Hydrogeology and Simulated Effects of Ground-Water Withdrawals for Citrus Irrigation, Hardee and De Soto Counties, Florida

By P.A. Metz

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 93-4158

Prepared in cooperation with the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

Tallahassee, Florida
1995

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
Suite 3015
227 N. Bronough Street
Tallahassee, FL 32301

Copies of this report can be purchased from:

U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, MS 517
Denver Federal Center
Denver, CO 80225

CONTENTS

Figure

Table

CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per day per foot [(ft/d)/ft]	1.00	meter per day per meter
mile (mi)	1.609	kilometer
foot squared per day (ft^2/d) [1]	0.0290	meter squared per day
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

[1] The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

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

Acronyms

GIS = geographical information system
MMSP = modular model statistical processor
RASA = Regional Aquifer System Analysis
RMSE = root mean square error
SWFWMD = Southwest Florida Water Management District
USGS = U.S. Geological Survey

Hydrogeology and Simulated Effects of Ground-Water Withdrawals for Citrus Irrigation, Hardee and De Soto Counties, Florida

By P.A. Metz

Abstract

The hydrogeology of Hardee and De Soto Counties in west-central Florida was evaluated, and a ground-water flow model was developed to simulate the effects of expected increases in ground-water withdrawals for citrus irrigation on the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer. In 1988, total citrus acreage in Hardee and De Soto Counties was 89,041 acres. By the year 2020, citrus acreage is projected to increase to 130,000 acres.

Ground water is the major source of water supply in the study area, and 94 percent of the ground-water withdrawn in the area is used for irrigation purposes. The principal sources of ground water in the study area are the surficial aquifer, the intermediate aquifer system, and upper water-yielding units of the Floridan aquifer system, commonly referred to as the Upper Floridan aquifer. The surficial aquifer is a permeable hydrogeologic unit contiguous with land surface that is comprised predominately of surficial quartz sand deposits that generally are less than 100 feet thick. The intermediate aquifer system is a somewhat less permeable hydrogeologic unit that lies between and retards the exchange of water between the overlying surficial aquifer and the underlying Upper Floridan aquifer. Thickness of the intermediate aquifer system ranges from about 200 to 500 feet and transmissivity ranges from 400 to 7,000 feet squared per day. The highly productive Upper Floridan aquifer consists of 1,200 to 1,400 feet of solution-riddled and fractured limestone and dolomite. Transmissivity values for this aquifer range from 71,000 to 850,000 feet squared per day. Wells open to the Upper Floridan aquifer, the major source of water in the area, can yield as much as 2,500 gallons of water per minute.

The potential effects of projected increases in water withdrawals for citrus irrigation on ground-water heads were evaluated by the use of a quasi-three-dimensional, finite-difference, ground-water flow model. The model was calibrated under steady-state conditions to simulate September 1988 heads and under transient conditions to simulate head fluctuations between September 1988 and September 1989. The calibrated model was then used to simulate hydraulic heads for the years 2000 and 2020 that might result from projected increases in pumpage for citrus irrigation.

The model simulation indicated that increased pumpage might be expected to result in:

- A maximum decline of more than 10 feet in the intermediate aquifer system at a proposed grove in eastern De Soto County and an average decline of more than 2 feet in much of the study area.
- An increase in downward leakage to the intermediate aquifer system from the overlying surficial aquifer system from 178 to 183 million gallons per day.

- A decrease in upward leakage from the intermediate aquifer system to the surficial aquifer from 1.58 to 1.47 million gallons per day.
- A maximum decline of about 5 feet in the Upper Floridan aquifer at a proposed grove in eastern De Soto County and a decline of more than 2 feet in much of the model area.
- An increase in downward leakage to the Upper Floridan aquifer from the intermediate aquifer system from 180 to 183 million gallons per day.
- A decrease in upward leakage from the Upper Floridan aquifer to the intermediate aquifer system from 4.32 million gallons per day in 1989 to 3.89 million gallons per day in the year 2,000, but an increase in upward leakage to 5.10 million gallons per day by the year 2020, reflecting a change in hydraulic gradient.

INTRODUCTION

Several periods of below freezing temperatures during the 1980's in northern and central Florida resulted in extensive damage to Florida's citrus crops. To avoid future crop damage, many citrus growers relocated to counties farther south, including Hardee and De Soto Counties. As a result, citrus acreage in Hardee and De Soto Counties has increased from 77,966 acres in 1978 to 89,041 acres in 1988 (Marella, 1992, table 13). The Southwest Florida Water Management District projects that total citrus acreage in those two counties will increase to more than 130,000 acres by the year 2020 (Taylor and others, 1990).

Ground water, the principal source of water supply in Hardee and De Soto Counties, is obtained from three aquifers in the study area: the surficial aquifer, the intermediate aquifer system, and the Upper Floridan aquifer. The surficial aquifer has limited use because of the low yield to wells and the potential for contamination. Water withdrawn from the surficial aquifer is used primarily for lawn irrigation and stock watering. The intermediate aquifer system is used extensively in some parts of Hardee and De Soto Counties as a source of water for irrigation and public and domestic supply. The yield to wells and total withdrawals of water from this aquifer system are greater than those of the surficial aquifer, but are much less than those of the deeper Upper Floridan aquifer. The Upper Floridan aquifer is the principal source of water supply in the study area. Water withdrawn from the Upper Floridan aquifer is used for irrigation and industrial, public, and domestic supply. Wells open to the Upper Floridan aquifer yield large quantities of freshwater; however, dissolved-solids concentrations exceed limits for potable supply in the southern half of the study area.

As the demand for water in Hardee and De Soto Counties increases, additional information about the aquifers is needed to manage and develop the water supply effectively. The U.S. Geological Survey (USGS), in cooperation with the Southwest Florida Water Management District (SWFWMD), conducted a study from 1987 to 1990 to evaluate the effects of increased citrus irrigation on the ground-water resources of Hardee and De Soto Counties. The results of the study are summarized in this report.

Purpose and Scope

This report presents the results of a study to describe the hydrogeology and ground-water flow of the multiaquifer system in Hardee and De Soto Counties. A digital ground-water flow model was developed and used to simulate the effects of anticipated increased ground-water withdrawals for citrus irrigation. A description of the hydrogeologic framework of the study area is presented, the long-term water-level trends are defined, and the results of model simulations of possible future pumping scenarios are described with respect to the intermediate aquifer system and the Upper Floridan aquifer.

Previous Investigations

Numerous investigations have contributed to an understanding of the geology, hydrogeology, and ground-water resources of Hardee and De Soto Counties. The geology of Hardee and De Soto Counties was described in reports by Bergendahl (1956), Puri and Vernon (1964), White (1970), Wilson (1977), and Scott (1988). Reports presenting results of investigations by Wilson (1972), Wolansky and Corral (1985), Duerr and

Wolansky (1986), Miller (1986), Aucott (1988), Duerr and others (1988), and Duerr and Enos (1991) describe the hydrogeology of the study area. Appraisals of the ground-water resources for the study area were included in reports by Kaufman (1967), Hutchinson (1978), Robertson and others (1978), Leach and Healy (1980), Duerr and Trommer (1982), Duerr and Sohm (1983), and Yobbi (1983). Reports that presented results of computer simulations of ground-water flow in or near the study area included those by Wilson (1977), Ryder (1982; 1985), Wilson and Gerhart (1982), and Tibbals (1990). A summary of the hydrology of the Floridan aquifer system, was presented by Johnston and Bush (1988).

Description of the Study Area

Hardee and De Soto Counties are in west-central Florida and have a combined area of 1,371 mi^2. The location of Hardee and De Soto Counties is shown in figure 1 along with the boundaries of the study area included in the ground-water flow model that will be discussed in subsequent sections of this report. The study area lies entirely in the midpeninsular physiographic zone described by White (1970) and includes parts of three subdivisions: the Polk Upland, the De Soto Plain, and the Gulf Coastal Lowlands (fig. 2). The physiographic subdivisions correspond approximately to several marine terraces or plains that were formed by the invasion of seas

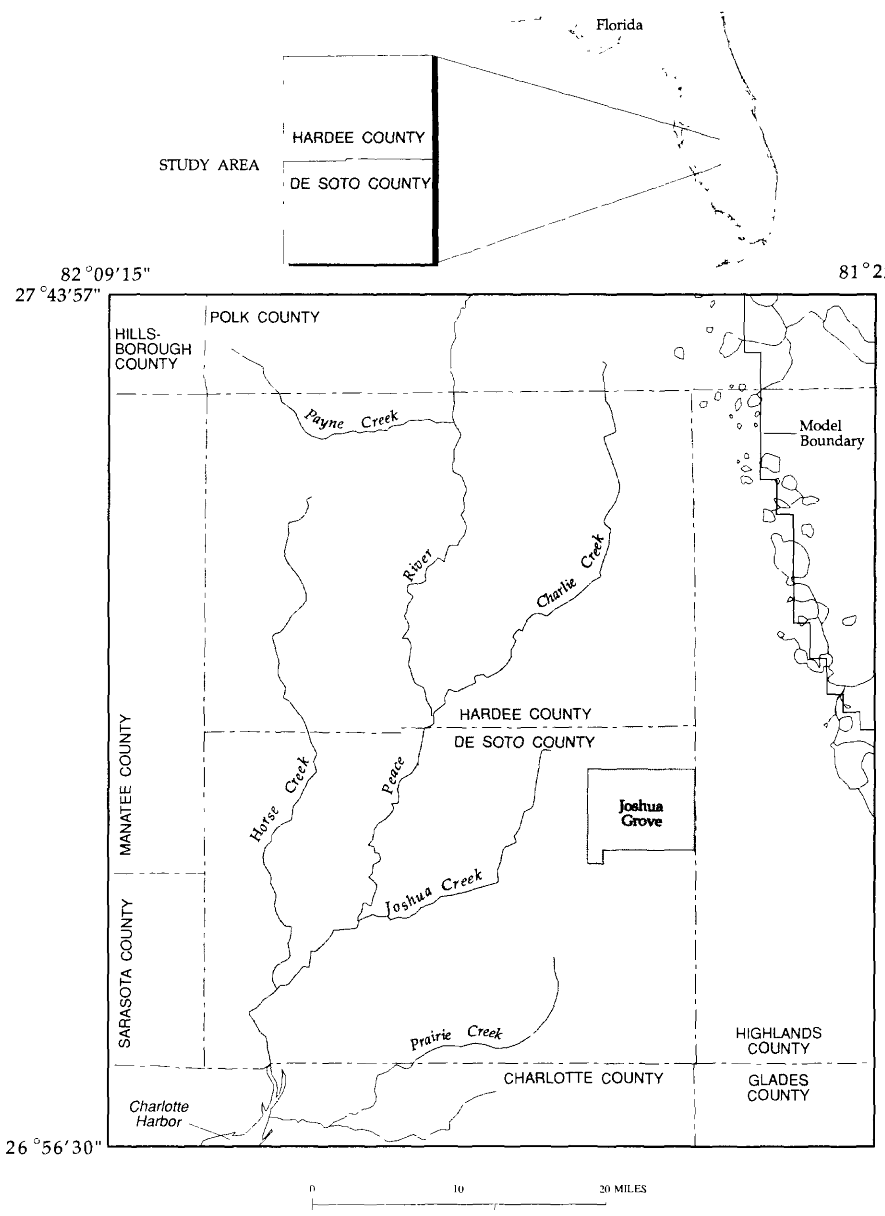


Figure 1. Location of the study and model area.

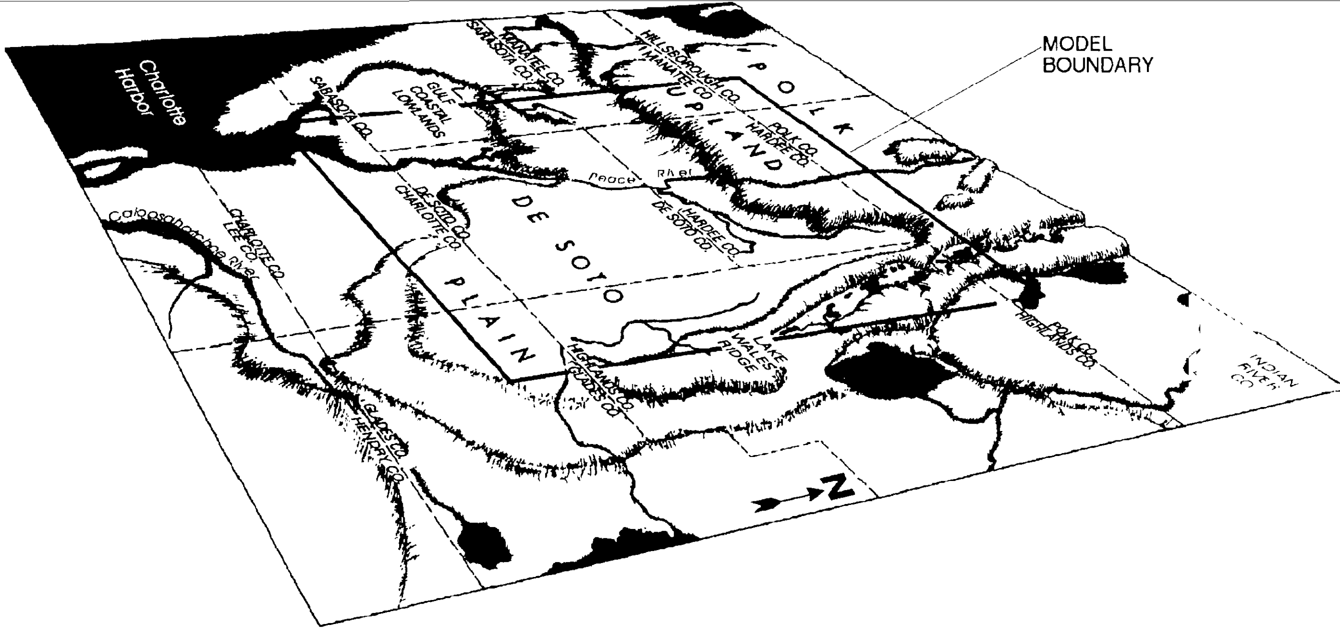


Figure 2. Physiographic subdivisions and boundaries of study and model area. (Modified from White, 1970.)

during the Pleistocene Epoch. The inland boundary of each subdivision is delineated by a low scarp or break in slope that represents the position of a former marine shoreline (Wilson, 1977). The Polk Upland is a broad, sandy area that ranges in altitude from 100 to 245 ft above sea level. A large part of the study area lies within the gently sloping De Soto Plain and ranges in altitude from 30 to 100 ft above sea level. The Gulf Coastal Lowlands subdivision, which encompasses a large part of the Peace River valley, consists of poorly drained, low-lying land at altitudes of 30 to 40 ft above sea level in central and southwestern De Soto County (Wilson, 1977). East of the study area is the Lake Wales Ridge, a major ground-water recharge area. Altitudes of the Lake Wales Ridge range from 100 to 245 ft above sea level. This long, narrow ridge is a series of subparallel, eroded, sandy ridges with intervening valleys that contain numerous lakes.

The study area is drained by the Peace River, which flows southward for about 70 mi from its source in Polk County to Charlotte Harbor in Charlotte County. Major tributaries that flow into the Peace River include Payne Creek, Charlie Creek, Joshua Creek, Horse Creek, and Prairie Creek (fig. 1).

Land Use

In 1988, 53 percent of the land in Hardee and De Soto Counties was agricultural, 31 percent was prairie grassland, and less than 4 percent was urban; the remaining 12 percent was undeveloped. Land-use data were obtained from the De Soto County 1987 comprehensive plan and from LANDSAT data imagery photographs. Agricultural land in Hardee and De Soto Counties is primarily in pasture, citrus groves, cropland, and nurseries. Citrus groves, which constituted the second largest agricultural land-use in the study area, covered 45,898 acres in Hardee County and 43,143 acres in De Soto County in 1988 (Florida Agricultural Statistical Service, 1989). Generalized locations of citrus groves in Hardee and De Soto Counties for 1988 are shown in figure 3. Future land-use projections by the SWFWMD indicate that a significant number of citrus growers will relocate southward into Hardee and De Soto Counties (Taylor and others, 1990). Citrus groves and other agricultural land-use projections for Hardee and De Soto Counties for 1990, 1995, 2000, 2010, and 2020 are shown in figure 4.

Climate

The climate of the study area is subtropical humid and is characterized by warm, relatively wet summers and mild, relatively dry springs. Rainfall averages about 53 in. per year and varies seasonally with more than half the annual rainfall occurring from June through September (Palmer and Bone, 1977). Rainfall tends to be distributed unevenly throughout the area during the summer because most summer rainfall in Florida is derived from localized, convective thunderstorms. Winter rainfall commonly is more evenly distributed throughout the study area because it generally results from frontal-type air masses that move from north to south across the State.

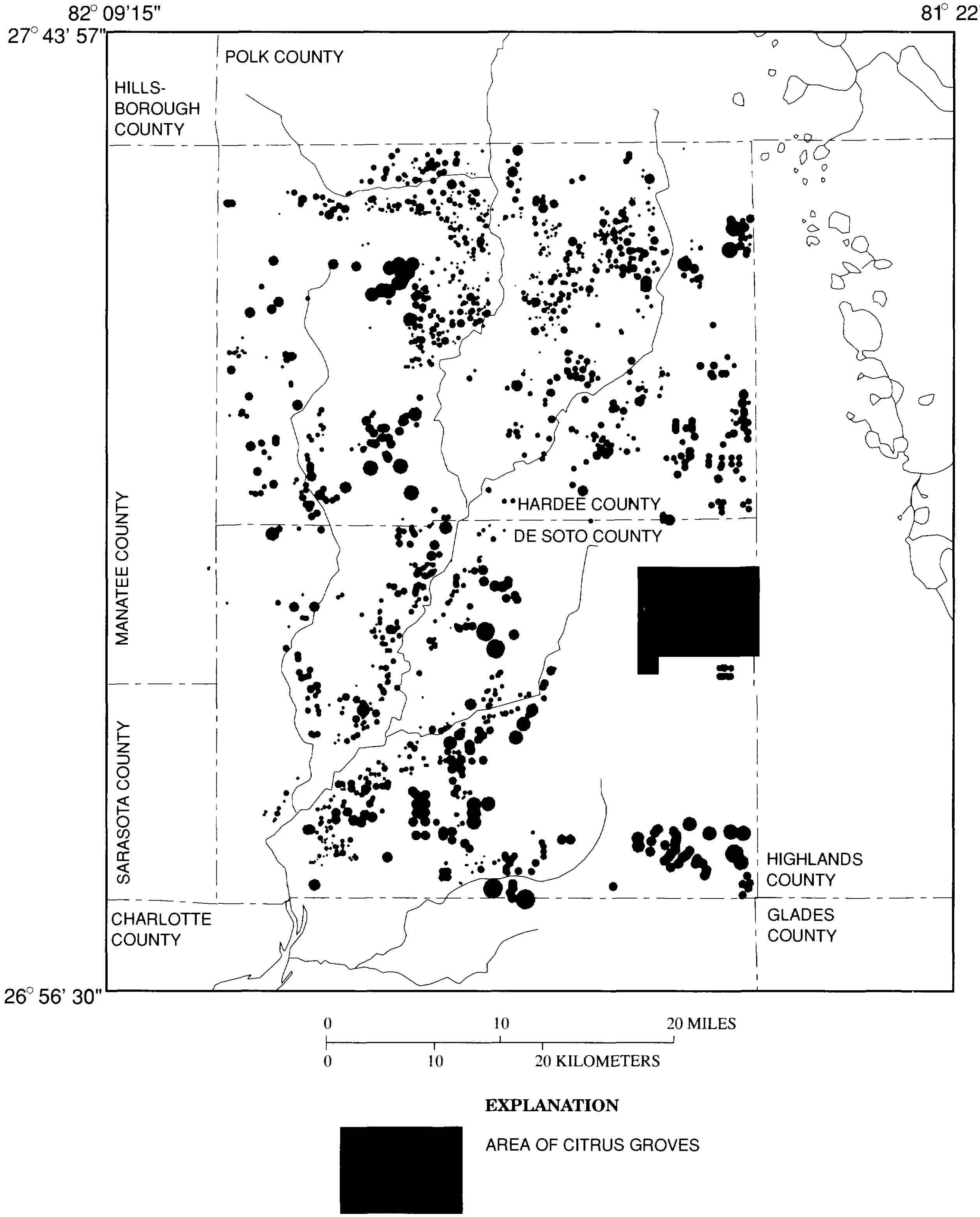


Figure 3. Generalized location of citrus groves in Hardee and De Soto Counties, 1988. (From LANDSAT data imagery photos.)

Approach

The hydrogeologic framework for the study area was defined through analyses of well logs, aquifer tests, and water-level measurements. Water-level trends were determined by reviewing historical water-level data from observation wells within and adjacent to the study area. Regional potentiometric-surface maps for the intermediate aquifer system and the Upper Floridan aquifer for September 1988, May 1989, and September 1989 were used to evaluate seasonal ground-water flow conditions. Quantitative estimates of flow to and from the ground-water system were made by calibrating and applying a quasi-three-dimensional ground-water flow model. Potentiometric-surface levels for the intermediate aquifer system and Upper Floridan aquifer for the years 2000 and 2020 were simulated by stressing the calibrated model with projected pumpage for citrus irrigation.

The model was calibrated and tested using input parameters stored in a geographical information system (GIS) data base. Except for head values and ground-water withdrawal rates, initial input parameters for the model were based on data from a coarse-grid model developed as part of a Regional Aquifer System Analysis (RASA) study (Ryder, 1985). A finer resolution ground-water flow model was developed from this regional scale model and subsequently was used to simulate hypothetical pumping scenarios.

The RASA data base was updated based on studies by subsequent investigators. Duerr and Enos (1991) defined the upper and lower confining units of the intermediate aquifer system in the study area from geologic logs. The results of an intermediate aquifer system aquifer test (Duerr and Enos, 1991) in west-central Hardee County also was incorporated into the hydrogeologic data base.

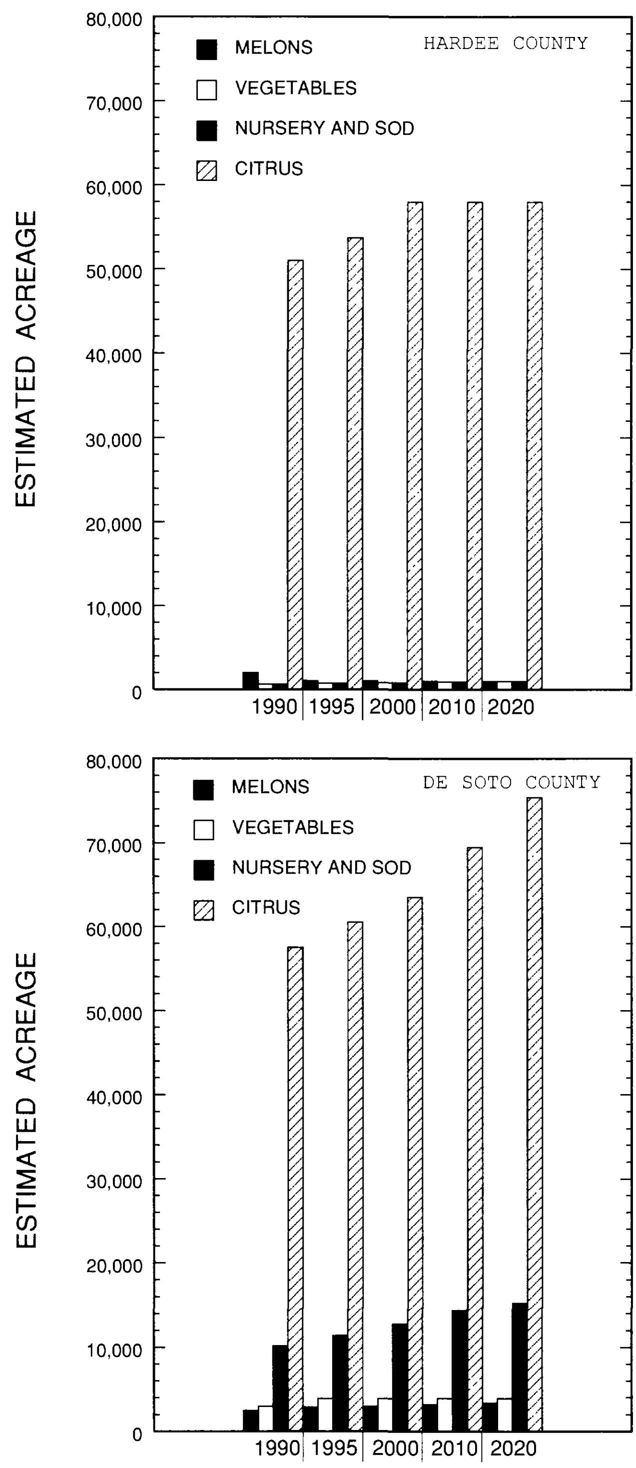


Figure 4. Projected agricultural land use for 1990, 1995, 2000, 2010, and 2020.

HYDROGEOLOGIC FRAMEWORK

The hydrogeologic units underlying the study area consist of deposits of sand, clay, marls, and carbonates that were deposited in a marine environment. These hydrogeologic units, their equivalent stratigraphic units, and brief lithologic descriptions of these units are presented in figure 5. Wilson and Gerhart (1982) grouped the units into four major lithologic sequences of hydrologic significance. From youngest to oldest, these sequences are:

System	Series	Stratigraphic Unit	General Lithology	Major Lithologic Unit	Hydrogeologic Unit	
Quarternary	Holocene and Pleistocene	Surficial sand, terrace sand, phosphorite	Predominantly fine sand; interbedded clay, marl, shell, and phosphorite.	Sand	Surficial aquifer	
Tertiary	Pliocene	Undifferentiated deposits[1] Tamiami Formation	Clayey and pebbly sand; clay, marl, shell, phosphatic.	Clastic	Confining unit	Intermediate Aquifer System
	Miocene	Hawthorn Group: Bone Valley Formation; Peace River Formation	Dolomite, sand, clay, and limestone, silty, phosphatic.	Carbonate and clastic	Aquifer	
		Hawthorn Group: Arcadia Formation; Tampa Member	Limestone, sandy, phosphatic, fossiliferous; sand and clay in lower part in some areas.		Confining unit	
	Oligocene	Suwannee Limestone	Limestone, sandy limestone, fossiliferous.	Carbonate	Upper Floridan aquifer	Floridan Aquifer System
	Eocene	Ocala Limestone	Limestone, chalky, foraminiferal, dolomitic near bottom.			
		Avon Park Formation	Limestone and hard brown dolomite; intergranular evaporite in lower part in some areas.			
				Carbonate with evaporites	Middle confining unit	
	Paleocene	Oldsmar and Cedar Keys Formations	Dolomite and limestone with intergranular gypsum and anhydrite.		Lower Floridan aquifer	
				Evaporites	Sub-Floridan confining unit	

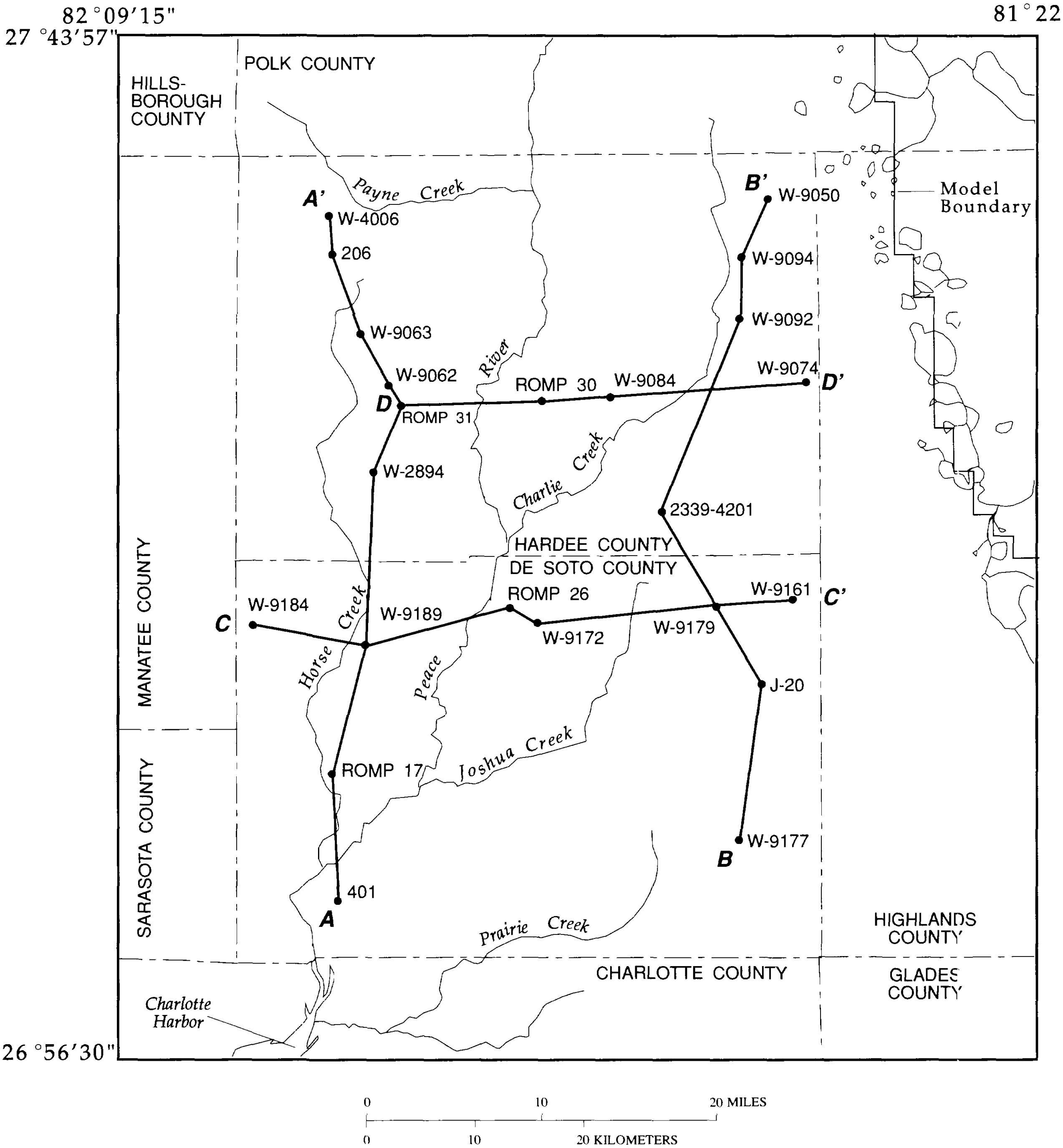
[1]Includes all or parts of Caloosahatchee Marl and Bone Valley Formation.

Figure 5. Correlation chart showing hydrogeologic framework. (Modified from Ryder, 1985, table 1.)

1. Surficial sand deposits, generally less than 100 ft thick;
2. A heterogeneous clastic and carbonate section of interbedded limestone, dolomite, sand, clay, and marl generally greater than several hundred feet thick;
3. A carbonate section of limestone and dolomite, generally more than 1,000 ft thick; and
4. Carbonate rocks containing intergranular anhydrite and gypsum.

The first three sequences constitute distinct water-bearing units of interest to this study: the surficial aquifer, the intermediate aquifer system, and the Upper Floridan aquifer. The Upper Floridan aquifer is underlain by the fourth sequence, the middle confining unit of the Floridan aquifer system.

Lines of hydrogeologic section and selected well sites in Hardee and De Soto Counties are shown in figure 6. Variations in the distribution, thickness, and dip of the hydrogeologic units are depicted in generalized hydrogeologic sections in figure 7.



EXPLANATION

D —— *D'* LINE OF SECTION SHOWN IN FIGURE 7

• W-9177 TEST WELL AND NUMBER

Figure 6. Locations of generalized hydrogeologic sections and selected well sites. (Modified from Duerr and Enos, 1991.)

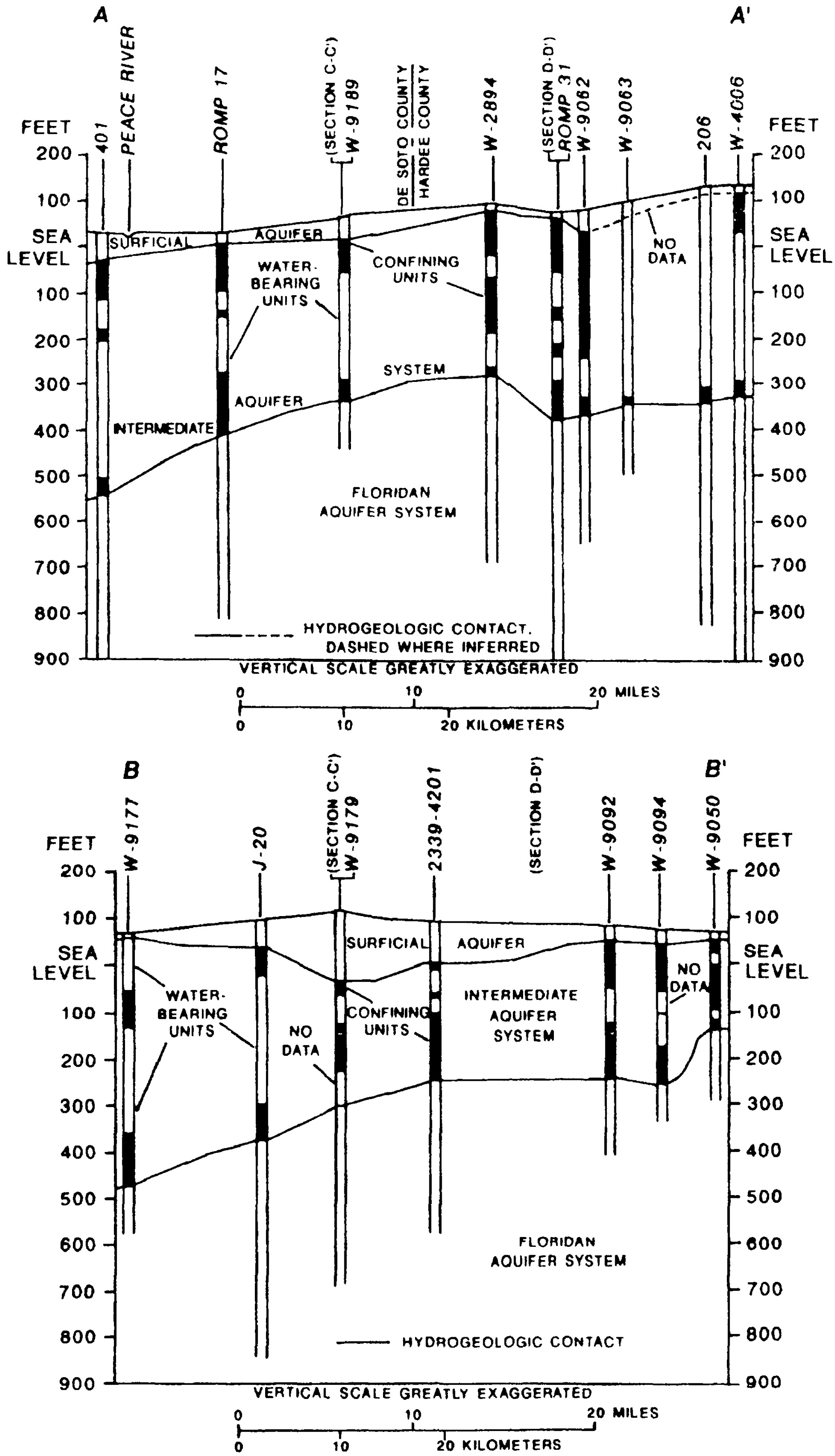


Figure 7. Generalized hydrogeologic sections *A-A'*, *B-B'*, *C-C'*, and *D-D'*. (Modified from Duerr and Enos, 1991. Lines of section are shown in fig. 6.)

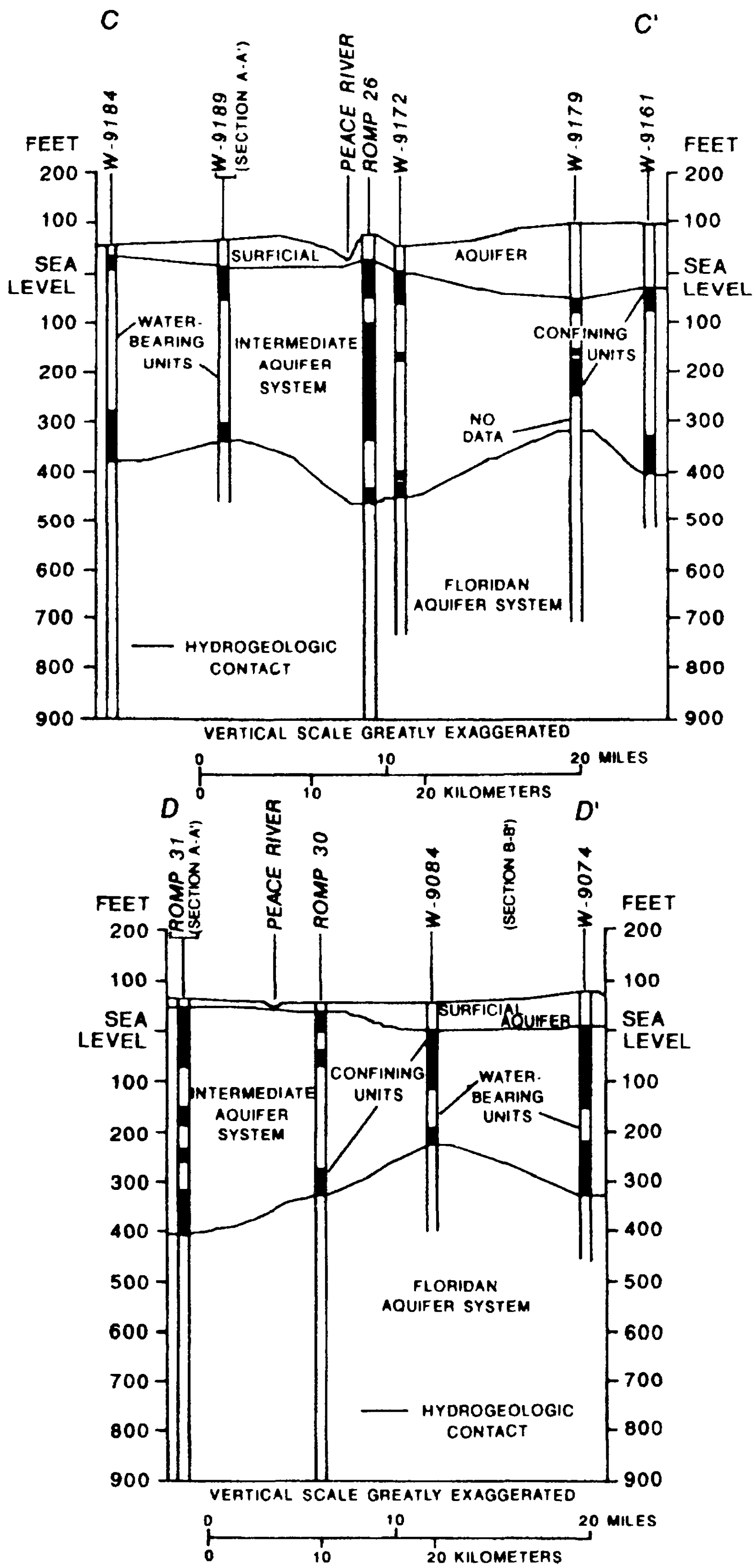


Figure 7. Generalized hydrogeologic sections *A-A'*, *B-B'*, *C-C'*, and *D-D'*. (Modified from Duerr and Enos, 1991. Lines of section are shown in fig. 6.)--Continued

The sections indicate that the units are laterally continuous and generally are uniform in thickness. The following descriptions of the areal distribution of hydraulic characteristics for aquifers and confining units are based largely on the results of RASA ground-water flow model investigations reported by Ryder (1985) and the results of similar investigations described in a later section of this report. A range of characteristic values derived from both studies is reported herein for each respective unit.

