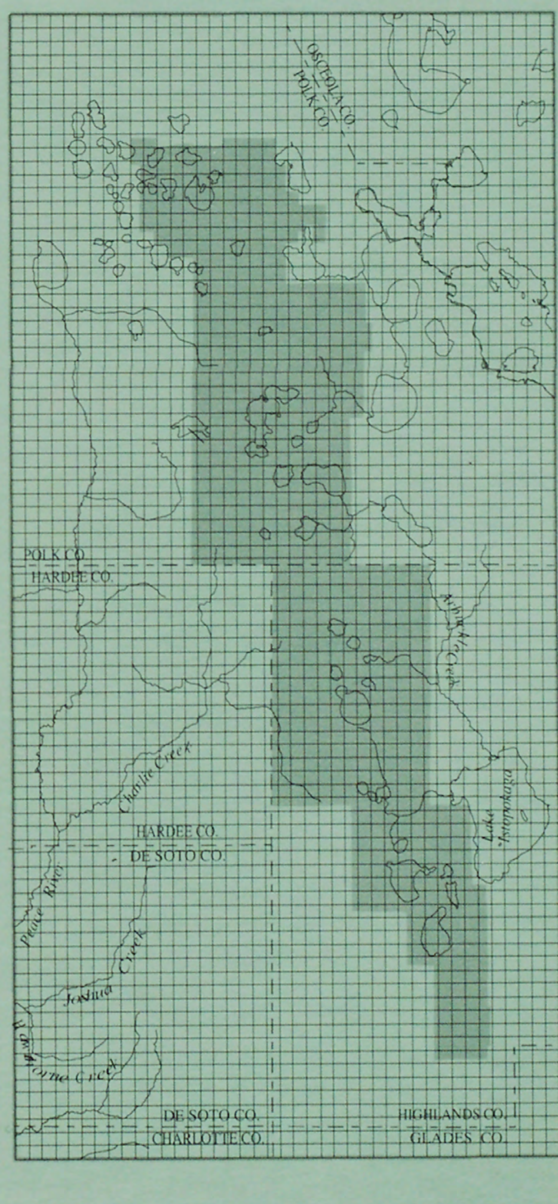
Analysis and Simulation of Ground-Water Flow in Lake Wales Ridge and Adjacent Areas of Central Florida

U.S. Geological Survey

Water-Resources Investigations Report 94-4254

Prepared in cooperation with the

Southwest Florida Water Management District



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By Dann K. Yobbi

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Prepared in cooperation with the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

Tallahassee, Florida
1996

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, VERTICAL DATUM, ADDITIONAL ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	2.54	centimeter per year
foot (ft)	0.3048	meter
foot per day per foot (ft/d)/ft	1.000	meter per day per meter
foot squared per day (ft^2/d)	0.0929	meter squared per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
million gallons per day (Mgal/d)	0.04381	cubic meters per second
cubic feet per second (ft 3/s)	0.02832	cubic meters per second

Temperature in degrees Fahrenheit (^oF) can be converted to degrees Celsius (^oC) as follows:

$$^oC = 5/9 \times (^oF - 32)$$

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.

ADDITIONAL ABBREVIATIONS AND ACRONYMS

ET	Evapotranspiration
RASA	Regional Aquifer Simulation Analysis
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey
WUCA	Water-use caution area
GHB	General head boundary

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Abstract

The Lake Wales Ridge is an uplands recharge area in central Florida that contains many sinkhole lakes. Below-normal rainfall and increased pumping of ground water have resulted in declines both in ground-water levels and in the water levels of many of the ridge lakes. A digital flow model was developed for a 3,526 square-mile area to help understand the current (1990) ground-water flow system and its response to future ground-water withdrawals.

The ground-water flow system in the Lake Wales Ridge and adjacent area of central Florida consists of a sequence of sedimentary aquifers and confining units. The uppermost water-bearing unit of the study area is the surficial aquifer. This aquifer is generally unconfined and is composed primarily of clastic deposits. The surficial aquifer is underlain by the confined intermediate aquifer and confining units which consists of up to three water-bearing units composed of interbedded clastics and carbonate rocks. The lowermost unit of the ground-water flow system, the confined Upper Floridan aquifer, consists of a thick, hydraulically connected sequence of carbonate rocks. The Upper Floridan aquifer is about 1,200 to 1,400 feet thick and is the primary source for ground-water withdrawals in the study area.

The generalized ground-water flow system of the Lake Wales Ridge is that water moves downward from the surficial aquifer to the intermediate aquifer and the Upper Floridan aquifer in the central area, primarily under the ridges, with minor amounts of water flow under the flatlands. The water flows laterally away from the central area, downgradient to discharge areas to the west, east, and south, and locally along valleys of major streams. Upward leakage occurs along valleys of major streams.

The model was initially calibrated to the steady-state conditions representing September 1989. The resulting calibrated hydrologic parameters were then tested by simulating transient conditions for the period October 1989 through 1990. A final test of model calibration was conducted by successfully simulating transient conditions for the period October 1988 through September 1989. Altitudes of the water table, base of the surficial aquifer, riverbed conductances, confining-unit leakances, aquifer transmissivities, and net recharge and discharge rates were determined during calibration.

Steady-state and transient simulations reasonably approximated measured aquifer heads and lake levels. Residuals were within the established calibration criteria that required 68 percent of all simulated heads to be within ±2 feet of observed surficial aquifer heads and lake levels and ±5 feet of observed intermediate and Upper Floridan aquifer heads. Simulation of streamflow was poor, probably due to the scale of the model and regulated streamflow conditions.

Simulation indicates a marked difference between the ground-water flow rates of September 1989 (steady-state conditions, end of wet season) and May 1990 (large pumpage, end of dry season) in million gallons per day:

	September 1989	May 1990
Pumping rate	126	486
Downward leakage (into Upper Floridan aquifer)	367	564
Stream flow	67	13
Net lateral boundary flow	218	115
Total discharge (excluding evapotranspiration)	479	626

The calibrated flow model was used to simulate the short-term (one year) effects of 1990 water year pumpage (349 Mgal/d) on the September 1989 ground-water flow system in response to five different pumping schemes: (1) no pumpage, (2) no public supply pumpage, (3) no industrial pumpage, (4) no agricultural pumpage, and (5) no regional pumping outside the Water Use Caution Area. Simulation of no pumpage indicated maximum aquifer head rises of about 2 feet in the surficial aquifer and lakes, about 12 feet in the intermediate aquifer and about 16 feet in the Upper Floridan aquifer. The high rate recharge areas along the Lake Wales Ridge are most affected by pumping. Simulation of no agricultural pumpage resulted in a maximum recovery of about 2 feet in each aquifer. Simulation of no industrial or mining pumpage resulted in a maximum of less than one foot in the surficial aquifer and lakes, about 10 feet in the intermediate aquifer, and about 14 feet in the Upper Floridan aquifer. Simulation of no public supply pumpage indicated a maximum recovery of less than one foot in the surficial aquifer and lakes, about 4 feet in the intermediate aquifer, and about 10 feet in the Upper Floridan aquifer. Simulation of no regional pumping outside the Water Use Caution Area indicated recoveries of less than 2 feet within the Water Use Caution Area.

Simulations were used to investigate long-term aquifer changes in response to two development alternatives: (1) continuation of 1990 water year hydrologic conditions and pumping rates (349 Mgal/d), and (2) increased pumpage (506 Mgal/d). Simulation of continued 1990 water year hydrologic conditions and pumping for 20 years indicated that head decline of more than 10 feet might be expected in each aquifer in the northern part of the Water Use Caution Area. Simulation of increased pumpage (an additional 45 percent) for 20 years indicated head declines of more than 20 feet in each aquifer in the northern part of the Water Use Caution Area. Because lakes are hydraulically connected to the surficial aquifer, lake levels within the Water Use Caution Area could decline substantially as a result of present and future pumping and a continuation of 1990 hydrologic conditions. These relatively large head declines were accompanied by decreased simulated lateral boundary outflow of about 40 percent and decreased simulated streamflow of about 32 percent. Equilibrium conditions at the end of the two 20-year simulations had not been attained.

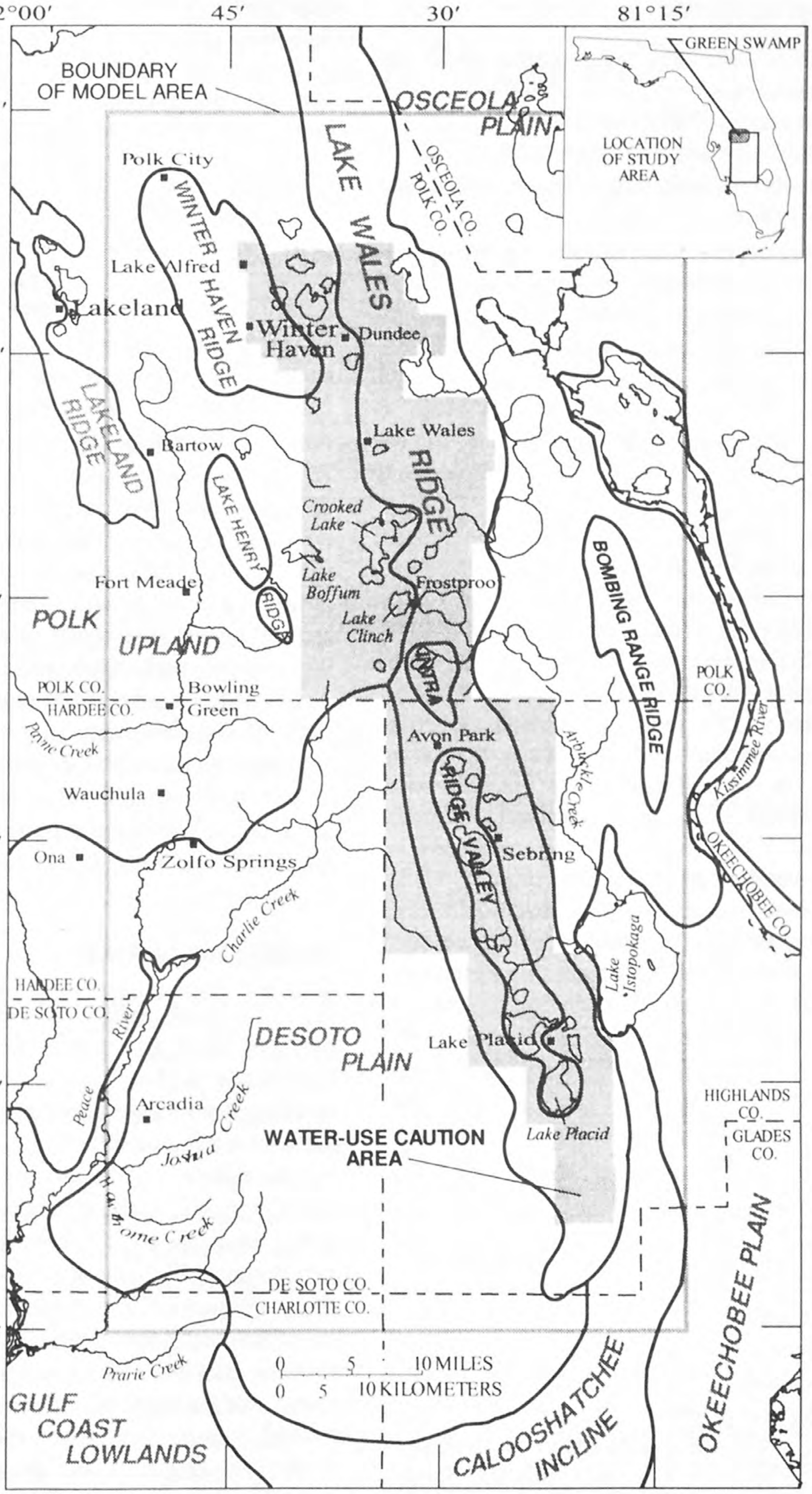
INTRODUCTION

The Lake Wales Ridge is an uplands recharge area in central Polk and Highlands Counties (fig.1) that contains many large sinkhole lakes. Since the early 1960's, declines in water levels in many of the ridge lakes have occurred in this important citrus-producing area. The problem of declining lake levels is apparently related to several factors, including below normal rainfall, increased ground-water pumpage for agricultural and industrial use, reduced recharge, and alterations to the surface-drainage systems (Barcelo, and others, 1990). In 1989, the Southwest Florida Water Management District (SWFWMD) declared a 750-mi^2 area that includes the Lake Wales Ridge, a Water Use Caution Area (WUCA). This declaration was the result of increasing ground-water use, declining ground-water and surface-water levels, and deterioration of water quality (Barcelo and others, 1990). To maintain lake water levels, it is important to understand and quantify the flow to, from, and within the related aquifers. In 1989, the U.S. Geological Survey (USGS) in cooperation with the SWFWMD began a study of the Lake Wales Ridge area to enhance the understanding of the ground-water flow system and how pumping effects aquifer heads in the Lake Wales Ridge.

Purpose and Scope

This report describes and quantifies ground-water flow in the major aquifers of central Florida. The hydrogeologic framework and conceptualization of the multi-aquifer flow system also is described for the study area. A digital model of ground-water flow was developed, calibrated, and used to simulate present and future aquifer response to ground-water pumping.

The emphasis of the study was on the 750-mi^2 WUCA upland area of western Highlands and central Polk Counties, but surrounding areas were included for digital modeling purposes. The model area covers 3,526 mi ^{2} and includes, in addition to the study area, parts of Charlotte, De Soto, Hardee, Okeechobee, and Osceola Counties.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 1. Location of study area, model area, water-use caution area and its relation to physiographic subdivisions.

Previous Investigations

Numerous reports have been written about the geology and ground-water resources of the study area. Complete descriptions of the geology of Florida are given by Cooke (1945) and Stringfield (1966). Miller (1986) describes the hydrogeologic framework of the Floridan aquifer system.

Many investigators have studied the hydrogeology of various counties within the study area. Bishop (1956), Stewart (1966) and Wilson (1977) described, respectively, the geology and ground-water resources of Highlands County, Polk County, Hardee County, and De Soto County. Duerr and Enos (1991) defined the hydrogeologic framework of the intermediate aquifer system and the Upper Floridan aquifer in Hardee and De Soto Counties.

A number of studies have described the hydrology of selected areas within the study area. Pride and others (1966) described the hydrology of the Green Swamp area of central Florida. Ground-water level changes and other hydrologic effects of ground-water withdrawals during the years 1934-65 were evaluated by Kaufman (1967) within the Peace River basin. Robertson (1973) assembled and summarized existing hydrologic data to determine trends of ground-water quality, ground-water levels, and water use in the Lakeland Ridge area. Hutchinson (1978) presented an appraisal of the shallow ground-water resources of the Upper Peace River basin. Geraghty and Miller, Inc. (1979, 1980) conducted a hydrologic investigation of the Highlands Ridge of Polk and Highlands Counties to determine the causes of the decline in water levels in many of the ridge area lakes. Shaw and Trost (1984) evaluated the regional hydrogeology of the Kissimmee River basin and adjacent areas to facilitate water management decision making, and simulation of ground-water flow in the Upper Floridan aquifer. Duerr and others (1988) described the geohydrologic framework of the intermediate aquifer system in west-central Florida, and Barcelo and others (1990) investigated the cause and effect relation of lake-level declines in the Highlands Ridge area.

Several reports have been written about the lakes that lie within the study area. Kohout and Meyer (1959) discussed the relation of ground water to lake level in Lake Istokpoga and Lake Placid areas of Highlands County from 1955 to 1959. The hydrology and limnology of Crooked Lake and Lake Buffum area were described by Bradburry and others (1978), and Jones (1978), respectively. Hammett (1981) described water-quality characteristics and presented a water-budget analysis of Lake Jackson from 1970 to 1973. Adams and Stoker (1985) described water quality, biological, and hydrogeologic characteristics of Lake Placid and adjacent areas, and Belles and Martin (1985) described the basin and lake characteristics, hydrologic cycle, and water-quality characteristics of Lake June-in-Winter.

Digital flow models have been used by several investigators to evaluate the ground-water flow in all or part of the study area. Grubb and Rutledge (1979) used a steady-state model to evaluate water-level change caused by pumping from the Floridan aquifer system in the Green Swamp area. Wilson and Gerhart (1982) used a digital model to predict changes in the potentiometric surface of the Upper Floridan aquifer in west-central Florida as a result of pumping. Ryder (1982, 1985) and Tibbals (1981, 1990) simulated predevelopment and post-development ground-water flow conditions in west-central and east-central Florida, respectively. Planert and Aucott (1985) simulated the drawdown of the potentiometric surface of the Floridan aquifer system as a result of pumping from numerous hypothetical well fields located in Osceola County. Shupe (1987) used a digital model to evaluate the possibility of encroachment of saline water to a proposed well-field in eastern Osceola County. The effects of future water-management schemes on the ground-water resources of west-central Florida were simulated by the SWFWMD (1993).

Description of Area

The study area has an area of 3,526 mi^2 and is centered about the Lake Wales Ridge (fig. 1). Surface topography is characterized by a series of north-south trending sand ridges separated by broad valleys. The surficial sands and other clastic materials are underlain by karstified carbonate rocks. Numerous lakes, swampy plains, and intermittent ponds occur generally along the ridge and adjacent flanks. The most prominent topographic feature of the area is the Lake Wales Ridge (White, 1970) that extends south through the center of the study area from Polk County into Highlands County. The Lake Wales Ridge is the highest and longest of five ridges in the area. Altitudes on the crest of the ridge range from about 150 to 300 feet above sea level. The southern part of the Lake Wales Ridge is split into two secondary ridges by the Intraridge Valley. This part of the study area is hydrologically dynamic because of the numerous karst features and the large quantities of recharge that occur through swallow holes, sinkholes, and sinkhole lakes.

Other major physiographic features within the general area of the study include the Polk Upland, De Soto Plain, Osceola Plain, Bombing Range Ridge, Okeechobee Plain, and the Caloosahatchee Incline (fig. 1) The Polk Upland is in the Polk County west of the Lake Wales Ridge and is a broad, elevated, sandy area that ranges in altitude from about 100 to 245 feet above sea level. The De Soto Plain occupies the southwestern part of the study area and has altitudes that decrease gradually toward the southwest and generally range from about 30 to 100 feet above sea level. The Osceola Plain is east of the Lake Wales Ridge and is characterized by little relief and altitudes that range from about 60 to 70 feet above sea level. A prominent feature of the Osceola Plain is known as the Bombing Range Ridge, which resembles a large marine bar.

The Okeechobee Plain occupies the southeastern part of the model area and has land altitudes that dip very gradually to the south and generally range from about 20 to 40 feet above sea level. The Caloosahatchee Incline borders the southern part of the De Soto Plain and the extreme southeastern part of the Lake Wales Ridge. This area is characterized by a long, narrow incline that gently slopes eastward and has altitudes that generally range from about 50 to 60 feet above sea level.

Nearly 200 lakes and ponds occur along the ridges and flanks of the Lake Wales Ridge. The lakes are probably the result of sinkholes formed by dissolution and collapse of the limestone and dolomite. The lakes vary in size from less than 20 acres to as much as 5,538 acres at Crooked Lake in southern Polk County. Surface-drainage alterations have been made on many of the lakes to facilitate routing of flood waters between lakes, although several of the lake basins, especially in the uplands part of the central ridge, have not discharged any surface water for the past 25 years because of low lake levels (Barcelo and others, 1990).

The Lake Wales Ridge is part of the surface drainage divide between the Peace and Kissimmee Rivers. The western part of the ridge is drained by the Peace River and its major tributaries, Payne, Charlie, Joshua and Prairie Creeks. The eastern part of the study area is drained by the Kissimmee River and its major tributaries, Arbuckle Creek and Josephine Creek. Runoff to streams ranges from zero in the sandhills to as much as 11 in/yr where surface drainage is well developed.

The climate of the study area is subtropical humid and is characterized by long, warm, relatively wet summers and mild, relatively dry winters. The average annual rainfall is about 53 in. at Avon Park. Annual rainfall is unevenly distributed with about 60 percent occurring during the four summer months June through September.

Evapotranspiration (ET) accounts for the greatest losses of rainfall in the study area and occurs in essentially three modes involving either evaporation or transpiration: (1) from plant surfaces, open-water bodies and bare ground; (2) from the unsaturated zone (above the water table but beneath land surface); and (3) from the water table. The average rate of actual ET from the study area is about 40 in/yr (Geraghty and Miller, 1980; Hutchinson, 1978; and Stewart, 1966). The upper limit of ET is approximately equal to the rate at which water can evaporate from a free-water surface (such as a lake). The maximum long-term average potential from free-water surface in the study area is about 46 to 50 in/yr (Visher and Hughes, 1975). The maximum rate occurs in areas where the water table is at or near land surface. The minimum or base rate of ET, which is independent of water level, ranges from 25 to 35 in/yr and occurs in areas where the water table is at a depth of 13 feet or greater (Tibbals, 1990).

GROUND-WATER FLOW SYSTEM

The ground-water flow system beneath the study area is a multiaquifer system consisting of a thick sequence of carbonate rock overlain by clastic deposits. The sediments are subdivided into a sequence of discrete lithologic units that form a layered sequence of aquifers and confining units. The framework includes the unconfined surficial aquifer, the confined intermediate aquifer system, and the confined Floridan aquifer system. Two low permeable confining units, the upper confining unit and the lower confining unit, separate the aquifers. The Floridan aquifer system is underlain by a low-permeability gypsiferous limestone that forms the bottom of the fresh ground-water flow system.

Hydrogeologic Framework

The following sections summarize the lithology and hydraulic properties of aquifers and confining units of the study area. The hydrogeologic units, the corresponding time-stratigraphic units, and general lithology are given in table 1. Lines of hydrogeologic sections through the study area are shown in figure 2 and the sections are shown in figures 3 and 4.

Table 1. Relation of geologic and hydrogeologic units in the Lake Wales Ridge area, Florida (modified from Wilson and Gerhart, 1982; Ryder, 1985; Swancar and Hutchinson, 1992)

System	Series	Stratigraphic unit	Major lithologic unit	Hydrogeologic unit
Quaternary	Holocene and Pleistocene	Surficial sand, terrace sand, phosphorite	Sand	Surficial aquifer system
Tertiary	Pliocene	Undifferentiated deposits	Sand, clay, and limestone	Intermediate aquifer system: Upper confining unit
Tertiary	Miocene	Hawthorn Group: Peace River Formation	Sand, clay, and limestone	Intermediate aquifer system: "water-bearing units"
Tertiary	Miocene	Hawthorn Group: Arcadia Formation	Sand, clay, and limestone / Limestone	Intermediate aquifer system: "water-bearing units"
Tertiary	Miocene	Hawthorn Group: Tampa Member	Limestone	Intermediate aquifer system: "water-bearing units" / Lower confining unit
Tertiary	Oligocene	Suwannee Limestone	Limestone	Floridan aquifer system: Upper Floridan aquifer
Tertiary	Eocene	Ocala Limestone	Limestone	Floridan aquifer system: Upper Floridan aquifer
Tertiary	Eocene	Avon Park Formation	Limestone and dolomite	Floridan aquifer system: Upper Floridan aquifer / Middle confining unit
Tertiary	Paleocene	Oldsmar and Cedar Keys Formation	Dolomite and limestone	Floridan aquifer system: Lower Floridan aquifer

Surficial Aquifer

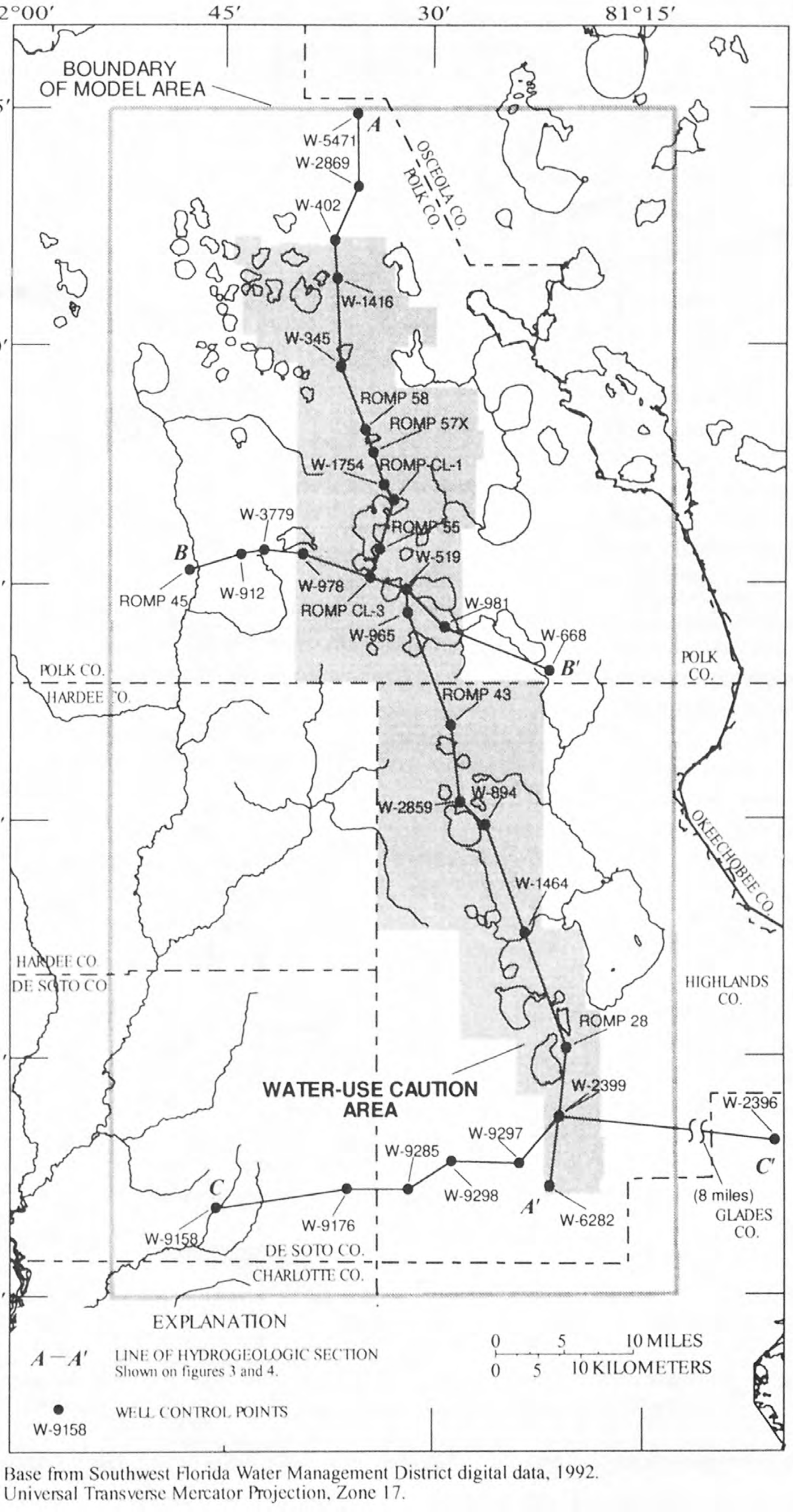
The surficial aquifer is the uppermost water-bearing formation. It consists chiefly of a single unconfined layer of sand of Holocene and Pleistocene age that generally grade into less permeable clayey or silty sands with depth. The aquifer is the major source of recharge to the underlying confined aquifer systems and is sometimes used as a source of irrigation water, especially in Highlands County.

Thickness of the surficial aquifer varies widely over the study area and generally ranges from 10 to 300 feet. Along the length of the Lake Wales Ridge, the aquifer thickness ranges from about 50 feet in Polk County to about 300 feet in southern Highlands County. Thickness decreases gradually toward the west from about 70 feet in eastern De Soto and Hardee Counties to about 10 feet along the Peace River. The thickness of the aquifer generally ranges from less than 100 feet in southwestern Polk County to generally less than 25 feet in northwestern Polk County. Aquifer thickness east of the Lake Wales Ridge generally ranges from more than 150 feet in Highlands County to about 70 feet in Osceola County.

Hydraulic properties of the surficial aquifer are highly variable because of large differences in lithology and thickness. Hutchinson (1978) estimated a transmissivity of 2,200 ft^2/d for the surficial aquifer at a test site near Bowling Green, and a specific yield of 0.29 based on a laboratory analysis of aquifer samples. Wilson (1977) estimated an average transmissivity of about 1,100 ft^2/d for De Soto and Hardee Counties. Model-derived values of horizontal hydraulic conductivity determined by Lee and Swancar (1994) at Lake Lucerne in western Polk County ranged from 8 ft/d in the upper part of the aquifer to 2 ft/d in the lower part of the aquifer, which corresponds to aquifer transmissivity of about 800 ft^2/d, respectively. Pride and others (1966) and Stewart (1966) determined a specific yield of 0.3 for the aquifer in Polk County.

Intermediate Aquifer System

The intermediate aquifer system includes all water-bearing units and confining units between the base of the surficial aquifer and the top of the Floridan aquifer system. The intermediate aquifer system consists of as many as three water-bearing units that are composed of clastic sediments interbedded with carbonate rocks. These water-bearing units collectively are called the intermediate aquifer in this report. The aquifer system is heterogenous and varies widely in lithology and thickness.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 2. Locations of hydrogeologic sections.

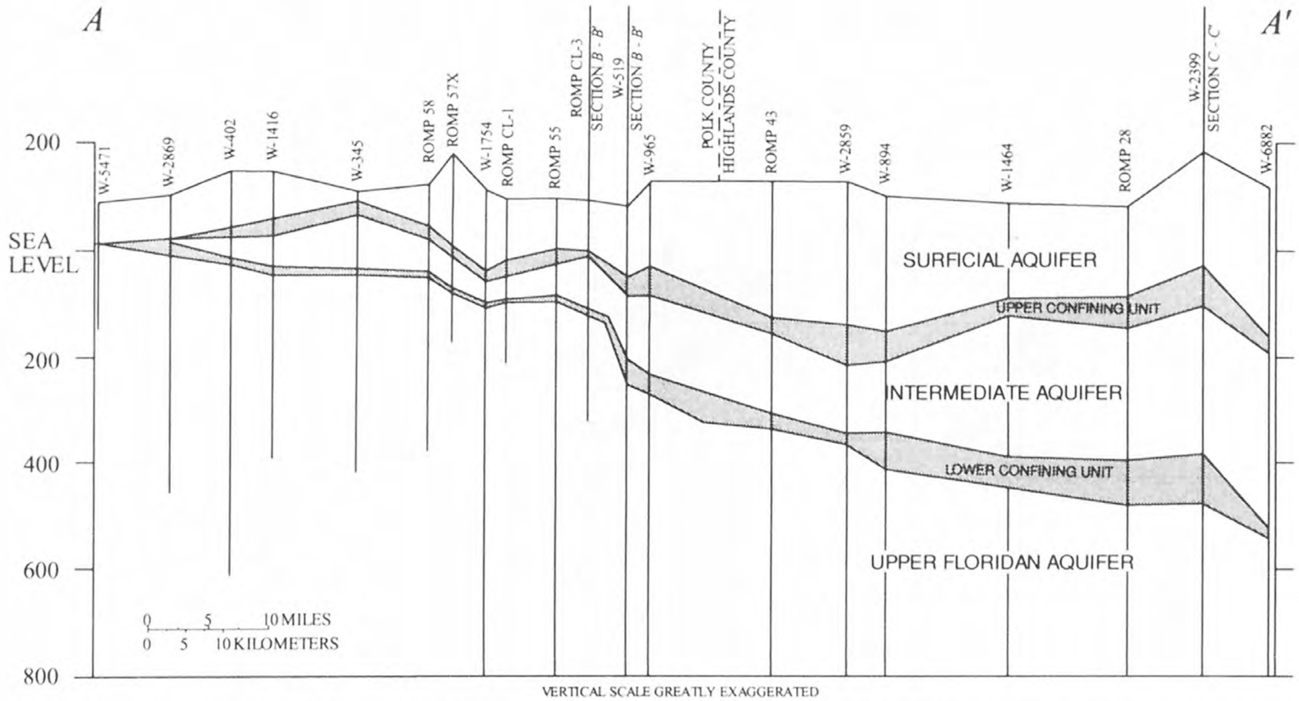


Figure 3. Hydrogeologic section *A-A'*. (Modified from Barcelo and others, 1990. Location of section is shown in fig. 2.)

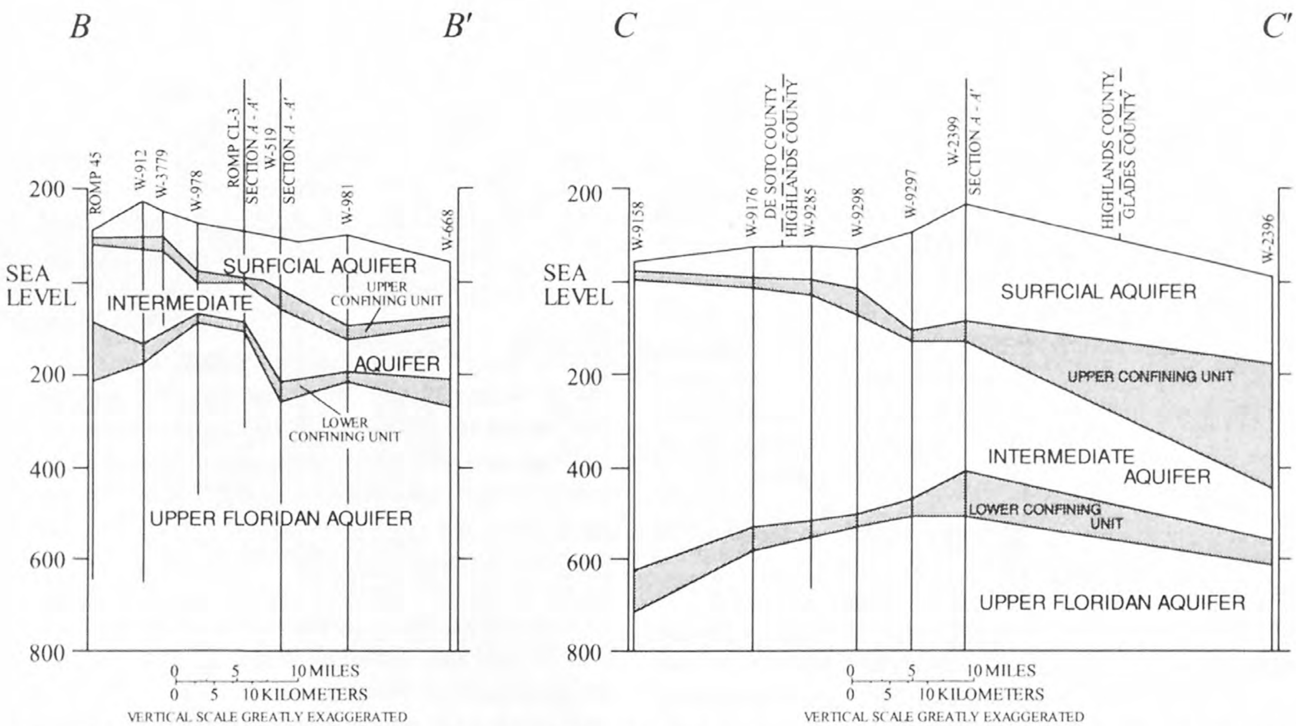


Figure 4. Hydrogeologic sections *B-B'* and *C-C'*. (Modified from Barcelo and others, 1990. Location of section is shown in fig. 2.)

The intermediate aquifer is confined above and below by the upper and lower confining units. Generally, the upper confining unit is comprised of clayey and pebbly sand, clay, marl, and shell, and the lower confining unit is comprised of sandy clay and clayey sand (Duerr and others, 1988; table 1). These confining units are highly variable both spatially and vertically. Rocks equivalent to the intermediate aquifer are thin and poorly permeable in the northern and eastern parts of the study area and comprise a complex confining unit between the Floridan aquifer system and the surficial aquifer.

The thickness of the intermediate aquifer ranges from nearly zero where the deposits pinch out in central Polk County to more than 500 feet in Highlands County. The intermediate aquifer is missing near its northern extent where poorly permeable equivalent rocks directly overlie the Floridan aquifer system (Hutchinson, 1978).

Transmissivity of the permeable units of the intermediate aquifer system is generally less than 13,000 ft^2/d, and the aquifer system exhibits storage characteristics of a confined aquifer (Hutchinson, 1978). Transmissivity is variable over short distances and is indicative of lithologic heterogeneity within the system.

Field hydraulic data for the confining units are nearly nonexistent. With few exceptions, estimates of the hydraulic properties of the confining units in the study area are available only from flow model simulations. Model-derived leakance values (the ratio of vertical hydraulic conductivity of the confining bed to its thickness) determined by Ryder (1985) in the study area ranged from 1×10^{-5} to 3×10^{-4} (ft/d)/ft for the upper confining unit, and from 7×10^{-6} to more than 1×10^{-4} (ft/d)/ft for the lower confining unit. Leakance values of both units generally are highest along the ridge, which is riddled with sinkholes, and lowest along the flanks of the ridge where karst features are less numerous.

Floridan Aquifer System

The Floridan aquifer system is a thick hydraulically connected, sequence of Tertiary age carbonate rocks. The degree of hydraulic connection is highly variable spatially and vertically. The Floridan aquifer system underlies the intermediate aquifer and consists of the Upper and Lower Floridan aquifers that are separated by a middle confining unit (Miller, 1986). The middle confining unit and the Lower Floridan aquifer generally contain saltwater in the study area, and freshwater flow is generally limited to the Upper Floridan aquifer (Ryder, 1985).

The geologic formations that make up the Upper Floridan aquifer in the study area include the permeable sections of the lower part of the Hawthorn Group, the Suwannee Limestone, the Ocala Limestone, and the Avon Park Formation (table 1). The thickness of the Upper Floridan aquifer ranges from about 1,200 to 1,400 feet. The Suwannee Limestone generally forms the top of the Upper Floridan aquifer which ranges in altitude from about zero to about 700 feet below sea level (Miller, 1986).

The base of the Upper Floridan aquifer is considered to be at the first occurrence of vertically persistent, intergranular evaporates in the Avon Park Formation. The permeability of these rocks is extremely low, ranging from five to six orders of magnitude less than the highly permeable rocks of the overlying Upper Floridan aquifer (Hickey, 1990).

