA EMBAYMENT-GULF TROUGH—Shows approximate location.

—100— STRUCTURE CONTOUR—Shows altitude of top of Upper Floridan aquifer. Contour interval is variable. Datum is sea level.

NORTHERN EXTENT OF UPPER FLORIDAN AQUIFER

U/D FAULT—Vertical or nearly vertical.
U Upthrown side
D Downthrown side

BARWICK ARCH

Figure 6. Structure at the top of the Upper Floridan aquifer (modified from Miller, 1986).

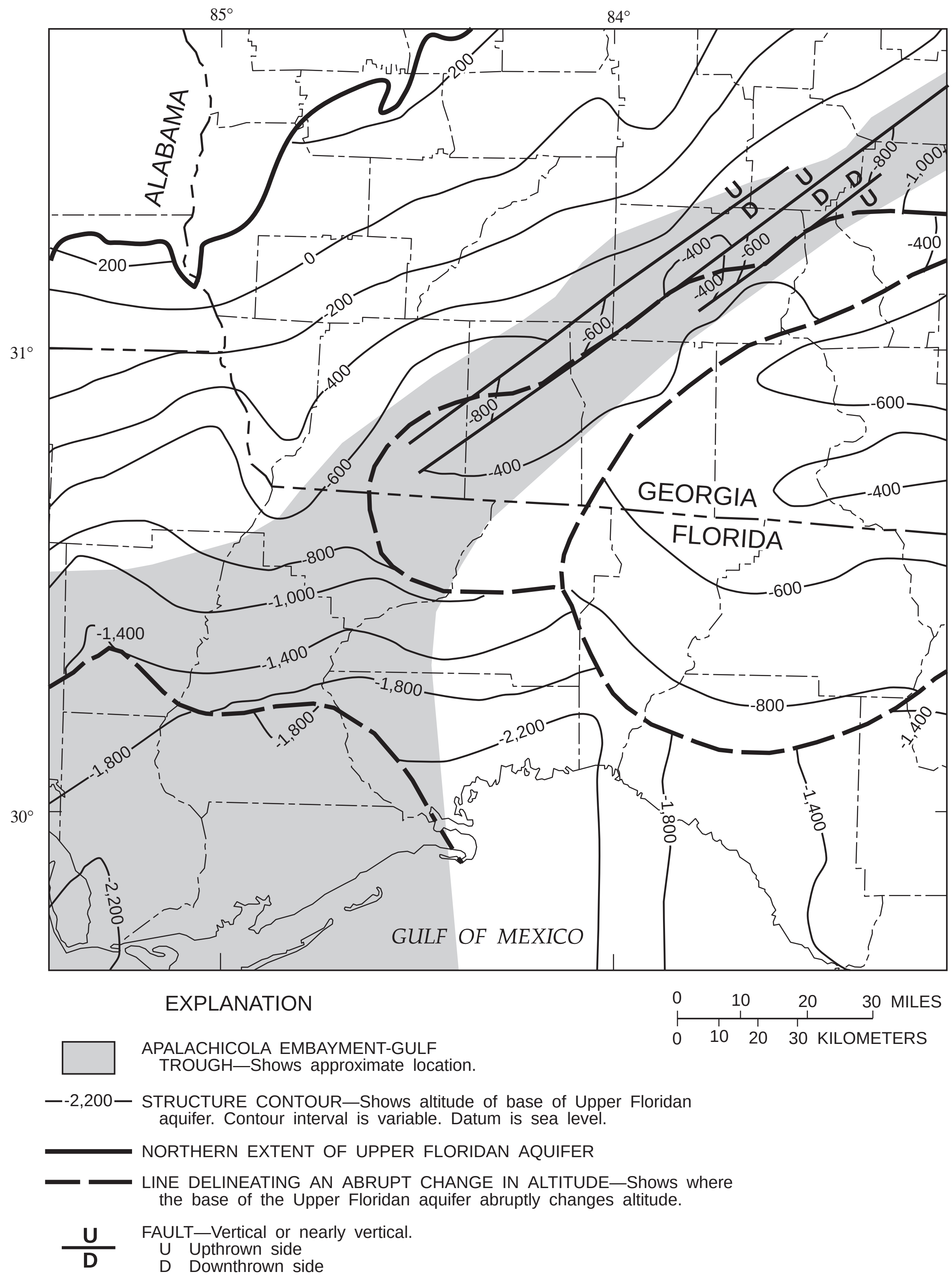


Figure 7. Structure at the base of the Upper Floridan aquifer (modified from Miller, 1986).

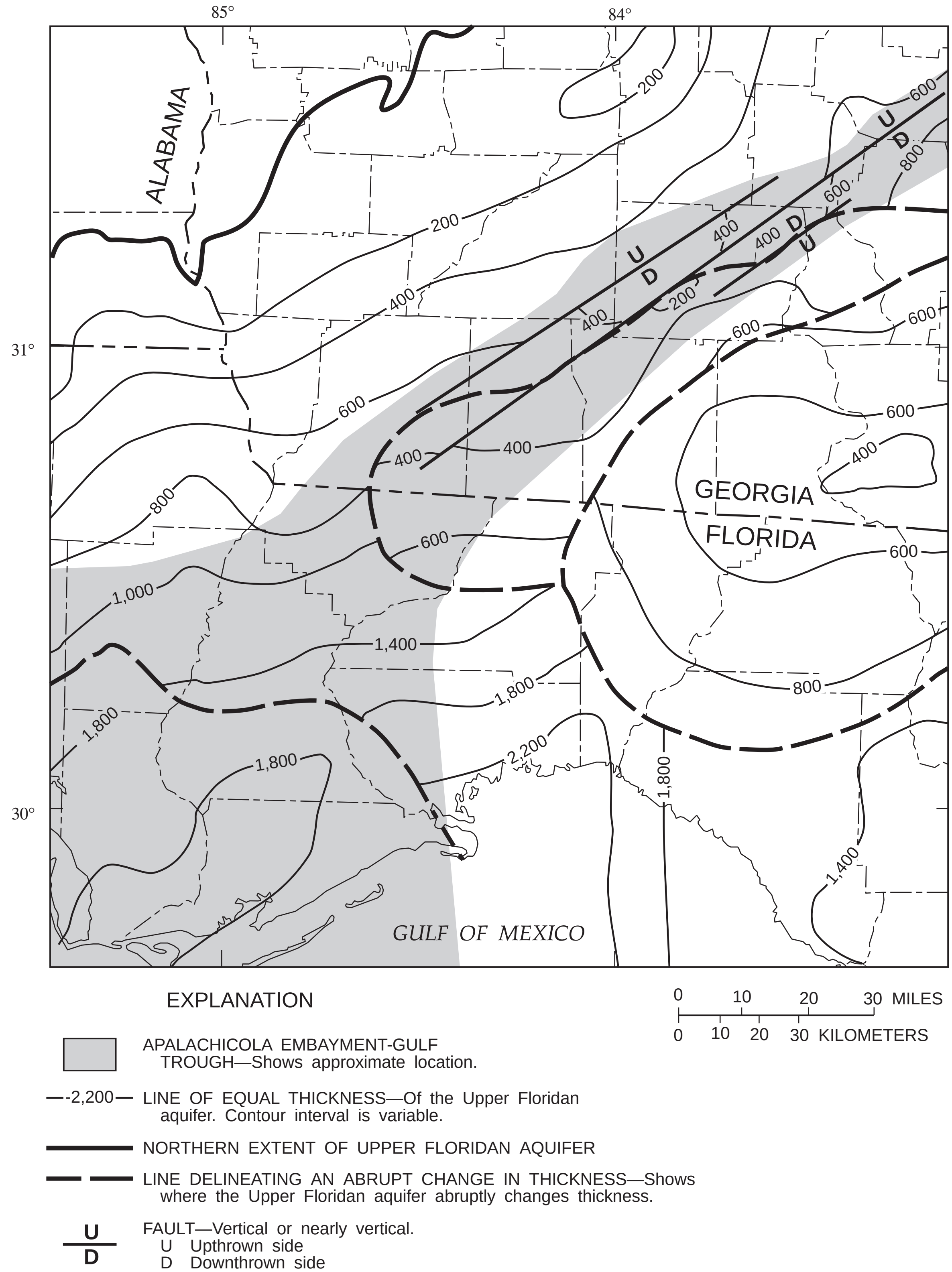


Figure 8. Thickness of the Upper Floridan aquifer (modified from Miller, 1986).

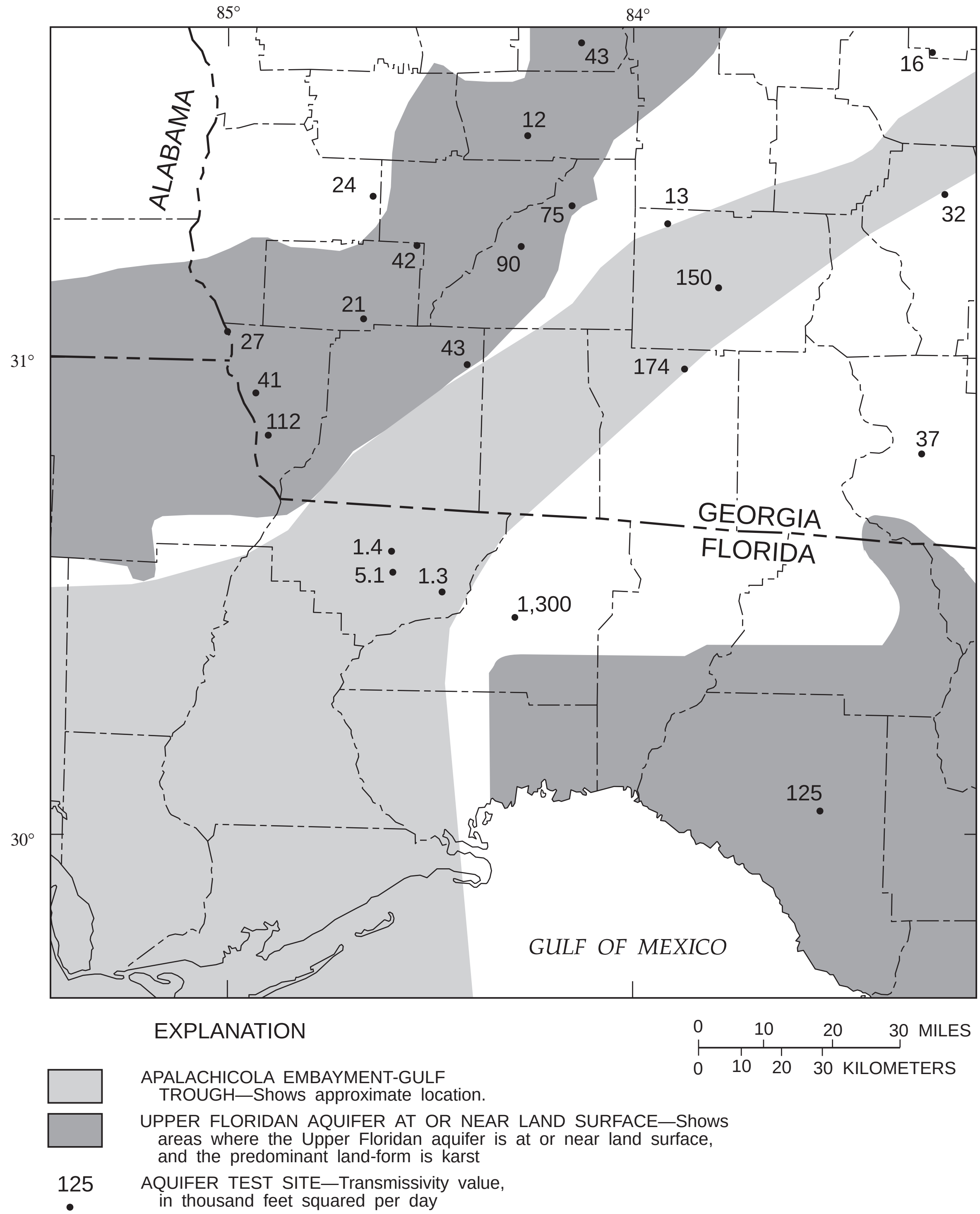


Figure 9. Values of transmissivity of the Upper Floridan aquifer as determined by aquifer testing (modified from Bush and Johnson, 1988).

average, greater than 70 gal/min, although systems that pump lower rates were included if the information was readily available. This list does not include any domestic supply wells, because they pump much less than 70 gal/min. Although individual domestic supply wells pump relatively small amounts of ground water, the number of these wells can be large. Within Leon County, Fla., more than 6,000 domestic supply wells have been drilled since 1976 (Jay Johnson, City of Tallahassee, oral commun., 1995).

Table 1. Pumpage from the Upper Floridan aquifer in north-central Florida and southwestern Georgia

[Source of pumping data for wells in Florida is the Northwest Florida Water Management District unless otherwise cited. Source for wells in Georgia is the U.S. Geological Survey unless otherwise cited; gal/min, gallons per minute]

Site	Owner	Pumping rate for well or well system, in gal/min[1]	County
	STATE OF FLORIDA		
1	CHATTAHOOCHEE- CITY OF	422	GADSDEN
2	SNEADS- TOWN OF	146	JACKSON
3	FL. DEPT OF CORRECTIONS	389	JACKSON
4	STATE OF FLORIDA	685	GADSDEN
5	GULF POWER PLANT	264	JACKSON
6	HAVANA- TOWN OF	363	GADSDEN
7	GRETNA- TOWN OF	116	GADSDEN
8	TALQUIN ELECTRIC	138	LEON
9	TALQUIN ELECTRIC	150	LEON
10	TALQUIN -LK JACKSON-9	64[2]	LEON
11	ROWE DRILLING	347	LEON
12	MONTICELLO- CITY OF	484[3]	JEFFERSON
13	TALQUIN -LK JACKSON-8	236[2]	LEON
14	TALQUIN -SHILOH	84[2]	GADSDEN
15	TALQUIN -LK JACKSON-5	56	LEON
16	TALQUIN -LK JACKSON-1	152	LEON
17	TALQUIN -LK JACKSON-4	79	LEON
18	TALQUIN -SHILOH	64[2]	GADSDEN
19	ROWE DRILLING	556	LEON
20	ROWE DRILLING	556	LEON
21	ROWE DRILLING	556	LEON
22	ROWE DRILLING	625	LEON
23	BELL- PEARLE MAE	625	LEON
24	ROWE DRILLING	694	LEON
25	TALLAHASSEE- POWER PLANT	2932	LEON
26	BRISTOL- CITY OF	123	LIBERTY
27	TALLAHASSEE- CITY OF	17,153	LEON
28	GREENVILLE- TOWN OF	81	MADISON
29	BLOUNTSTOUN- CITY	278	CALHOUN
30	U.S. DEPT. OF JUSTICE	144	LEON
31	DEERTREE HILLS	417	LEON
32	POSEY, HOMER	556	LEON
33	TALQUIN ELECTRIC	75	LEON
34	TALQUIN ELECTRIC	80	LEON
35	NOVAK- BILL	556	LEON
36	TIMBER ENERGY	394	LIBERTY
37	TALQUIN ELECTRIC	134	WAKULLA
38	OLIN BALL POWDER	556	WAKULLA
39	TALLAHASSEE- CITY OF	229	WAKULLA
40	SOPCHOPPY- CITY OF	185	WAKULLA
41	PANACEA WATER SYSTEM	116	WAKULLA
42	ALLIGATOR POINT	69	FRANKLIN
43	LANARK WATER & SEWER	104	FRANKLIN
44	CARABELLE- CITY OF	130	FRANKLIN
45	LEISURE PROPERTIES	111	FRANKLIN
46	APALACHICOLA- CITY	465	FRANKLIN
	STATE OF GEORGIA		
1	MILLER BREWING CO	590	DOUGH-ERTY
2	US MARINE CORPS LOGISTICS	548	DOUGH-ERTY
3	PROCTOR&GAMBLE PROD	253[4]	DOUGH-ERTY
4	CITY OF SYLVESTER WAT&LT	479[4]	WORTH
5	ABRAHAM BALDWIN AG COLLEG	69	TIFT
6	MERCK & CO INC	3271	DOUGH-ERTY
7	CITY OF TIFTON	3701	TIFT
8	TIFT CO WATER SYSTEM	131[4]	TIFT
9	CITY OF OMEGA	90	TIFT
10	CITY OF NEWTON	69[4]	BAKER
11	TOWN OF NORMAN PARK	104[4]	COLQUITT
12	CITY OF CAMILLA	35[4]	MITCHELL
13	SWIFT INDEPENDENT PACKING	385[4]	COLQUITT
14	CITY OF MOULTRIE	1625	COLQUITT
15	CITY OF ADEL	1062	COOK
16	CITY OF PELHAM	1513[4]	MITCHELL
17	CITY OF MEIGS	83	THOMAS
18	CITY OF CECIL	69[4]	COOK
19	WAVERLY MINERAL PRODUCTS	69[4]	THOMAS
20	OIL DRI CORP OF GA	90[4]	THOMAS
21	AMOCO FABRICS	389	DECATUR
22	CITY OF BAINBRIDGE	1590[4]	DECATUR
23	DECATUR CO INDUST AIR PK	125	DECATUR
24	CITY OF BARWICK	48[4]	BROOKS
25	CITY OF CAIRO	1631	GRADY
26	SUNNYLAND FOODS INC	83[4]	THOMAS
27	CITY OF THOMASVILLE	2489	THOMAS
28	CITY OF BOSTON	76	THOMAS
29	CITY OF QUITMAN	632	BROOKS
30	CITY OF ATTAPULGUS	69[4]	DECATUR

[1]Average pumping rate during November 1991, unless otherwise cited.

[2]Source: Florida Department of Environmental Protection sanitary well permits.

[3]Source: Suwannee River Water Management District.

[4]Average pumping rate for November 1990.

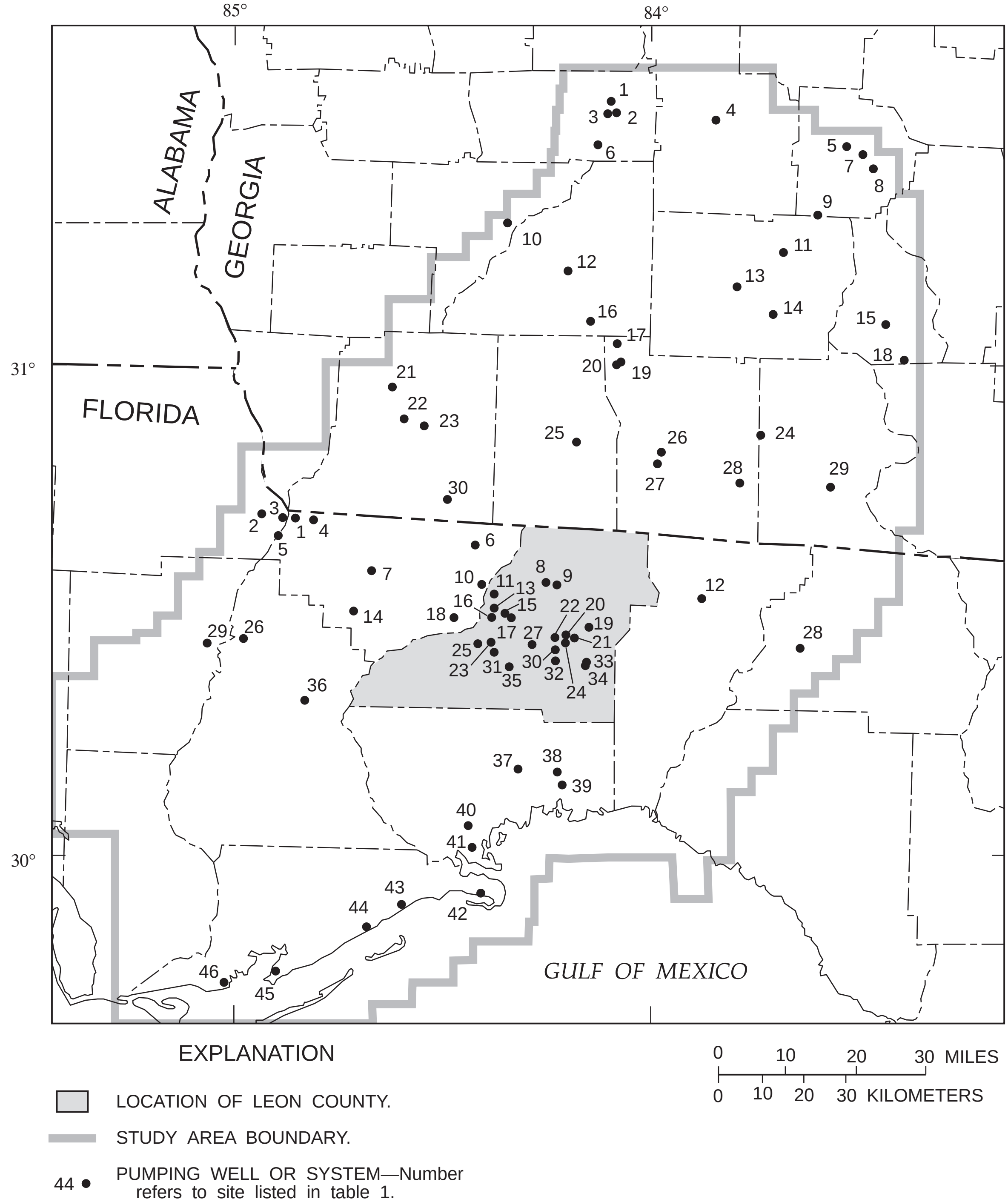


Figure 10. Water-supply wells and systems that withdraw water from the Upper Floridan aquifer (numbers refer to wells or systems listed in table 1).