Surficial Aquifer

The unconfined surficial aquifer is the permeable hydrogeologic unit contiguous with land surface. This aquifer is composed principally of unconsolidated to poorly indurated clastic deposits (Southeastern Geological Society, 1986). The surficial aquifer consists of predominately fine sand and interbedded clay, marl, shell, and phosphorite (fig. 5). More than one permeable zone may be present where these deposits are interbedded; where this occurs, the unit commonly is termed the surficial aquifer system. However, for purposes of this report, the deposits are considered to form a single homogeneous aquifer, which is referred to as the surficial aquifer.

Hydraulic Properties

The water-bearing properties of the surficial aquifer are largely dependent upon aquifer thickness and the grain-size distribution of the sediments within the aquifer (Wilson, 1977). Thickness of the deposits ranges from about 25 ft in Hardee County to about 100 ft in northeastern De Soto County (Wolansky and others, 1979). Average transmissivity of the surficial aquifer is estimated to be 1,100 ft^2/d on the basis of an average hydraulic conductivity of 20 ft/d and an average saturated thickness of 55 ft (Wilson, 1977). The surficial aquifer is an insignificant source of water supply when compared to the thicker and more transmissive underlying aquifers.

Water Table

During years of normal rainfall in the study area, the altitude of the water table in the surficial aquifer probably is similar to that shown for September 1988 in figure 8. Based on this figure, the altitude of the water table in the study area ranges from about 20 ft above sea level in southwestern De Soto County to about 125 ft above sea level in northeastern Hardee County. The water-table contours in figure 8 were based on field measurements of water levels in selected wells, on river and lake elevations, and on estimates based on land-surface elevations from USGS topographic maps (scale 1:24,000). Water levels were estimated to be at or a few feet below land surface in swampy areas, at depths of 5 to 10 ft below land surface for the lowlands plain area, and 15 to 20 ft below land surface along the Lake Wales Ridge. Relatively moderate water-table gradients exist near the major stream courses, and gentle gradients exist in the broad interstream areas.

The water table fluctuates with seasonal rainfall (fig. 9). Water-table altitudes are highest during the wet season, June through September, and lowest during the dry season, October through May. Long-term hydrographs for wells completed in the surficial aquifer (fig. 9) indicate that seasonal fluctuations of 3 to 5 ft are common and that recharge from the summer rains generally is adequate to replenish the aquifer.

Ground-water movement in the surficial aquifer involves a complex interrelation between recharge, runoff, infiltration, discharge, and evapotranspiration. The surficial aquifer is recharged directly by rainfall that annually averages about 53 in. in the study area (Palmer and Bone, 1977). Most of the rain that falls in the study area drains to local streams or is lost to evapotranspiration. Some rainfall, however, percolates down through the surficial deposits and enters the surficial aquifer. Recharge to the surficial aquifer also includes some downward percolation of septic-tank effluent and irrigation water and by upward leakage of water from underlying aquifers in areas where the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer are above the water table. Discharge from the surficial aquifer is by pumpage; seepage to lakes, streams, and ditches; downward leakage to lower aquifers where the hydraulic gradient is downward; and evapotranspiration from the water table.

Intermediate Aquifer System

The intermediate aquifer system includes all water-bearing units (aquifers) and confining units between the overlying surficial aquifer and the underlying Upper Floridan aquifer (Duerr and others, 1988). The intermediate aquifer system consists of the undifferentiated deposits of Pleistocene and Pliocene age and the Hawthorn Group of Pliocene and Miocene age (fig. 5).

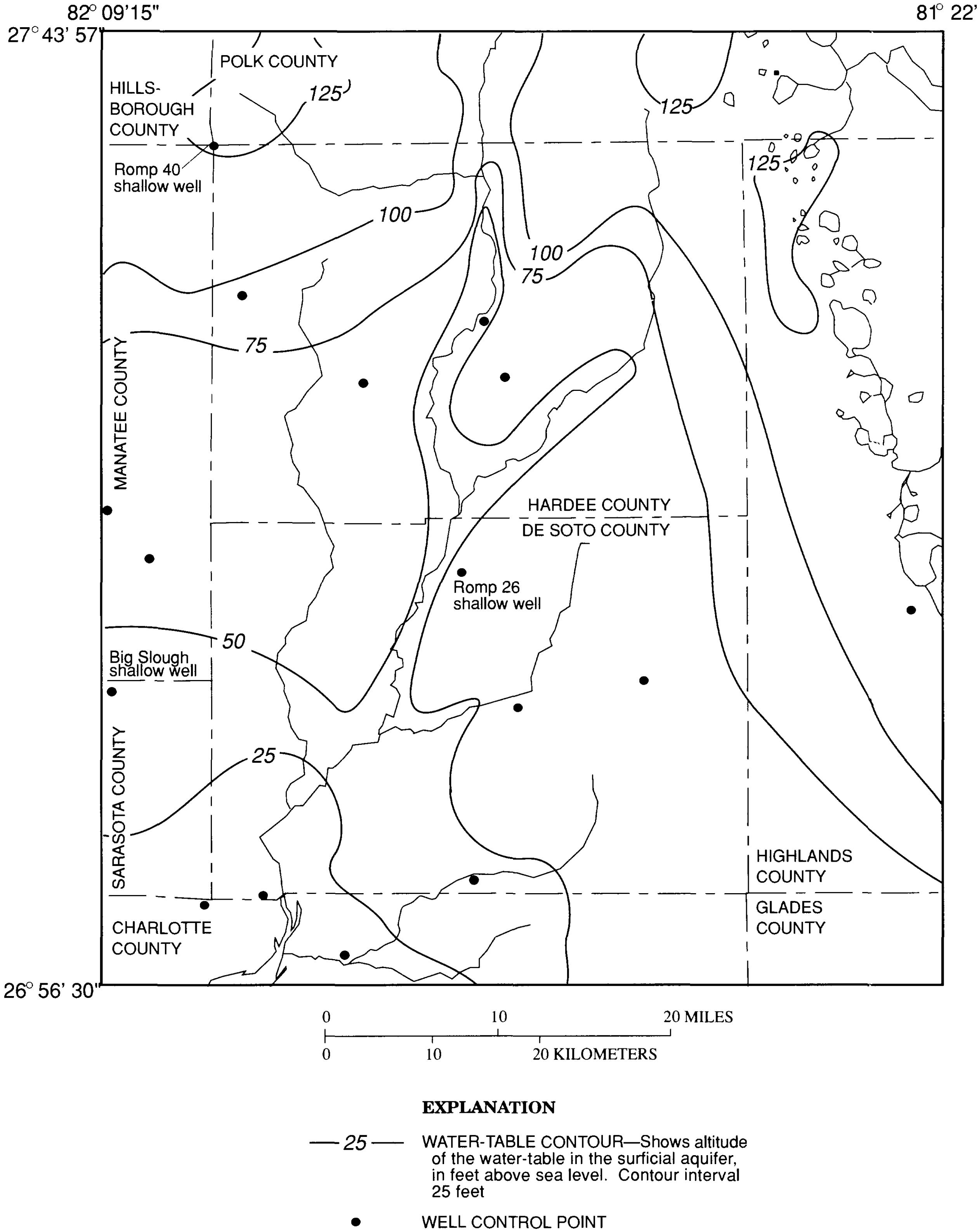


Figure 8. Altitude of the water table in the surficial aquifer, September 1988.

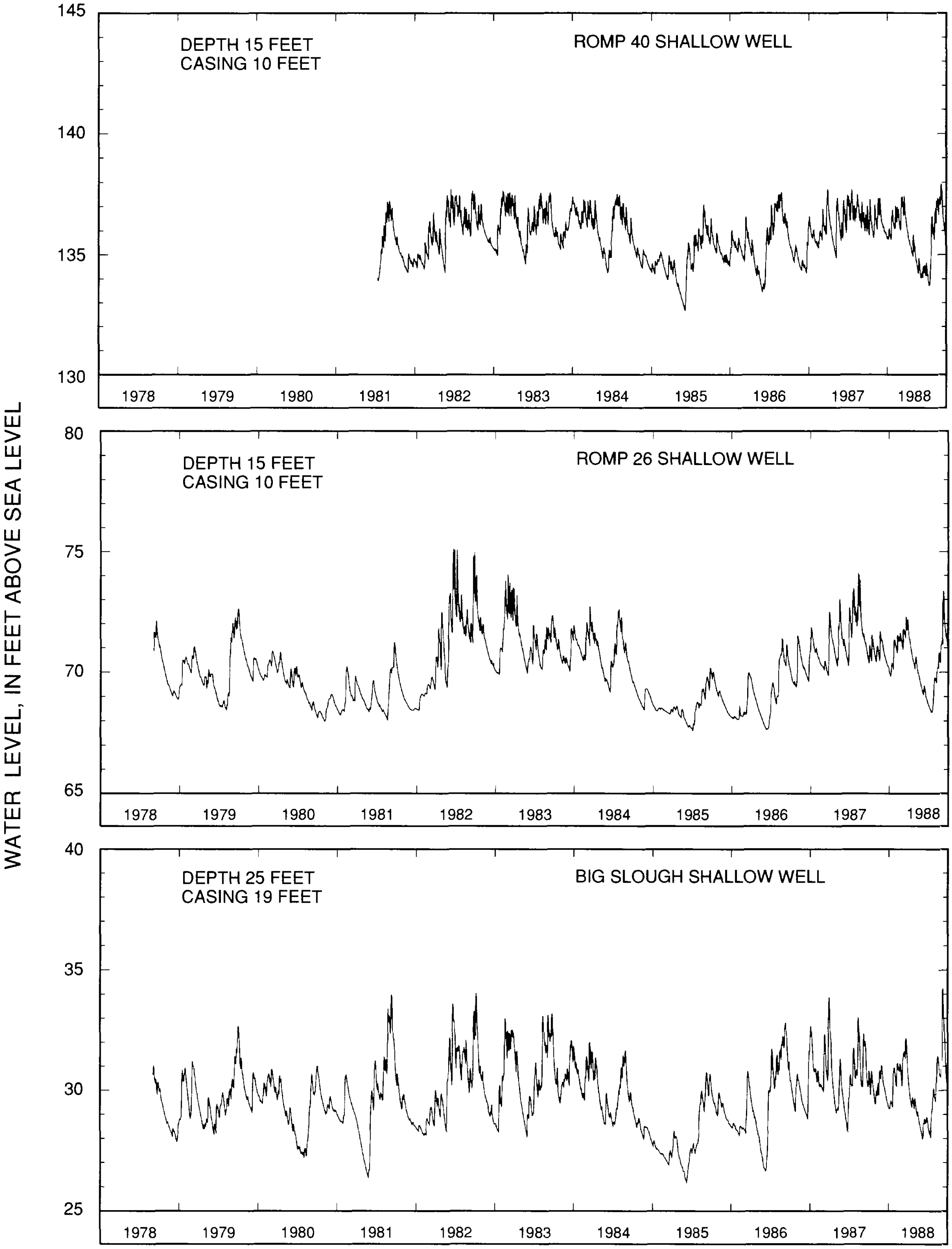


Figure 9. Long-term water-level trends in surficial aquifer wells in or near the study area, 1978-88. (Locations of wells are shown in fig. 8.)

The intermediate aquifer system consists of at least three hydrogeologic units (fig. 5): a clayey and pebbly sand, clay, and marl upper confining unit that separates the uppermost water-bearing unit in the intermediate aquifer system from the surficial aquifer; one to three water-bearing units composed primarily of carbonate rocks, sand, and discontinuous beds of sand and clay; and a sandy clay or clayey sand lower confining unit that lies directly over the Upper Floridan aquifer (Ryder, 1985). The diversity in lithology of the intermediate aquifer system reflects the variety of depositional environments in west-central Florida that occurred during the Pliocene and Miocene Epochs. These environments included open-marine, shallow-water, coastal-marine, and fluvial and estuarine processes (Gilboy, 1985).

Hydraulic Properties

The intermediate aquifer system underlies all of Hardee and De Soto Counties and is hydraulically separated from the surficial aquifer by the upper confining unit. The upper confining unit has a low vertical hydraulic conductivity and, consequently, retards interaquifer flow. For most of the study area, however, the upper confining unit does transmit, or leak, water downward from the surficial aquifer into the intermediate aquifer system, and the system is referred to as a leaky-aquifer system (Wilson, 1977). Water is also transmitted upward through the upper confining unit into the surficial aquifer and Peace River where the hydraulic gradient is upward. Areas of upward and downward leakage through the upper confining unit of the intermediate aquifer system in September 1988 are shown in figure 10. The thickness of the intermediate aquifer system is shown in figure 11. Thickness of the intermediate aquifer system ranges from about 200 ft in northeastern Hardee County to about 500 ft in southern De Soto County (Duerr and Enos, 1991).

The thickness of the upper confining unit varies widely in the study area and ranges from less than 25 ft to about 265 ft (Duerr and Enos, 1991) (fig. 12). Little is known about the areal variations in hydraulic conductivity and hydraulic properties of the upper confining unit in the study area. Ryder (1985, p. 20) reported that the leakance (the ratio of an estimated vertical hydraulic conductivity of the confining unit to its thickness), as derived from RASA flow-model investigations, ranges from 3×10^{-3} to 1×10^{-5} (ft/d)/ft for the upper confining unit in the study area. Leakance values used in this study ranged from 3×10^{-3} to 1×10^{-6} (fig. 12).

The water-bearing units of the intermediate aquifer system consist of limestone and dolomite. Clay beds of variable lateral extent and thickness can occur within the water-bearing units of the intermediate aquifer system (Duerr and Enos, 1991). Transmissivity of these water-bearing units in Hardee and De Soto Counties, as determined from aquifer tests, ranges from 400 to 7,000 ft^2/d (Ryder, 1982). The highest transmissivity in the study area is in areas adjacent to the Peace River, indicating that a more active flow system exists where ground water moves upward into the river and enhances development of secondary porosity in the carbonate rock (Ryder, 1985). Areally distributed values of transmissivity for the intermediate aquifer system are shown in figure 13. The wide range of transmissivity values for the intermediate aquifer system indicates formational heterogeneity that is substantiated by geophysical logs (Hutchinson, 1978). Storage coefficients for the intermediate aquifer system were estimated to range from 2.0×10^{-4} to 5.0×10^{-4}.

The lower confining unit lies at the base of the intermediate aquifer system and hydraulically separates the water-bearing deposits of the intermediate aquifer system from the underlying Upper Floridan aquifer. The lower confining unit has a low vertical hydraulic conductivity and consequently retards interaquifer flow. For most of the study area, however, the lower confining unit does allow water to leak downward from the intermediate aquifer system into the Upper Floridan aquifer. In some areas, hydraulic gradients are such that water is transmitted from the Upper Floridan aquifer upward through the lower confining unit into the intermediate aquifer system. Areas of upward and downward leakage through the lower confining unit of the intermediate aquifer system in September 1988 are shown in figure 14.

The thickness of the lower confining unit of the intermediate aquifer system varies widely in the study area and ranges from less than 25 ft to 185 ft (Duerr and Enos, 1991) (fig. 15). Little is known about the areal variations in hydraulic conductivity and other hydraulic properties of the lower confining unit in the study area. Ryder (1985, p. 16) reported leakance values for this unit derived from RASA ground-water flow investigations model that range from 3×10^{-4} to 7×10^{-5} (ft/d)/ft over most of the study area (fig. 15). Leakance values determined in this study, range from 1×10^{-4} to 1×10^{-5} (ft/d)/ft (fig. 15). Wilson (1977) reported that the effectiveness of this unit as a confining unit is variable. The variability in lithology and thickness of the lower confining unit result in a wide variation in the amount of leakage occurring through this unit.

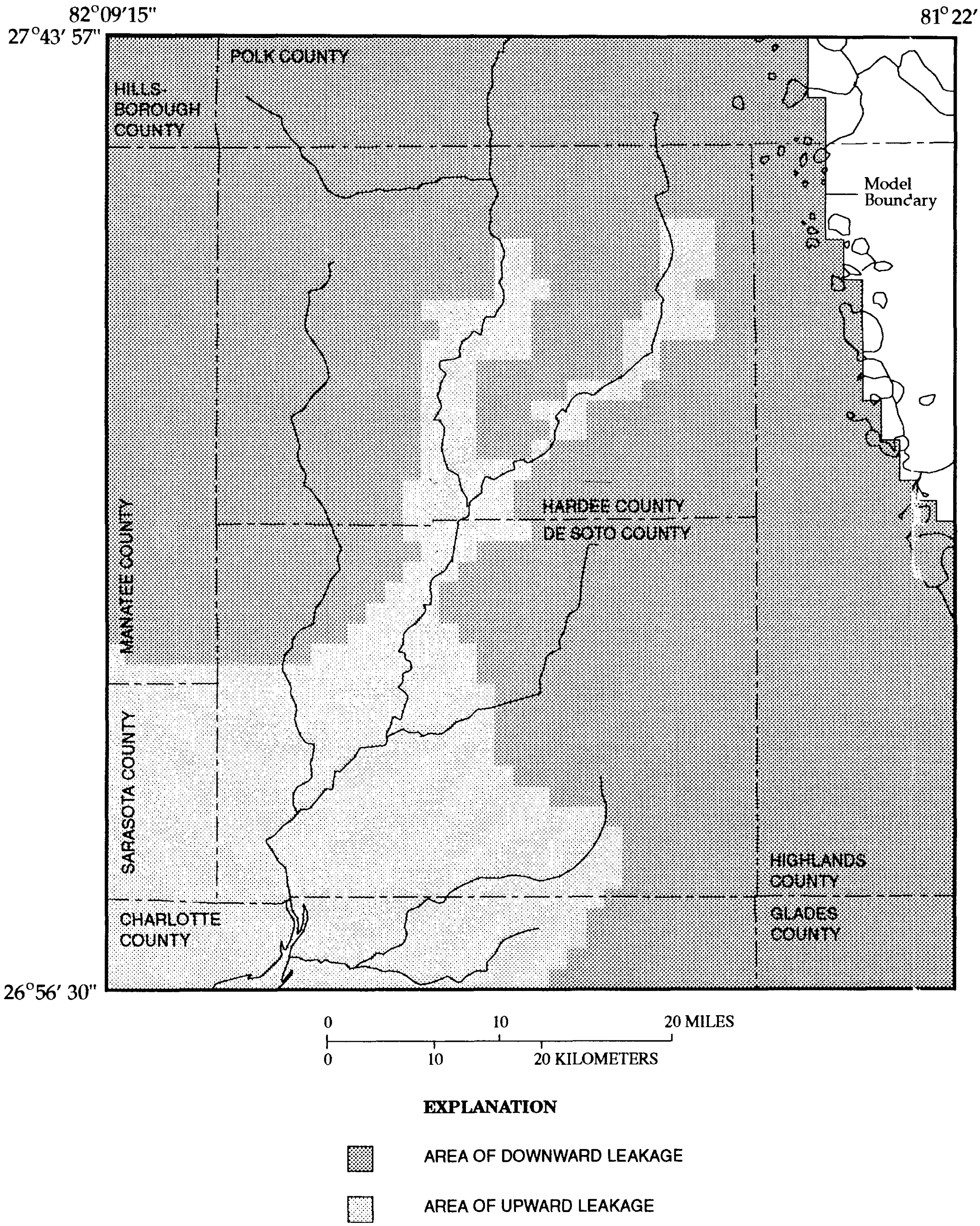


Figure 10. Areas of upward and downward leakage through the upper confining unit of the intermediate aquifer system, September 1988.

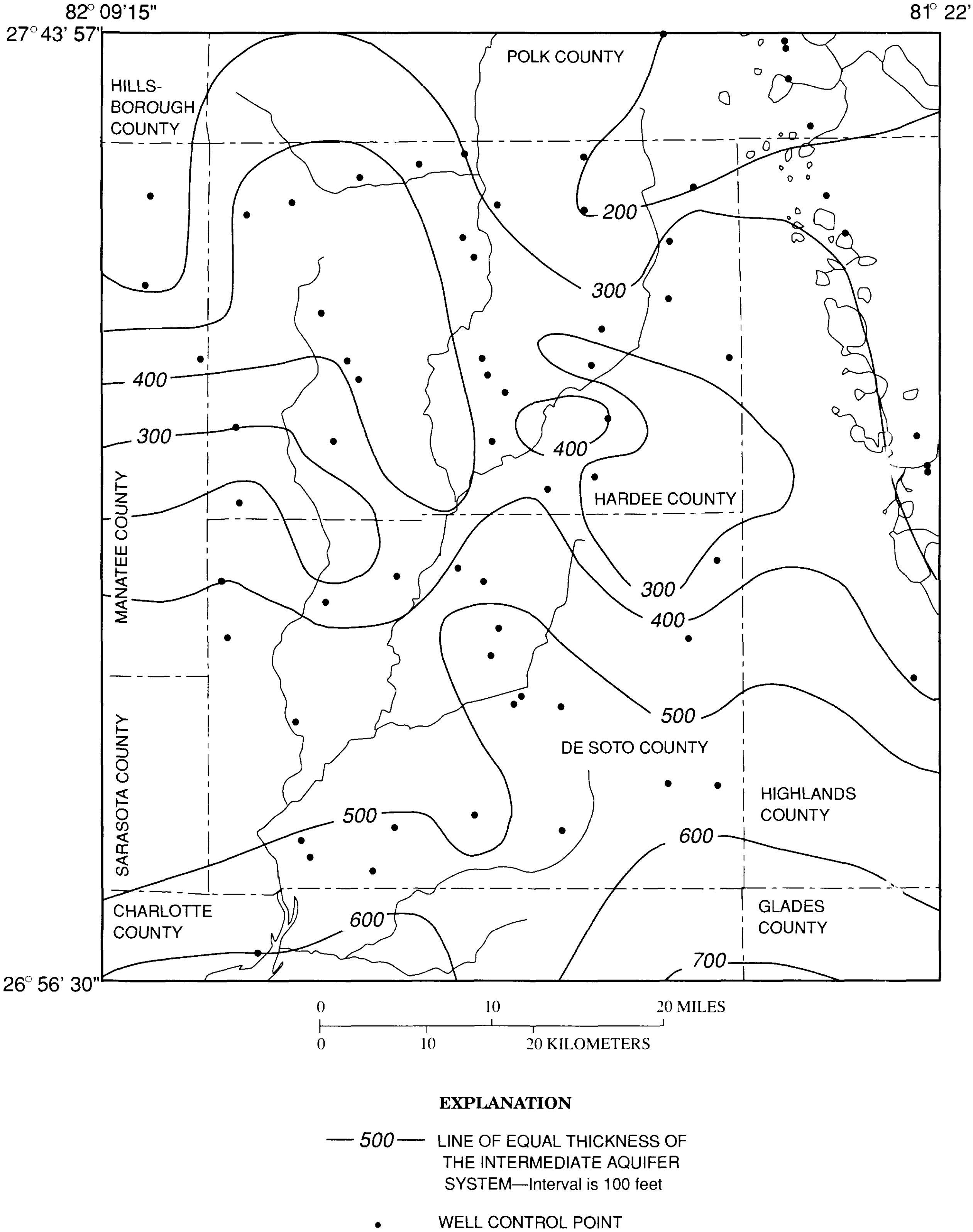


Figure 11. Thickness of the intermediate aquifer system. (Modified from Duerr and Enos, 1991; and Duerr and others, 1988.)

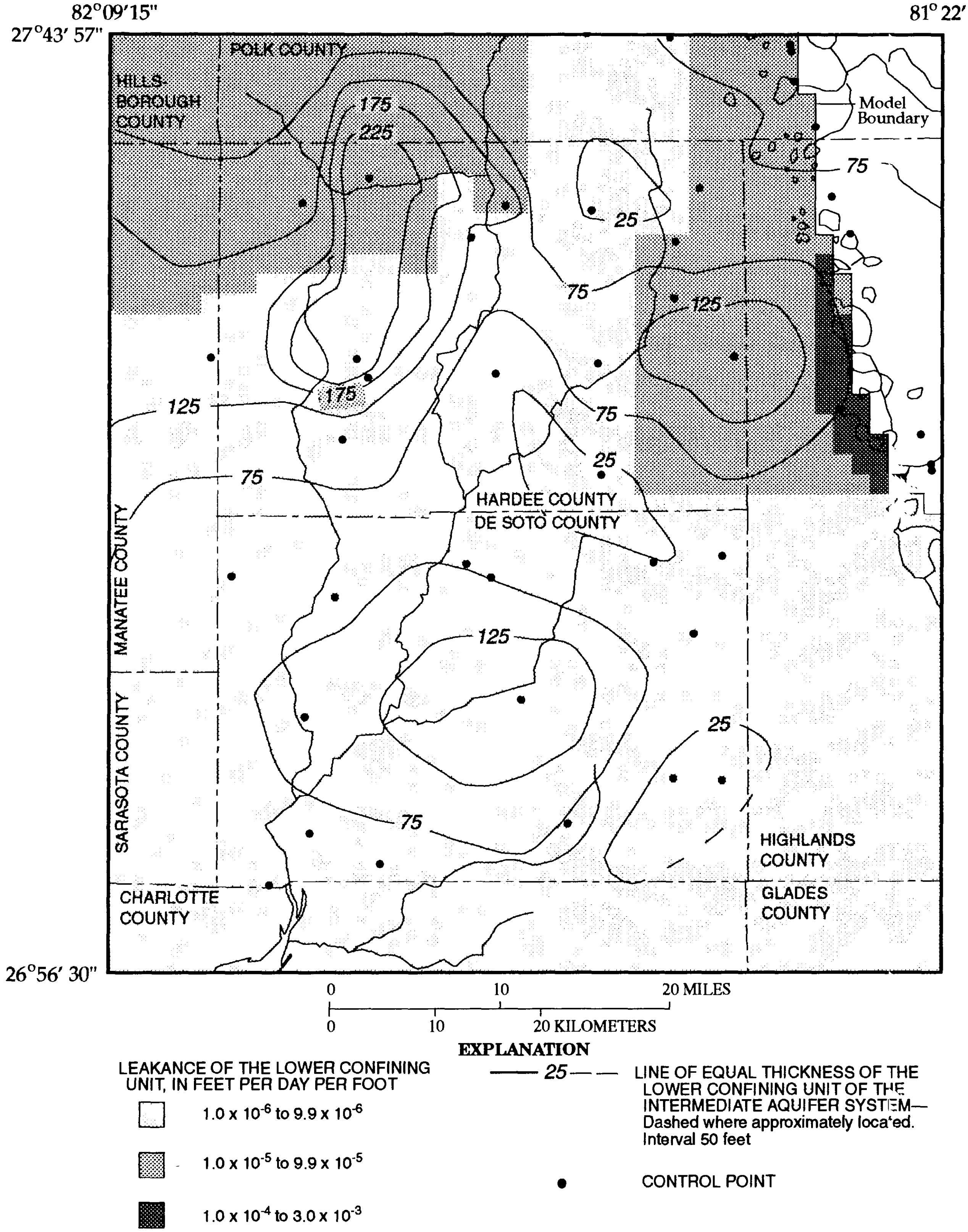


Figure 12. Thickness and model-derived leakance of the upper confining unit of the intermediate aquifer system. (Modified from Duerr and Enos, 1991; and Ryder, 1985.)

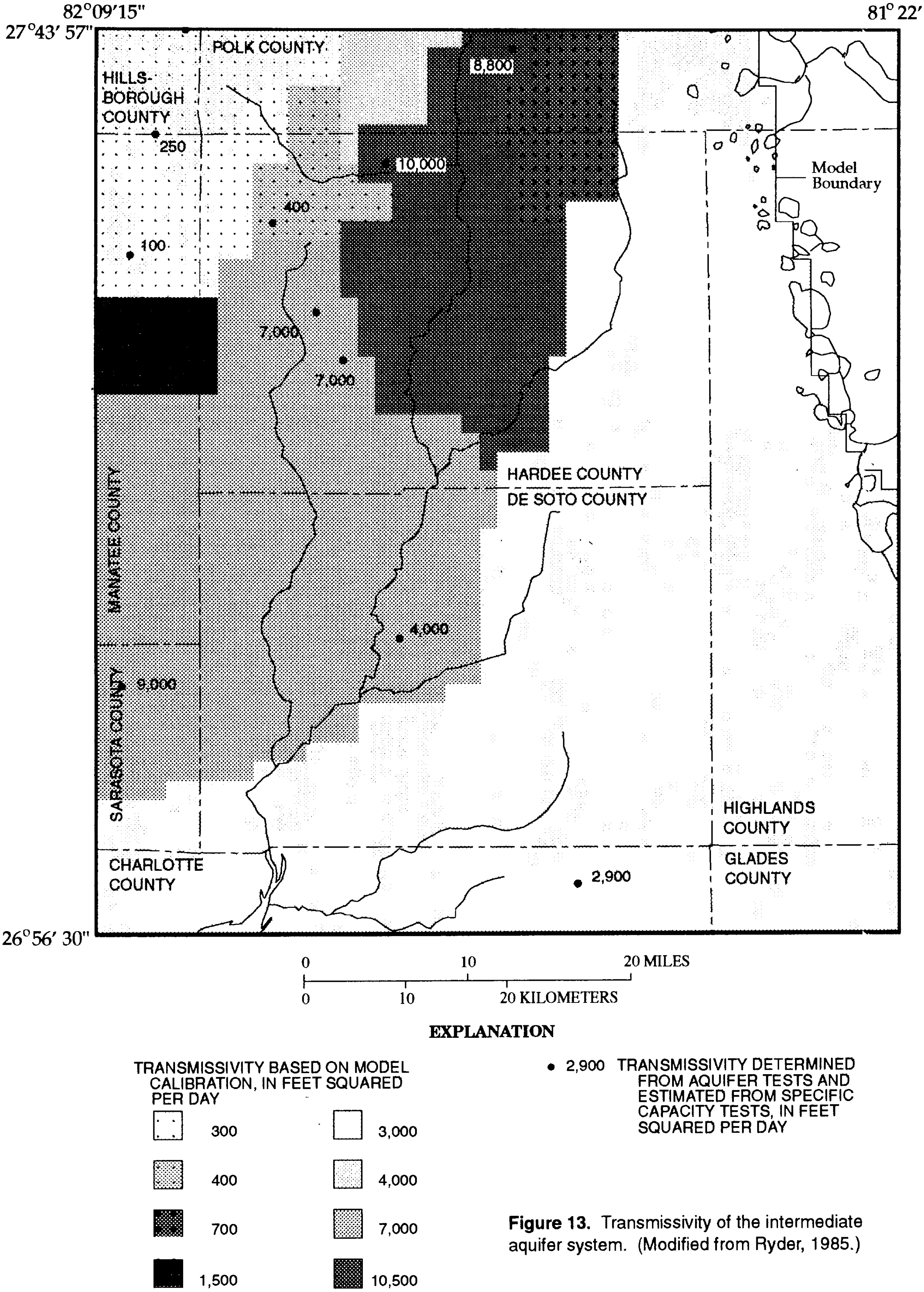


Figure 13. Transmissivity of the intermediate aquifer system. (Modified from Ryder, 1985.)

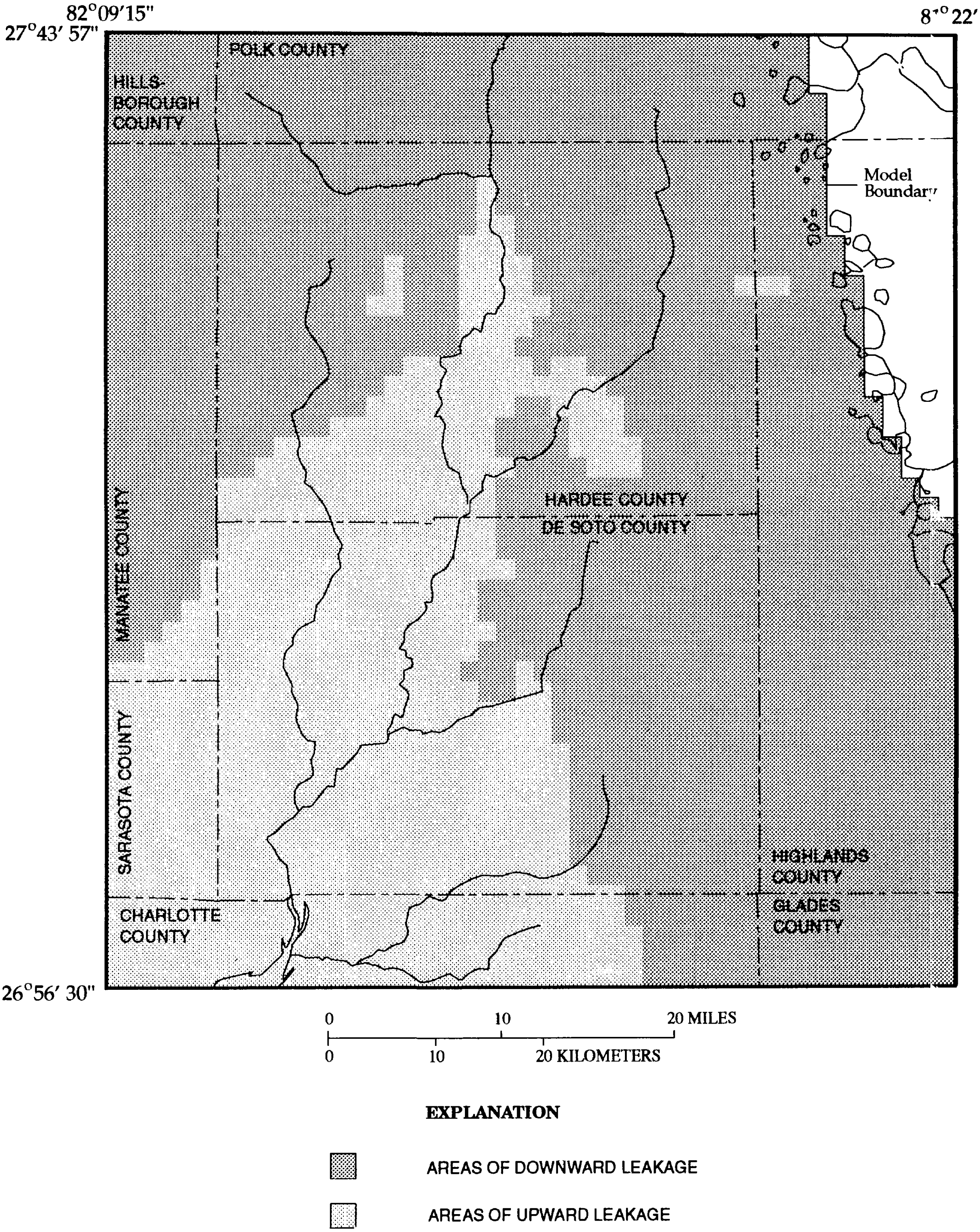


Figure 14. Areas of upward and downward leakage through the lower confining unit of the intermediate aquifer system, September 1988.

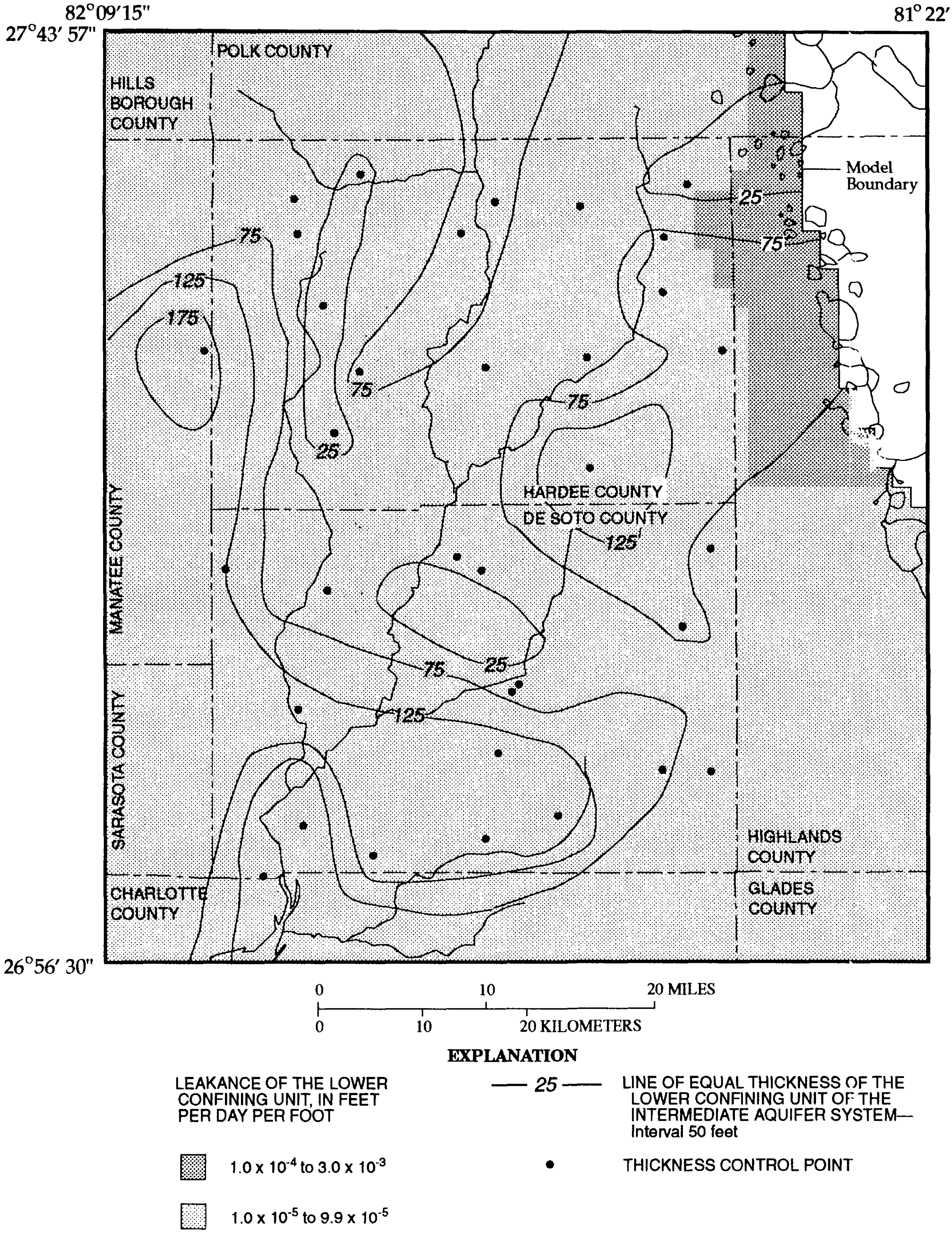


Figure 15. Thickness and leakance of the lower confining unit of the intermediate aquifer system. (Modified from Duerr and Enos, 1991; and Ryder, 1985.)

Potentiometric Surface and Water-Level Fluctuations

The potentiometric surface is an imaginary surface representing the level to which water will rise in tightly cased wells (Lohman and others, 1972). The potentiometric surface of the intermediate aquifer system in west-central Florida is mapped semiannually by the USGS in cooperation with the SWFWMD during periods when water levels are at their highest (September) and lowest (May). These maps contain potentiometric contours based on synoptic measurements of water levels in hundreds of wells open to the intermediate aquifer system.

The potentiometric surface of the intermediate aquifer system in September 1988 for Hardee and De Soto Counties and adjacent areas is shown in figure 16. This potentiometric surface represents conditions near the end of the summer rainy season at a time when the aquifer is generally unstressed by irrigation pumpage. In September 1988, the potentiometric surface ranged from about 120 ft above sea level in northwestern Hardee County to about 40 ft above sea level in southwestern Hardee County and northwestern De Soto County (fig. 16). Barr (1989a) reported that water levels in September 1988 were an average of about 2 ft higher than the levels measured in September 1987. Major features of the potentiometric surface in figure 16 are the potentiometric-surface highs in the northeastern and northwestern parts of the area and the relatively gentle hydraulic gradients throughout most of Hardee and De Soto Counties.