The Upper Floridan aquifer consists of two significant water-bearing zones separated by a less permeable zone. The upper water-bearing zone includes the Tampa Member of the Hawthorn Group and parts of the upper Ocala Limestone. This zone is less permeable than the lower water-bearing zone. The lower water-bearing zone, which includes the Avon Park Formation, is highly permeable and contains large solution channels that have developed along fractures (Wolansky and Corral, 1985). The upper and lower water-bearing zones are separated by less permeable sections of the Ocala Limestone. There is, however, enough vertical interconnection between zones to consider the Upper Floridan aquifer a single hydrologic unit (Ryder, 1985).

Hydraulic characteristics of the Upper Floridan aquifer vary widely within the study area due to the heterogeneity of the aquifer, which is largely attributable to secondary porosity and permeability in the carbonate rock. The high permeability of the aquifer generally results from fractures and the dissolution of the limestone and dolomite. A major assumption of the hydrologic analysis for this study is that regional flow in the Upper Floridan aquifer can be analyzed using methods developed for investigating the hydraulics of porous media. This assumption is justified because the aquifer has been shown to approximate a uniformly porous media when the scale of the investigation is large (Hutchinson, 1984; Bengtsson, 1987; and Fretwell, 1988). In addition, Hickey (1984) was able to confirm that flow in the Upper Floridan aquifer is Darcian. Analysis of aquifer-test data indicated that, for a particular distance at a specific time, a linear relation exists between drawdown and discharge.

Computed field values of transmissivity of the Upper Florida aquifer range from 10,300 to 270,000 ft^2/d (Ryder, 1985). Transmissivity is lowest in the north where low values probably reflect the presence of sand-filled fractures (Pride and others, 1966). Transmissivity is highest in the southwestern part of the study area where large solution channels have developed along fractures (Wolansky and Corral, 1985).

The storage coefficient of the Upper Floridan aquifer determined from aquifer-test analyses ranges from about 1.8×10^{-2} to about 3.1×10^{-4}. The storage coefficient in confined aquifers is directly proportional to aquifer thickness; however, in the Floridan aquifer system, storage coefficients sometimes bear no discernible relation to aquifer thickness on a regional scale (Maslia and Hayes, 1988).

In the extreme eastern part of the study area, the Upper Floridan aquifer is separated from the Lower Floridan aquifer by a separate semi-confining unit composed primarily of soft, chalky limestone and dolomitic limestone (Tibbals, 1990). Because of the small areal extent, this unit is only of minor importance to the Floridan aquifer system in west-central Florida and was not represented in the calibrated flow model.

Water Use

In calendar year 1990, a combined total of about 401 Mgal/d of freshwater was withdrawn in the study area from the surficial aquifer, the intermediate aquifer and the Upper Floridan aquifer for irrigation, public, industry, recreation, and mining uses (table 2). The primary use of ground-water in the area is for agriculture, which accounts for withdrawals of 275 Mgal/d. Mining is the second largest user of ground-water and accounts for withdrawals of 60 Mgal/d. Withdrawals for public supply average about 48 Mgal/d. Recreation and industrial water use accounts for 11 and 8 Mgal/d, respectively.

Table 2. Ground-water withdrawals within the Lake Wales Ridge area, Florida, by use category, and aquifer, calendar year 1990 (January 1, 1990 to December 31, 1990)

Category	Surficial aquifer	Intermediate aquifer	Upper Floridan aquifer	Total
Agriculture	13.7	8.9	252.0	274.6
Mining	0.2	1.9	57.4	59.5
Public Supply	0.0	1.1	47.1	48.2
Recreation	0.1	0.1	10.5	10.7
Industry	0.1	0.0	7.6	7.7
Total	14.1	12.0	374.6	400.7

Withdrawals of ground water vary seasonally. In 1990, nearly 32 percent of total withdrawals occurred during March, April, and May. Withdrawal fluctuations are a result of seasonal variations in rainfall, temperature, and demand for irrigation supplies (Marella, 1992).

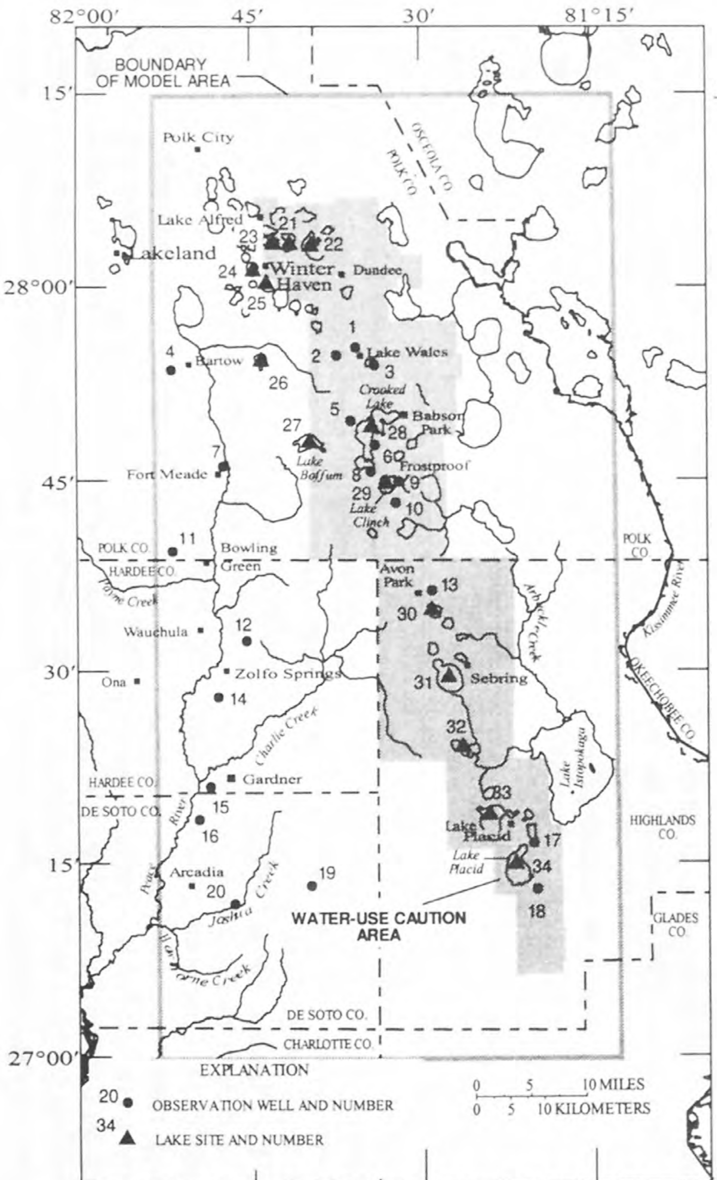
The Upper Floridan aquifer is the major source of water and supplies more than 30 times the amount of water pumped from either the surficial or intermediate aquifer (table 2). Water use from the intermediate aquifer system is most significant in areas where wells are cased to the first persistent rock unit and contain an open hole section finished into both the intermediate aquifer system and the underlying Upper Floridan aquifer. Water use from the surficial aquifer system is small because of low yields and a high potential for contamination; however, because of the system's greater thickness in Highlands County, it is an important source for irrigation supply in this county.

Water-use estimates for this study were obtained from the water-use permitting files of both the Southwest Florida and the South Florida Water Management Districts. Public supply and large industrial water users meter their usage and their values are the most accurate. Estimates of agricultural water use, on the other hand, are the least accurate because such use is generally not metered. Pumpage estimates for agricultural withdrawals were based on irrigated crop averages obtained from the SWFWMD. Water-use permits do not delineate withdrawals by aquifer; therefore, values of pumpage assigned to individual aquifers were based upon (1) well-construction data, including total well depth and cased interval; (2) aquifer depths and thicknesses data; and (3) specific capacity and transmissivity value for multiple aquifer wells.

Water-Level Fluctuations

Water levels for 20 ground-water monitoring sites and 14 lakes in the study area were used to evaluate water-level fluctuations. The primary factors influencing water levels are rainfall and pumpage. Location of wells and lakes used in this report are shown in figure 5.

Water levels in the surficial aquifer system fluctuate seasonally in response to recharge from rainfall, evapotranspiration, lateral discharge of water to lakes and streams, and downward leakage of water to underlying aquifers. Seasonal fluctuations may be as much as 5 feet in areas of high topographic relief where the aquifer is composed of highly permeable material and



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

SITE NUMBER	SITE NAME	SITE NUMBER	SITE NAME
1	ROMP 58 Ocala well near Lake Wales	17	ROMP 28 Shallow well near Lake Placid ROMP 28 Floridan well near Lake Placid
2	ROMP 57 Hawthorn well near Lake Wales ROMP 57 Floridan well near Lake Wales	18	Bairs Den well near Lake Placid
3	ROMP 57A Ocala well near Lake Wales	19	ROMP 15 Avon Park well near Arcadia
4	ROMP 59 Avon Park well at Bartow	20	ROMP 16 Ocala well near Arcadia
5	ROMP 44 NRSD well near Babson Park ROMP 44 Floridan well near Babson Park	21	Lake Fannie
		22	Lake Hamilton
6	ROMP 55 FLRD well near Babson Park	23	Lake Smart
7	ROMP 45 Hawthorn well at Ft. Meade ROMP 45 Avon Park well at Ft. Meade	24	Lake Howard
8	ROMP CL-3 NRSD well near Frostproof ROMP CL-3 FLRD well near Frostproof	25	Lake Otis
		26	Lake Garfield
9	Coley well at Frostproof	27	Lake Buffum
10	USGS Shallow well P-48 near Frostproof	28	Crooked Lake
11	Maddox well near Bowling Green	29	Lake Clinch
12	Rowell deep well near Wauchula	30	Lake Lotela
13	ROMP 43 Floridan well near Avon Park	31	Lake Jackson
14	ROMP 30 Shallow well near Zolfo Springs ROMP 30 Avon Park well near Zolfo Springs	32	Lake Josephine
15	Marshall deep well near Gardner	33	Lake June-In-Winter
16	ROMP 26 Shallow well near Gardner ROMP 26 Hawthorn well near Gardner ROMP 26 Avon Park well near Gardner	34	Lake Placid

Figure 5. Location of selected water-level data-collection sites used for hydrograph analysis.

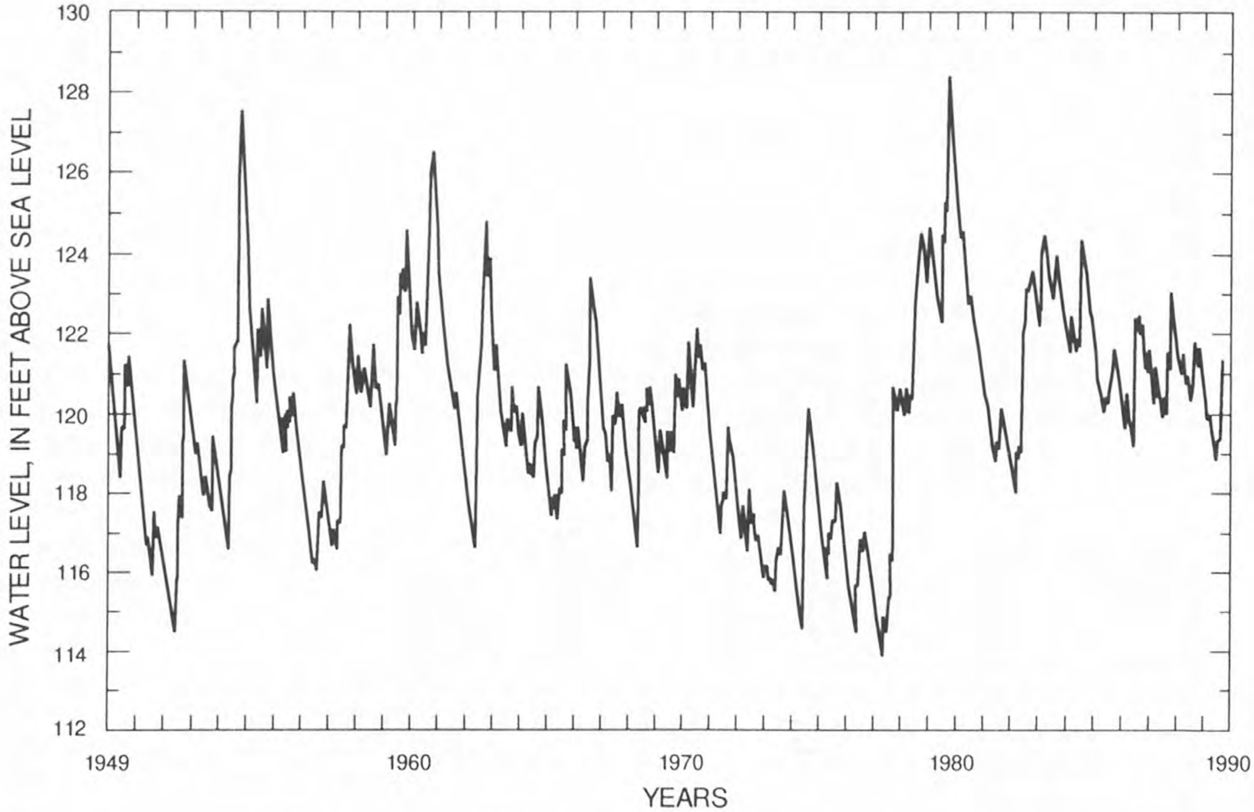


Figure 6. Water levels in the surficial aquifer at the Bairs Den well near Lake Placid, 1949 through 1989. (Location of well site 18 is shown in fig. 5.)

rapid infiltration of rainfall occurs. More commonly, seasonal fluctuations are less than 5 feet in flat-lying areas where material of low permeability is within and near the top of the aquifer. The hydrograph for the Bairs Den well (site 18) shows typical fluctuations that correlate closely with changes in rainfall patterns (fig. 6). Higher water levels reflect wetter years while lower water levels reflect drier years.

Lake levels fluctuate naturally in response to variations in rainfall, evaporation, and surface-water and ground-water inflow and outflow. In Florida, the magnitude of lake-level fluctuations can differ greatly for adjacent lakes in the same general area, even though the net rainfall and evaporation over the long term is about the same for all lakes in the same general area (Hughes 1974). For example, during 1950 to 1990, the range in water level for Crooked Lake (site 28) was about 16 feet and for Lake Clinch (site 29) was less than 8 feet even though rainfall accumulations were similar (fig. 7). The contrast in lake levels is probably due to differences in the thickness and permeability of the confining unit underlying the lakes and the proximity and magnitude of ground-water pumpage. In addition, lakes of higher altitude, greater depths, smaller drainage areas, and located in areas of concentrated ground-water pumpage have experienced larger water-level fluctuations.

Long-term declines in water levels have occurred in some lakes and in the surficial aquifer in surrounding areas. Most of the declines are probably a result of below normal rainfall and ground-water pumpage; however, other factors, including the hydrogeologic setting of the lakes and surface drainage alterations, also have contributed to lowered lake levels (Barcelo and others, 1990).

Water levels in the intermediate aquifer and in the Upper Floridan aquifer respond seasonally to rainfall and pumpage. Seasonal fluctuations in water levels of wells completed in the intermediate aquifer and the Upper Floridan aquifer are shown in figures 8 and 9. The hydrographs show that the water-level fluctuation pattern for wells completed in the intermediate aquifer are similar to patterns for wells completed in the Upper Floridan aquifer. The graphs also show that water levels generally are at, or near, their minimum during May. Beginning in late May, and continuing through September, water levels in wells rise rapidly in response to summer rains and the cessation of irrigation pumpage.

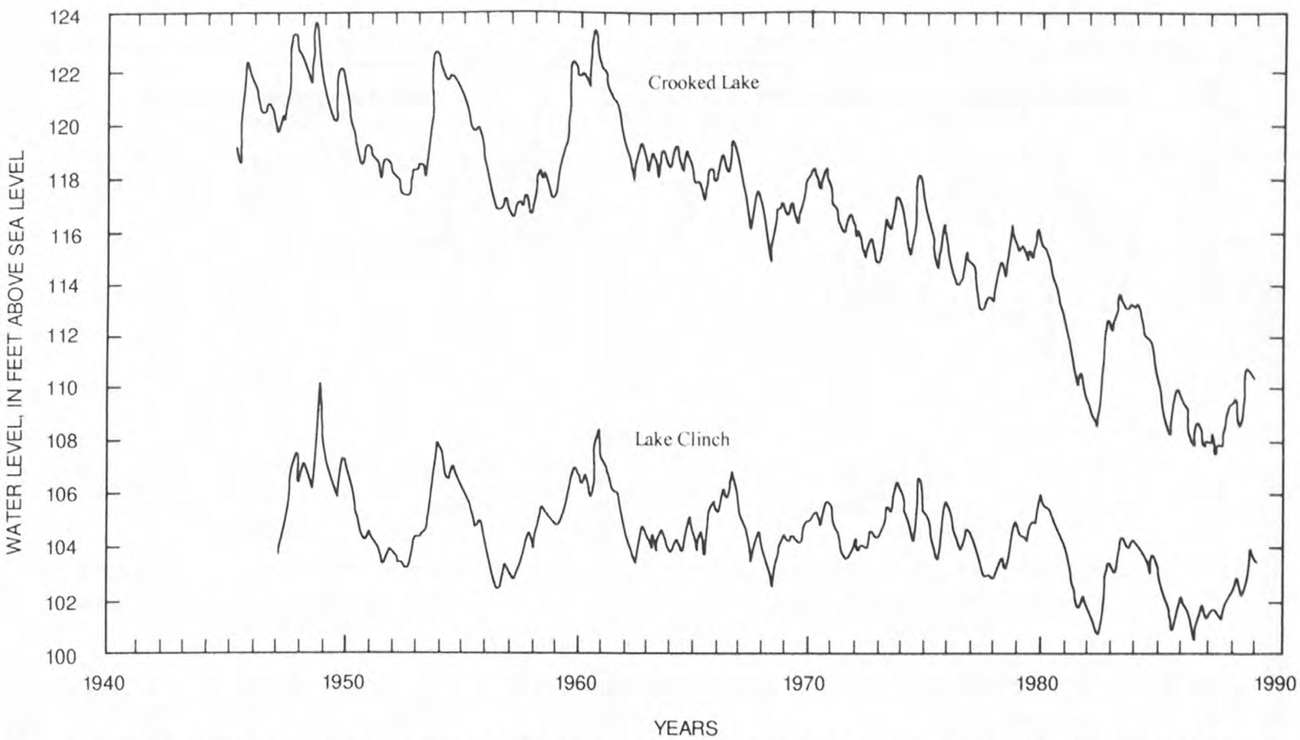


Figure 7. Water levels in Crooked Lake and Lake Clinch near Frostproof, 1945 through 1989. (Location of lakes (sites 28 and 29) are shown in fig. 5.)

The range of water-level fluctuation in the Upper Floridan aquifer varies to some extent with geographic location. Seasonal water levels can vary as much as 30 feet near major agricultural and industrial pumping areas. One such area is in northern Hardee County and southern Polk County where the potentiometric surface of the Upper Floridan aquifer ranges between 40 and 70 feet above sea level. In areas where pumpage for irrigation use is small, water levels seldom vary more than 10 feet between September and May. One such area is in the Green Swamp where the potentiometric surface of the Upper Floridan aquifer generally ranges from 120 to 130 feet above sea level.

The long-term trend in water levels in the intermediate aquifer and in the Upper Floridan aquifer is one of decline (figs. 10 and 11). One of the major centers of decline is in the phosphate mining area of central southern Polk County where long-term observed head loss is 60 feet or more since predevelopment. Long-term water-level declines in other parts of the study area range from a few feet in De Soto County to about 20 feet in northeast Hardee County. In a few areas where little ground-water development has occurred, water levels have remained unchanged. These areas are primarily in eastern Polk County, in the area immediately west of the Kissimmee River, in northeast Highlands County, and in southern De Soto County.

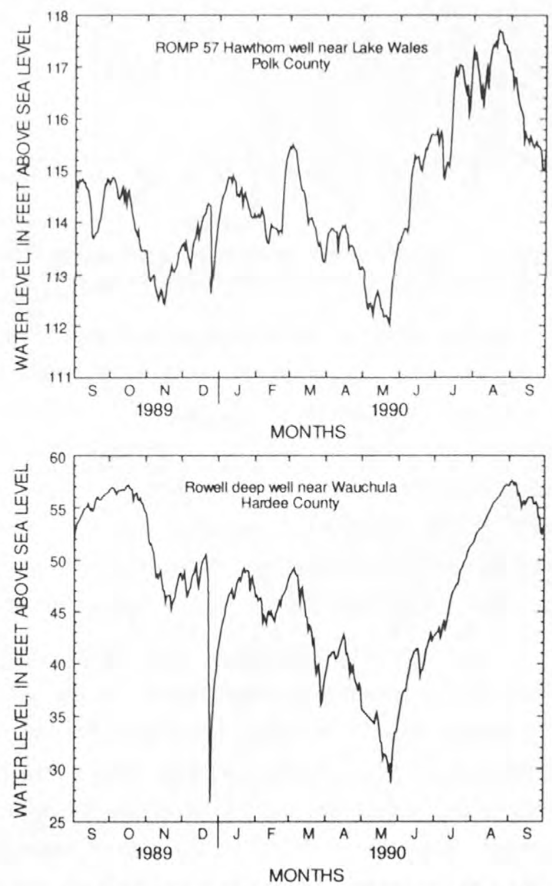


Figure 8. Water levels in wells open to the intermediate aquifer, September 1989 through September 1990. (Location of wells (sites 2 and 12) are shown in fig. 5.)

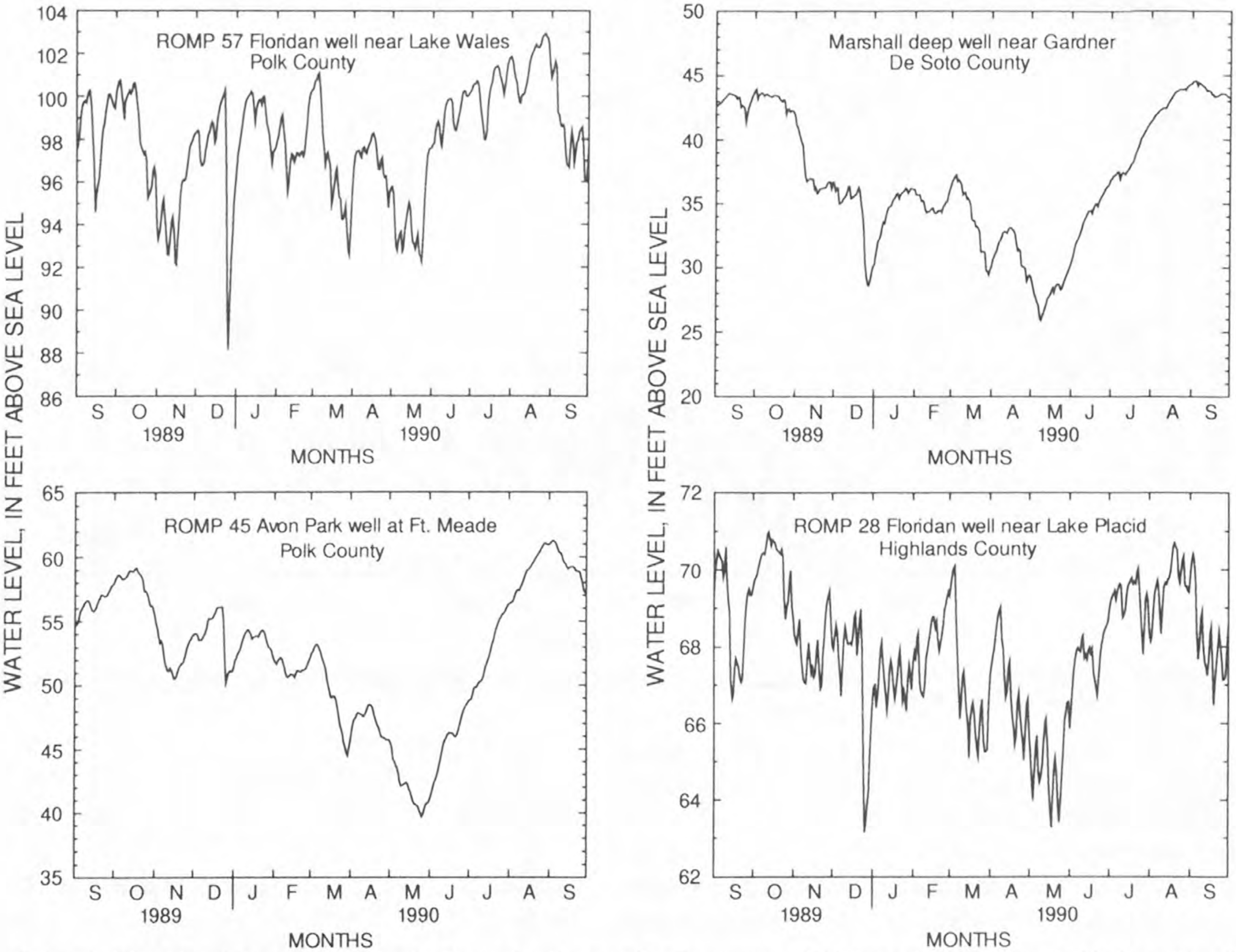


Figure 9. Water levels in wells open to the Upper Floridan aquifer, September 1989 through September 1990. (Location of wells (sites 2, 15, 7, and 17) are shown in fig. 5.)

Hydrographs of long-term water levels shown in figures 10 and 11 indicate long-term water-level declines in their annual high water levels and an increase in the range between the seasonal low and high water levels, especially during the late 1960's and early 1970's. Since about 1975, water levels in these wells generally have maintained their wet-season levels; however, water levels have not recovered to pre-1960 levels.

The water-level declines in wells are directly attributed to substantial stresses placed on the ground-water system due to pumpage, primarily for irrigation and mining (Yobbi, 1983). During 1960's and early 1970's, water levels declined in response to increased pumping. Since the mid-1970's, the rate of water-level decline has decreased in response to relatively constant pumping rates. This is primarily due to a decrease in pumpage associated with the phosphate industry.

Areal Ground-Water Flow

The ground-water flow system in the Lake Wales Ridge area was defined using potentiometric- surface maps constructed from water-level measurements obtained in about 200 wells and lakes and by examining the spatial, seasonal, and the historical change of ground-water levels within the aquifers. Semi-annual maps were used to indicate the seasonal dry (May), seasonal wet (September), potentiometric surfaces, and annual variations in water levels.

The water table in the surficial aquifer was mapped using (1) the data from 6 observation wells, (2) records of 9 streams and 50 lake stages in the study area, (3) estimated average water-table altitude based on the relation between land-surface altitude and measured depths to water in wells, and (4) modification of water-table altitude at a few locations following calibration of a ground-water model as described in the following

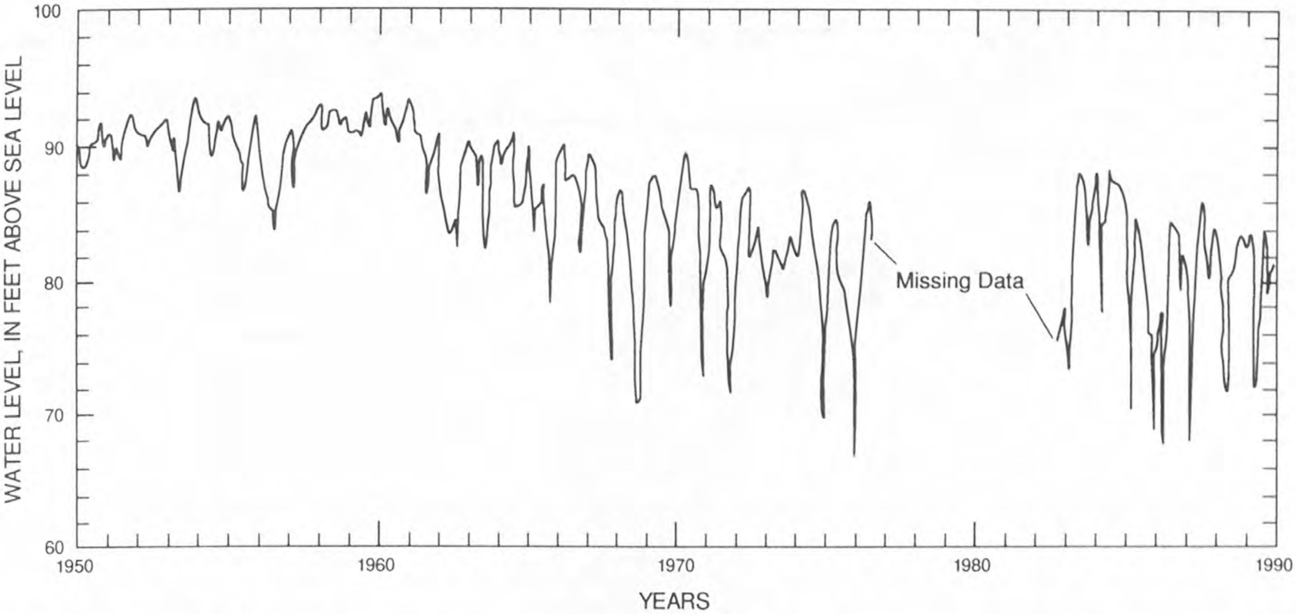


Figure 10. Water levels in the Upper Floridan aquifer at the Coley well at Frostproof 1950 through 1989. (Location of well (site 9) is shown in fig. 5.)

section. Data from additional Southwest Florida Water Management District wells drilled during the project were used to verify the relation between land-surface altitude and measured depths to water. The water table was estimated to be at or a few feet below land surface in swampy areas and at depths greater than 5 feet below land surface for the lowlands plain and ridge areas. The maximum depth of the water table below land surface is about 100 feet.

The configuration of the resulting water-table surface is illustrated by the contour map shown in figure 12. Ground-water flow within the surficial aquifer is predominantly local. The aquifer is hydraulically continuous with surface-water bodies, and ground-water discharges from the aquifer support the dry-weather flow of many streams in the area. Relatively steep gradients in the water table adjoin the major streams, and relatively gentle gradients exist in the broad interstream areas. The highest water levels occur in the northern Lake Wales Ridge area, but the water table maintains a relatively high altitude along the length of the ridge into Highlands County.

The water table is lower than the potentiometric surface of the underlying confined aquifer over about an 800 mi ^{2} area. In this primarily swampy area, upward flow occurs from the underlying confined aquifer to the surficial aquifer and streams. Within the ridge areas the water table is about 10 to 90 feet higher than the potentiometric surface of the intermediate aquifer and the Upper Floridan aquifer.

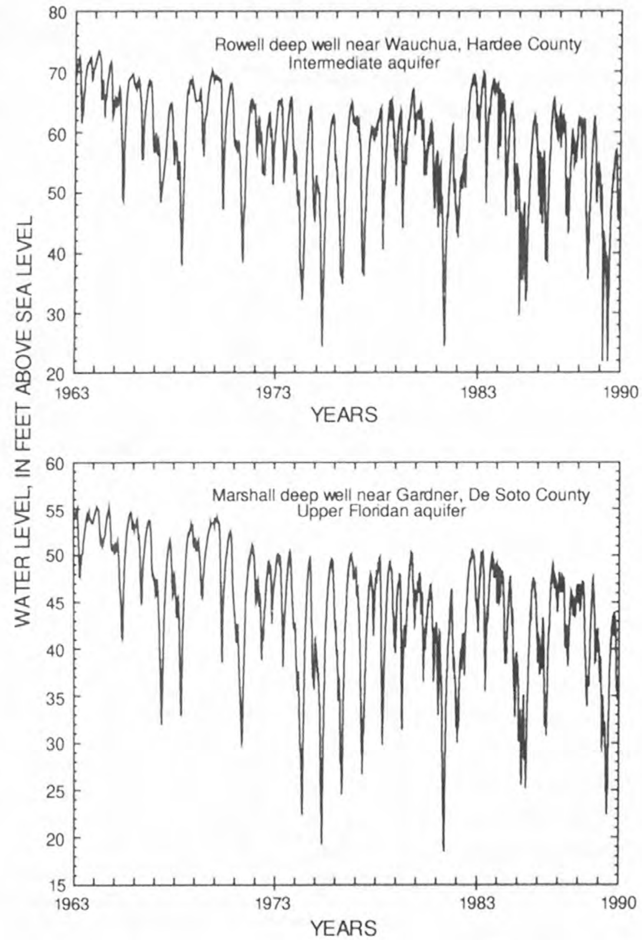
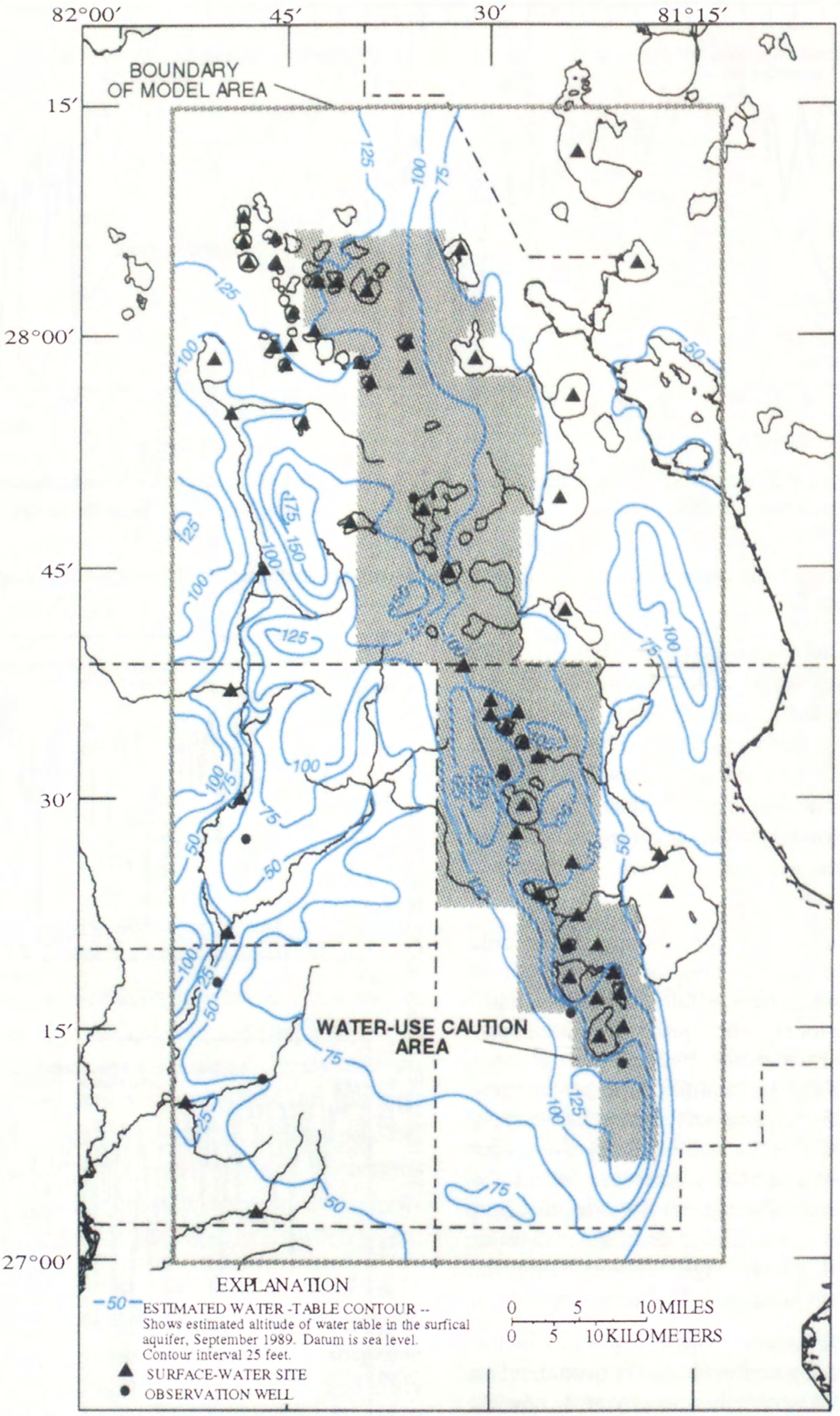
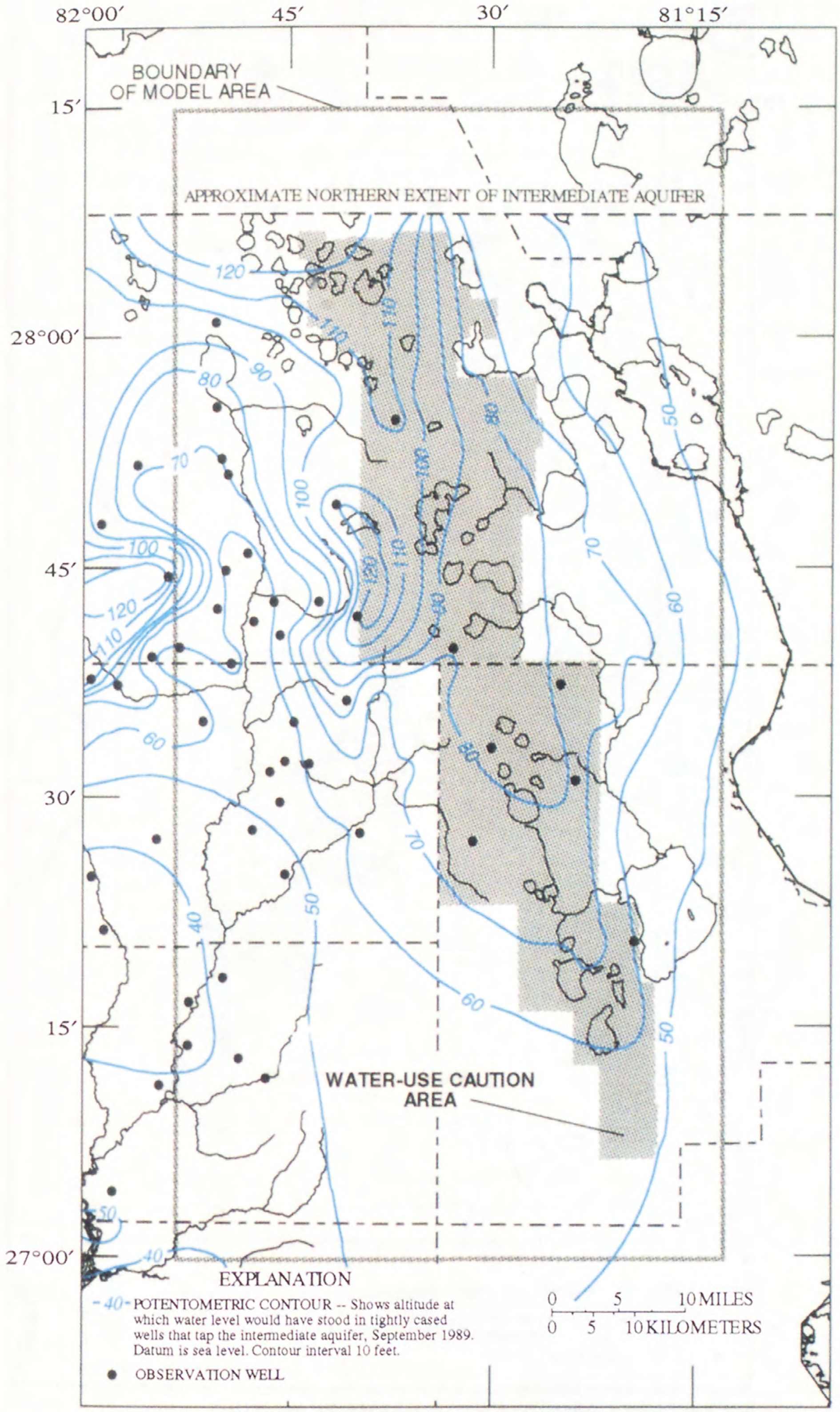


Figure 11. Water levels in wells open to the intermediate aquifer and the Upper Floridan aquifer,1963 through 1989. (Location of wells (sites 12 and 15) are shown in fig. 5.)