DATA COLLECTION

A data-collection program was undertaken to quantify hydrologic conditions needed for calibration of a ground-water flow model. Model calibration involves successfully simulating measured hydrologic conditions within acceptable limits of error, as will be discussed later. The potentiometric surface of the Upper Floridan aquifer was estimated by measuring ground-water levels in a network of wells. The rate of ground-water discharge to rivers from the Upper

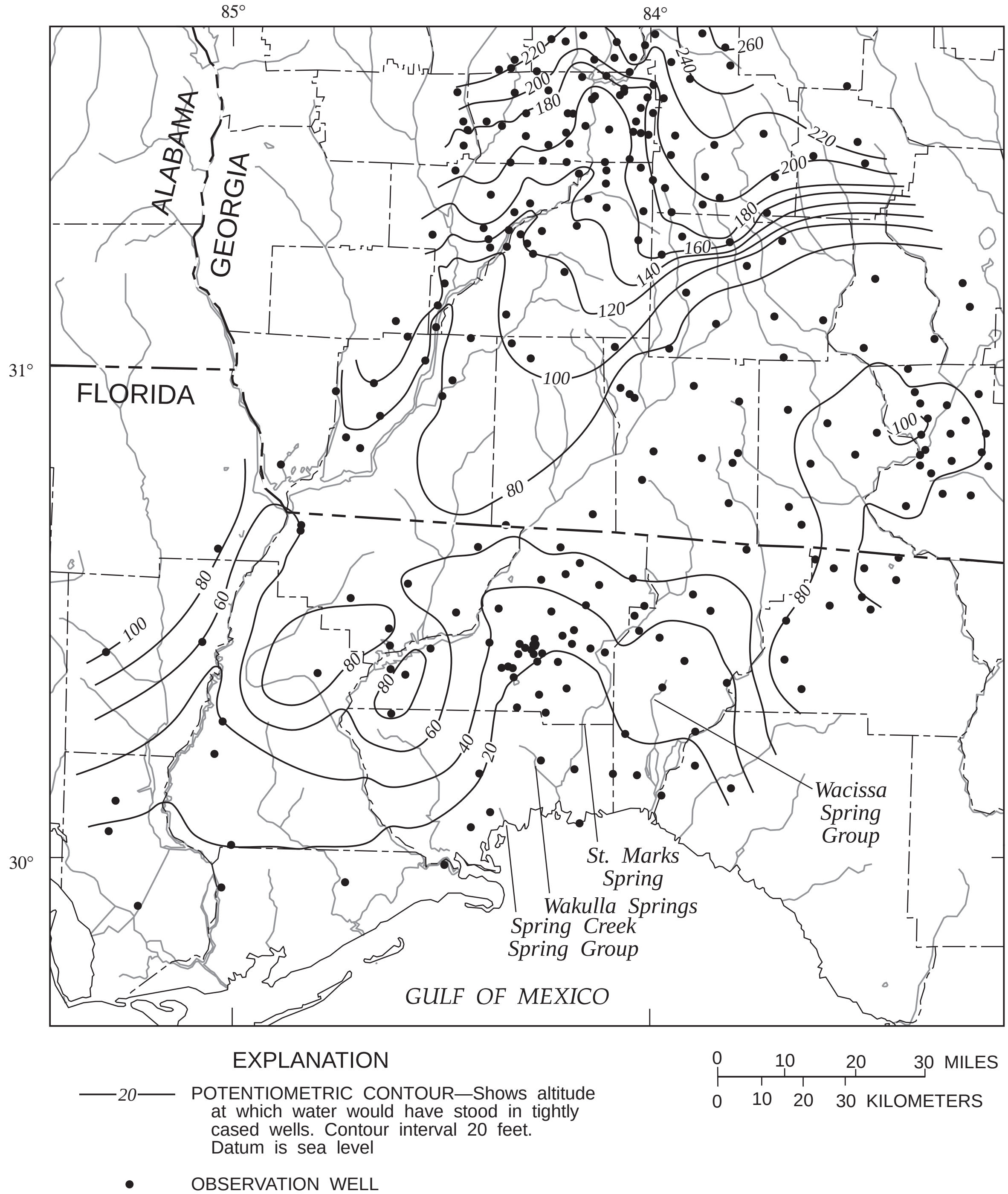


Figure 11. Altitude of the potentiometric surface of the Upper Floridan aquifer during October- November 1991.

Floridan aquifer was quantified by measuring river-discharge rates under base-flow conditions. One aquifer test was conducted to determine the transmissivity of the Upper Floridan aquifer that underlies downtown Tallahassee.

Water-Level Measurements

A potentiometric surface map of the Upper Floridan aquifer (fig. 11) was constructed from ground-water measurements made in 274 wells during the period October 21 to November 8, 1991. Wells

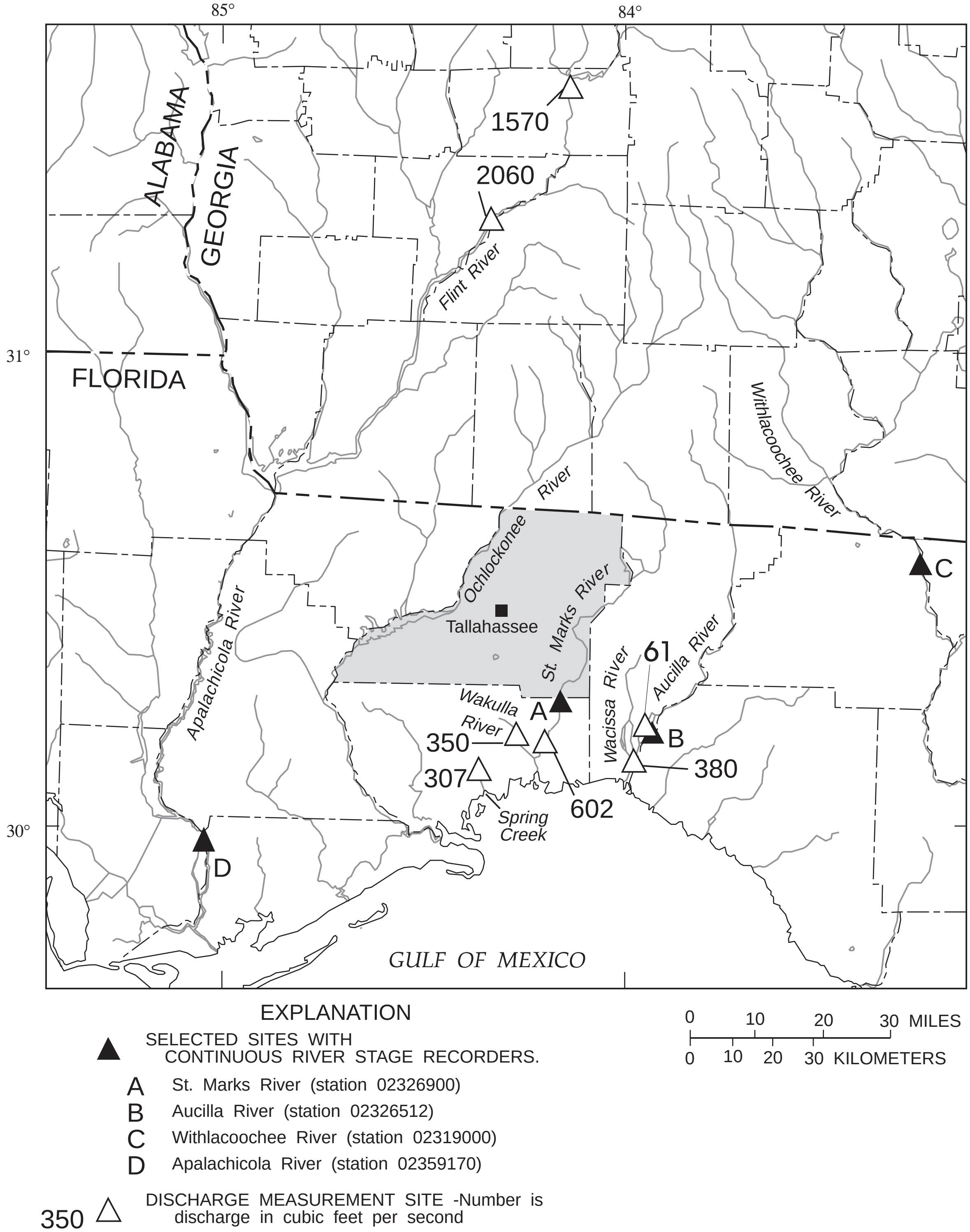


Figure 12. River-discharge measurement sites and related discharge rates on November 1, 1991.

were selected from data bases of agencies that included the USGS, Northwest Florida Water Management District, City of Tallahassee, and Florida Department of Environmental Protection.

River-Discharge Measurements

River-discharge measurements were made at seven locations, on November 1, 1991 (fig. 12) and were made concurrently with the ground-water level

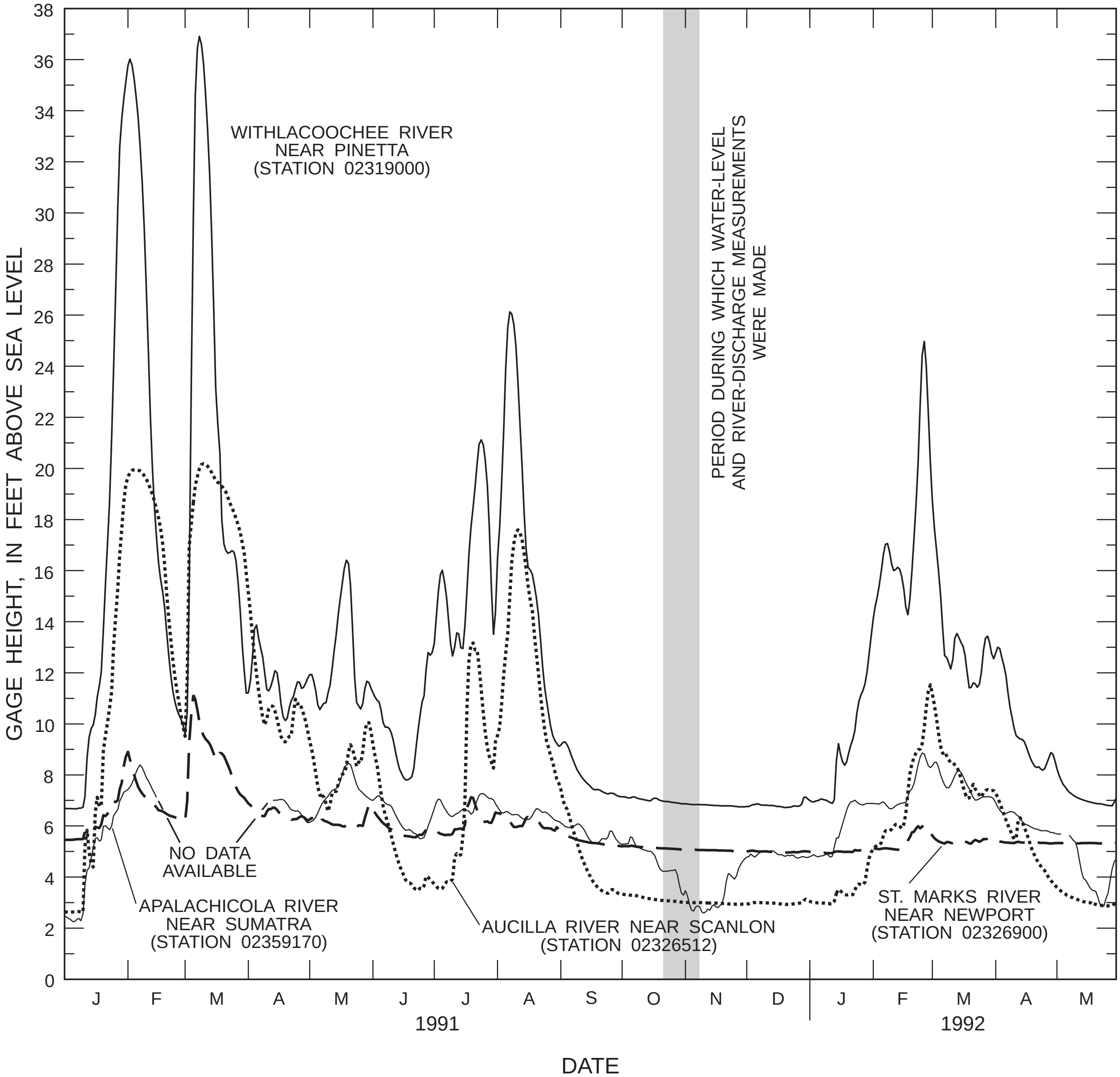


Figure 13. River stages at stations on the St. Marks, Aucilla, Withlacoochee, and Apalachicola Rivers from January 1991 through May 1992.

measurements. Three of the discharge measurements were obtained at established USGS gaging stations. Discharges of the Aucilla, St. Marks, and Wakulla Rivers, and Spring Creek were measured directly using a Price current meter and standard USGS flow-measuring techniques. The amount of error in measuring river discharges varies from station to station and measurement quality can range from very good (within 5 percent) to good (5 - 8 percent) to poor (greater than 10 percent). The error in the discharge measurements of the Aucilla, St. Marks, and Wakulla Rivers, and Spring Creek was estimated at about 10 percent; the other measurements ranged from very good to good. Discharge in the Apalachicola River and the Ochlockonee River and its tributaries was not measured because they are separated from the Upper Floridan aquifer by low-permeability sediments, and are not considered lines of discharge from the Upper Floridan aquifer.

Rivers in the study area were at base-flow conditions during field-data collection due to several months of low rainfall. Base-flow conditions were indicated by constant and low river stages in the Withlacoochee, St. Marks, Aucilla, and Apalachicola Rivers (fig. 13). Variability in stage in the

Apalachicola River is due to dams upstream storing and releasing water and not the variability caused by base flow.

Aquifer Testing

An aquifer test was conducted during November 1992. The purpose of the test was to: 1) determine the transmissivity of the Upper Floridan aquifer at a site within Tallahassee, 2) determine if the aquifer is a single vertically connected hydraulic unit, and 3) to determine if the aquifer acted as porous medium at the aquifer test scale. The test was conducted using the following methodology: City of Tallahassee well 2 was pumped at 1,400 gal/min for 8 days while water levels were measured in five monitoring wells (table 2, fig. 14). After 8 days, the pumping well was turned off and recovery was monitored for 5 hours in well 4, which was equipped with a pressure transducer.

Table 2. Description of pumping and monitoring wells used for aquifer test analysis

[--, not applicable. Locations of wells are shown on fig. 14.]

Monitoring well number	Altitude, in feet above sea level	Well depth, in feet below land surface	Casing depth, in feet below land surface	Distance from pumping well, in feet
Pumping Well:				
City #2	187	415	213	--
Monitoring Wells:				
1	213.32	300	220	1,127
2	212.60	602	485	1,108
3	195.89	340	189	1,220
4	205.47	320	210	805
5	185.99	300	190	1,325

Monitoring wells 1, 3, 4, and 5 had been installed prior to this investigation. Monitoring well 2 was drilled as part of this study. One purpose of the deep well (well 2) was to allow observation of the aquifer response in the lower part of the Upper Floridan aquifer during the aquifer test. Many existing wells penetrate the upper part of the aquifer, but very few penetrate the lower part. Consequently, little is known about the vertical hydraulic connection between the upper and lower parts of the Upper Floridan aquifer. Caliper, natural-gamma, acoustic-velocity, gamma-gamma, salt-tracer, fluid-resistivity, electric long- and short-normal resistivity, focused-resistivity, and spontaneous-potential geophysical logging was performed on the deep well. The geophysical logs showed numerous small openings of several inches in the upper 300 ft of the limestone. The openings are attributed to circulating ground water which dissolved the limestone as it moved along bedding planes and fractures. Such openings were not observed in the limestone in the lower 100 ft of the well; however, this section was believed to be very porous due to the loss of circulation during mud-rotary drilling. Based on the geophysical logs, the permeability of the Upper Floridan aquifer at the test site is considered the result of a mosaic of many fractures and solution-widened joints and openings in loosely cemented fossil hashes that are similar to the interstices of sands.

The aquifer-test data were analyzed by the Theis method (Lohman, 1979). A composite log-log plot of the water-level drawdown data and fitted Theis curve is shown in figure 14. Only data from the first 24 hours of the test were used in the calculation of transmissivity because the later data were affected by city pumpage occurring in areas away from the test and by rainfall. The drawdown data from wells 3, 4, and 5 plotted near a single line (the fitted Theis curve). Using these wells, a transmissivity of 1,300,000 ft^2/d was computed for the Upper Floridan aquifer. Although this is a large transmissivity value, it falls well within the range of values determined by Bush and Johnston (1988).

Wells 1 and 2 are located side-by-side, with well 1 completed in the upper third of the aquifer and well 2 completed in the lower half. The drawdown data from well 2 plotted slightly to the right of the fitted Theis curve, whereas drawdown data from well 1 plotted farther to the right. The delayed response of water levels at these wells could be due to an increase in aquifer storage in the direction of these wells. An increase in storage could be caused by greater dissolution of the limestone creating, a greater volume of void space than elsewhere in the aquifer.

During the aquifer test, water levels at well 2 (the deep well) responded to pumping slightly more quickly than well 1 (the shallow well), even though the pumping well is open at approximately the same interval as well 1 and above well 2. This indicates that a good vertical connection exists between the upper and lower parts of the aquifer and that the Upper Floridan aquifer does act as a single vertically connected unit. Long-term water-level measurements made in these two wells from May 1992 through October 1993

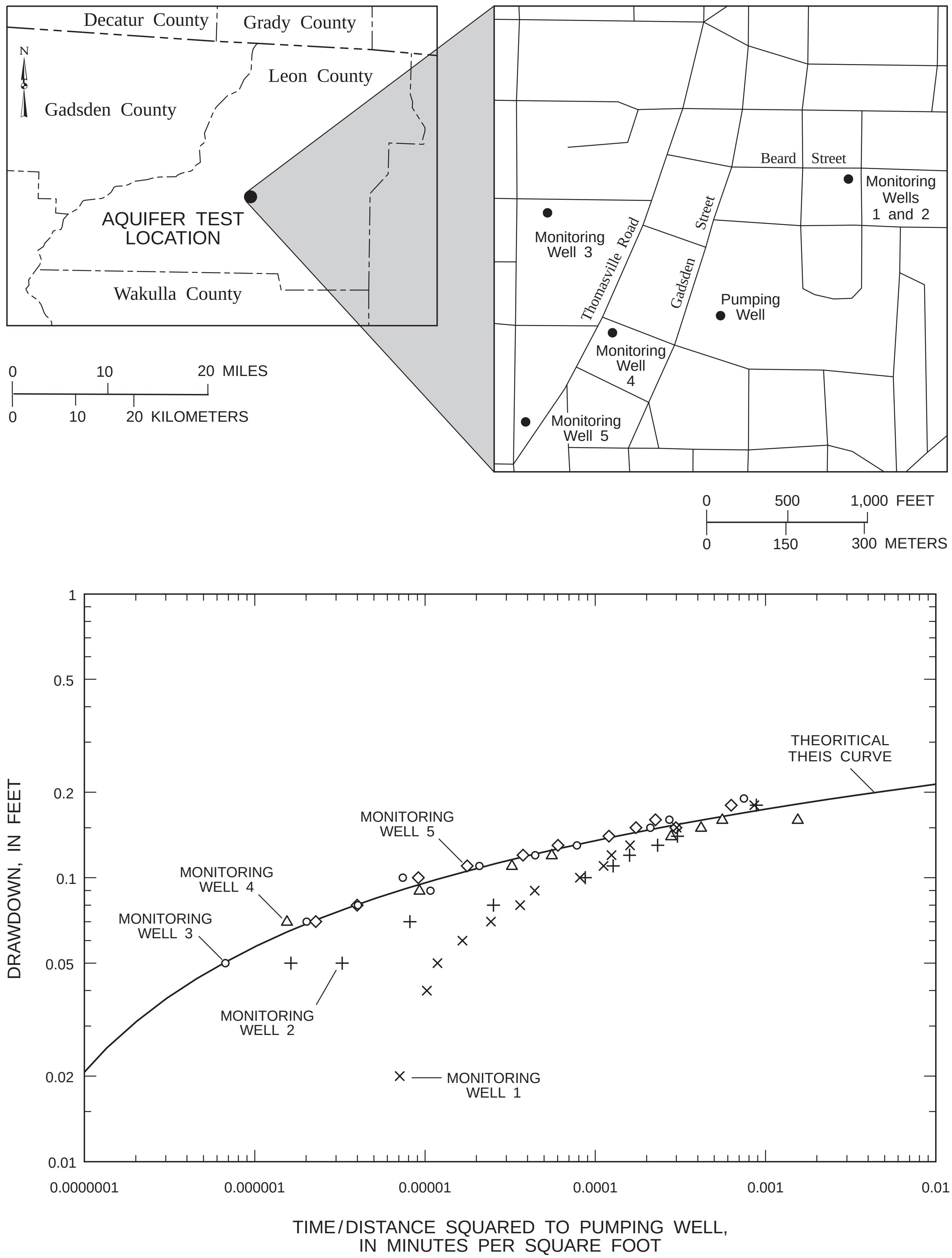


Figure 14. Aquifer response during testing conducted in November 1992, Tallahassee, Fla.