The potentiometric surface of the intermediate aquifer system in May 1989 is shown in figure 17. This potentiometric surface represents conditions near the end of a dry season during which extensive irrigation pumpage had occurred. In May 1989, the potentiometric surface ranged from about 110 ft above sea level in northwestern Hardee County to about 5 ft above sea level in southwestern Hardee County (fig. 17). May 1989 water levels reported by Barr (1989b) averaged about 5 ft lower than the May 1988 levels reported by Lewelling (1989). This decline was the result of below normal rainfall and heavy seasonal ground-water withdrawals for irrigation. The major feature of the potentiometric-surface contours in figure 17 is a closed depression in southwestern Hardee and northwestern De Soto Counties. The closed depression is the result of large ground-water withdrawals for agriculture.

Major changes in the potentiometric surface from September 1988 to May 1989 included an overall decline in the potentiometric surface and the development of the closed depression described earlier. A comparison of figures 16 and 17 indicates the potentiometric surface declined about 10 ft along the ridge in the eastern part of the study area and about 35 ft in the area of the closed depression.

The potentiometric surface of the intermediate aquifer system in September 1989 is shown in figure 18. The September maps for 1988 and 1989 show similar configurations; however, September 1989 potentiometric levels averaged about 4 ft lower than corresponding September 1988 levels (Knochenmus and Barr, 1990a). Rainfall for the study area was 15 in. below normal for the period September 1988 to September 1989 (Southwest Florida Water Management District, 1989), resulting in additional demands on the ground-water resources for irrigation (Knochenmus and Barr, 1990a).

Fluctuations and long-term trends of water levels in two wells open to the intermediate aquifer system are shown in figure 19. The locations of these wells are shown in figure 18. In general, these hydrographs show that (1) the altitude of the potentiometric surface changes dramatically in response to changes in discharge and recharge; (2) there is a slight downward trend in water levels from 1970 through 1988; (3) the trends in the water levels for the two wells open to the intermediate aquifer system are similar; and (4) the average annual water-level fluctuations in the wells are as much as 35 ft for the Rowell deep well and 30 ft for the Marshall deep well.

Floridan Aquifer System

The Floridan aquifer system, as defined by Miller (1986, p. 44), is a vertically continuous sequence of carbonate rocks of generally high permeability that are hydraulically connected in varying degrees and are characterized by permeabilities generally an order to several orders of magnitude greater than those rocks bounding the system above and below. The Floridan aquifer system in the study area consists of two aquifers: the Upper Floridan aquifer, which contains freshwater, and the Lower Floridan aquifer, which contains highly mineralized water. The Upper and Lower Floridan aquifers are separated by the middle confining unit (Miller, 1986). The Upper Floridan aquifer commonly consists of a few highly permeable zones separated by less permeable zones (Johnston and Bush, 1988).

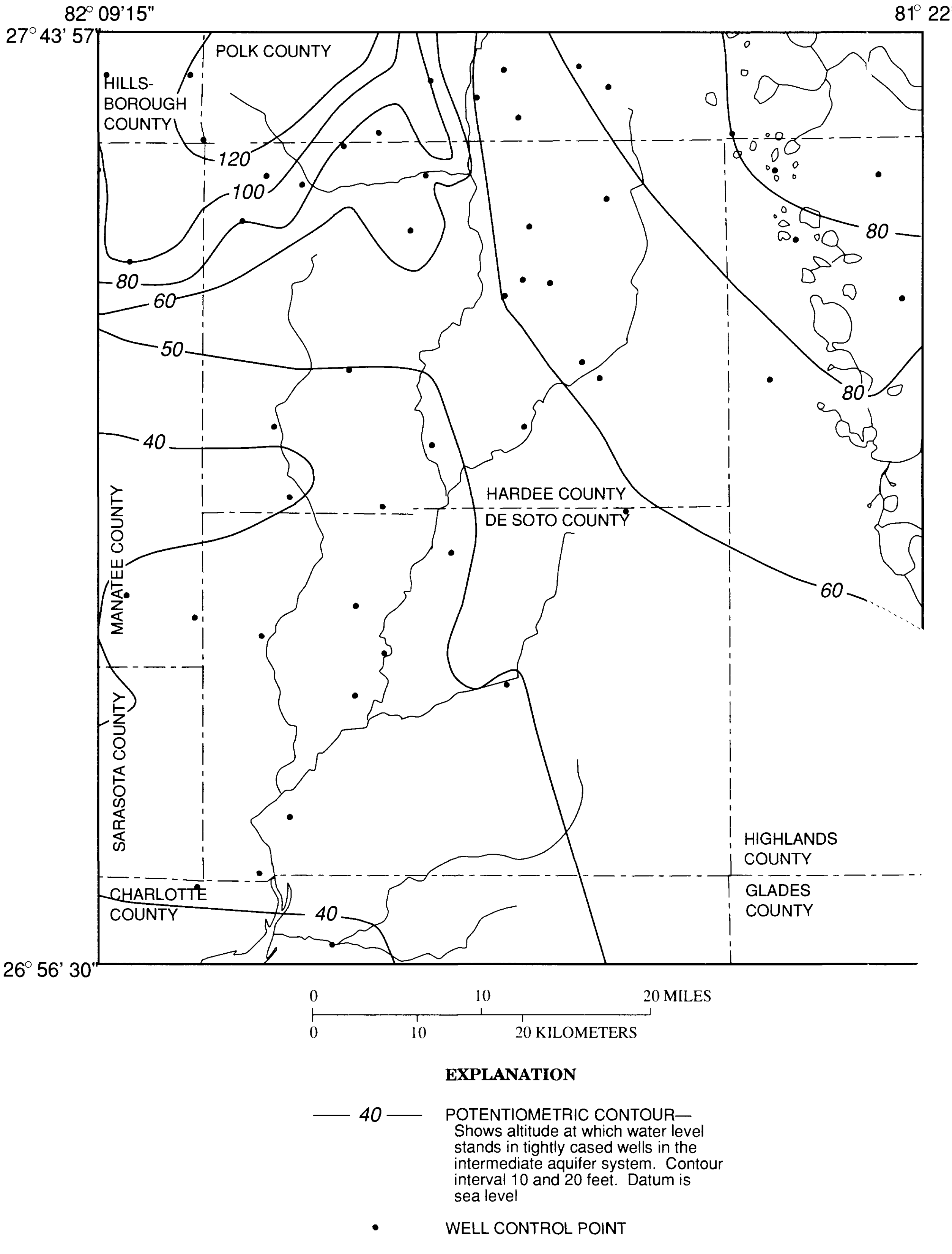
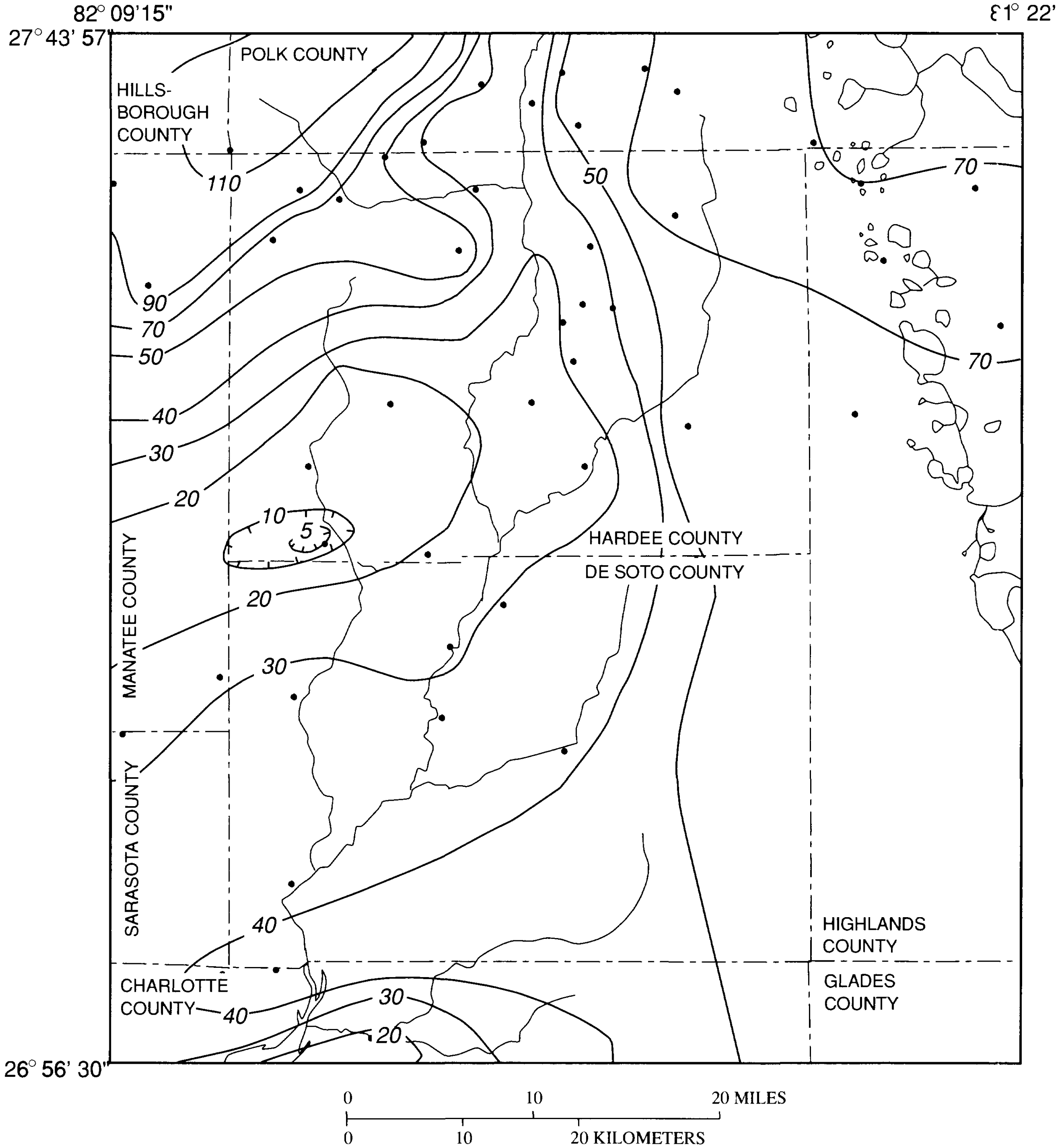


Figure 16. Potentiometric surface of the intermediate aquifer system, September 1988. (Modified from Barr, 1989a.)

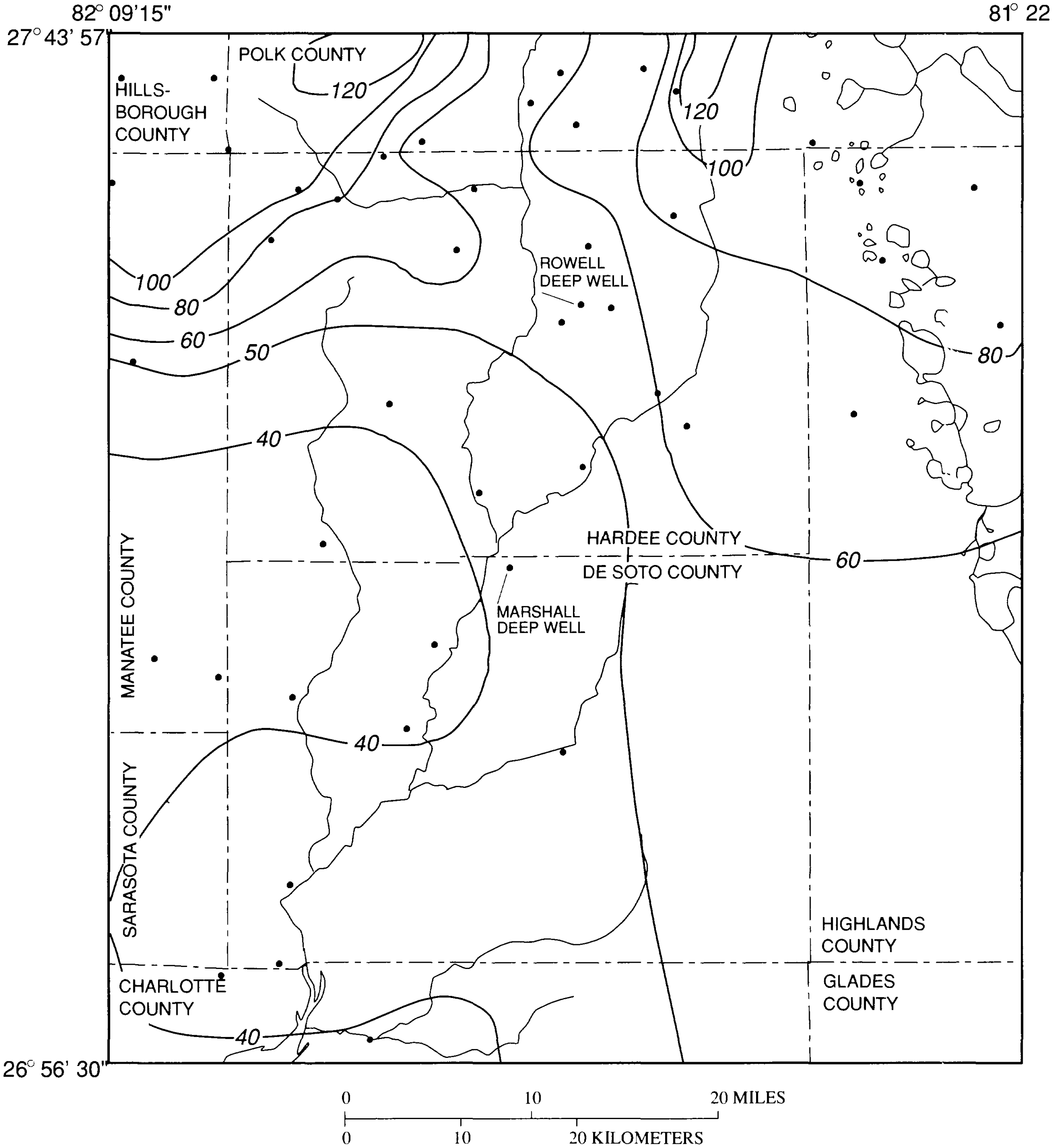


EXPLANATION

—— 30 —— POTENTIOMETRIC CONTOUR—Shows altitude at which water level stands in tightly cased wells in the intermediate aquifer system. Contour interval 5, 10, and 20 feet. Hachures indicate depressions. Datum is sea level

• WELL CONTROL POINT

Figure 17. Potentiometric surface of the intermediate aquifer system, May 1989. (Modified from Barr, 1989b.)



EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level stands in tightly cased wells in the intermediate aquifer system. Contour interval 10 and 20 feet. Datum is sea level

• WELL CONTROL POINT

Figure 18. Potentiometric surface of the intermediate aquifer system, September 1989. (Modified from Knochenmus and Barr, 1990a.)

Throughout much of the study area, however, there is enough vertical interconnection between the permeable zones for these zones to function as a single hydrogeologic unit (Ryder, 1985). The top of the Upper Floridan aquifer is the horizon below which carbonate rocks consistently occur. The base of the Upper Floridan aquifer, the middle confining unit, is characterized by limestone with a drastically reduced permeability due to the presence of intergranular evaporites (Southeastern Geological Society, 1986). In the study area, the rocks below the middle confining unit have relatively low transmissivity and commonly do not contain freshwater (Ryder, 1985). Only the freshwater part of the Floridan aquifer system, the Upper Floridan aquifer, is of interest in this report. The base of the freshwater flow system is considered the top of the middle confining unit.

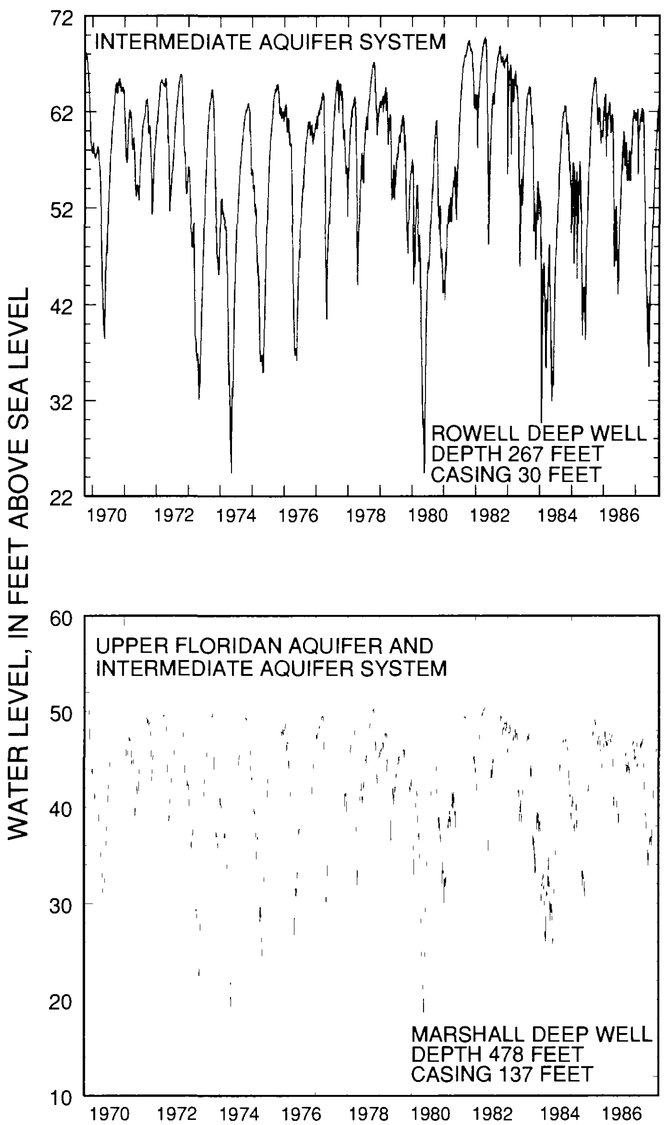


Figure 19. Long-term water-level trends for selected intermediate aquifer system wells, 1970-88. (Locations of wells are shown in fig. 18.)

Hydraulic Properties

The Upper Floridan aquifer, which is the most productive and widely used aquifer in the study area, consists of the Suwannee Limestone, the Ocala Limestone, and the Avon Park Formation (fig. 5). Thickness of the Upper Floridan aquifer ranges from 1,200 ft in northeastern Hardee County to 1,400 ft in western Hardee and De Soto Counties (fig. 20). The Upper Floridan aquifer consists of limestone and dolomite containing solution-enlarged fractures that commonly yield abundant supplies of water to wells. The most productive part of the aquifer generally occurs in a fractured dolomite section within the Avon Park Formation. The fractured dolomites in this unit are the principal sources of water to large-capacity irrigation wells in the study area (Wilson and Gerhart, 1982).

The areal distribution of transmissivity of the Upper Floridan aquifer, as determined from aquifer tests and specific capacity tests (point values) and results of flow model calibration is shown in figure 21. Transmissivities determined from aquifer tests of the Upper Floridan aquifer range from 70,600 ft^2/d in central Hardee County to 850,000 ft^2/d in northeastern De Soto County (fig. 21). The large range in transmissivities is characteristic of fractured-rock aquifers and could be due to variations in the number and size of fractures intercepted by the test well or variations in the extent of the aquifer penetrated by the well. Storage coefficients for the Upper Floridan aquifer were estimated to range from 1.0×10^{-4} to 1.2×10^{-4}.

Potentiometric Surface and Water-Level Fluctuations

The potentiometric surface of the Upper Floridan aquifer in west-central Florida is mapped semiannually by the USGS in cooperation with the SWFWMD during periods when water levels are at their highest (September) and lowest (May). These maps contain potentiometric contours based on water levels in hundreds of wells open to the Upper Floridan aquifer.

The potentiometric surface of the Upper Floridan aquifer in September 1988 for Hardee and De Soto Counties and adjacent areas is shown in figure 22.

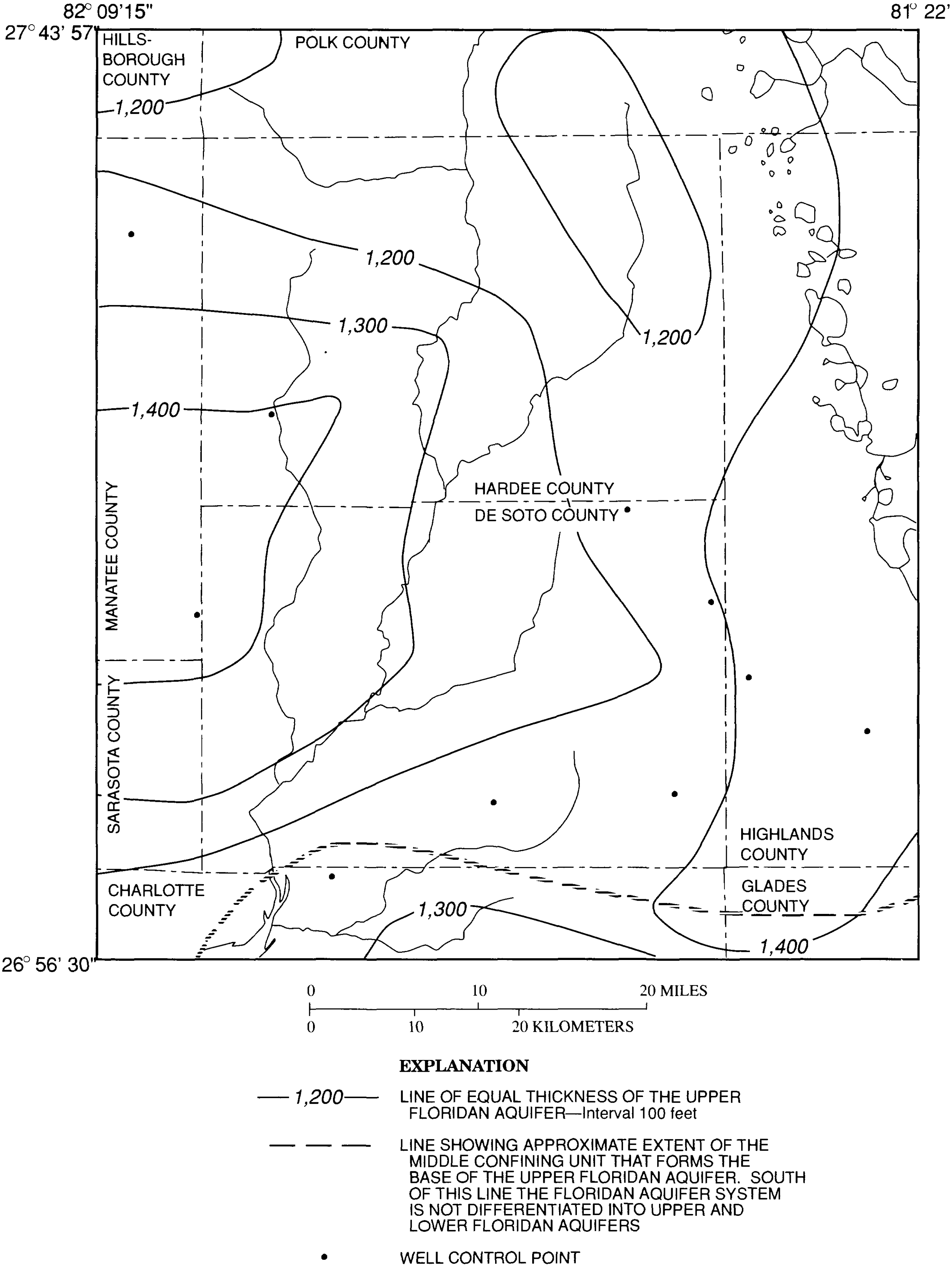
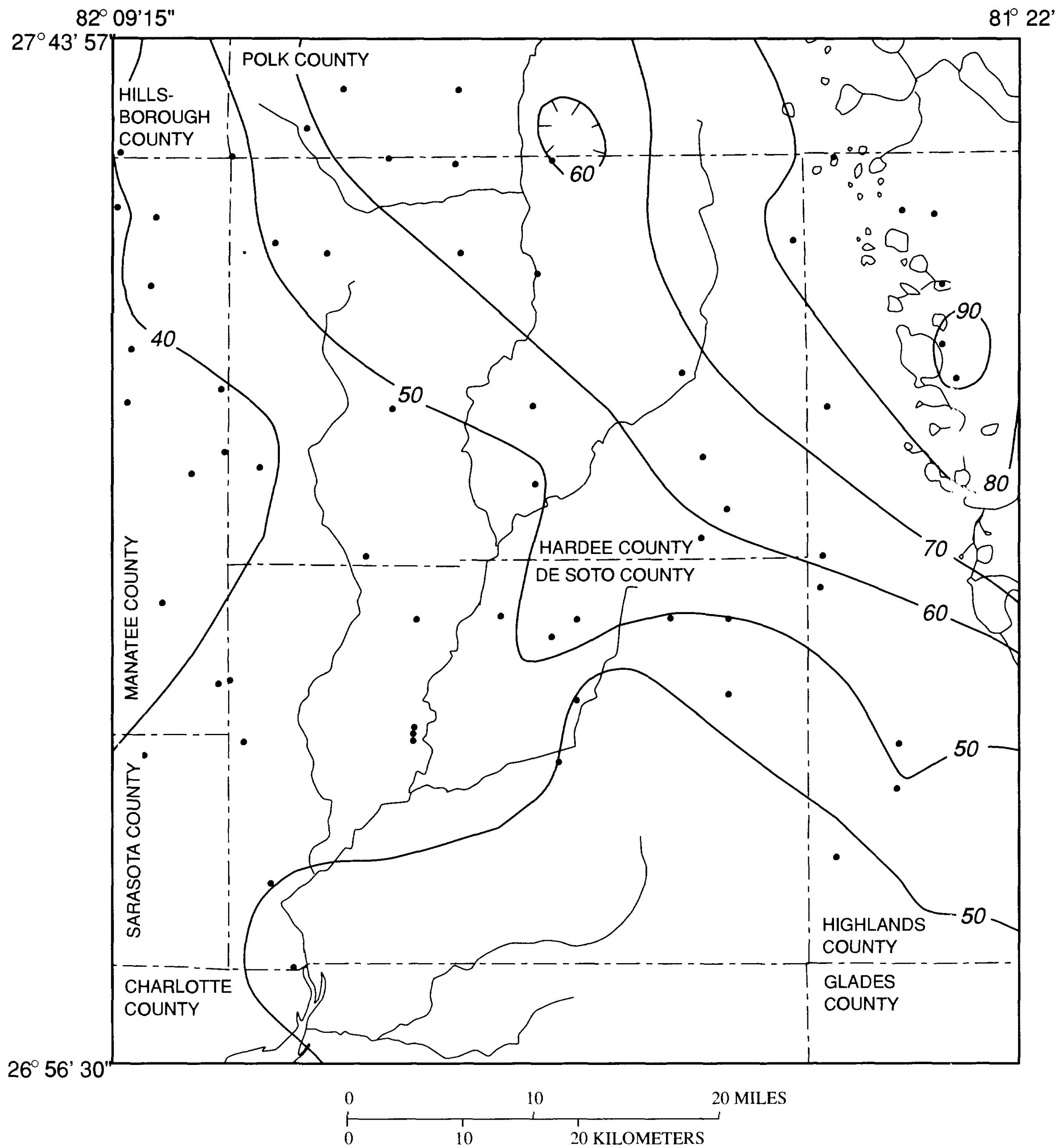


Figure 20. Thickness of the Upper Floridan aquifer. (Modified from Miller, 1982.)



EXPLANATION

— 50 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level stands in tightly cased wells in the Upper Floridan aquifer. Contour interval 10 feet. Hachures indicate depressions. Datum is sea level

• WELL CONTROL POINT

Figure 22. Potentiometric surface of the Upper Floridan aquifer, September 1988. (Modified from Barr, 1989b.)

The potentiometric surface depicted in figure 22 represents conditions near the end of the summer rainy season when the aquifer generally is unstressed by irrigation pumping. In September 1988, the potentiometric surface ranged from about 80 ft above sea level in northeastern Hardee County to about 40 ft above sea level in southwestern Hardee County and northwestern De Soto County (fig. 22). Barr (1989c) reported that water levels in September 1988 were an average of about 2 ft higher than the levels measured in September 1987. Major features of the potentiometric surface in figure 22 are the potentiometric-surface highs in the northeastern part of the study area and the relatively gentle hydraulic gradients throughout most of Hardee and De Soto Counties.

The potentiometric surface of the Upper Floridan aquifer in May 1989 is shown in figure 23. This surface represents conditions near the end of a dry season during which extensive irrigation pumpage occurred. In May 1989, the potentiometric surface ranged from about 60 ft above sea level in northeastern Hardee County to about 5 ft above sea level in western Hardee County (fig. 23). May 1989 water levels averaged about 3 ft lower than the May 1988 levels reported by Lewelling (1988). This decline was the result of below normal rainfall and unusually large ground-water withdrawals for irrigation. A major feature of the potentiometric surface in figure 23 is an east-west trough in southern Hardee and northern De Soto Counties caused by large ground-water withdrawals for irrigation.

The major change in the potentiometric surface from September 1988 to May 1989 is an overall decline. A comparison of figures 22 and 23 indicates that the declines in the potentiometric surface during this period were about 20 ft in the eastern part of Hardee County and about 35 to 40 ft in western Hardee County and eastern Manatee County.

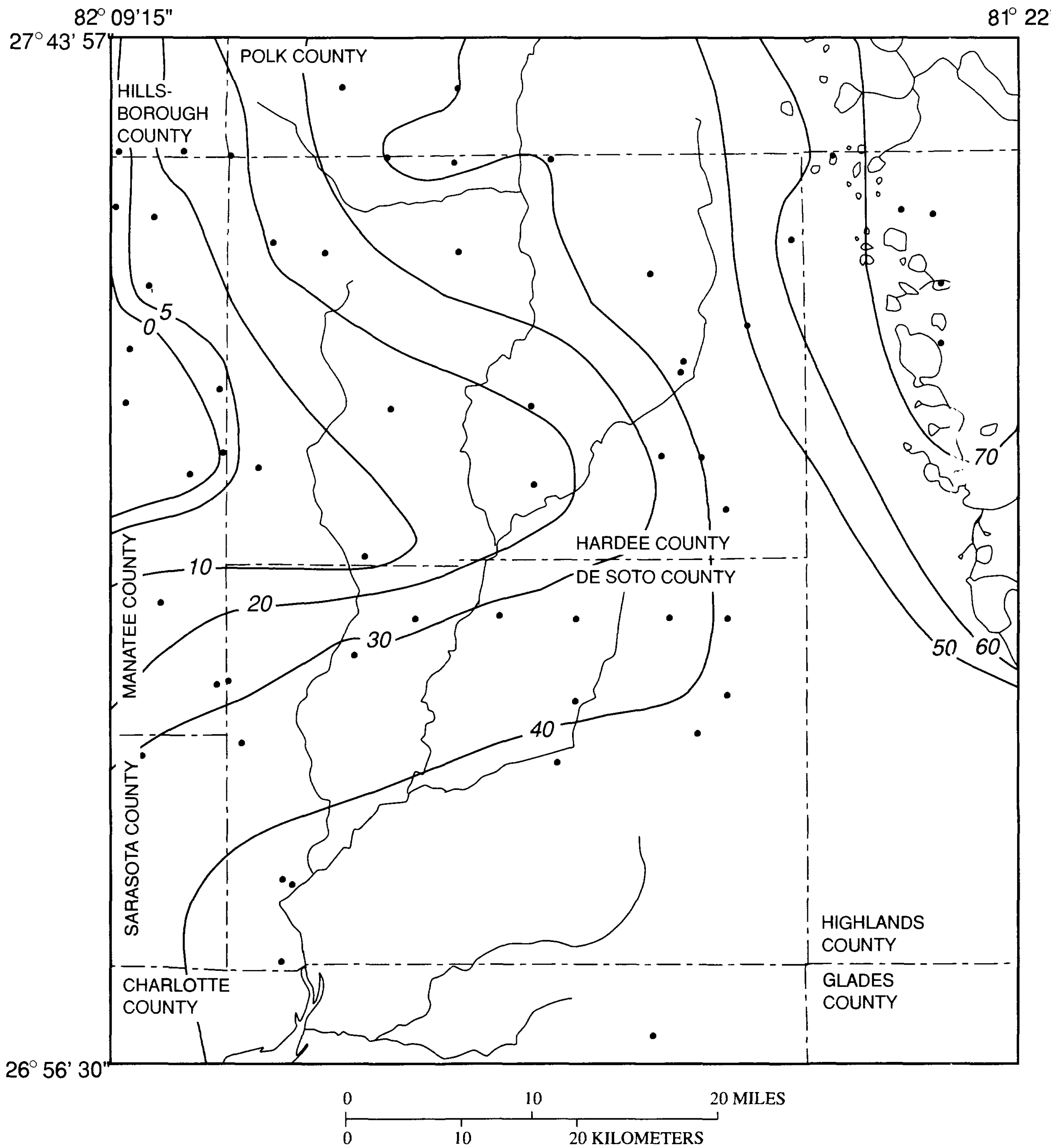
The potentiometric surface of the Upper Floridan aquifer in September 1989 is shown in figure 24. This potentiometric surface is similar to that for September 1988, except the potentiometric surface averaged about 4 ft lower in September 1989 than in September 1988 (Knochenmus and Barr, 1990b). As stated previously, rainfall for the study area was 15 in. below normal for the period September 1988 to September 1989, resulting in increased ground-water withdrawals for irrigation (Southwest Florida Water Management District, 1989).

Fluctuations and long-term trends in water levels for two wells open to the Upper Floridan aquifer are shown in figure 25. The locations of these wells are shown in figure 24. In general, these hydrographs show that (1) the altitude of the potentiometric surface changes dramatically in response to changes in discharge and recharge; (2) there is a slight downward trend in water levels from 1978 through 1988; (3) the trends in the water levels for the two wells open to the Upper Floridan aquifer are similar; and (4) seasonal water-level fluctuations were as much as 20 ft for the ROMP 26 Avon Park well and 40 ft for the ROMP 31 Avon Park well.

WATER USE

In 1988, water was withdrawn from the intermediate aquifer system and the Upper Floridan aquifer at a combined rate of 122 Mgal/d in Hardee and De Soto Counties for public supply, rural (self-supplied domestic), industrial, irrigation, and miscellaneous uses (table 1). Estimated water use in the study area for 1988 is listed by county, category of use, and aquifer in table 1. The accuracy of these water-use estimates varies from category to category. For example, public-supply and larger industrial water-use estimates are usually more accurate because most public-supply systems and industrial facilities meter their usage, whereas agricultural and rural (self-supplied domestic) water-use estimates are often less accurate because these types of water use generally are not metered. For 1988, water-use estimates for agricultural withdrawals were based on irrigated crop acreage estimates from the water-use permitting files of the SWFWMD. Seasonal variations in agricultural water use were estimated based on studies of water use on selected benchmark farms (Duerr and Trommer, 1982; Duerr and Sohm, 1983). Additional water-use data were obtained from Geurink (1986). Water-use permits do not delineate withdrawal data by aquifer; therefore, estimates of water withdrawn from the intermediate aquifer system and from the Upper Floridan aquifer were based upon well-construction data, including total depth and cased interval, aquifer depth, and transmissivity.

Of the five water-use categories, irrigation accounted for the largest percentage of the ground water withdrawn. Irrigation is used extensively for crop production because of the unpredictable rainfall distribution and the low water-retention capacity of the sandy soils in the study area. In Hardee and De Soto Counties, 115.6 Mgal/d was withdrawn for irrigation use during 1988, of which 78.6 Mgal/d, or 68 percent, was used for citrus irrigation (fig. 26). Ground water withdrawn for all uses, irrigated citrus acreage, and rainfall for 1975-88 are shown in figure 27. The quantity of ground water withdrawn for citrus irrigation generally has increased since 1983, even though overhead sprinklers have been replaced with more efficient microjet systems at many groves.

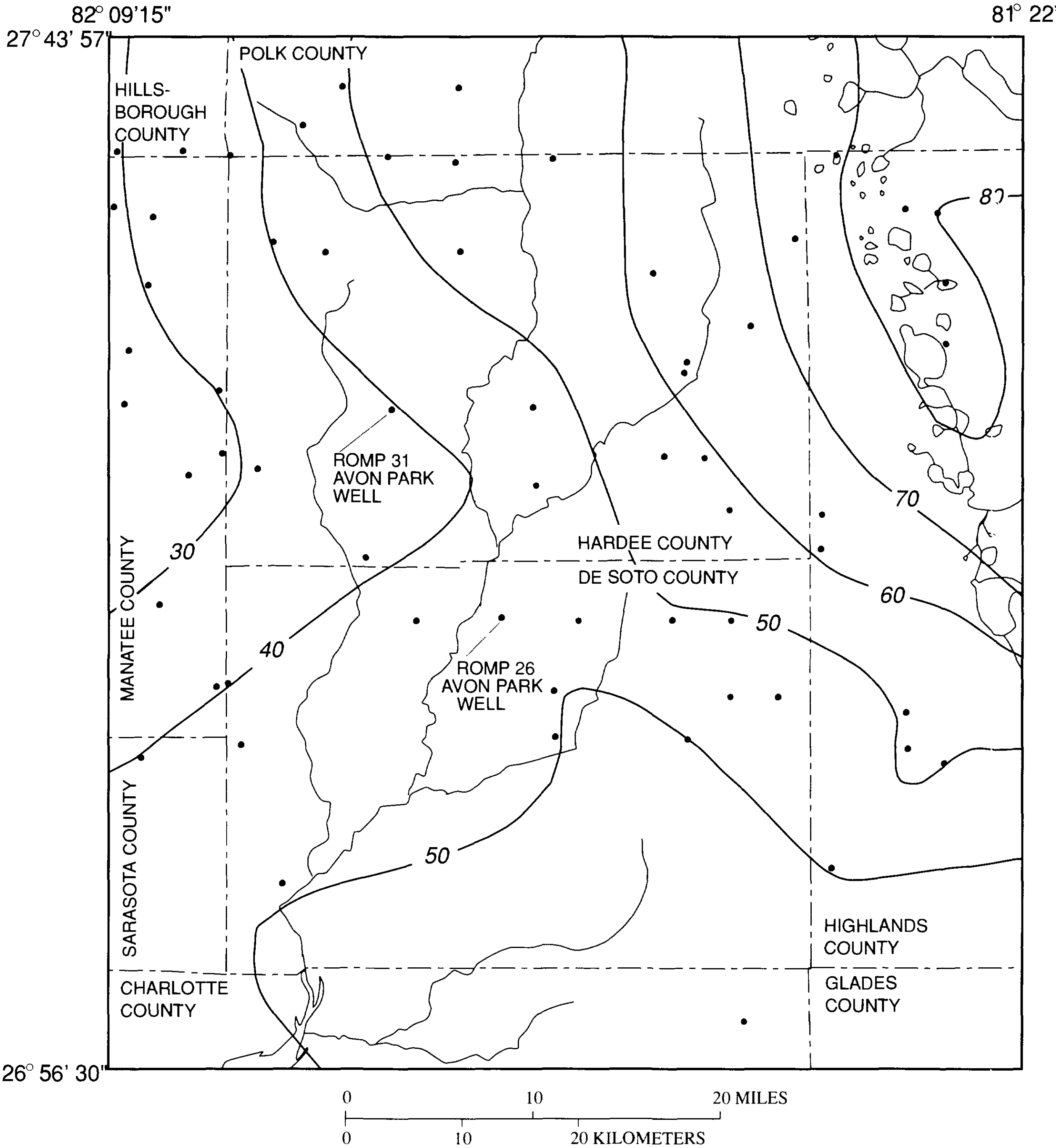


EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level stands in tightly cased wells in the Upper Floridan aquifer. Contour interval 10 feet. Datum is sea level

• WELL CONTROL POINT

Figure 23. Potentiometric surface of the Upper Floridan aquifer, May 1989. (Modified from Barr, 1989.)



EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level stands in tightly cased wells in the Upper Floridan aquifer. Contour interval 10 feet. Datum is sea level

• WELL CONTROL POINT

Figure 24. Potentiometric surface of the Upper Floridan aquifer, September 1989. (Modified from Knochenmus and Barr, 1990b.)