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 12. Estimated water table in the surficial aquifer, September 1989.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 13. Potentiometric surface of the intermediate aquifer, September 1989. (Modified from Knochenmus and Barr, 1990a.)

Water in the intermediate aquifer and the Upper Floridan aquifer occurs under confined conditions. Figures 13 through 16 show the potentiometric surface of the intermediate aquifer and the Upper Floridan aquifer in September 1989 and May 1990. These potentiometric-surface maps are a representation of the hydraulic head in the aquifers and depict the altitude to which water will rise in tightly cased wells that penetrate the aquifers. The September maps represent hydrologic conditions near the end of the summer rainy season when ground-water withdrawals for agriculture use are low and water levels are at their seasonal high. The May maps represent hydrologic conditions near the end of the dry season when ground-water withdrawals are greatest and water levels are near their seasonal lows.

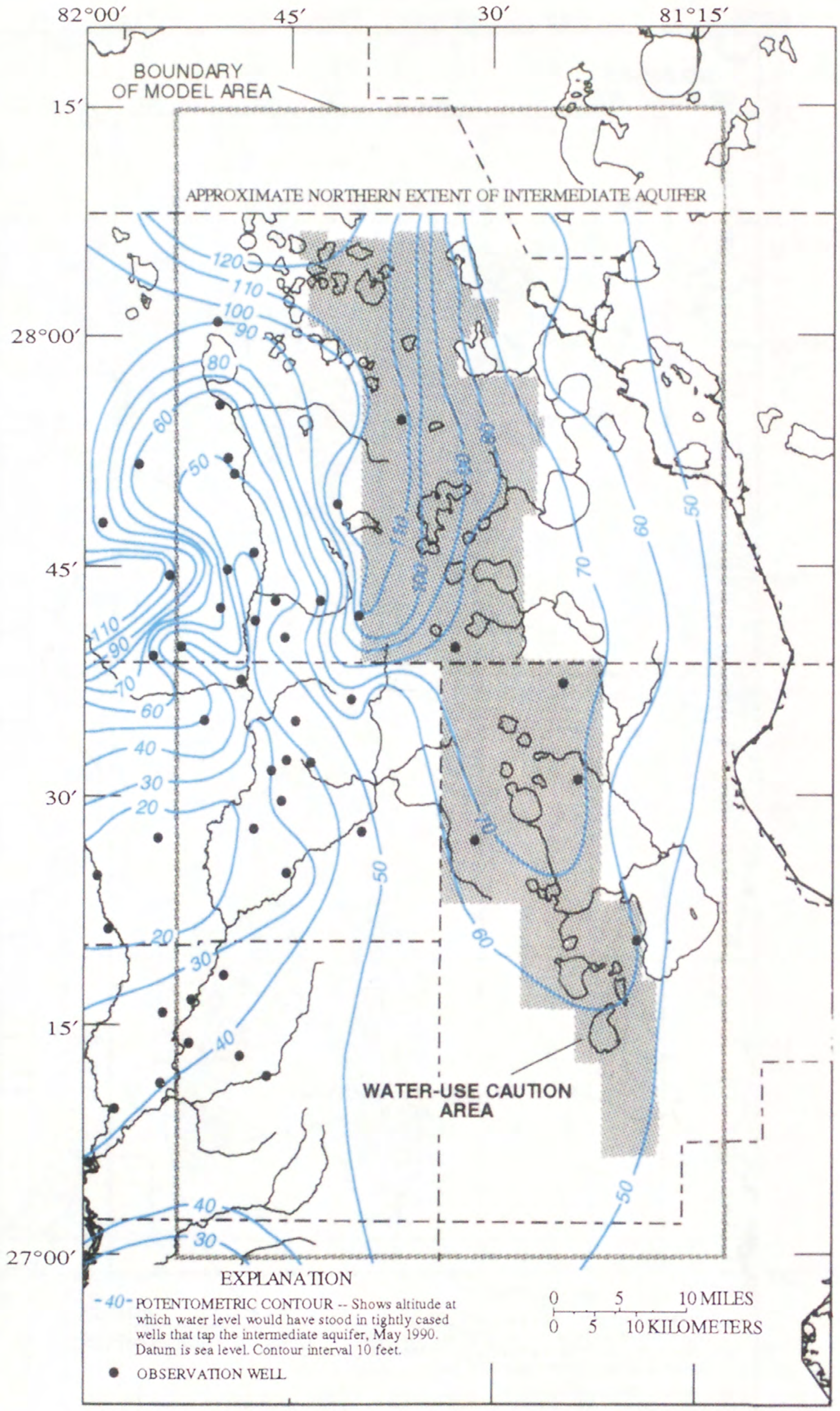
The configuration of the potentiometric surface of the intermediate aquifer in September 1989 and May 1990 indicates that ground water flows away from the ridge area to the east, south and west (fig. 13 and 14). Inflow to the study area and ridges occurs from the northwest. Differences in water levels of the intermediate aquifer ranged from about 1 to 20 feet lower in May 1990 compared to September 1989 levels, but the general configuration and head gradients did not change significantly.

The potentiometric surface of the intermediate aquifer is generally higher than the water table in the surficial aquifer in the low-lying areas and near several streams in the study area. As a result, ground water in these areas moves upward from the intermediate aquifer into the surficial aquifer, and in some areas, eventually discharges into the streams. Duerr and Enos, (1991) reports the Peace River gaining about 4 ft ^{3}/s per river mile over a 6-mile reach upstream of Zolfo Springs.

Potentiometric-surface maps of the Upper Floridan aquifer for September 1989 and May 1990 provide a typical representation of the wet and dry season water-level conditions for the aquifer (figures 15 and 16). Major features of the maps are a potentiometric-surface high in northwestern Polk County and a regional ground-water divide that trends along the Lake Wales Ridge. The principal directions of ground-water flow in the Upper Floridan aquifer are west toward the Peace River and east toward the Kissimmee River. The September 1989 and the May 1990 potentiometric-surface configurations are uniformly similar; however, the potentiometric-surface contours in May compared to September, shifted inland and locally water levels are about 1 to 30 feet lower.

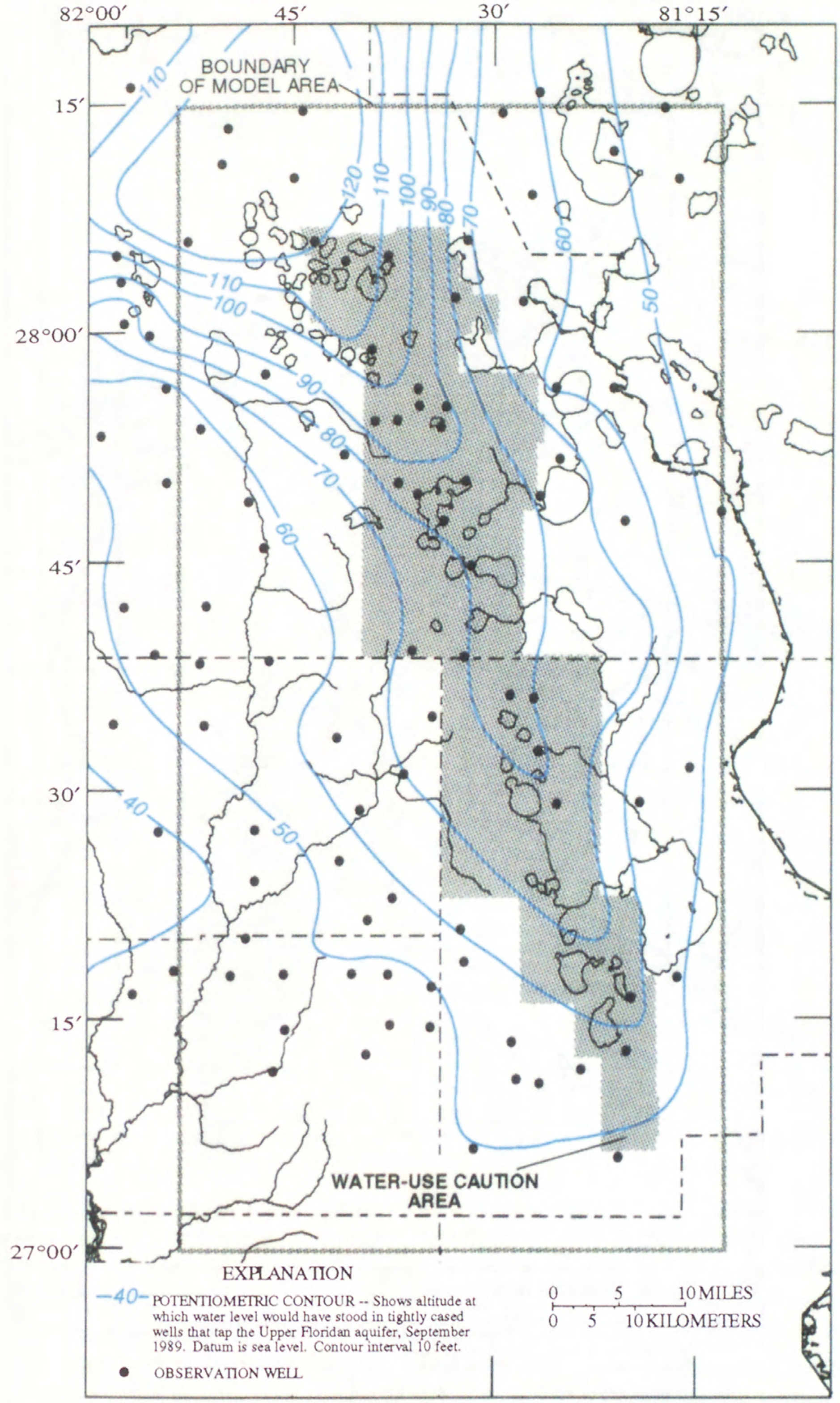
SIMULATION OF GROUND-WATER FLOW

The ground-water flow system in the study area was analyzed using a numerical flow model. Numerical flow models are used to test and to qualitatively and quantita-



Base from Southwest Florida Water Management District digital data, 1992. Universal Transverse Mercator Projection, Zone 17.

Figure 14. Potentiometric surface of the intermediate aquifer, May 1990. (Modified from Knochenmus, 1990a.)



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 15. Potentiometric surface of the Upper Floridan aquifer, September 1989. (Modified from Knochenmus and Barr, 1990 b.)

tively improve conceptual models. Once calibrated the digital model can be used to analyze the response of an aquifer system to past or present ground-water withdrawals, and possibly to predict the response of the systems to future pumpage.

The Lake Wales Ridge model was initially calibrated for the quasi-steady-state conditions reflected by water levels representing September 1989 conditions. The calibrated results were tested by simulating transient conditions for the periods October 1989 through September 1990 and October 1988 through September 1989. Tests also were made to assess the sensitivity of the model to extreme ranges in the input parameters. The model was then used to simulate responses of the hydrologic system to various rates of pumping.

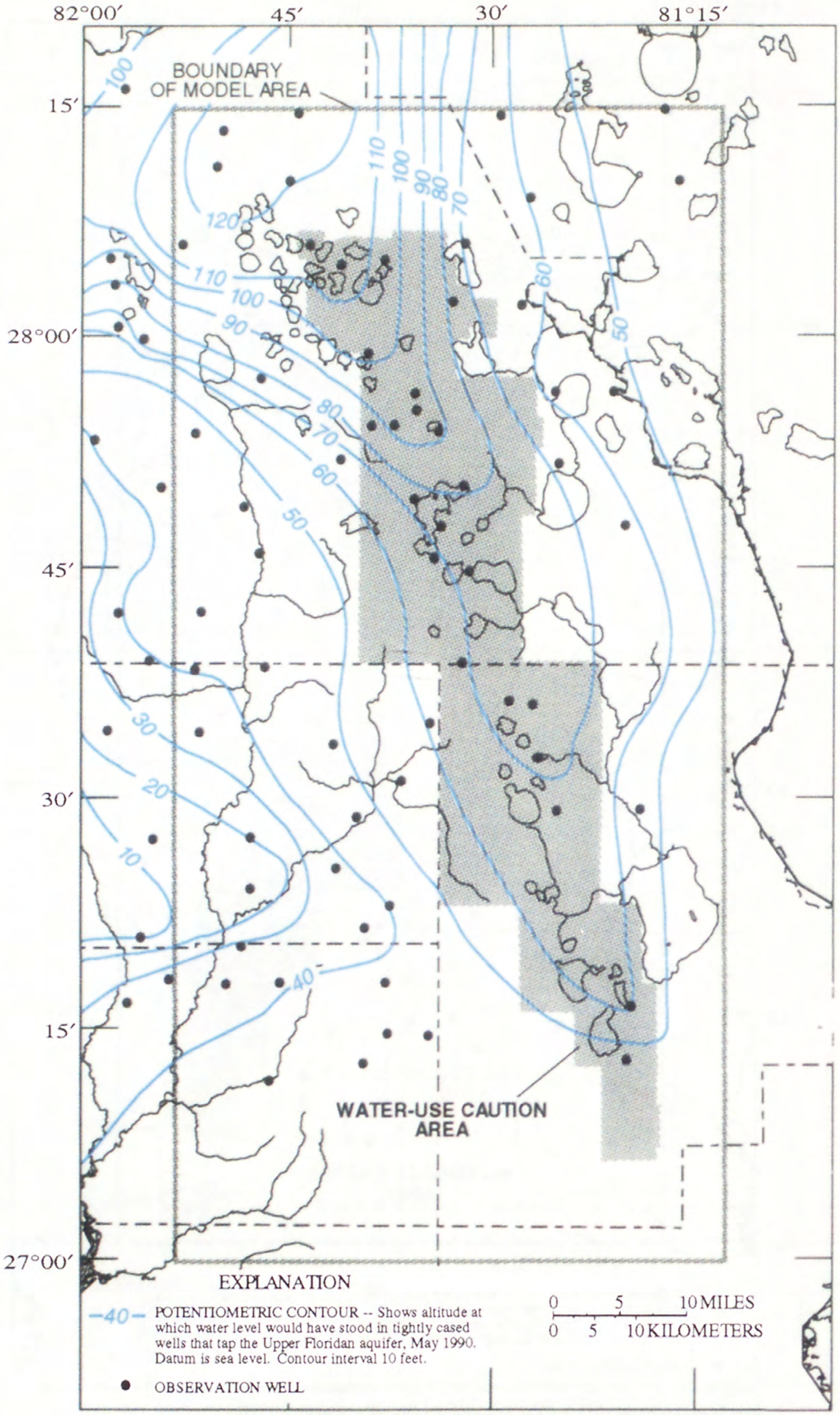
Conceptual Description of the Ground-Water Flow System

Development of a conceptual model that can integrate the geology and hydrology of the study-area flow system is essential in evaluating the ground-water flow system. Simulation with a computer-based model, using the physical properties estimated from the conceptual model, leads to further refinements to the understanding of the flow system. An established and calibrated numerical flow model can be used to evaluate the potential impact of future ground-water development.

Procedures in the conceptualization include developing an understanding of the ground-water system in terms of external and internal geometry (geologic framework), material and fluid parameters (transmissivity), and character and physical extent of the boundaries. The information necessary to describe a ground-water system are then transformed into mathematical terms in the numerical model.

Existing literature provided the necessary information for the conceptualization of the multiaquifer system for this study. The physical boundaries of individual aquifers and confining units are presented in hydrogeologic maps by Wolansky and others (1979), Shaw and Trost (1984), Miller (1986) and Barr (1992). Hydraulic characteristics of aquifers and confining units are presented in Tibbals (1981; 1990), Ryder (1982; 1985) and Barcelo and others (1990).

A highly generalized description of the hydrogeologic framework and related ground-water flow along an east-west section in the central part of the study area is shown in figure 17. The water table defines the uppermost boundary of the ground-water flow system and occurs in the surficial aquifer throughout the study area. Recharge to the water table generally occurs from rainfall and irrigation return flow and moves downgradient toward local points of discharge, such as lakes, swamps, streams, or wells.



Base from Southwest Florida Water Management District digital data, 1992.
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Figure 16. Potentiometric surface of the Upper Floridan aquifer, May 1990. (Modified from Knochenmus, 1990b.)

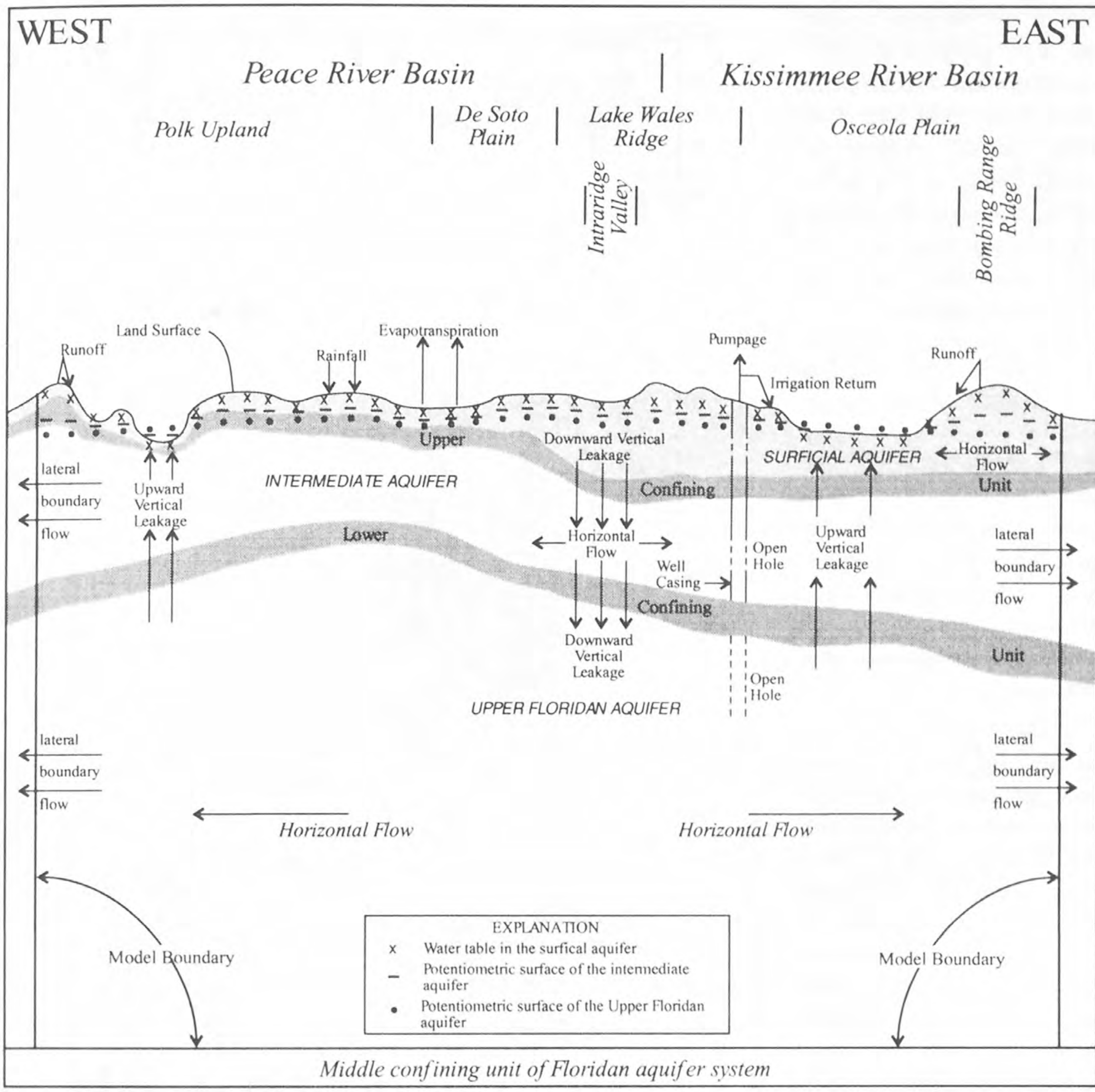


Figure 17. Generalized conceptual model of the ground-water system showing major components and directions of steady-state flow.

Other discharge from the surficial aquifer occurs as pumpage, evaporation and transpiration, and downward leakance through the upper confining unit to the intermediate aquifer. Recharge to the intermediate aquifer primarily occurs only as downward leakage through the upper confining unit. Water discharges from the intermediate aquifer as base flow to nearby streams, as diffuse leakage to the surficial aquifer, downward leakance through the lower confining unit into the Upper Floridan aquifer, or as lateral boundary outflow. In the Upper Floridan aquifer, water moves laterally in the direction of decreasing head or moves upward as diffuse leakage into the intermediate aquifer or surficial aquifer. The rate of leakage between aquifers is controlled by the thickness of the confining units, the vertical hydraulic conductivity of confining unit, and the head differences between aquifers.

Recharge to the surficial aquifer can occur wherever the surficial sediments have an unsaturated zone and are permeable. This occurs in most areas, particularly where the water table in the surficial aquifer is higher than the potentiometric surface of the underlying aquifers (fig. 18). In areas where the potentiometric surfaces of the underlying aquifers are above the water table of the surficial aquifer, there is the potential for water to move upward to recharge the surficial aquifer. In such areas, rainfall can still recharge the surficial aquifer as long as the surficial sediments are unsaturated. Recharge is highest in the internally drained sand hill ridges where infiltration rates are high and water levels are deep. In these areas, recharge could reach a maximum of about 27 in/yr. Lakes with leaky bottoms probably concentrate recharge. Recharge is lowest in the terrace and river valley areas where recharge is being rejected because of a thin unsaturated zone and an upward vertical hydraulic gradient.

The generalized conceptualization of the Lake Wales Ridge ground-water flow system is that water moves downward from the surficial aquifer to the intermediate aquifer and the Upper Floridan aquifer in the central area, primarily under the ridges, with minor amounts under the flatlands. Ground-water then flows laterally away from the central area, downgradient to discharge areas to the west, east, and south, and locally along valleys of major streams. Finally, upward leakage from the Upper Floridan into the intermediate system occurs where significant vertical head gradient exists. In the valleys of major streams, rainfall that recharges the surficial aquifer does not reach the underlying aquifers, but is discharged to streams within short distances.

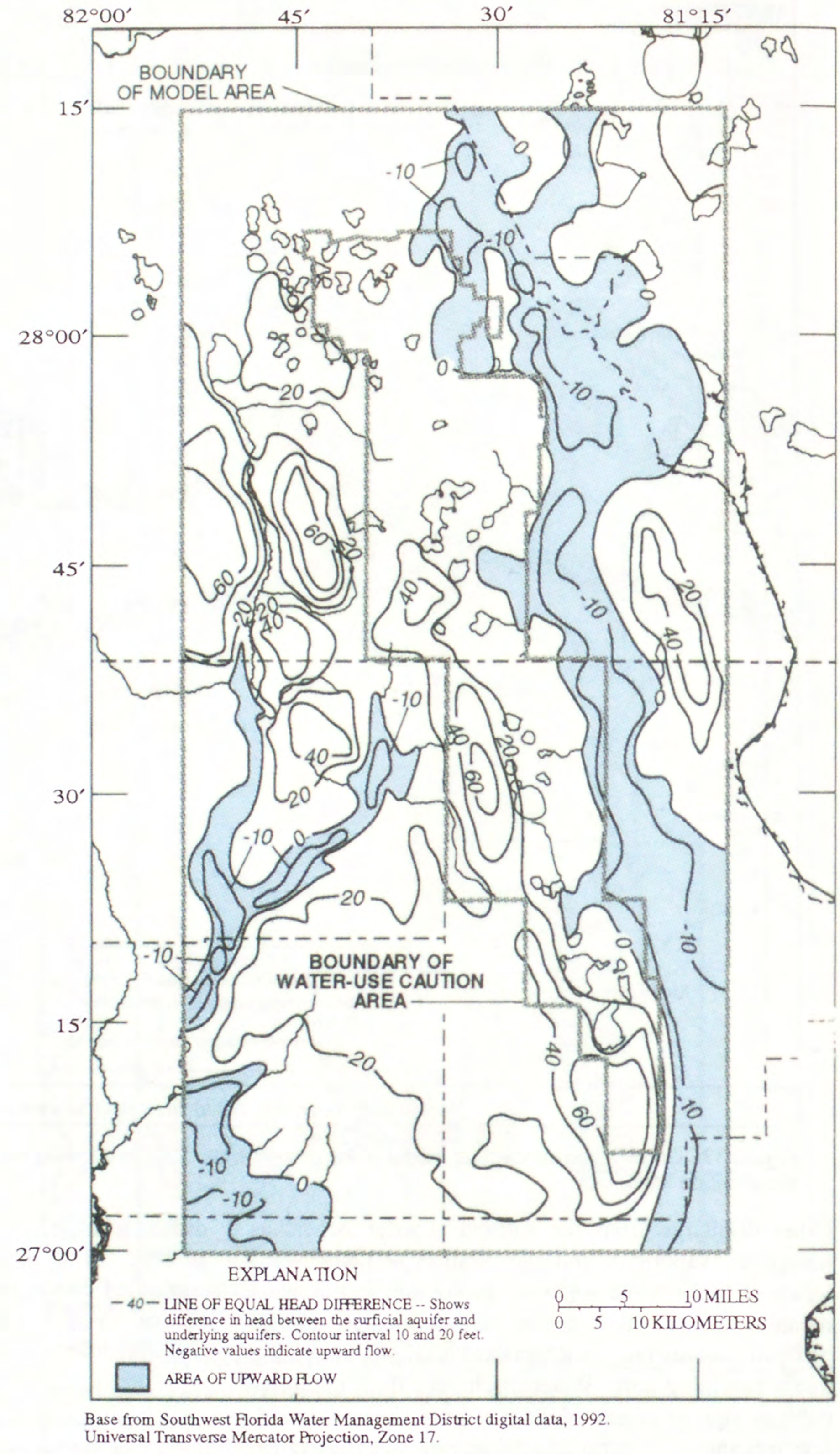
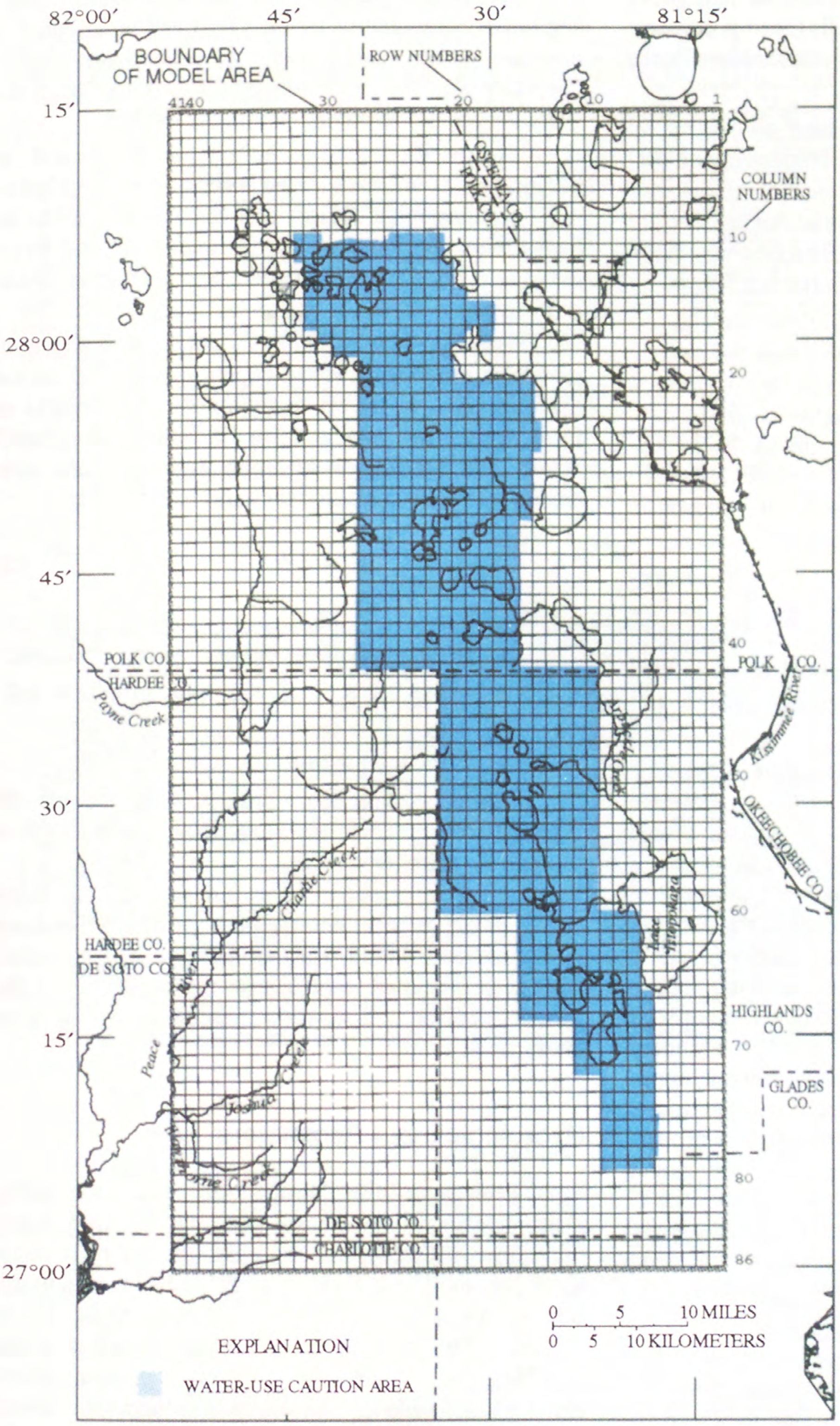


Figure 18. Head difference between the surficial aquifer and underlying aquifers and areas of upward flow, September 1989.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 19. Model grid used in simulation of flow system.

Model Description, Grid Design and Boundaries

The numerical model code used to analyze ground-water flow in the study area is a three-dimensional finite-difference model code developed by McDonald and Harbaugh (1984). The code numerically solves a set of simultaneous finite-difference equations that describe ground-water flow in the aquifer. The equations require that hydraulic properties, boundaries, and stresses be defined for the area modeled. A quasi-three-dimensional model was configured as a sequence of three horizontal layers, representing the surficial, intermediate, and Upper Floridan aquifers, coupled by two leakance layers used to simulate vertical leakage through the upper and lower confining units.

Major assumptions made in the model analysis are as follows:

1. The surficial aquifer, the intermediate aquifer and the Upper Floridan aquifer are single layer, isotropic media,
2. Ground-water flow in each layer is horizontal,
3. Movement between aquifers is vertical,
4. Horizontal flow and storage of water in the confining units are negligible, and
5. General head boundary conditions accurately represent hydrologic con-ditions in the intermediate aquifer and the Upper Floridan aquifer near, but outside, the model-grid boundary.

The modeled area was subdivided into a grid with equally spaced nodal dimensions. The grid dimensions are 41 rows by 86 columns. Each grid cell represents a uniformly square mile area. (A cell is inactive if the transmissivity in that cell is equal to zero, and active where the transmissivity is greater than zero.) A total of 3,526 cells per layer are active (fig. 19). The active cells are separated into variable-head cells (head varies in time) and constant-head cells (head is constant in time). The model contains 250 constant-head cells and 10,328 variable-head cells.

The limits of the model area were chosen on the basis of (1) the configuration of the potentiometric surface of the Upper Floridan aquifer, and (2) the distance away from the WUCA to receive minimal effect from pumping stress within the WUCA. The area within the WUCA is 750 mi ^{2} while the model area is 3,526 mi^2.

Boundary conditions are used to constrain the lateral and vertical extent of the simulated flow system and its variation with time. Lateral boundaries are prescribed, not simulated, and are designed to conform to the physical and hydrologic conditions at the boundaries of the aquifer or aquifer systems. Lateral boundary conditions inputed to the model are shown in figure 20.

The base of the Upper Floridan aquifer was considered impermeable and was designated as a no-flow boundary. The northern boundary was specified along a flow path of the Upper Floridan aquifer, consequently, no flow of water moves in or out of the model in this area of the Upper Floridan aquifer.

Lateral model boundaries ideally are selected to coincide with natural hydrologic boundaries unaffected by pumping. Such boundaries, however, can extend many miles beyond the modeled area. Accordingly, a head-dependent flow boundary was used to simulate flow at most of the lateral boundary cells of the intermediate aquifer and the Upper Floridan aquifer (fig. 20). This boundary condition was selected because it allows simulated heads at the boundary to change along with corresponding changes in computed cross-boundary flow. The boundary condition is based on the assumption that, beyond each boundary cell, a point exists where the head will not change and that aquifer properties are uniform between this point and the model boundary. The use of this boundary reduces the size of the area required for flow simulation. This head-dependent boundary was simulated using the general head boundary (GHB) of McDonald and Harbaugh, 1984.

Data that describe the GHB condition consist of three parameters: the boundary head (h), the specified head outside the model boundary head (H), and the horizontal conductance (C) of aquifer media between the model boundary and the specified point.

The equation that determines the cross-boundary flow (Q) is:

$$Q = C(H-h) \tag{1}$$

Because of pumping outside the western boundary, heads computed using the GHB can be affected in this part of the model area. However, the western boundary was designed sufficiently far away from the WUCA to minimize errors within the WUCA.

A specified-head condition was selected to describe the boundaries of the surficial aquifer. Hydrologic events outside the model area have little effect on the surficial aquifer at the model boundaries and errors introduced by specified boundary heads are assumed to be minimal.

Major streams in the model area were represented by stream cells (head-dependent flux) within the modeled area, as shown in figure 20. Leakage to or from streams in governed by "stream conductance," which is a function of streambed geometry and streambed hydraulic characteristics and is defined as:

$$k\,A/b \tag{2}$$

where:

k is the hydraulic conductivity of streambed,

A is the plan area of the stream within the cell, and,

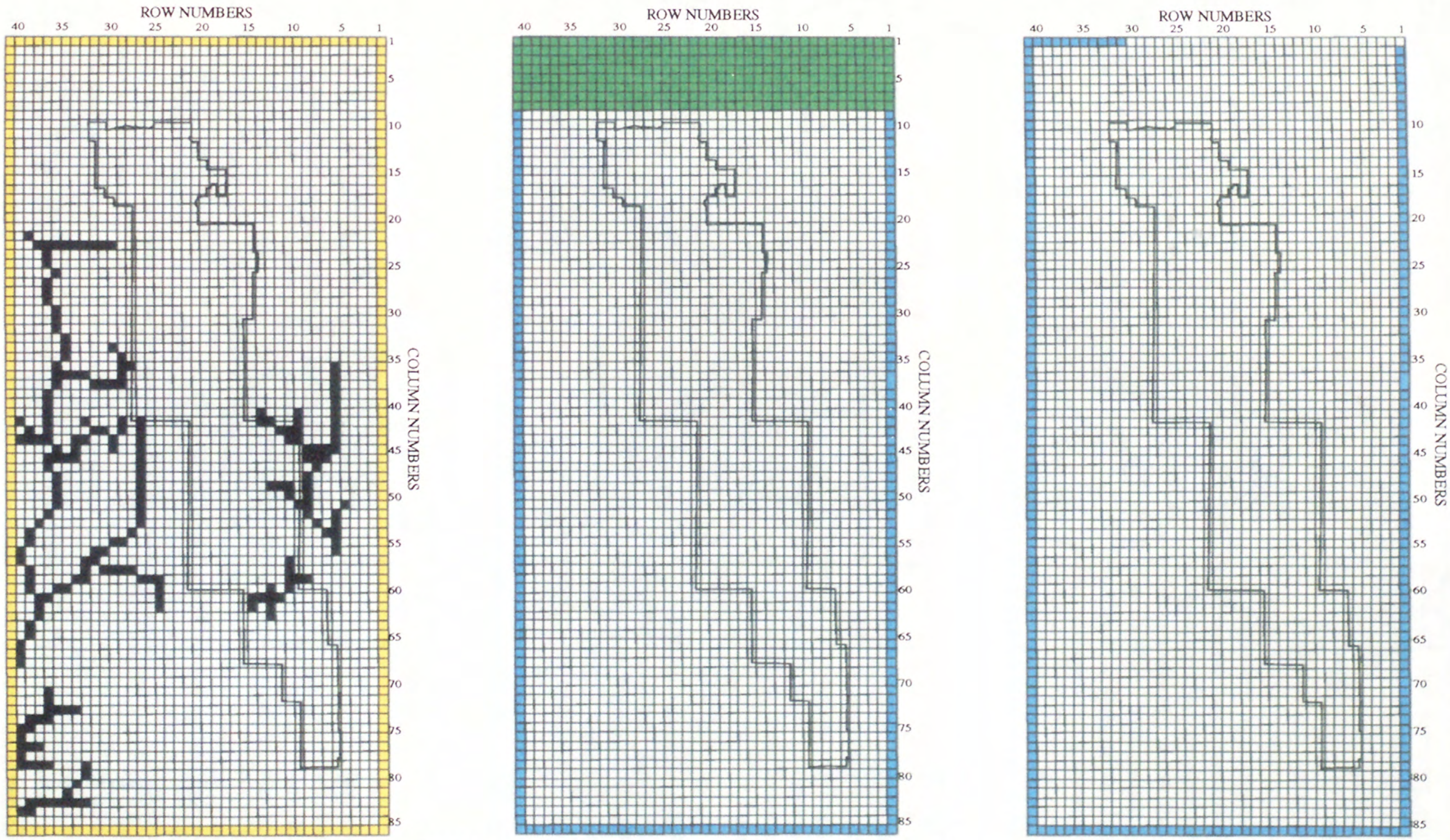
b is the thickness of the streambed

The product of streambed conductance and the head difference across the streambed equals the flow through the streambed.