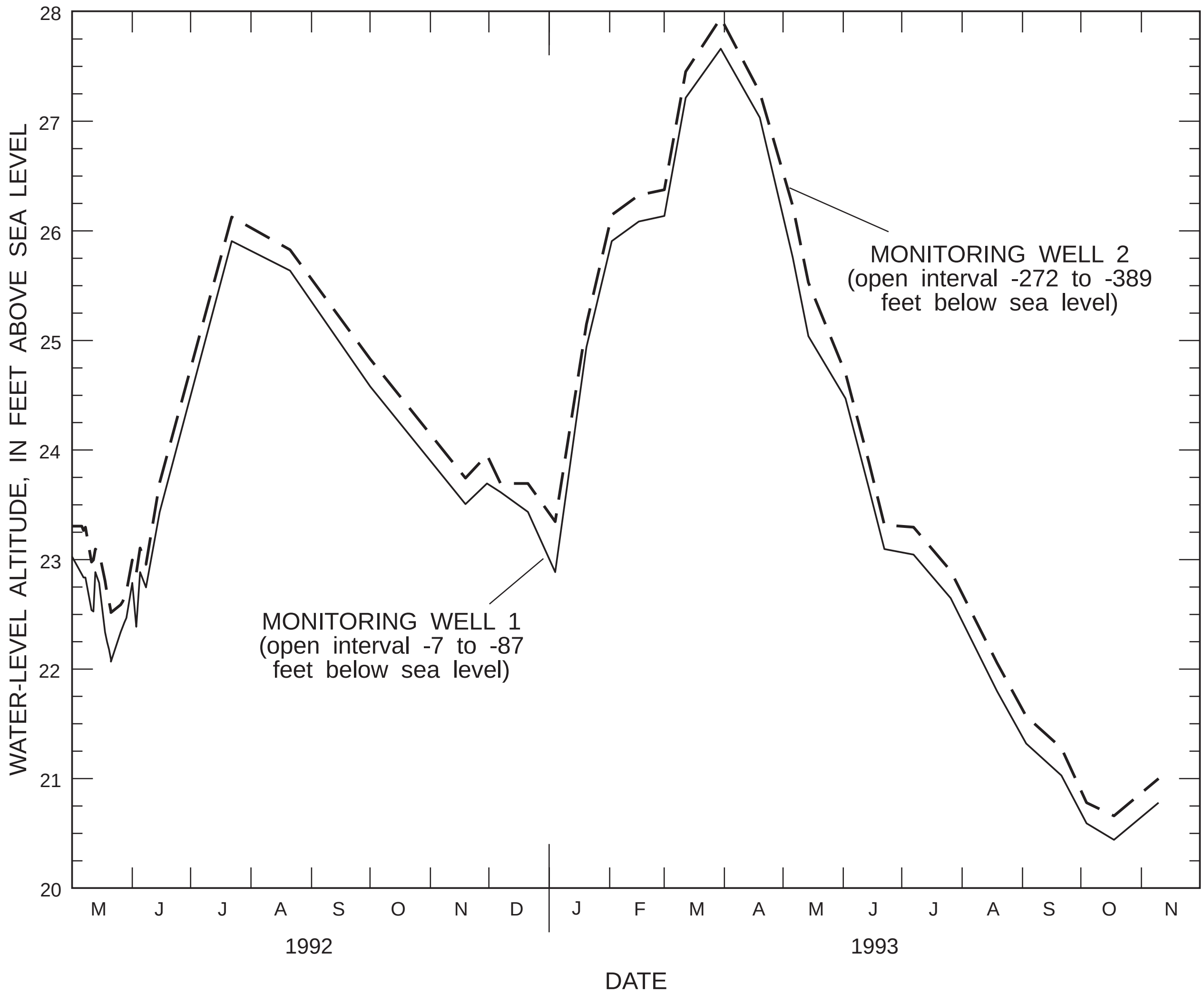


Figure 15. Water-level altitudes in monitoring wells 1 and 2 in Tallahassee, Fla., May 1992 through October 1993.

(fig. 15) show a close correlation of water-level altitudes, further indicating a good vertical connection.

Bush and Johnston (1988) reviewed many Floridan aquifer tests and found that data for many of these tests could be matched to the classic nonleaky, leaky, or delayed-yield response curves, even though the methods are based strictly on porous media assumptions. However, they further argued that porous media assumptions are probably valid in the Upper Floridan aquifer on the scale of the typical aquifer test where the cone of depression is hundreds if not thousands of feet across and where the aquifer response curves matched theoretical curves. For the Tallahassee test, the match between the theoretical Theis curve and the aquifer test data indicated that at the aquifer test scale, the Upper Floridan aquifer responded as a porous medium.

CONCEPTUAL MODEL OF THE GROUND-WATER FLOW SYSTEM

Developing a conceptual model of the aquifer system is an important step in constructing a computer model that accurately simulates ground-water flow. The Upper Floridan aquifer is conceptualized as having the following characteristics: 1) ground-water flow is in a state of dynamic equilibrium and thus can be investigated by assuming steady-state conditions during long term periods, 2) the aquifer acts a single water-bearing unit, 3) the aquifer is recharged by precipitation, and 4) discharge occurs as spring flow, leakage to rivers, leakage to the Gulf of Mexico, and pumpage. Developing a conceptual model also includes locating ground-water divides, determining ground-water flow directions, and determining areas of recharge and discharge.

The location of the ground-water divides and general directions of ground-water flow were determined from the potentiometric surface map (fig. 16). The most prominent ground-water divide is positioned almost parallel to the axis of the Apalachicola Embayment-Gulf Trough feature. Ground water, on the western side of this divide, will discharge directly into the Flint River or discharge as upward diffuse leakage in the region of the Apalachicola River and Gulf of Mexico. Ground water east of this divide moves generally south toward either the large springs in and around Leon County or toward the Withlacoochee River near the Florida-Georgia border. The exact location of the dividing line between the ground-water basin drained by the large springs in and around Leon County and the basin drained by the Withlacoochee River is not readily apparent and was not drawn. Ground water in the Upper Floridan aquifer, moving beneath Leon County, could have entered the aquifer in counties to the west and north as shown in figures 16 and 17.

The position of the ground-water divides are not necessarily fixed and could move with changing recharge and discharge rates. The position of the divide along the Apalachicola Embayment-Gulf Trough probably fluctuates very little whereas the position of the divide that separates flow to the large springs in and around Leon County and flow to the springs in the Withlacoochee River could fluctuate significantly. For this reason, the study area boundaries were chosen to coincide with rivers, where possible, because their locations are fixed.

As indicated on the regional potentiometric maps for May 1985 (Bush and others, 1987) and May 1980 (Bush and Johnston, 1988), a saddle in the potentiometric surface occurs in Georgia along the eastern part of the study area. Only the westward half of this saddle is indicated on figure 16, the eastward half would occur outside the study area. A ground-water divide would occur at the low point of the saddle. However, the exact location of this divide is difficult to determine because the gradients are so low. Accordingly, ground-water flow out of the study area could occur, and because the transmissivity is high, this outflow could be significant.

The Upper Floridan aquifer within the study area is considered to be in a state of dynamic equilibrium. Dynamic equilibrium is indicated because there have been no known long term changes in the potentiometric surface of the Upper Floridan aquifer, although it has fluctuated seasonally and yearly in response to variations in rainfall (fig. 18). As shown in the figure, water levels rise in this Leon County well during extended periods of high rainfall and slowly decline during periods of low rainfall, but there appears to be no long-term trend of rising or declining water levels in the period from 1984 to 1992. Other studies agree with this finding. Hydrographs were examined from wells located in Leon and Wakulla Counties, Florida, and Seminole, Decatur, Miller, Mitchell, and Dougherty Counties, Georgia. These hydrographs also indicated only seasonal variation and no long-term water-level declines; consequently, the Leon County hydrograph is considered representative of Upper Floridan aquifer hydrographs in the study area and is the only one presented. Bush and Johnston (1988) found that the net decline between the estimated predevelopment potentiometric surface and the observed potentiometric surface in May 1980, was less than 10 ft (and could have been zero). The potentiometric surface shown on figure 16 was similar to the potentiometric surface measured in May 1985 (Bush and others, 1897) and in May 1980 (Bush and Johnston, 1988). The minor differences that occurred were attributed to different data point densities or minor seasonal fluctuations. Hendry and Sproul (1966) plotted the water-level altitudes of two Upper Floridan aquifer wells and one water-table aquifer well (located in Leon County) for the time period 1946 to 1965. The water levels showed seasonal and yearly fluctuations, but no long-term changes were apparent.

Ground-water flow in the Upper Floridan aquifer can be evaluated using steady-state methods, which are a special case of dynamic equilibrium. Assuming long-term steady-state conditions, the net recharge rate to the aquifer is the flux necessary to maintain the head in the aquifer at a constant level. This implies that the average recharge rate is equal to the average discharge rate over the long term, and that the volume of ground water stored in the aquifer does not change. No ground-water system will ever be at true steady-state. Freeze and Cherry (1979, p. 194) stated that if fluctuations in water-level altitudes are small in comparison with the total vertical thickness of the aquifer and the relative configuration of the potentiometric surface remains the same, then the system can be considered steady state. Hendry and Sproul (1966), after examining water-level records for 20 wells within Leon County, determined the maximum range in water-levels (the difference between the highest and lowest) was

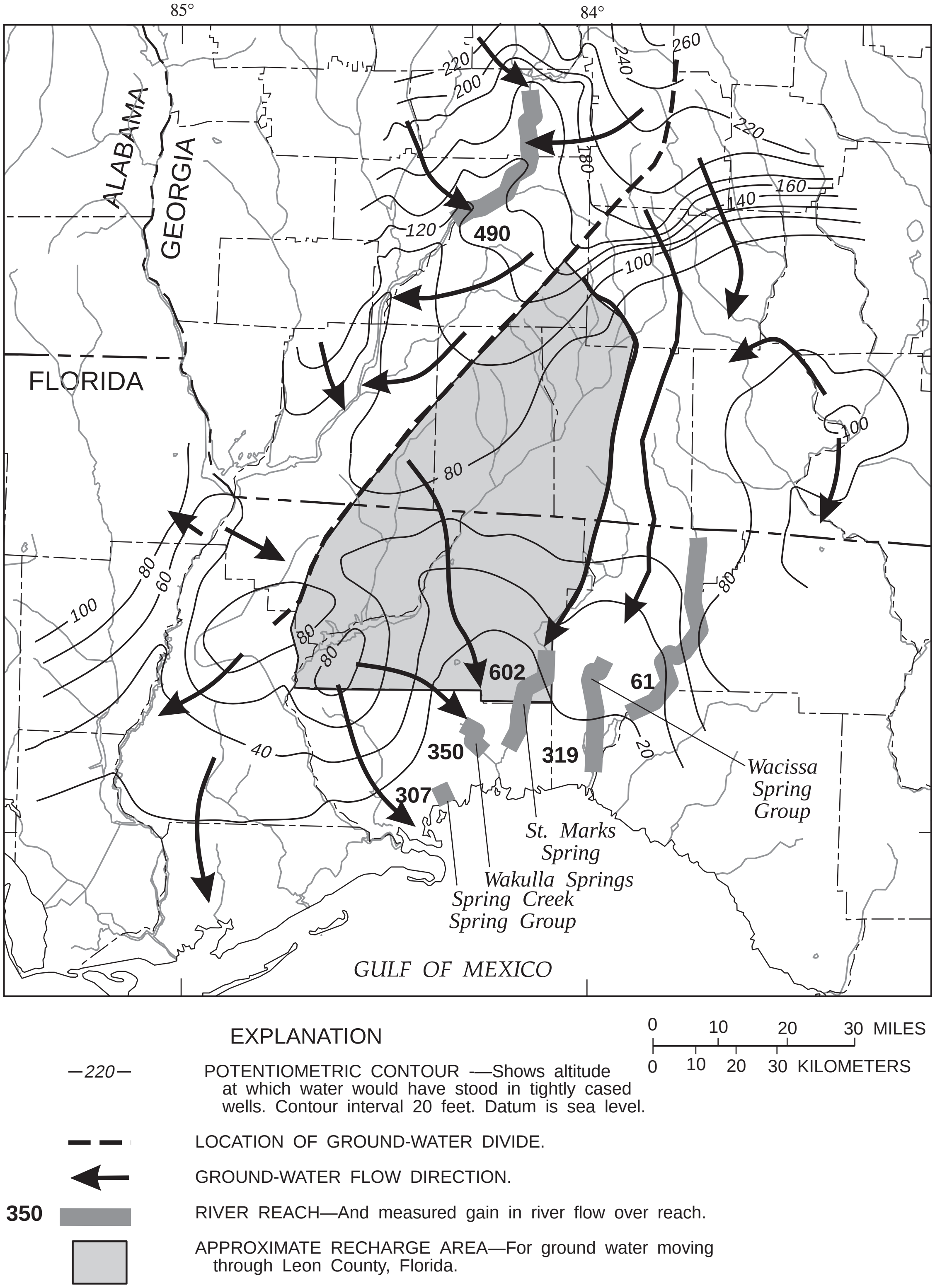


Figure 16. Ground-water flow directions, and net gain in river flow during October-November 1991.

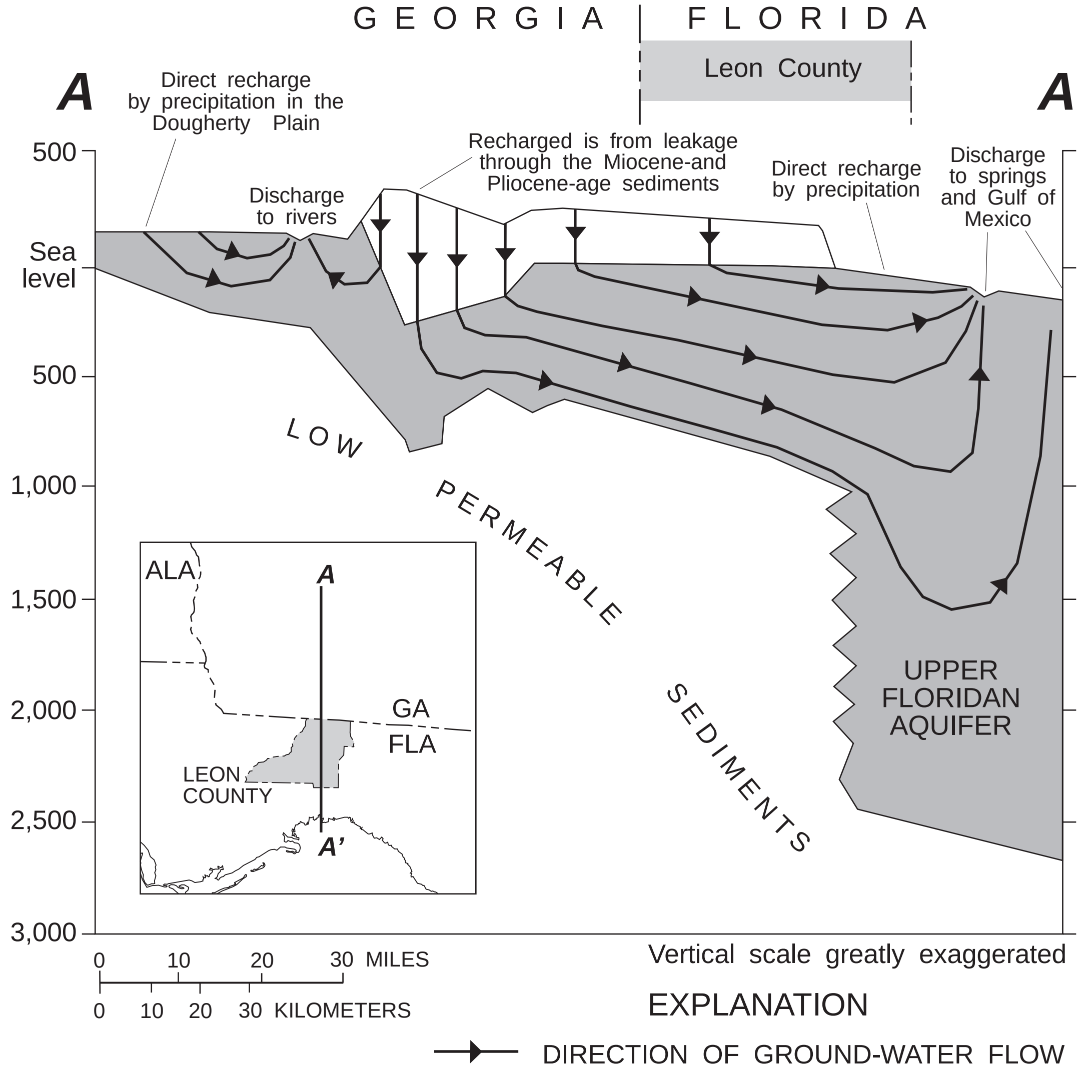


Figure 17. Conceptual model of the Upper Floridan aquifer system showing ground-water flow directions.

less than 14 ft between the years 1959 and 1965. A similar range was observed between 1984 and 1992 (fig. 18). Within Leon County, the Upper Floridan aquifer ranges in thickness between 500 ft in the north and 1,800 ft in the south. Using the argument of Freeze and Cherry (1979) and the fact that the maximum change in water levels in relation to aquifer thickness is about 3 percent, then long-term average conditions of ground-water flow within the Leon County area can be considered to be at steady state. Steady-state conditions were also indicated by the relatively constant stages of rivers that drained ground water from the Upper Floridan aquifer during the period September 1991, to January 1992 (fig.13).

The head in the Upper Floridan aquifer in Tallahassee, during field data collection, was very close to the average head for the period 1984 to 1992 (fig. 18). The average water-level altitude in well FSU 1 during October 21 to November 8, 1991, was 26.8 ft and the average water-level altitude from 1984 to 1992 was 26.2 ft, indicating that aquifer conditions were near a long-term average.

The Upper Floridan aquifer probably acts locally as well as regionally as single water-bearing unit within the study area. That is, there are no zones of sufficient areal extent and low permeability to divide the aquifer into distinct permeable units (Miller, 1986; and Bush and Johnston, 1988). Such assumptions are supported within the Tallahassee area by water-level data collected from two adjacent wells (discussed earlier) and shown in figure 15. The small upward gradient of between 0.2 and 0.5 ft could be caused by City of Tallahassee pumpage from the upper third of the aquifer.

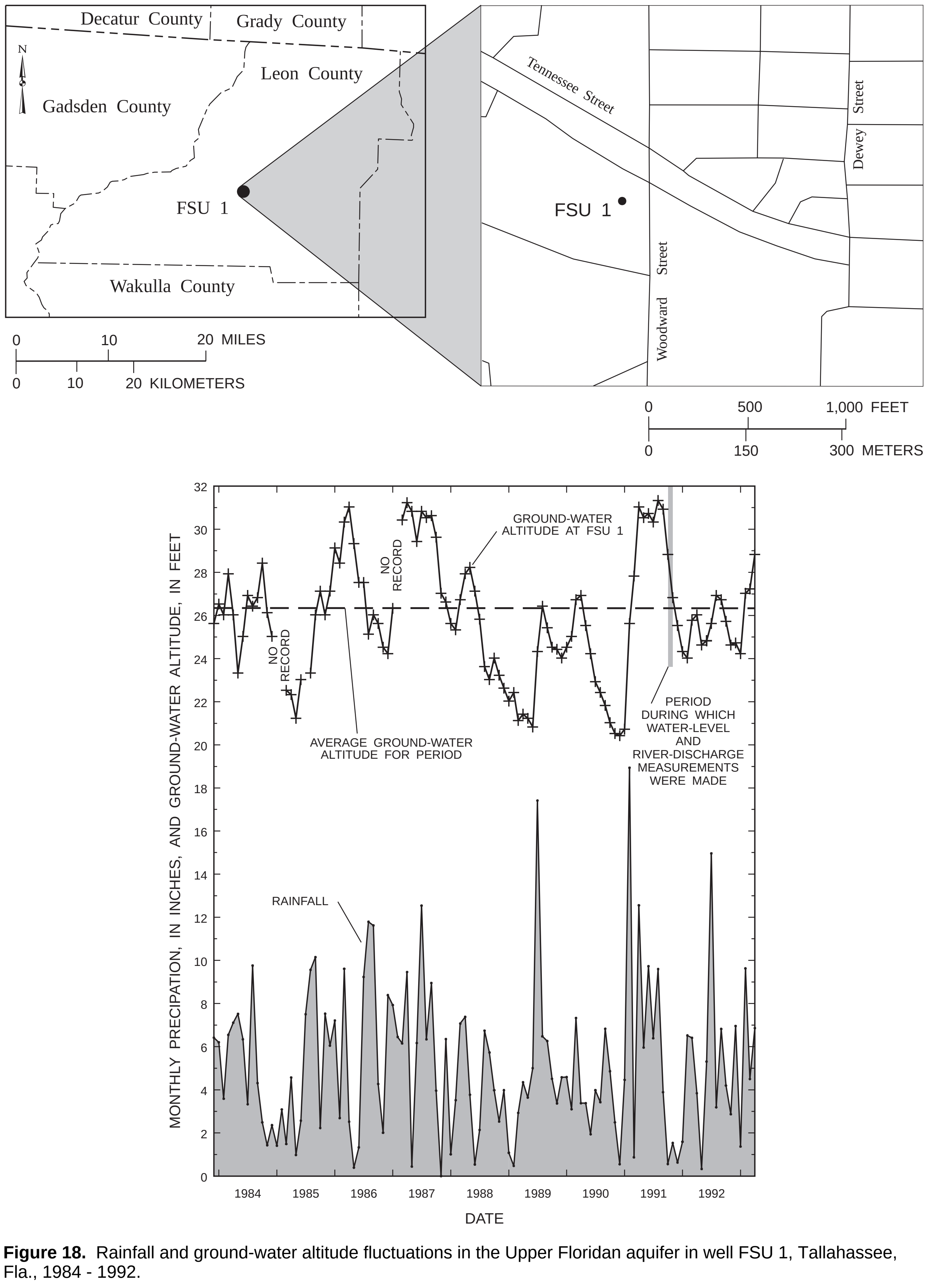


Figure 18. Rainfall and ground-water altitude fluctuations in the Upper Floridan aquifer in well FSU 1, Tallahassee, Fla., 1984 - 1992.

The ultimate source of recharge to the Upper Floridan aquifer is precipitation. Net recharge rates are relatively high in the karst areas (fig. 9) because the aquifer is exposed at land surface or covered only by a thin veneer of sediments. Precipitation falling in these areas can rapidly infiltrate through the overlying sediments or directly enter the aquifer through sinkholes and sumps. Outside the karst areas, the aquifer is overlain by low-permeability Miocene-and Pliocene-age sediments. Net recharge rates in these areas are less than in the karst areas because the low-permeability sediments cause a large proportion of precipitation to become runoff to streams. Model calibrated recharge rates determined by Bush and Johnston (1988) ranged from as high as 20 in/yr in the Ocala Uplift District to less than 1 in/yr in parts of the Apalachicola Embayment - Gulf Trough area.

The Upper Floridan aquifer is confined in some areas and unconfined in others (fig. 19). Unconfined conditions exist in the karst areas and in the area of the Barwick Arch. Near the center of the arch, the limestones comprising the Upper Floridan aquifer reach an elevation of about 150 ft and the potentiometric surface is about 60 ft (Sever, 1966). In this region, the limestones in the uppermost part of the Upper Floridan aquifer are unsaturated and unconfined conditions exist. A large part of Leon County lies within this area. Although the Upper Floridan aquifer is unconfined in the Barwick Arch area, the limestones comprising the aquifer are overlain by the low-permeability sediments which limits recharge to the aquifer. Outside the karst and Barwick Arch areas, the Upper Floridan aquifer is confined by the low-permeability Miocene-and Pliocene-age sediments.

In areas where the low-permeability sediments confine the Upper Floridan aquifer, the rate of recharge (leakage downward) is proportional to the difference in head between the water table and Upper Floridan aquifer. The rate of recharge is also proportional to the vertical hydraulic conductivity of the low-permeability sediments and inversely proportional to the thickness of these sediments. In the Barwick Arch area, the Upper Floridan aquifer is unconfined but overlain by the low-permeability sediments, here the rate of leakage is not dependent on the head in the Upper Floridan aquifer. In these areas, fluctuations in the head of the Upper Floridan aquifer do not change the rate of leakage through the overlying sediments.