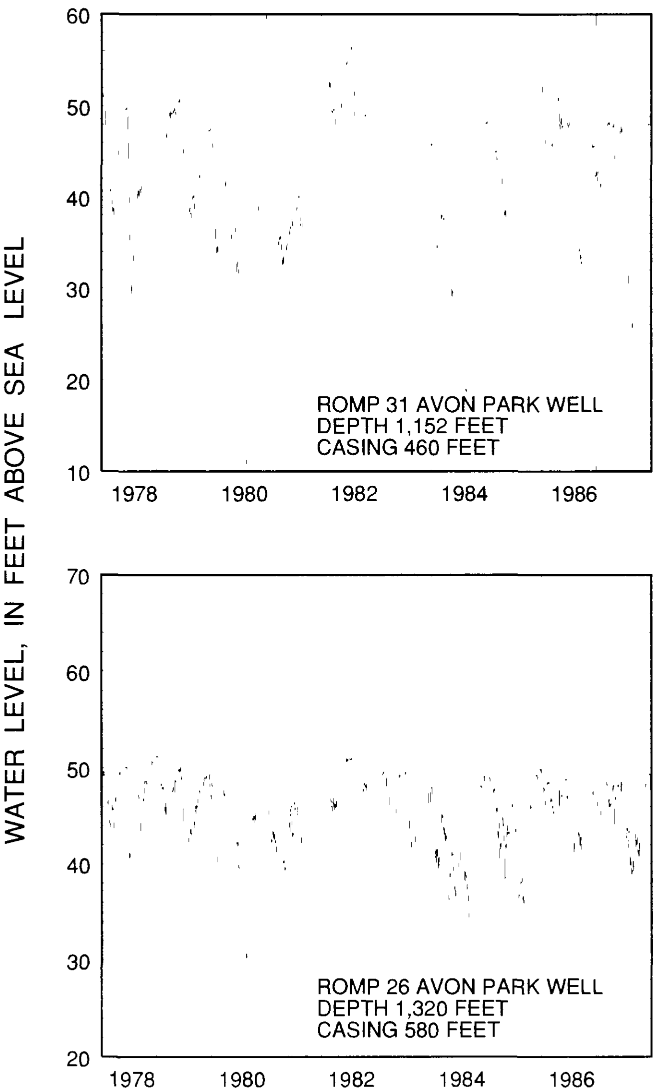


Figure 25. Long-term water-level trends for selected Upper Floridan aquifer wells, 1978-88. (Locations of wells are shown in fig. 24.)

Of the 122 Mgal/d withdrawn in 1988 for all five water-use categories, 13 percent was from the intermediate aquifer system and 87 percent was from the Upper Floridan aquifer. Little water is withdrawn from the surficial aquifer in Hardee and De Soto Counties, and water use from this aquifer was considered to be zero for this study. On the basis of SWFWMD water-use permits, 302 irrigation wells are open to the intermediate aquifer system in Hardee and De Soto counties and parts of adjacent counties, and, of those wells, 258 are used for citrus irrigation (fig. 28). Wells open to the intermediate aquifer system generally yield less than 300 gal/min (Wilson, 1977).

Table 1. Ground-water withdrawals in Hardee and De Soto Counties, by use category, 1988

[All values are in million gallons per day. Modified from Sorensen and others, 1990]

Category	Hardee	De Soto	Total
Public supply			
Intermediate aquifer system	0	0.8	0.8
Upper Floridan aquifer	1.4	0	1.4
Total	1.4	0.8	2.2
Rural			
Intermediate aquifer system	2.0	1.6	3.6
Upper Floridan aquifer	0	0	0
Total	2.0	1.6	3.6
Industrial			
Intermediate aquifer system	0	0	0
Upper Floridan aquifer	.2	0	.2
Total	0.2	0	0.2
Irrigation			
Intermediate aquifer system	6.6	4.9	11.5
Upper Floridan aquifer	59.2	44.9	104.1
Total	65.8	49.8	115.6
Miscellaneous			
Intermediate aquifer system	.2	.1	.3
Upper Floridan aquifer	0	.1	.1
Total	0.2	0.2	0.4
Total (all uses)			
Intermediate aquifer system	8.8	7.4	16.2
Upper Floridan aquifer	60.8	45.0	105.8
Total	69.8	52.4	122.0

The principal source of ground-water supply in the study area is the highly productive Upper Floridan aquifer. On the basis of SWFWMD water-use permits, 1,036 irrigation wells are open to the Upper Floridan aquifer in Hardee and De Soto Counties and parts of adjacent counties. Of these wells, 799 are used for citrus irrigation (fig. 29). Upper Floridan aquifer wells can yield as much as 2,500 gal/min and are commonly 10 to 16 in. in diameter (Duerr and Enos, 1991). Although many wells are open to the Upper Floridan aquifer, it was estimated that only 10 percent of the irrigation wells are open only to this unit; the remaining 90 percent are open to both the intermediate aquifer system and the Upper Floridan aquifer.

Ground-water withdrawals for irrigation vary seasonally as a result of variations in temperature and precipitation. There are two irrigation seasons each year: a fall season from October through December and a winter-spring season from January through May. There generally are little or no withdrawals for irrigation during the rainy season of June through mid-September.

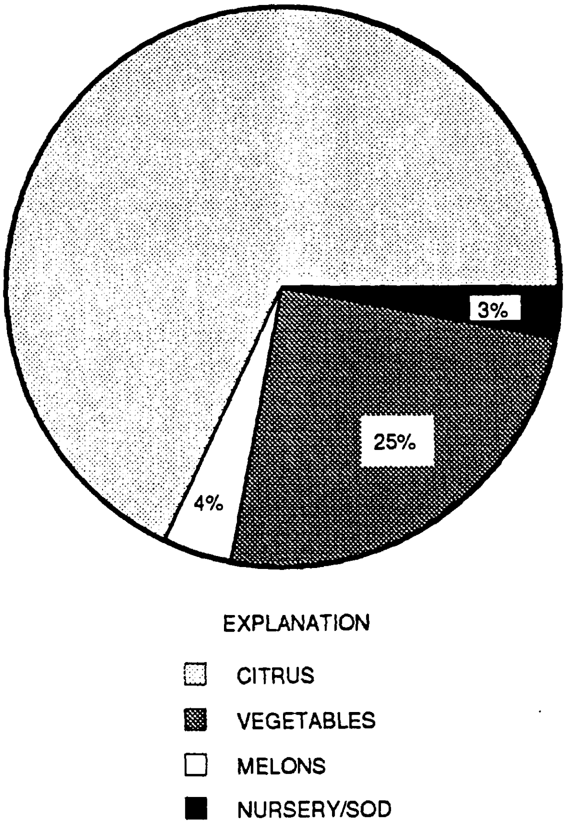


Figure 26 (above). Percentage distribution of irrigation water use, by crop, Hardee and De Soto Counties, 1988. (Modified from Sorenson and others, 1990.)

The interrelation between rainfall, irrigation pumpage, and water levels for 1988-89 is apparent from a comparison of the graphs shown in figure 30. The September water levels in this figure represent conditions near the end of the summer rainy season when both the intermediate aquifer system and the Upper Floridan aquifer are usually unstressed by irrigation pumpage. The steep downward trend in ground-water levels during the winter and spring is due to low rainfall and increased withdrawals for irrigation. The water levels are lowest in May, but recover rapidly with the onset of summer rains and the decrease in withdrawals for irrigation.

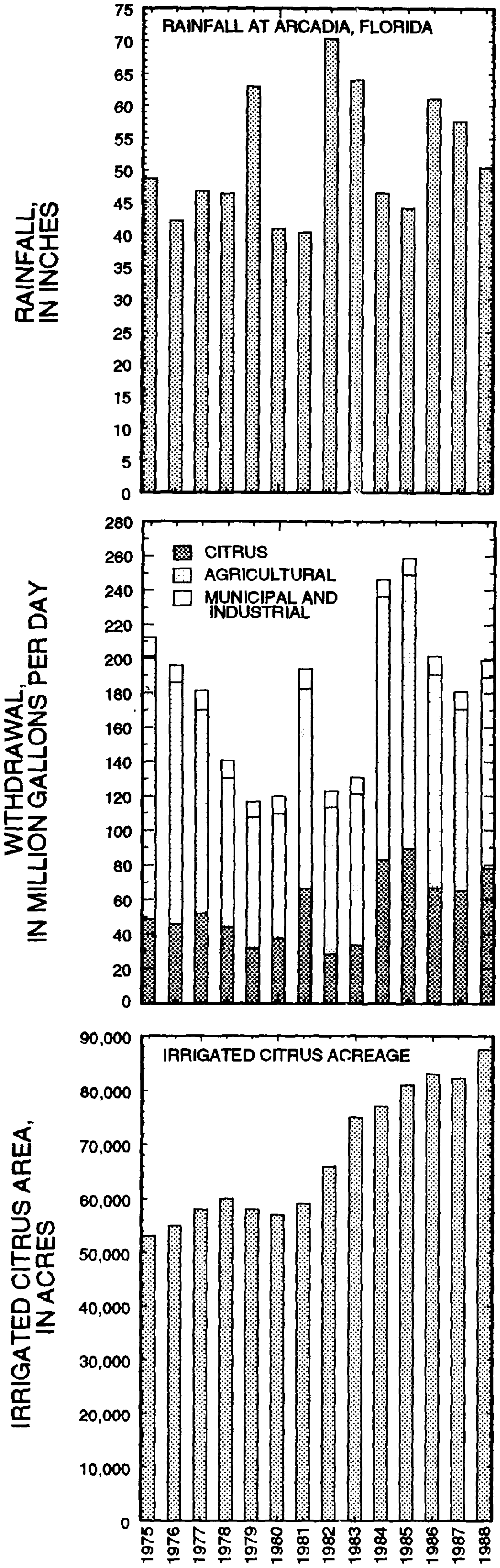


Figure 27 (at right). Rainfall at Arcadia, ground-water withdrawals, and irrigated citrus acreage in Hardee and De Soto Counties, 1975-88.

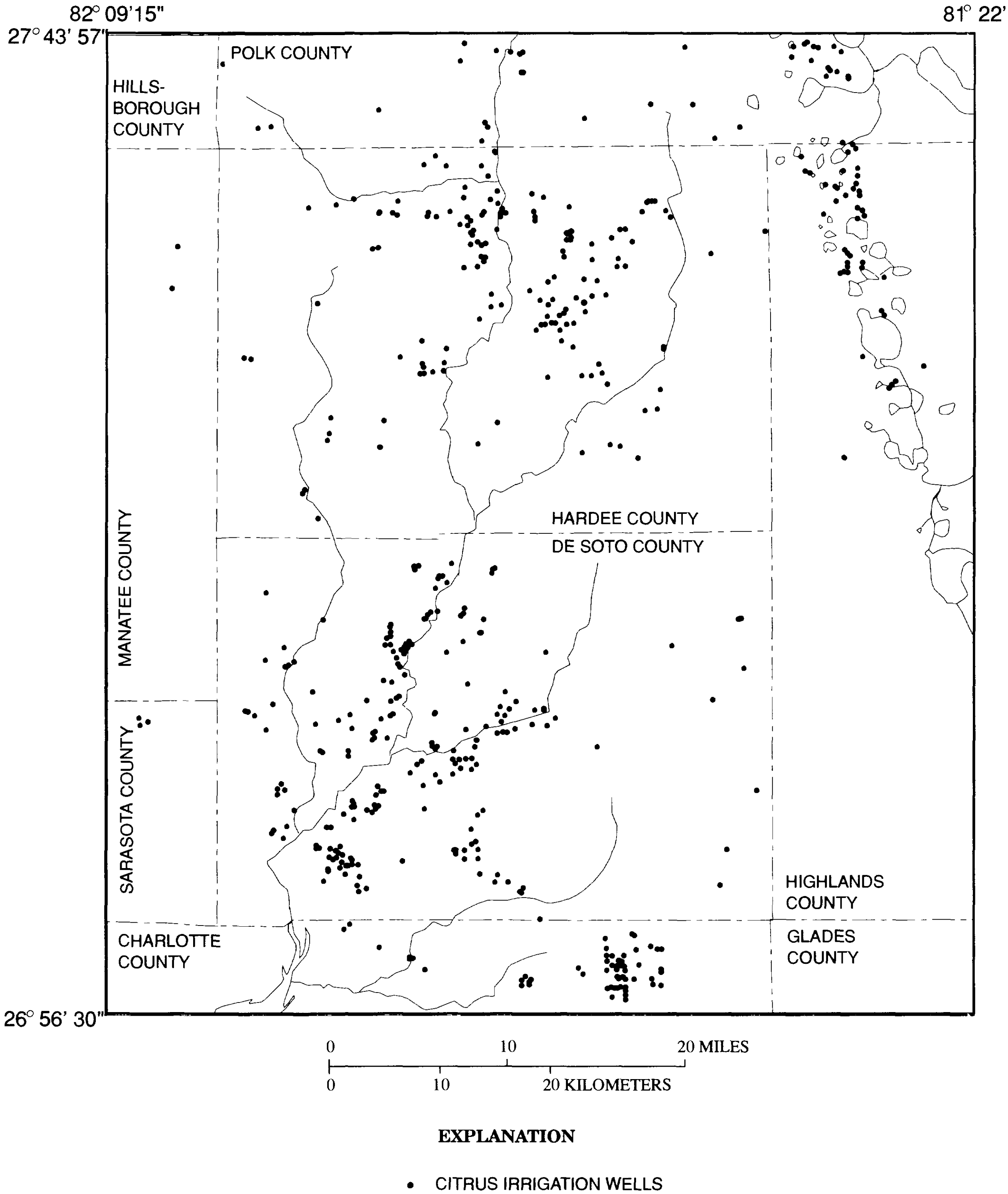


Figure 28. Locations of citrus irrigation wells open to the intermediate aquifer system, 1988.

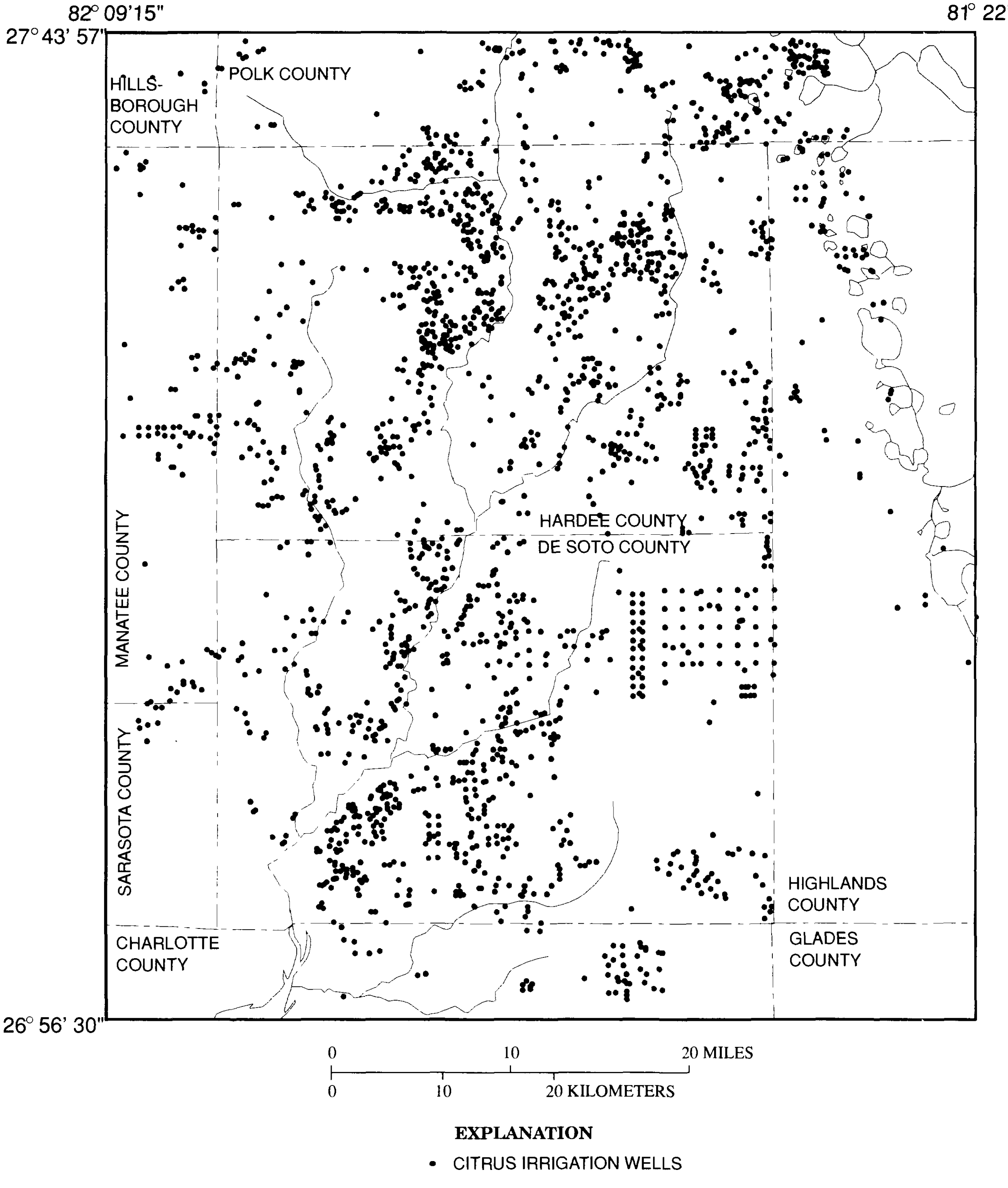


Figure 29. Locations of citrus irrigation wells open to the Upper Floridan aquifer, 1988.

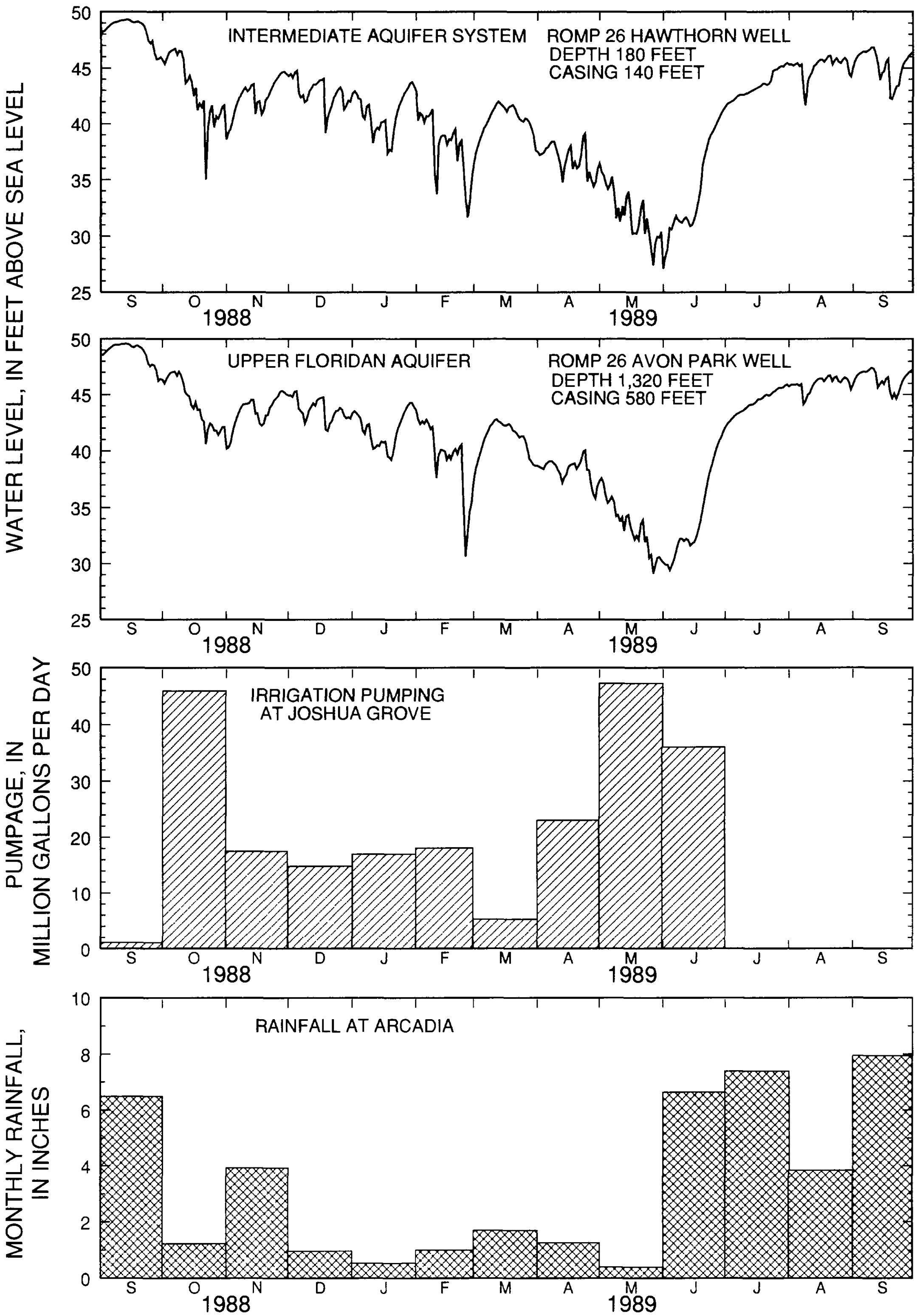


Figure 30. Ground-water levels in wells open to the intermediate aquifer system and the Upper Floridan aquifer, irrigation pumpage at Joshua Grove, and monthly rainfall at Arcadia, September 1988 through September 1989. (See fig. 1 for site location.)

SIMULATION OF GROUND-WATER FLOW

The preceding analysis of the hydrogeologic framework formed the basis for developing a conceptual model of ground-water flow. A generalized north-south hydrogeologic representation of the aquifer system is illustrated in figure 31. Procedures in the conceptualization include developing an understanding of the ground-water system in terms of external and internal geometry (the geologic framework), material and fluid parameters (transmissivity and hydraulic gradients), and physical and hydraulic boundaries. This conceptual model of how the ground-water system functions was then used to develop a numerical ground-water flow model.

For simulation purposes, the designated hydrogeologic units in the study area are represented by three model layers corresponding to the surficial aquifer (layer 1), the intermediate aquifer system (layer 2), and the Upper Floridan aquifer (layer 3) (fig. 32). Layer 1, representing the surficial aquifer, is represented in the model by a distribution of specified heads that correspond to water-table elevations of the surficial aquifer during a specified period. These heads remain constant (do not change) during simulation representing infinite sources or sinks to ground-water flow. Layer 1, herein, is termed a source-sink layer. Layers 2 and 3 are termed active layers. The modeling approach used in this study does not account for changes in storage or horizontal flow in confining units. Accordingly, confining units between the surficial aquifer and the intermediate aquifer system and between the intermediate aquifer system and the Upper Floridan aquifer are represented by confining unit leakance distributions, and only vertical flow is simulated, representing leakage between aquifers. Vertical flow within aquifers in the study area is considered negligible, and only horizontal flow is simulated within active model layers.

The USGS modular ground-water flow model (McDonald and Harbaugh, 1984) was used to simulate ground-water flow in the intermediate aquifer system and the Upper Floridan aquifer. The model uses a finite-difference method in which partial-differential equations that describe ground-water flow are solved numerically. The model is termed quasi-three-dimensional as it computes two-dimensional (x,y) flow in the horizontal (x,y) plane of each model layer and one-dimensional vertical (z) flow across confining beds.

The model area covers 2,592 mi^2 and, in addition to Hardee and De Soto Counties, includes parts of Sarasota, Manatee, Hillsborough, Polk, Highlands Glades, and Charlotte Counties (fig. 1). The model area is subdivided into a finite-difference, block-centered grid of 47 rows and 46 columns (fig. 33). Each of the 2,162 grid blocks is 5,390 ft wide (1 minute of latitude) by 6,050 ft long (1 minute of longitude). Because of the configuration of the model boundaries, ground-water flow is actively simulated only at 2,030 grid blocks, representing a surface area of about 2,374 mi^2.

Boundary Conditions

Boundary conditions simulated in this model are an upper specified-head boundary that represents the water table of the surficial aquifer, a no-flow boundary at the base of freshwater flow that represents the top of the middle confining unit of the Floridan aquifer system, and a lateral no-flow boundary oriented along the Lake Wales Ridge in the northeastern part of the study area that represents a hydraulic divide in both the intermediate aquifer system and the Upper Floridan aquifer (figs. 16-18, 22-24). Other lateral boundaries for model layers 2 and 3 are all general head boundaries.

The upper boundary, the water table in the surficial aquifer, was assigned a specified head because the seasonal fluctuation of the water table throughout most of the study area generally is small (in the range of 2-7 ft). There is no-long term change (fig. 9), indicating that the summer rains generally are adequate to replenish winter storage depletions of the surficial aquifer. Small fluctuations in the water table are assumed to be controlled by loss of water to evapotranspiration and drainage to streams. Pumping from underlying aquifers is assumed to have little effect on the water table on a regional scale because of the low leakance of the upper confining unit of the intermediate aquifer system and the large storage capacity of the surficial aquifer.

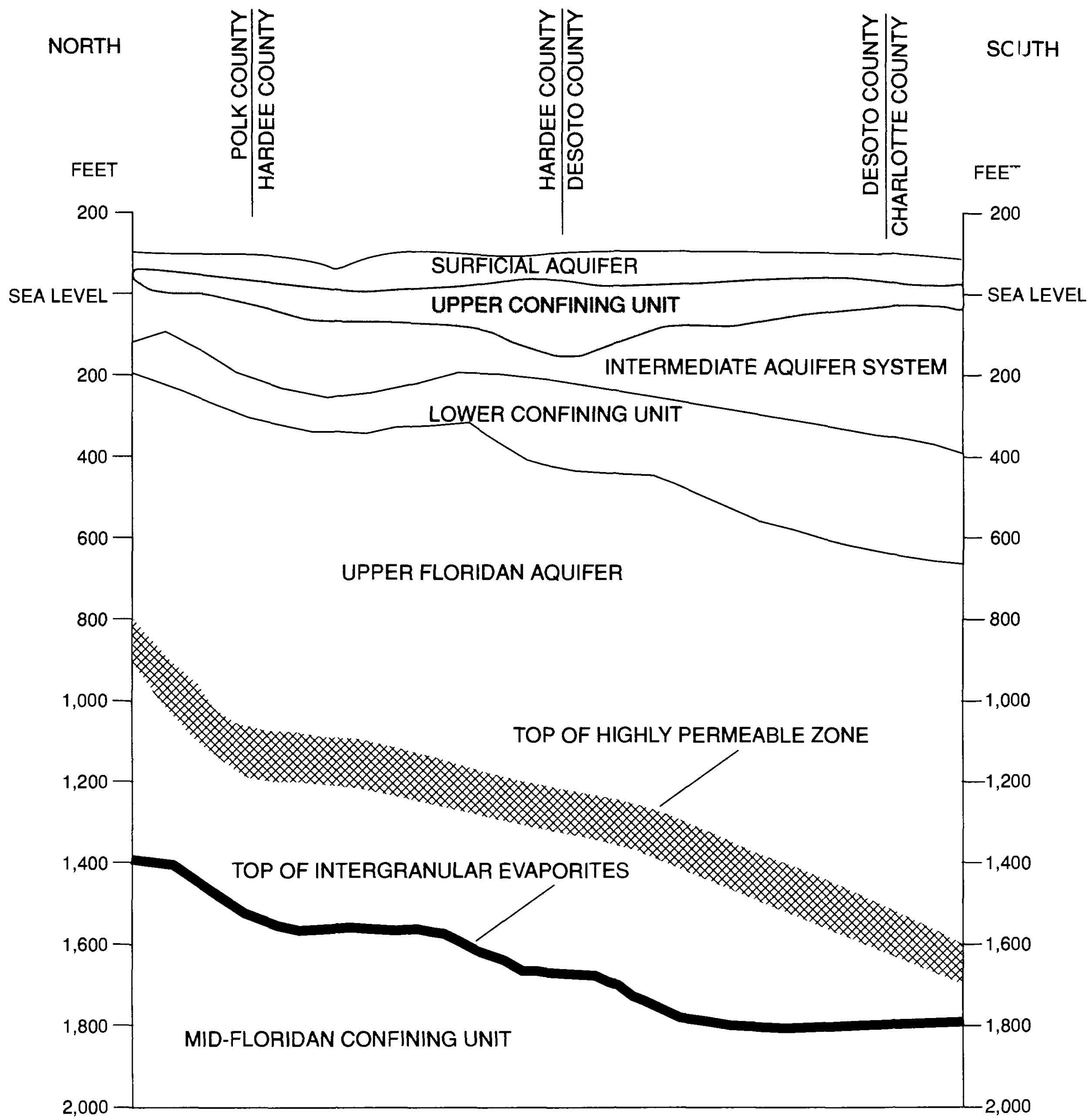


Figure 31. Conceptualized hydrogeologic representation of a north-south section of the aquifer system. (Modified from Ryder, 1985.)

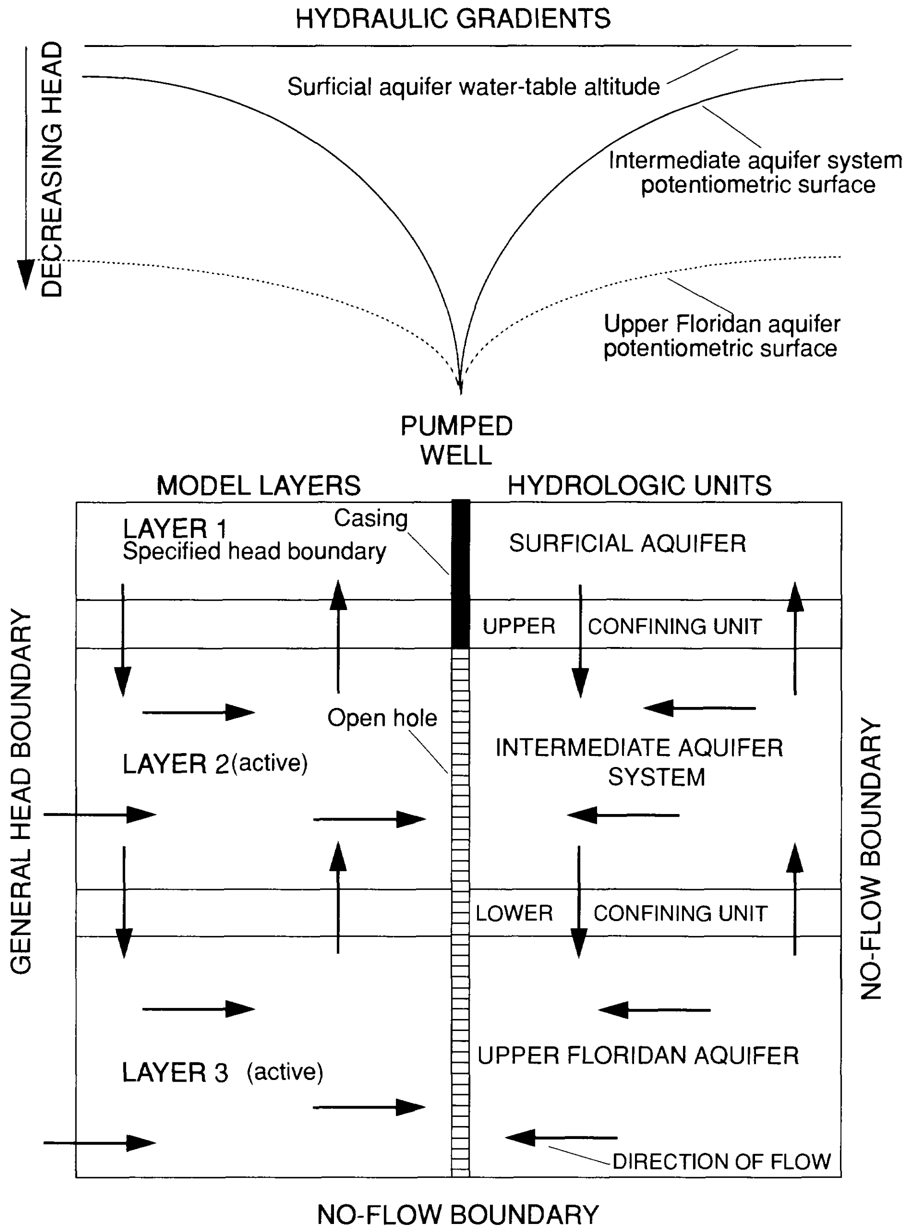


Figure 32. Schematic cross section of the layered digital ground-water model and the hydrologic units represented by the model layers.

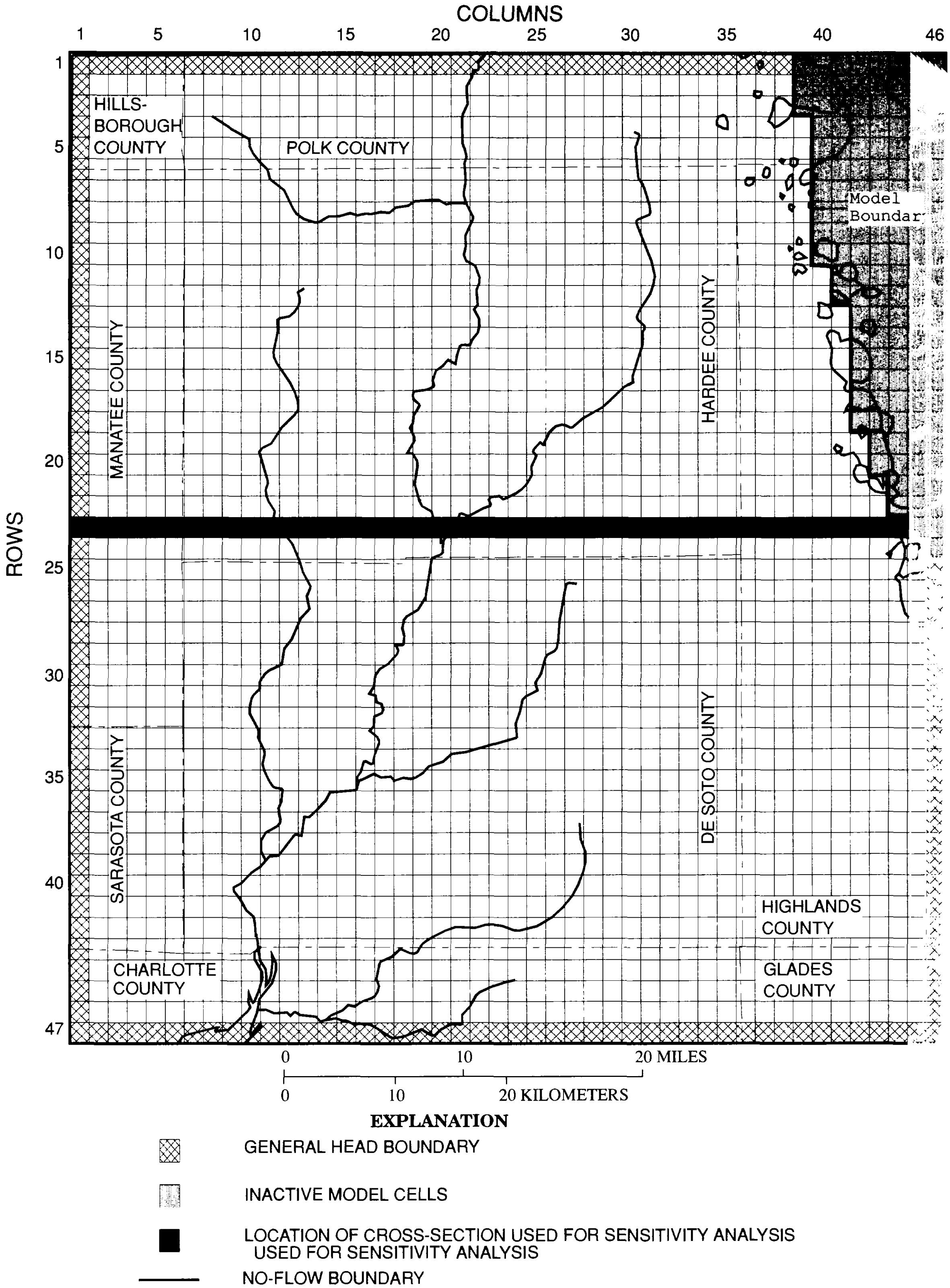


Figure 33. Finite-difference grid, lateral boundary conditions, and cross section used for sensitivity analysis.

A no-flow boundary was used along the northeastern lateral boundary. This lateral boundary coincides with a ground-water divide in the vicinity of the Lake Wales Ridge (fig. 2) and is approximately 12 mi east of Hardee and De Soto Counties. Because recharge at the ridge is high (3-20 in/yr) (Tibbals, 1990), it is expected that seasonal shifts in the ground-water divide as a result of pumping and climatic stress will be minimal.

The remaining lateral boundaries in layers 2 and 3 are represented by a general head boundary. This feature of the model allows water to enter or leave the system at rates that are dependent upon the aquifer properties and head gradients near the boundary as follows:

$$Q = C(H1-H2), \qquad (1)$$

where

Q is the flow rate into (+) or out (-) of the model area across the boundary, in cubic feet per day;

C is the lateral conductance term, in feet squared per day;

H1 is the controlling head outside the model boundary, in feet; and

H2 is the model-simulated head in boundary grid block, in feet.

During initial calibration, these lateral boundaries were designated as specified-head boundaries to determine model-computer flow rates to and from each specified-head boundary cell. The computed flow rates (Q) and head values (H2) in each lateral boundary cell were then assigned a controlling head (H1) value. The H1 value was based on heads from the September 1988 potentiometric-surface maps (Barr, 1989a,c) along a flow pathline at a distance of 6 mi from the model boundary. A conductance term (C) for each specified-head boundary cell was calculated using equation 1. After the conductance term was calculated, the specified-head lateral boundary condition in the intermediate aquifer system and the Upper Floridan aquifer was converted to a general-head boundary condition. Model simulations were made to determine whether flow rates computed at specified-head boundary cells matched flow rates (Q) computed using the general head boundary conditions; negligible error was detected.

Input Parameters

Input data necessary to initiate model simulation consist of the altitude of the water table in the surficial aquifer; leakance values for both the upper and lower confining units of the intermediate aquifer system; and the hydraulic heads, transmissivities, storage coefficients, lateral boundary cell heads and related conductance values at general head boundaries, and pumping rates for both the intermediate aquifer system and the Upper Floridan aquifer.

Geographical Information System Procedures

An important component of this study was the interface of a GIS with the modular model. GIS is a computerized data base that allows spatial data analysis with a display of the data. Spatial data analysis allows location, shape, and relations among features to be analyzed graphically. The ARC/INFO GIS system was used as an aid in the input data-base design and in the construction, calibration, and presentation of the model input and simulation results. Computer programs developed by D.O. Winkless and J.M. Kernodle (J.M. Kernodle, U.S. Geological Survey, written commun., 1988) were used to create the model grid and data arrays, to populate the data base, and to analyze the data.

The model grid was generated with row and column numbers as well as an x- and y-coordinate system. This feature allowed data to be added to the spatial data base and linked to each grid cell in the model area. Model input parameters were created as maps, or "coverages," in the GIS data base. Coverages were overlain with the model grid, and geographic locations and hydraulic features were assigned to the rows and columns of the model grid.

Water levels were the basis for hydraulic head data coded in the model. The water-table map for September 1988 (fig. 8) was used in conjunction with GIS to assign head values for grid nodes in active layer 1 of the model. Input data for the hydraulic heads in active layers 2 and 3 were the potentiometric surface of the intermediate aquifer system and the Upper Floridan aquifer shown in figures 16 through 18 and 22 through 24. The potentiometric-surface maps for September 1988, May 1989, and September 1989 in these figures were entered into the GIS data base. Coverages were generated from digitized potentiometric-surface contour lines. Head values were assigned for each model cell by interpolation between contour line using GIS commands. Coverages were then checked for accuracy by plotting automated data at the same scale as the original map.