Lakes in the study area are considered to be "windows" in the surficial aquifer through which the water table can be observed. In the steady-state simulation, lakes were assumed to behave in the same way as the surficial aquifer, and were not treated separately from the surficial aquifer.

Hydrologic Input Parameters

Data input to the steady-state model as spatially distributed arrays include values of starting head, transmissivity for the intermediate and Upper Floridan aquifers, confining-unit leakance, hydraulic conductivity, bottom altitude of the surficial aquifer, boundary heads and boundary conductance values for the intermediate aquifer and the Upper Floridan aquifer, pumping rates, and stream heads and riverbed conductance values. Input data arrays for the surficial aquifer also include rates of specified net recharge and discharge. Parameter array values were estimated from available reports, but where estimates of certain parameters were not available, representative values were selected from ranges in published reports.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

SURFICIAL AQUIFER

INTERMEDIATE AQUIFER

UPPER FLORIDAN AQUIFER

EXPLANATION

- SPECIFIED-HEAD GRID BLOCK
- GENERAL HEAD-DEPENDENT FLOW GRID BLOCK
- RIVER BLOCK
- VERTICAL-FLOW GRID BLOCK - Intermediate aquifer is absent but block is needed by model to maintain continuity between surficial and Upper Floridan aquifer
- BOUNDARY OF WATER-USE CAUTION AREA

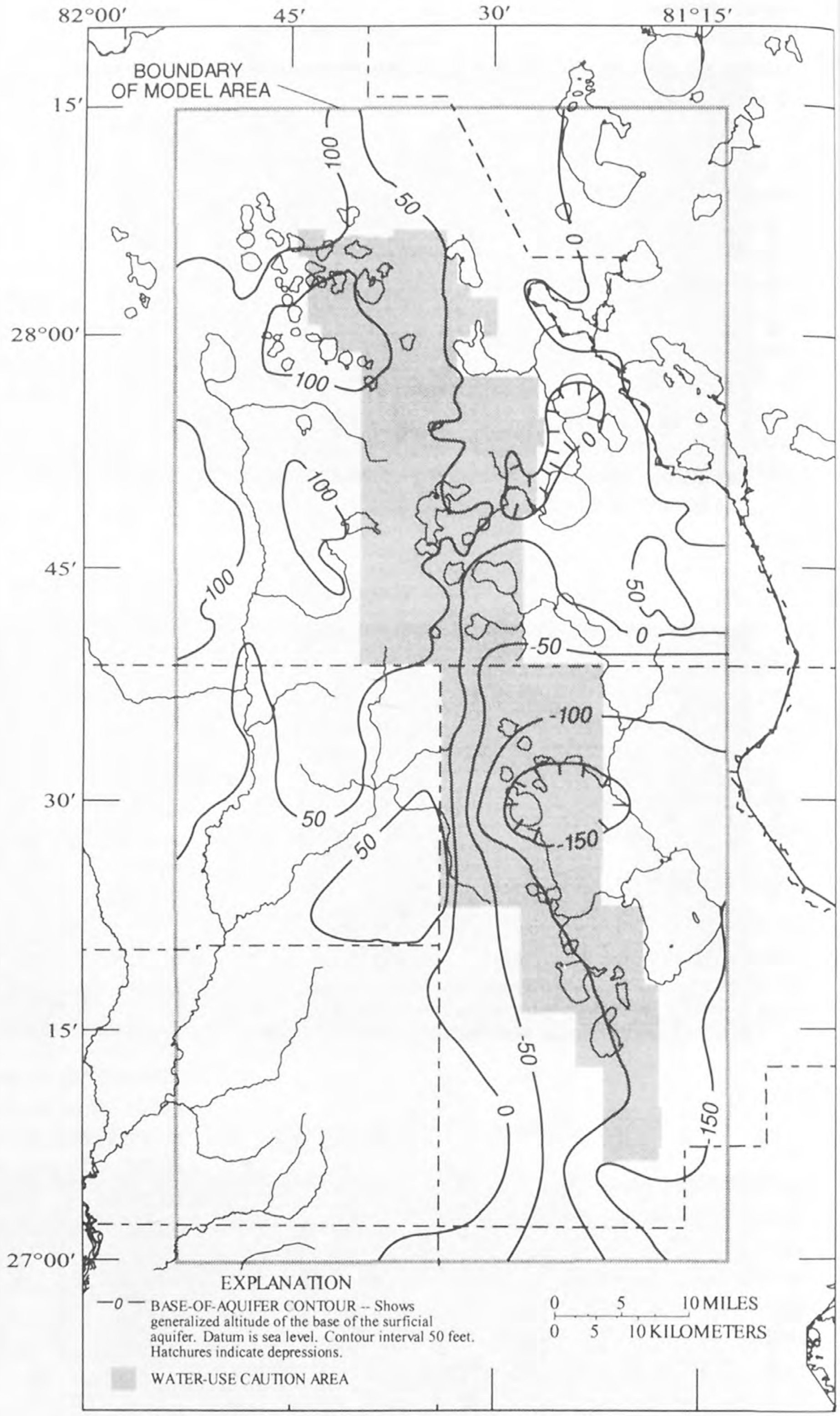
Figure 20. Model boundary conditions for the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer.

Initial Conditions

Heads in the surficial aquifer were estimated from the water-table map for September 1989, shown in figure 12. Water-level altitudes of the intermediate aquifer and the Upper Floridan aquifer were estimated from field measurements of water levels in a network of wells and from potentiometric-surface maps (figs. 13 and 15). The head values in cells without wells were interpolated directly using potentiometric-surface contours and in cells with wells, head values were taken from the measurements. Observation wells are about 2 percent of the cells in the Upper Floridan aquifer and about 1 percent of the cells of the intermediate aquifer. Lakes with water-level measurements are about 9 percent of the cells of the surficial aquifer.

Transmissivity of Aquifers

The hydraulic conductivity of the surficial aquifer was assumed to be a uniform 8 ft/d (Lee and Swancar, 1994). The model uses the product of this hydraulic conductivity and the saturated thickness of the surficial aquifer to calculate transmissivity. The base of the surficial aquifer was determined from logs of wells and test holes and by subtracting the thickness of the surficial deposits defined by Wolansky and others (1979), Shaw and Trost (1984), and Barr (1992) from land-surface datum (fig. 21). The base altitudes were calculated, plotted on a grid, and contoured. Cell values inputed to the model were adjusted according to the contours. The average altitude of land surface in



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 21. Generalized altitude of the base of the surficial aquifer.

each grid block was estimated from USGS 1:24,000 topographic maps.

The starting transmissivity arrays input for the intermediate aquifer and the Upper Floridan aquifer were derived from the Regional Aquifer System Analysis (RASA) models of Ryder (1985) and Tibbals (1990). The transmissivity arrays for the intermediate and Upper Floridan aquifers differ somewhat from those of the RASA models due to finer discretization, different grid orientation, and the incorporation of new field test data obtained after completion of the RASA models (Barcelo and others, 1990).

Leakance of Confining Units

The vertical resistance to ground-water flow was simulated in the model with a leakance term. Leakance is used in the model to simulate vertical flow between model layers. Initial values of leakance in this model were obtained from Ryder (1985). These values were adjusted, however, through calibration. A great spatial variation in leakance is expected because of the discontinuity and highly variable hydraulic characteristics of the confining unit media.

The absence of the intermediate aquifer is simulated by assigning a very high leakance value (50 ft/d/ft) to the upper confining unit and a very low transmissivity value (1 ft^2/d) to the aquifer. This value assignment allows the lateral flow in the area to be negligible and all flow to be in the vertical direction, controlled by the vertical hydraulic properties of the lower confining units.

Lateral Boundary Flow

The steady-state lateral boundary conditions for the intermediate and Upper Floridan aquifers in the modeled area were first simulated as a specified-head. This was designed to simulate the regional flow rates to and from each specified-head cell. Once calibration was achieved the calculated flow rate (Q) and the specified head (HB) in each boundary cell was assigned a controlling boundary source head (h). Initial boundary source heads were chosen along flow paths 6 to 10 miles beyond the model boundary and were interpolated from the September 1989 potentiometric-surface maps of the intermediate aquifer and the Upper Floridan aquifer (Knochenmus and Barr, 1990a; 1990b). By using equation 1, a conductance term for each specified-head cell was calculated. After the conductance term was calculated, the specified-head boundary condition in the intermediate and Upper Floridan aquifers was converted to a general-head boundary condition. A proof run of the model was made to test whether simulated boundary heads (HB) and flow rates (Q) matched those of the previous calibration run, which was employed for this constant-head boundary condition.

Net Recharge and Discharge

Rates of net recharge to and discharge from the surficial aquifer were unknown prior to model calibration and were model generated. Initial estimates of these values were generated using the September 1989 water-table head distribution and the aquifer properties calibrated for the steady-state model (discussed in the next section). This simulation first treated the surficial aquifer as a specified-head boundary and the steady-state leakage across the confining units to or from the surficial aquifer was determined for each cell by the model. Once this first, preliminary calibration was achieved, the cell values of leakage were then inputed to the surficial aquifer as a net recharge/discharge array and the specified-head boundary in the surficial aquifer was converted to a free-surface boundary for the final calibration. This net recharge/discharge represents water that moves upward or downward as leakage across the upper confining unit. In setting net recharge/discharge in this manner, recharge is defined so as to exclude water lost to evapotranspiration.

Stream Leakage

The effects of several streams (Peace River and tributaries, Joshua Creek, Prairie Creek, Arbuckle Creek, and Josephine Creek) were simulated in the model. Streams were assumed to be hydraulically connected to the surficial aquifer through leaky streambeds. Connection between the streams and the surficial aquifer depends on the streambed conductance and the hydraulic gradient between the stream or stream bottom and the aquifer.

The rate and direction of flow through the streambed is given by:

$$Q = \frac{klw}{b}(H-h) \qquad (3)$$

where:

- Q is the flow rate between the stream and aquifer,
- k is the hydraulic conductivity of the streambed,
- l is the length of the stream,
- w is the width of the stream,
- b is the thickness of the streambed,
- H is the head in the stream, and,
- h is the head in the aquifer.

For modeling purposes each stream was divided into reaches, each of which is contained in a single cell. A streambed *k/b* of 0.1 d^{-1}, a relatively high value, was used for all stream cells. Widths of stream reaches were derived from measurement notes for discharge measurements at gaging stations and from 7.5 minute topographic maps. Lengths of individual stream reaches were measured from 7.5 minute topographic maps with the model grid superimposed. These lengths are unique to this model discretization. Stage for each stream cell was estimated from stream-gage data and from 7.5 minute topographic maps. Bottom altitudes of streams were arbitrarily set at 3 feet below river stages along all stream reaches.

Steady-State Simulation

The steady-state simulation had two primary purposes. The first was to calibrate the model to a selected equilibrium hydrologic condition in which the stress and response characteristics of the system are well documented. The second was to provide the steady-state simulation needed as the initial conditions for subsequent transient-state simulation.

The conventional approach for steady-state calibration is to use long-term average heads and stresses for definition of model parameters. Such conditions for the study area are highly uncertain because the distribution and rates of ground-water withdrawals for agricultural use generally are unknown. Therefore, for this study, steady-state conditions were defined by conditions at the end of the rainy season when pumpage for agricultural use is zero and water-level hydrographs showed little regional change in head. September 1989 was considered a suitable period for assuming steady-state conditions for several reasons:

1. Principal stresses during this time were withdrawals from industrial and municipal supply wells, which are known within reasonable accuracy. Pumping rates for these users vary during the year, but variations generally are too small to have much affect on the regional fluctuation of the potentiometric surface.
2. The relatively short time it takes the system to reach equilibrium following initiation or cessation of pumping. Evidence of this is seen in the response of water levels in December 1989 in the intermediate and Upper Floridan aquifers to large increases in pumpage for freeze protection. For the 3-day pumping period, in December 1989, there was a 14- to 21-day period of drawdown and recovery to previous levels (fig. 9).
3. The seasonal May to June decline from about 500 Mgal/d to 300 Mgal/d pumpage. Bush and Johnston (1988), simulated drawdown versus time and showed that at a given pumping rate, steady state is nearly reached in about 120 days in the Upper Floridan aquifer in Polk County with a storage coefficient of 1.2×10^{-3} or about 20 days with a storage coefficient of 1.2×10^{-4}.
4. Well hydrographs that show a flattening of water levels in August to early September 1989 in most recorder wells.
5. The small range of fluctuation for the past 10 years for September water levels in the surficial, intermediate, and Upper Floridan aquifers.

In summary, it seems likely that steady-state conditions are reached in a relatively short time (few months), and that there was adequate time from May to September 1989 for this to occur.

Calibration Procedure and Results

The calibration of a numerical model of ground-water flow is a subjective process because the data upon which a model is based usually contain some errors of measurement, the model may be based on possible conceptual errors, and the results of the model calibration may not be a unique solution to the ground-water flow equations. Calibration of the digital flow model for this study involved adjusting hydrologic properties within reasonable ranges until the model closely approximated observed field conditions (aquifer heads and river discharge) within acceptable limits of error. Success of the calibration was evaluated through comparisons between the simulated and measured heads at selected observation wells and lakes, and simulated and measured river discharge.

The calibration procedure began by comparing the model output to observed field conditions to determine the reasonableness of the hydrologic properties. The model was tested to determine its sensitivity to changes in hydrologic properties and input data were varied to achieve a better fit to known conditions. Adjustments were made to least known and most sensitive model parameters.

The steady-state model was calibrated by adjusting altitudes of the water table and of the base of the surficial aquifer, streambed conductances, intermediate and Upper Floridan aquifer transmissivities, leakance of the confining units, and net recharge and discharge rates.

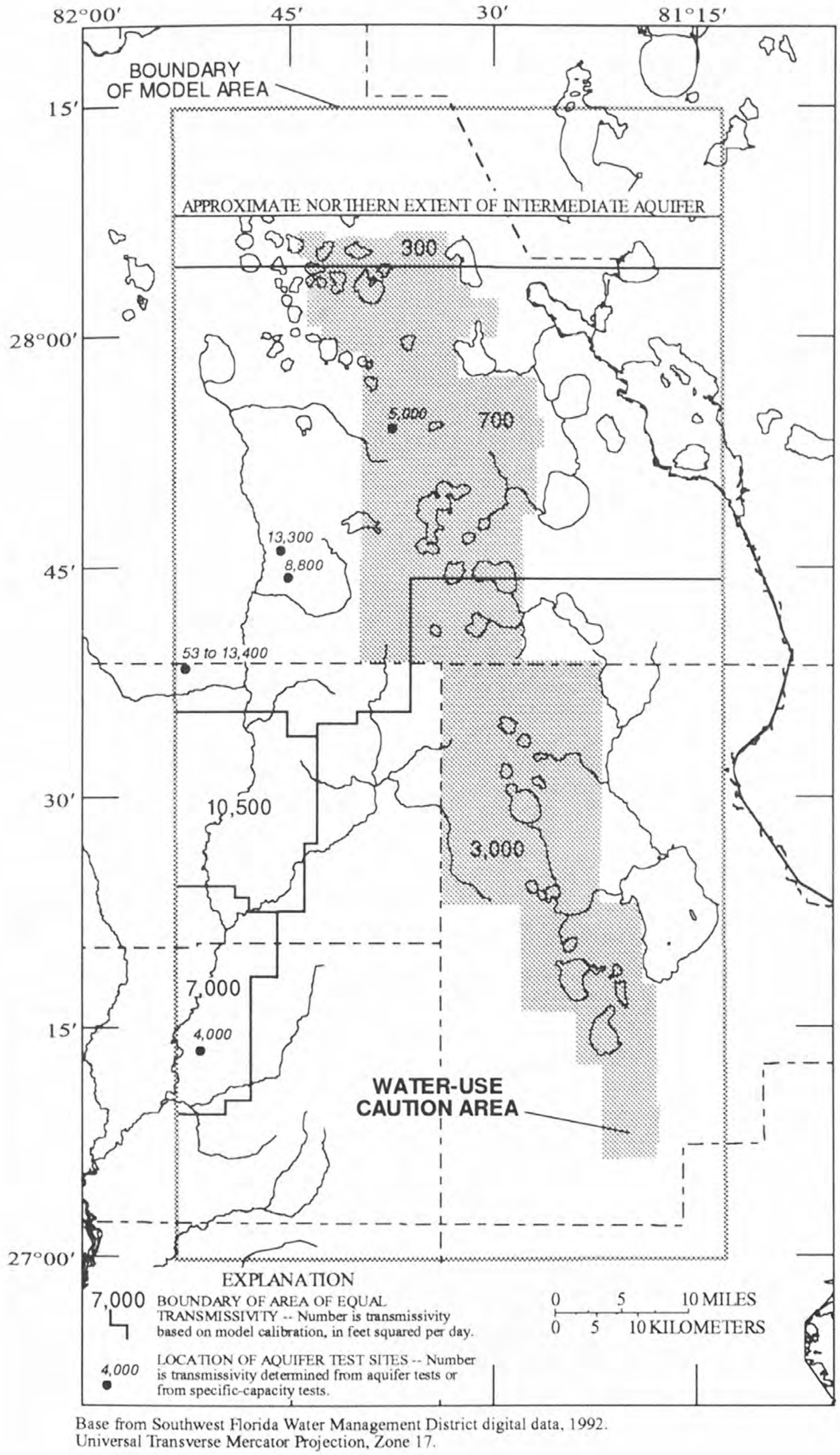


Figure 22. Calibrated transmissivity array of the intermediate aquifer and locations of selected aquifer test sites.

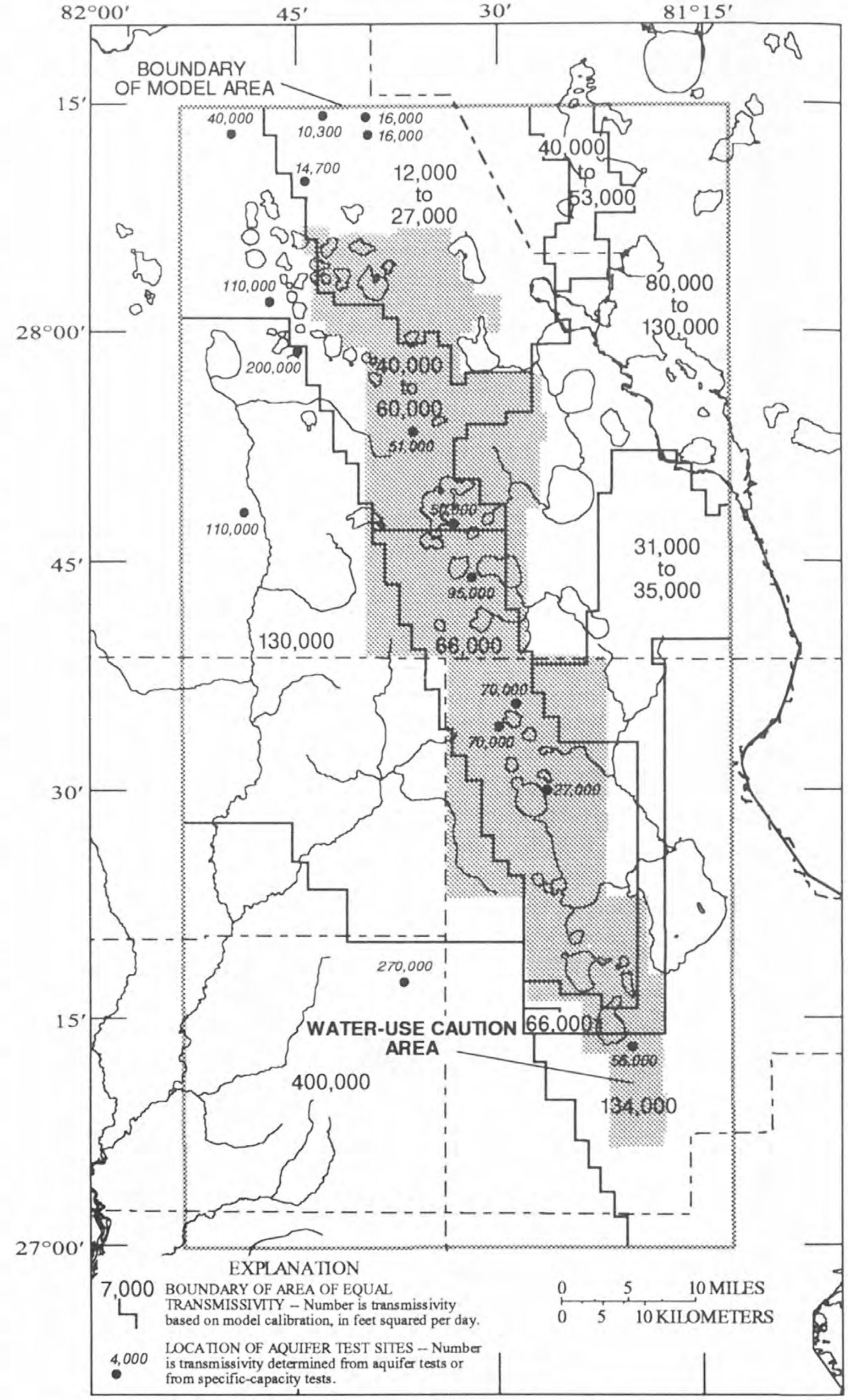
Calibration was done in three phases. In the first phase, the water table in the surficial aquifer and boundary heads in the intermediate and Upper Floridan aquifers were held constant (the head was assumed correct), while one set of hydraulic values was adjusted at a time. Recharge to the surficial aquifer, considered to be derived from rainfall, was equal to the model-computed leakage rate across the upper confining unit. In the second phase, the water-table was activated and net recharge/discharge array (determined in phase one), river simulation cells, and GHB cells were added to the model simulation. Repeated adjustments were made to each of the sets of data during the first and second phases. The third and final phase of the steady-state calibration was done while simulating the 12-month transient period from October 1989 through September 1990 (discussed in the next section). Adjustments to leakance values of the upper confining unit and the bottom altitudes of the surficial aquifer were made.

Water-table altitudes were not varied much from the initial values derived from observed and estimated data. In the calibrated model, water-table altitudes were checked to ensure they were below land surface and they agreed with observed stream stages and lake levels. The base of the surficial aquifer was lowered slightly in select grid blocks to prevent the cells from dewatering. Riverbed conductance values were adjusted to provide a reasonable match between simulated and measured river discharges.

Transmissivity values for the intermediate and Upper Floridan aquifers (figs. 22 and 23) were not varied significantly from the initial values specified in RASA models. Changes in values of transmissivity generally did not affect the model as much as leakance; however, changes in transmissivity were effective in achieving a more accurate simulation of localized variation in the potentiometric surface. Simulation indicates that transmissivity is high throughout most of the model area with the exception of the Lake Wales Ridge area (figure 23). Transmissivities in the Lake Wales Ridge area are influenced by the presence of sand-filled solution features associated with cavities and sinks developed in the limestone units of the Upper Floridan aquifer.

The transmissivity of the Upper Floridan aquifer varies throughout the model area. A comparison of field values of transmissivity derived from aquifer tests and transmissivity values obtained in the model development and calibration is shown in figure 23. The average model derived transmissivity values for the Upper Floridan is about 130,000 ft^2/d and ranges from 12,000 to 400,000 ft^2/d. Transmissivity is highest west and southeast of the Lake Wales Ridge and is lowest in the north. Generally, the model-derived transmissivities are higher than those obtained from aquifer tests. This is mainly because the wells used in the aquifer tests generally tap less than the full thickness of the Upper Floridan aquifer. Such partial penetration plus the highly heterogeneous and anisotropic nature of the cavernous limestone aquifer system make the application of standard methods of aquifer test analysis uncertain and the results questionable (Tibbals, 1990).

The relation between transmissivity of the Upper



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 23. Calibrated transmissivity array of the Upper Floridan aquifer and locations of selected aquifer test sites.

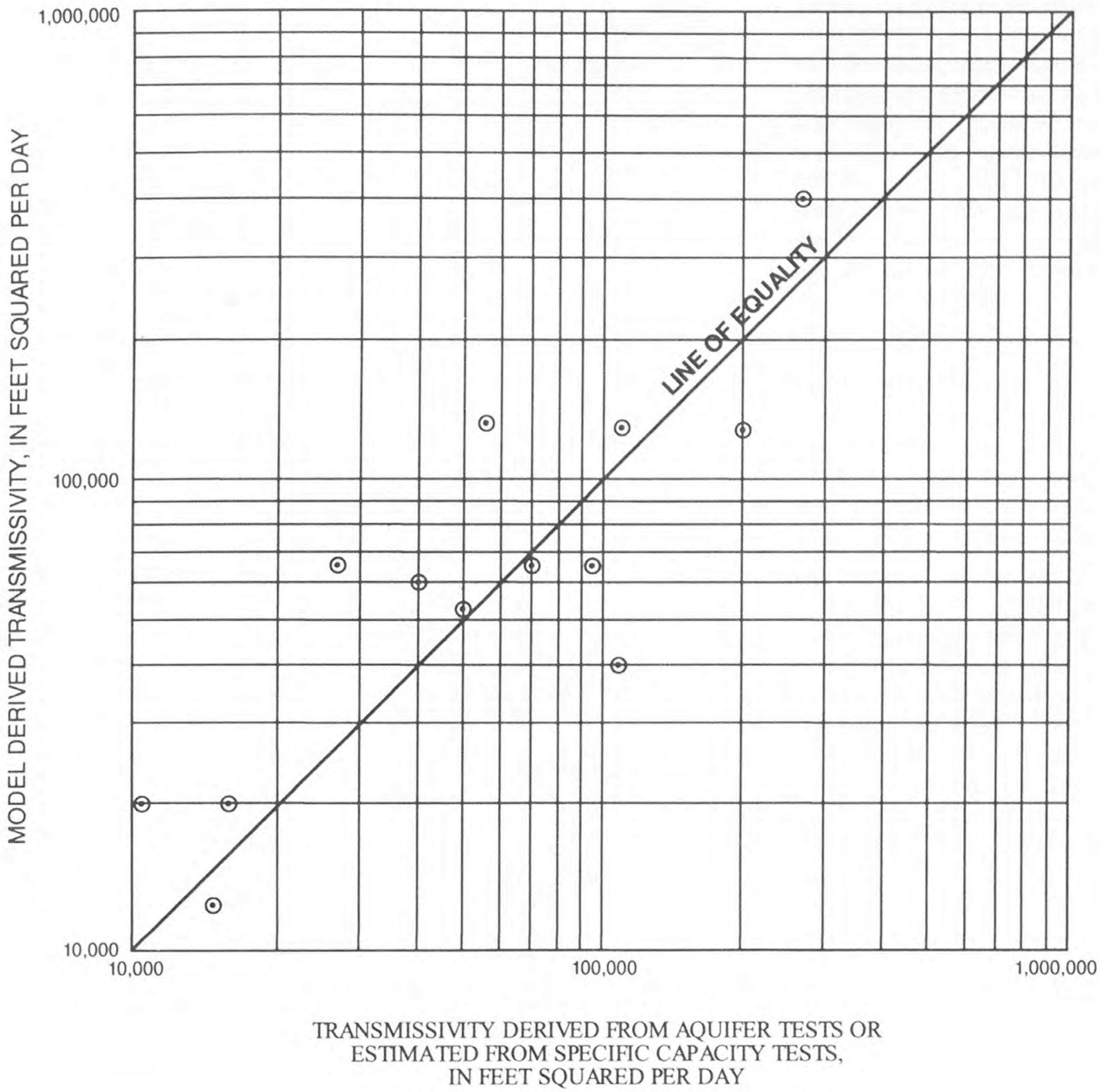


Figure 24. Relation between calibrated transmissivity values and corresponding values calculated from aquifer tests or specific capacity tests.

Floridan aquifer, based on model simulations and transmissivity of the Upper Floridan aquifer derived from aquifer tests or estimated from specific capacity data, is shown in figure 24. Transmissivity values from aquifer tests and from specific capacity tests plot reasonably close to the line of equality. The average of transmissivities derived from aquifer tests and of those derived from model simulations are different by about 31,000 ft^2/d. The standard deviation of differences is about 38,000 ft^2/d. Some scatter is expected because a model-derived value represents an average transmissivity over 1 mi^2 in the model simulation, whereas transmissivity determined from an aquifer test or estimated from specific capacity data is a point value that represents the aquifer in a smaller area. Generally, the aquifer test values for transmissivity of the Upper Floridan aquifer are within ranges of values determined by computer simulation.

Confining-unit leakance of both units were considered the most uncertain parameters and were adjusted the most. A check was conducted after each confining-unit leakance adjustment to ensure values were not unrealistic and that simulated leakage rates were in general agreement with estimated values of net recharge and discharge. Confining-unit leakance of both units, in general, were increased during the calibration process. Leakance values of the upper and lower confining units range from 1.0 x 10^{-6} to 1.0 x 10^{-3} (ft/d)ft (figs. 25 and 26). The highest values occur in areas where aquifer recharge are highest and where confining beds are relatively thin or permeable. The lowest confining-unit leakance occurs along the flanks of the ridge where karst features are less numerous, where recharge rates are low, and where confining units are relatively thick or have low permeability.

Finally, net recharge and discharge rates were adjusted to produce a more accurate simulation of the localized variation in the water table and base flow to streams. Figure 27 shows the final areal distribution of net recharge to and net discharge from the surficial aquifer. Simulation indicates that the distribution of recharge to the surficial aquifer is not uniform over the study area and is highest in areas of higher altitude. Recharge rates are highest on the Lake Wales Ridge and adjacent ridge areas. Throughout this area, the land surface altitude is mostly greater than 100 feet. The ridges, which are karst areas, have little or no surface drainage and thus most of the water that enters the surficial aquifer moves quickly downward, recharging the intermediate or Upper Floridan aquifers. By contrast, in the areas of relatively low land-surface altitude, such as the De Soto Plain, Osceola Plain, and along the river valleys, low or rejected recharge to the surficial aquifer occurs because the unsaturated surficial sediments are thin and

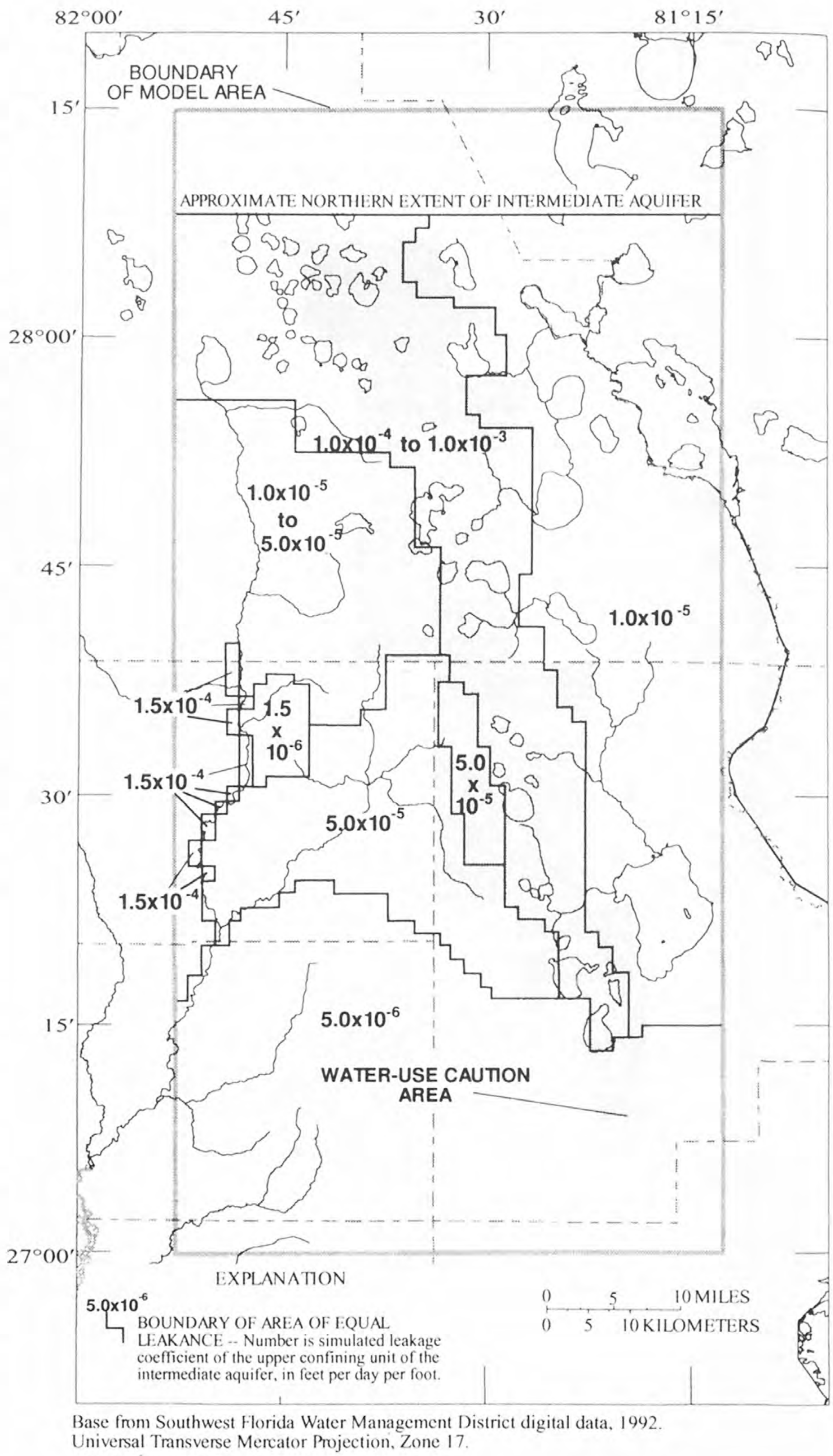
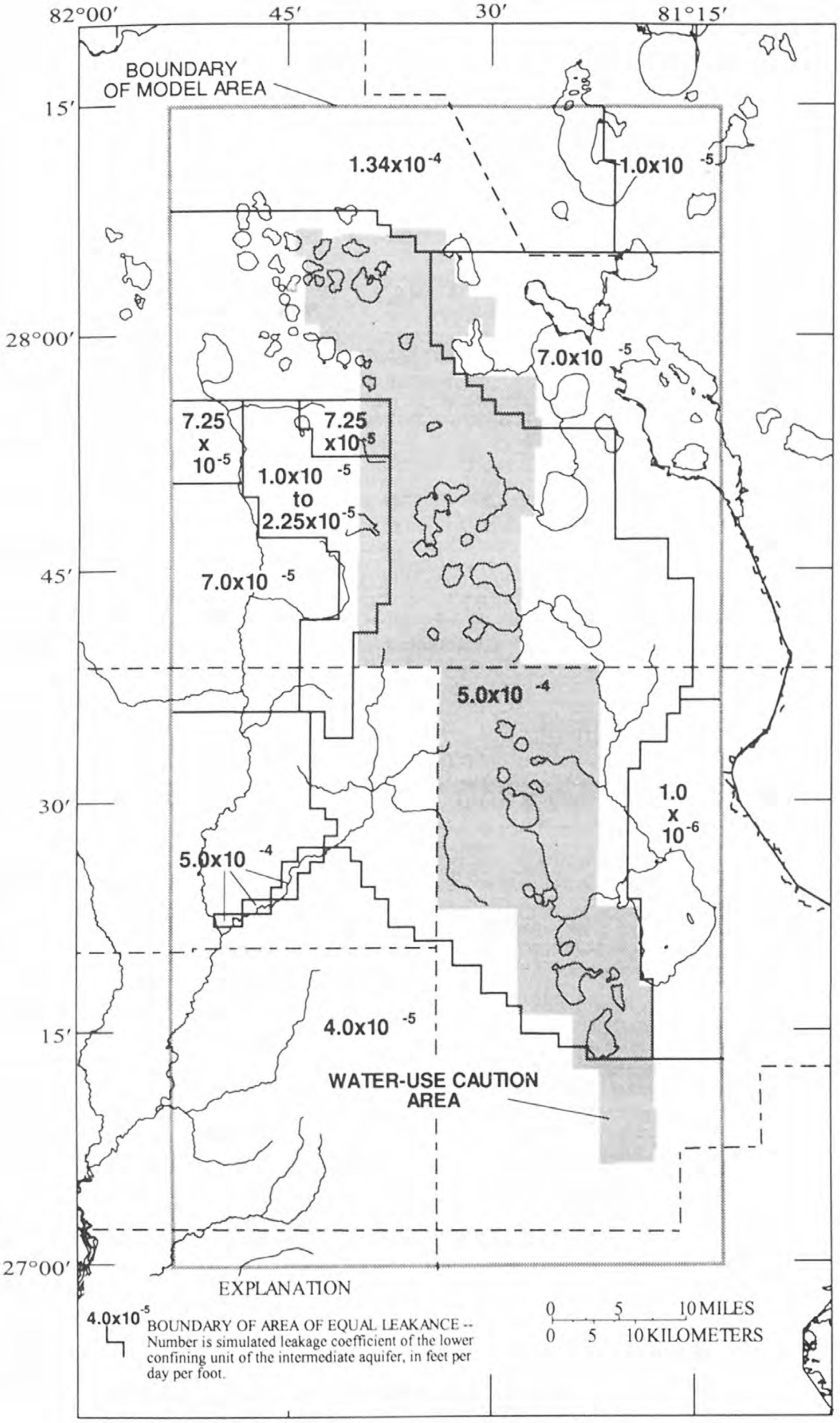


Figure 25. Calibrated leakance array of the upper confining unit of the intermediate aquifer.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 26. Calibrated leakance array of the lower confining unit of the intermediate aquifer.

the sediments between the surficial aquifer and underlying confined aquifers are thick and have low permeability.

An important part of the modeling involved the relation between hydraulic conductivity in the surficial aquifer and net recharge rates to the surficial aquifer in the Lake Wales-Polk Upland area and adjacent stream valley areas. In the high upland relief areas, hydraulic conductivity values of more than 8 ft/d required the specification of unacceptably high net recharge rates to obtain a relatively good head match. A better head match was obtained using a hydraulic conductivity of 1 ft/d, however, 8 ft/d was chosen because it is in keeping with the generally accepted values of hydraulic conductivity in the area. In areas adjacent to streams, hydraulic conductivities of less than 8 ft/d required unacceptably low recharge values to obtain a relatively good head and stream flow match. A better stream flow match was obtained using hydraulic conductivities greater than 8 ft/d.