Discharge of water from the Upper Floridan aquifer occurs as spring flow, seepage into rivers and the Gulf of Mexico, and withdrawals from wells. Rivers (or reaches of rivers) within the karst areas are directly hydraulically connected with the Upper Floridan aquifer, but rivers (or reaches of rivers) not in the karst areas are generally separated from the aquifer by the low-permeability Miocene- and Pliocene-age sediments. Rivers in the karst areas receive large volumes of water from the Upper Floridan aquifer, mostly as spring flow. A net gain in flow of 490 ft^3/s was measured for one reach of the Flint River in southern Lee and Dougherty County, Georgia (fig.16). In the karst areas of the Ocala Uplift, water is drained from the aquifer by several large springs and spring groups. The major springs in the southern part of the study area are Spring Creek Spring group, Wakulla Spring, St. Marks Spring, and the Wacissa Spring group. These four are among the eight largest springs in Florida (Rosenau and others, 1977). Discharges measured on November 1, 1991, in the rivers directly downstream of these springs were: Spring Creek (307 ft^3/s), Wakulla River (350 ft^3/s), St. Marks River (602 ft^3/s), and Wacissa River (319 ft^3/s). When the measurements were made, the rivers derived most, if not all, of their flow from spring discharges. Some discharge also occurs in smaller springs along the coast and directly to the Gulf of Mexico; however, the rate of discharge from these springs is unknown.

SIMULATION OF GROUND-WATER FLOW IN THE UPPER FLORIDAN AQUIFER

Ground-water flow in the Upper Floridan aquifer was simulated using the USGS modeling software MODFLOW (McDonald and Harbaugh, 1988). The modeling software requires that the aquifer system be divided into a horizontal grid of rows and columns and vertically into layers, creating a three- dimensional matrix of cells. Aquifer properties are assigned to cells (such as top of aquifer, base of the aquifer, hydraulic conductivity of the aquifer, and so forth) so that the cell matrix is tailored to represent known conditions present in the Upper Floridan aquifer. MODFLOW then uses finite-difference equations to simulate three-dimensional ground-water flow. The software iteratively solves the system of equations for hydraulic head at each active model cell and calculates the rate of ground-water flow between cells.

To ensure that the model simulation accurately reflects conditions present in the Upper Floridan aquifer, the model must be calibrated. Calibration is the

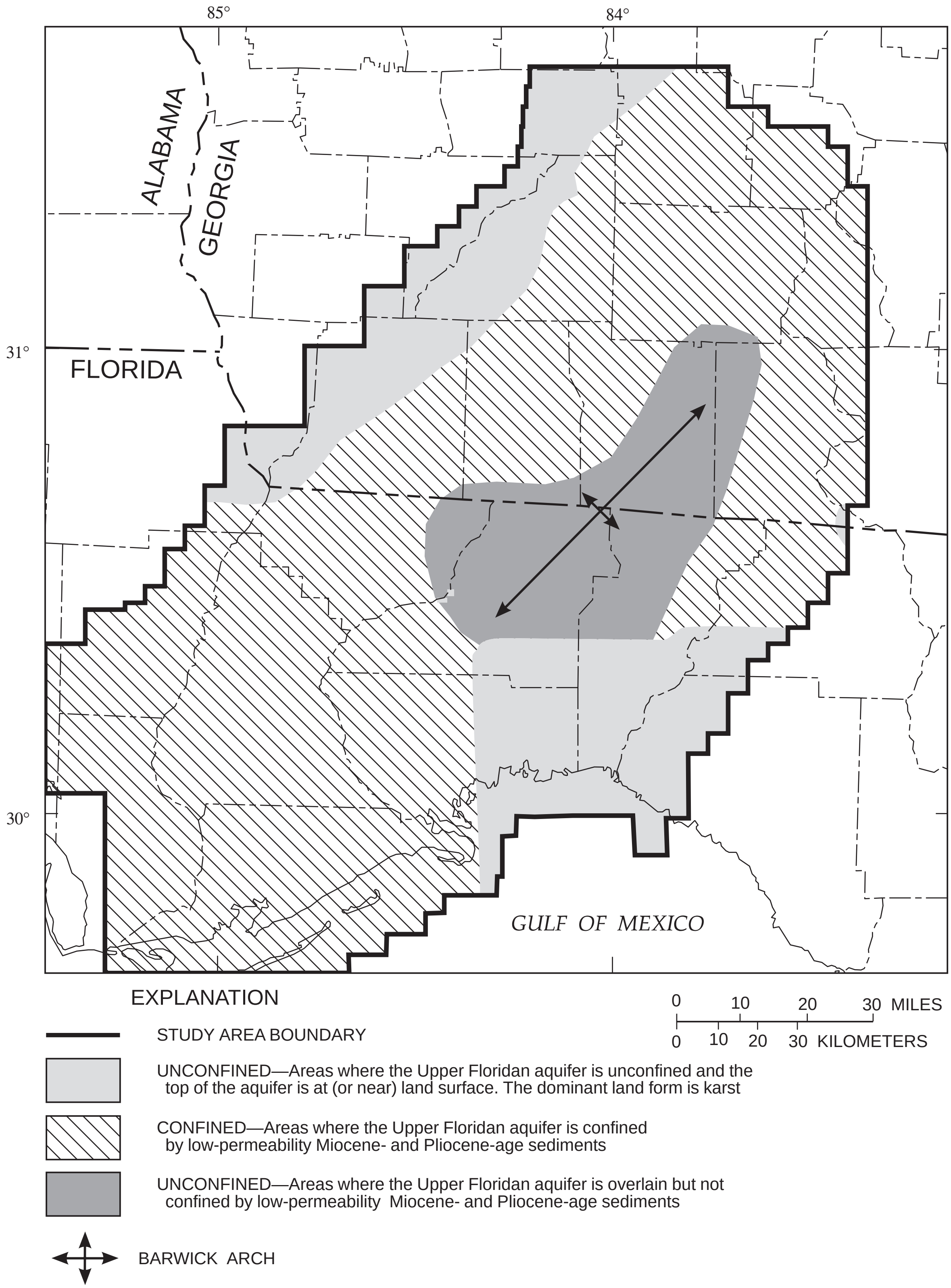


Figure 19. Areas where the Upper Floridan aquifer is confined and unconfined.

process of varying aquifer properties assigned to cells until the computer-simulated aquifer conditions match measured-aquifer conditions. The model was calibrated to hydrologic conditions measured during the data collection part of this investigation, which was late October to early November 1991. Ground-water flow was simulated as steady state, which assumes that the volume of ground-water recharge equals the volume of ground-water discharge. Once calibrated, the model was coupled with particle-tracking techniques to delineate the contributing areas to five City of Tallahassee municipal supply wells.

The model simulates the aquifer as an heterogeneous porous medium and assumes that ground-water flow is uniformly distributed within each active model cell. As discussed earlier, this assumption is valid over most of the study area. However, conduit flow occurs near large springs and near some sinkholes where cave systems are present. In these areas, the aquifer does not behave like a porous medium and the model may predict average ground-water flow velocities that are slower than those that actually occur within the conduits.

Grid Design

The first step in simulating ground-water flow was to divide the entire study area into a grid of cells. The grid consisted of 176 rows and 162 columns (fig. 20), resulting in 28,512 model cells per layer (fig.21). The aquifer system was simulated using 3 layers. Orientation of the grid was north-south. Cell size is variable with the smallest cells occurring near the center of the study area and larger cells occurring near the perimeter. Row and column spacing was chosen so that the water-supply wells, in which contributing areas were to be determined, would be positioned in the smallest model cells. The smallest cells are 30 by 30 ft and the largest cells are 3 by 3 mi. Not all cells in the matrix were used during the simulation of ground-water flow. Some cells were inactive, which allowed the study area to conform to irregular boundaries.

Model Layer 1

Layer 1 in the model represents the water-table aquifer. Layer 1 model cells are utilized only where the low-permeability Miocene- and Pliocene-age sediments confine the Upper Floridan aquifer (figs. 21 and 22). In these areas, layer 1 cells are treated as a specified-head boundary. For this type boundary condition, each cell in the layer can either provide water to or drain water from the cell in the next layer below, while maintaining a head at a specified altitude. If the head in a layer 1 cell is higher than the head in a layer 2 cell, water will flow from layer 1 to layer 2, and vice-versa. During ground-water flow simulation, the head of layer 1 cells was specified to represent the average head for the water-table aquifer located within that cell. The head within the water-table aquifer, in most places, reflects the land-surface topography and generally is a few feet below land surface (but can be tens of feet in some places). For most layer 1 cells, the head was specified to be a few feet below average land-surface altitude. However, in some highland areas the head was specified to be as much as 50 ft below land surface. The low-permeability Miocene- and Pliocene-age sediments were generally several hundred feet thick where the water-table aquifer was simulated, so small errors in the estimated head had a negligible effect on simulated leakage rates.

The movement of water to and from the water-table aquifer is restricted by low-permeability sediments. This resistance to flow between cells in layer 1 and layer 2 is a model input parameter designated Vcont 1. Vcont 1 is calculated for layer 1 cells using the following formula:

$$\text{Vcont 1} = 1/(b_1/VK_1) \qquad (1)$$

where: b_1 is the thickness of the low-permeability Miocene- and Pliocene-age sediments (ft), and

VK_1 is the vertical hydraulic conductivity of the low-permeability Miocene- and Pliocene-age sediments (ft/d),

The thickness of the low-permeability Miocene- and Pliocene-age sediments is shown on figure 5 and the vertical hydraulic conductivities are discussed with the description of model calibration. An initial value of 0.00005 ft/day was assumed for the vertical hydraulic conductivity. However, this value was changed during model calibration.

Model Layers 2 and 3

The Upper Floridan aquifer is represented in the simulation by model layers 2 and 3 (fig. 21 and 22). Layer 2 represents the upper 230 ft of the aquifer, which, on average, is the zone penetrated by City of Tallahassee water-supply wells. Layer 3 represents the difference between the total thickness of the Upper

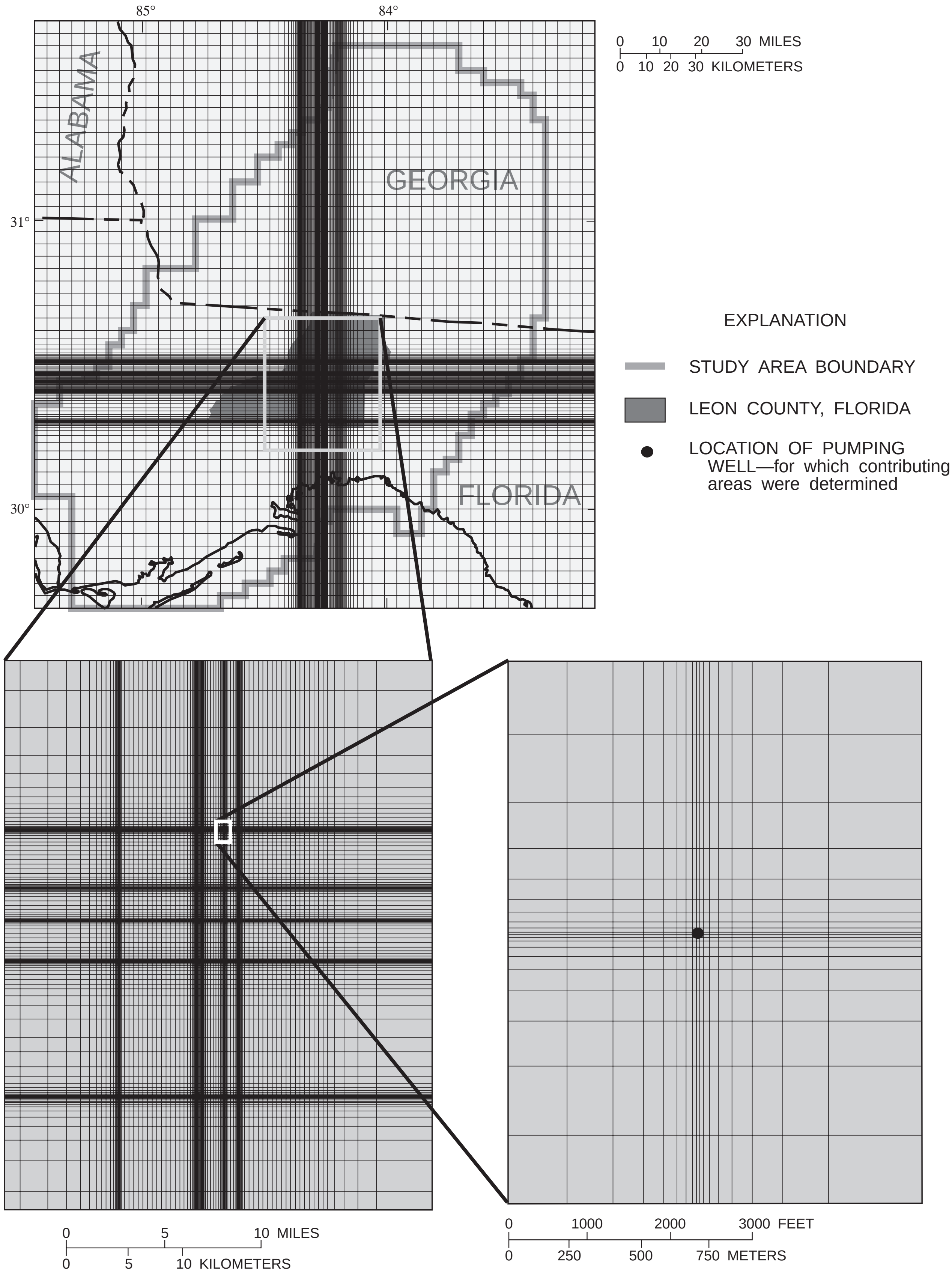


Figure 20. Location and orientation of finite-difference model grid.

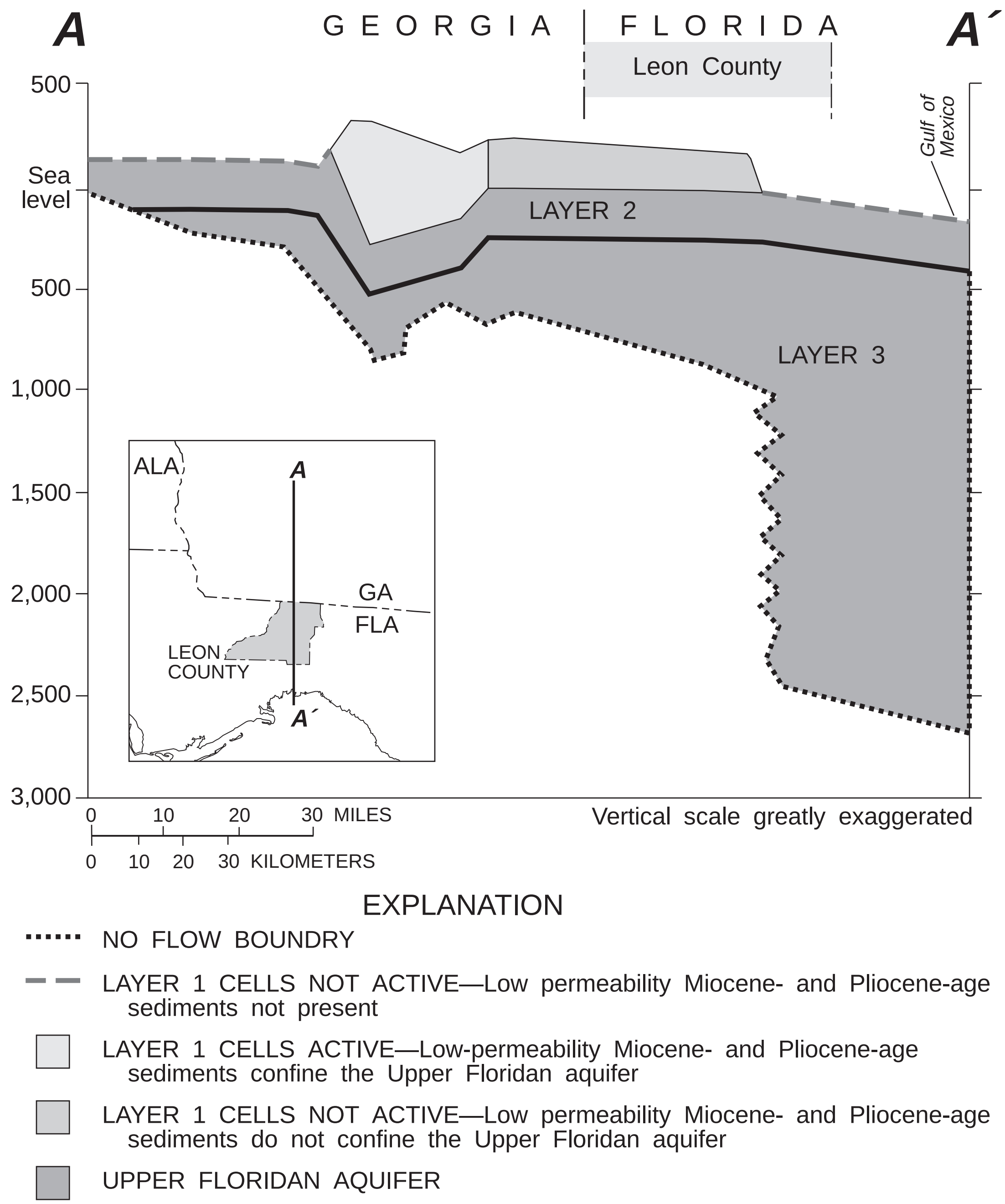


Figure 21. Generalized hydrogeologic section showing model layers.

Floridan and the thickness of layer 2. The Upper Floridan aquifer acts as a single water-bearing unit within the study area. The sole purpose for dividing the aquifer into two layers is to simulate withdrawals from water-supply wells at approximately their actual depths. This is important for accurate delineation of contributing areas (discussed in a later section). Layer 2 is the most areally extensive layer and defines the maximum lateral extent of the model. In the northwestern part of the study area, the Upper Floridan aquifer thins to less than 230 ft and the aquifer is represented completely by layer 2. The Upper Floridan aquifer is bounded below by low-permeability sediments so the base of the model is a no-flow boundary.

The resistance to vertical ground-water movement between layers 2 and 3 is a model input parameter designated Vcont 2, and was calculated by the equation:

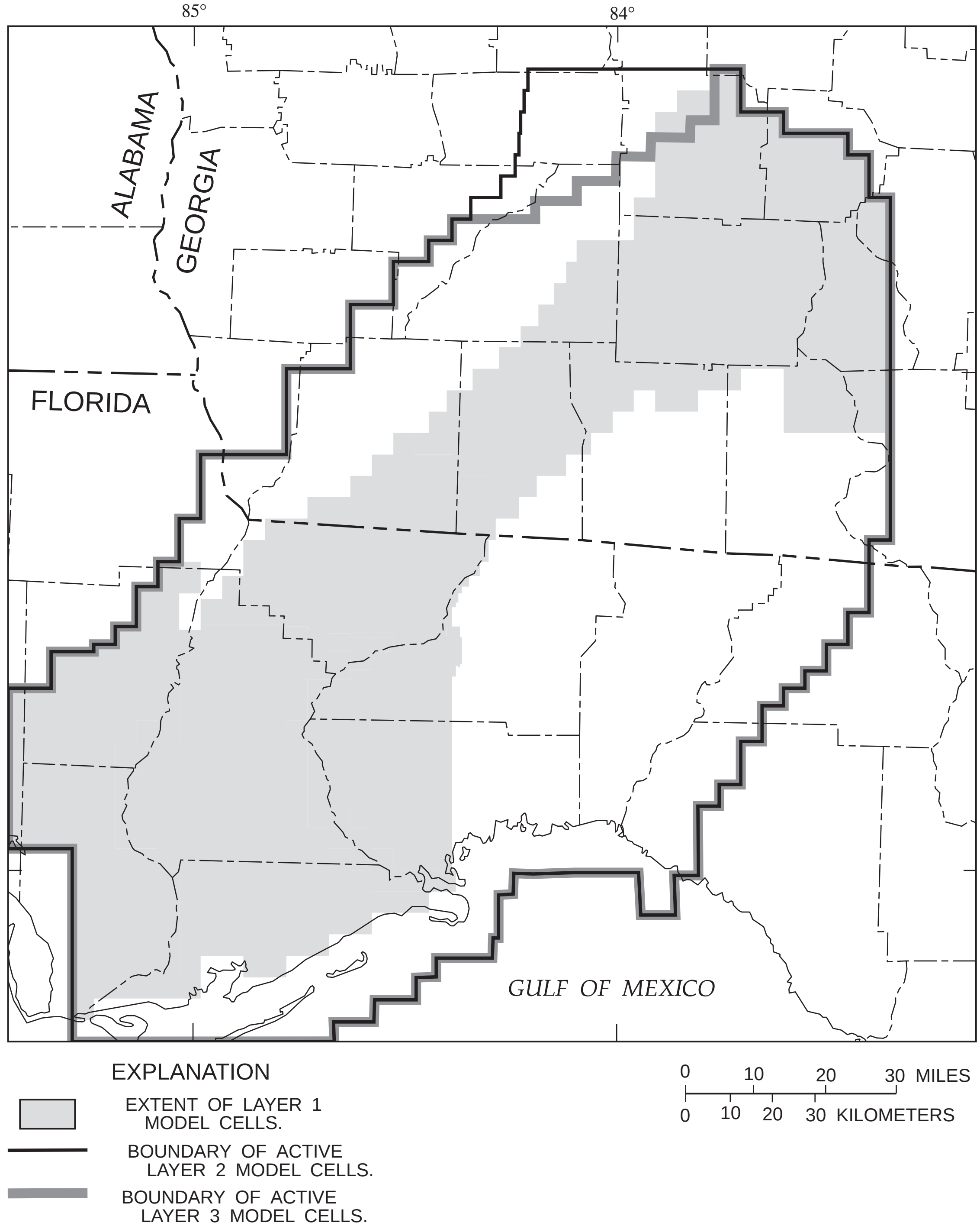


Figure 22. Location of model areas for layers 1, 2, and 3.

$$Vcont\ 2 = 1/[(230\ ft/2/VK_{UF}) + ([(b_{UF} - 230\ ft)/2]/VK_{UF})] \qquad (2)$$

where:

VK_{UF} is the vertical hydraulic conductivity of the Upper Floridan aquifer (ft/d), and

b_{UF} is the thickness of the Upper Floridan aquifer (ft).