Transmissivity data for both the intermediate aquifer system and the Upper Floridan aquifer were entered directly from the RASA model (Ryder, 1985). Because this model represents a finer resolution ground-water flow model than that developed for the regional scale RASA study, input values were changed slightly along transmissivity boundaries to smooth transitions between zones.

Initial leakance values of the upper and lower confining units of the intermediate aquifer system were based on estimates from Ryder (1985). Additional data pertaining to the thickness of the upper and lower confining units reported by Duerr and Enos (1991) were used to refine the leakance values reported by Ryder (1985).

Storage-coefficient arrays for the intermediate aquifer system and the Upper Floridan aquifer were constructed on the basis of aquifer thickness. Thickness maps for both aquifers were integrated with the GIS. The storage coefficient arrays for the intermediate aquifer system and the Upper Floridan aquifer were then determined by multiplying an estimated average specific storage of 1.0×10^{-6} ft^{-1} times the permeable aquifer thickness (Lohman, 1979).

To determine the distribution and magnitude of pumpage, a GIS data base of wells was created from the water-use permit files of the SWFWMD. Those files included descriptions of well locations, well depths, casing depths, well use, total permitted acres for each well, permitted average pumping rate, and projected citrus acreage. Other sources of information used to create the coverage were Sorensen and others (1990) for metered pumpage and Taylor and others (1990) for projected citrus acreage.

The relational data-base management capabilities of the GIS were utilized to determine the following model input data arrays: (1) total pumpage from multiple wells in each grid cell; (2) cumulative pumping rates for citrus and other agricultural uses; (3) distributions of wells for each aquifer based on correlation of aquifer thickness maps and well depths; (4) pumping rates from each aquifer where wells were open to multiple layers; (5) variations in pumping rates on the basis of monthly benchmark farm data; (6) locations of future wells for citrus irrigation on the basis of existing land use; (7) pumping rates for proposed citrus irrigation wells; and (8) areas of municipal, industrial, and agricultural land uses.

Steady-State Conditions

The simulation of steady-state conditions is a useful adjunct to model calibration and is frequently used to evaluate initial descriptions of transmissivity and leakance arrays and the suitability of boundary conditions. However, the selection of a period of time that is representative of steady-state conditions is difficult, particularly where aquifers are stressed by pumping. In the study area, the high diffusivity of the Upper Floridan aquifer, the lack of direct aquifer recharge from rainfall to the intermediate aquifer system and the Upper Floridan aquifer, and the lack of direct aquifer continuity with streams tend to support a relatively rapid achievement of equilibrium following the cessation or initiation of pumping. On the other hand, the relatively low diffusivity of the intermediate aquifer system and the low leakance of confining units tend to bring into question the development of short-term equilibrium conditions. Because of the low confining unit leakance, vertical leakance across the defined confining units in the study area probably never reaches a steady-state condition during any month of the annual cycle of pumping and rainfall previously described.

For modeling purposes, an initial calibration to steady-state conditions should be based on long-term average descriptions of head and stress. Such descriptions for the study area are highly uncertain because the distribution and rates of agricultural withdrawals are generally unknown. Accordingly, for this study, a quasi-steady-state condition was defined at the end of the rainy season when agricultural pumpage is zero and water-level hydrographs show little regional change in head. September 1988 was selected for the quasi-steady-state simulation period because pumpage was known with reasonable certainty and the heads were not changing appreciably during that period (fig. 34). Principal stresses on the aquifer during this time were withdrawals from industrial and municipal supply wells, which are known with reasonable certainty.

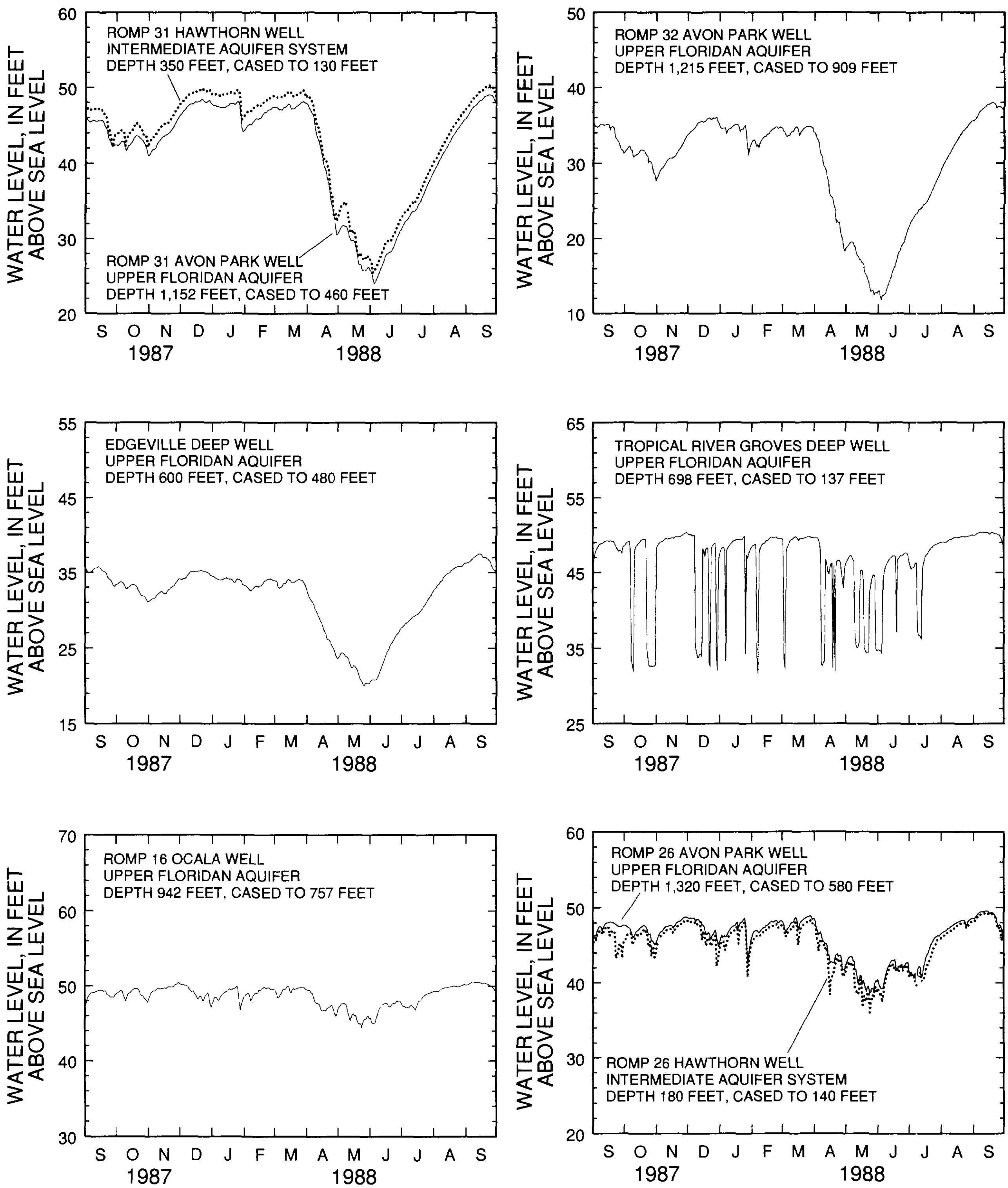


Figure 34. Maximum daily water levels for selected wells open to the intermediate aquifer system and the Upper Floridan aquifer, September 1987 through September 1988. (Locations of wells are shown in fig. 39.)

Detailed pumpage records for Florida's largest citrus grove, a 42-mi grove in northeastern De Soto County, indicated that no pumpage for citrus irrigation occurred from August 1 through September 25, 1988. Field observations indicated no citrus irrigation occurred September 18-21, 1988, the time period when water-level measurements were collected for use in preparing the potentiometric-surface maps for the intermediate aquifer system and the Upper Floridan aquifer.

The flow model was initially calibrated to September 1988 conditions. Following this calibration, simulated September 1988 conditions were used as initial conditions for subsequent transient simulations. Final model calibration was achieved when quasi-steady-state and transient conditions were simulated within predetermined limits of accuracy using duplicate arrays of transmissivity and confining unit leakance.

Steady-State Calibration

Two procedures were used in the calibration process: (1) analysis of residuals; and (2) conversion of model output to contour maps. Residuals are the differences between the observed and the simulated heads at observation well sites. A negative residual occurs when the simulated heads are greater than the observed heads, and a positive residual occurs when the simulated heads are less than the observed heads. An "error" criterion of 10 ft was established for nodes where head residuals were determined by comparing simulated results to interpolated values from potentiometric-surface maps. An error criterion of 6 ft was used for nodes where heads were determined from observation well measurements.

Statistical analysis of model residuals involved the use of a statistical processor for analyzing simulations made using the model (Scott, 1990). The modular model statistical processor (MMSP) provided the capabilities to calculate descriptive statistics, such as root mean square error (RMSE), for the error analysis of simulated and interpolated water levels. The RMSE, used to judge the goodness of fit, is given by

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} (h_s - h_o)^2 / n} \tag{2}$$

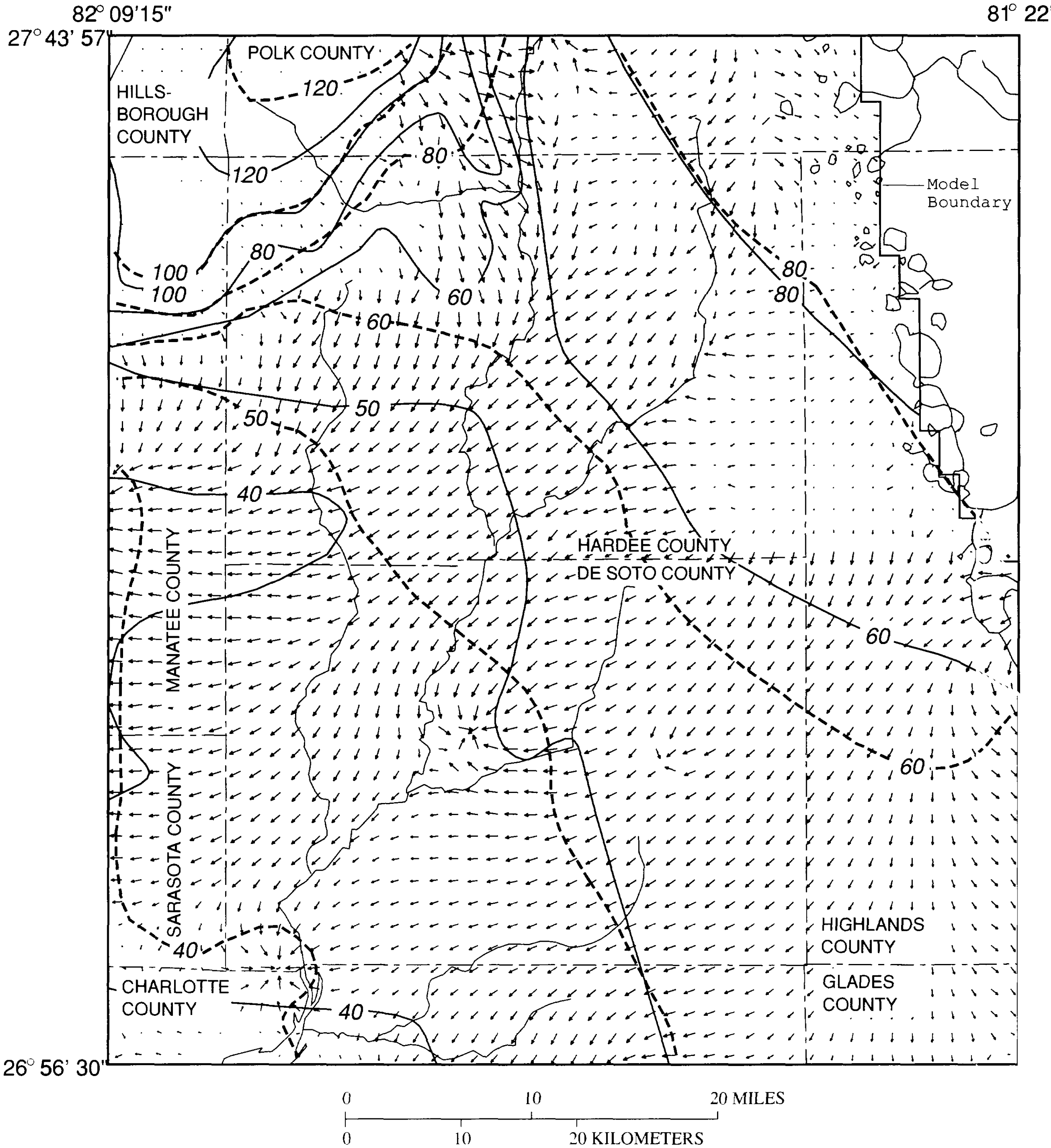
where

n is the number of observations;
h_s is the simulated head, in feet; and
h_o is the observed or interpolated head, in feet.

Another technique used in the calibration process was the conversion of simulated model output to contour maps using GIS. Simulated contour maps of heads were compared to published maps by Barr (1989a,b, c,d) and Knochenmus and Barr (1990a,b). Areal distribution of discharge and recharge were compared to published maps by Ryder (1985), Aucott (1988), and Tibbals (1990).

Interpolated and simulated potentiometric surfaces for the intermediate aquifer system and the Upper Floridan aquifer is shown in figures 35 and 36, respectively. An error analysis for the model calibration of the intermediate aquifer system and Upper Floridan aquifer is presented in table 2. The residuals were analyzed for all 2,030 active nodes of the intermediate aquifer system and the Upper Floridan aquifer. Based on the interpolated potentiometric data shown for September 1988 (fig. 35), the standard deviation about the -1.0-ft mean of the residuals for the intermediate aquifer system was 3.2 ft, which indicates that the model-simulated heads for the intermediate aquifer system match the interpolated heads within a range of 4.2 ft above to 2.2 ft below at about 67 percent of the nodes. Similarly, the simulated potentiometric surface for the Upper Floridan aquifer matched the interpolated September 1988 surface (fig. 36) at 67 percent of the nodes within a range of 4.4 ft above to 3.6 ft below on the basis of a standard deviation of 4.0 ft about a residual mean of -0.4 ft. Maximum differences between the interpolated September 1988 potentiometric-surface values and the simulated values ranged from +10.0 to -10.2 ft for the intermediate aquifer system and +13.9 to -8.2 ft for the Upper Floridan aquifer.

A comparison between the observed and simulated water levels for wells open to the intermediate aquifer system and the Upper Floridan aquifer also was used to demonstrate calibration of the steady-state model. Residuals were computed for 48 nodes of the intermediate aquifer system and 64 nodes of the Upper Floridan aquifer that correspond to observation well locations. Based on September 1988 measurements, the standard deviation about the 0.69-ft mean of the residuals for the intermediate aquifer system was 1.5 ft, which indicates that the model-simulated heads for the intermediate aquifer system match the observed heads within a range of 2.2 ft above to 0.8 ft below at about 67 percent of the nodes. Similarly, the model-simulated water levels for the Upper Floridan aquifer matched the observed September 1988 water levels at 67 percent of the nodes within a range of 1.3 ft above to 2.1 ft below on the basis of a standard deviation of 1.72 ft and a residual mean of -0.41 ft. Maximum differences between the observed September 1988 water levels and the simulated values ranged from +4.2 to -5.6 ft for the intermediate aquifer system and from +5.9 to -4.5 ft for the Upper Floridan aquifer.



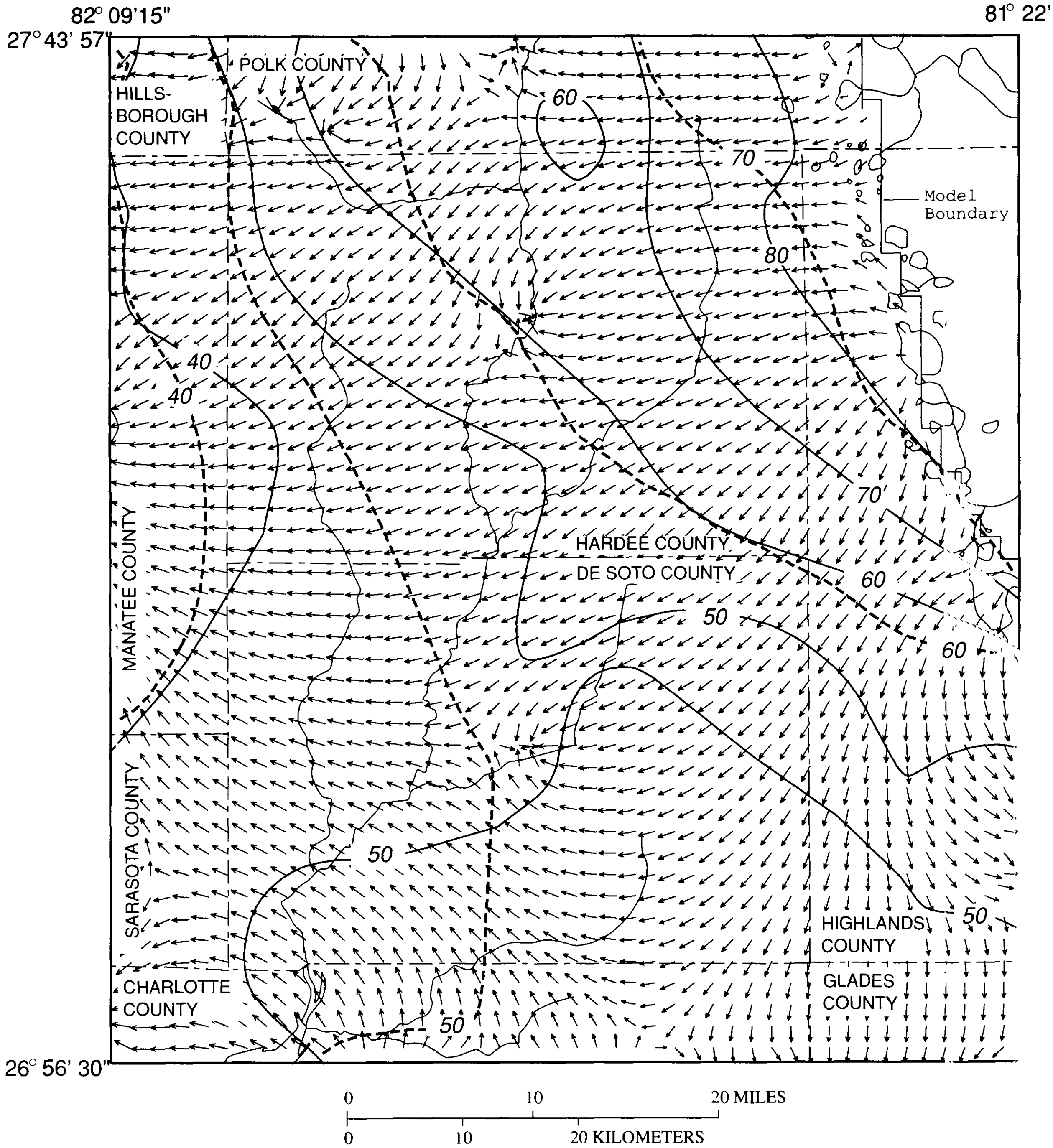
EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells open to the intermediate aquifer system. Contour intervals 10 and 20 feet. Datum is sea level

– – 40 – – SIMULATED POTENTIOMETRIC CONTOURS OF THE INTERMEDIATE AQUIFER SYSTEM

← FLOW VECTOR—Shows direction of ground-water flow. Length of vector is proportional to velocity

Figure 35. Interpolated (modified from Barr, 1989a) and simulated potentiometric surfaces and direction of ground-water movement in the intermediate aquifer system, September 1988.



EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR—
Shows altitude at which water level stands in tightly cased wells in the Upper Floridan aquifer. Contour interval 10 feet. Datum is sea level

-- 40 -- SIMULATED POTENTIOMETRIC CONTOURS OF THE UPPER FLORIDAN AQUIFER

← FLOW VECTOR—Shows direction of ground-water flow. Length of vector directly proportional to velocity

Figure 36. Interpolated (modified from Barr, 1989c) and simulated potentiometric surfaces and direction of ground-water movement in the Upper Floridan aquifer, September 1988.

Table 2. Statistical summary of differences between observed and simulated heads for the intermediate aquifer system and the Upper Floridan aquifer, September 1988

Statistics	Model-simulated heads		Observed heads	
	Intermediate aquifer system	Upper Floridan aquifer	Intermediate aquifer system	Upper Floridan aquifer
Number of active nodes	2,030	2,030		
Number of individual wells			48	64
Maximum range in residuals (feet)	10.0 to -10.2	13.9 to -8.2	4.2 to -5.6	5.9 to -4.5
Arithmetic mean of residuals (feet)	-1.04	- .37	.69	- .41
Absolute mean of residuals (feet)	2.61	2.97	1.14	1.36
Standard deviation of residuals (feet)	3.27	4.00	1.51	1.72
Mean deviation	2.48	2.91	1.00	1.32
Median	- .76	- .66	.51	.33
Variance	10.71	16.03	2.28	2.95
Sum of absolute value of residuals (feet)	-2,122.58	-762.75	32.97	26.17
Root mean square error	3.44	4.02	4.06	3.92

Sensitivity Analysis

An analysis was made to determine the sensitivity of the calibrated model to changes in input parameters. Transmissivity and leakance were varied one at a time, over a reasonable range that might exist, and changes in the simulated heads were observed. These tests describe the relative importance of these input parameters to model simulation results.

Results of sensitivity tests for the intermediate aquifer system and the Upper Floridan aquifer are shown in figure 37. Cross sections along row 23 and extending from column 1 through column 44 were constructed to show the effects of the parameter changes on aquifer heads. A summary of residuals due to changes in parameters for all 2,030 active nodes also are listed in figure 37. The results of the analysis indicate that:

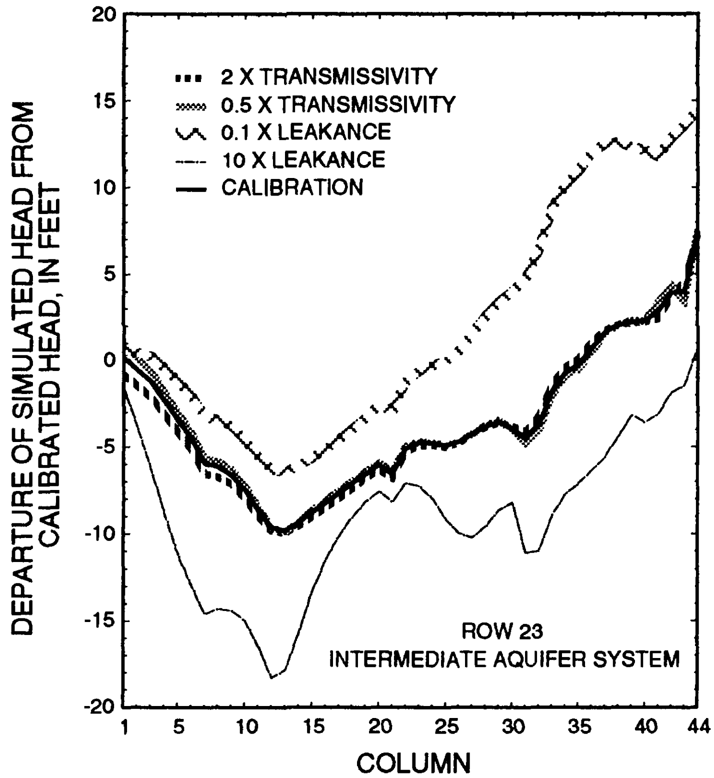
(1) The model is relatively insensitive to doubling or halving transmissivity of the intermediate aquifer system and the Upper Floridan aquifer, because the residuals are not substantially larger than those in the calibrated model.

(2) The model is sensitive to tenfold changes in the vertical hydraulic conductivity of the upper and lower confining units of the intermediate aquifer system. Residuals are substantially larger than those in the calibration run. The hydrographic section for the intermediate aquifer system in figure 37 shows that the departure of computed heads from observed heads is greatest for the model run with increased leakance.

Transient Conditions

The purpose of the transient simulation was to determine the effects of ground-water pumping on storage and ground-water flow directions in the intermediate aquifer system and the Upper Floridan aquifer. Two simulation periods were selected and results were compared to potentiometric-surface maps. The first period corresponds to a 236-day irrigation season; the second to a 128-day wet-season recovery period. The 236-day irrigation season was simulated using nine monthly stress periods from the beginning of the fall irrigation season, September 1988, to the approximate end of the spring irrigation season, May 1989. The 128-day wet-season recovery period was simulated by removing the irrigation pumpage and simulating monthly conditions from June 1989 through September 1989. Simulated monthly water levels were compared to observed water levels for individual wells in the model area.

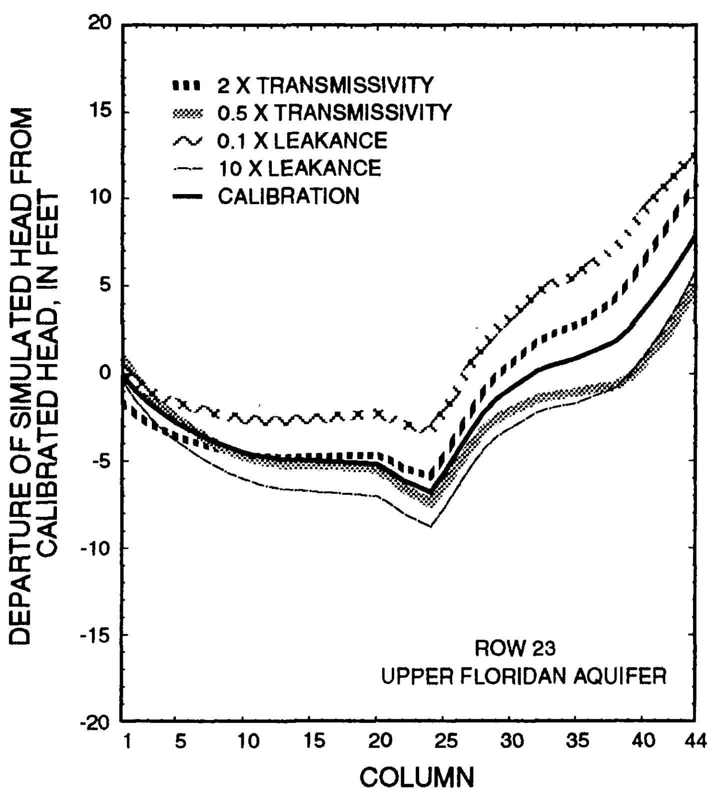
Seasonal fluctuations of the potentiometric surface during a 1-year period for six wells in the model area are shown in figure 34. The graphs show that the potentiometric surface may undergo several cycles of decline and rise during the year, but, generally, the surface is highest in autumn and lowest in spring. Long-term hydrographs repeat this yearly cycle (figs. 19 and 25). The Upper Floridan aquifer in the region of a 42-mi citrus grove in northeastern De Soto County was modeled by Wilson (1972), who determined that, when a multiyear, hypothetical pumping schedule was simulated, the decline in potentiometric surface was about the same at the end of the spring pumping period each year and that the potentiometric surface recovered to



INTERMEDIATE AQUIFER SYSTEM
Residuals (2,030 grid blocks)

Parameter and multiplier	Maximum negative residual (ft)	Maximum positive residual (ft)	Mean of absolute residual (ft)
calibration	-10.2	10.0	2.6
2.0 X transmissivity	-11.1	13.4	2.7
0.5 X transmissivity	-9.9	15.1	2.7
0.1 X leakance[1]	-6.4	49.2	7.2
10 X leakance[1]	-36.5	17.8	10.3

[1] Leakance for the upper confining unit of the Intermediate aquifer system



UPPER FLORIDAN AQUIFER
Residuals (2,030 grid blocks)

Parameter and multiplier	Maximum negative residual (ft)	Maximum positive residual (ft)	Mean of absolute residual (ft)
calibration	-8.3	13.9	2.9
2.0 X transmissivity	-7.5	19.2	3.3
0.5 X transmissivity	-8.9	16.2	2.8
0.1 X leakance[1]	-4.9	24.1	3.3
10 X leakance[1]	-10.8	10.1	3.7

[1] Leakance for the lower confining unit of the Intermediate aquifer system

Figure 37. Results of sensitivity analysis of the steady-state model parameters for the intermediate aquifer system and the Upper Floridan aquifer, September 1988.

near prepumping conditions by September. Because of the cyclic nature of this trend and because the potentiometric surface recovers to near prepumping conditions at the end of the irrigation season, a transient calibration can be obtained by analyzing 1 year of water-level fluctuations.

An ideal test of the applicability of the model would be to run the model through a series of year-long simulation periods that, collectively, would span the length of the observed long-term record of water levels. However, data on areal distributions of pumping are poor, and long-term pumping data for agriculture are too sparse to consider this approach.

Boundaries

The initial boundary conditions for the transient calibration were the same as those assigned to the intermediate aquifer system and the Upper Floridan aquifer for the steady-state calibration. These boundaries were deemed suitable for the September 1988 starting conditions in the transient calibration; however, the assumption of a "constant" external head (H1) used in the computation of flow across the general head boundaries was known to be invalid for successive stress periods. Observed water levels fluctuated as much as 30 ft between September 1988 and May 1989 in parts of Sarasota, Manatee, and Polk Counties (fig. 38). Accordingly, boundary head values (H1) were adjusted during each stress period for each active layer to account for these changes and to reflect as closely as possible the hydrographic trends of nearby wells. These trends were approximated by two linear segments during the transient calibration period; the declining trend from September 1988 to May 1989, and the rising trend from May 1989 to September 1989 (fig. 38). End points for each trend segment were estimated using potentiometric-surface maps for September 1988, May 1989, and September 1989. Rates of head change were based on the slopes of trend lines shown in figure 38.

The specified heads representing the water table of the surficial aquifer throughout the model area during the irrigation season (October 1988 through May 1989) were assumed to average 3 ft lower than the heads in September 1988 and were adjusted accordingly. Similarly, the specified heads during the nonirrigation season (June 1989 through September 1989) were assumed to average 1 ft lower than the head in September 1988. These adjustments were based on 1988-89 hydrographs of water levels in observation wells open to the surficial aquifer (fig. 9).

Transient Calibration

The equilibrium conditions simulated during the steady-state calibration were used as the initial condition for the transient simulation. Input parameters for the transient-model calibration were the same as those used for the calibrated steady-state model with the addition of arrays representing storativity and pumpage distributions for the intermediate aquifer system and the Upper Floridan aquifer. Storage coefficients were adjusted during transient calibration for layers 2 and 3 to minimize differences between simulated and observed water levels. Storage coefficients were adjusted within a range determined from previous reports by Ryder (1982; 1985), Wilson and Gerhart (1982), and Tibbals (1990).

Irrigation pumpage arrays were developed using data from a benchmark farms program (Duerr and Trommer, 1982) to determine the monthly pumping rates for citrus, vegetables, melons, nurseries, and pasture. Coefficients were determined for each crop type on the basis of seasonal irrigation use and were applied to the monthly pumping rates (table 3). The pumping rates for agricultural use, industrial use, and public supply for the period September 1988 through May 1989 for the model area are listed in table 4.

The accuracy of the transient calibration was evaluated by comparing simulated potentiometric levels with observed water levels on interpolated water levels from May 1989 and September 1989 potentiometric-surface maps for the intermediate aquifer system and the Upper Floridan aquifer. Simulated heads over time at specific grid blocks also were compared with hydrographs for wells in corresponding locations (fig. 39). Simulated water-levels for 16 observation wells were compared to water levels collected during the period September 1988 through September 1989 (fig. 40). Particularly good comparisons were noted for the ROMP 30 well open to the intermediate aquifer system and the ROMP 32 well open to the Upper Floridan aquifer. The most notable deviations between observed water levels and simulated hydrographs were for the Rowell deep well open to the intermediate aquifer system and the ROMP 30 well open to the Upper Floridan aquifer. The comparisons indicated that the simulated heads were higher than the observed water levels at these sites. Pumpage in these areas is not accurately defined and possibly accounts for these differences.

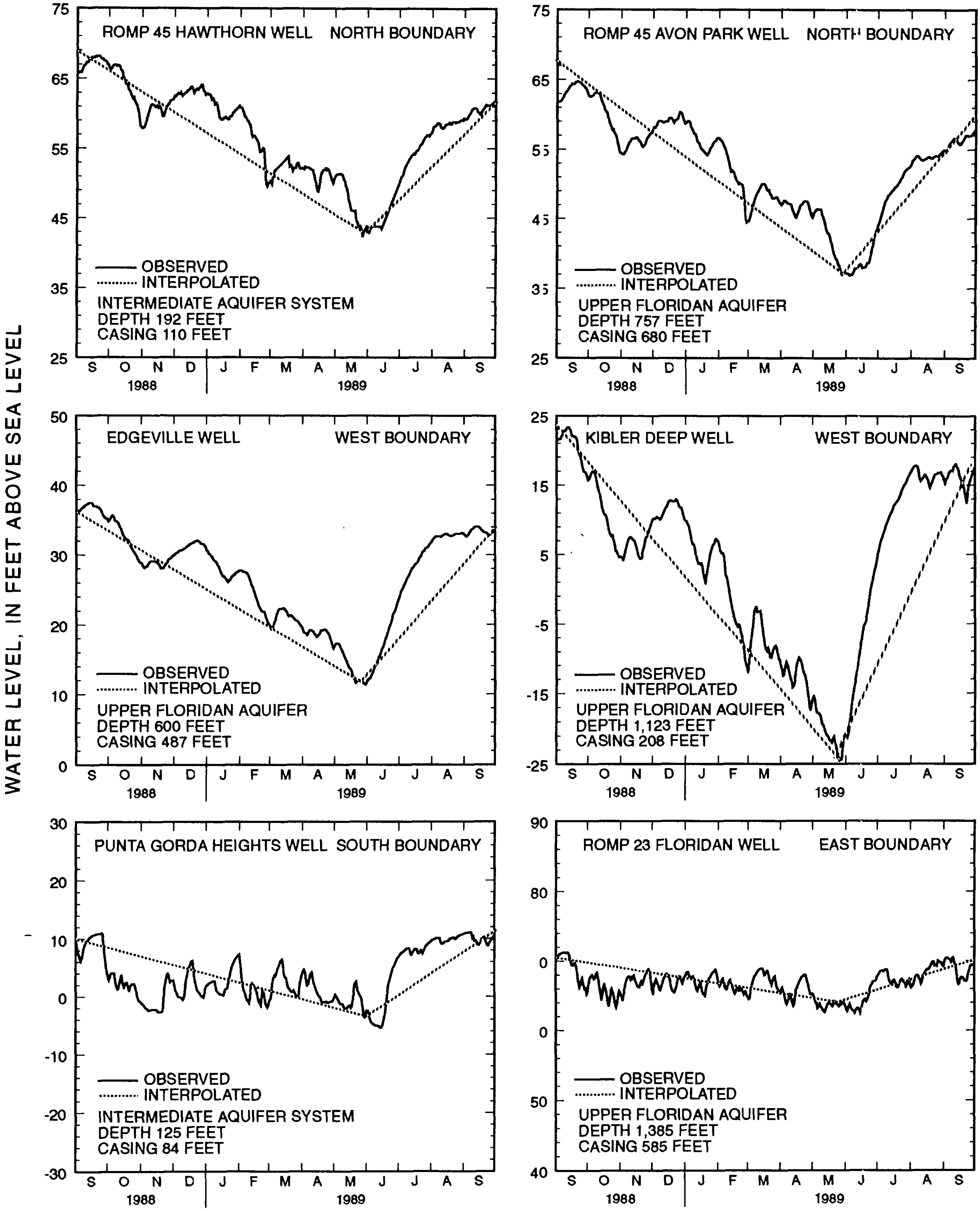


Figure 38. Hydrographic linear template used to estimate general head boundaries for transient simulation. (Locations of wells are shown in fig. 39.)

Table 3. Coefficients used for determining monthly irrigation pumping rates

Month	Crop			
	Nursery and sod	Citrus	Vegetables	Melons
September	0.60	0.39	2.38	0
October	.59	.76	4.19	0
November	.85	.67	3.05	0
December	2.06	1.15	1.36	0
January	1.54	1.09	1.18	.53
February	.76	1.05	2.26	2.33
March	1.12	1.33	2.53	2.82
April	.98	1.31	2.68	1.58
May	1.24	2.03	3.00	3.29

Table 4. Ground-water pumpage for public supply, industrial use, and irrigation from the intermediate aquifer system and the Upper Floridan aquifer during the irrigation period, September 1988 through May 1989

[All values are in million gallons per day]

Date	Public supply	Industrial use	Crop irrigation				Total
			Nursery and sod	Citrus	Vegetables	Melons	
			Intermediate aquifer system				
1988							
September	0.85	0	1.42	3.40	5.20	0	10.9
October	.85	0	1.40	6.89	7.67	0	16.8
November	.85	0	2.30	8.62	6.68	0	18.4
December	.85	0	4.80	3.25	2.98	0	11.9
1989							
January	.85	0	3.73	13.44	1.09	0.12	19.2
February	.85	0	1.80	14.47	.85	.53	18.5
March	.85	0	1.39	13.44	1.39	.47	17.5
April	.85	0	1.12	14.57	.44	.23	17.2
May	.85	0	1.20	25.60	.22	.42	28.3
			Upper Floridan aquifer				
1988							
September	10.30	39.40	4.11	25.10	78.20	0	157.1
October	10.30	39.40	4.03	50.10	78.20	0	182.0
November	10.30	39.40	5.86	62.60	78.20	0	196.4
December	10.30	39.40	4.00	87.70	44.70	0	196.1
1989							
January	10.30	39.40	0.80	97.70	16.40	0	174.6
February	10.30	39.40	5.20	105.20	13.10	4.08	177.3
March	10.30	39.40	3.99	97.70	9.96	3.64	165.0
April	10.30	39.40	3.59	105.20	6.57	1.82	166.9
May	10.30	39.40	3.39	170.30	3.29	3.27	230.0

The interpolated and simulated potentiometric surfaces for the intermediate aquifer system and the Upper Floridan aquifer for May 1989 are shown in figures 41 and 42, respectively. These potentiometric surfaces represent conditions near the end of a long dry season during which maximum pumping for irrigation occurred. The interpolated and simulated potentiometric-surface contours compare reasonably well for both the intermediate aquifer system and the Upper Floridan aquifer, except for the western part of the model area. The poor correlation between the interpolated and simulated heads in this area is possibly the result of inaccurately determined pumping rates.