Model performance was evaluated both objectively and subjectively. A statistical analysis between simulated and measured head values and simulated and head values interpolated from water-level-surface maps were used for the objective analysis. Inspection of the distribution of errors of head, flow distribution, and flux quantity was used to subjectively analyze model performance.

Calibration of the model was considered to be achieved when, on the average:

1. Simulated heads were within 2 feet of measured well or lake-level heads for the surficial aquifer, and within 5 feet

of measured well heads for the intermediate and Upper Floridan aquifers.

2. Simulated heads were within 5 feet of interpolated heads described by the water-table contour map, and within 10 feet of heads interpolated from potentiometric-surface maps of the intermediate and Upper Floridan aquifers.

Assuming the head difference is a normal distribution function, then the described calibration criteria would ensure that 68 percent of the simulated heads would be within 2 feet of the measured heads described for the surficial aquifer and within 5 feet of the measured heads described for the intermediate and Upper Floridan aquifer.

Although flux distribution within a particular source (river, underlying aquifers, or from confining units) was evaluated during calibration, this subjective criteria was mainly used to spot gross input errors. The quantity of flux from rivers was used only as a qualitative check on the plausibility of results.

Maps showing points where water levels were measured at individual wells or lakes and the distribution of water-level residuals (observed minus simulated heads) over the model area are shown in figures 28, 29, and 30. A statistical summary of the difference between observed and simulated heads is presented in table 3. The difference between the observed and the simulated heads for each observation are called residuals. A negative residual indicates that the simulated head is higher than the observed head, and a positive residual indicates that the simulated head is lower than the observed head. The residuals were analyzed for 50 observations of the surficial aquifer,

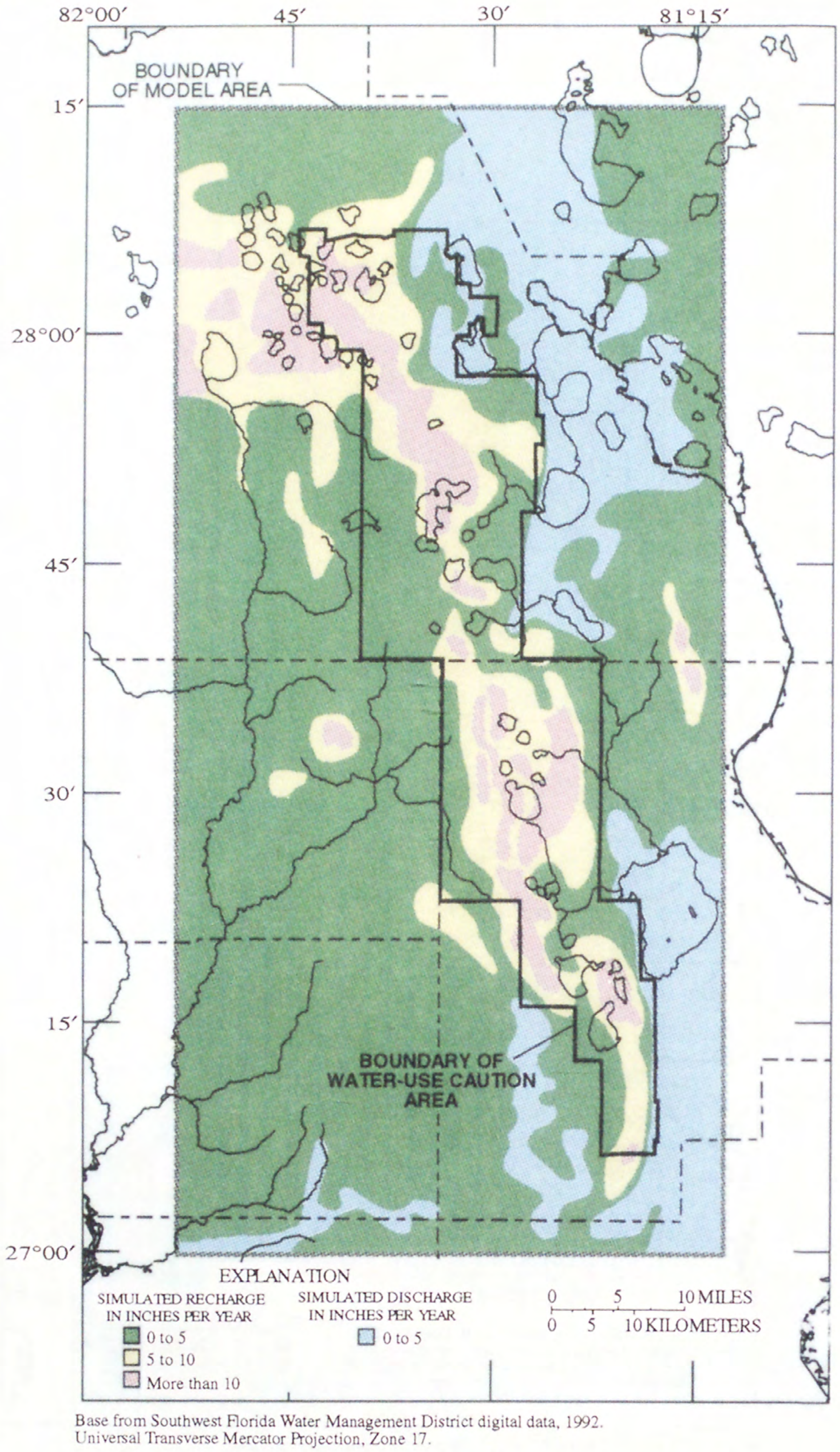
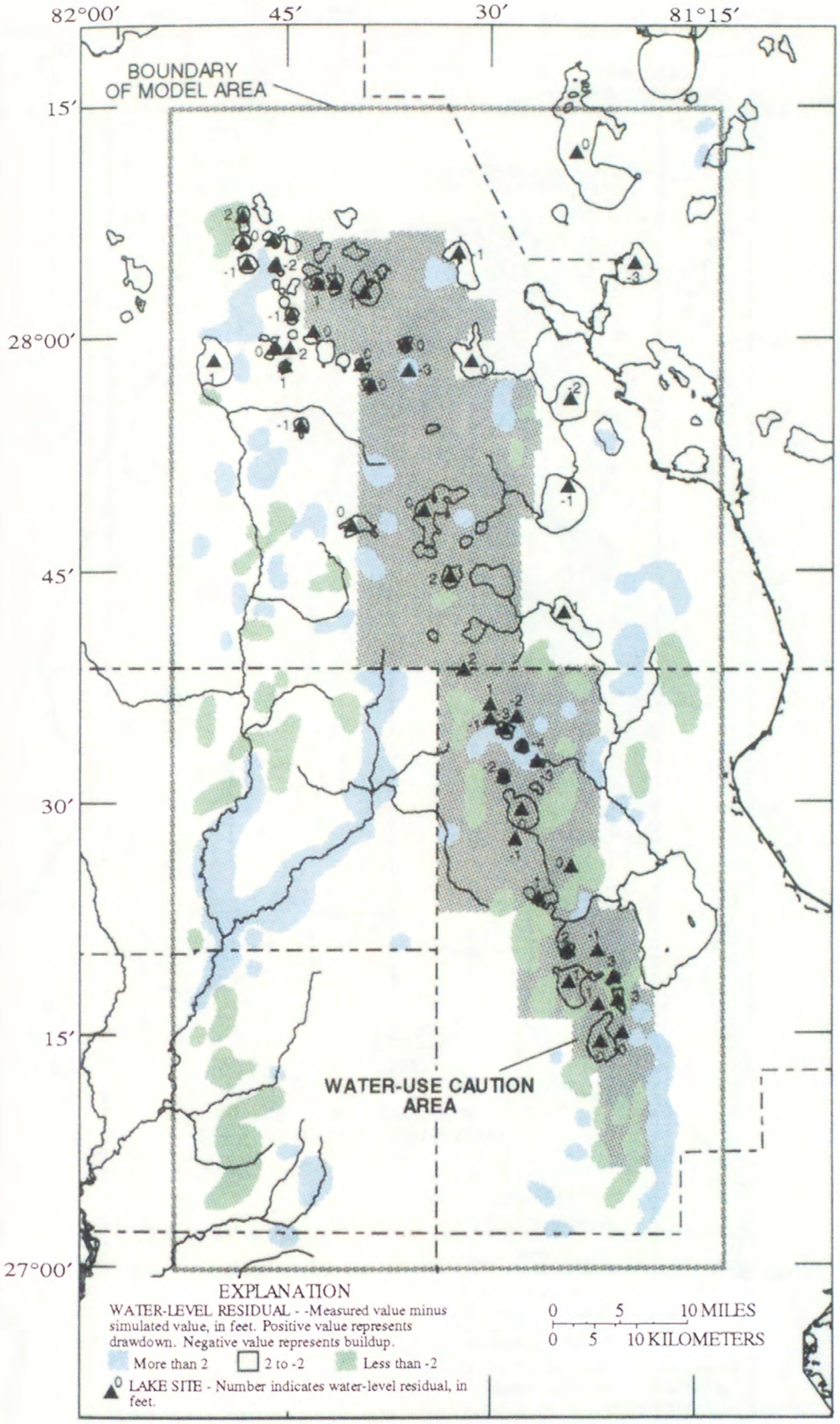


Figure 27. Simulated rates of net recharge to and net discharge from the surficial aquifer, September 1989.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

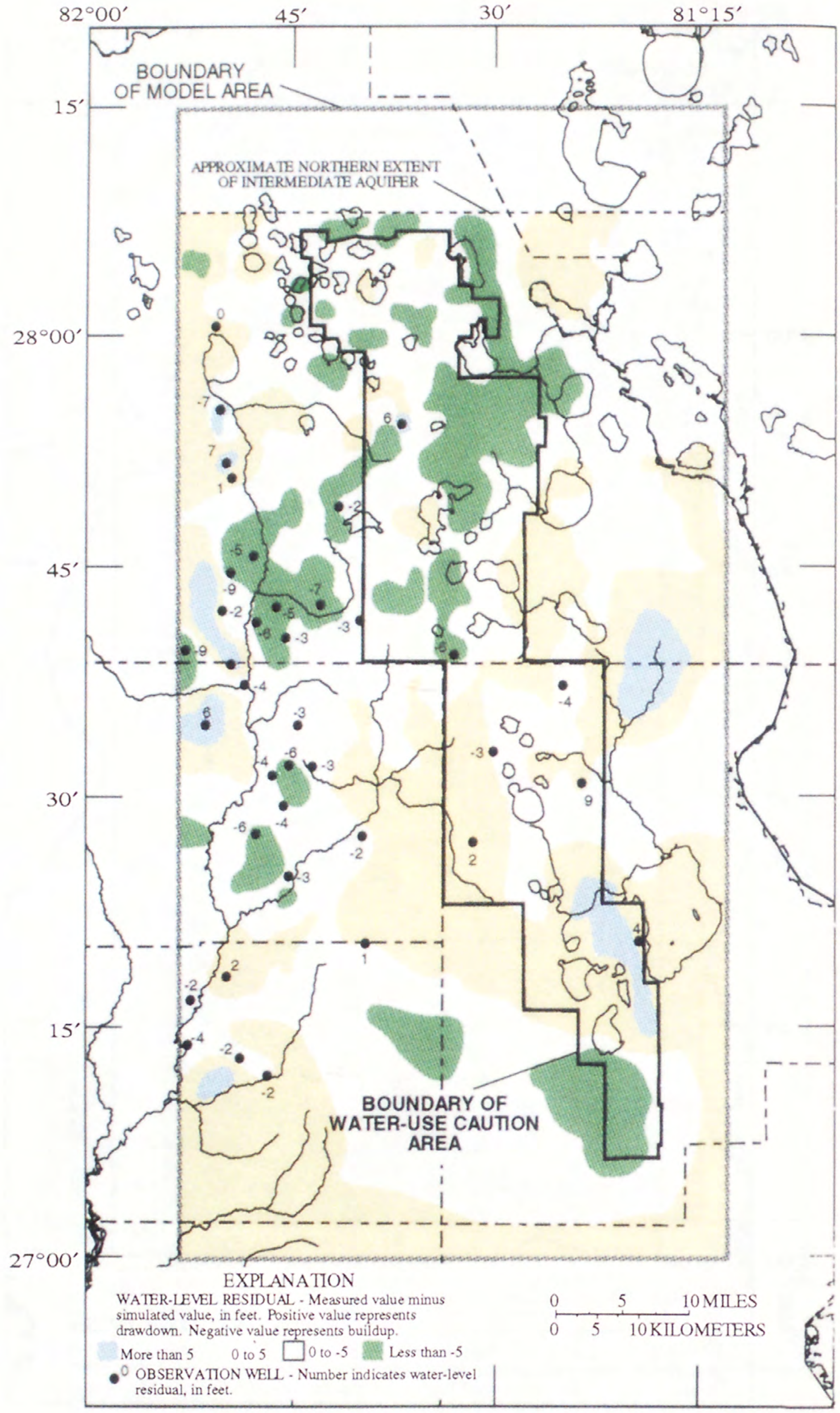
Figure 28. Locations of water-level measurements, values of water-level residuals, and areal distribution of water-level residuals for the surficial aquifer, September 1989.

39 observations for the intermediate aquifer, and 72 observations for the Upper Floridan aquifer. In cases where lakes occupy more than one cell, the simulated head was an arithmetic average for all the cells representing the lakes. Based on the observations in September 1989, the standard deviation about the 0.0 mean of the residuals for the surficial aquifer was 1.6 feet. This indicates that the model-simulated heads for the surficial aquifer match the observed heads within a range of 1.6 feet above to 1.6 feet below at about 68 percent of the observations.

Similarly, the model-simulated heads for the intermediate aquifer matched the observed heads at about 68 percent of the observations within a range of 6.3 feet above to 2.9 feet below, based on a standard deviation of 4.6 feet about a residual mean of -1.7 feet. The model-simulated heads for the Upper Floridan aquifer matched the observed heads at 68 percent of the observations within a range of 3.6 feet above to 1.2 feet below, based on a standard deviation of 2.4 feet, about a residual mean of -1.2 feet. This was within the assumed calibration limits, which required 68 percent of all simulated heads to be within ±5 feet of heads derived from measured water levels. The high correlation coefficients indicate a strong positive association between observed and model-simulated heads in each aquifer (table 3).

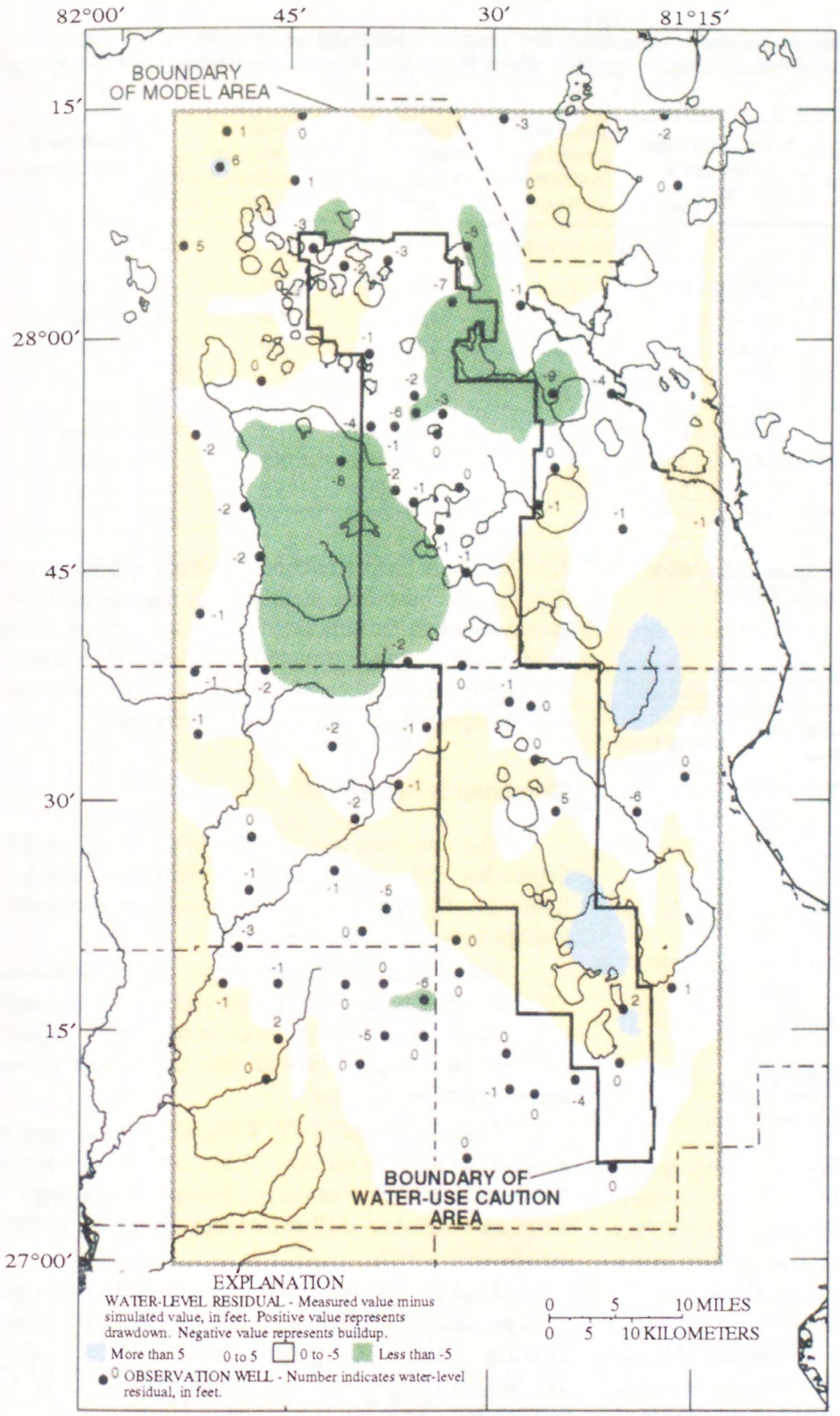
The results of the model calibration also were assessed by comparing the magnitude and distribution of residuals for all 10,000 variable head cells (table 3). Areas where the intermediate aquifer is absent, (rows 1 -41 and columns 1-8), simulation residuals were not used in the statistical analysis. The average simulation residual and the standard deviation of the residual were computed to be -0.2 and 1.7 feet, respectively for the surficial aquifer, -1.1 and 3.2 feet, respectively for the intermediate aquifer, and -1.1 and 3.2 feet, respectively for the Upper Floridan aquifer. These residuals were within the established calibration criteria that require 68 percent of all simulated heads to be within ±5 feet of surficial aquifer heads and ±10 feet of the intermediate and Upper Floridan heads derived from water-level surface contour maps.

The distribution of water-level residuals over the model area is shown in figures 28, 29, and 30. Figure 28 shows that the distribution of signs and magnitude of values were nearly random for the surficial aquifer. Most of the larger differences between the observed and simulated heads occur in areas with large differences in head between the surficial and intermediate aquifers. For the intermediate and Upper Floridan aquifers, figures 29 and 30 generally show several areas with consistently high positive or negative residuals. These areas roughly correspond to the Polk Uplands, the Bombing Range Ridge, and a northern and southern portion of the Lake Wales Ridge. The difficulty in obtaining a good match between simulated and measured heads is due in part to major changes in aquifer properties over short distances. This precludes simulation of small-scale local variations in head, especially where head gradients are steep. Reasonable changes to hydrologic parameters were unable to affect the residuals so that they would be randomly distributed.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 29. Locations of water-level measurements, values of water-level residuals, and areal distribution of water-level residuals for the intermediate aquifer, September 1989.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 30. Locations of water-level measurements, values of water-level residuals, and areal distribution of water-level residuals for the Upper Floridan aquifer, September 1989.

The flow model also was used to simulate ground-water discharge to streams. Ground-water discharge to streams was simulated as about 67 ft^3/s for the September 1989 conditions (table 4). Base runoff, determined by the streams' 90 percent flow duration, was estimated as about 204 ft^3/s. The simulated discharge compares poorly with the estimated discharge. This discrepancy could be due to factors that are unrepresentative of the basin affecting the base flows. For instance, the discharge of Peace River is inflated due to large volumes of treated domestic and industrial discharge that originates as ground water pumped from the Upper Floridan aquifer. About 85 facilities have permits from the Department of Environmental Regulations to discharge domestic and industrial effluent to the Peace River and its tributaries (Hammett, 1990). The combined design capacity for all domestic discharges is about 200 Mgal/d (30.9 ft^3/s) and discharges of 10 to 15 Mgal/d at a single plant are quite common (Hammett, 1990). The number and magnitude of discharges represent a potentially significant augmentation of river flow.

Similarly, the discharge of several other streams in the modeled area also may not represent natural conditions. Joshua, Prairie, and Hawthorn Creeks carry water that originates from flowing wells, while discharge for several streams in the Kissimmee River Basin has been affected by flow control structures.

Table 3. Statistical summary of differences between model-computed heads and observed water levels for the surficial aquifer, intermediate aquifer, and Upper Floridan aquifer in the Lake Wales Ridge area, Florida, September 1989 steady-state conditions

	Number of observations	Maximum range in residuals (feet)	Arithmetic mean of residuals (feet)	Absolute mean of residuals (feet)	Standard deviation of residuals (feet)	Coefficient of determination
			Individual wells			
Surficial aquifer	50	-3.0 to 3.6	0.0	1.3	1.6	0.9966
Intermediate aquifer	39	-9.4 to 8.9	-1.7	4.2	4.6	0.9512
Upper Floridan aquifer	72	-9.4 to 5.7	-1.2	1.7	2.4	0.9901
			Entire grid			
Surficial aquifer	3,276	-8.0 to 7.4	-0.2	1.2	1.7	0.9969
Intermediate aquifer	3,198	-12.7 to 13.4	-1.1	2.4	3.2	0.9766
Upper Floridan aquifer	3,526	-12.2 to 12.2	-1.1	2.3	3.2	0.9768

Table 4. Observed verses model-computed steady-state base flows for the Lake Wales Ridge area, Florida, September 1989

[values are in cubic feet per second]

Gaging station name	Estimated 1990 water-year base flow	Net model-computed steady-state base flows
Peace River at Arcadia (row 41 column 71)	114.0	35.9
Joshua Creek at Nocatee (row 41 column 75)	11.1	4.0
Prarie Creek near Ft. Ogden (row 36 column 83)	12.2	2.7
Arbuckle Creek near De Soto City (row 30 column 61)	57.0	17.8
Josephine Creek near DeSoto City (row 36 column 55)	9.4	6.2
Total	203.7	66.6

The small calculated base flow also may be the result of the scale of the model. Winter (1976) investigated the interaction of lakes and ground water. In his study, the ground-water flow system was divided into a local flow system, an intermediate flow system, and a regional flow system. In the local flow system, recharge travels through the aquifer to be discharged into the adjacent lake; in the intermediate flow system, recharge travels to a nearby lake. If these results are applicable to this study, the base flow simulated in the model is only the intermediate or regional component of base flow. The estimated base flow contains the local and intermediate flow-system components as well as the regional flow components. The relative magnitude of each of these components are unknown. Hence, drawing conclusions about the differences between estimated base flow and the base flow simulated by the model is difficult, except that the simulated regional base flow should be less than the total estimated base flow. The degree of the difference between simulated and estimated base flow is dependent on the scale of the model.

Simulated Water Budget

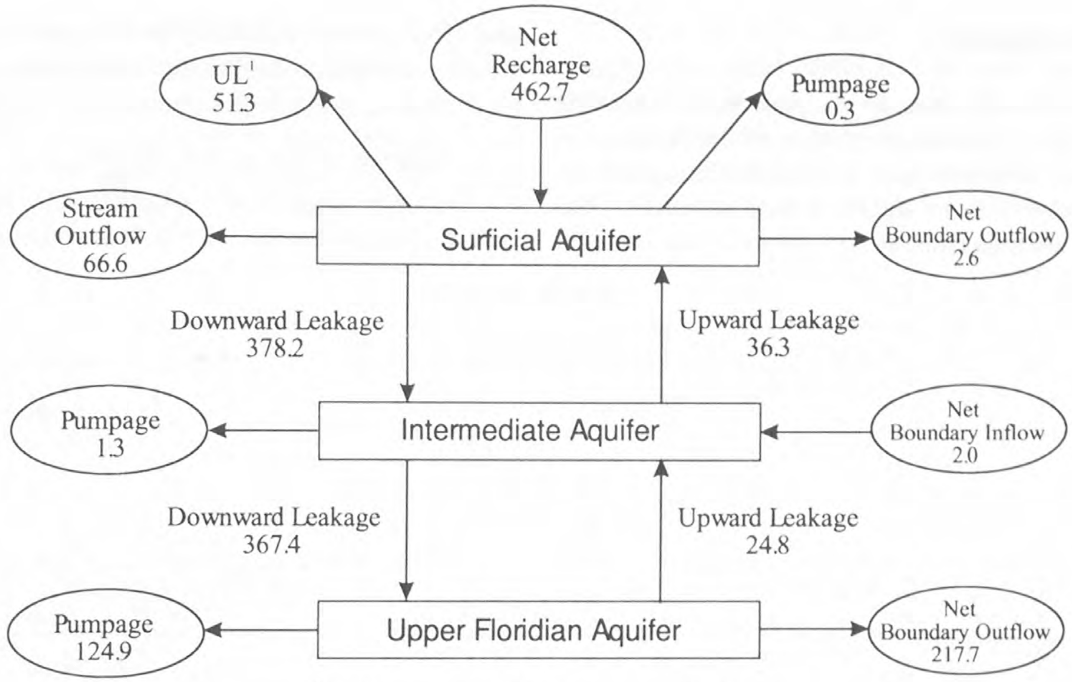
The simulated water budget of the model area for September 1989 steady-state conditions is shown in figure 31. The water budget also includes the rates of leakage between adjacent aquifers.

Model results indicate that under September 1989 steady-state conditions, net recharge to the surficial aquifer from rainfall was about 462.7 Mgal/d. Another 16.1 Mgal/d flowed into the aquifer system across lateral boundaries.

The total inflow of 478.8 Mgal/d was balanced by an equal quantity of outflow. This outflow consisted of flow across model boundaries, pumpage, discharge to rivers, and upward diffuse seepage from the surficial aquifer to wetlands.

Total discharge across model boundaries is simulated as about 234 Mgal/d. Discharge from the Upper Floridan aquifer by lateral boundaries is about 223 Mgal/d (47 percent) and occurs chiefly along the western boundary.

About 126 Mgal/d (26 percent) of ground-water discharge was pumpage from the surficial, intermediate, and Upper Floridan aquifers. The model simulated about 67 Mgal/d (14 percent) ground-water contributions to rivers and about 51 Mgal/d (11 percent) diffuse upward seepage to wetlands.



[1] Diffuse upward leakage to wetlands

	Inflow	Outflow
Net Recharge	462.7	
Net Discharge		51.3
Boundary Flow		
Surficial Aquifer	2.1	4.7
Intermediate Aquifer	6.5	4.5
Upper Floridian Aquifer	7.5	225.2
Streams		66.6
Pumpage		126.5
Totals	478.8	478.8

(All values are in million gallons per day)

Figure 31. Simulated water budget of the aquifer system in the model area, September 1989.

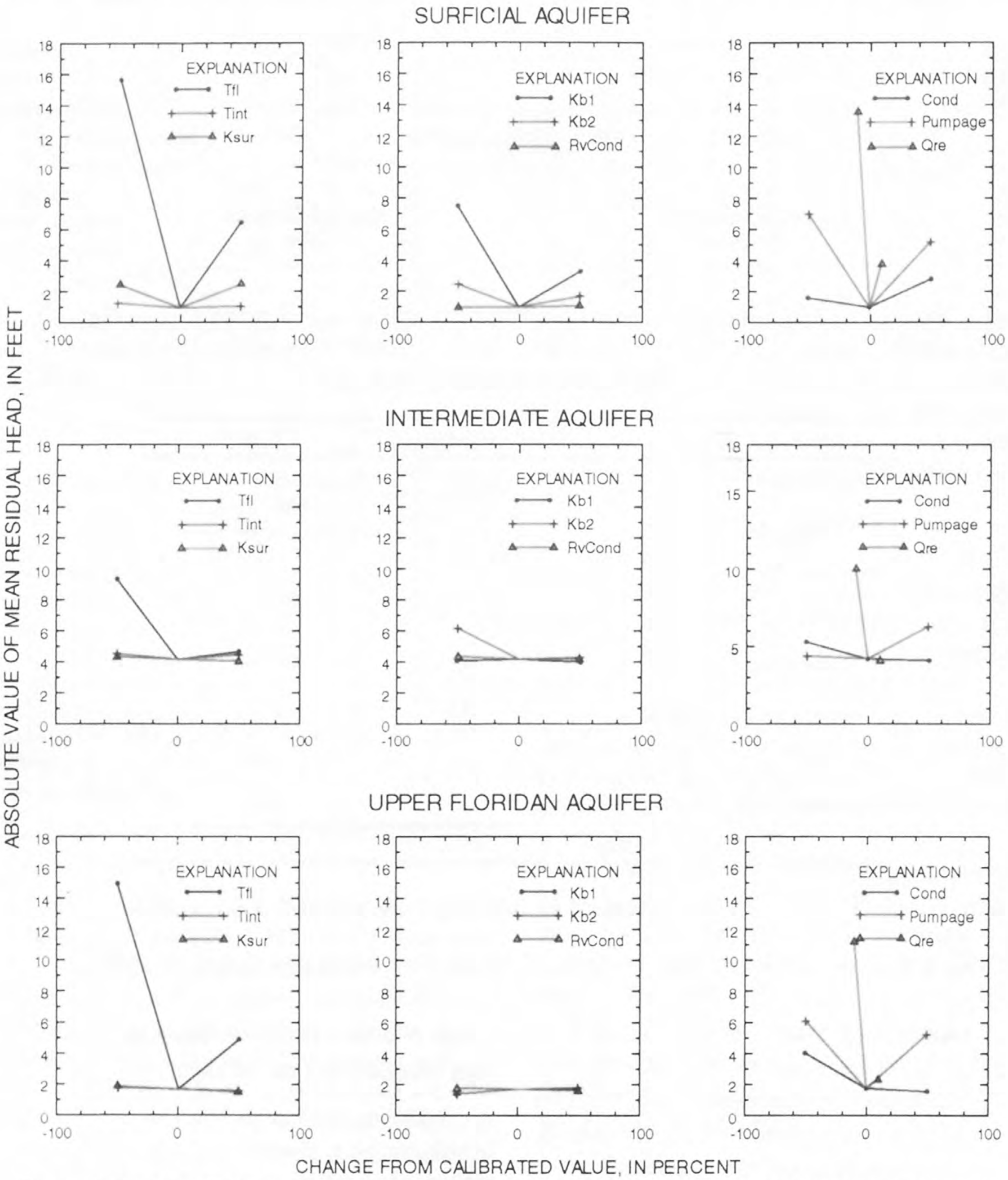
Downward leakage was a major component of the water budget of the intermediate and Upper Floridan aquifers. Leakage into the intermediate aquifer from the surficial aquifer was simulated at about 378 Mgal/d. The amount of downward leakage (representing the amount of natural recharge within the model area) is equivalent to about 2.3 in/yr of water over the model area. This recharge rate is comparable with those determined in other studies (Geraghty and Miller, 1980 and Wilson and Gerhart, 1980). Downward leakage into the Upper Floridan from the intermediate aquifer system was simulated at a rate of about 367 Mgal/d.

During September 1989, leakage across the upper confining unit is simulated predominately downward in ridge and upland areas, and upward in the lowlying lands paralleling east of the Lake Wales Ridge area, as well as upward along the lowlands of the Peace River and Charlie Creek. Upward flow areas also include most of the southwestern corner of the model area.

Sensitivity Analysis

A sensitivity analysis was performed to evaluate the response of the steady-state model to a range of hydrologic parameters and to identify the hydrologic variables to which the model is most sensitive. The sensitivity analysis consisted of uniformly increasing or decreasing values of one model input parameter while others remained at calibration levels, then noting the change in water levels as a result of the change.

Transmissivity of the intermediate and Upper Floridan aquifers, hydraulic conductivity of the surficial aquifer, vertical conductivity of the confining units, net



Tfl=transmissivity of Upper Floridan aquifer
Tint=transmissivity of intermediate aquifer
Ksur=hydraulic conductivity of surficial aquifer

Kb1=vertical hydraulic conductivity of upper confining unit
Kb2=vertical hydraulic conductivity of lower confining unit
RvCond=hydraulic conductivity of riverbed

Cond=horizontal boundary conductance
Qre=net recharge/discharge

Figure 32. Sensitivity of calibrated steady-state model to variations in various input parameters on the absolute value of mean residual head for the surficial, intermediate, and Upper Floridan aquifers.

recharge/discharge rates, pumpage, and riverbed and lateral boundary conductances were increased and decreased by 50 percent, with the exception of net recharge/discharge rates, which was increased and decreased by 10 percent. Parameter changes were applied uniformly across the entire model area.

The results of the sensitivity analysis for the steady-state period model are shown in figures 32 and 33. The effect of the change in the parameter or stress was measured through the change in absolute value of the mean residual head or as a change in the total base flow for rivers, or as a change in lateral boundary flow.

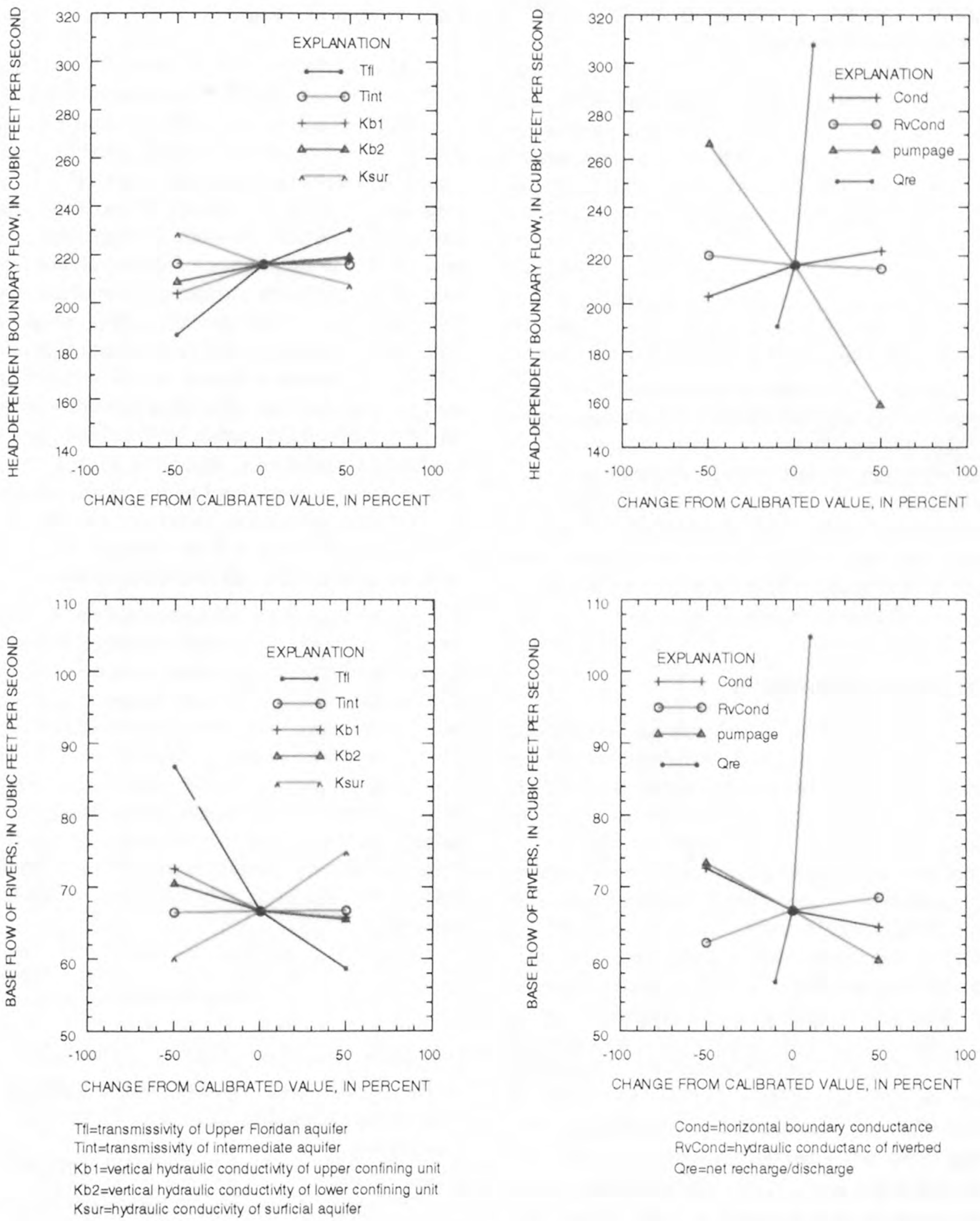


Figure 33. Sensitivity of calibrated steady-state model to variations in various input parameters on base flow and lateral boundary flow.

The sensitivity analysis showed that simulated heads are generally more sensitive to decreases in parameter values than to increases in the tested values. The model calibration is very sensitive to changes in transmissivity of the Upper Floridan aquifer, net recharge/discharge, and pumpage. The model calibration is comparatively insensitive to changes in transmissivity of the intermediate aquifer, hydraulic conductivity of the surficial aquifer, and river-bed conductances.

The sensitivity of the simulated base flow to rivers and of the simulated flow to lateral head-dependent boundaries to variations in various input parameters also was tested. Simulated base flows were most sensitive to changes in net recharge/discharge and transmissivity of the Upper Floridan aquifer, particularly, higher values of net recharge/discharge. Simulated flow to lateral head-dependent flow boundaries was most sensitive to changes in net recharge/discharge and pumpage. The model is very insensitive to changes in transmissivities of the intermediate aquifer and riverbed conductance.

In addition to the above mentioned hydrologic parameters, specified source heads for hydrologic units outside the model boundary were increased and decreased by 5 feet. In both cases, the model was relatively insensitive to these boundary changes. The largest absolute value of the mean residual was 2.5 feet in the surficial aquifer when the source heads were either increased or decreased. This compares to the mean residual of 1.0 ft at calibration.