In calculating Vcont 2, the vertical hydraulic conductivity was set equal to the horizontal hydraulic conductivity of the Upper Floridan aquifer. Under this assumption, ground water can move both horizontally and vertically with equal resistance.

Model Input Parameters and Boundary Conditions

Model input parameters are specified and spatially distributed at active cells before simulation of ground-water flow begins. MODFLOW uses the input parameters to tailor the finite-difference equations to the particular aquifer being investigated. The model input parameters used for this investigation are altitude of the water-table which defines the top of layer 1, altitude at the base of layer 1, Vcont 1, altitude at the top of layer 2, altitude at the base of layer 2, hydraulic conductivity of layer 2, transmissivity of layer 3, and net recharge rates.

Initial estimates of transmissivity for the Upper Floridan aquifer were computed by contouring the transmissivity values (fig. 9) and assigning a transmissivity to each model cell from the contoured data. Values of horizontal hydraulic conductivity for layer 2 were calculated by dividing transmissivity by the total thickness of the aquifer. The transmissivity for each cell of layer 3 was computed by multiplying the thickness of layer 3 at each cell by the corresponding hydraulic conductivity.

An initial estimate of direct recharge to the Upper Floridan aquifer of 7 in/yr was calculated by dividing the net river gains by the approximate area of the aquifer drained by the rivers. This constant recharge rate was applied directly to layer 2 in areas where the Upper Floridan aquifer was unconfined (fig. 23) and was varied separately during model calibration.

Model boundaries were selected and located to approximate natural hydrologic boundaries of the Upper Floridan aquifer. Where feasible, the model boundaries were located at or slightly beyond the major rivers that drain water from the aquifer because these are permanent hydrologic boundaries. The result of the hydraulic connection between the aquifer and river is that stresses imposed on the aquifer (such as pumping) are unlikely to propagate beyond the rivers, both in the natural system and in the simulated system.

The western model boundary is located just west of the Apalachicola and Flint Rivers (fig.24). The eastern boundary is located approximately parallel to ground-water flow paths in the northeastern third of the study area, along the Withlacoochee River and its tributaries in the middle third of the study area, and just east of the Aucilla River at a natural ground-water divide in the lower third of the study area. The southern boundary is located just offshore to simulate diffuse upward leakage to the Gulf of Mexico.

The boundary conditions along the perimeter of the modeled area were either specified head or no flow. Specified-head cells were placed in areas where the potentiometric surface of the Upper Floridan aquifer indicated that ground water could potentiality enter or leave the modeled area due to lateral flow (fig. 24). Specified-head cells were placed west of the Flint River. Specified-head cells were placed in the Gulf of Mexico to simulate diffuse upward leakage of ground water at and near the coastline. The head in these cells was specified at sea level and the placement of the boundary was determined by projecting the onshore gradient offshore to zero. Specified-head cells were placed in two locations on the eastern model boundary. The southern specified heads were used to simulate the flow of ground water out of the model toward large springs located along the Withlacoochee River just outside the modeled area. The northern specified heads were similarly used where the potentiometric surface map indicated possible movement of groundwater out of the modeled area (fig. 16).

The modeled location of rivers that drain ground water from the Upper Floridan are shown in figure 24. A model cell containing a river reach is referred to as a river cell and was assigned a river stage, a river bottom elevation, and riverbed conductance. The volume of water flowing into or out of a river cell is dependent on the difference in altitude between the river stage and simulated head in the aquifer, and on the riverbed conductance. The higher the riverbed conductance, the larger the volume of water that will move between the river and the aquifer per unit head difference. The model input parameter, riverbed conductance, was calculated by the equation:

$$\text{riverbed conductance} = K*L*W / M$$

(McDonald and Harbaugh, 1988)

where:

- K is the vertical hydraulic conductivity of riverbed material (ft per day),
- L is the length of the river reach (ft),
- W is the width of river (ft), and
- M is the thickness of the riverbed material (ft).

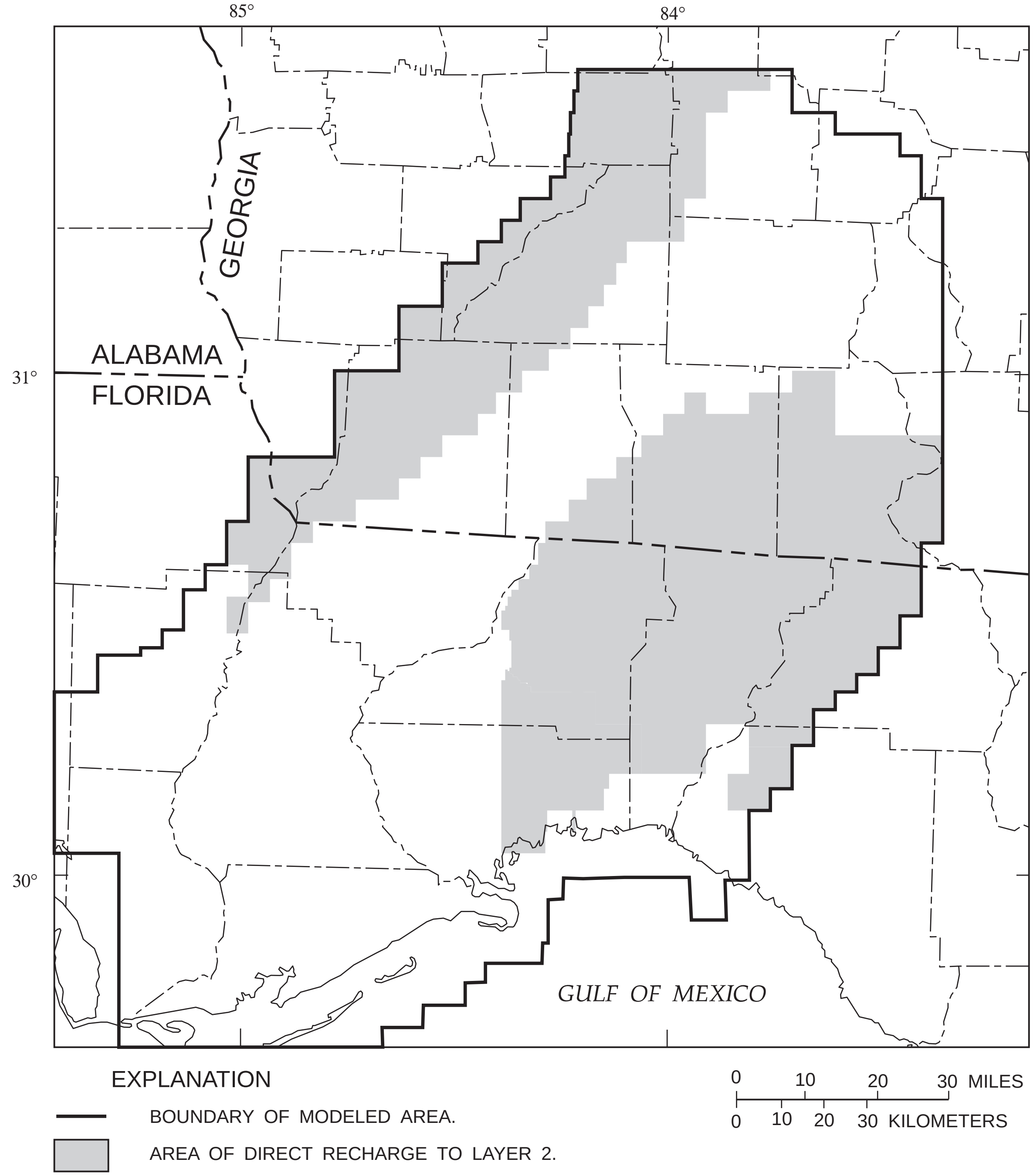


Figure 23. Areas of direct recharge to model layer 2.

Rivers in both the Ocala Uplift and Dougherty Plains are fed by springs. These springs, typically, are the terminal ends of conduit systems that extend for short distances (typically less than 2 miles) into the Upper Floridan aquifer. The riverbed conductances were calculated using a hydraulic conductivity equal to the conductivity of the aquifer material where the river cell resided. Rivers outside the karst areas are separated from the Upper Floridan aquifer by the low-permeability Miocene- and Pliocene-age sediments, do not interact directly with the aquifer, and were not simulated using river cells.

Municipal and industrial pumpage included in the simulation is listed in table 1. Generally,

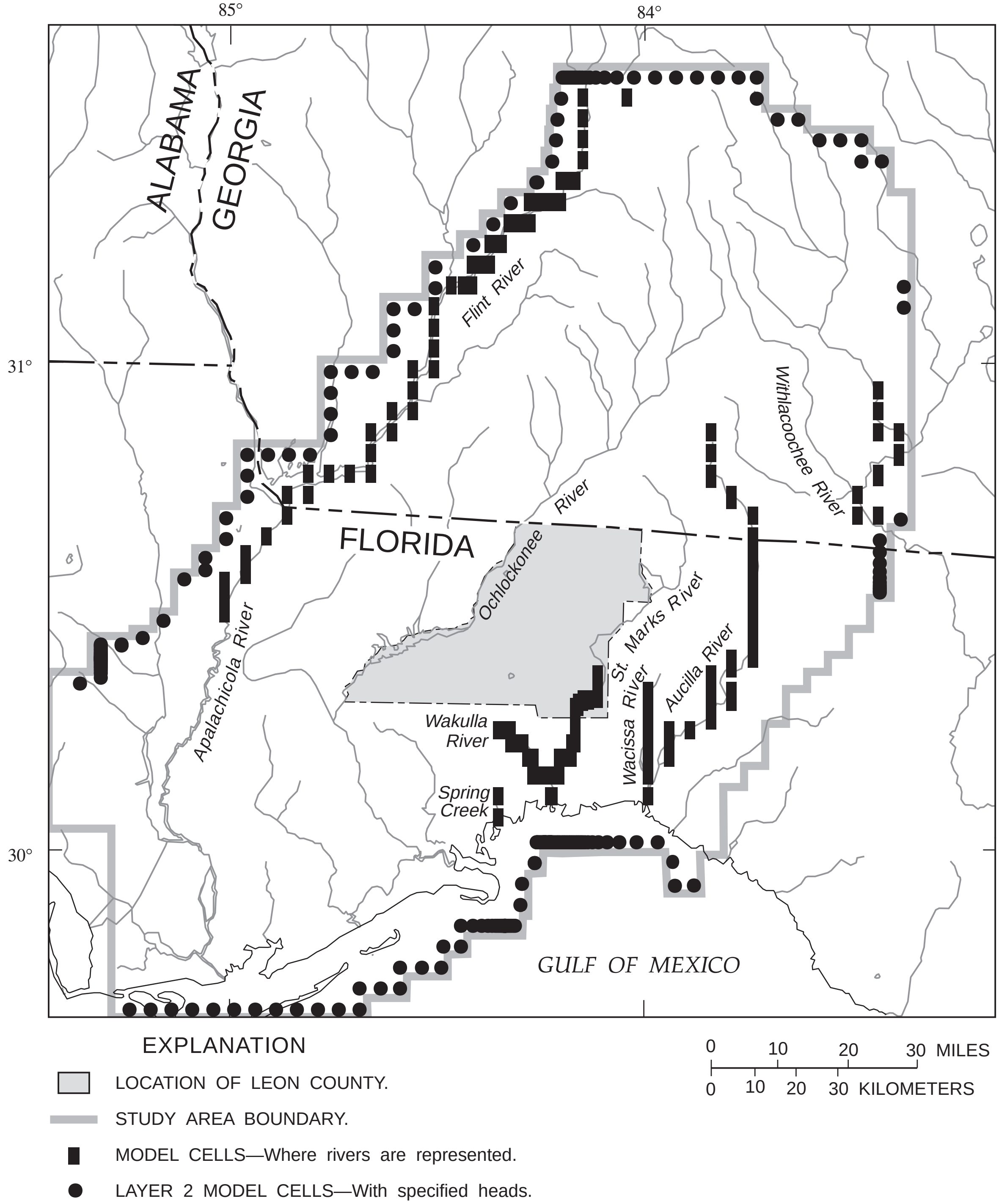


Figure 24. Location of model boundaries, specified-head cells, and cells representing rivers.

only wells at which average pumping is greater than 70 gal/min were included in the simulation; however, wells pumping lower rates were included if the information were readily available. The total pumpage used to calibrate the model was 53,000 gal/min (118 ft^3/s).

Model Calibration

The model calibration process consisted of 1) selecting input parameters, 2) simulating ground-water flow using MODFLOW, 3) comparing simulated heads with measured heads, 4) comparing simulated river discharges with measured river discharges, and then 5) selecting new values for the input parameters aimed at minimizing the difference between simulated values and measured values. The calibration criteria established for simulated heads was arbitrarily chosen at plus or minus 10 feet of the measured values. The calibration criteria for simulated river gains was established as plus or minus 8 percent of the measured values, which is the accuracy of these measurements. The model was calibrated to the streamflow and water-level conditions observed during late October to early November 1991. Of the 274 water-levels measured to define the potentiometric surface of the Upper Floridan aquifer, 199 were within the boundary of the modeled area.

The input parameters varied during calibration were: transmissivity of the Upper Floridan aquifer, Vcont 1, and direct recharge to layer 2. The parameter Vcont 2 was changed as an artifact of changing the transmissivity of the Upper Floridan aquifer, but it was not independently changed during calibration. River-bed conductance was recalculated between simulations using the same hydraulic conductivity as the Upper Floridan aquifer. The other input parameters were not varied because they were sufficiently constrained by measured values.

Calibration Results

After calibration, 197 simulated heads were within 10 ft of the 199 measured values and 132 of these were within 5 ft. Simulated and measured heads are compared in figure 25. Simulated and measured river discharge gains are listed in table 3 and shown on figure 26. All simulated river gains were within 6 percent of the measured values and well within the established calibration criteria of 8 percent. The simulated potentiometric surface of the Upper Floridan aquifer is shown in figure 27. Simulated conditions are considered equivalent to long-term average conditions.

The calibration-derived transmissivity distribution of the Upper Floridan aquifer (fig. 28) is the sum of the transmissivities for layers 2 and 3. The sum represents the transmissivity for the entire thickness of the Upper Floridan aquifer. The model-derived transmissivity distribution ranged from less than 5,000 ft^2/d in the region of the Apalachicola Embayment—Gulf Trough to greater than 10,000,000 ft^2/d in the area surrounding the large springs in extreme southern Leon County and west and south of Leon County. The low transmissivity applied to the Apalachicola Embayment—Gulf Trough was necessary to match the rapid potentiometric gradient change in the central and northern parts of the study area and to match the mounding of ground water in western Leon County and Gadsden County. Very high transmissivity values were necessary to match the very low potentiometric gradients in the areas around the large springs. The complex transmissivity distribution applied in and around Leon County was necessary to match the measured potentiometric surface changes which ranged from greater than 80 ft in western Leon County to less than 10 ft in the south.

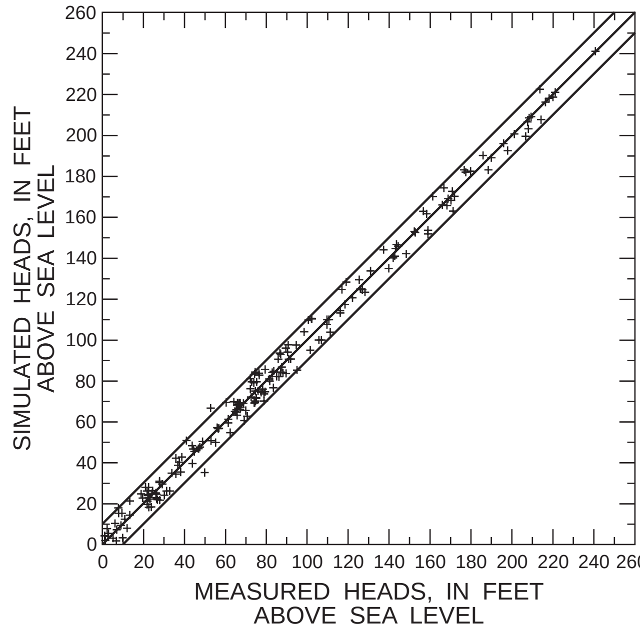


Figure 25. Simulated heads and measured heads.

Table 3. Comparison of measured net river gains, November 1991, and simulated net river gains

[ft^3/s, in cubic feet per second]

River	Measured gain in river reach, in ft^3/s	Model-derived gain in river reach, in ft^3/s	Difference, in percent
Aucilla	61	58	5
Wacissa	319	338	-6
St. Marks	602	601	0
Flint	490	499	-2
Wakulla	350	355	-1
Spring Creek	307	290	6

The calibration-derived vertical hydraulic conductivity distribution of the low-permeability Miocene- and Pliocene-age sediments is shown in figure 29. The vertical hydraulic conductivities were 2.0 $x10^{-3}$ ft/d and 2.0 $x10^{-2}$ ft/d in the southern part of the study area, 2.0 $x10^{-6}$ ft/d in the central part, and

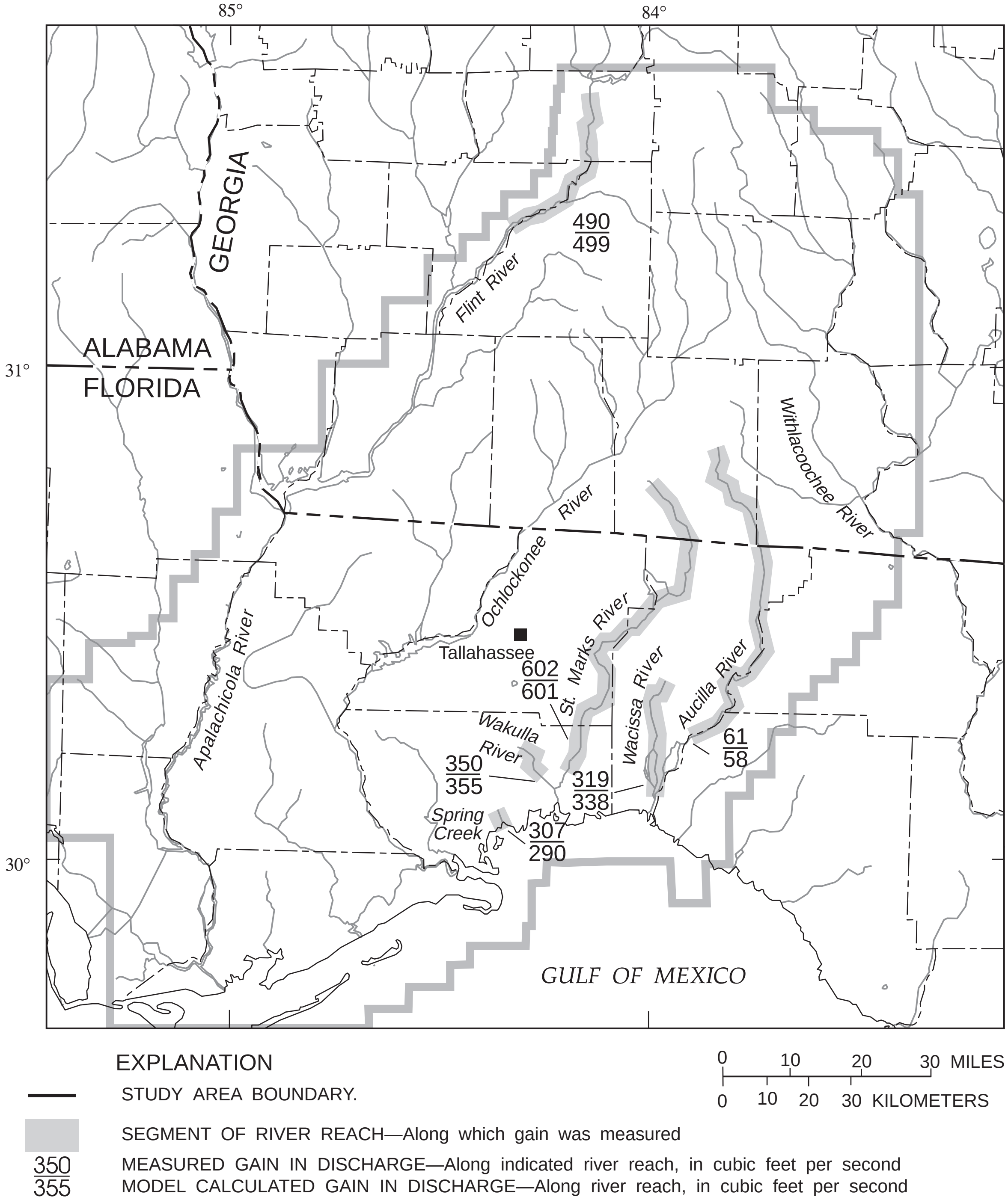


Figure 26. Measured net river gains, November 1991, and simulated net river gains.

7.8 x10^{-4} ft/d in the northern part. The variability in the vertical hydraulic conductivity distribution is probably due to changes in the complex lithology of the sediments. In the two narrow zones in the southern part of the study area (darker areas in fig. 29) the vertical hydraulic conductivity is 2.0 x10^{-2} ft/d. Rivers are present here, but are separated from the Upper Floridan aquifer by the low-permeability sediments. The relatively high vertical hydraulic conductivity allowed greater upward leakage in the vicinity of these rivers. The upward leakage rates were relatively small, a few cubic feet per second over distances of several miles.