The transient model was used to simulate the effects of decreased pumpage during a 12?-day recovery period on the potentiometric surface. All model input parameters were the same as those used for the irrigation calibration period, except that irrigation pumpage was removed. The interpolated and simulated potentiometric surfaces for the intermediate aquifer system and the Upper Floridan aquifer for September 1989 are shown in figures 43 and 44, respectively. The map of the simulated potentiometric surface of the intermediate aquifer system for September 1989 compares reasonably well with the map of the interpolated potentiometric surface, except in the northeastern part

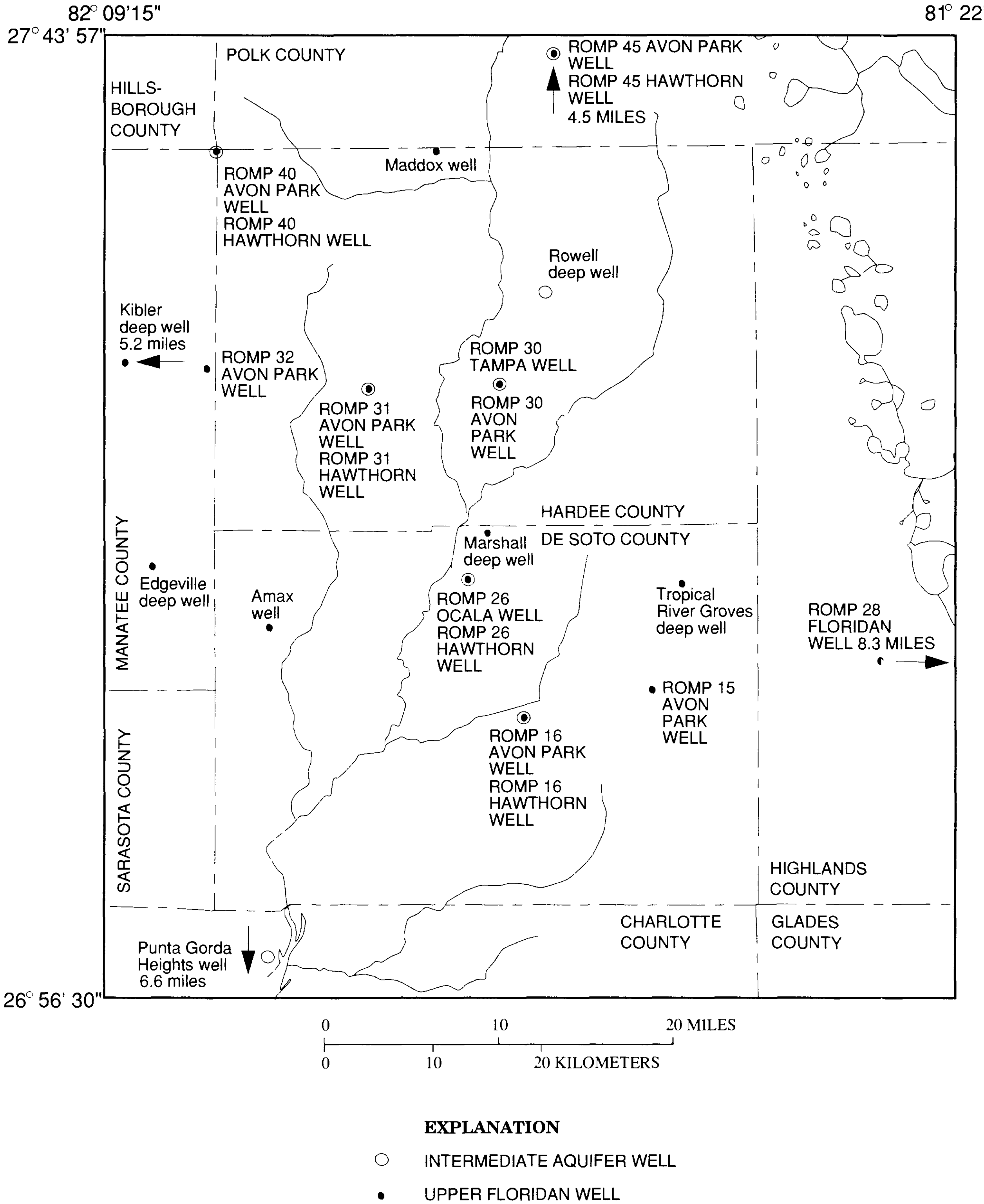


Figure 39. Locations of wells used for hydrographic analysis.

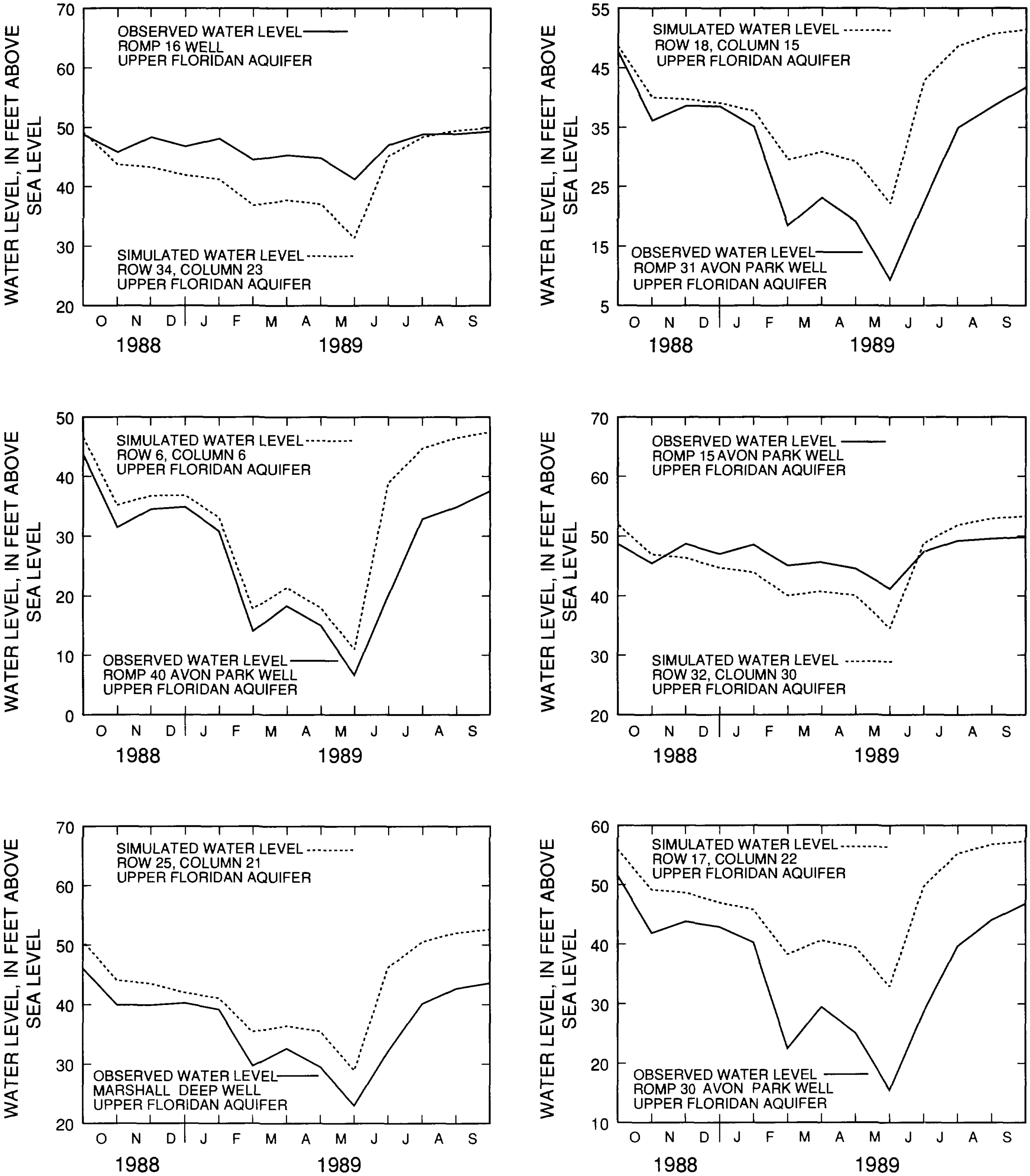


Figure 40. Simulated and observed water levels in selected wells open to the intermediate aquifer system and the Upper Floridan aquifer, October 1988 through September 1989.

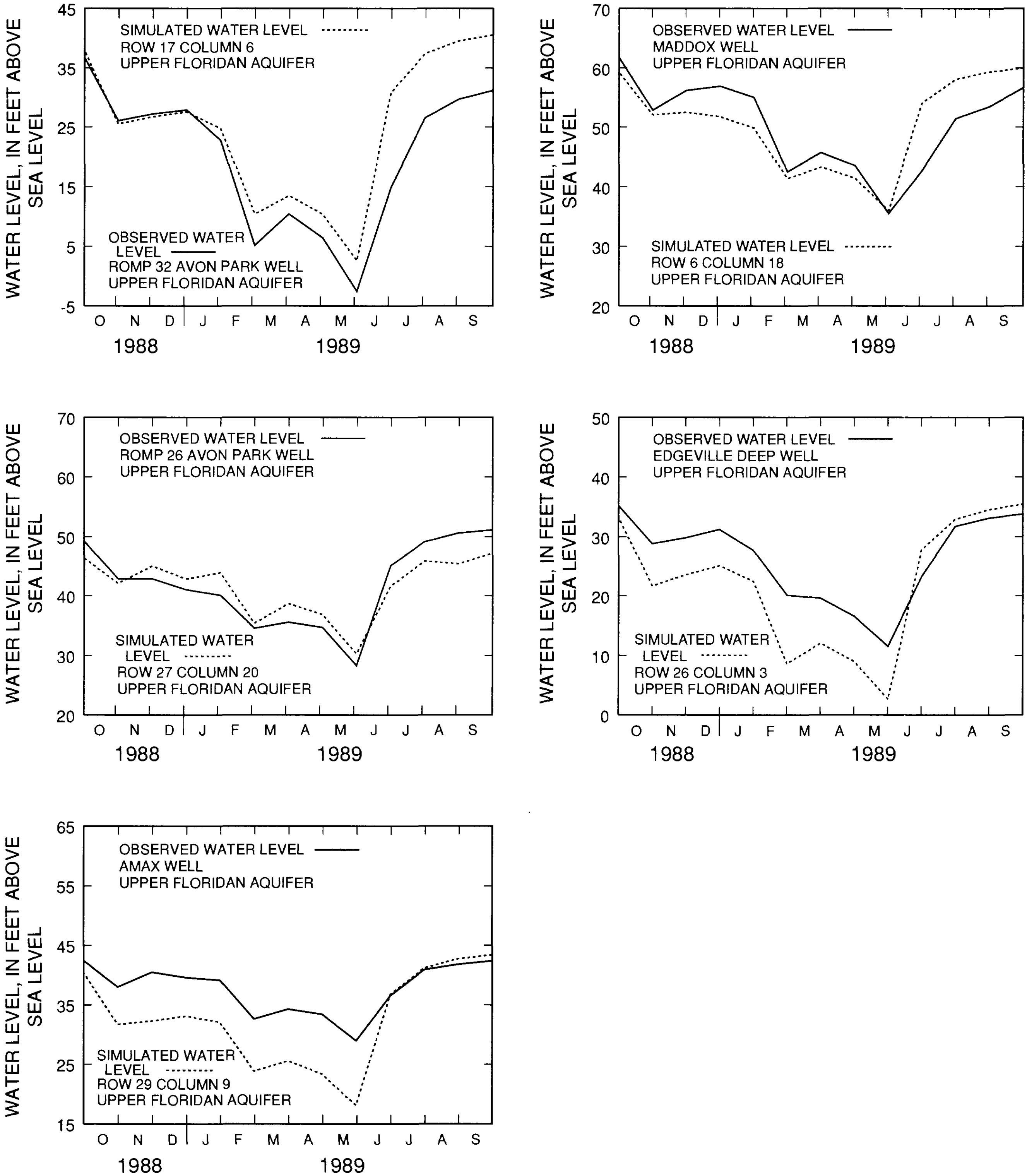


Figure 40. Simulated and observed water levels in selected wells open to the intermediate aquifer system and the Upper Floridan aquifer, October 1988 through September 1989--Continued.

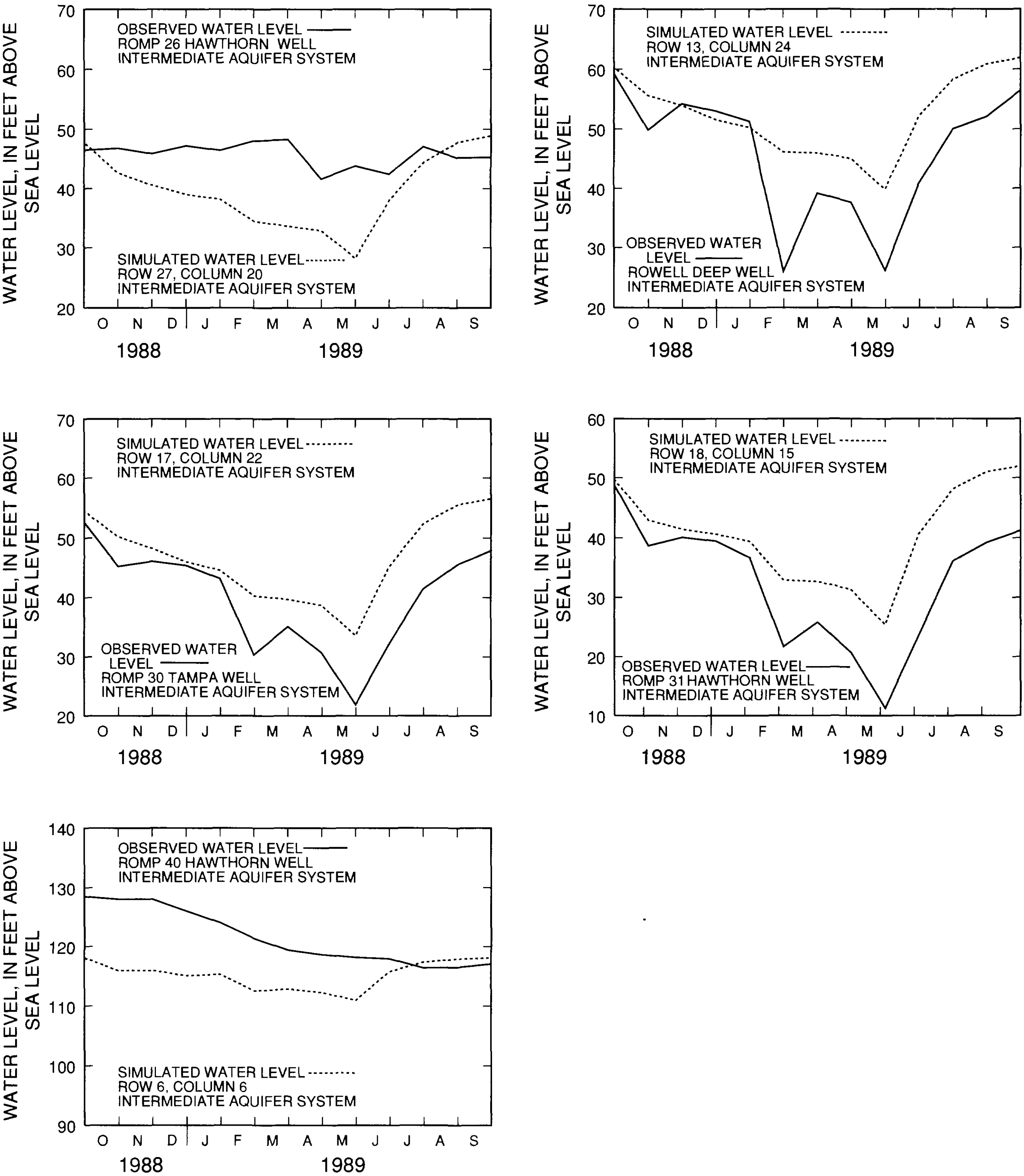
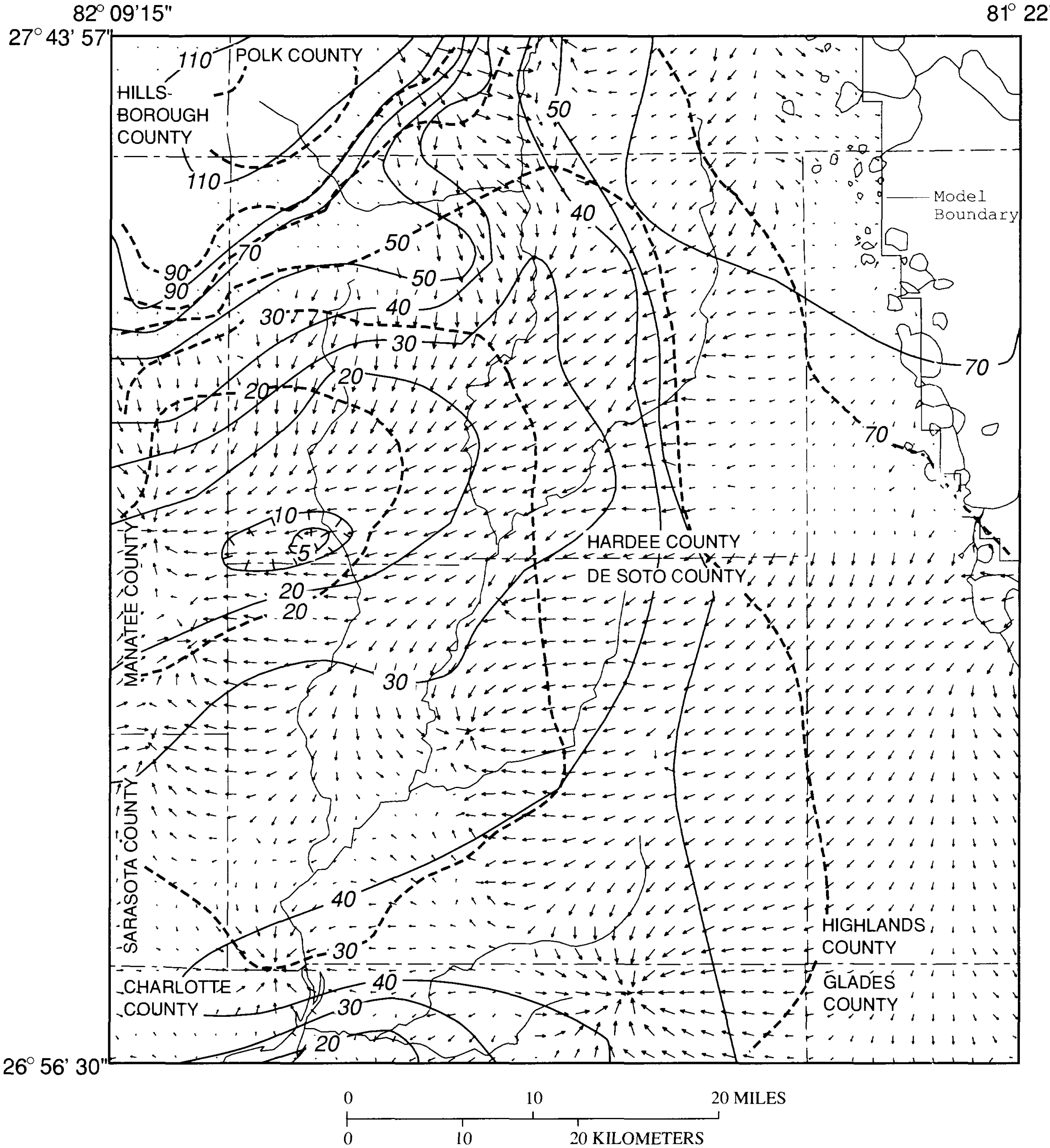


Figure 40. Simulated and observed water levels in selected wells open to the intermediate aquifer system and the Upper Floridan aquifer, October 1988 through September 1989--Continued.



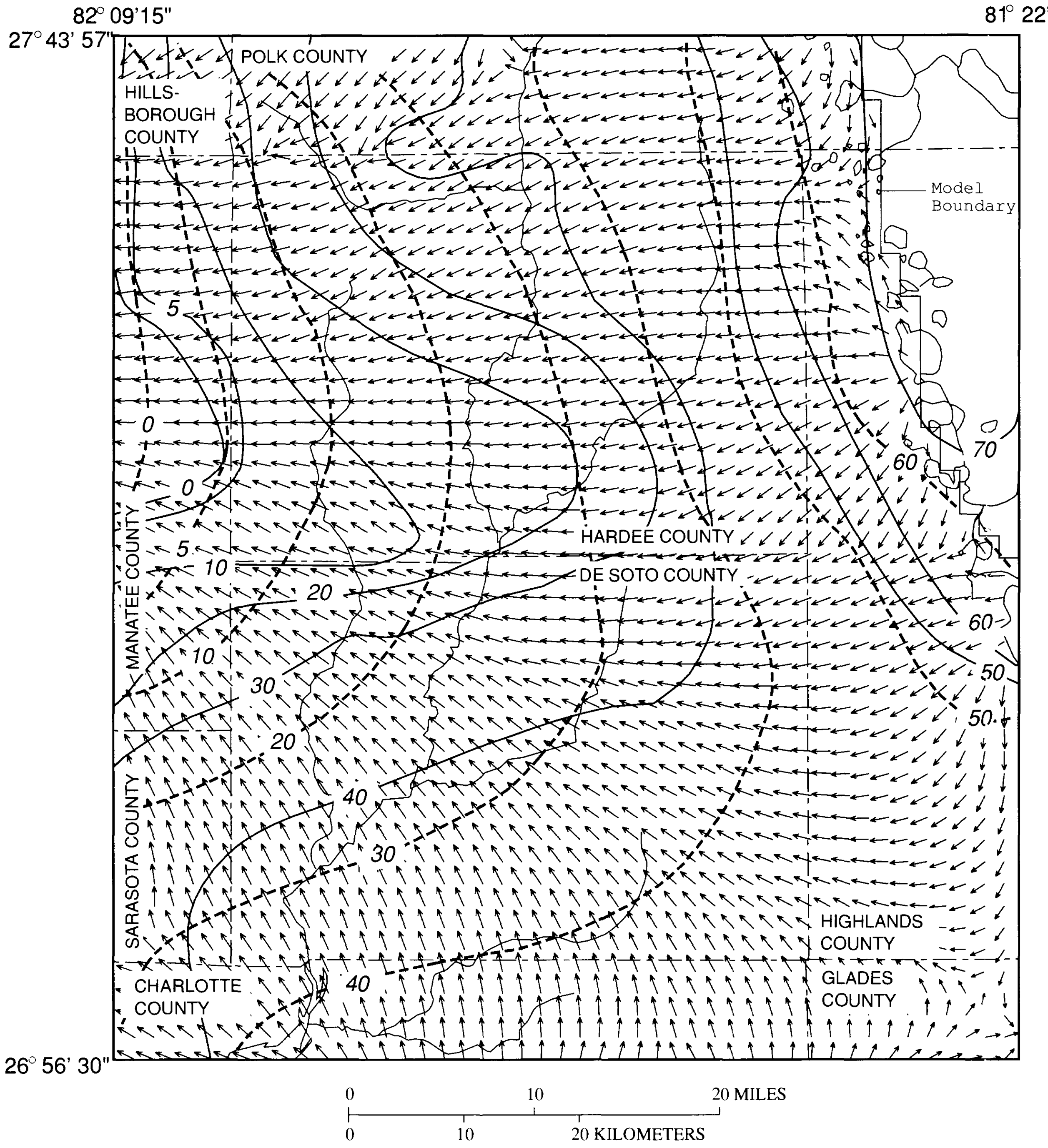
EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells open to the intermediate aquifer system. Contour intervals 5, 10, and 20 feet. Hachures indicate depressions. Datum is sea level

— — 40— — SIMULATED POTENTIOMETRIC CONTOURS OF THE INTERMEDIATE AQUIFER SYSTEM

← FLOW VECTOR—Shows direction of ground-water flow. Length of vector is directly proportional to velocity

Figure 41. Interpolated (modified from Barr, 1989b) and simulated potentiometric surfaces and direction of ground-water movement in the intermediate aquifer system, May 1989.



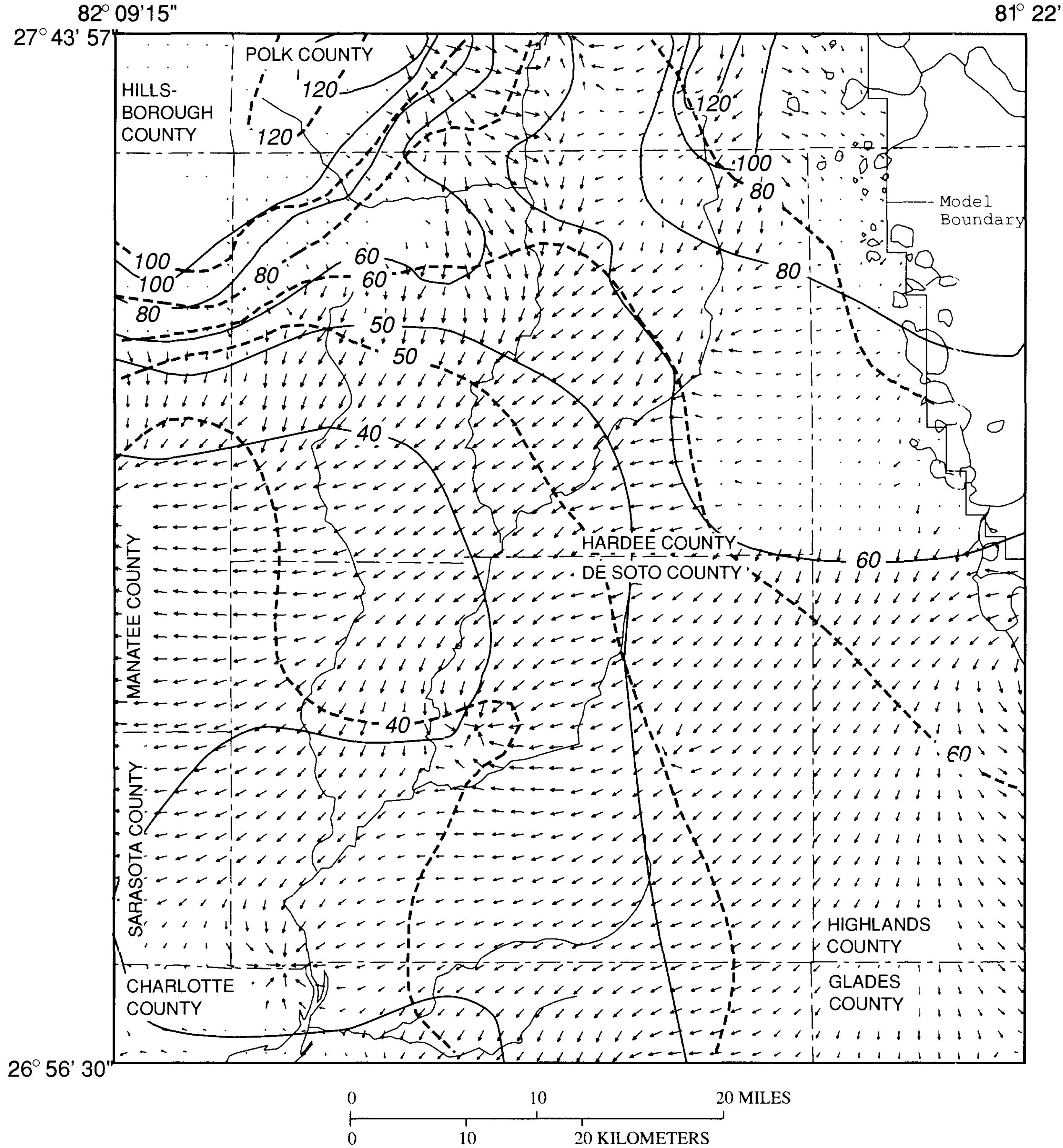
EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells open to the Upper Floridan aquifer. Contour intervals 5 and 10 feet. Datum is sea level

– – 40 – – SIMULATED POTENTIOMETRIC CONTOURS OF THE UPPER FLORIDAN AQUIFER

← FLOW VECTOR—Shows direction of ground-water flow. Length of vector is directly proportional to velocity

Figure 42. Interpolated (modified from Barr, 1989d) and simulated potentiometric surfaces and direction of ground-water movement in the Upper Floridan aquifer, May 1989.



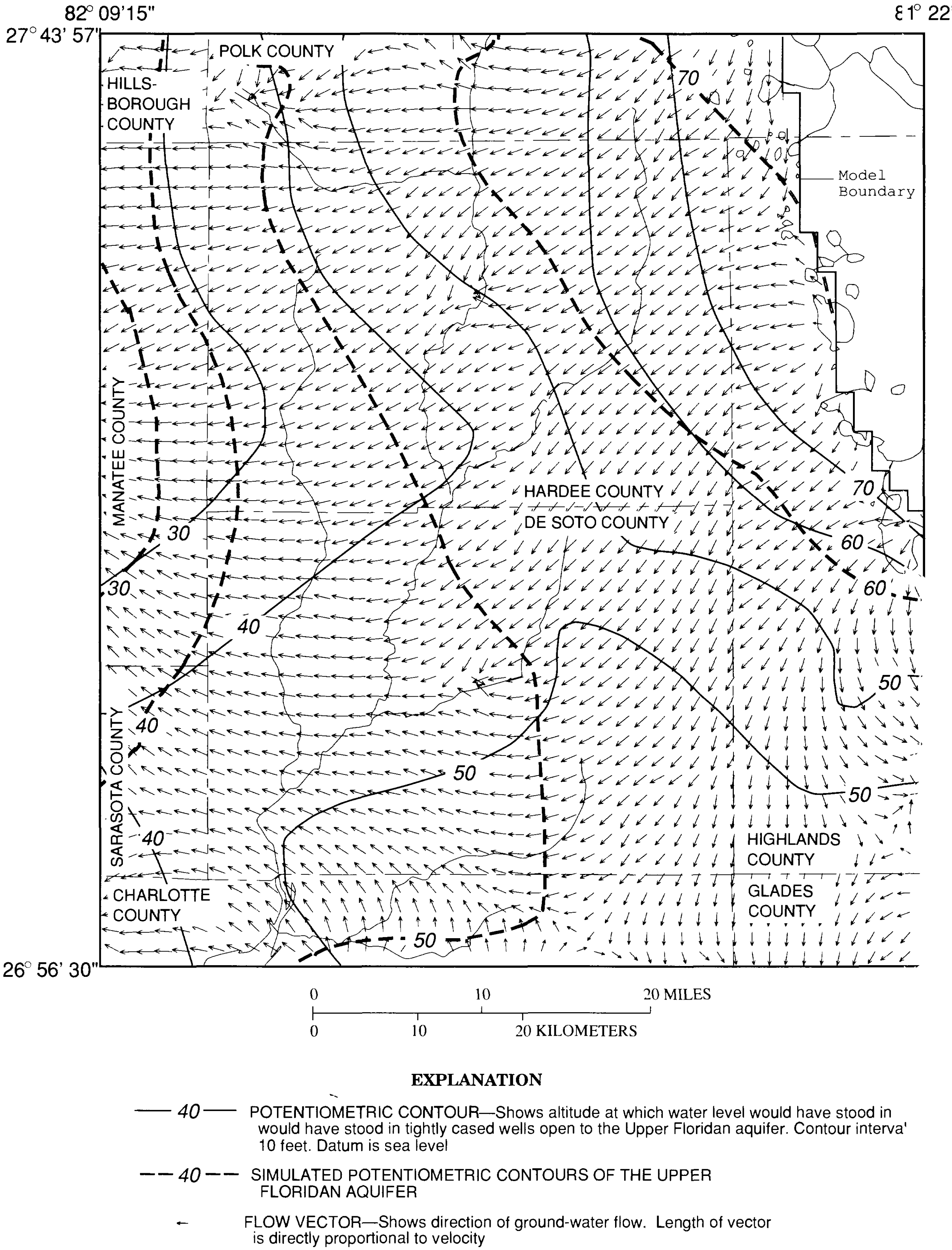
EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells open to the intermediate aquifer system. Contour intervals 10 and 20 feet Datum is sea level

-- 40 -- SIMULATED POTENTIOMETRIC CONTOURS OF THE INTERMEDIATE AQUIFER SYSTEM

← FLOW VECTOR—Shows direction of ground-water flow. Length of vector is directly proportional to velocity

Figure 43. Interpolated (modified from Knochenmus and Barr, 1990a) and simulated potentiometric surfaces and direction of ground-water movement in the intermediate aquifer system, September 1989.



EXPLANATION

—— 40 —— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in would have stood in tightly cased wells open to the Upper Floridan aquifer. Contour interva' 10 feet. Datum is sea level

— — 40 — — SIMULATED POTENTIOMETRIC CONTOURS OF THE UPPER FLORIDAN AQUIFER

← FLOW VECTOR—Shows direction of ground-water flow. Length of vector is directly proportional to velocity

Figure 44. Interpolated (modified from Knochenmus and Barr, 1990b) and simulated potentiometric surfaces and direction of ground-water movement in the Upper Floridan aquifer, September 1989.

Table 5. Statistical summary of differences between observed and simulated heads for the intermediate aquifer system and the Upper Floridan aquifer, May and September 1989

Statistical parameter	May 1989		September 1989	
	Intermediate aquifer system	Upper Floridan aquifer	Intermediate aquifer system	Upper Floridan aquifer
Number of individual wells	47	48	48	56
Maximum range in residuals (feet)	32.71 to -28.17	18.19 to -14.12	15.20 to -20.74	10.40 to -24.88
Arithmetic mean of residuals (feet)	0.45	5.07	-1.38	3.99
Standard deviation of residuals (feet)	12.32	7.40	7.44	5.97
Median	1.56	5.83	-1.48	-3.68
Variance	151.80	54.79	55.41	35.65
Sum of absolute value of residuals (feet)	21.05	243.54	-66.34	-223.95
Root mean square error	3.07	35.15	9.58	29.92

of the model area where a new control well was introduced for this map. The map of the September 1989 simulated potentiometric surface of the Upper Floridan aquifer compares reasonably well with the map of the interpolated potentiometric surface, except for the western part of the model area where pumping rates could be inaccurate.

A statistical summary of differences between observed and simulated heads for the intermediate aquifer system and the Upper Floridan aquifer for May and September 1989 are listed in table 5. Residuals were computed for 47 nodes of the intermediate aquifer system and 48 nodes for the Upper Floridan aquifer that correspond to the locations of observation wells for May 1989. Based on the observations in May 1989, the mean difference between observed and simulated surfaces was 0.45 ft and the RMSE was 3.07 ft for the intermediate aquifer system. The mean and RMSE for the Upper Floridan aquifer was 5.07 ft and 35.15 ft, respectively. Residuals were computed for 48 nodes of the intermediate aquifer system and for 56 nodes of the Upper Floridan aquifer that correspond to the locations of observation wells for September 1989. Based on the observed surfaces for September 1989, the mean difference between observed and simulated surfaces was -1.38 ft and the RMSE was 9.58 ft for the intermediate aquifer system. The mean and RMSE for the Upper Floridan aquifer was 3.99 ft and 29.92 ft, respectively.

Sensitivity Analysis

Sensitivity tests were run to determine the relative importance of pumping rates, storage coefficients, and boundary conditions in the calibration of the transient model. Transmissivity and leakance arrays used in transient simulations were the same arrays used in the steady-state model calibration. Results of sensitivity tests of the calibrated transient model for the intermediate aquifer system and the Upper Floridan aquifer are shown in figure 45 for row 23, columns 1 through 44.

Pumping rates were changed by first doubling the pumping rate and then reducing the rate by half. Results of sensitivity tests indicate that a change in pumping rates significantly affects transient model simulations for both aquifers. Figure 45 shows that the departure of observed heads from computed heads for May 1989 could be reduced along row 23 by increasing withdrawal rates in the model.

Storage coefficients were changed by a factor of 10 for each aquifer. Results of the sensitivity test for this change for the intermediate aquifer system indicate that the model is relatively sensitive to increases and relatively insensitive to decreases in storage coefficients. Results of the sensitivity test for the Upper Floridan aquifer indicate that changes in storage coefficients had little effect on the aquifer, which, in turn, indicates that only a small amount of the water withdrawn is released from aquifer storage.

The effects of varying boundary conditions for both aquifers are shown in figure 46. Raising and lowering the water table by 3 ft throughout the model area resulted in a corresponding rise and drop in the simulated heads, averaging less than 1 ft for both aquifers. The model was tested to estimate the range in error that could result from selecting specified-head and no-flow lateral boundary conditions in the model rather than the general head boundary conditions that were used for calibration. Changing the general-head boundaries to specified-head boundaries resulted in a head change of approximately 20 ft at the eastern and western boundaries for both aquifers. Changing the general-head boundary to a no-flow boundary resulted in a maximum head decline of about 10 ft at the eastern boundary and a rise of about 30 ft along the western boundary for

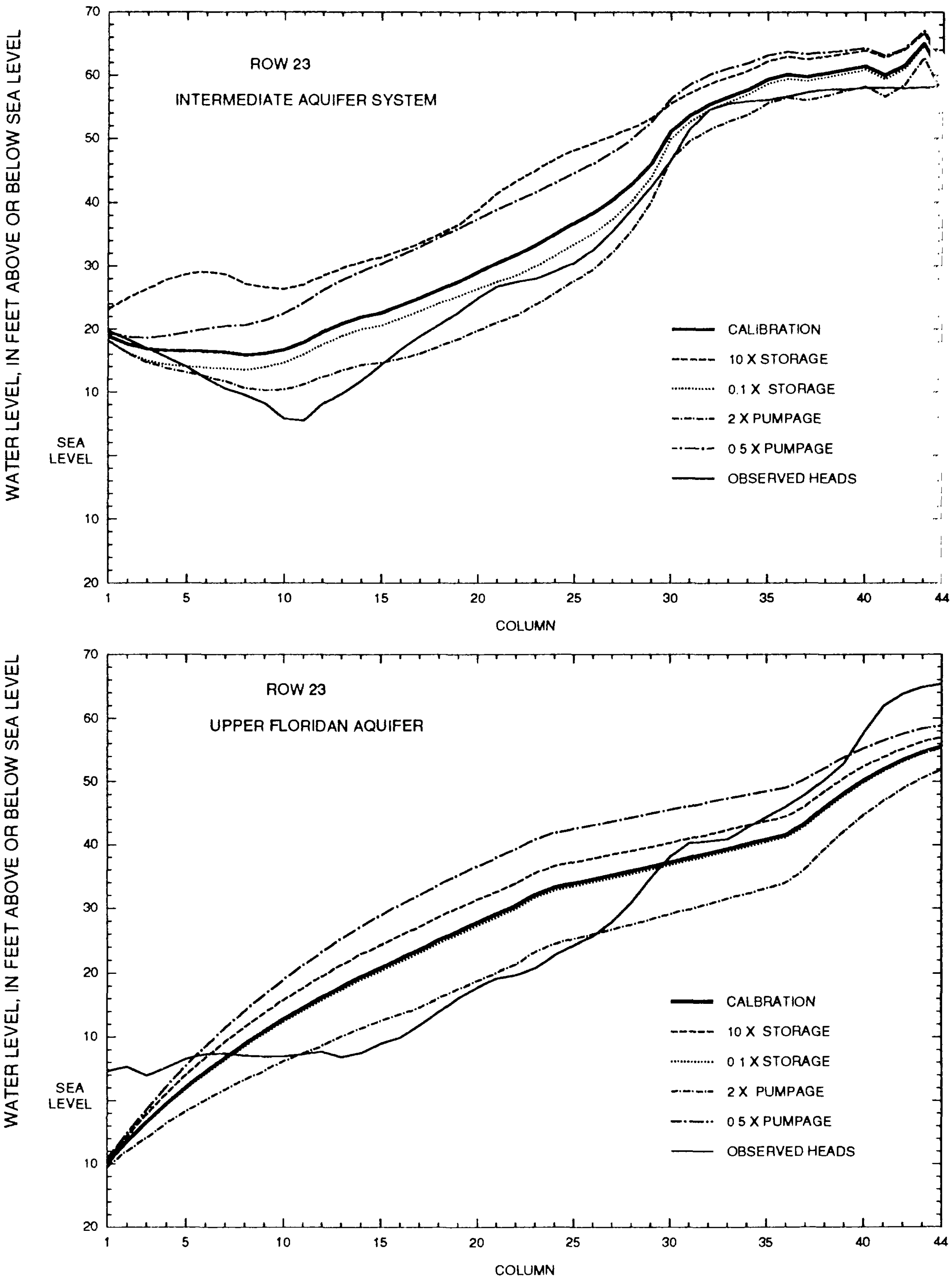


Figure 45. Results of sensitivity analyses of storage and pumpage parameters on the transient calibration for the intermediate aquifer system and the Upper Floridan aquifer, May 1989.