Initial Transient Simulation

The objective of the simulation was to evaluate the ability of the model to simulate the transient effects of agricultural, municipal, and industrial pumpage on lake and ground-water levels. The time period simulated was October 1989 through 1990, a rather short period, but one in which the ground-water system experienced a significant stress from agricultural pumping. This time period was selected because detailed data were available on water levels and monthly water use. The 1989-90 flow conditions also were used as an independent check of the steady-state calibration resulting in some further adjustments to the input parameters of the model. The simulation was divided into 12 monthly stress periods. The heads simulated for May 1990 and September 1990 were compared to observed water levels for individual wells and lakes.

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 record of water levels. However, data on the spatial distribution of pumping are poor and long-term pumping records for irrigation are too sparse to consider this approach. Thus, the transient model was calibrated over a shorter-time period when the amounts and areal distribution of pumping are better known.

Calibration and Results

Initial conditions for the model were the same as for the calibrated steady-state model with the exception of storage characteristics of the aquifers, pumpage arrays, boundary source heads, stream heads, and monthly rates of recharge and potential ET. Average head values for stream stages in the simulation were assumed to remain constant through the simulation period. This assumption is valid over annual conditions because storage in the stream is minimal and water levels return to base flow quickly. Appropriate monthly variations in pumping rates, rates of recharge and potential ET and boundary source heads, were input to the model to accommodate changing conditions from October 1989 through September 1990 (tables 5 and 6). The equilibrium conditions simulated during the steady-state calibration were used as the initial conditions for this transient simulation, therefore, simulated changes were assumed to result from changes in model input, not from non-equilibrium initial conditions.

A change from the basic calibration model was the method used to calculate recharge to the surficial aquifer. Recharge to the water table was calculated for each month using a simple water-budget approach, rather than using the model-computed leakage rate derived in the steady-state simulation. The basis for estimating recharge over the model area were actual measurements of rainfall, pan evaporation, and surface runoff. An assumption is made that recharge is derived from rainfall and rainfall is areally uniform over the model area. Recharge was estimated by the following equation:

$$QRE = P - OF - ET \qquad (4)$$

where:

QRE is the rate of ground-water recharge, in inches per month;

P is the average rainfall, in inches per month;

OF is overland flow, in inches per month;

ET is minimum evapotranspiration, in inches per month.

Table 5. Monthly hydrologic data for the Lake Wales Ridge area, Florida, transient-model calibration periods

[ET, evapotranspiration]

Month	Rainfall (inches)	Surface runoff (inches)	Pan evapo-ration (inches)	Pan coefficient	Maximum[1] evapotrans-piration (inches)	Minimum evapotrans-piration (inches)	Potential[2] evapotranspiration from the water table (inches)	Recharge[3] (inches)
				Initial calibration period				
1989								
October	1.5	0.5	5.9	0.74	4.4	2.2	2.2	0.0
November	2.2	.0	4.5	.72	3.2	1.7	1.5	.5
December	3.9	.1	3.5	.70	2.5	1.3	1.2	2.5
1990								
January	.4	.1	4.2	.70	2.9	1.6	1.3	.0
February	3.4	.1	5.4	.77	4.2	1.8	2.4	1.5
March	1.7	.1	7.6	.72	5.5	2.3	3.2	.0
April	2.0	.1	8.0	.74	5.9	2.8	3.1	.0
May	3.0	.0	9.4	.72	6.8	4.0	2.8	.0
June	5.9	.2	8.8	.76	6.7	3.1	3.6	2.6
July	8.6	.3	7.6	.75	5.7	3.3	2.4	5.0
August	8.2	.7	8.4	.76	6.4	3.1	3.3	4.4
September	3.6	.1	7.5	.75	5.6	2.7	2.9	.7
Total	44.4	2.3	80.8		59.8	29.9	29.9	17.2
				Final calibration period				
1988								
October	1.2	.2	6.4	.74	4.8	2.4	2.4	.0
November	5.7	.3	4.3	.72	3.1	1.6	1.5	3.8
December	1.4	.2	3.6	.70	2.5	1.2	1.3	.0
1989								
January	2.9	.2	4.2	.70	2.9	1.4	1.5	1.3
February	.5	.1	5.1	.77	3.9	2.0	1.9	.0
March	2.4	.2	6.5	.72	4.7	2.4	2.3	.0
April	2.6	.1	8.0	.74	5.9	3.0	2.9	.0
May	1.5	.0	10.3	.72	7.4	3.7	3.7	.0
June	7.3	.1	8.4	.76	6.4	3.2	3.2	4.0
July	7.1	.3	8.8	.75	6.6	3.3	3.3	3.5
August	5.7	.6	8.5	.76	6.5	3.2	3.3	2.9
September	6.6	.6	7.0	.75	5.3	2.6	2.7	3.4
Total	44.9	2.9	81.1		60.0	30.0	30.0	18.9

[1]maximum ET = (monthly pan evaporation x pan coefficient)
[2]potential ET = (maximum ET - minimum ET)
[3]recharge = rainfall - (surface runoff + minimum ET)

Average monthly rainfall was determined from data recorded at 20 rainfall stations within the model area (Southwest Florida Water Management District, 1989; 1990). Overland runoff was determined for 10 stream-flow gaging stations by hydrograph separation techniques using a computer program developed by White and Sloto (1991). Minimum ET was estimated to be 30 in/yr and was adjusted on a monthly basis using pan evaporation coefficients developed for Lake Lucerne (Lee and Swancar, 1994).

Another change from the basic calibrated model was the calculation of ET from the water table. ET directly from the water table was simulated in the model using the position of the water table relative to land surface after each time step and a potential ET rate. The potential ET rate is estimated to be 30 in/yr

Table 6. Pumping rates used in the Lake Wales Ridge area, Florida, transient-model calibration periods

[values are in million gallons per day]

	Surficial aquifer	Intermediate aquifer	Upper Floridan aquifer	Total
		Initial calibration period		
1989				
October	5.6	12.8	388.2	406.8
November	16.7	17.1	457.8	491.6
December	13.0	19.7	485.5	518.2
1990				
January	8.2	9.6	281.3	299.1
February	6.3	7.8	247.6	261.7
March	13.3	14.1	388.2	415.6
April	11.3	15.7	393.5	420.5
May	17.6	14.7	454.1	486.4
June	8.2	10.9	275.3	294.4
July	6.0	6.4	217.7	230.1
August	6.0	6.1	232.6	244.7
September	.3	2.5	117.4	120.2
		Final calibration period		
1988				
October	18.5	17.1	535.6	571.2
November	9.1	11.0	353.1	373.2
December	17.9	16.6	530.4	564.9
1989				
January	11.8	16.3	386.7	414.8
February	17.6	26.9	594.7	639.2
March	13.1	17.4	436.1	466.6
April	16.1	23.1	564.0	603.2
May	18.0	29.9	666.5	714.4
June	14.1	13.3	459.3	486.7
July	10.5	6.5	267.8	284.9
August	7.6	10.2	349.3	367.1
September	.3	1.3	124.9	126.5

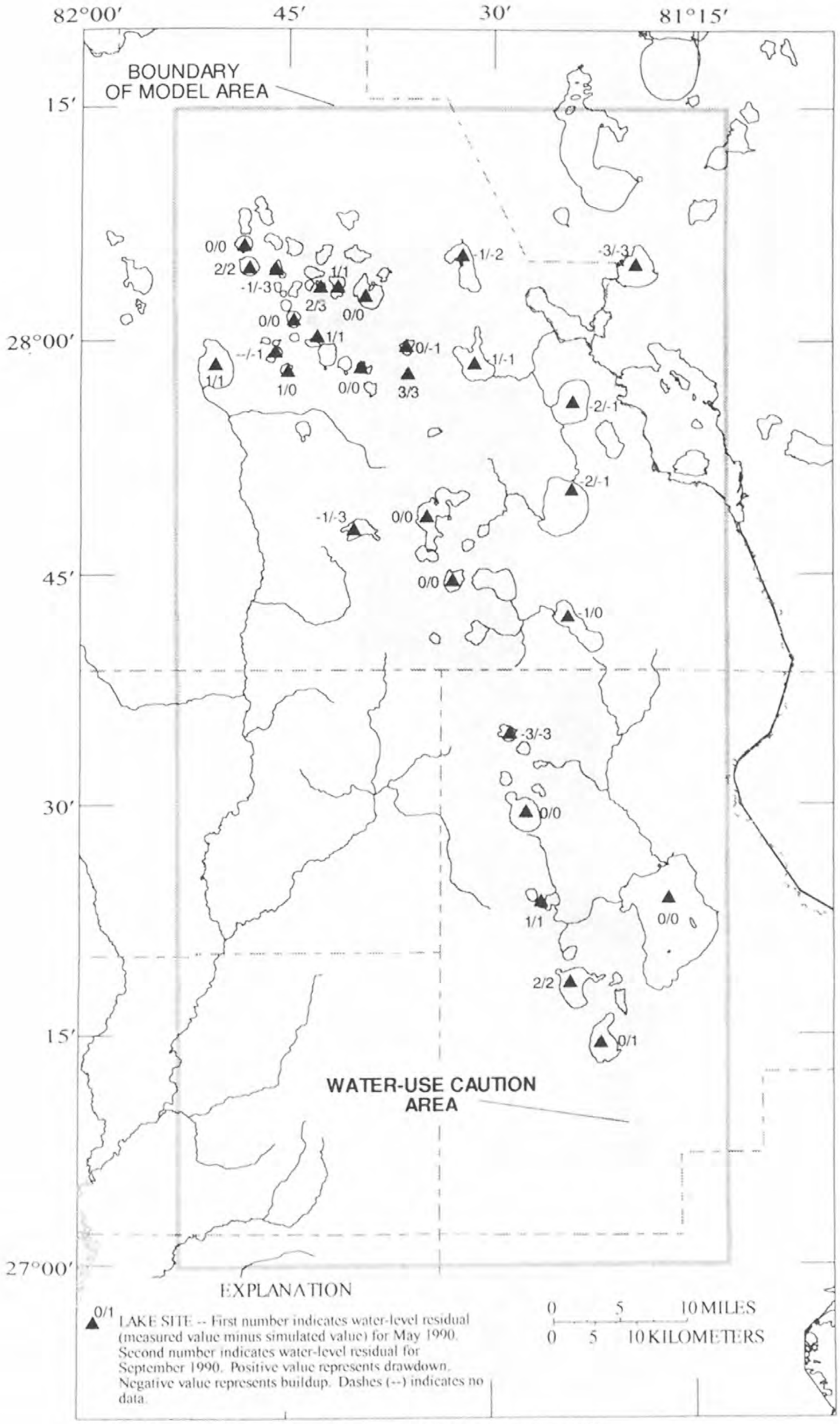
in areas where the water table is at land surface (such as a lake) and is assumed to decrease linearly to zero at a depth of 13 or more feet below land surface. The potential ET from the water table was determined from monthly pan evaporation measurements at Lake Alfred and modified according to monthly pan-evaporation coefficients developed for Lake Lucerne (Lee and Swancar, 1994). ET is from the water table and, thus, is only a component of the total ET found in standard hydrologic budget analysis. ET from plant surfaces, bare land, and the unsaturated zone are not handled directly in this model. The minimum ET rate (30 in/yr) could be added to the simulated rates to get an estimate of actual annual ET.

A value of 1.0×10^{-3} was used to represent storativity in the entire Upper Floridan aquifer. Storativity in the intermediate aquifer was represented by a constant value of 1.0×10^{-4}. These values are in agreement with the assumption that for most confined aquifers, the storage coefficient is about 1×10^{-6} per foot of aquifer thickness (Lohman, 1979). A specific yield value of 0.30 was used to simulate storage for the surficial aquifer where lakes are not present and a value of 1.0 was used to simulate storage for the surficial aquifer where lakes are present.

The general head boundaries of the steady-state model were modified in the transient model by changing boundary source heads to match observed water levels in the intermediate aquifer and in the Upper Floridan aquifer for the 1989-90 period. The source heads were varied 12 times (monthly) over the simulation period to match water-level trends observed at nearby wells. Initial source heads were interpolated from the September 1989 potentiometric maps of the intermediate aquifer (Knochenmus and Barr, 1990a) and the Upper Floridan aquifer (Knochenmus and Barr, 1990b).

As in the steady-state simulation, lakes were treated as "windows" in the surficial aquifer through which the water table can be observed. However, at lake cells, the storage coefficient was set to one and ET was set at the potential rate. Land surface was set well below the bottom of the lake to ensure calculation of maximum ET. It became obvious during early calibration of the transient-state model that the net ground-water flow to lakes was too small because simulated lake heads were too low. This error in computing lake heads is probably due to the inability of the model to simulate the local flow patterns around lakes. A large part of the ground-water inflow to lakes is from local flow with short flow paths that cannot be accurately represented with the 1 mi^2 grid size used in this model (Lee and Swancar, 1994). Because no reasonable change in any hydraulic parameter could solve this problem, ET was reduced at lake cells to compensate for the inability of the model to accurately simulate ground-water inflow from the surficial aquifer to lakes. The best results were obtained when the initial estimates of monthly ET were reduced by 80 percent at lake cells. This reduction is equivalent to about a 45 percent increase in recharge to cells representing lakes.

During the calibration process, adjustment of some leakance values of the upper confining unit along the Lake Wales Ridge was necessary. Generally, these



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 34. Locations of water-level measurements and values of water-level residuals for the surficial aquifer, May 1990 and September 1990.

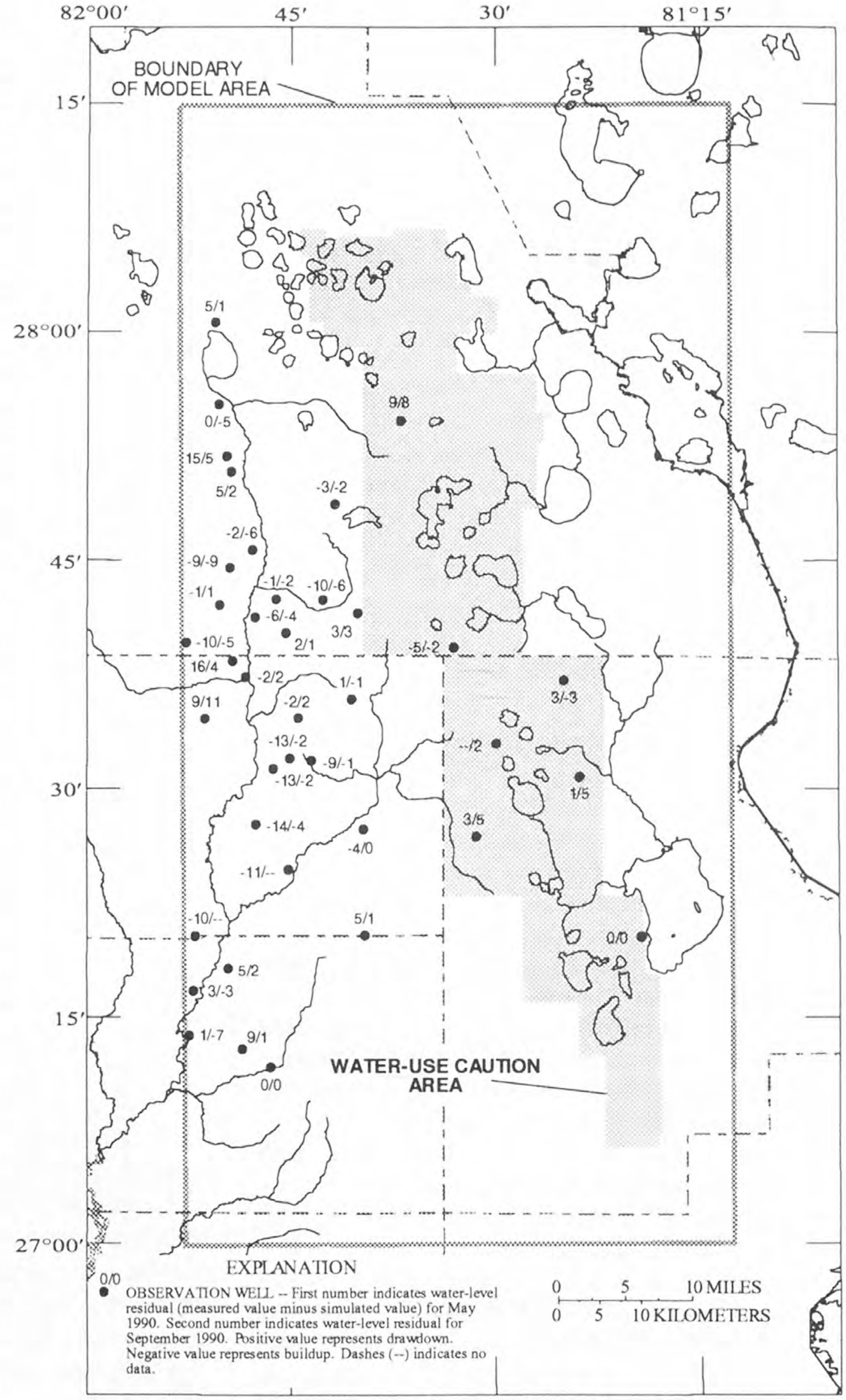
adjustments in leakance increased recharge to the intermediate aquifer system and improved calibration of the transient model. The altitude of the bottom of the surficial aquifer also had to be adjusted in some cells. These adjusted values then became the final calibrated values used in the steady-state calibration model.

Transient-model performance was evaluated by: (1) comparing model-simulated and measured heads at individual wells and lakes for May 1990 and September 1990, (2) comparing hydrographs of simulated heads with observed water-level hydrographs at 25 wells and 14 lakes, and (3) inspection of the distribution of errors in head. The simulated heads for May 1990 and September 1990 approximate end-of-dry-season and end-of-wet-season conditions, respectively.

Maps showing the water-level residuals at individual wells and lakes for each aquifer are shown in figures 34, 35 and 36. A statistical summary of differences between the simulated and observed heads in each aquifer is presented in table 7. The average simulated head differences for May 1990 and September 1990 were computed to be 0.0 and -0.2 feet respectively, for the surficial aquifer, 1.1 and 0.2 feet respectively, for the intermediate aquifer, and 1.5 and -0.1 respectively, for the Upper Floridan aquifer. On a model-wide basis, there is a tendency toward underestimating heads in May, while in September there is as much error on the plus side as on the minus side. Overall, observed heads agreed reasonably well with heads simulated by the model. Considering that the simulated heads are an average head over a month, as compared to an instantaneous observed water-level measurement, the simulation results seem to adequately represent conditions in the aquifer system.

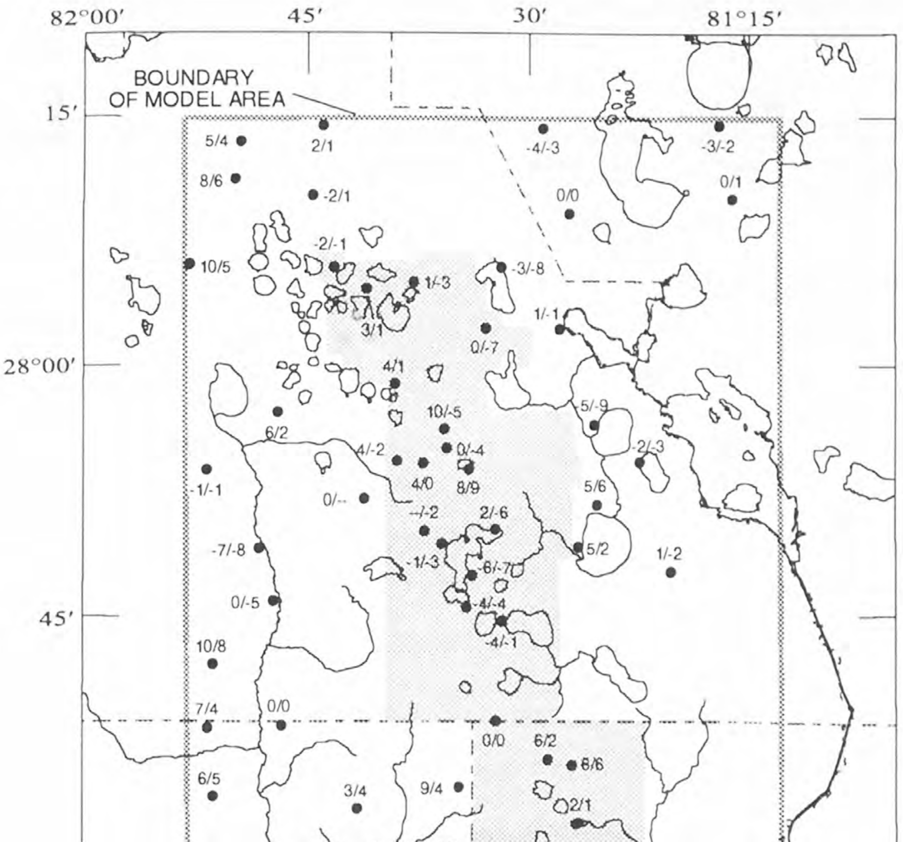
The plot of water-level residuals over the modeled area show several areas with consistently high positive or negative residuals. For the surficial aquifer an area of negative residuals was shown east of the WUCA, in eastern Polk County. This is an area of upward leakage and well-developed surface drainage and it appears that additional ET and runoff from the surficial aquifer should be simulated. At the northern and southern ends of the WUCA, simulated heads are shown to be lower than observed heads. The lower simulated heads may be the result of the scale of the model. The large cell size limits the ability of the model to simulate the local flow system.

For the intermediate and Upper Floridan aquifers, an area of negative residuals for May 1990 is shown between the Peace River and Charlie Creek. Nearly all pumpage in this area is irrigation pumpage, the most difficult of all water-use data to estimate. The higher simulated heads maybe the result of errors in the distribution and quantity of irrigation pumpage. Additionally, areas of both positive and negative residuals are shown for areas along the western edge of the model in Polk and northern Hardee Counties. The most likely explanation for these differences is that boundary flows and pumpage are poorly defined. Also, an area of positive residuals for the Upper Floridan aquifer is shown at the southern end of the WUCA in Highlands County. The lower



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 35. Locations of water-level measurements and values of water-level residuals for the intermediate aquifer, May 1990 and September 1990.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 36. Locations of water-level measurements and values of water-level residuals for the Upper Floridan aquifer, May 1990 and September 1990.

simulated heads are mostly the result of errors in the starting condition heads.

The accuracy of the transient model also was based on a comparison between simulated heads at specific cells and hydrographs of selected monitor wells and lakes at the appropriate cell. The locations of these wells and lakes, many of which are near major ground-water users, are shown in figure 5.

Simulated water-level fluctuations for 25 wells and 14 lakes, from September 1989 through September 1990, vary similarly with measured water levels for the same period (figs. 37, 38, 39, and 40). This indicates that the model simulates the transient response reasonably well on a monthly basis. The major difference between simulated and observed heads is the starting head. Differences in head may be related to the location of the well in the cell in addition to inadequate estimates of flow or hydrologic properties.

A notable deviation between simulated heads and observed hydrographs occurs for the intermediate and Upper Floridan aquifer wells in September 1990. The model simulates increasing heads from August to September 1990 while the hydrographs show decreasing heads for the same period. The most likely explanation is that pumpage is inaccurately defined. Possibly, actual pumpage during September 1990 may have been different than the rates used in the model, which is quite likely since the rate used in the model for September 1990 does not include any irrigation pumpage.

Table 7. Statistical summary of differences between model-computed heads and observed water levels for the surficial aquifer, intermediate aquifer, and Upper Floridan aquifer for the Lake Wales Ridge area, Florida, May 1990 and September 1990

Statistics	May 1990			September 1990		
	Surficial aquifer	Intermediate aquifer	Upper Floridan aquifer	Surficial aquifer	Intermediate aquifer	Upper Floridan aquifer
Number of observations	29	39	63	30	38	70
Maximum range in residuals (feet)	-3 to 3	-14 to 16	-11 to 11	-3 to 3	-9 to 11	-9 to 9
Arithmetic mean of residuals (feet)	0.0	1.1	1.5	-0.2	0.2	-0.1
Absolute mean of residuals (feet)	0.7	5.6	3.5	1.3	3.3	3.0
Standard deviation of residuals (feet)	0.9	7.3	4.4	0.8	3.8	3.6
Standard error of regression (feet)	1.4	7.0	4.5	1.7	4.0	3.9
Coefficient of determination	0.9979	0.8980	0.9728	0.9970	0.9579	0.9726

Simulated Water Budget

Figure 41 shows sources and discharges of ground-water in the modeled area for the pumping period May 1990. Ground-water was derived from aquifer storage, flow across lateral boundaries, and streams. Ground-water was discharge by ET, flow across lateral boundaries, pumpage, and streams.

Under May 1990 transient conditions, almost all the inflow water (99 percent) was derived from storage from the surficial aquifer. About 11 Mgal/d was derived from flow across lateral boundaries and another 7.3 Mgal/d was derived from streams.

Total inflow of 4,420 Mgal/d was balanced by an equal quantity of outflow. Most (86 percent) of ground-water discharge was by ET. About 486 Mgal/d (11 percent) of ground-water discharge was pumpage and about 13 Mgal/d of ground-water discharge was by streams, and about 126 Mgal/d (3 percent) of ground water was discharged across lateral boundaries.

In May 1990, the average rate of pumping was about 486 Mgal/d, about 360 Mgal/d more than during the steady-state simulation. Most (93 percent) of the water was pumped from the Upper Floridan aquifers. This additional water was obtained mostly from an increase in downward leakage and from a decrease in lateral boundary flow and stream flow. Leakage into the Upper Floridan aquifer from the intermediate aquifer increased 197 Mgal/d, from about 367 to about 564 Mgal/d, an increase of about 54 percent. Net lateral flow at boundaries decreased 103 Mgal/d, from about 218 to about 115 Mgal/d, a decrease of about 47 percent. Streamflow decreased about 54 Mgal/d, from about 67 to 13 Mgal/d, a decrease of about 80 percent.

As simulated, net difference in flow between the surficial aquifer and the intermediate aquifer and between the intermediate aquifer and the Upper Floridan aquifer is small (less than 2 Mgal/d). This is because water that leaks downward from the surficial aquifer to the intermediate aquifer ultimately leaks downward and recharges the Upper Floridan aquifer.

Sensitivity Analysis

The transient model was tested for sensitivity to changes in net recharge/discharge, ET, storage, and pumpage. Transmissivity and leakance were kept the same as in the steady-state model calibration. Each model parameter was increased by a factor of 2 and decreased by a factor of 0.5. The effect of the change in the parameter or stress was measured through the

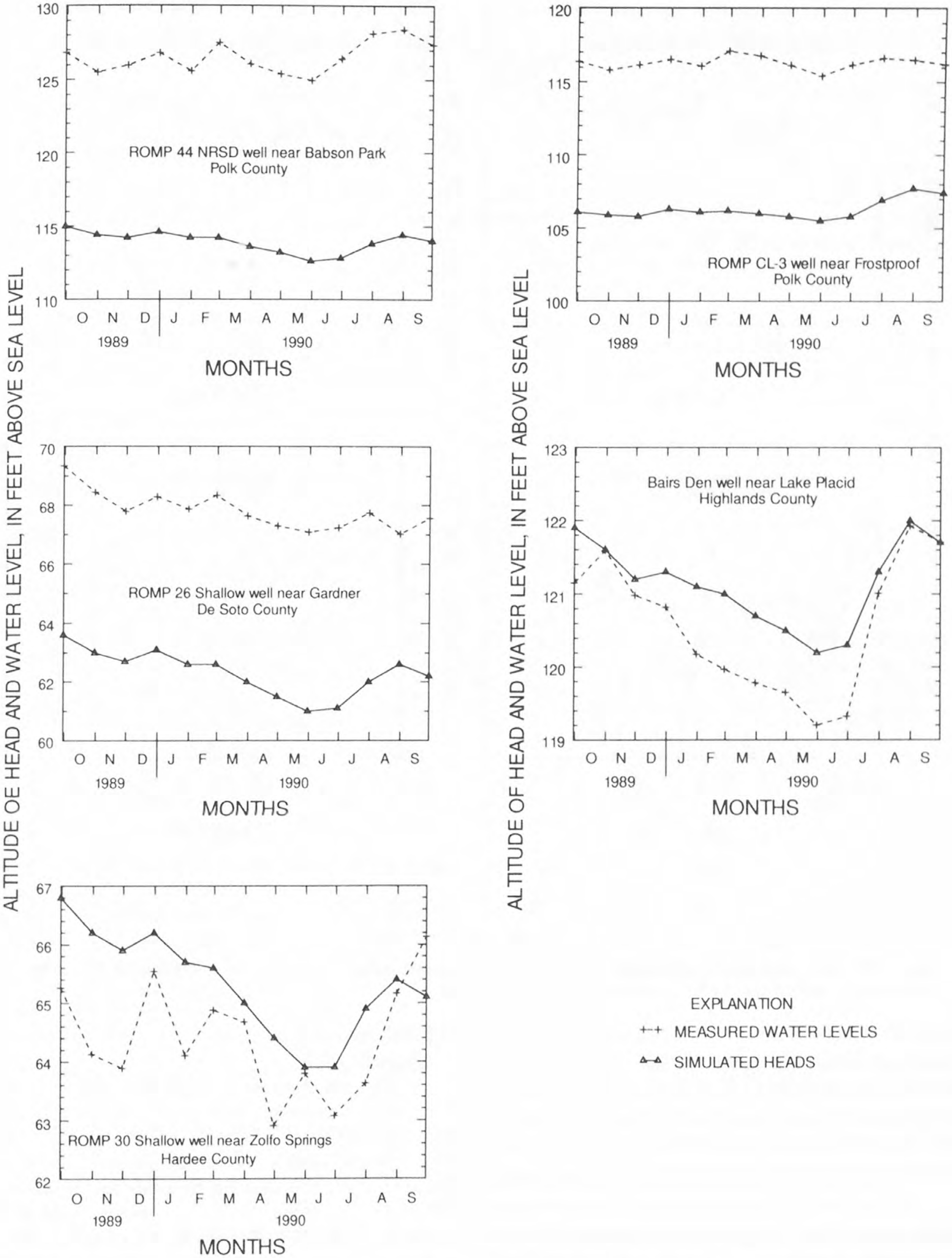


Figure 37. Simulated heads and observed water levels in selected wells open to the surficial aquifer, October 1989 through September 1990. (Location of wells shown in fig. 5.)

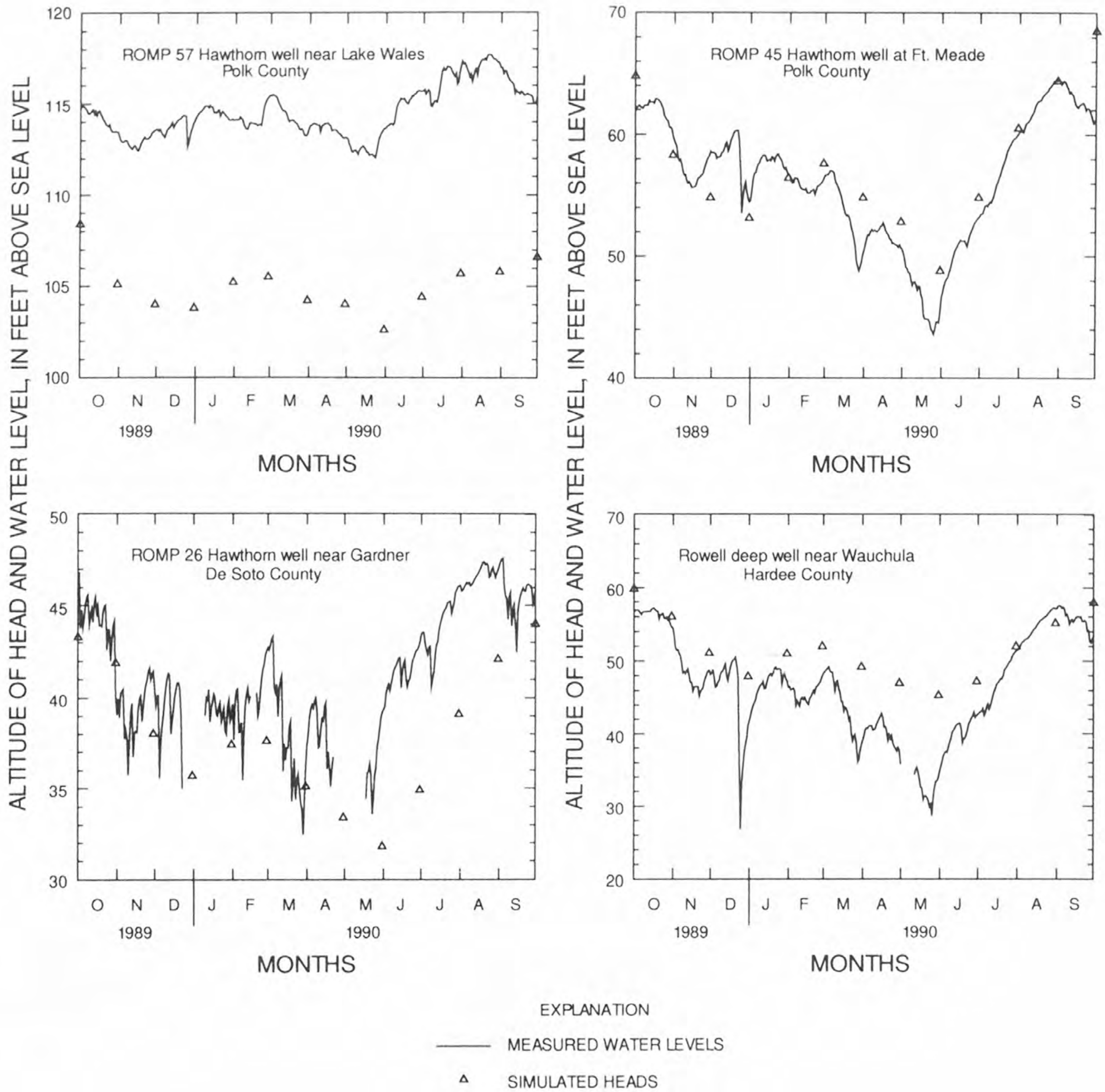
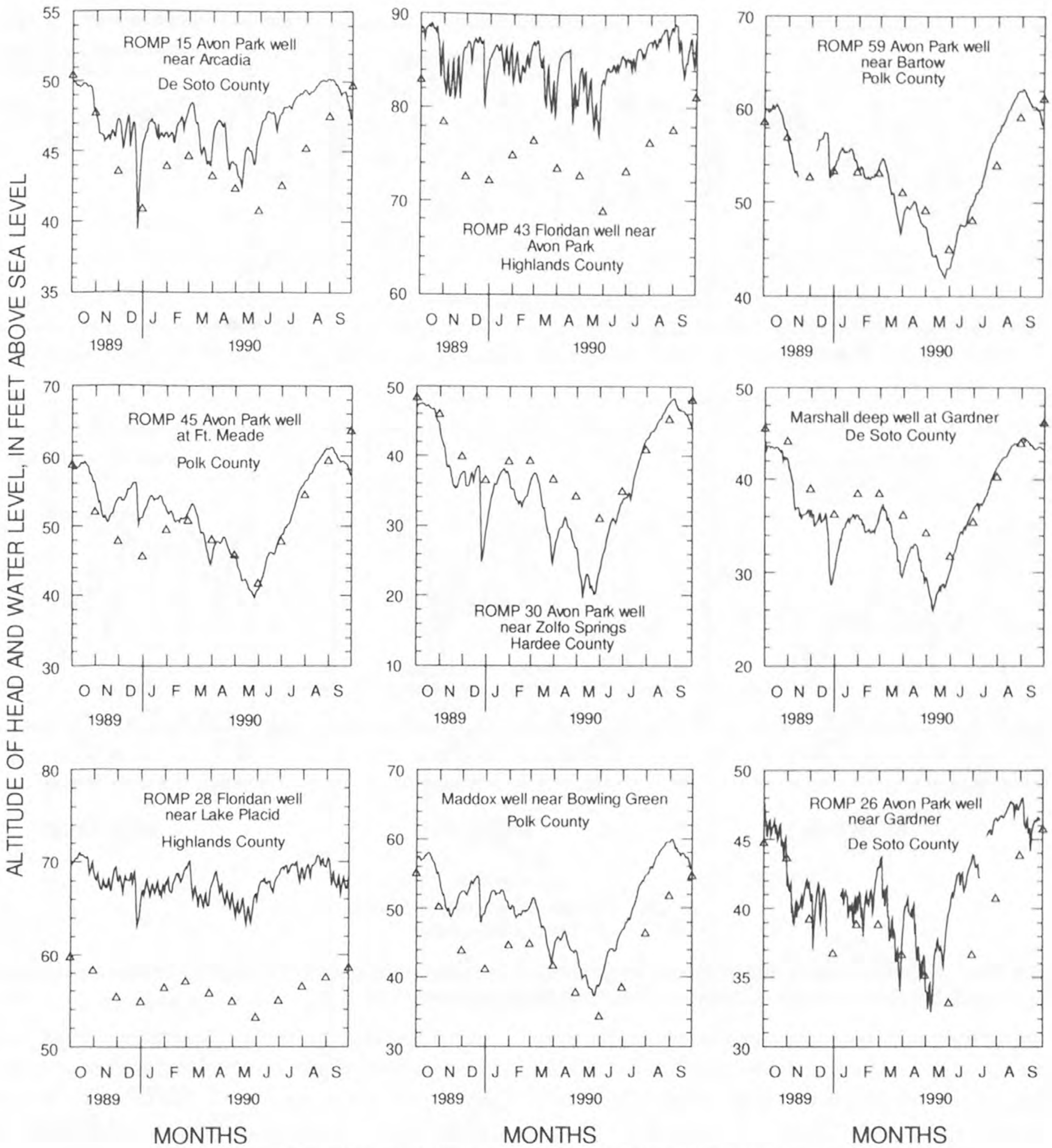


Figure 38. Simulated heads and observed water levels in selected wells open to the intermediate aquifer, October 1989 through September 1990. (Location of wells shown in fig. 5.)

change in absolute value of the mean residual head, or as a change in total base flow to rivers, or as a change in lateral boundary flow. Figure 42 shows the results of the sensitivity analysis for September 1990 conditions resulting from each of the tests in which the individual parameters were varied separately.

The sensitivity analysis indicated that simulated heads were most sensitive to changes in net recharge/discharge and pumpage, particularly increased recharge/discharge. Head deviations increased about 2 feet in each aquifer when recharge was multiplied by 2.0 and decreased by 0.2 to 0.8 ft when recharge was multiplied by 0.5.