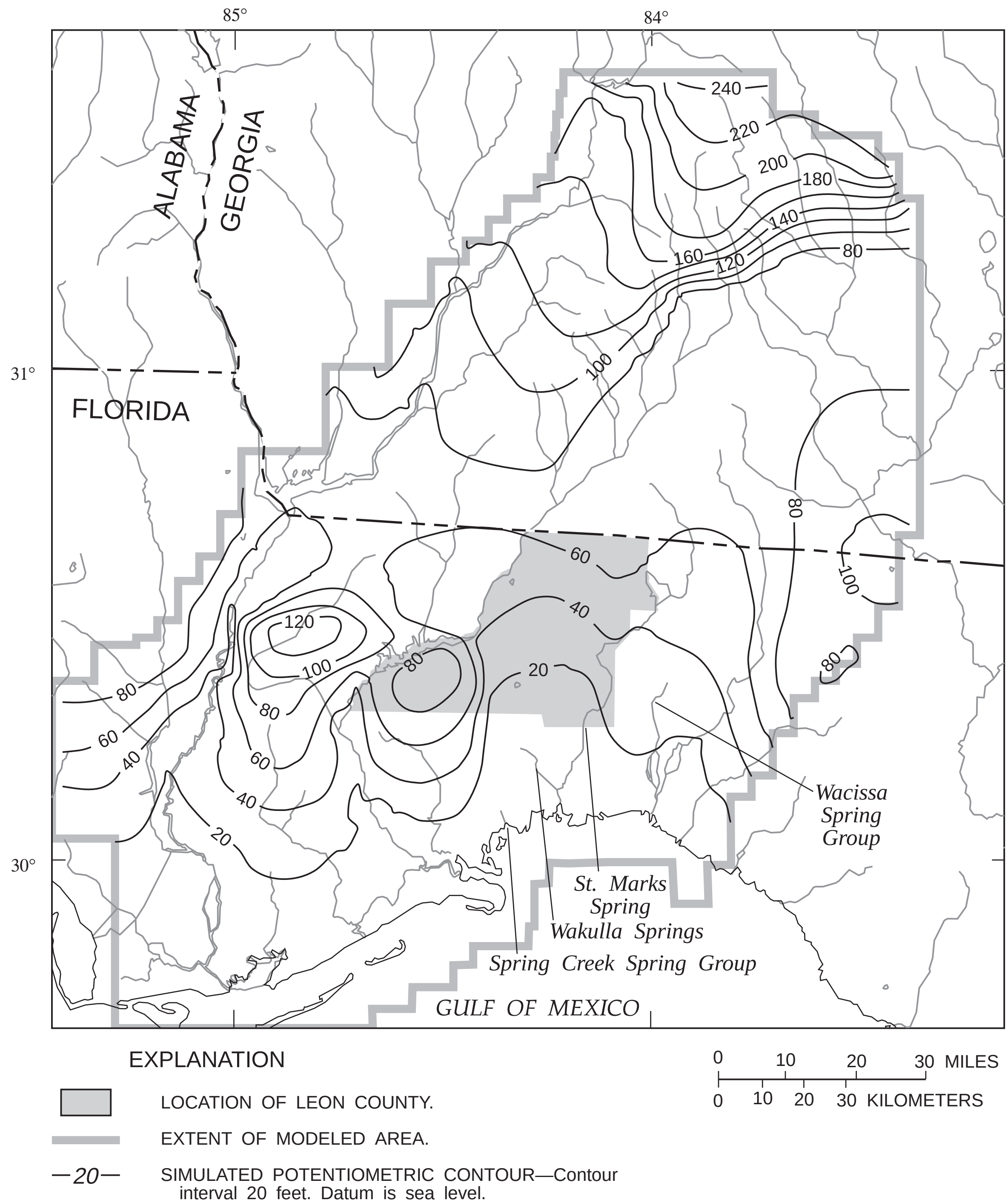
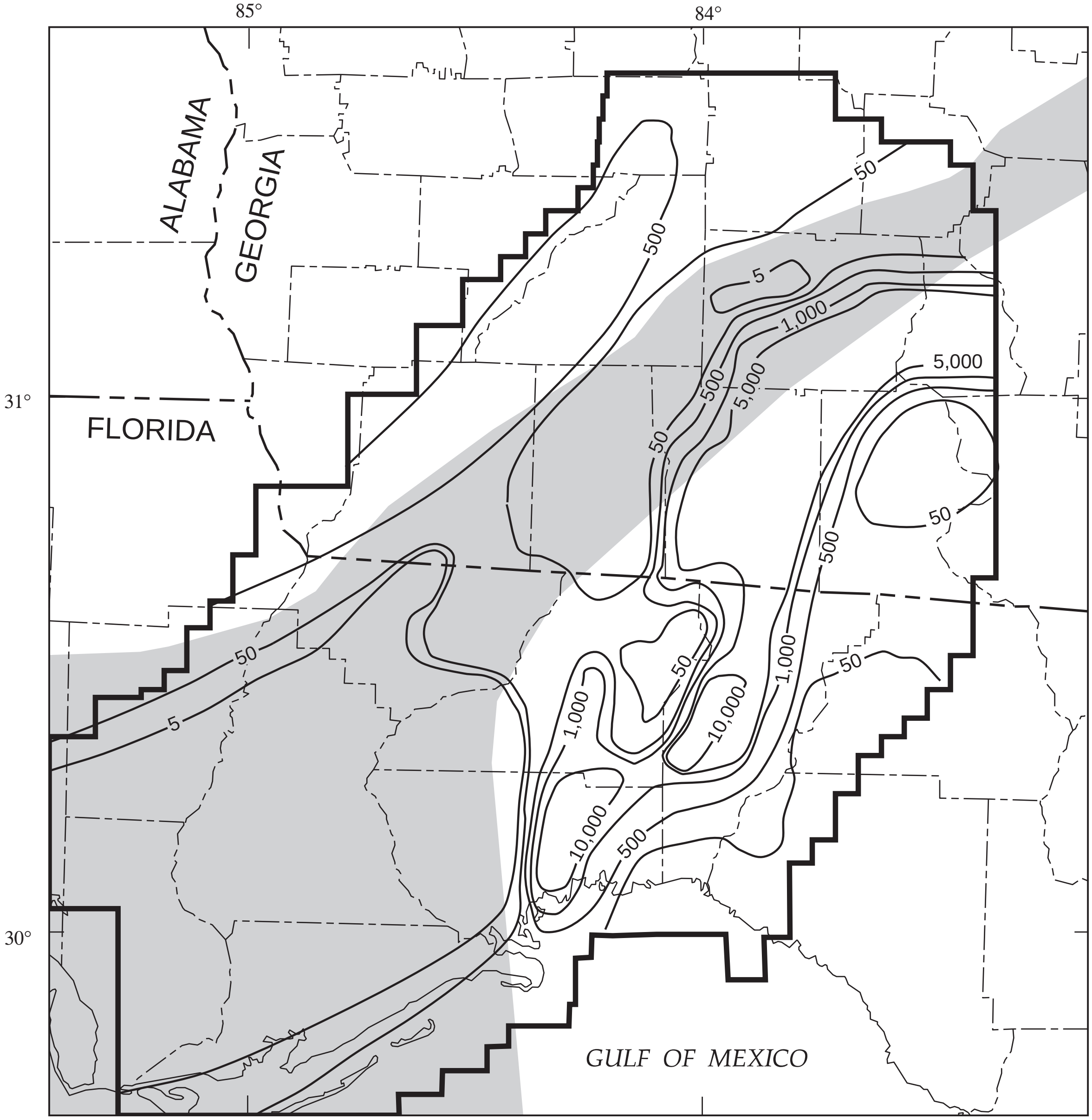


Figure 27. Simulated potentiometric surface of the Upper Floridan aquifer.

However, this leakage was needed to simulate the measured heads in the area. The calibration-derived vertical hydraulic conductivities fall within the range of expected values. The hydraulic conductivity of marine clay ranges from 3 x10^{-7} ft/d to 3 x10^{-4} ft/d and silt ranges from 3 x10^{-4} ft/d to 3 ft/d (Freeze and Cherry, 1979).

The distribution of calibration-derived net recharge and leakage rates are shown in figure 30. The leakage rates between layers 1 and 2 were computed by MODFLOW and were dependent on Vcont 1 and the head difference between the layers. The relatively low rates of leakage were due to the low vertical hydraulic conductivities associated with the thick accumulations of



EXPLANATION

APALACHICOLA EMBAYMENT-GULF TROUGH—Shows approximate location.

STUDY AREA BOUNDARY

—500— LINE OF EQUAL TRANSMISSIVITY—Values in thousands of feet squared per day. Contour interval is variable.

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Figure 28. Calibration-derived transmissivities of the Upper Floridan aquifer.

low-permeability sediments in the Apalachicola Embayment - Gulf Trough area. The rates of direct net recharge were higher and occurred in karst areas and where the low-permeability Miocene- and Pliocene- age sediments were relatively thin. The highest rate was 62.0 in/yr and occurred at the Tallahassee wastewater sprayfields. The next highest net recharge rate of 18.0 in/yr occurred in the karst area in and south of Leon County. In this area, the Upper Floridan aquifer is covered by only a thin veneer of sand or directly exposed at land surface. The net recharge rate was 7.5 in/yr in the Dougherty Plain and 7.9 in/yr in most of the Ocala Uplift.

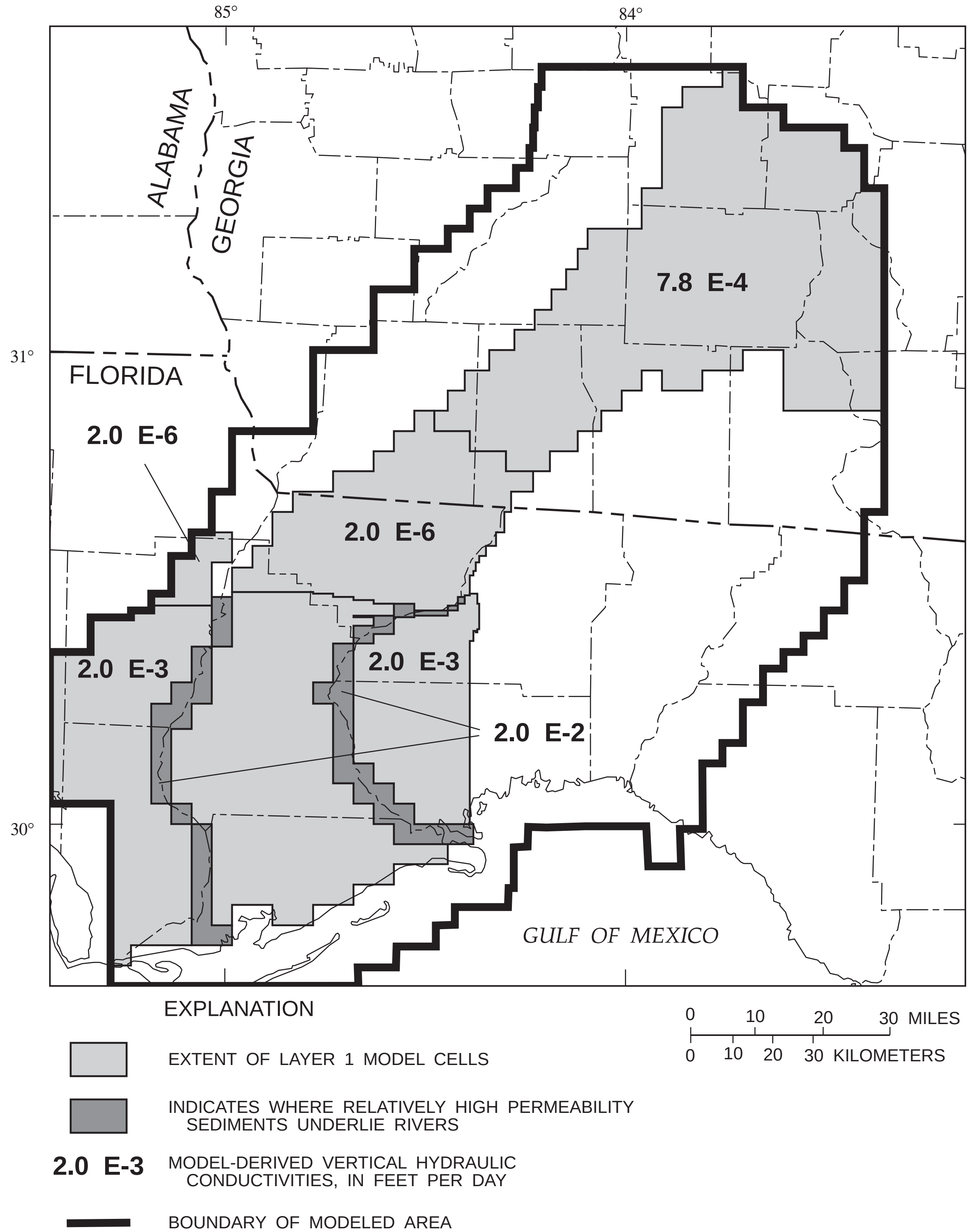


Figure 29. Calibration-derived vertical hydraulic conductivities for layer 1.

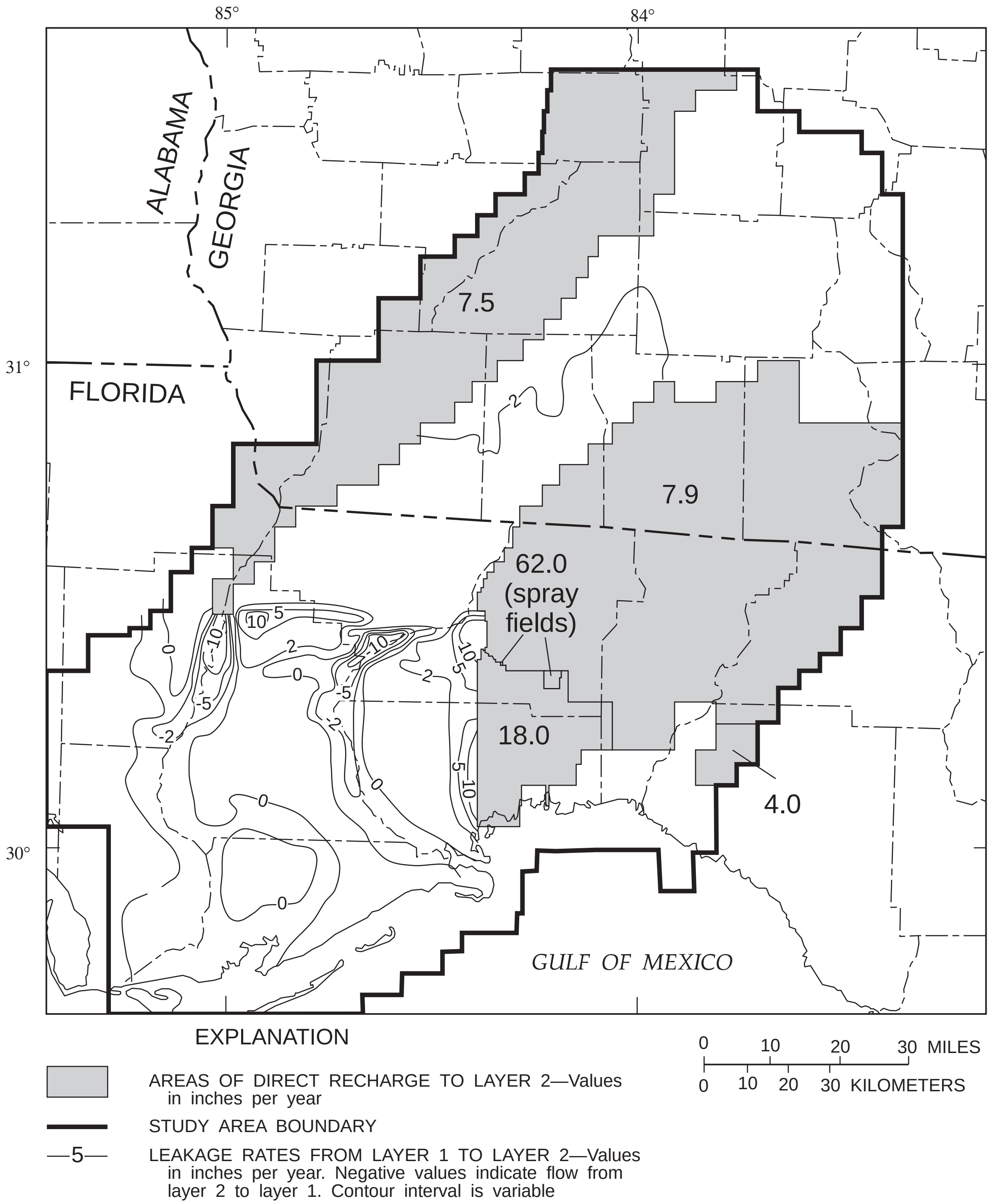


Figure 30. Calibrated leakage and recharge rates to the Upper Floridan aquifer.

Simulation-Derived Water Budget

The ground-water flow simulation was steady state, so the rate of inflow to the Upper Floridan aquifer in the study area (4,334 ft^3/s) was equal to the outflow. The sources of inflow were: direct net recharge to layer 2 (2,413 ft^3/s), subsurface inflow from specified-head cells in layer 2 (1,392 ft^3/s), and vertical leakage from specified-head cells in layer 1 (529 ft^3/s). The outflows were: subsurface discharge to river cells (3,555 ft^3/s), subsurface outflow to specified-head cells in layer 2 (582 ft^3/s), pumpage (118 ft^3/s), and upward leakage to layer 1 (79 ft^3/s). Ground-water inflows and outflows were summed for subregions of the modeled area (fig. 31). Direct net recharge to layer 2 was the largest source of water to the Upper Floridan

BOUNDARY CONDITION TYPE (Values in cubic feet per second)	INFLOW	OUTFLOW
Direct recharge to layer 2	2,413	0
Leakage from specified-head cells in layer 1	529	79
Flow from specified-head cells in layer 2	1,392	582
River cells	0	3,555
Pumpage	0	118
Total	4,334	4,334

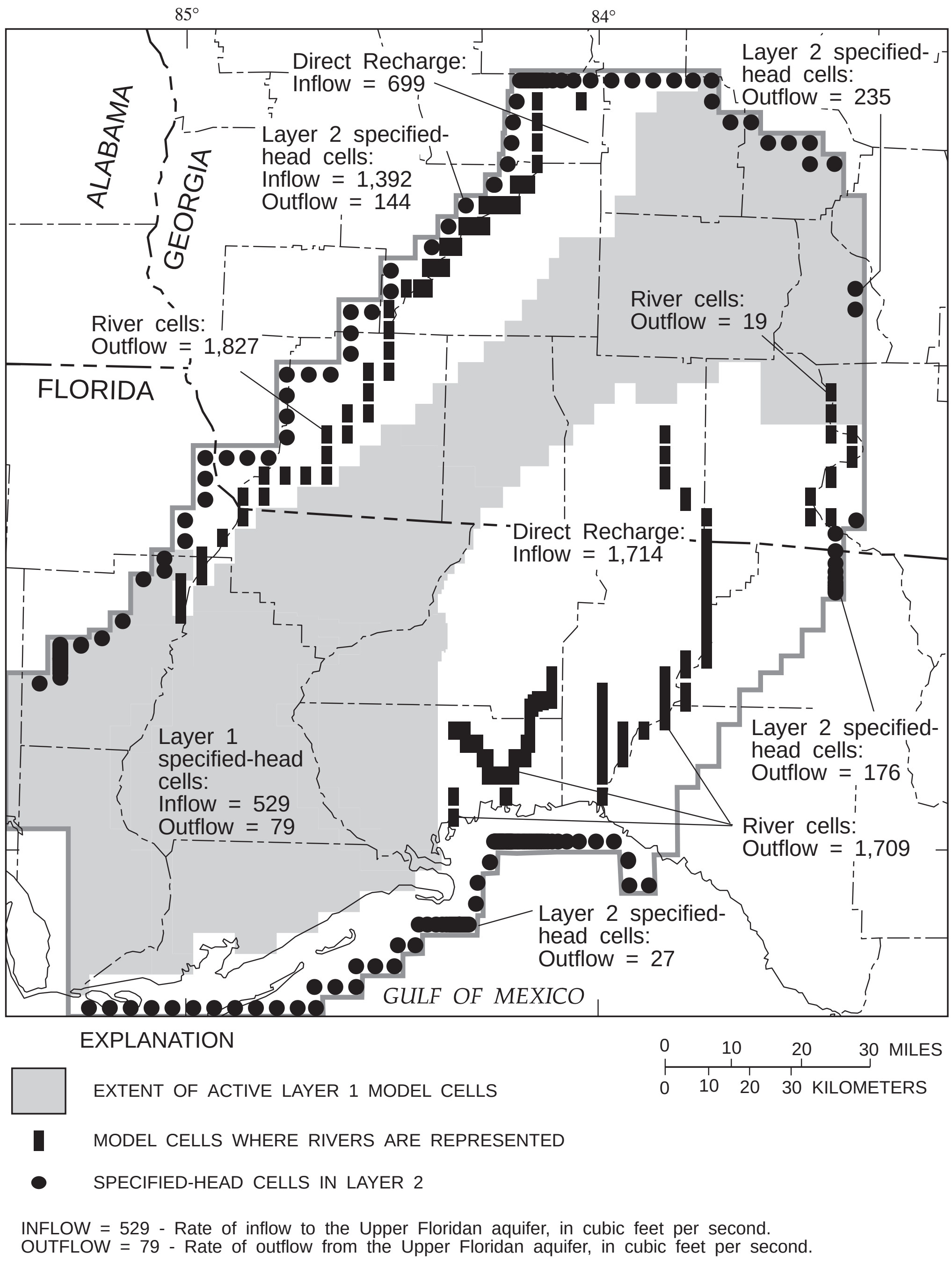


Figure 31. Simulated inflow and outflows in subregions of the study area.

aquifer with 1,714 ft^3/s occurring in the eastern part of the study area and 699 ft^3/s occurring in the Dougherty Plain. The specified-head cells in layer 2, located along the west and north perimeter of the modeled area, provided 1,392 ft^3/s to the aquifer. Almost all of this water later discharged to the Flint River. River cells accounted for most of the ground water discharged, with 1,827 ft^3/s being drained by rivers in the Dougherty Plain and 1,728 ft^3/s by rivers in the southeastern part of the modeled area. The northern set of specified-head cells on the eastern study area boundary drained 235 ft^3/s. The southern set of specified-head cells on the eastern boundary (in the vicinity of the Withlacoochee River) drained 176 ft^3/s. The rate of discharge to the Gulf of Mexico (27 ft^3/s) was relatively low because the large springs in the south-central part of the modeled area effectively drained ground water from the aquifer before it reached the coastline. Upward leakage from the Upper Floridan aquifer to layer 1 (79 ft^3/s) occurred in the southern areas of the Apalachicola Delta District.