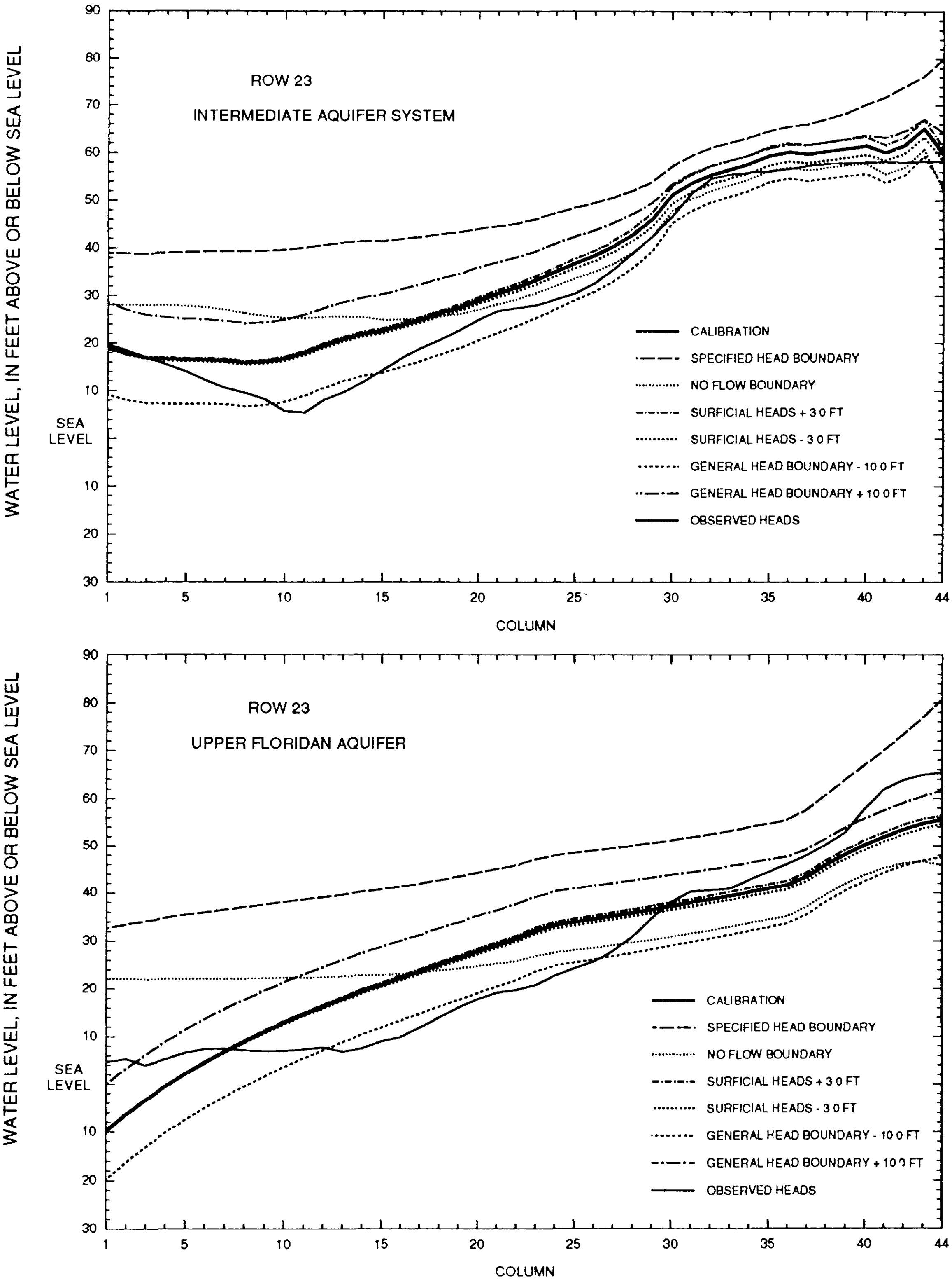


Figure 46. Results of sensitivity analyses of model boundary conditions on the transient calibration for the intermediate aquifer system and the Upper Floridan aquifer, May 1989.

Table 6. Simulated water budget for 1988-89 flow conditions
[Mgal/d, million gallons per day]

Parameter	Steady-state model calibration, September 1988		Transient model calibration, May 1989		Transient model calibration, September 1989	
	Mgal/d	Percent	Mgal/d	Percent	Mgal/d	Percent
Intermediate aquifer system						
From storage	0	0	27	13	1	1
Boundary flow (in)	3	3	4	2	3	3
Downward leakage from the surficial aquifer	100	93	178	84	99	92
Upward leakage from the Upper Floridan aquifer	5	4	2	1	4	4
Total inflow	108	100	211	100	107	100
Into storage	0	0	0	0	0	0
Boundary flow (out)	4	4	1	1	9	8
Downward leakage to the Upper Floridan aquifer	98	91	180	85	93	87
Upward leakage to the surficial aquifer	4	4	2	1	4	4
Pumpage	1	<1	28	13	1	1
Total outflow	108	100	211	100	107	100
Upper Floridan aquifer						
From storage	0	0	47	12	2	1
Boundary flow (in)	88	47	171	43	80	46
Downward leakage from the intermediate aquifer system	98	53	180	45	93	53
Total inflow	186	100	398	100	175	100
Into storage	0	0	0	0	0	0
Boundary flow (out)	112	60	157	39	100	57
Upward leakage to the intermediate aquifer system	5	3	4	1	6	4
Pumpage	69	37	237	60	69	69
Total outflow	186	100	398	100	175	100

both aquifers. These extreme head changes resulted from a lack of inflow at the potentiometric-surface high along the eastern boundary and a buildup at the western boundary where ground water could not flow laterally out of the model area.

The model was tested to estimate the range in error that would result from raising and lowering the general-head boundary (H1) by 10 ft (fig. 46). When this test was performed, the heads showed corresponding increases or decreases of approximately 10 ft from the calibrated heads. This test indicates that the model calibration is sensitive to small changes in assigned general-head boundaries.

Simulated Ground-Water Budget for 1988-89

The sources and amounts of ground-water inflow to and outflow from the intermediate aquifer system and the Upper Floridan aquifer in the model area for 1988-89 are listed in table 6. Volumetric-balance computations used to compute the water budget given in table 6 are based on the September 1988 steady-state and the May 1989 and September 1989 transient-calibration periods. The components of ground-water inflow were derived from aquifer storage, cross-boundary flow, and downward leakage through the upper and lower confining units of the intermediate aquifer system. Ground-water outflows were derived from aquifer storage, pumpage, upward leakage through the upper and lower confining units of the intermediate aquifer system, and cross-boundary flow.

Total inflow and outflow through the aquifers during the September 1988 steady-state model run was 108 Mgal/d for the intermediate aquifer system and 186 Mgal/d for the Upper Floridan aquifer. Results of the water-budget analysis for the intermediate aquifer system indicate that 93 percent of total inflow was downward leakage from the surficial aquifer, 4 percent was upward leakage from the Upper Floridan aquifer, and 3 percent was from cross-boundary flow. Outflow from the intermediate aquifer system consisted of 91 percent downward leakage into the Upper Floridan aquifer, 4 percent upward leakage into the surficial aquifer, 4 percent cross-boundary flow, and less than 1 percent pumpage. Results of the water-budget analysis for the Upper Floridan aquifer during this same period indicate that 53 percent of inflow was derived from downward leakage from the intermediate aquifer system and 47 percent was from cross-boundary flow. Outflow from the Upper Floridan aquifer was 60 percent cross-boundary flow, 37 percent pumpage, and 3 percent upward leakage into the intermediate aquifer system. The amount of downward leakage (representing the natural recharge within the model area) was equivalent to 0.85 in/yr. This recharge value is comparable to those determined in other studies (Wilson and Gerhart, 1982; Ryder, 1985; Aucott, 1988).

Total inflow and outflow through the aquifers during the pumping period of May 1989 was 211 Mgal/d for the intermediate aquifer system and 398 Mgal/d for the Upper Floridan aquifer. Results of the simulated water-budget analysis for the intermediate aquifer system indicate that 84 percent of inflow was derived from downward leakage from the surficial aquifer, 13 percent from aquifer storage, 2 percent from cross-boundary flow, and 1 percent from upward flow from the Upper Floridan aquifer. Outflow from the intermediate aquifer system was 85 percent downward leakage through the lower confining unit, 13 percent pumpage, 1 percent cross-boundary flow, and 1 percent upward leakage to the surficial aquifer. Results of the water-budget analysis for the Upper Floridan aquifer during this same period indicate that 45 percent of inflow to the aquifer was from downward leakage, 43 percent was from cross-boundary flow, and 12 percent was from aquifer storage. Outflow from the aquifer was 60 percent pumpage, 39 percent cross-boundary flow, and 1 percent upward leakage to the intermediate aquifer system.

Total inflow and outflow through the aquifers during the nonirrigation period of September 1989 was 107 Mgal/d for the intermediate aquifer system and 175 Mgal/d for the Upper Floridan aquifer. Results of the water-budget analysis for the intermediate aquifer system indicate that 92 percent of total inflow was downward leakage from the surficial aquifer, 4 percent was upward leakage from the Upper Floridan aquifer, 3 percent was from cross-boundary flow, and 1 percent was from aquifer storage. Outflow from the intermediate aquifer system consisted of 87 percent downward leakage into the Upper Floridan aquifer, 4 percent upward leakage into the surficial aquifer, 8 percent cross-boundary flow, and less than 1 percent pumpage. Results of the water-budget analysis for the Upper Floridan aquifer during this same period indicate that 46 percent of inflow was derived from downward leakage from the intermediate aquifer system, 53 percent was from cross-boundary flow, and 1 percent was from aquifer storage. Outflow from the Upper Floridan aquifer was 57 percent from cross-boundary flow, 39 percent from pumpage, and 4 percent from upward leakage to the intermediate aquifer system.

The water-budget analysis results indicate that most of the pumpage discharged from the Upper Floridan aquifer under heavy pumping conditions in May 1989 was derived about equally from boundary inflow and downward leakage. Pumpage from the intermediate aquifer system was derived primarily from downward leakage from the surficial aquifer. The relatively low transmissivity of the intermediate aquifer system limits the amount of water that is derived from boundary inflow.

Simulated Ground-Water Flow Analysis for September 1988, May 1989, and September 1989

The generalized directions and relative darcian velocities of the simulated ground-water flow system are illustrated in figures 35 and 36 and figures 41 through 44. The flow-vector diagrams were used to illustrate the results of the ground-water simulation and the magnitude and direction of water movement. The magnitude and direction of flow were calculated from the cell-by-cell flow terms in the modular model using the MMSP program by Scott (1990). The darcian velocity for ground water is the rate of discharge of ground water per unit area of porous medium measured at right angles to the direction of flow (Lohman and others, 1972). Each vector point represents the direction of flow indicated by the x-y gradients and the length of the vector is proportional to the darcian velocity.

The generalized directions and relative darcian velocities of ground-water flow in the intermediate aquifer system for September 1988, May 1989, and September 1989 are shown in figures 35, 41, and 43; respectively. Regional ground-water flow is from areas of high potential to areas of low potential. Two areas of high potential in the model area are the Polk Upland and the Lake Wales Ridge (fig. 2). Regional flow-line directions are south to southwest toward the coast, and localized flow-line directions are toward the Peace River and toward local pumping centers. The regional ground-water flow paths are similar for all time periods, except in areas where ground-water pumpage increases in May. Darcian velocities are lowest at the Lake Wales Ridge and the Polk Upland and are highest along the Peace River where flow is toward the river.

The generalized directions and relative darcian velocities of ground-water flow in the Upper Floridan aquifer for September 1988, May 1989, and September 1989 are shown in figures 36, 42, and 44; respectively. As indicated by the flow vectors, regional ground-water flow is from areas of high potential to areas of low potential. The high potentiometric surface along the Lake Wales Ridge indicates that this area is a recharge area. Regionally, the flow vectors are oriented toward the west or southwest toward southern Hillsborough and Manatee Counties where large ground-water withdrawals for irrigation have resulted in a perennial cone of depression in the potentiometric surface. The regional ground-water flow paths were toward this cone of depression during September 1988 and September 1989. In May 1989, flow vectors were primarily oriented toward local pumping centers. Darcian velocities in these figures are relatively uniform for the Upper Floridan aquifer throughout the model area except at pumping centers where the darcian velocities are slightly higher and along the Lake Wales Ridge where the darcian velocities are slightly lower.

HYPOTHETICAL DEVELOPMENT SCENARIOS

The calibrated transient model was used to simulate changes in the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer that might result from increased ground-water withdrawals for citrus irrigation for the years 2000 and 2020. Only the effects of projected increases in withdrawals for citrus irrigation were evaluated for this investigation. Withdrawals for public, industrial, and other agricultural uses were assumed to remain constant in future pumping scenarios.

Model runs were made to simulate the irrigation season (September through May). Because the September potentiometric surface recovers to nearly the same level each year, the model-simulation runs for projected withdrawals used starting heads based on the calibrated September 1988 potentiometric surface. Nine monthly stress periods were used to simulate existing and projected seasonal pumping rates for the irrigation period. Projected ground-water withdrawal rates for citrus irrigation were determined by multiplying the projected increase in acreage used for citrus by an average historical application rate of 11 in/yr for citrus drip irrigation (Duerr and Trommer, 1982; Taylor and others, 1990). The projected citrus irrigation pumping rates were added to the transient model pumping arrays.

The areal distribution of the projected new citrus acreage was selected on the basis of the proximity of existing citrus groves to vacant land or to existing melon and pasture acreage (Mark Hammond, Southwest Florida Water Management District, written commun., 1990). The projected increase in citrus acreage is widely dispersed for the year 2000, but included a 15-mi area in eastern De Soto County representing a large new grove for the year 2020. The locations of these projected citrus groves in the study area are shown in figure 47. The current and projected citrus acreage and pumping rates used in the model simulations for 1989, 2000, and 2020 are presented in table 7.

Results of the transient model runs with increased pumpage for citrus irrigation are presented as a series of contour maps that show the potentiometric surface for each aquifer for the end of the simulation periods, which represent May 2000 and May 2020. Results also are presented as a series of change maps that show the amount of decline between the May 1989 calibration period and May 2000 and between May 1989 and May 2020. September was not illustrated in the change-map series because the potentiometric surface recovered to September 1989 simulated heads after pumpage was removed for each successive recovery period. Distribution of pumpage from the intermediate aquifer system and the Upper Floridan aquifer used in the simulations for May 1989, May 2000, and May 2020 are shown in appendix I.

May 2000

The simulated potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer for May 2000 and the departure from May 1989 heads are shown in figures 48 and 49, respectively. These simulations are the result of increasing pumpage for the 1988-89 water year by 11 percent in the intermediate aquifer system and 10 percent in the Upper Floridan aquifer.

For the intermediate aquifer system, a maximum decline of 3 ft was simulated in three localized areas, and an average decline of more than 1.5 ft was simulated for most of the model area (fig. 48). For the Upper Floridan aquifer, a maximum decline of about 4 ft was simulated in a 1-mi area in Hardee County, and an average decline of about 1.5 ft was simulated in the two-county area (fig. 49).

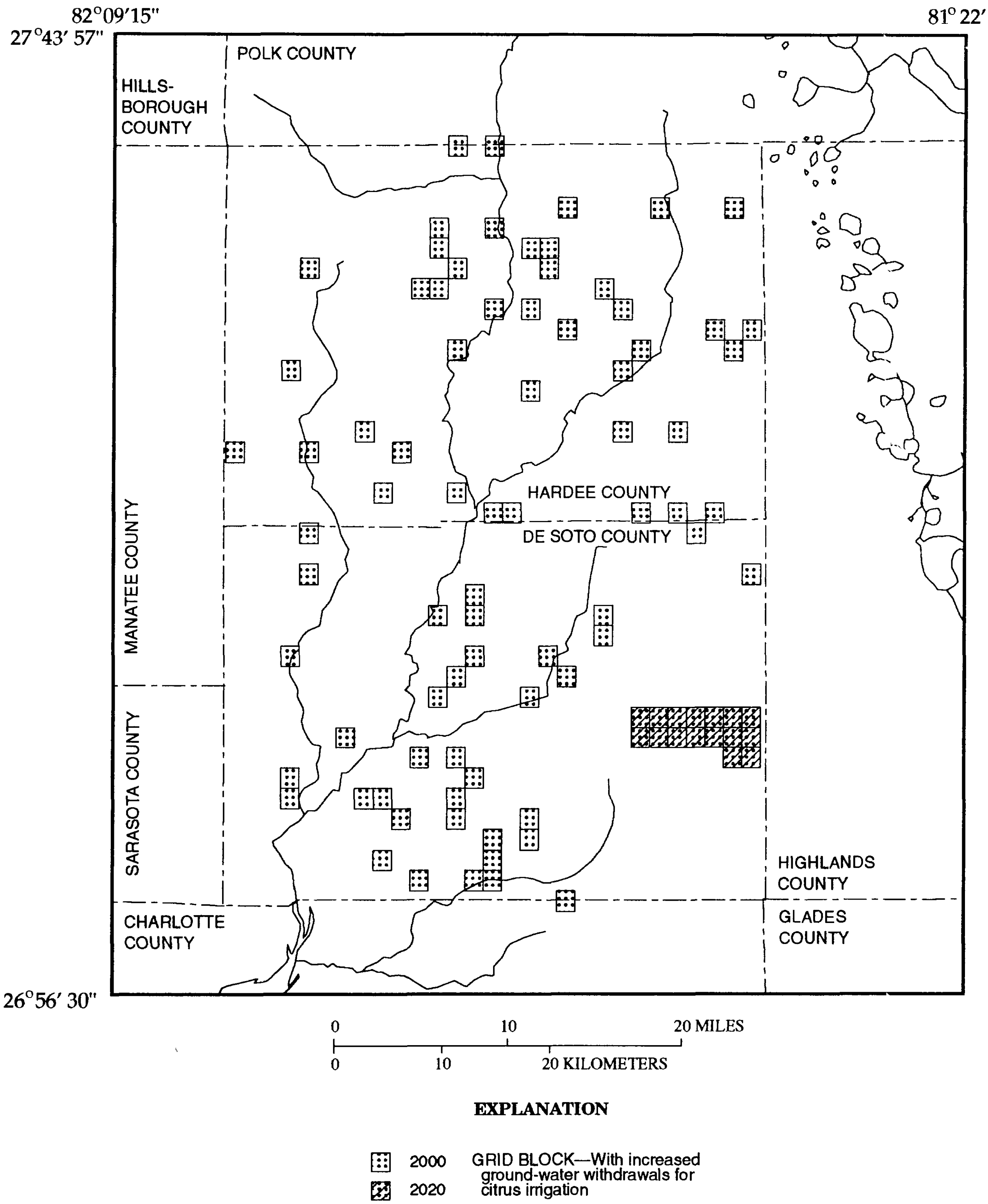


Figure 47. Locations of model grid blocks with projected increases in citrus acreage zones for the years 2C00 and 2020.

Table 7. Current and projected ground-water withdrawal rates and citrus acreage for 1989, 2000, and 2020

Parameter	Ground-water withdrawals, in million gallons per day		
	Hardee County	De Soto County	Total
1989			
Citrus acreage	43,143	45,898	89,041
Source of withdrawals			
Intermediate aquifer system	4	4	8
Upper Floridan aquifer	34	35	69
Total	38	39	77
2000			
Citrus acreage	59,047	63,518	122,565
Source of withdrawals			
Intermediate aquifer system	5	5	10
Upper Floridan aquifer	47	51	98
Total	52	56	108
2020			
Citrus acreage	59,047	75,377	134,424
Source of withdrawals			
Intermediate aquifer system	5	6	11
Upper Floridan aquifer	47	60	107
Total	52	66	118

May 2020

The simulated potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer for May 2020 and the departure from May 1989 heads are shown in figures 50 and 51, respectively. These simulations are the result of increasing pumpage for the 1988-89 water year by 25 percent in the intermediate aquifer system and 21 percent in the Upper Floridan aquifer.

For the intermediate aquifer system, a maximum decline of more than 10 ft was simulated in eastern De Soto County, and an average decline of more than 2 ft was simulated for much of the model area (fig. 50). For the Upper Floridan aquifer, a maximum decline of about 5 ft was simulated in eastern De Soto County, and a decline of more than 2 ft was simulated for much of the model area (fig. 51). The largest declines occurred at the postulated 15-mi citrus grove.

SIMULATED EFFECTS OF INCREASED WITHDRAWALS FOR CITRUS IRRIGATION

The computed rates of upward and downward leakage, lateral inflow and outflow, pumpage, and water released from storage during May 1989 and under conditions of increased citrus irrigation projected for May 2000 and May 2020 are listed in table 8.

The projected increase in ground-water withdrawals would alter the flow system from that which existed in 1988-89, but not to a great degree. The simulations were used to investigate the potential effects of hypothetical development between May 1989 and May 2000 and between May 1989 and May 2020. The results indicated that major effects of increased withdrawals include:

- A maximum decline of more than 10 ft in the potentiometric surface of the intermediate aquifer system at a projected grove in eastern De Soto County and a decline of more than 2 ft in the potentiometric surface of this aquifer system throughout much of the study area.
- An increase in downward leakage from the overlying surficial aquifer system to the intermediate aquifer system from 178 to 183 Mgal/d.
- A decrease in upward leakage from the intermediate aquifer system to the surficial aquifer from 1.58 to 1.47 Mgal/d.
- A maximum decline of about 5 ft in the potentiometric surface of the Upper Floridan aquifer at a projected grove in eastern De Soto County and a decline of more than 2 ft in the potentiometric surface of this aquifer throughout much of the study area.
- An increase in downward leakage from the intermediate aquifer system to the Upper Floridan aquifer from 180 to 183 Mgal/d.
- A decrease in upward leakage from the Upper Floridan aquifer to the intermediate aquifer system from 4.32 Mgal/d in May 1989 to 3.89 million gallons per day, in May 2000 but an increase in upward leakage to 5.10 Mgal/d between May 1989 and May 2020, reflecting a change in hydrologic gradient.

SUMMARY AND CONCLUSIONS

The hydrogeology of Hardee and De Soto Counties in west-central Florida was evaluated to estimate changes in the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer as a result of expected increases in ground-water withdrawals for citrus irrigation for the years 2000 and 2020. Citrus groves constitute the second largest land-use category in Hardee and De Soto Counties, and citrus acreage in these counties is expected to increase because of the favorable climatic conditions. Total citrus acreage in Hardee and De Soto Counties in 1988 was 89,041 acres, and it is projected that citrus acreage will increase to about 130,000 acres by the year 2020.

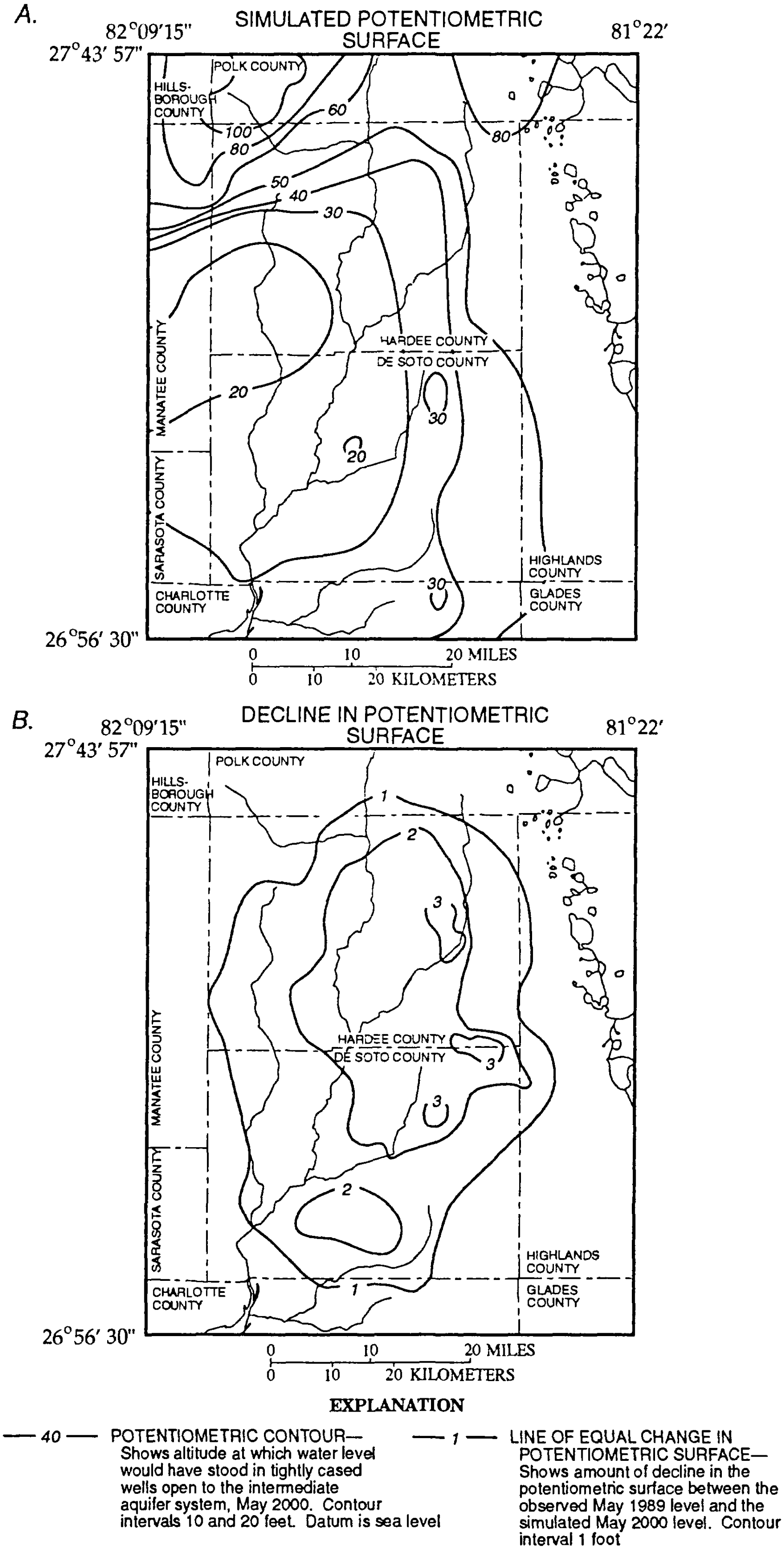
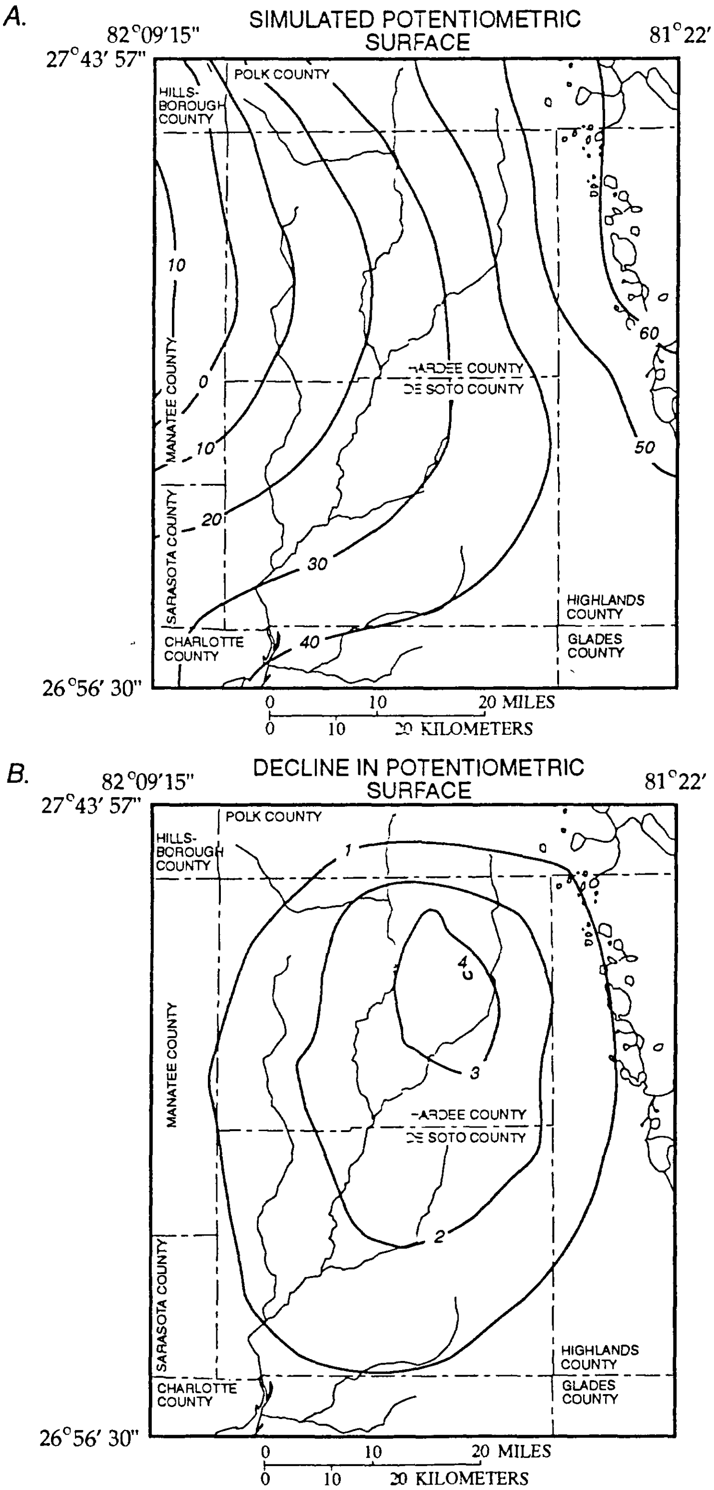


Figure 48. Simulated potentiometric surface of the intermediate aquifer system, May 2000, and simulated declines in the potentiometric surface as a result of projected increases in ground-water withdrawals for citrus irrigation, May 1989 to May 2000.



EXPLANATION

— 40 — POTENTIOMETRIC CONTOUR— Shows altitude at which water level would have stood in tightly cased wells open to the Upper Floridan aquifer, May 2000. Contour interval is 10 feet. Datum is sea level

— 1 — LINE OF EQUAL CHANGE IN POTENTIOMETRIC SURFACE— Shows amount of decline in the potentiometric surface between the observed May 1989 level and the simulated May 2000 level. Contour intervals are 1 and 5 feet

Figure 49. Simulated potentiometric surface of the Upper Floridan aquifer, May 2000, and simulated declines in the potentiometric surface as a result of projected increases in ground-water withdrawals for citrus irrigation, May 1989 to May 2000.

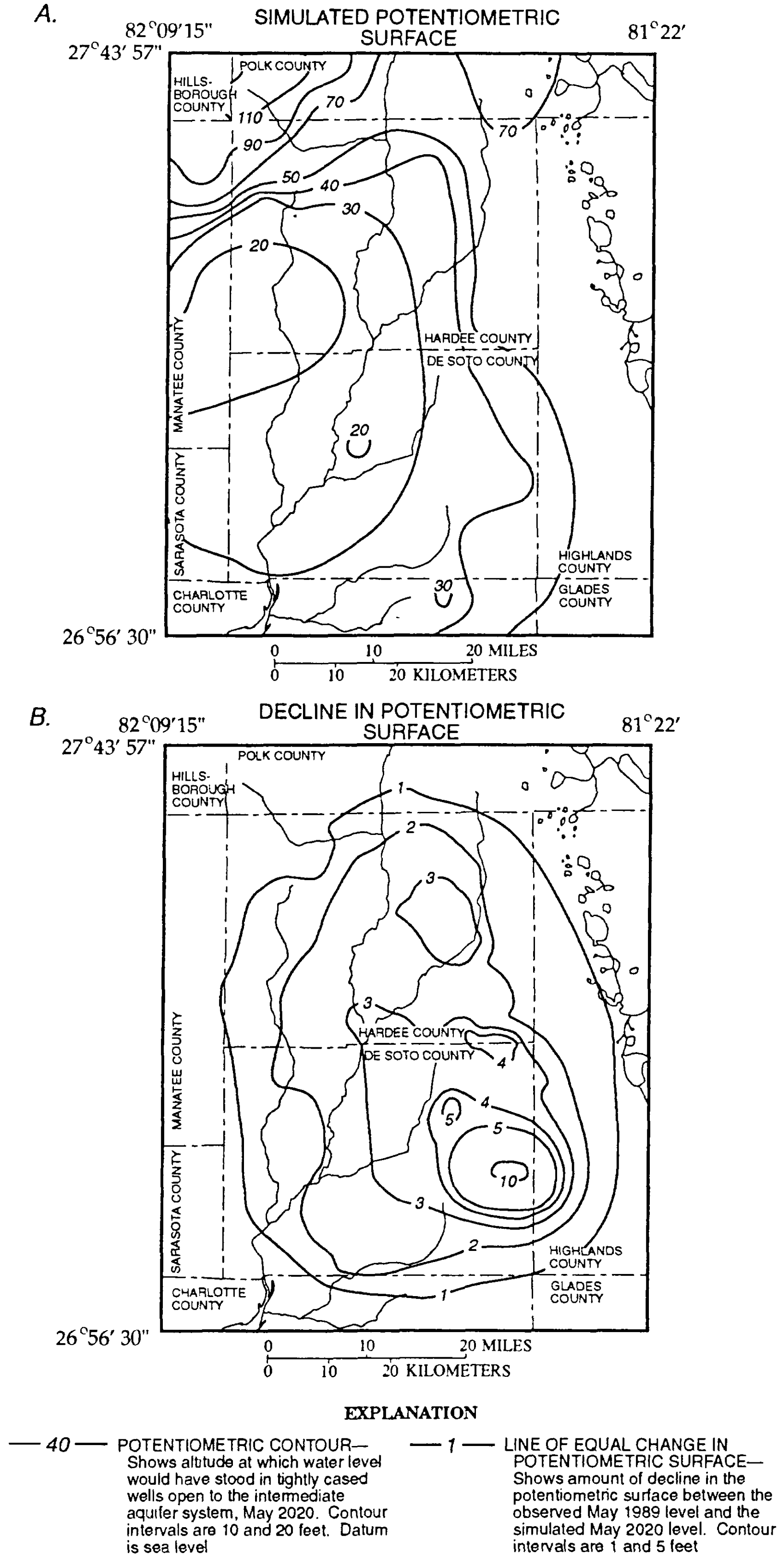
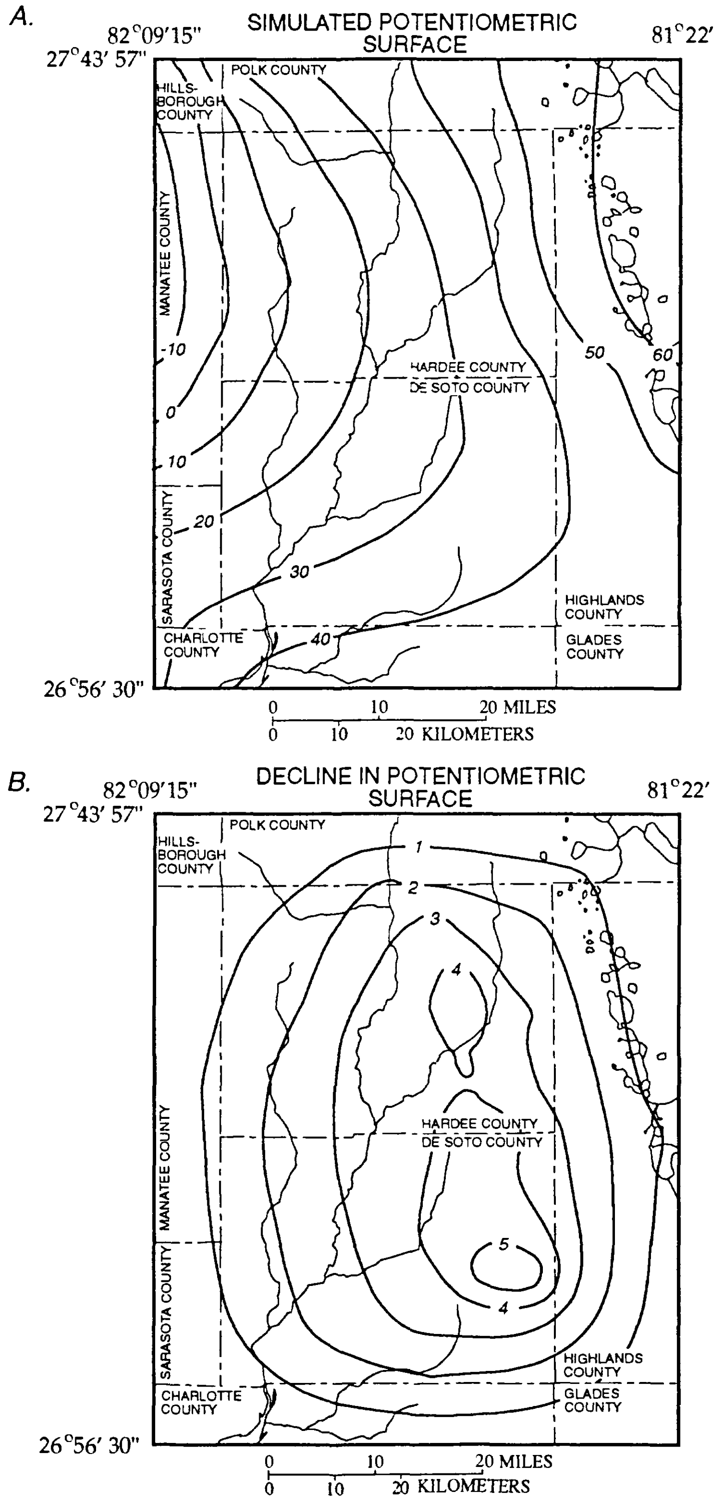


Figure 50. Simulated potentiometric surface of the intermediate aquifer system, May 2020, and simulated declines in the potentiometric surface as a result of projected increases in ground-water withdrawals for citrus irrigation, May 1989 to May 2020.



EXPLANATION

—40— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells open to the Upper Floridan Aquifer, May 2020. Contour interval 10 feet. Datum is sea level

—1— LINE OF EQUAL CHANGE IN POTENTIOMETRIC SURFACE—Shows amount of decline in the potentiometric surface between the observed May 1989 level and the simulated May 2020 level. Contour interval is 1 foot

Figure 51. Simulated potentiometric surface of the Upper Floridan aquifer, May 2020, and simulated declines in the potentiometric surface as a result of projected increases in ground-water withdrawals for citrus irrigation, May 1989 to May 2020.

Table 8. Simulated water budgets for May 1989, May 2000, and May 2020 flow conditions
[Mgal/d, million gallons per day]

Parameter	Transient model calibration, May 1989		Transient model calibration, May 2000		Transient model calibration, May 2020	
	Mgal/d	Percent	Mgal/d	Percent	Mgal/d	Percent
Intermediate aquifer system						
From storage	27	13	27	12	26	12
Boundary flow (in)	4	2	5	2	7	3
Downward leakage from the surficial aquifer	178	84	182	84	183	83
Upward leakage from the Upper Floridan aquifer	2	1	4	2	5	2
Total inflow	211	100	218	100	221	100
Into storage	0	0	0	0	0	0
Boundary flow (out)	1	1	2	1	1	<1
Downward leakage to the Upper Floridan aquifer	180	85	183	84	183	83
Upward leakage to the surficial aquifer	2	1	2	1	2	1
Pumpage	28	13	31	14	35	16
Total outflow	211	100	218	100	221	100
Upper Floridan aquifer						
From storage	47	12	33	8	33	8
Boundary flow (in)	171	43	199	48	205	49
Downward leakage from the intermediate aquifer system	180	45	183	44	183	43
Total inflow	398	100	415	100	421	100
Into storage	0	0	0	0	0	0
Boundary flow (out)	157	39	150	36	130	31
Upward leakage to the intermediate aquifer system	4	1	4	1	5	1
Pumpage	237	60	261	63	286	68
Total outflow	398	100	415	100	421	100

Fresh ground water is obtained from three principal aquifers in the study area: the surficial aquifer, the intermediate aquifer system, and the highly productive Upper Floridan aquifer. The surficial aquifer is composed predominantly of quartz sand deposits that generally are less than 100 ft thick. Ground water in the surficial aquifer is unconfined, and the water table in this aquifer fluctuates about 2 to 7 ft seasonally. The surficial aquifer is recharged by rainfall.

The intermediate aquifer system lies beneath the surficial aquifer and is composed of the rocks and clastic deposits of the Hawthorn Group. The intermediate aquifer system generally is 200 to 500 ft thick and contains a permeable unit composed of interbedded limestone and dolomite. Transmissivities of the intermediate aquifer system range from about 400 to 7,000 ft^2/d and storage coefficients range from about 2.0×10^{-4} to 5.0×10^{-4}.