The model was insensitive to changes in the specific yield of the surficial aquifer, storage coefficients of the intermediate and Upper Floridan aquifer, and ET. The absolute value of the mean residual head was the same or nearly the same for the calibrated model run as it was for the tested changes in specific yield, storage coefficients, and ET. However, if specific yield of the surficial aquifer is considered in conjunction with net recharge/discharge, determination is critical to proper simulation of the aquifer system.



October 1989 through September 1990. (Location of wells shown in fig. 5)

EXPLANATION
—— MEASURED WATER LEVELS
△ SIMULATED HEADS

Figure 39. Simulated heads and observed water levels in selected wells open to the Upper Floridan aquifer, October 1989 through September 1990. (Location of wells shown in fig. 5.)

Base flow to rivers and net lateral boundary flows were most sensitive to net recharge/discharge. The model was slightly sensitive to pumpage and ET. The model was relatively insensitive to changes in the specific yield of the surficial aquifer. Of relatively minor importance to model response were changes in storage coefficients of the intermediate and Upper Floridan aquifers. Storage coefficients are less important because high transmissivities allow rapid head changes throughout the confined regional system.

Final Transient Calibration

A final test of the model was made against a data set that represents hydrologic conditions different from those used for the initial transient calibration. The period selected was October 1988 through September

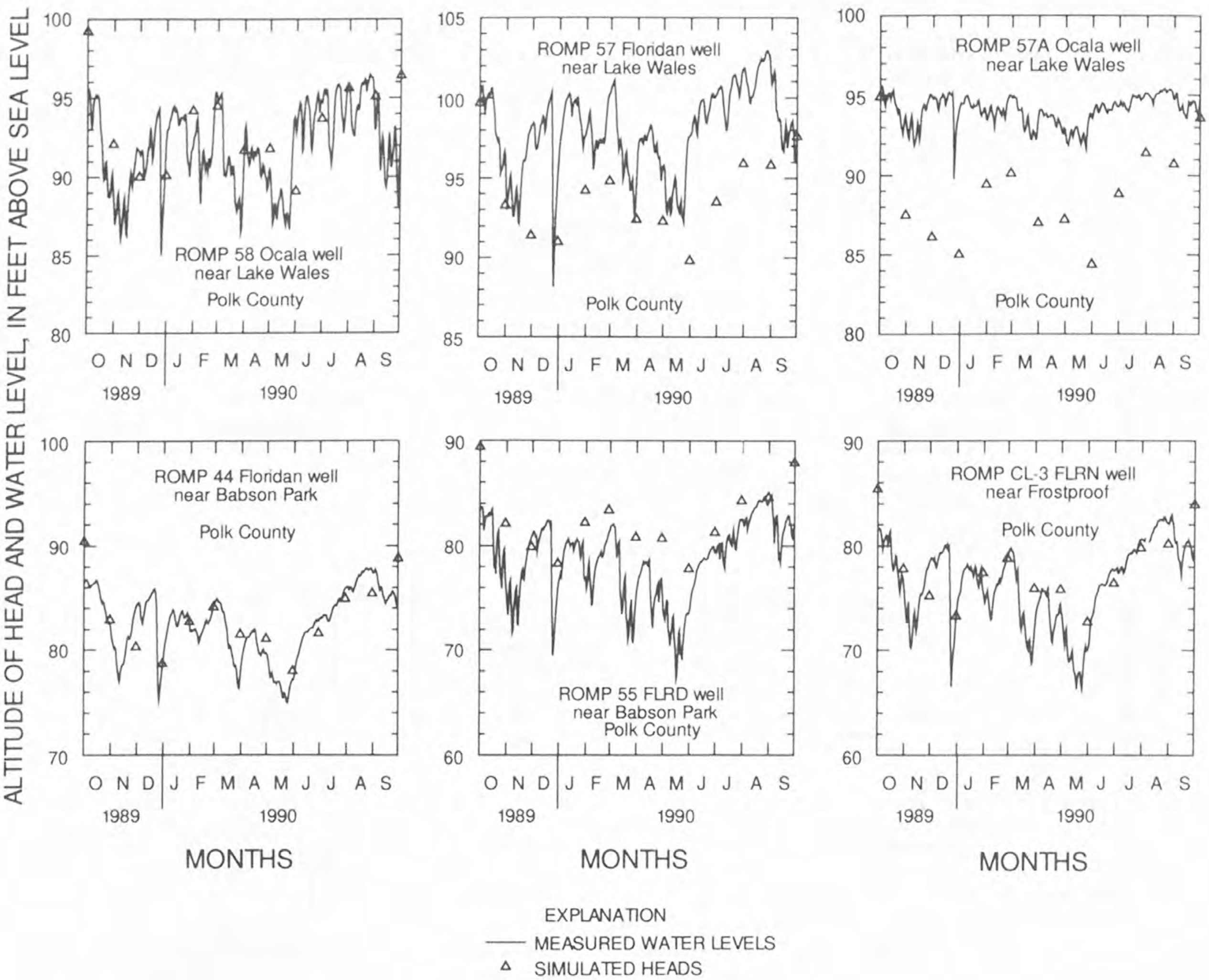


Figure 39A. Simulated heads and observed water levels in selected wells open to the Upper Floridan aquifer, October 1989 through September 1990—Continued. (Location of wells shown in fig. 5.)

1989. Input hydraulic characteristics to the model were the same as for the initial transient-state model, with the exception of the irrigation pumpage arrays, boundary source heads, and monthly rates of ET and net recharge. Another change from the basic calibration model was the use of average stream heads rather than updated monthly values. Appropriate monthly variations in pumping, rates of recharge and ET, and boundary source heads were used to approximate the changing conditions from October 1988 through September 1989. These variations are shown in tables 3 and 6. Initial heads were estimated for September 1988 based on the calibrated September 1989 steady-state heads and the change in heads measured in wells and lakes between September 1989 and September 1988. A steady-state proof run using the estimated September 1988 heads was made to test for equilibrium conditions. Boundary flows, net recharge/discharge rates, and pumpage arrays of the calibrated September 1989 steady-state model were adjusted to reflect September 1988 conditions. Comparison of model-simulated and observed September 1988 heads was good statistically; thus, the estimated heads were considered to adequately represent September 1988 conditions. Effects of the initial condition heads should not adversely influence the transient-condition solution.

The final transient results were assessed by comparing model-simulated heads and observed water levels for individual wells and lakes in May and September 1989. The statistics of the final model calibration indicate that there is a reasonable match between model-simulated and observed heads (table 8). However, the May 1989 transient calibration has greater error and deviation than the May 1990 calibration results. The absolute average error for the surficial aquifer, intermediate aquifer, and the Upper Floridan aquifer, for the May 1989 transient conditions is 1.7, 6.7, and 6.1 feet, respectively, compared to 0.7, 5.6, and 3.5 feet,

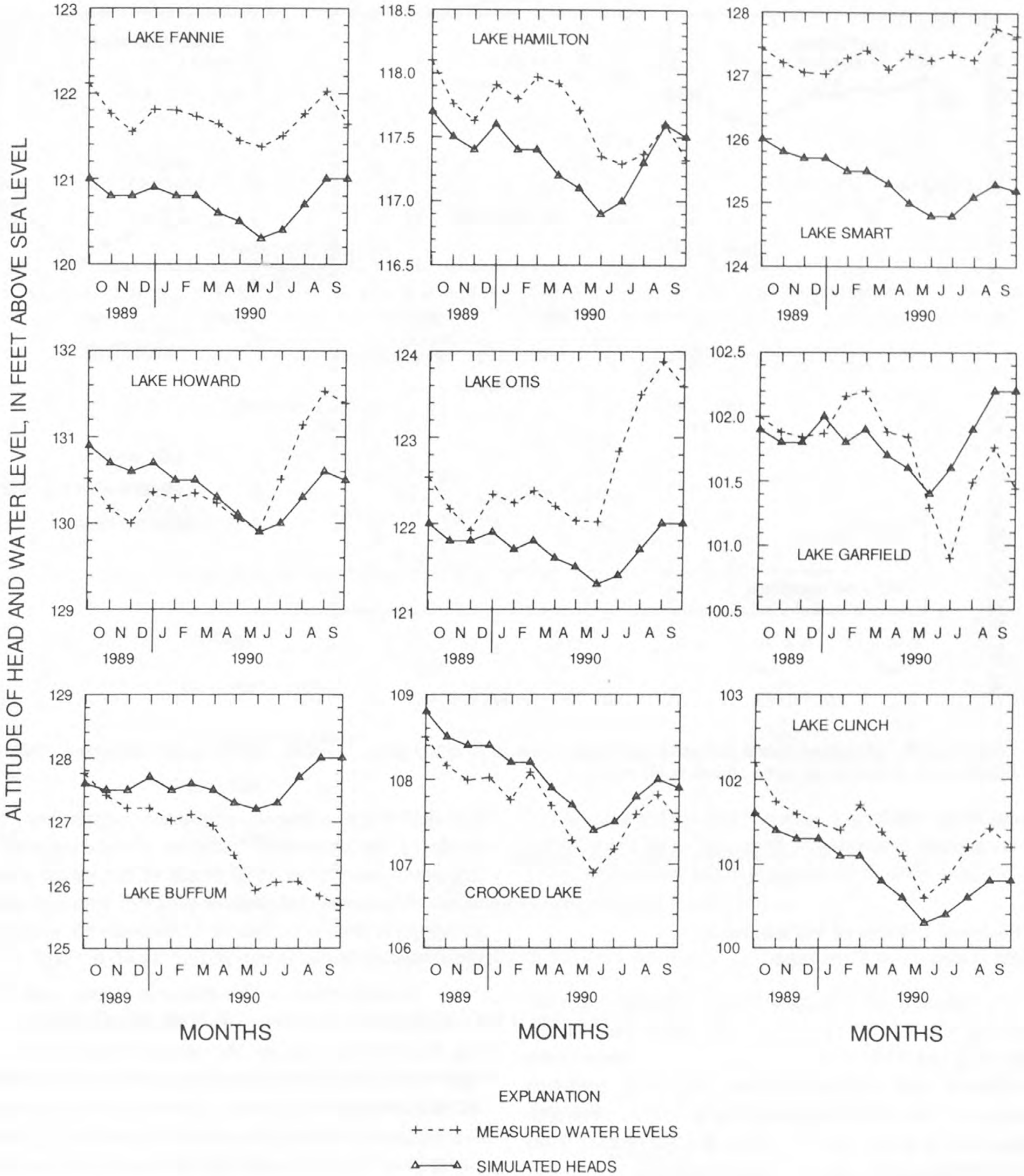


Figure 40. Simulated heads and observed water levels in selected lakes, October 1989 through September 1990. (Location of lakes shown in figure 5.)

respectively, for the surficial aquifer, intermediate aquifer, and the Upper Floridan aquifer for the May 1990 calibration period. Discrepancies could be the result of errors in defining initial conditions or the result of inaccurately determined pumping rates and areal distribution of water use.

Application of Flow Model

The calibrated ground-water flow model of the Lake Wales Ridge and adjacent areas was used in a series of simulations to evaluate the short-term and long-term effects of pumping on ground-water levels.

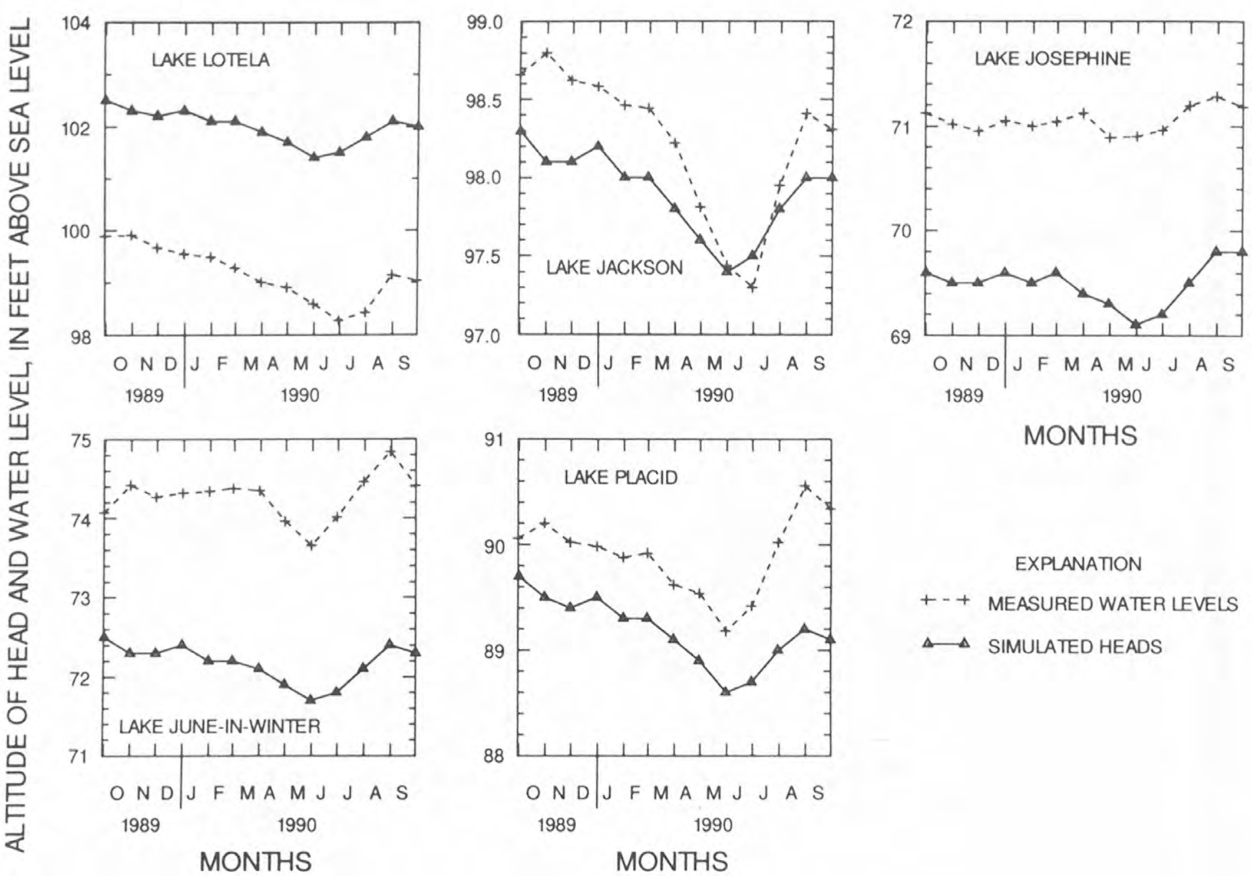


Figure 40A. Simulated heads and observed water levels in selected lakes, October 1989 through September 1990—Continued. (Location of lakes shown in figure 5.)

Simulation results are summarized in this section and are presented in a series of maps that show the resulting net ground-water level changes in the model area.

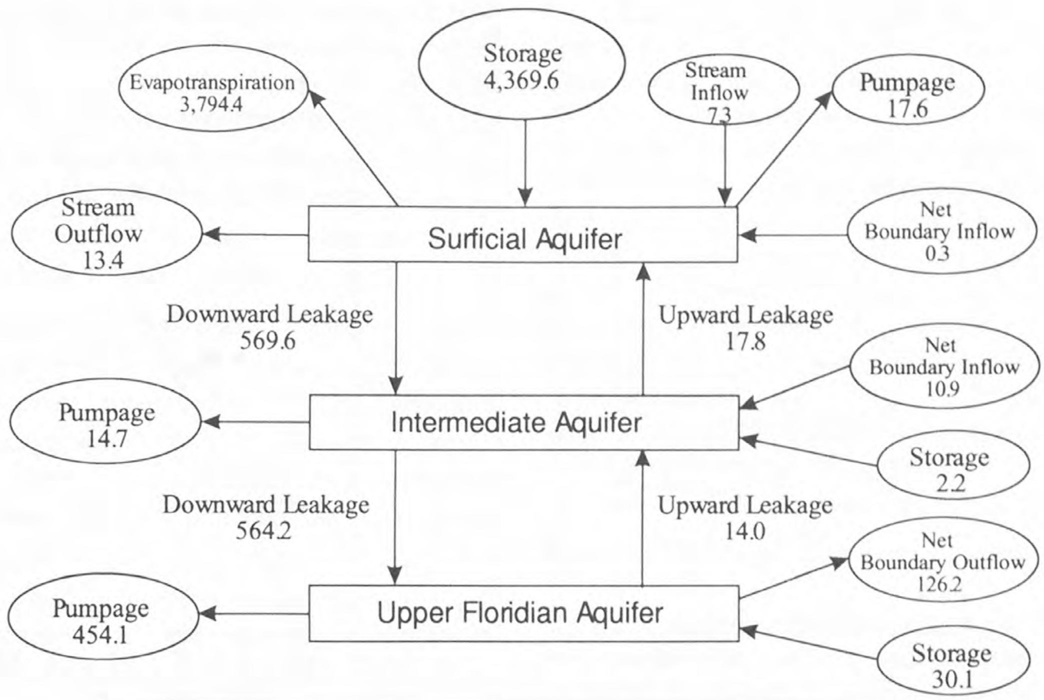
Simulated Effects of Variations in 1990 Water Year Pumpage

The calibrated transient model was used to evaluate the short-term effects of 1990 water-year pumpage on ground-water levels. Simulations were made to assess the effects of five different pumping schemes. The following pumping scenarios were simulated for a 1-year period using the September 1989 steady-state conditions as initial conditions:

1. No pumpage,
2. No public supply pumpage,
3. No industrial or mining pumpage,
4. No agricultural pumpage, and
5. No pumpage outside the WUCA.

Input parameters and boundary conditions were the same as specified in the calibrated transient model. The simulated effects of pumping were calculated as the difference between simulated September 1989 heads of the calibrated transient simulation and the simulated September 1990 heads of the tested simulations. The areal distribution of 1990 average annual pumpage is shown in figures 43 through 45. Results of the simulations are shown in figures 46 through 50.

Ground-water withdrawals in water year 1990 averaged about 349 Mgal/d. The net effect of removing all pumpage across the model area is shown in figure 46. The effect of pumpage can be inferred from the no pumpage condition. Effects of no pumpage on the surficial aquifer are greatest within the WUCA along the Lake Wales and Winter Haven Ridges where recharge rates are high and where the confining units are thin or permeable. Effects of no pumpage on the intermediate aquifer and the Upper Floridan aquifer are greatest in areas where pumping rates are highest, especially in southwestern Polk County. The change maps show that, if no ground-water pumpage occurred during the 1990 water year, simulated water levels would have reached a maximum recovery of about 2 feet in the surficial aquifer, about 12 feet in the



	Inflow	Outflow
Storage	4,401.9	
Boundary Flow	11.2	126.2
Evapotranspiration		3,794.4
Streams	7.3	13.4
Pumpage		486.4
Totals	4,420.4	4,420.4

(All values are in million gallons per day)

Figure 41. Simulated water budget of the aquifer system in the model area, May 1990.

intermediate aquifer, and about 16 feet in the Upper Floridan aquifer. Within the WUCA, the area affected most by pumpage is in the high-rate recharge areas, whereas the least affected area is in the low-rate recharge areas along the eastern boundary of the WUCA where recovery is less than 2 feet. In the high-rate recharge areas, the confining units that separate the aquifer tend to be thin or permeable and there is an intimate hydraulic connection between the aquifers. Therefore, in high-rate recharge areas, the surficial aquifer will be most affected by pumping from the intermediate and Upper Floridan aquifers. Similarly, in low-rate recharge areas, there is a poor hydraulic connection between aquifers and the surficial aquifer heads will be least affected by pumping.

Agriculture is the largest user of ground water in the model area; however, the rates and areal distribution of this water-use category are the least accurately known. Water year 1990 agricultural withdrawals are estimated at about 238 Mgal/d, about 68 percent of the total pumpage in the study area. The simulation in which there was no pumpage for agricultural use resulted in a maximum recovery of about 2 ft in the surficial aquifer, about 2 ft in the intermediate aquifer, and about 2 ft in the Upper Floridan aquifer (fig. 47).

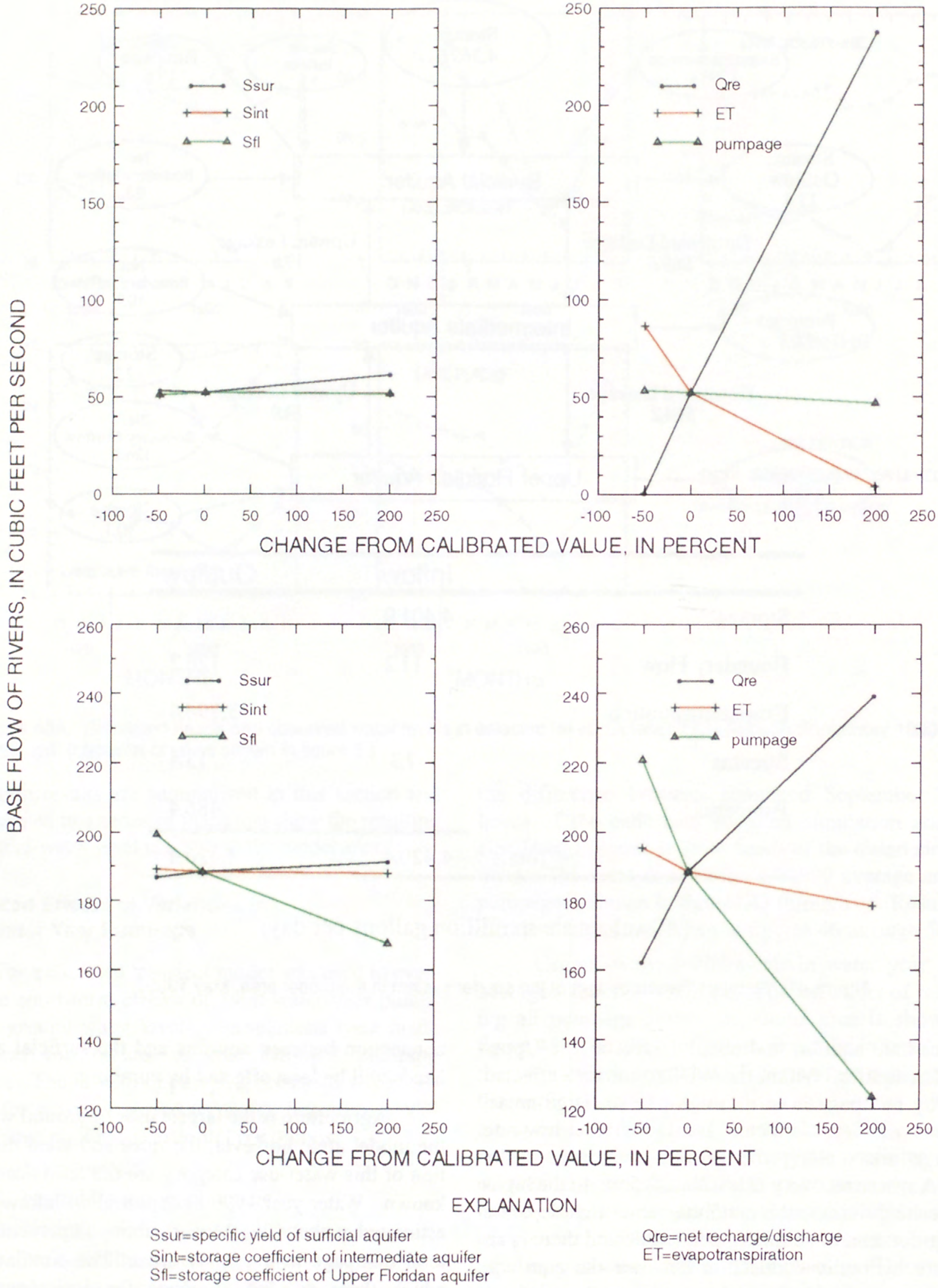


Figure 42. Sensitivity of calibrated transient-state model to variations in various input parameters.

The simulated effects of agricultural pumpage on the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer are relatively small due to the relatively short time it takes the confined system to reach equilibrium following cessation of pumping in May, whereas the effects of pumpage on the surficial aquifer are relatively large due to the cumulative effects of water lost from storage.

Pumpage for industrial and mining use in water year 1990 was about 67 Mgal/d, about 17 percent of the total pumpage. The net effect of no industrial and mining pumpage across the model area is shown in figure 48. The simulation indicated a maximum recovery of less than 0.5 ft in the surficial aquifer, about 10 ft in the intermediate aquifer and about 14 ft in the Upper Floridan aquifer. The simulated effect of pumpage are greatest in areas where large quantities of ground water are withdrawn for phosphate mining and the effects extend to the western boundary of the WUCA.

Pumpage for public supply in water year 1990 was about 42 Mgal/d, about 12 percent of total pumpage. Public supply pumpage is the most accurately known pumping category in terms of rates and areal distribution. The simulated effect across the model area of no public supply pumping is shown in figure 49. The simulation indicated a maximum recovery of about 0.5 ft in the surficial aquifer, about 4 ft in the intermediate aquifer and about 10 ft in the Upper Floridan aquifer. The simulated effect of no pumpage for public supply are greatest near the larger municipalities, and extend to outlying areas.

The WUCA is affected by regional pumping for municipal supply, agriculture, and industry. Pumping outside of the WUCA in water year 1990 was about 220 Mgal/d, about 63 percent of the total pumpage. The simulated effect of pumpage outside the WUCA on the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer is shown in figure 50. The simulated effects of regional pumpage on the WUCA are greatest in Polk County along the western boundary of the WUCA where maximum recoveries are less than 2 ft in the intermediate aquifer and in the Upper Floridan aquifer. The change map shows several small areas in Polk County where a recovery in the surficial aquifer system is less than 1 ft.

Potential Effects of Long-Term Pumpage

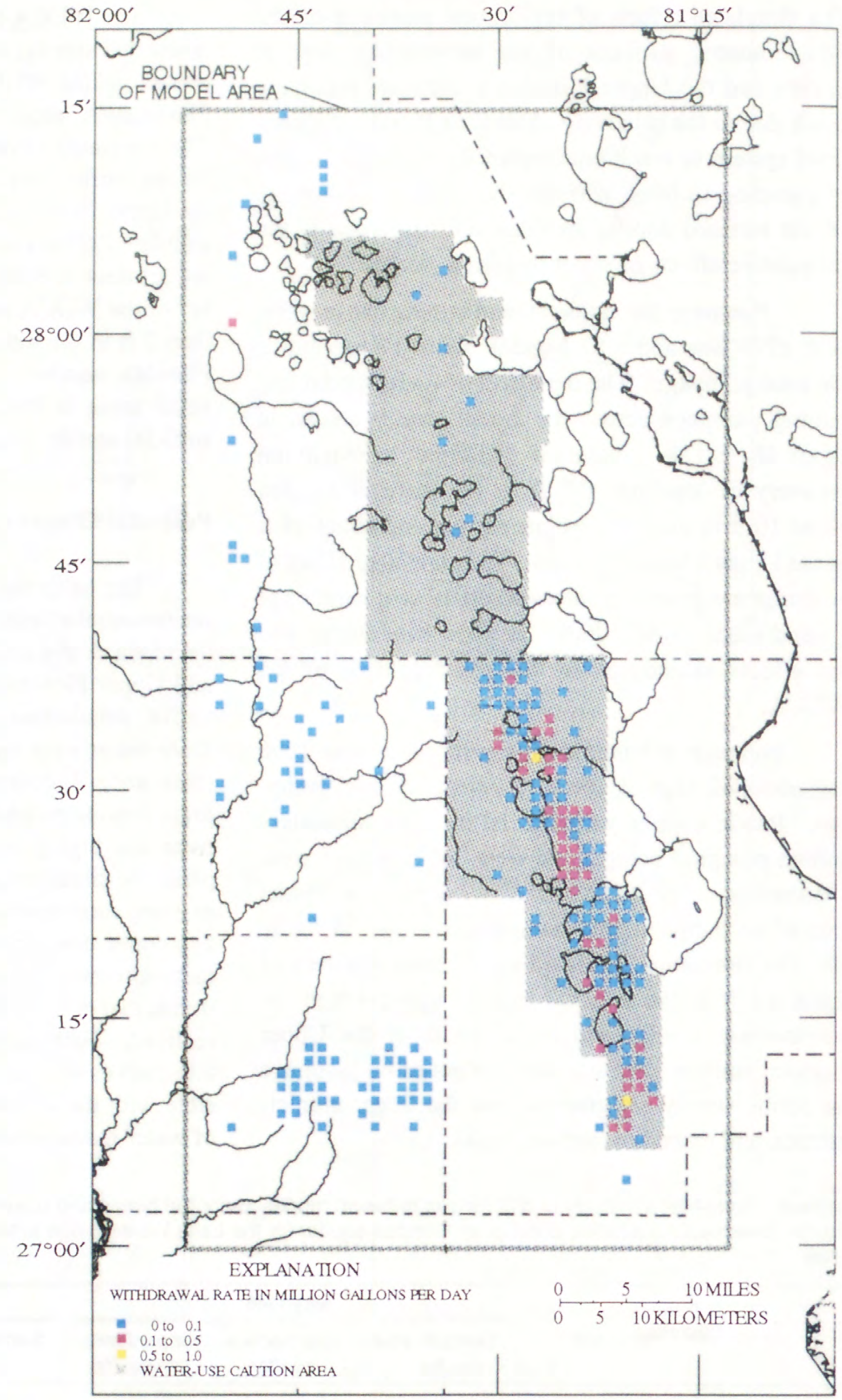
The calibrated flow model was used to evaluate the potential effects of long-term pumpage on hydraulic heads of the surficial aquifer, intermediate aquifer, and Upper Floridan aquifer. Two development alternative simulations were made: (1) continuation of 1990 water year hydrologic conditions and pumping rates, and, (2) continuation of 1990 water year hydrologic conditions and increased pumpage. The alternatives are highly simplified, and a large number of plausible situations involving various combinations of existing conditions and hypothetical changes in pumpage could develop. The purpose of testing development alternatives was to evaluate general hydrologic trends that might be expected should the alternative be realized. Although testing of specific management alternatives was not an objective of the study, it is possible with the calibrated model to evaluate the effects of water-management proposals on the aquifer system.

Table 8. Statistical summary of differences between model-computed heads and observed water levels for the surficial aquifer, intermediate aquifer, and Upper Floridan aquifer for the Lake Wales Ridge area, Florida, May 1989 and September 1989

Statistics	May 1989			September 1989		
	Surficial aquifer	Intermediate aquifer	Upper Floridan aquifer	Surficial aquifer	Intermediate aquifer	Upper Floridan aquifer
Number of observations	33	39	65	50	38	71
Maximum range in residuals (feet)	-4 to 4	-13 to 20	-7 to 15	-5 to 8	-5 to 12	-9 to 10
Arithmetic mean of residuals (feet)	-0.7	1.4	5.1	-0.5	1.3	0.3
Absolute mean of residuals (feet)	1.7	6.7	6.1	2.1	3.2	3.2
Standard deviation of residuals (feet)	2.0	7.9	5.4	2.6	3.9	4.1
Coefficient of determination	0.9961	0.8993	0.9628	0.9905	0.9622	0.9712

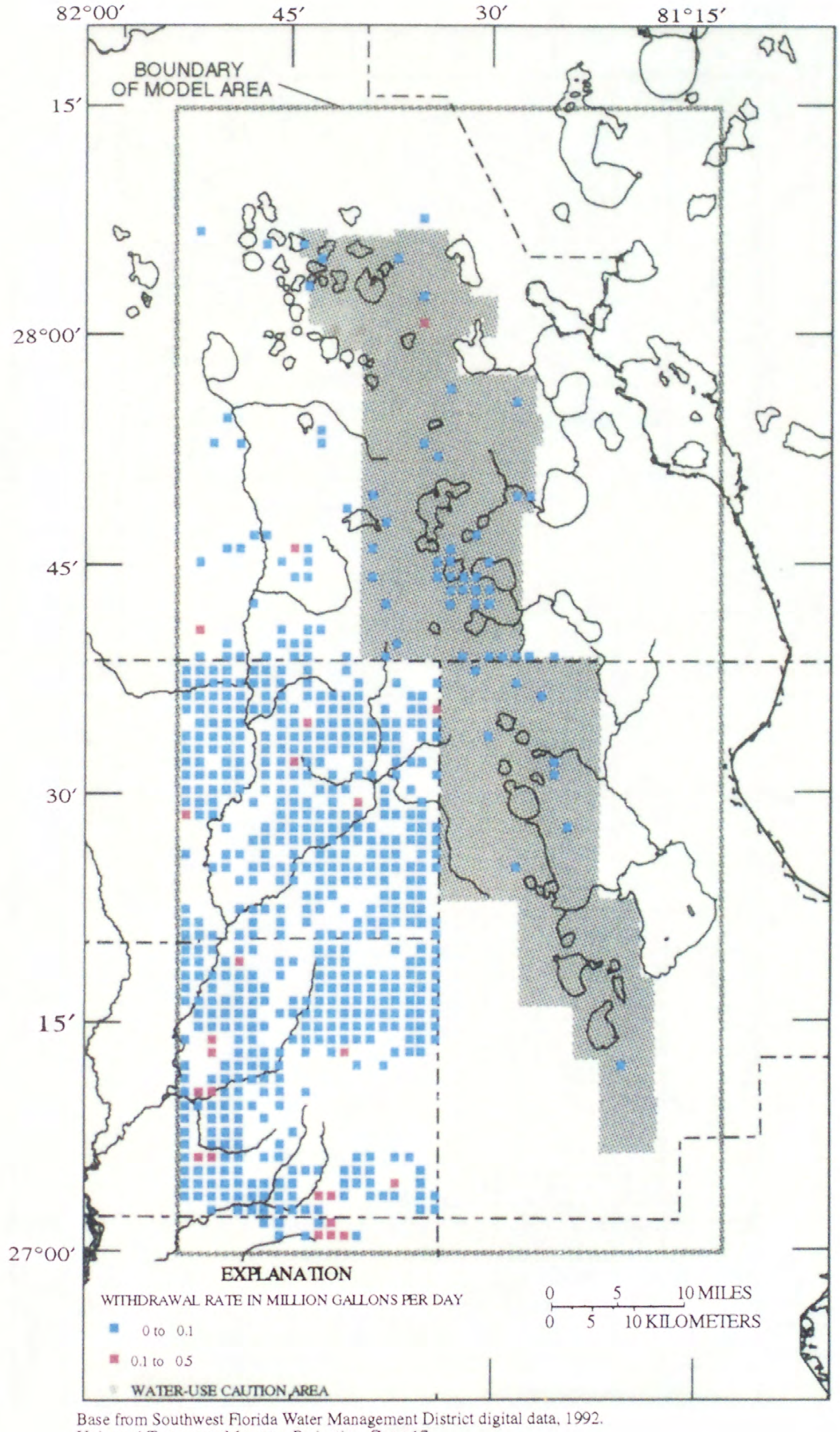
Development alternatives were simulated for an arbitrary 20-yr period to allow the flow system to respond to stresses and approach a new equilibrium condition. Each year of the development period was divided into 12 stress periods, each representing 1 month. Pumpage and general head boundary source heads varied monthly to account for changes with time. Another change from the basic calibration model was the use of average stream heads rather than updated monthly values. Net recharge/discharge rates used in the steady-state model were assumed to have the appropriate spatial distribution. ET was neglected in the hypothetical projections because little is known about the quantitative effects of large temporal changes in the depth to the water table and how much ET would be reduced for a given decline in water-table altitude. In addition, the discharge of ground water by ET is difficult to predict because the roots of established plants may, to a limited extent, keep pace with a declining water level, especially if the depth to water increases slowly (Durbin, 1978). Other hydrologic variables specified in the calibrated transient-state model were unchanged in the projection simulations. The simulated September 1989 hydraulic heads were used as starting heads for each projection.

Pumpage was varied monthly for the hypothetical projections to see what effects seasonal pumpage has on the aquifer system. Unlike other major users, withdrawals for irrigation are highly seasonal and annual water-use estimates are misleading. Typically the bulk of



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 43. Areal distribution of average annual 1990 ground-water withdrawals from the surficial aquifer.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

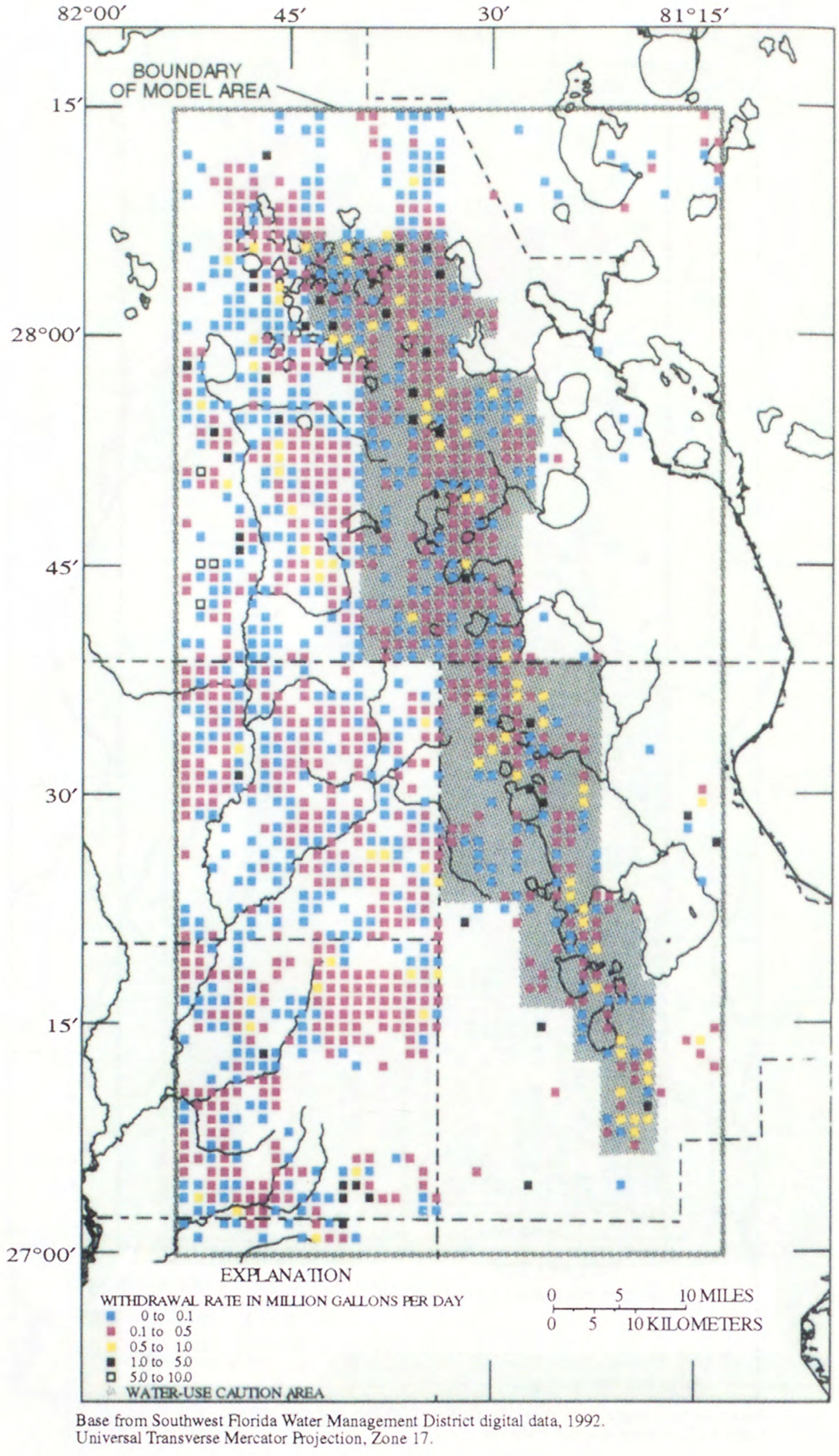
Figure 44. Areal distribution of average annual 1990 ground-water withdrawals from the intermediate aquifer.

citrus irrigation, which is the largest single use of ground water for irrigation in the model area, occurs in a six-month period from January to June. During this six-month period actual per day pumpage may greatly exceed the annual water-use values (Geraghty and Miller, 1980).