Sensitivity Analysis

Sensitivity tests were conducted to assess the response of the calibrated model to a change in one input parameter while the calibrated values of other parameters were unchanged. The input parameters tested were the overall transmissivity of the Upper Floridan aquifer, direct net recharge to layer 2, Vcont 1, Vcont 2, and riverbed conductance. The sensitivity tests were conducted by: 1) changing an input parameter by plus or minus 50 percent from the calibrated value, 2) calculating the number of simulated heads exceeding the error criteria, and 3) comparing the simulated rate of ground-water discharge to rivers with the measured values. The greater the number of heads that exceeded the error criteria (by not being within 10 ft of the measured values) and the larger the difference between simulated-river discharges and measured discharges, the greater the sensitivity of the model to changes in that particular parameter. The results of the sensitivity analysis are listed in table 4.

The model was most sensitive to changes in transmissivity. A decrease in transmissivity of 50 percent caused the number of simulated heads exceeding the error criteria to increase from 2 to 85; simulated ground-water discharge to rivers also fluctuated substantially from the measured values. An increase in transmissivity of 50 percent caused the number of simulated heads exceeding the error criteria to increase to 25.

Table 4. Results of model sensitivity analysis

[trans, transmissivity; Vcont 1, layer 1 vertical conductance; river, river bed conductance; Vcont 2, layer 2 vertical conductance; %, percent]

Parameter changed	Number of cells where the difference between simulated head and measured head exceeded 10 feet	Difference between measured river gain and simulated ground-water discharge, in percent					
		Acuilla River	Wacissa River	St. Marks River	Flint River	Wakulla River	Spring Creek
Calibrated	2	-4	6	0	2	1	5
Trans - 50 %	85	44	29	-24	-25	-21	-41
Trans + 50 %	25	-26	-18	19	21	26	29
Vcont 1 - 50 %	14	-7	-2	2	-3	-2	-7
Vcont 1 + 50 %	18	-3	13	1	6	4	-4
Recharge - 50 %	28	-59	-66	-27	-20	-33	-16
Recharge + 50 %	35	68	79	25	23	36	5
River - 50 %	3	-13	8	-5	1	10	-6
River + 50 %	3	-2	5	2	2	-2	6
Vcont 2 - 50 %	3	-5	7	-2	2	4	-7
Vcont 2 + 50 %	2	-5	6	1	2	1	-5

The model also was sensitive to changes in direct recharge to layer 2. A decrease in recharge of 50 percent caused the number of simulated heads exceeding the error criteria to increase from 2 to 28. The corresponding simulated ground-water discharge to rivers decreased substantially compared to the measured values. An increase in recharge of 50 percent caused the number of simulated heads exceeding the error criteria to increase to 35 and the simulated ground-water discharges to rivers increased substantially compared to the measured values. Simulations were sensitive to recharge rate because it is the largest source of water to the Upper Floridan aquifer.

Another source of water to the Upper Floridan aquifer was leakage from layer 1. A decrease in Vcont 1 of 50 percent caused the number of simulated heads exceeding the error criteria to increase from 2 to 14; an increase of 50 percent caused the number of simulated heads exceeding the error criteria to increase to 18. Simulated ground-water discharge to rivers did not fluctuate significantly from the measured values because leakage from layer 1 was not a substantial part of the overall water budget.

The model was not sensitive to changes in the riverbed conductance. Both an increase and decrease of 50 percent caused the number of simulated heads exceeding the error criteria to increase from 2 to 3. Simulated ground-water discharge to rivers was only slightly different than the measured values. The riverbed conductances were relatively high because they were calculated using the same hydraulic conductivity as the Upper Floridan aquifer (for reasons discussed earlier). With these high conductances, the simulated volume of ground water leaking into the rivers was controlled by the potentiometric gradients in the surrounding aquifer and not the riverbed conductance. Overall changing the riverbed conductance by plus or minus 50 percent did not greatly affect the simulation results.

The model also was not sensitive to changes in Vcont 2. A decrease of 50 percent caused the number of simulated heads exceeding the error criteria to increase from 2 to 3; an increase in Vcont 2 of 50 percent caused no change in the number of simulated heads exceeding the error criteria. Simulated ground-water discharges to rivers were not substantially different than the measured values. Vcont 2 values were calculated using a vertical hydraulic conductivity equal to the horizontal hydraulic conductivity (for reasons discussed earlier) resulting in relatively high values. The high Vcont 2 values allowed water to move easily from layer 2 to layer 3, and changing this value by plus or minus 50 percent did not sufficiently restrict the movement of water to affect the ground-water flow simulation.

PARTICLE-TRACKING ANALYSIS OF CONTRIBUTING AREAS

The calibrated model was used in combination with the post-processing-program MODPATH (Pollock, 1989) to delineate the contributing areas of five City of Tallahassee water-supply wells. The five wells were chosen because their locations span the range of transmissivities present in the Tallahassee area (fig. 32). Table 5 lists the characteristics of the wells, including the depth, open-hole interval, pumping rate, and relation of well depth and open-hole interval to the thickness of the Upper Floridan aquifer. All of the wells listed partially penetrate the aquifer, and the percent of penetration ranges from 19 percent for well 12 to 28 percent for well 23. The contributing areas were delineated assuming steady-state flow conditions. In reality, the City of Tallahassee operates its wells as needed to meet demand. Only one well was modeled at a time, thus the effects of well interference were not simulated.

Procedure for Delineation of Contributing Areas

The post-processing program MODPATH uses the intercell flow rates (the flow rate at the face of each cell in the model) calculated by MODFLOW to compute ground-water flow directions and velocities. The contributing area to a water-supply well was delineated by “seeding” the simulated pumping well location with particles and then tracking the particles backward toward areas of recharge. Particle tracking was arbitrarily stopped at a time-of-travel of 5 years, thus the time-related contributing area is a fraction of the overall contributing area. The contributing area includes only the time-of-travel within the Upper Floridan aquifer. The time-of-travel of a water particle from land surface, through the water-table aquifer and the low-permeability Miocene- and Pliocene-age sediments, was not included. MODPATH requires the same input parameters as MODFLOW and, additionally requires that porosity be specified for each active

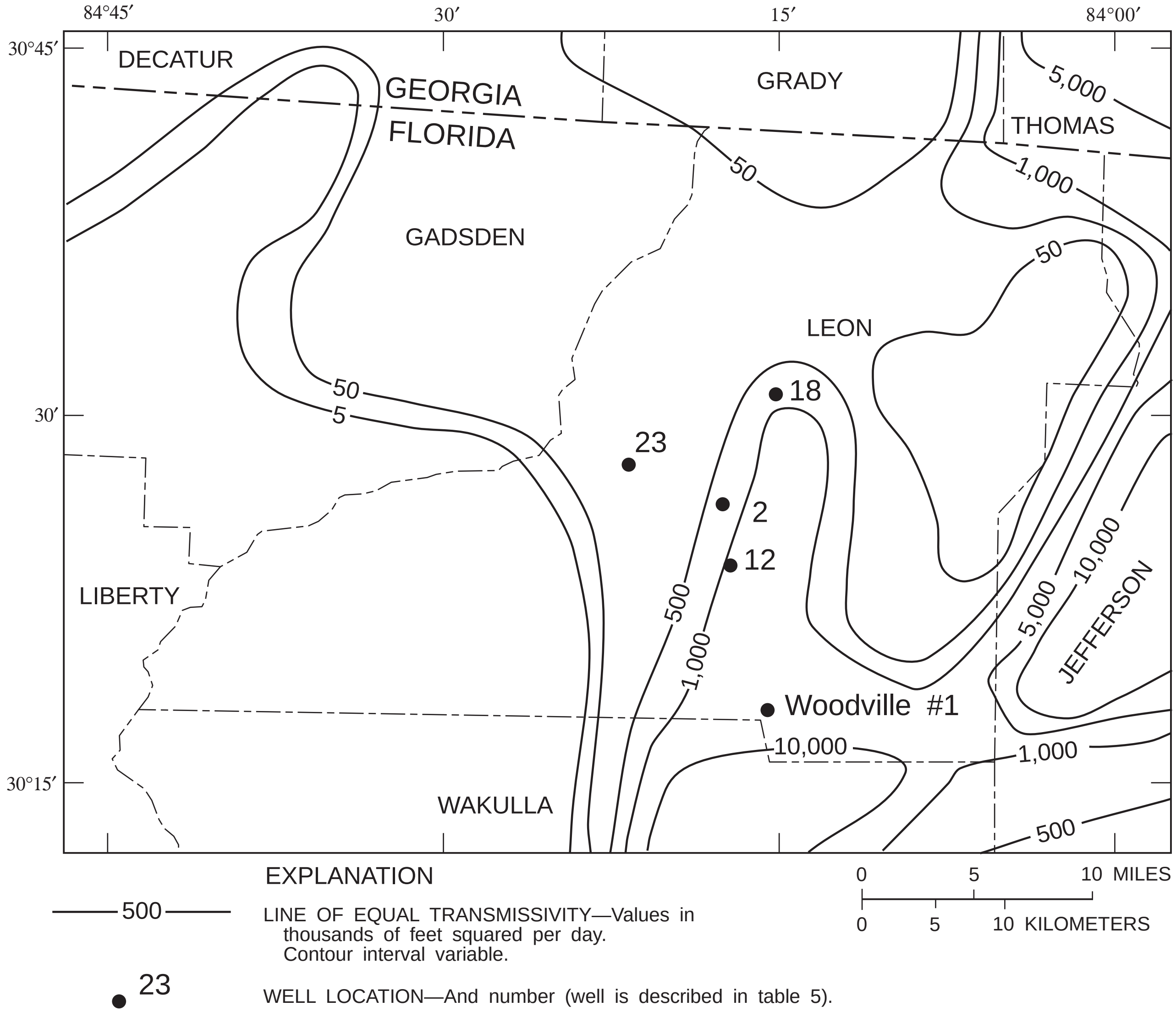


Figure 32. City of Tallahassee, Fla., water-supply wells for which contributing areas were delineated.

cell. The porosity is necessary for the calculation of ground-water velocity.

Porosity within the Upper Floridan aquifer is variable and the distribution is not accurately known. For this reason, the contributing areas were delineated twice, using porosities of 25 and 5 percent. The 25 percent porosity represents an approximate average value for the total porosity in a limestone. The porosity of 5 percent represents only the void space present in interconnected zones created by the dissolution of limestone along bedding planes and fractures. These interconnected zones would have a much higher permeability than the other, much larger, fraction of the aquifer that had not undergone dissolution. A pumping well would draw most of its water from the high-permeability zones where the resistance to ground-water flow is less than the remainder of the aquifer, which would be largely bypassed. The 5 percent porosity is not intended to represent the total porosity present in the Upper Floridan aquifer, but instead represents an estimate of the effective porosity where dissolution has occurred.

The contributing area for a 5 percent porosity is always much larger than the contributing area for a 25 percent porosity. For a lower porosity, the well has to draw water from greater distances to meet the pumping rate because there is less water per unit volume of aquifer. The contributing areas in Leon County are generally elliptical in shape, which reflects the influence of the slope of the potentiometric surface.

Table 5. Characteristics of City of Tallahassee, Florida, water-supply wells for which contributing areas were delineated

Well	Altitude of top of casing, in feet	Depth of well, in feet	Open hole interval, feet below sea level	Pumping rate, in gpm	Altitude of top of Upper Floridan aquifer, in feet above sea level	Altitude of base of Upper Floridan aquifer, in feet below sea level	Depth of penetration of well into the saturated thickness of the Upper Floridan aquifer, in feet[1]	Penetration of well into the saturated thickness of the Upper Floridan aquifer, in percent[2]
2	187	415	-26 to -228	2,050	61	-1,241	248	20
12	125	365	-67 to -240	3,000	55	-1,346	260	19
18	185	388	-82 to -203	2,900	100	-948	223	23
23	120	410	-130 to -290	3,800	34	-1,091	310	28
Woodville 1	35	199	-82 to -157	575	10	-1,575	167	21

[1]Calculated distance from the top of the Upper Floridan aquifer to the bottom of the well.
[2]Calculated by dividing adjacent column by the saturated thickness of the Upper Floridan aquiifer.

Simulated Contributing Areas

The two simulated contributing areas delineated for Tallahassee well 23 are shown in figure 33. The transmissivity in the vicinity of this well is about 100,000 ft^2/d, which is the lowest of the five wells (fig. 32). The pumping rate was 3,800 gal/min. This well penetrates approximately the upper 28 percent of the aquifer. However, because of the relatively low transmissivity and high pumping rate, ground water is drawn from the total thickness of the aquifer (fig. 34). The average ground-water velocity within the contributing area was 1.0 ft/d assuming a 25 percent porosity and 2.4 ft/d assuming a 5 percent porosity.

The two contributing areas simulated for the City of Tallahassee well Woodville 1 are shown in figure 35. The transmissivity in the vicinity of this well is about 10,000,000 ft^2/d, the highest of all the wells. The pumping rate was 575 gal/min. This well penetrates approximately the upper 21 percent of the aquifer. However, ground water is drawn from about the upper 25 percent of the aquifer (fig. 36), because of the high transmissivity and low pumping rate. The average ground-water velocity within the contributing area was 1.6 ft/d assuming a 25 percent porosity, and 7.4 ft/d assuming a 5 percent porosity.

The simulated contributing areas for wells 2, 12 and 18 are shown in figures 37, 38, and 39, respectively. The transmissivities at these wells are intermediate to that of the two wells previously discussed. The transmissivities at wells 2 and 12 are about 1,000,000 ft^2/d and the transmissivity at well 18 is about 750,000 ft^2/d. The pumping rates were 2,050 gal/min for well 2, 3,000 gal/min for well 12, and 2,900 gal/min for well 18. The ground-water velocities within the contributing areas of these wells were between those of well 23 and Woodville 1.

Comparison of Simulated and Analytically Derived Contributing Areas

Contributing areas to pumping wells can also be computed using analytical methods. This methodology is quick compared to the numerical modeling approach; however, the analytical method does not have the flexibility to incorporate a variety of hydrologic conditions. For this reason, simplifying assumptions about the aquifer must be made. For the purpose of comparison, the maximum upgradient width of the contributing area for each of the five Tallahassee wells was determined analytically and compared to the width delineated by particle tracking. The equation used to calculate the contributing area widths was (modified from Todd, 1980):

$$Y_L = Q / T i \qquad (3)$$

where:

- Y_L is the upgradient maximum width of the contributing area (ft),
- Q is the discharge rate of the well, (ft^3/s),
- T is transmissivity (ft^2/d), and
- i is the slope of the water table (dimensionless).

Base from U.S. Geological Survey
Tallahassee, Florida, 1:24000, 1970

N

0 1,000 2,000 3,000 FEET

0 500 1,000 METERS

EXPLANATION

5% POROSITY—Simulated contributing area to the pumping well assuming 5% porosity, a time-of-travel of five years, and a pumping rate of 3,800 gallons per minute.

25% POROSITY—Simulated contributing area to the pumping well assuming 25% porosity, a time-of-travel of five years, and a pumping rate of 3,800 gallons per minute.

PARTICLE PATHLINE—Represents flow to well.

B—B´ TRACE OF CROSS-SECTION B-B´

LOCATION OF WELL

Figure 33. Simulated contributing areas to City of Tallahassee well 23.

This equation is commonly used to calculate contributing areas where a sloping water table is present (U.S. Environmental Protection Agency, 1987). The simplifying assumptions made when using this equation are: steady-state flow conditions, uniformly sloping potentiometric surface, constant pumping rate, uniform constant transmissivity, and a fully penetrating well. Over relatively small areas of 1 to 2 mi^2 within the Tallahassee area, all of these simplifying assumptions are probably valid except the last one.

Simulated and analytically derived contributing-area widths are listed in table 6. The analytically derived width for well 23 was 7,536 ft and the model-derived width was 7,500 ft. These values compare closely because well 23 draws water from the full thickness of the aquifer (even though the well was not fully penetrating, as discussed earlier). The analytically derived contributing-area width for Woodville 1 was 161 ft and the model-derived width was 900 ft. For this well, the analytical equation underestimates

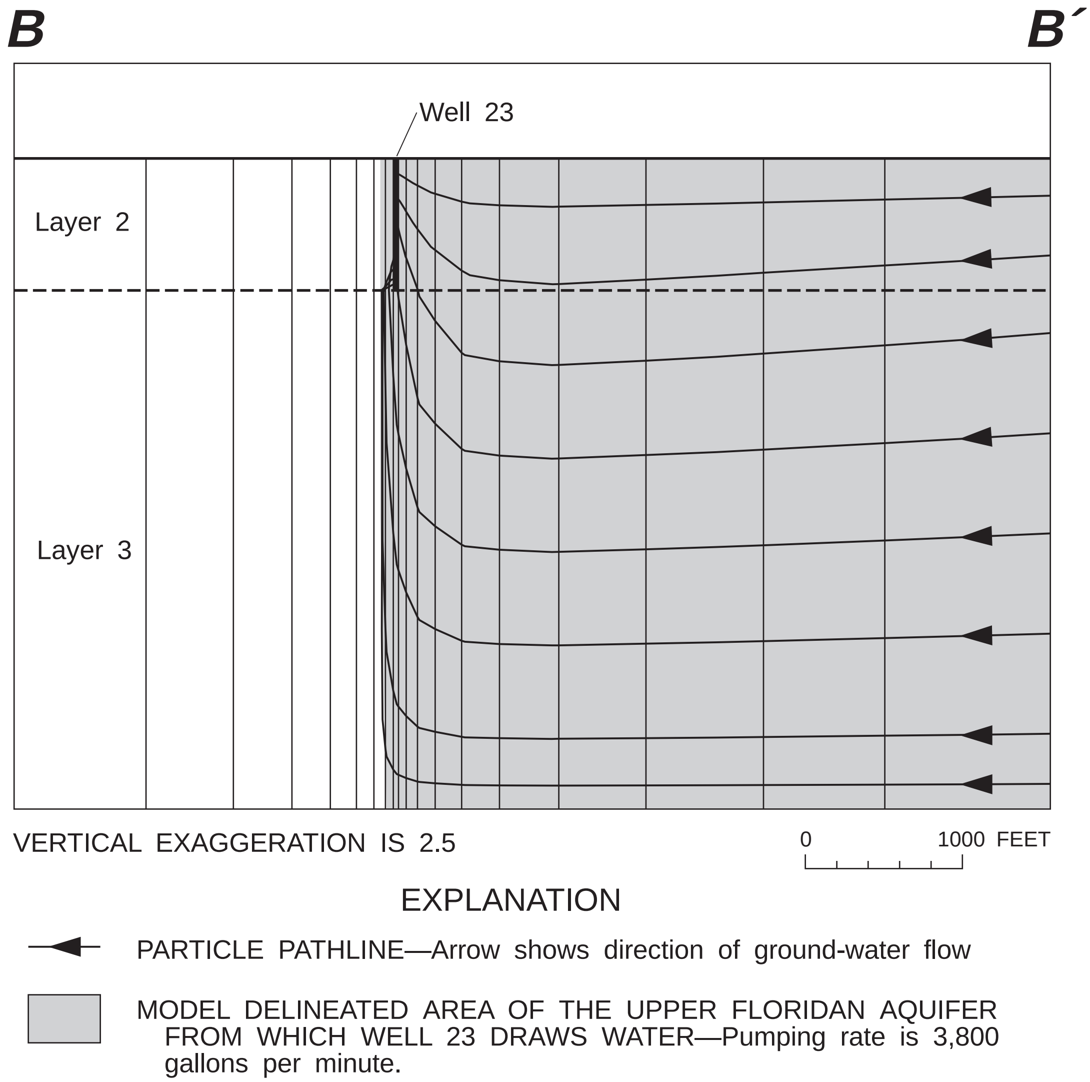


Figure 34. Particle pathlines showing the extent of the Upper Floridan aquifer from which City of Tallahassee well 23 draws water (line of section shown on figure 33).

the width of the contributing area because it assumes that ground water is drawn from the full thickness of the aquifer. The numerical model, which was able to simulate the well as partially penetrating, determined a shallower, wider contributing area which is more accurate. The vertical extent of the aquifer from which wells 2, 12, and 18 drew water was intermediate between those of well 23 and Woodville 1. Thus the differences between the simulated widths and the analytically derived widths were also intermediate between these two wells.

Determination of the contributing areas by model simulation is a more accurate method than analytical approaches because complex, three-dimensional aquifer characteristics can be incorporated into the solution. However, if the characteristics of a particular aquifer match the assumptions of the analytical methods, then these methods could produce good results for considerably less effort. The complexity of the ground-water system must be assessed to determine whether contributing areas should be calculated using numerical ground-water flow models or by simpler analytical methods.

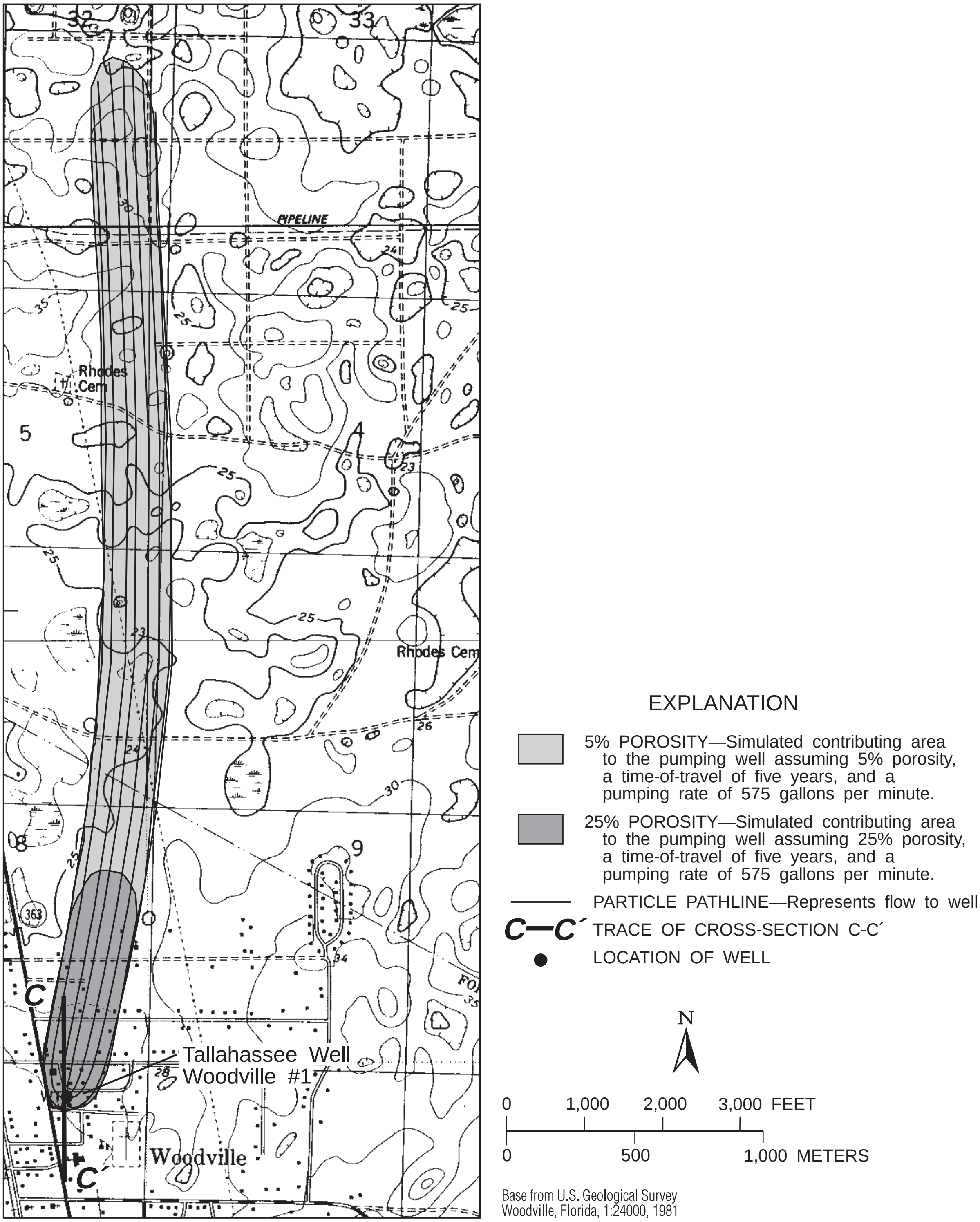


Figure 35. Simulated contributing areas to City of Tallahassee well Woodville 1.