The intermediate aquifer system has an upper and a lower confining unit. The upper confining unit ranges in thickness from less than 25 to about 265 ft and consists of dolomite, sand, clay, silt, and phosphorite. As determined by model calibration, leakance for the upper confining unit in the study area ranges from 3.0×10^{-3} to 1.0×10^{-6} (ft/d)/ft. The lower confining unit ranges in thickness from less than 25 to about 185 ft and consists of sand and clay, sand, and phosphorite. As determined by model calibration, leakance of the lower confining unit ranges from 1.0×10^{-4} to 1.0×10^{-5} (ft/d) ft.

The potentiometric surface of the intermediate aquifer system fluctuates seasonally; the highest levels occur in September, and the lowest levels occur in May. The potentiometric surface in September 1988 ranged from 120 ft above sea level in northwestern Hardee County to 40 ft above sea level in southwestern Hardee County and northwestern De Soto County. The potentiometric surface ranged from about 110 ft above sea level in northwestern Hardee County to 5 ft above sea level in southwestern Hardee County in May 1989 at the end of the irrigation season. Regional ground-water flow in the intermediate aquifer system generally is south to southwest from the Polk Upland and the Lake Wales Ridge toward the Gulf of Mexico; locally, ground-water flow is toward the Peace River and pumping wells.

The intermediate aquifer system is the second largest source of water supply in the study area. In 1988, ground-water withdrawals from this aquifer system averaged 16 Mgal/d and were primarily for irrigation and public supply. Several hundred wells are open to this aquifer system, and it is a valuable source of water in the southern part of the study area where the highly productive Upper Floridan aquifer contains mineralized water.

The highly productive Upper Floridan aquifer consists of fractured and solution-riddled carbonate rocks. The Upper Floridan aquifer includes all or parts of the Suwannee Limestone, the Ocala Limestone, and the Avon Park Formation. The top of the Upper Floridan aquifer is the horizon below which carbonate rocks consistently occur. The base of the Upper Floridan aquifer, the middle confining unit of the Floridan aquifer system, is the first persistently occurring, intergranular evaporite in the carbonate rocks. Thickness of the Upper Floridan aquifer ranges from 1,200 to 1,400 ft in the study area. Transmissivity values for this aquifer range from 70,600 to 850,000 ft^2/d, and storage coefficients range from 1.0×10^{-4} to 1.2×10^{-4}.

The potentiometric surface of the Upper Floridan aquifer fluctuates seasonally; the highest levels occur in September and the lowest levels occur in May. In September 1988, the altitude of the potentiometric surface of this aquifer ranged from about 80 ft above sea level in northeastern Hardee County to 40 ft above sea level in southwestern Hardee County and northwestern De Soto County. In May 1989 at the end of the irrigation season, the altitude of the potentiometric surface of the Upper Floridan ranged from 60 ft above sea level in northeastern Hardee County to about 5 ft above sea level in western Hardee County. Regional ground-water flow generally is toward the west or southwest from the Lake Wales Ridge toward the Gulf of Mexico and toward large pumping centers in Hillsborough and Manatee Counties. Locally, ground-water flow is toward pumping wells.

The Upper Floridan aquifer is the major source of water supply in the study area; wells open to this aquifer can yield more than 2,500 gal/min. Thousands of wells are open to this aquifer and are used for irrigation, industrial, domestic, and public supply. Ground-water withdrawals from the Upper Floridan aquifer in the study area in 1988 averaged 106 Mgal/d, mostly for agricultural, public supply, and industrial use.

A quasi-three-dimensional ground-water flow model was used to compute hydraulic head changes in response to changes in projected pumping rates in the intermediate aquifer system and the Upper Floridan aquifer. A steady-state model was calibrated to better define the hydrogeologic parameters of the aquifer system and to serve as the initial point for subsequent transient simulations. A steady-state calibration was achieved by systematically varying transmissivity and leakance until model simulations approximated field conditions. Principal stresses on the aquifer system in September 1988, at the end of the wet season, were withdrawals for industrial and municipal supplies. Irrigation pumpage was assumed to be zero for the calibration period.

A transient simulation was performed to determine the effects of municipal, industrial, and agricultural pumping on the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer. The transient model was considered calibrated when simulated hydrographs for the period from September 1988 to September 1989 were in reasonable agreement with observed hydrographs and when simulated May 1989 and September 1989 potentiometric surfaces were in reasonable agreement with the previously mapped surfaces for the intermediate aquifer system and the Upper Floridan aquifer.

Transient-model analyses were used to simulate the change in the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer for the years 2000 and 2020 that might result from projected ground-water withdrawals for citrus irrigation. Simulation results indicated that the projected increase in ground-water withdrawals would alter the flow system from that observed in 1988, but not to a great degree. The principal effects of hypothetical development are:

- A maximum decline of more than 10 ft in the potentiometric surface of the intermediate aquifer system at a projected grove in eastern De Soto County and an average decline of more than 2 ft in the potentiometric surface of this aquifer throughout much of the study area.
- An increase in downward leakage from the overlying surficial aquifer system to the intermediate aquifer system from 178 to 183 Mgal/d.
- A decrease in upward leakage from the intermediate aquifer system to the surficial aquifer from 1.58 to 1.47 Mgal/d.

- A maximum decline of about 5 ft in the potentiometric surface of the Upper Floridan aquifer at a projected grove in eastern De Soto County and a decline of more than 2 ft in the potentiometric surface of this aquifer throughout much of the study area.
- An increase in downward leakage from the intermediate aquifer system to the Upper Floridan aquifer from 180 to 183 Mgal/d.
- A decrease in upward leakage from the Upper Floridan aquifer to the intermediate aquifer system from 4.32 Mgal/d in May 1989 to 3.89 Mgal/d in May 2000, but an increase in upward leakage to 5.10 Mgal/d between May 1989 and May 2020, reflecting a change in hydrologic gradient.

SELECTED REFERENCES

Aucott, W.R., 1988, Areal variations in recharge to and discharge from the Floridian aquifer system in Florida: U.S. Geological Survey Water-Resources Investigations Report 88-4057, 1 sheet.

Barr, G.L., 1989a, Potentiometric surface of the intermediate aquifer, west-central Florida, September 1988: U.S. Geological Survey Open-File Report 89-36, 1 sheet.

——1989b, Potentiometric surface of the intermediate aquifer, west-central Florida, May 1989: U.S. Geological Survey Open-File Report 89-394, 1 sheet.

——1989c, Potentiometric surface of the Upper Floridan aquifer, west-central Florida, September 1988: U.S. Geological Survey Open-File Report 88-730, 1 sheet.

——1989d, Potentiometric surface of the Upper Floridan aquifer, west-central Florida, May 1989: U.S. Geological Survey Open-File Report 89-393, 1 sheet.

Bergendahl, M.H., 1956, Stratigraphy of parts of De Soto and Hardee Counties, Florida: U.S. Geological Survey Bulletin 1030-B, p. 65-97.

Duerr, A.D., and Enos, G.M., 1991, Hydrogeology of the intermediate aquifer system and Upper Floridan aquifer, Hardee and De Soto Counties, Florida: U.S. Geological Survey Water-Resources Investigations Report 90-4104, 46 p.

Duerr, A.D., Hunn, J.D., Lewelling, B.R., and Trommer, J.T., 1988, Geohydrology and 1985 water withdrawals of the aquifer systems in southwest Florida, with emphasis on the intermediate aquifer system: U.S. Geological Survey Water-Resources Investigations Report 87-4259, 119 p.

Duerr, A.D., and Sohm, J.E., 1983, Estimated water use in southwest Florida, 1981, and summary of water use 1970, 1975, and 1977-81: U.S. Geological Survey Open-File Report 83-45, 75 p.

Duerr, A.D., and Trommer, J.T., 1982, The benchmark farm program--a method for estimating irrigation water use in southwest Florida: U.S. Geological Survey Water-Resources Investigations 82-17, 49 p.

Duerr, A.D., and Wolansky, R.M., 1986, Hydrogeology of the surficial and intermediate aquifers of central Sarasota County, Florida: U.S. Geological Survey Water-Resources Investigations Report 86-4068, 48 p.

Florida Agricultural Statistical Service, 1989, Citrus summary, 1987-88: Orlando, Florida Department of Agriculture and Consumer Services Report.

Geurink, J.S., 1986, Agricultural water use permitting procedures: Brooksville, Southwest Florida Water Management District Report.

Gilboy, A.E., 1985, Hydrogeology of the Southwest Florida Water Management District: Brooksville, Southwest Florida Water Management District Report, 18 p.

Harrison, D.S., Smajstrla, A.G., Choate, R.E., and Isaacs, G.W., 1983, Irrigation in Florida agriculture in the '80s: Gainesville, University of Florida/IFAS, Florida Cooperative Extension Service, Bulletin 196.

Hickey, J.J., 1990, An assessment of the flow of variable-salinity ground water in the middle confining unit of the Floridan aquifer system, west-central Florida: U.S. Geological Survey Water-Resources Investigations Report 89-4142, 13 p.

Hutchinson, C.B., 1978, Appraisal of shallow ground-water resources and management alternatives in the upper Peace and eastern Alafia River basins, Florida: U.S. Geological Survey Water-Resources Investigations 77-124, 57 p.

Johnston, R.H., and Bush, P.W., 1988, Summary of the hydrology of the Floridian aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-A, 24 p., 4 pl.

Kaufman, M.I., 1967, Hydrologic effects of ground-water pumpage in the Peace and Alafia River basins, Florida, 1934-1965: Florida Division of Geology Report of Investigations no. 49, 32 p.

Kernodle, J.M., and Philip, R.D., 1989, Using a geographic information system to develop a ground-water flow model, *in* Regional aquifer systems of the United States--Aquifers of the western mountain area: American Water Resources Association Monograph Series 14, p. 191-202.

Knochenmus, L.A., and Barr, G.L., 1990a, Potentiometric surface of the intermediate aquifer, west-central Florida, September 1989: U.S. Geological Survey Open-File Report 90-134, 1 sheet.

——1990b, Potentiometric surface of the Upper Floridan aquifer, west-central Florida, September 1989: U.S. Geological Survey Open-File Report 90-133, 1 sheet.

Krause, R.E., and Randolph, R.B., 1989, Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina: U.S. Geological Survey Professional Paper 1403-D, 65 p.

Leach, S.D., and Healy, H.G., 1980, Estimated water use in Florida, 1977: U.S. Geological Survey Water-Resources Investigations 79-112, 76 p.

Lewelling, B.R., 1988, Potentiometric surface of the Upper Floridan aquifer, west-central Florida, May 1988: U.S. Geological Survey Open-File Report 88-461, 1 sheet.

——1989, Potentiometric surface of the intermediate aquifer system, west-central Florida, May 1988: U.S. Geological Survey Open-File Report 88-721, 1 sheet.

Lohman, S.W., 1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Lohman, S.W., and others, 1972, Definitions of selected ground water terms--revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

McDonald, M.G., and Harbaugh, A.W., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83-875, 528 p.

Marella, R.L., 1992 Water withdrawals, use, and trends in Florida, 1990: U.S. Geological Survey Water-Resources Investigations Report 92-4140, 38 p.

Miller, J.A., 1982a, Configuration of the base of the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1177, 1 sheet.

——1982b, Geology and configuration of the base of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1176, 1 sheet.

——1982c, Geology and configuration of the top of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1178, 1 sheet.

——1982d, Thickness of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1124, 1 sheet.

——1982e, Thickness of the upper permeable zone of the Tertiary limestone aquifer system, southeastern United States: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-1179, 1 sheet.

——1986, Hydrogeologic framework of the Floridan aquifer system in Florida, and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p., 33 pl.

Mills, L.R., and Laughlin, C.P., 1976, Potentiometric surface of Floridan aquifer, May 1975, and change of potentiometric surface 1969 to 1975, Southwest Florida Water Management District and adjacent areas: U.S. Geological Survey Water-Resources Investigations 76-80, 1 sheet.

Palmer, C.E., and Bone, L.P., 1977, Some aspects of rainfall deficits in west-central Florida, 1961-1976: Southwest Florida Water Management District Hydrometeporological Report No. 1, 19 p.

Puri, H.S., and Vernon, R.O., 1964, Summary of the geology of Florida and a guidebook to the classic exposures: Florida Geological Survey Special Publication no. 5, 312 p.

Robertson, A.F., Mills, L.R., and Parsons, D.C., 1978, Ground water withdrawn for municipal, industrial, and irrigation use in the upper Peace and Alafia River basins, west-central Florida, 1970-74: U.S. Geological Survey Open-File Report 78-29, 59 p.

Ryder, P.D., 1982, Digital model of predevelopment flow in the Tertiary limestone (Floridan) aquifer system in west-central Florida: U.S. Geological Survey Water-Resources Investigations 81-54, 61 p.

——1985, Hydrology of the Floridian aquifer system in west-central Florida: U.S. Geological Survey Professional Paper 1403-F, 63 p.

Scott, J.C., 1990, A statistical processor for analyzing simulations made using the modular finite-difference ground-water flow model: U.S. Geological Survey Water-Resources Investigations Report 89-4159, 218 p.

Scott, T.M., 1988, The lithostratigraphy of the Hawthorn group (Miocene) of Florida: Florida Geological Survey Bulletin no. 59, 149 p.

Sorensen, L.A., Burns, L.L., Miles, D.M., Norris, H., and Tuttell, M., 1990, 1988 estimated water use in the Southwest Florida Water Management District: Brooksville, Southwest Florida Water Management District, Planning Department, 96 p.

Southeastern Geological Society, 1986, Hydrogeological units of Florida: Florida Geological Survey Special Publication no. 28, 8 p.

Southwest Florida Water Management District, 1989, Summary of hydrologic conditions, September 1989: 58 p.

Stewart, J.W., Mills, L.R., Knochenmus, D.D., and Faulkner, G.L., 1971, Potentiometric surface and areas of artesian flow, May 1969, and change of potentiometric surface 1964 to 1969, Floridan aquifer, Southwest Florida Water Management District, Florida: U.S. Geological Survey Hydrologic Investigations Atlas HA-440, 1 sheet.

Stieglitz, E.H., 1985, Estimated water use in the Southwest Florida Water Management District, 1983: Brooksville, Southwest Florida Water Management District, 33 p.

——1985, Estimated water use in the Southwest Florida Water Management District, 1984: Brooksville, Southwest Florida Water Management District, 44 p.

Taylor, T.G., Reynolds, J.E., and Bedigian, K.J., 1990, Agricultural land use projections for the Southwest Florida Water Management District: Brooksville, Southwest Florida Water Management District Report, p. 13-19.

Tibbals, C.H., 1990, Hydrology of the Floridian aquifer system in east-central Florida: U.S. Geological Survey Professional Paper 1403-D, 98 p.

Tucker, P.H., 1980, Citrus irrigation management: Gainesville, University of Florida/IFAS, Florida Cooperative Extension Service Circular 729, 13 p.

Tuttell, M., and Sorensen, L.A., 1989, 1987 Estimated water use in the Southwest Florida Water Management District: Brooksville, Southwest Florida Water Management District, 99 p.

White, W.A., 1970, The geomorphology of the Florida Peninsula: Florida Bureau of Geology Bulletin no. 51, 164 p.

Wilson, W.E., 1972, Hydrogeology of Florida's largest citrus grove: American Society of Civil Engineers, Irrigation and Drainage Division Specialty Conference, Proceedings, p. 293-307.

——1977, Ground-water resources of De Soto and Hardee Counties, Florida: Florida Bureau of Geology Report of Investigations no. 83, 102 p.

Wilson, W.E., and Gerhart, J.M., 1982, Simulated effects of ground-water development on potentiometric surface of the Floridan aquifer, west-central Florida: U.S. Geological Survey Professional Paper 1217, 83 p.

Wolansky, R.M., and Corral, M.A., Jr., 1985, Aquifer tests in west-central Florida, 1952-76: U.S. Geological Survey Water-Resources Investigations Report 84-4044, 127 p.

Wolansky, R.M., Spechler, R.M., and Buono, Anthony, 1979, Generalized thickness of the surficial deposits above the confining bed overlying the Floridan aquifer, Southwest Florida Water Management District: U.S. Geological Survey Water-Resources Investigations Open-File Report 79-1071, 1 sheet.

Yobbi, D.K., 1983, Trends and fluctuations in the potentiometric surface of the Floridian aquifer, west-central Florida, 1961-80: U.S. Geological Survey Water-Resources Investigations 82-4086, 1 sheet.

Appendix

Pumpage Distribution for Transient Simulations for the Intermediate Aquifer System and Upper Floridan Aquifer, Hardee and De Soto Counties, Florida

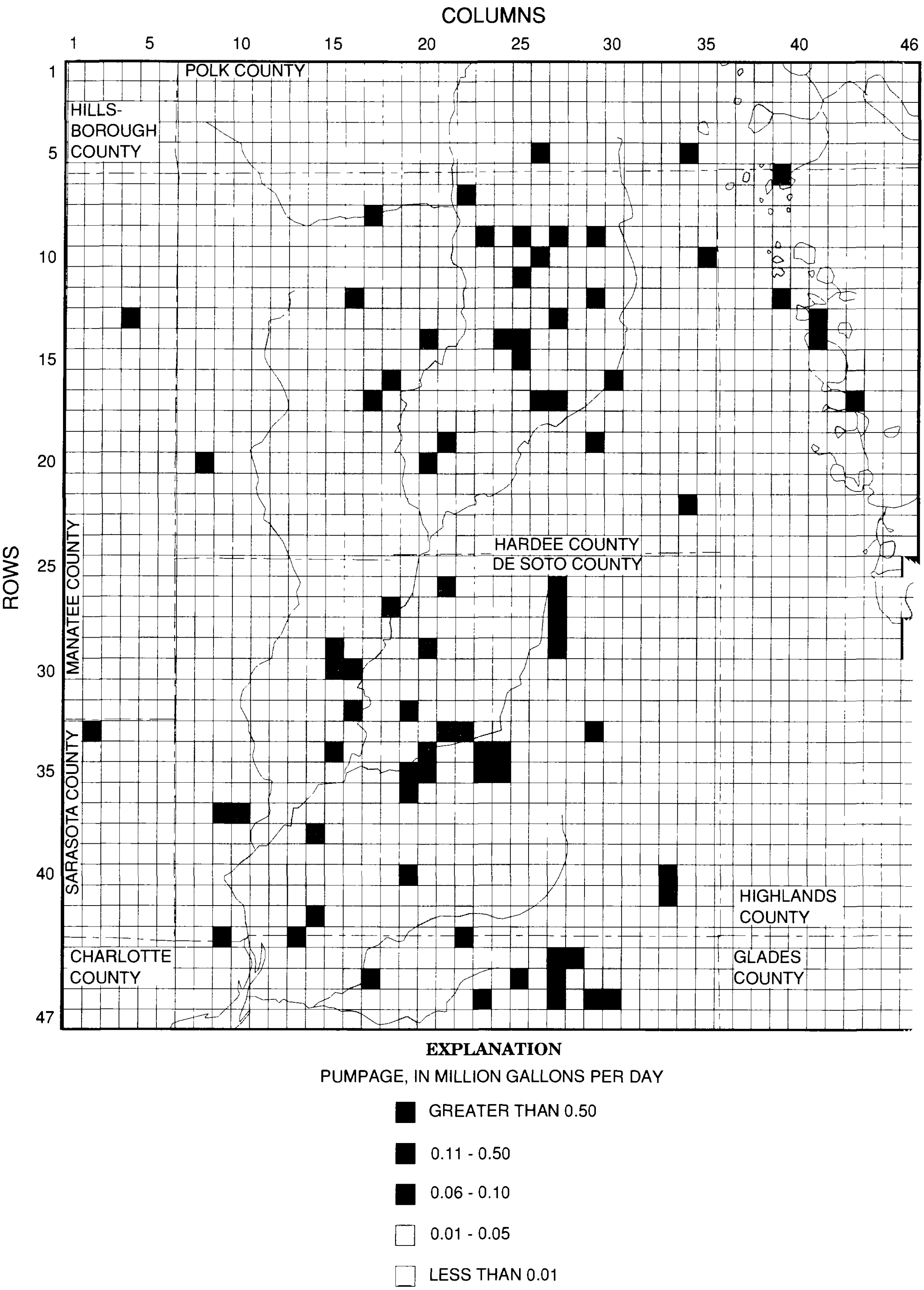


Figure 52. Pumpage distribution used in transient simulations for the intermediate aquifer system, May 1989.

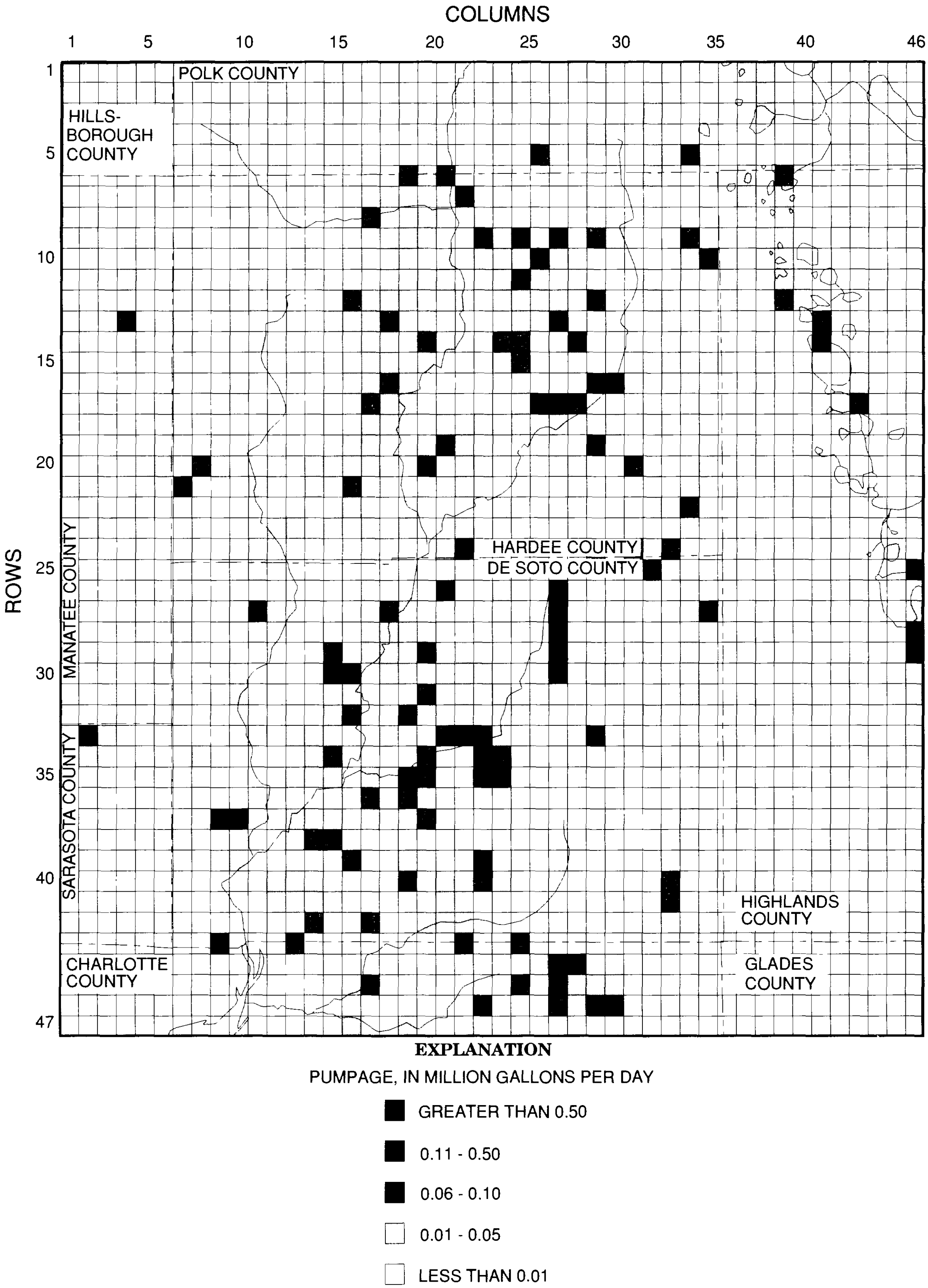


Figure 53. Pumpage distribution used in transient simulations for the intermediate aquifer system, May 2000.

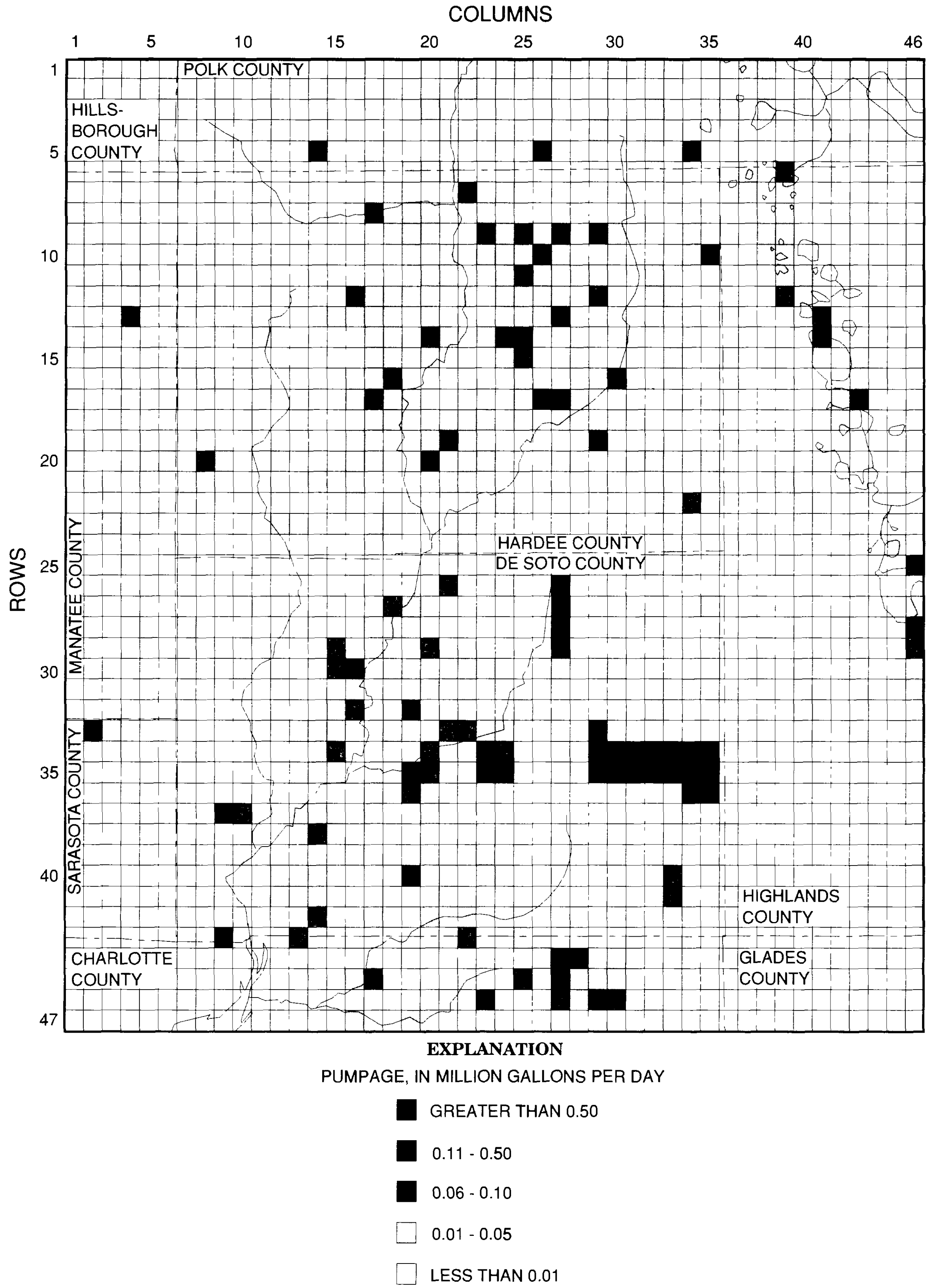


Figure 54. Pumpage distribution used in transient simulations for the intermediate aquifer system, May 2020.

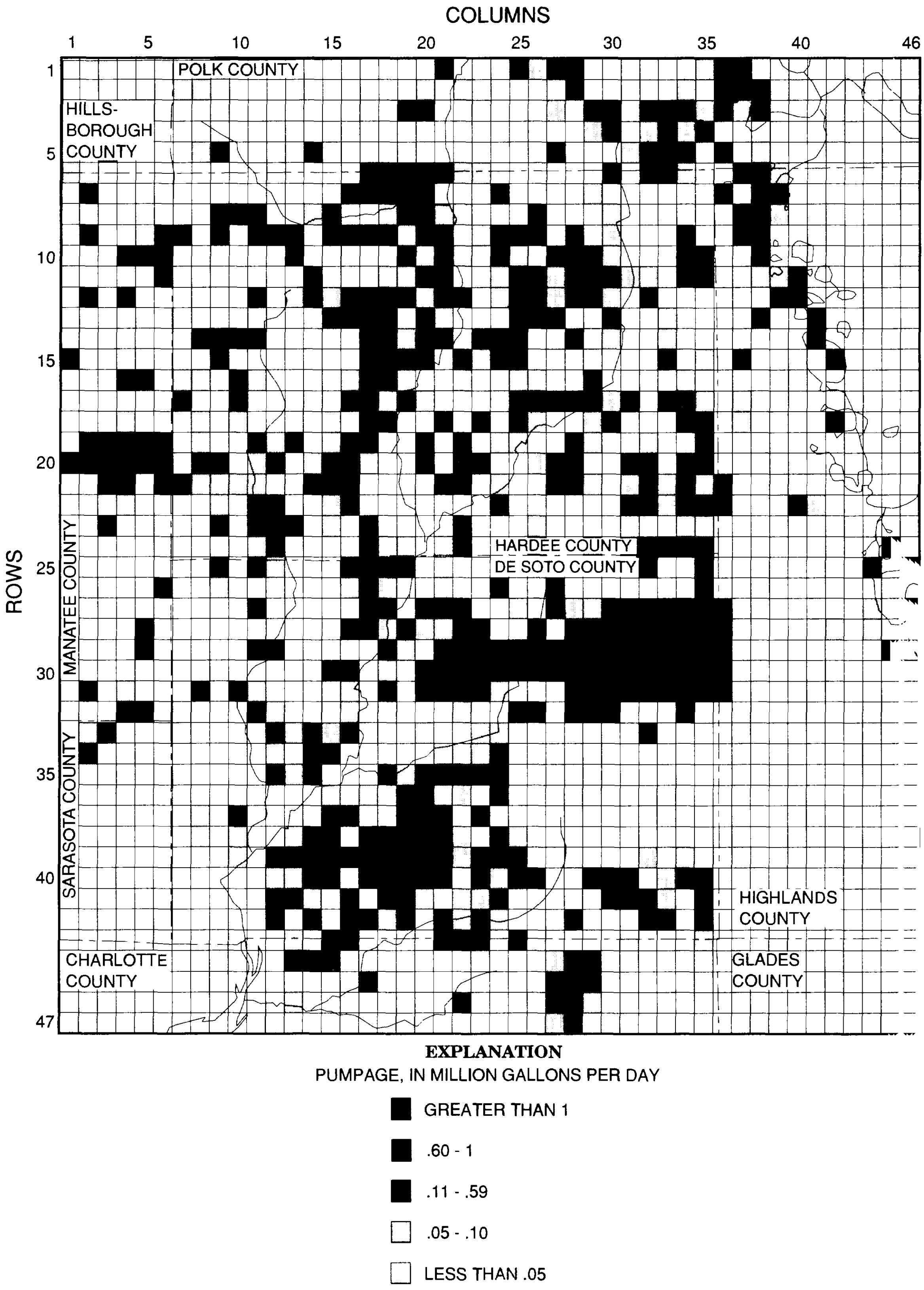


Figure 55. Pumpage distribution used in transient simulations for the Upper Floridan aquifer, May 1989.

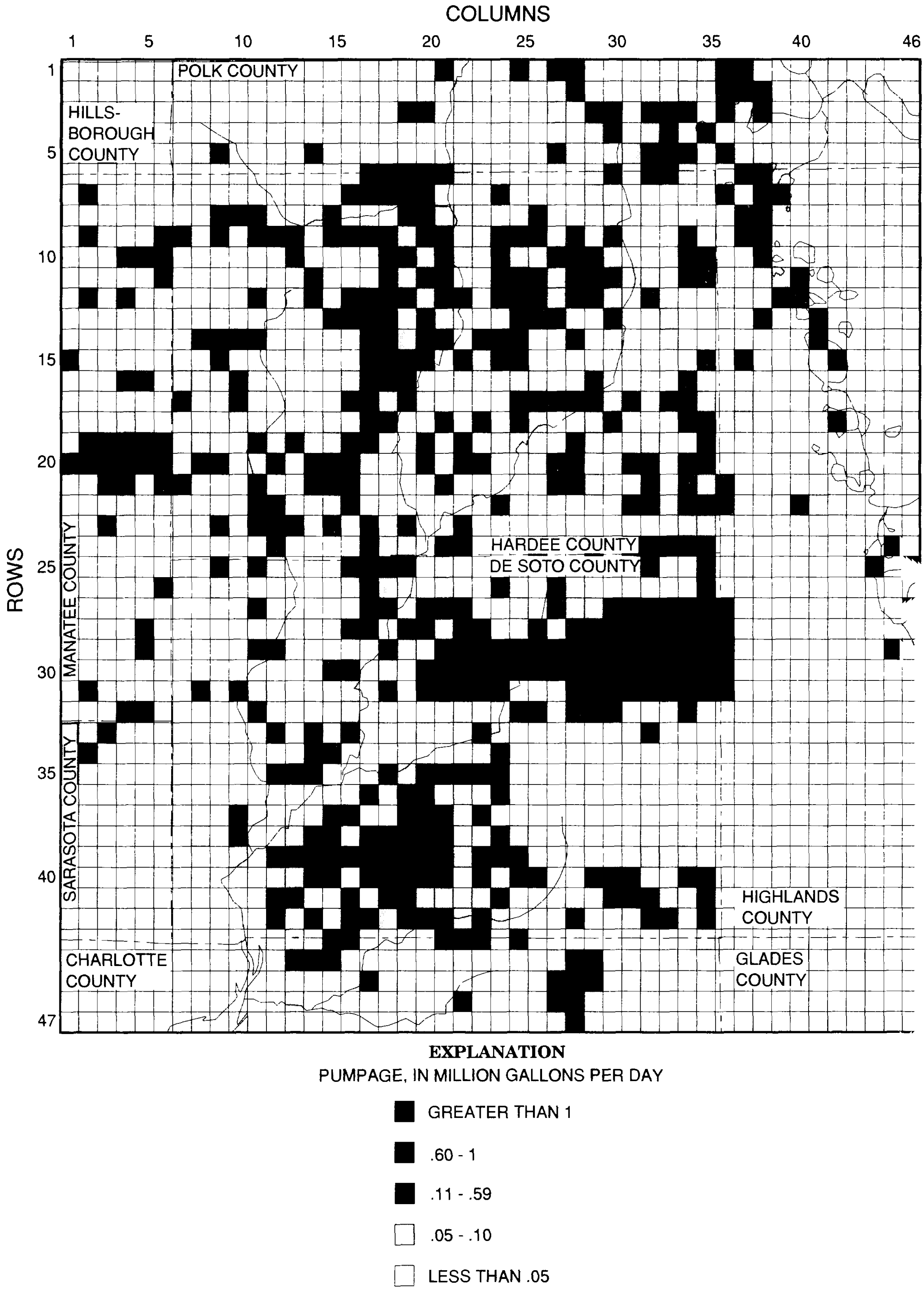
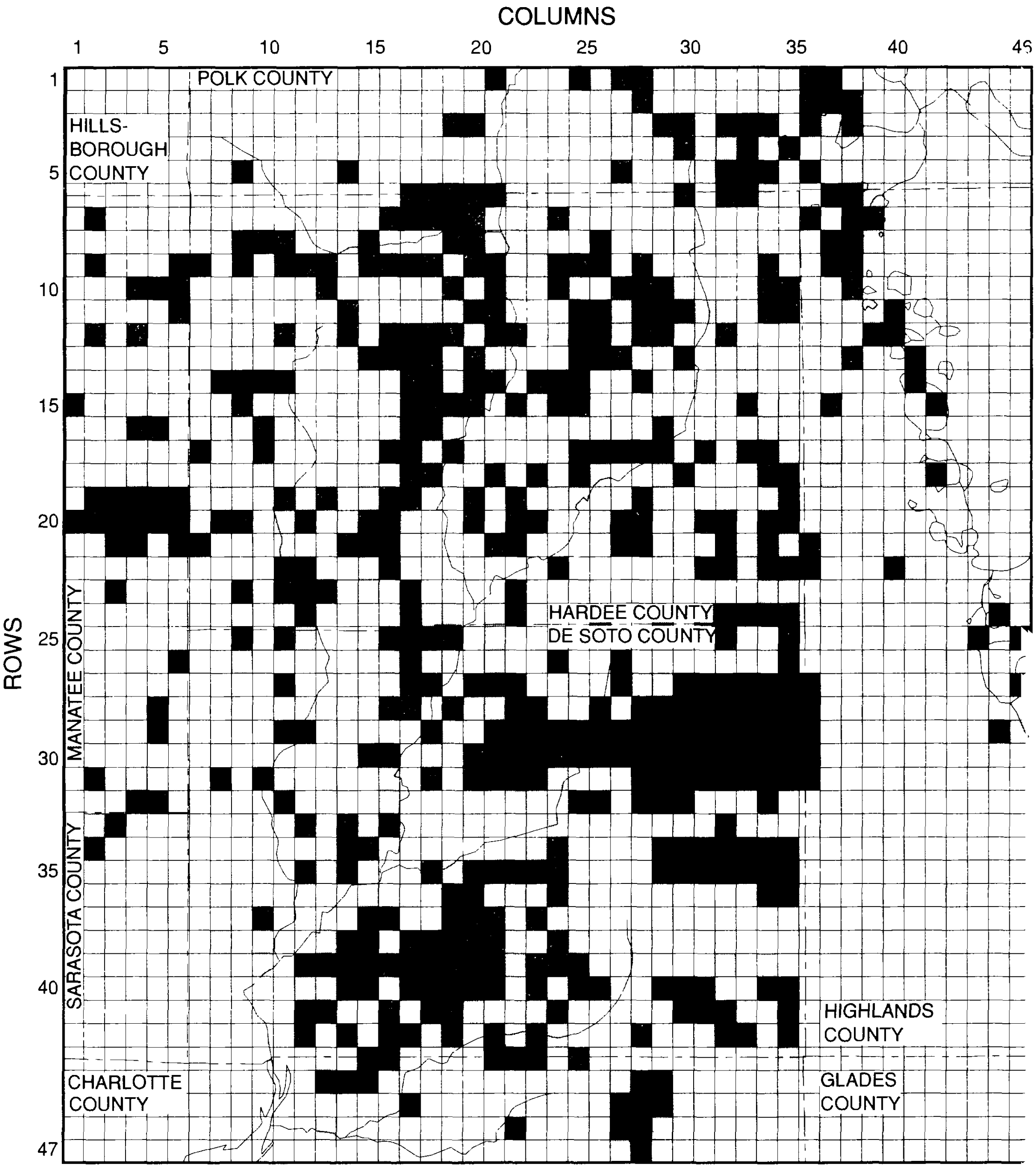


Figure 56. Pumpage distribution used in transient simulations for the Upper Floridan aquifer, May 2000.



EXPLANATION

PUMPAGE, IN MILLION GALLONS PER DAY

- GREATER THAN 1
- .60 - 1
- .11 - .59
- .05 - .10
- LESS THAN 0.5

Figure 57. Pumpage distribution used in transient simulations for the Upper Floridan aquifer, May 2020.