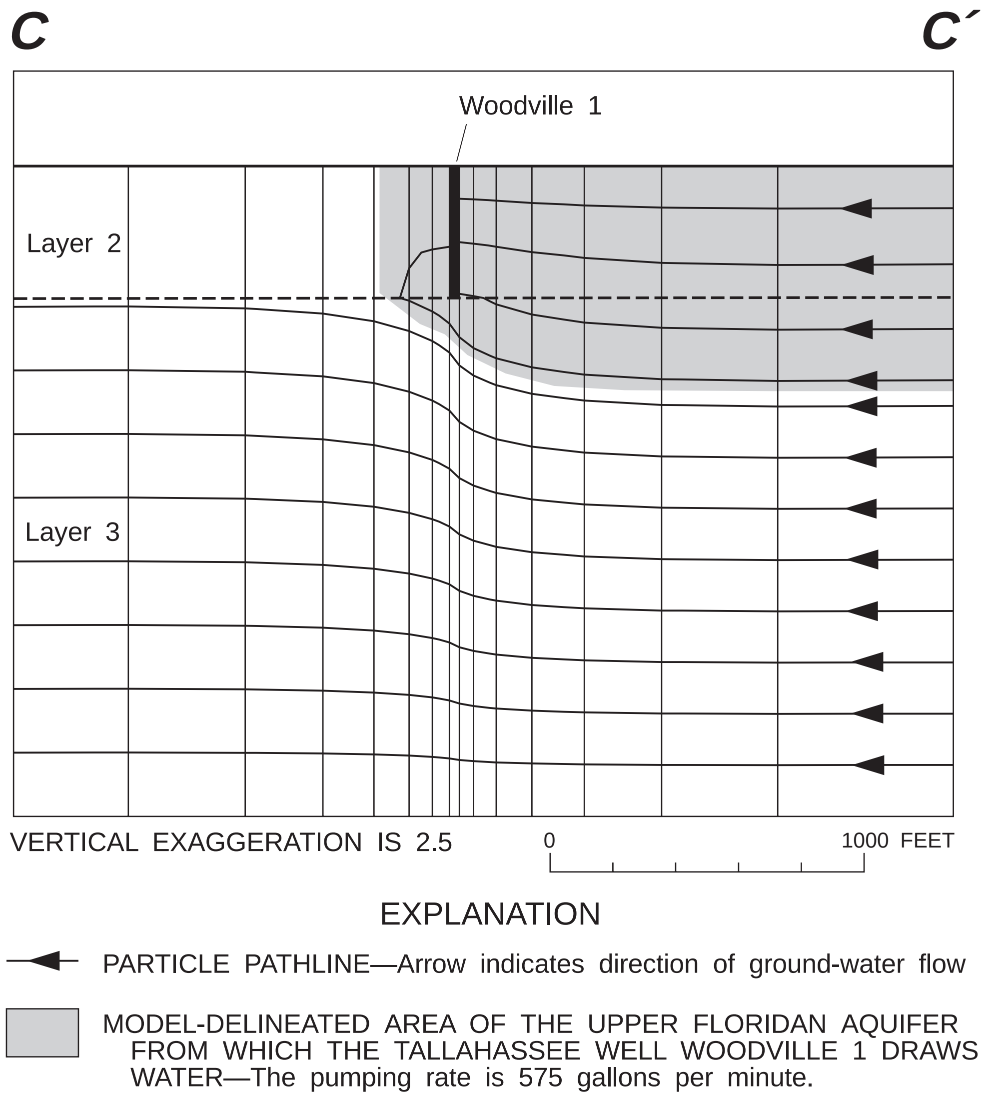
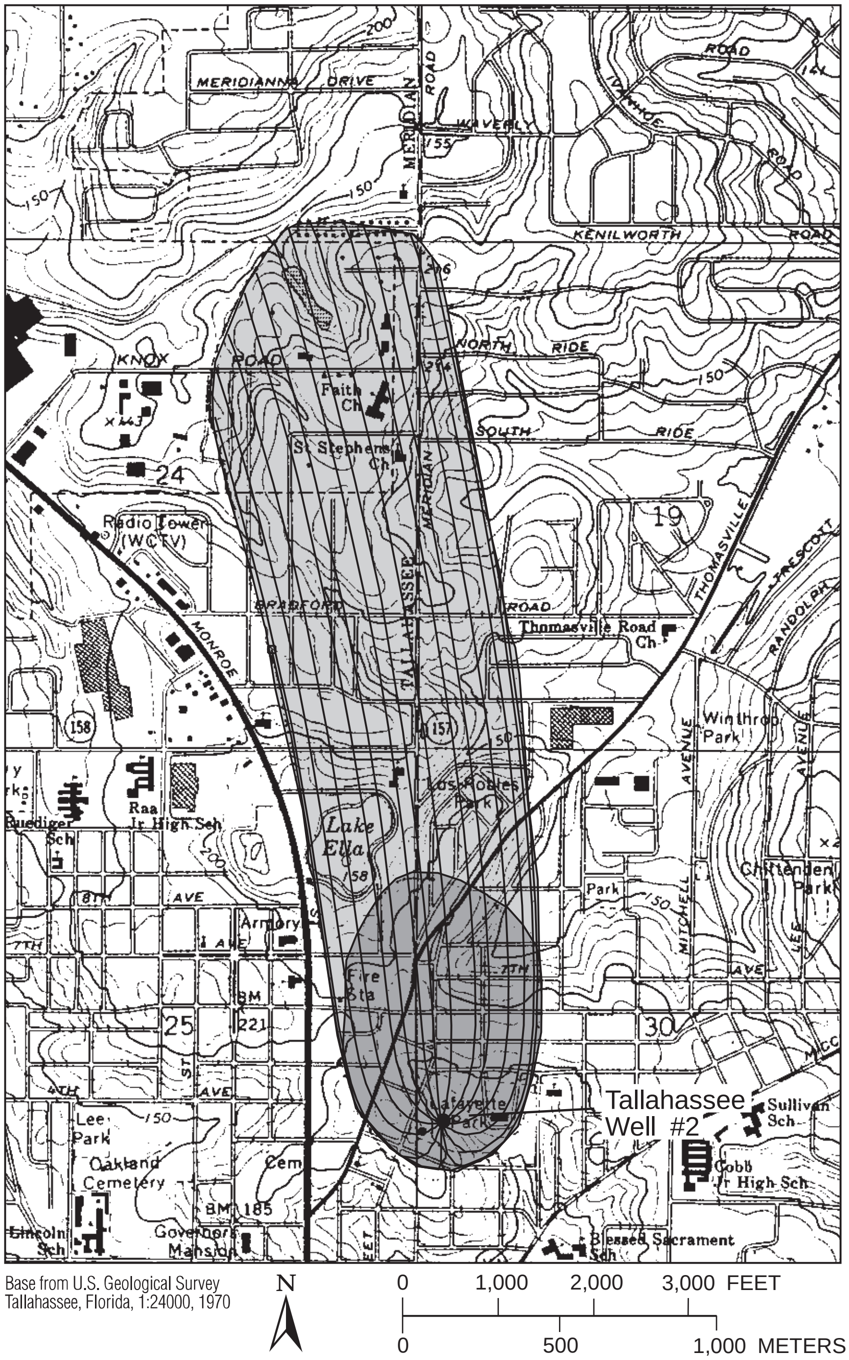


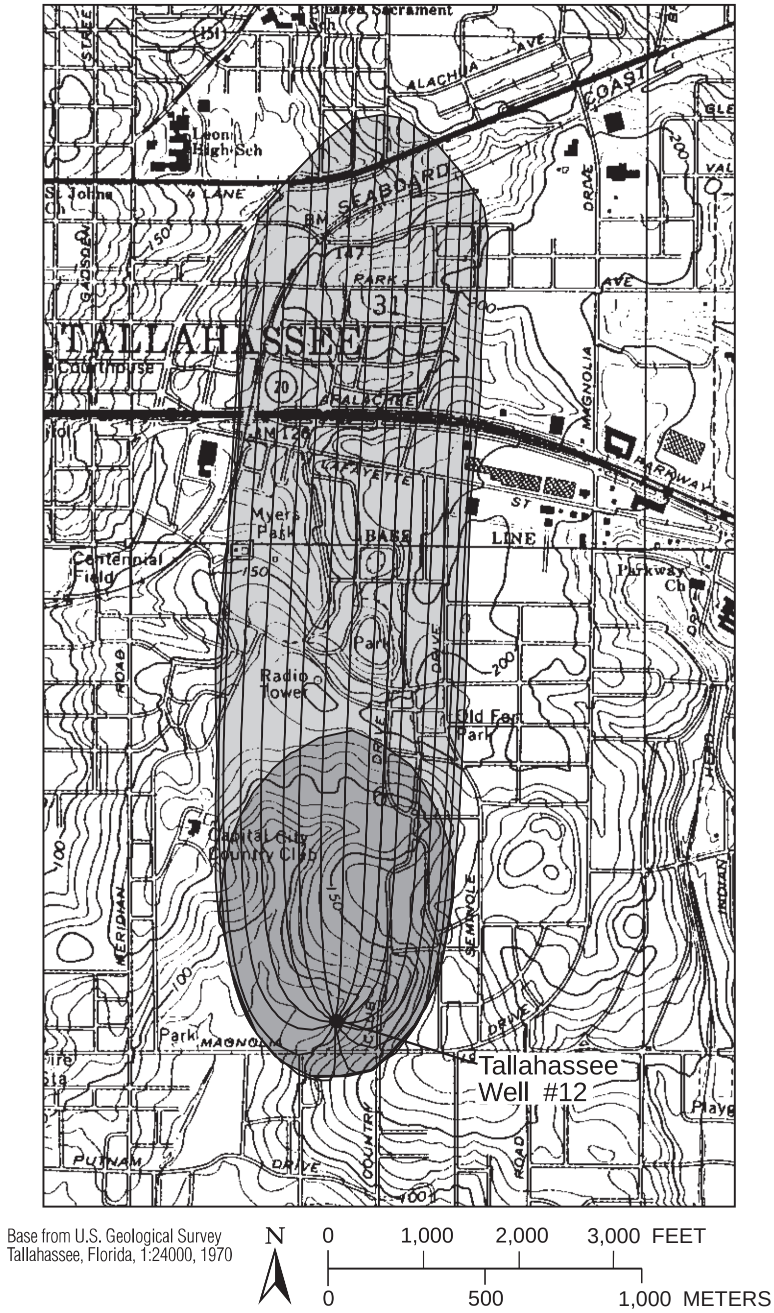
Figure 36. Particle pathlines showing the extent of the Upper Floridan aquifer from which City Tallahassee well Woodville 1 draws water (line of section shown on figure 35).



EXPLANATION

- 5% POROSITY—Simulated contributing area to the pumping well assuming 5% porosity, a time-of-travel of five years, and a pumping rate of 2,050 gallons per minute.
- 25% POROSITY—Simulated contributing area to the pumping well assuming 25% porosity, a time-of-travel of five years, and a pumping rate of 2,050 gallons per minute.
- PARTICLE PATHLINE—Represents flow to well.
- LOCATION OF WELL

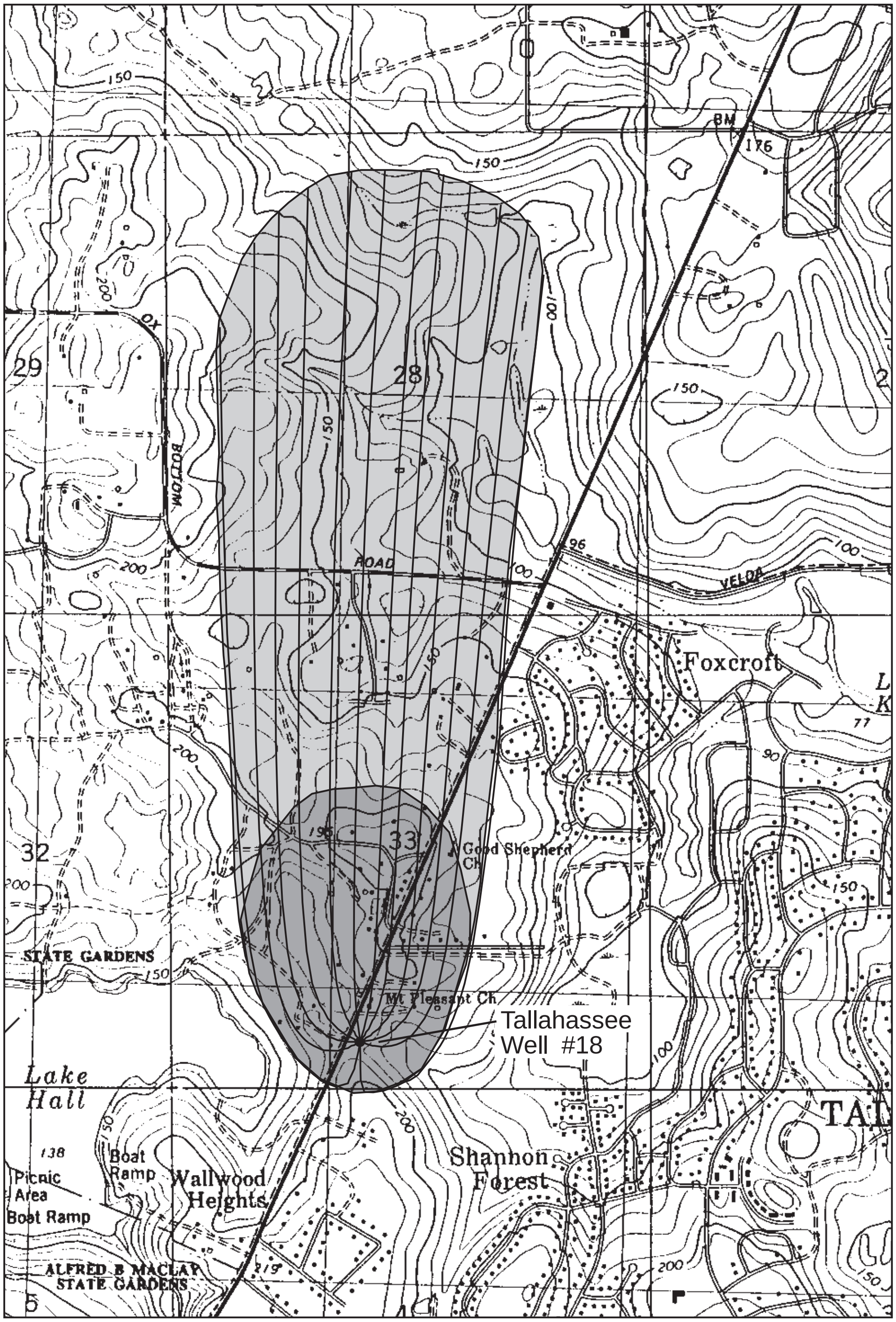
Figure 37. Simulated contributing areas to City of Tallahassee well 2.



EXPLANATION

- 5% POROSITY—Simulated contributing area to the pumping well assuming 5% porosity, a time-of-travel of five years, and a pumping rate of 3,000 gallons per minute.
- 25% POROSITY—Simulated contributing area to the pumping well assuming 25% porosity, a time-of-travel of five years, and a pumping rate of 3,000 gallons per minute.
- PARTICLE PATHLINE—Represents flow to well.
- LOCATION OF WELL

Figure 38. Simulated contributing areas to City of Tallahassee well 12.



Base from U.S. Geological Survey
Bradfordville, Florida, 1:24000, 1982

N

0 1,000 2,000 3,000 FEET

0 500 1,000 METERS

EXPLANATION

5% POROSITY—Simulated contributing area to the pumping well assuming 5% porosity, a time-of-travel of five years, and a pumping rate of 2,900 gallons per minute.

25% POROSITY—Simulated contributing area to the pumping well assuming 25% porosity, a time-of-travel of five years, and a pumping rate of 2,900 gallons per minute.

PARTICLE PATHLINE—Represents flow to well.

LOCATION OF WELL

Figure 39. Simulated contributing areas to City of Tallahassee well 18.

Table 6. Contributing area widths determined by numerical and analytical models for five Tallahassee, Florida, water-supply wells

Well	Width of simulated contributing area, in feet	Width of analytically calculated contributing area, in feet
2	2,700	1,067
12	2,500	1,561
18	3,500	2,044
23	7,500	7,536
Woodville 1	900	161

SUMMARY AND CONCLUSIONS

Ground water from the Upper Floridan aquifer is the source of water supply for Tallahassee, Fla., and for many parts of the surrounding area. In most areas, the aquifer yields an ample supply of good quality water; however, in recent years low levels of tetrachloroethylene (PCE) have been detected in ground-water samples taken from seven City of Tallahassee water-supply wells. The PCE is attributed to past disposal practices of dry cleaners, service stations, and other businesses within the downtown area. The City of Tallahassee removes PCE from the water by passing it through granular-activated carbon units before distribution. To ensure that water-supply wells, presently free of contamination, remain clean, it is necessary to understand the ground-water flow system in sufficient detail to protect the contributing areas. The contributing area of a pumping well is the land area that has the same horizontal extent as that part of the aquifer from which ground-water flow is diverted. To gain an understanding of the ground-water flow system, a 4-year investigation of the Upper Floridan aquifer was conducted. The study area was centered in Leon County, Fla., and extended to surrounding counties in north-central Florida and southwestern Georgia.

The study area is underlain by sedimentary rocks of Tertiary through Quaternary age that consists of limestone, dolostone, clay, and sand of varying degrees of lithification. Aquifers in the study area include the water-table aquifer and Upper Floridan aquifer, which are separated by low-permeability sediments. The water-table aquifer yields only small amounts of water when pumped and generally is not used. The Upper Floridan aquifer is utilized for municipal, industrial, agricultural, and domestic water supply. The transmissivity of the Upper Floridan aquifer ranges over several orders of magnitude.

The potentiometric surface of the Upper Floridan aquifer was defined by measuring ground-water levels in a network of 274 wells. The rate of ground-water discharge from the Upper Floridan aquifer to rivers was quantified by measuring river-discharge rates in area rivers. One aquifer test was conducted that determined a transmissivity of 1,300,000 ft^2/d for the Upper Floridan aquifer in downtown Tallahassee.

A conceptual model describing ground-water flow was developed to aid in building a computer model that accurately simulates ground-water flow. The Upper Floridan aquifer is conceptualized as having the following characteristics: ground-water flow is at steady state; the aquifer acts as a single water-bearing unit; and recharge is by precipitation and discharge occurs as spring flow, leakage to rivers, leakage to the Gulf of Mexico, and pumpage. The recharge area for ground-water moving beneath Leon County extends to counties to the west and north.

Steady-state ground-water flow in the Upper Floridan aquifer was simulated using the USGS modeling software MODFLOW. The model was calibrated to hydrologic data collected from late October to early November 1991. The model grid consisted of 176 rows, 162 columns, and 3 layers with 28,512 model cells per layer. Cell size was variable with the smallest cells being near the center of the study area and larger cells being near the perimeter. Row and column spacing was chosen so that water-supply wells, in which contributing areas were to be determined, would be positioned in the smallest model cells. The smallest cells are 30 ft on each side and the largest cells are 3 mi on each side.

The calibrated model was used in combination with the post-processing program MODPATH to simulate the contributing areas of five Tallahassee water-supply wells. The five wells were chosen because their locations spanned the range of transmissivities present in the Tallahassee area. All of the wells partially penetrated the aquifer and penetration ranged from 19 to 28 percent. The contributing area was delineated by “seeding” the simulated pumping well location in the model with particles and then tracking the particles backward toward areas of recharge.

Porosity within the Upper Floridan aquifer is variable and the distribution not accurately known. For this reason, the contributing areas were simulated twice, using a porosity of 25 and 5 percent. The contributing areas using a 5 percent porosity were always much larger than for the higher porosity. The contributing areas in Leon County are generally elliptical in shape, which reflects the influence of the slope of the potentiometric surface. The lowest average ground-water velocity within a contributing area, assuming a 25 percent porosity, was 1.0 ft/d and the highest velocity was 1.6 ft/d. The lowest average ground-water velocity, assuming a 5 percent porosity, was 2.4 ft/d and the highest was 7.4 ft/d.

The simulated contributing-area width was equivalent to the analytically derived width for only one of the five wells. The model could more accurately delineate contributing areas because of its ability to simulate wells as partially penetrating and by incorporating complex, three-dimensional aquifer characteristics, which the analytical method could not do. However, if the characteristics of a particular aquifer match the assumptions of the analytical methods, then these methods could produce good results for considerably less effort. The complexity of the ground-water system must be assessed to determine whether delineation of the contributing areas should be calculated by computer simulation or by simpler analytical methods.

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