The rates and distribution of pumpage selected for the hypothetical projections are based on the water-use estimates for the 1990 water year. The 1990 water year represents below normal hydrologic conditions and correspondingly above normal pumpage. Thus, the model would simulate heads with lower than normal rainfall conditions. Three irrigation seasons occurred during the 1990 water year; a fall season, a winter-spring season, and a summer season during which withdrawals for irrigation were small. Withdrawal rates for irrigation during the summer season were slightly less than half of those in the winter-spring season, and the rates in the winter-spring season were slightly more than two-thirds of those in the fall season. The rates in the fall season were about the same as the annual average rates.

Model runs were made simulating head changes expected at the end of the irrigation season (May) and the non-irrigation season (September) in 20 years. Head changes were computed as the difference between the simulated aquifer heads in September 1989 and the simulated aquifer heads in May 2009 and September 2009.

Simulation of a continuation of 1990 hydrologic conditions and pumpage produced a decline in aquifer heads throughout all of the WUCA and most of the modeled area as the system approached a new equilibrium condition after 20 years of pumping (figs. 51 and 52). By May 2009, the greatest head declines in the surficial aquifer and lakes are predicted to occur in Polk County at the northern end of the WUCA where a good hydraulic connection between aquifers is believed to exist. Head declines in the surficial aquifer averaged 2.8 ft, and are predicted to exceed 10 feet in a broad area near the northern half of the WUCA. Head declines in the intermediate aquifer averaged 8.9 feet and are predicted to exceed 10 feet in most of the WUCA. Head declines also are predicted to exceed 15 ft in two areas in the WUCA in Polk County and in one area of northwestern Highlands and northeastern Hardee Counties. Head declines in the Upper Floridan aquifer are predicted to average 11.1 ft and exceed 10 feet over most of the WUCA and more than 20 feet of decline is predicted to occur along the west-central edge of the model in Polk and Hardee Counties. By September 2009, aquifer heads have recovered from lows in May 2009; however, a net head decline of 10 feet or more in aquifer heads is predicted to occur in Polk County near the northern half of the WUCA. Maxium declines of 10 feet or more are predicted to occur in each aquifer and the average decline for all model cells in the surficial aquifer, intermediate aquifer, and the Upper Floridan aquifer are predicted to average about 2.8, 3.3, and 3.4 feet, respectively. The decline in September aquifer heads indicates that discharge from pumpage exceeded the September 1989 rate of recharge.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 45. Areal distribution of average annual 1990 ground-water withdrawals from the Upper Floridan aquifer.

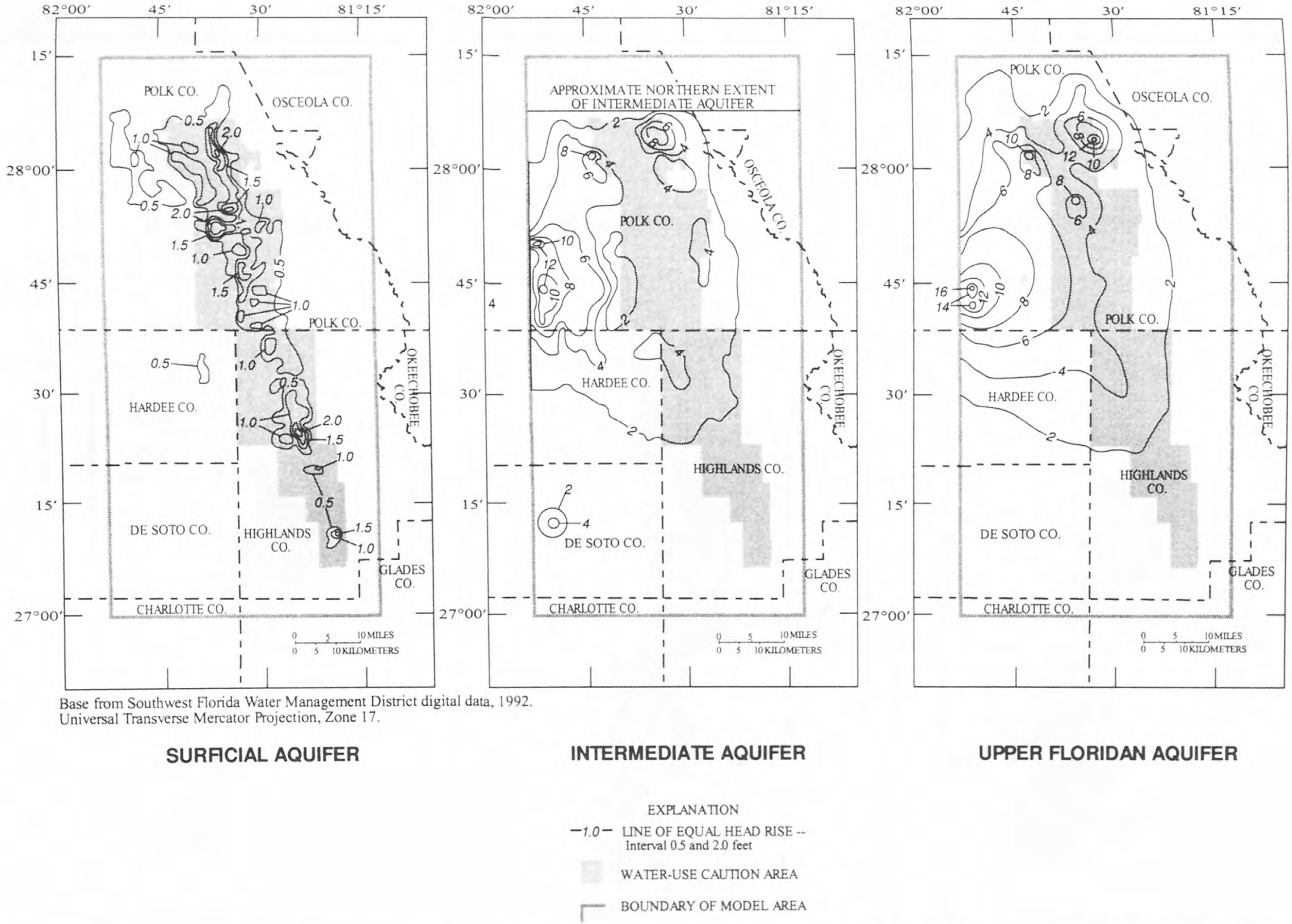


Figure 46. Simulated rise of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer when all categories of pumpage are removed.

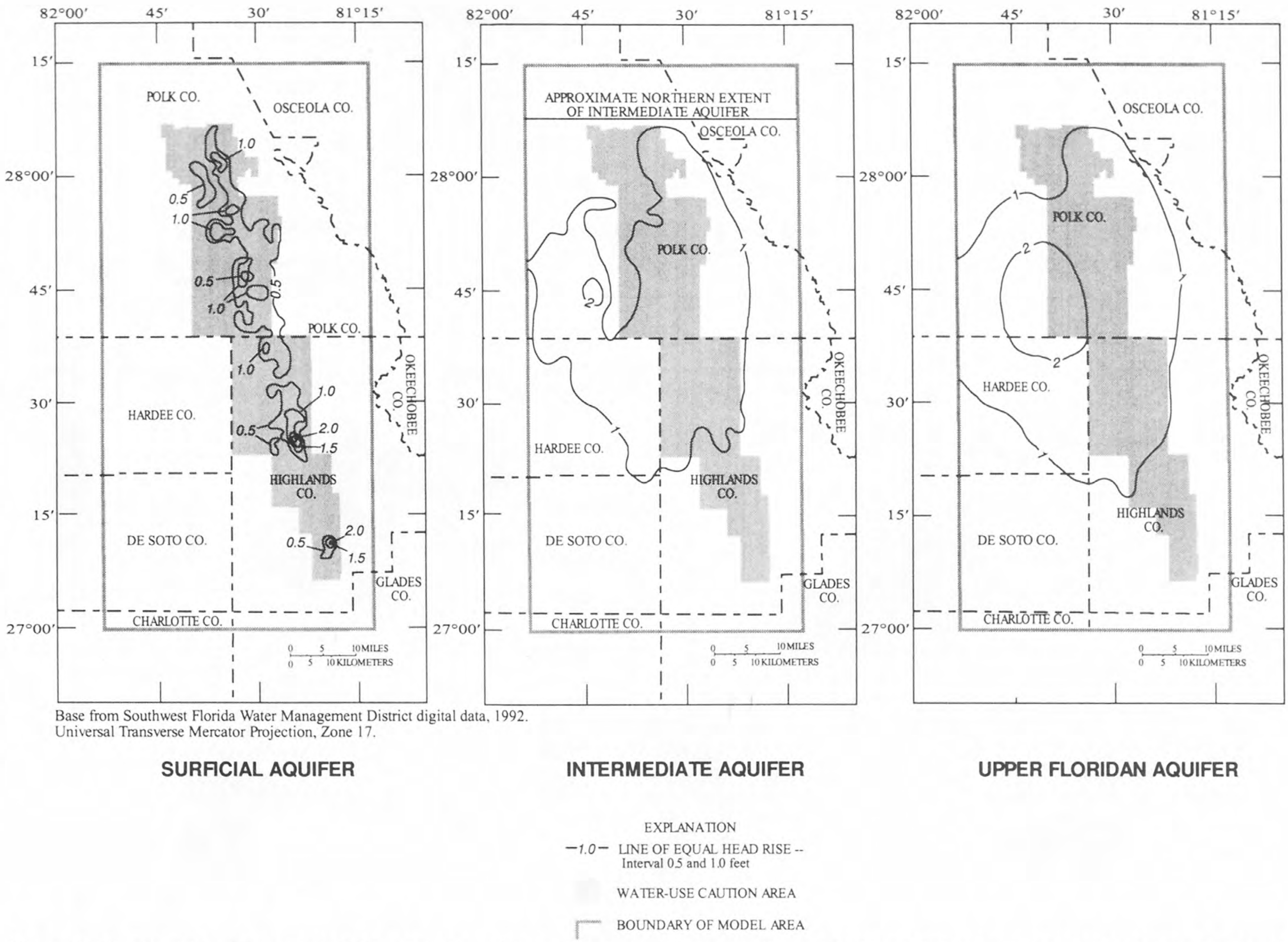


Figure 47. Simulated rise of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer when all agricultural pumpage is removed.

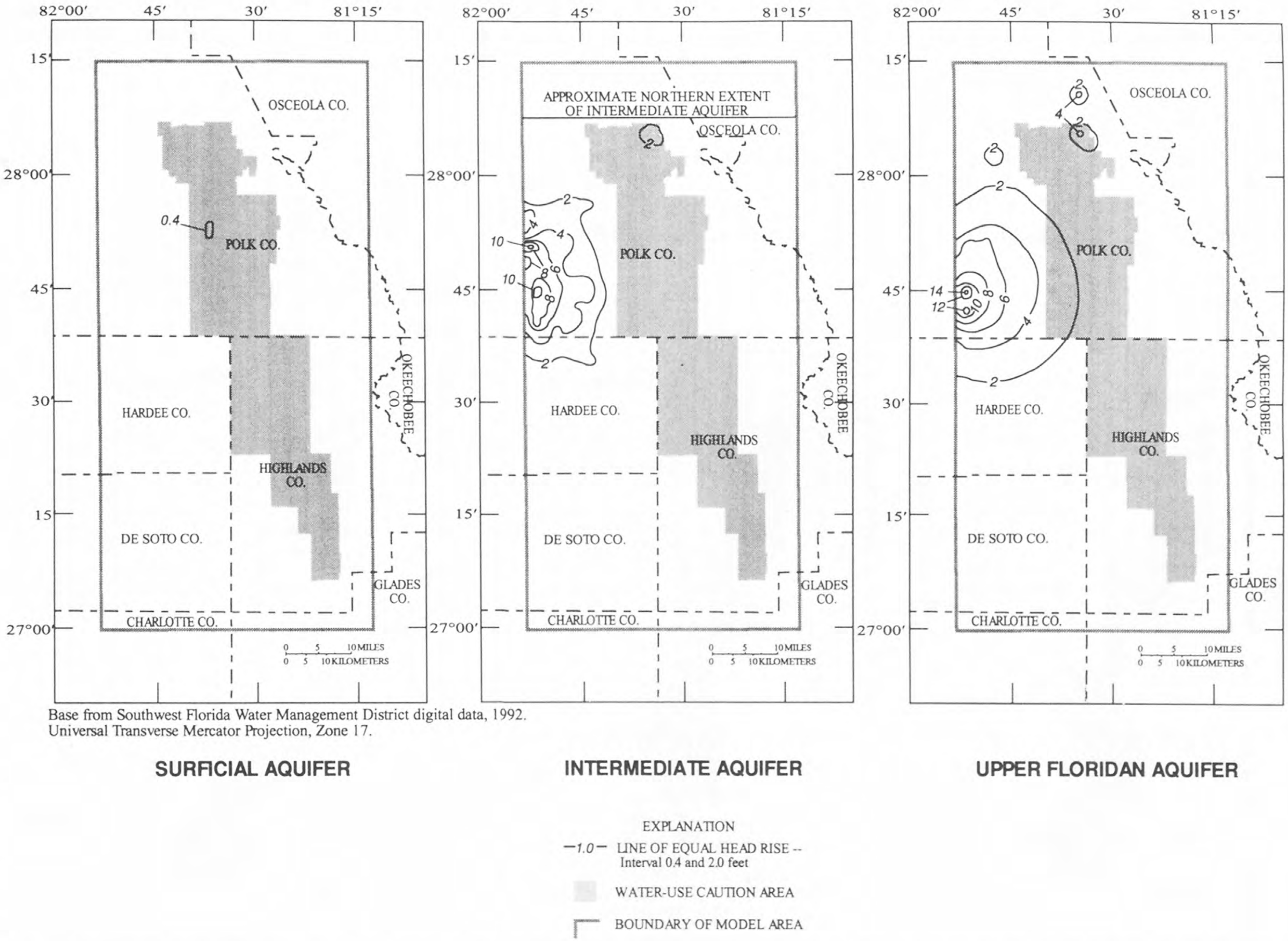


Figure 48. Simulated rise of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer when industrial and mining pumpage is removed.

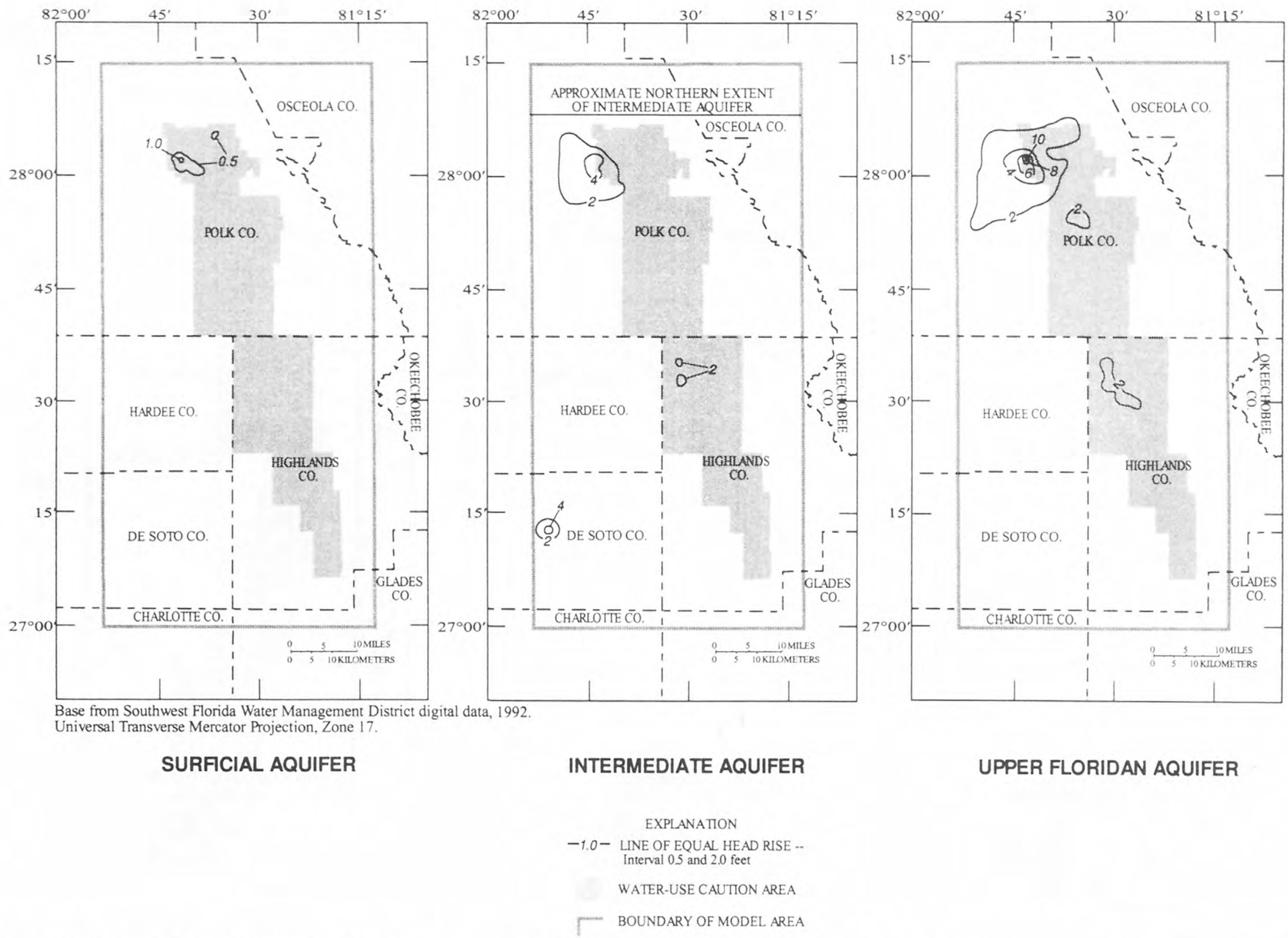


Figure 49. Simulated rise of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer when public-supply pumpage is removed.

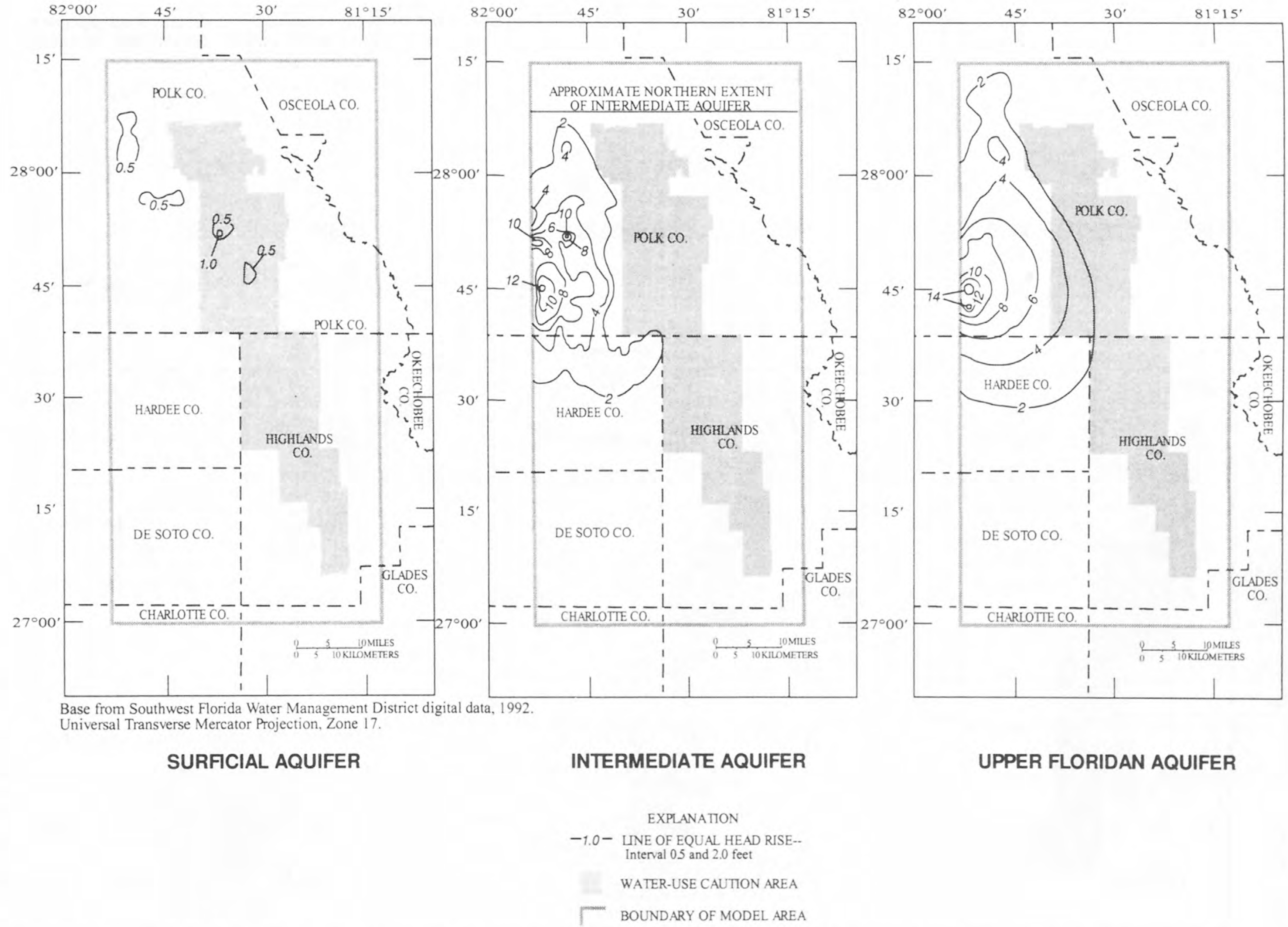


Figure 50. Simulated rise of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer when all categories of pumpage outside of the water-use caution area are removed.

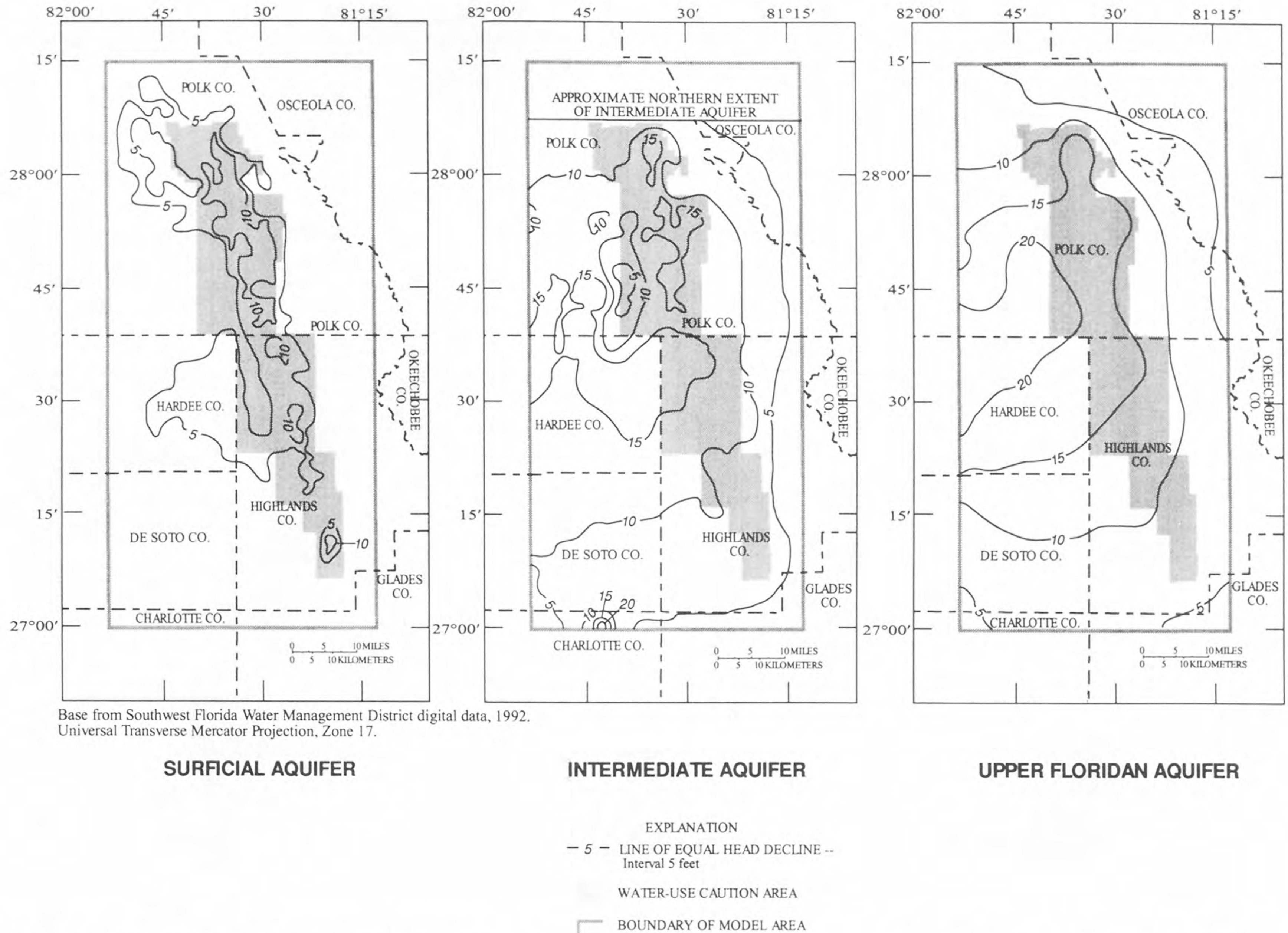


Figure 51. Simulated decline of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer at the end of May 2009 as a result of the continuation of present (1990 water year) average ground-water withdrawals of 349 million gallons per day.

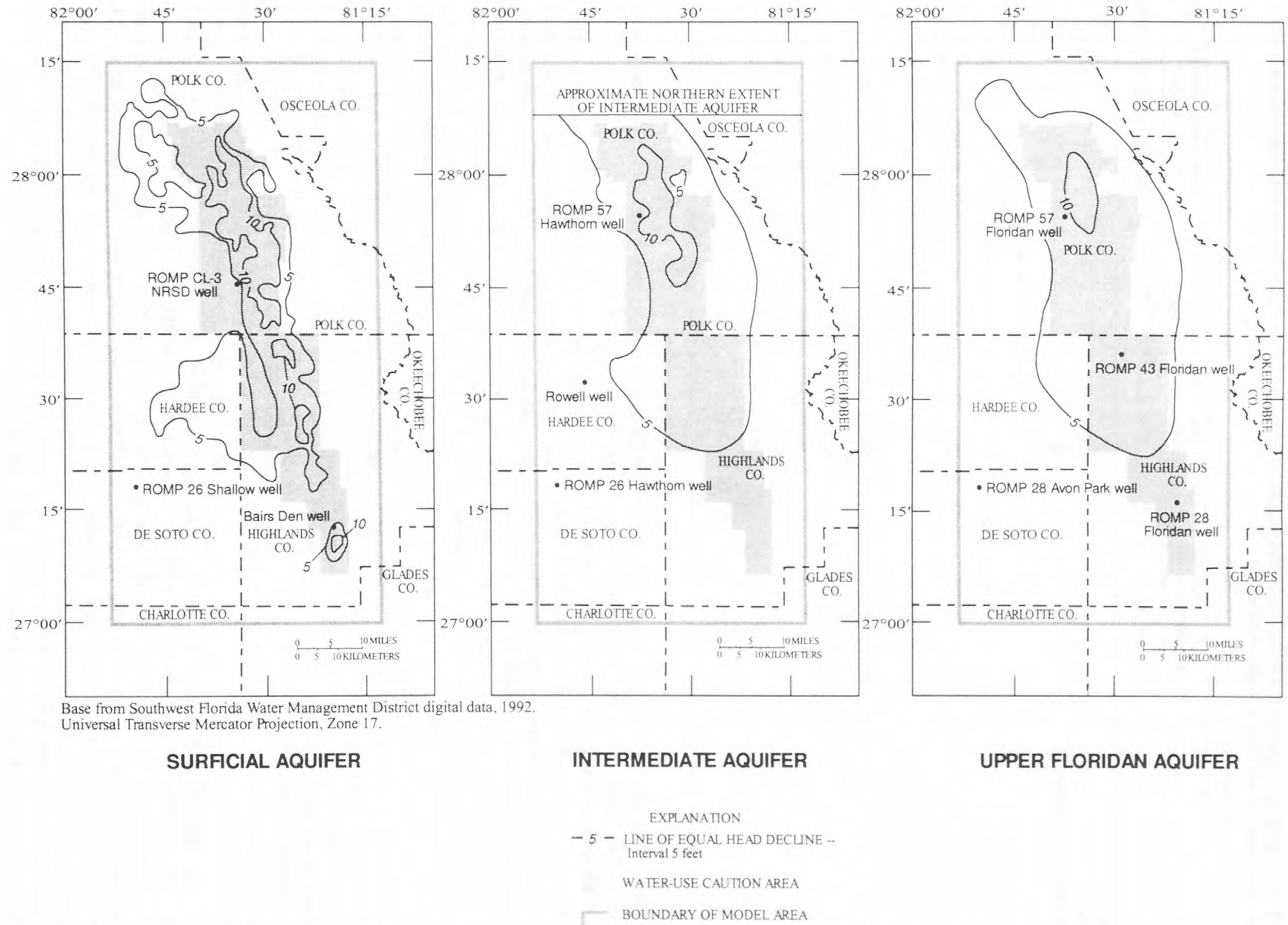


Figure 52. Simulated decline of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer at the end of September 2009 as a result of the continuation of present (1990 water year) permitted ground-water withdrawals of 506 million gallons per day.

Table 9. Simulated ground-water flow rates within the Lake Wales Ridge area, Florida, for September 1989 and at the end of 20 years as a result of selected changes in pumpage

[values are in million gallons per day

	September 1989 steady-state conditions	Continuation of 1990 water year conditions and pumpage		Pumpage increased by 45 percent	
		May 2009	September 2009	May 2009	September 2009
Inflows					
Recharge	446.0	446.0	446.0	439.7	439.5
Head dependent boundaries	13.9	65.2	14.1	121.3	23.3
Streams	0.0	1.0	1.0	2.8	2.6
Constant heads	18.9	27.4	22.3	31.5	25.5
Storage	0.0	239.7	22.0	342.0	48.0
Total inflow	478.8	779.3	505.4	937.3	538.9
Outflows					
Upward discharge	48.7	48.7	48.7	48.4	48.4
Head-dependent boundaries	229.7	187.0	177.3	133.9	139.5
Streams	66.6	51.0	52.0	43.8	45.0
Constant heads	7.3	6.2	6.8	5.9	6.4
Pumpage	126.5	486.4	120.1	705.2	174.1
Storage	0.0	0.0	100.4	0.0	125.6
Total outflow	478.8	779.3	505.3	937.2	539.0

Changes in head also would cause changes in volumetric flow rates (table 9). In the steady state simulation, most of the water pumped was obtained from recharge. As shown for all simulations, water was discharged mostly across lateral head-dependent boundaries but a significant amount (26 percent) also discharged by pumping. As the aquifer heads declined during the irrigation season, water was obtained mostly from recharge, but about 31 percent came from aquifer storage and about 18 percent came from decreased lateral boundary outflow. During the non-irrigation season, total pumpage decreased substantially. As aquifer heads rose, a lesser proportion of water came from lateral boundary flows, while ground water returned to aquifer storage. The single largest net change was a decrease of about 22 percent in lateral boundary flows.

In the second simulation, the aquifer was pumped for 20-years at 1.45 times the rate (349 Mgal/d) used in the first alternative, using the same well distribution pattern as alternative one. The 45-percent increase represents the largest possible increase in rate based on predicted water demands. Although an increase in pumpage of this magnitude is unlikely, this simulation illustrates the potential for large changes in aquifer conditions if pumpage were increased substantially.

Increasing the pumping rate increased the extent and magnitude of head declines throughout the modeled area (figs. 53 and 54). After 20 years of pumping at an average rate of 506 Mgal/d, the prominent depression in Polk County at the northern end of the WUCA is predicted to be about twice as deep than that produced by pumping at a rate of 349 Mgal/d. By the end of the irrigation season in May 2009, maximum declines are predicted to exceed 20 feet in the surficial aquifer and exceed 30 feet in the intermediate and Upper Floridan aquifers. The average decline for all model cells in the surficial aquifer, intermediate aquifer, and Upper Floridan aquifer are predicted to be about 4.4, 13.0, and 16.0 feet, respectively. By the end of the non- irrigation season in September 2009, maximum declines are predicted to exceed 20 feet in each aquifer and the average decline for all model cells in the surficial aquifer, intermediate aquifer, and the Upper Floridan aquifer are predicted to be about 4.4, 5.8, and 6.2 feet, respectively. By the end of the second alternative model simulation, 12 grid blocks representing the surficial aquifer had gone dry, indicating dewatering of the aquifer.

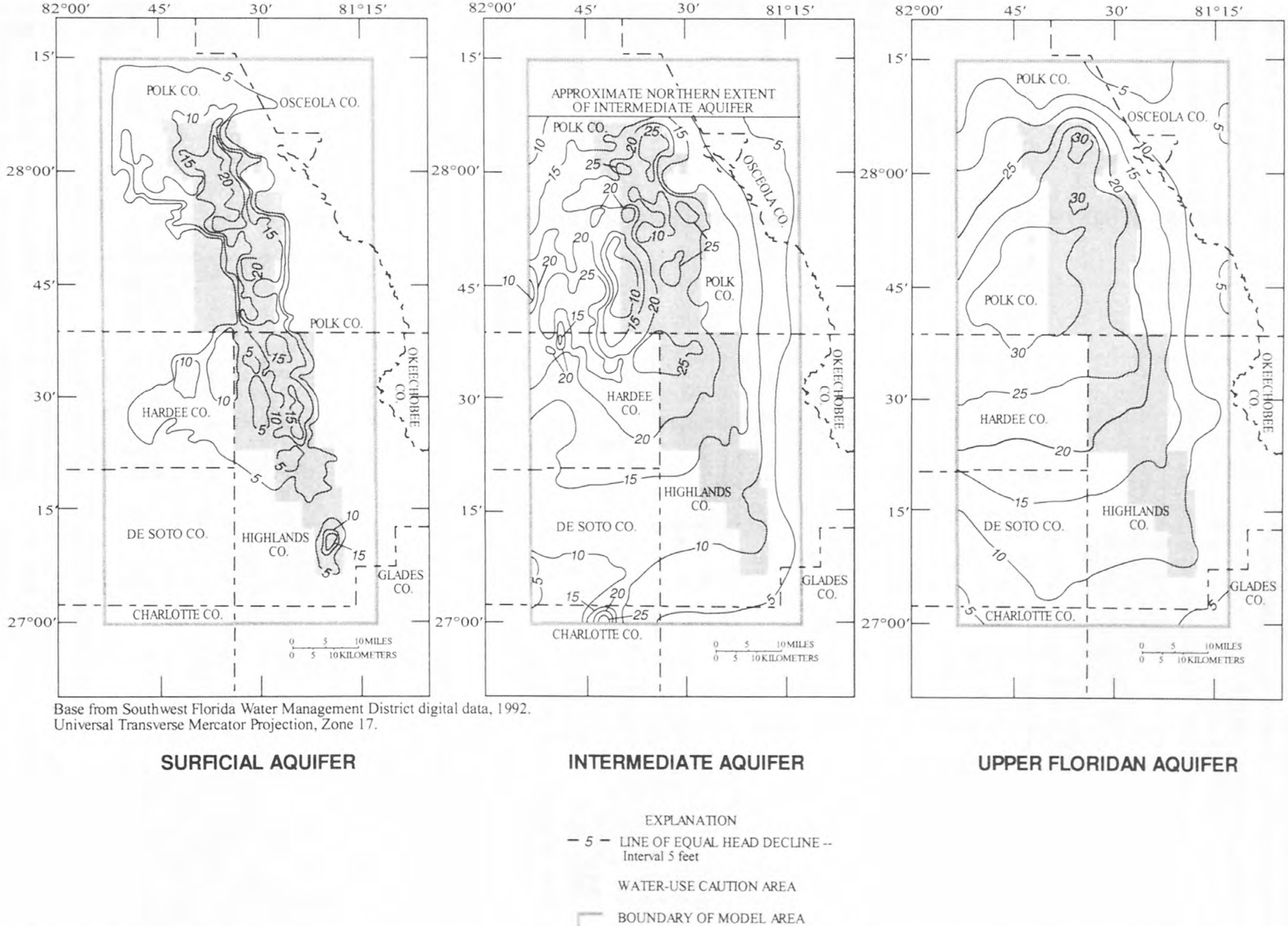


Figure 53. Simulated decline of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer at the end of May 2009 as a result of the continuation of present (1990 water year) permitted ground-water withdrawals of 506 million gallons per day.

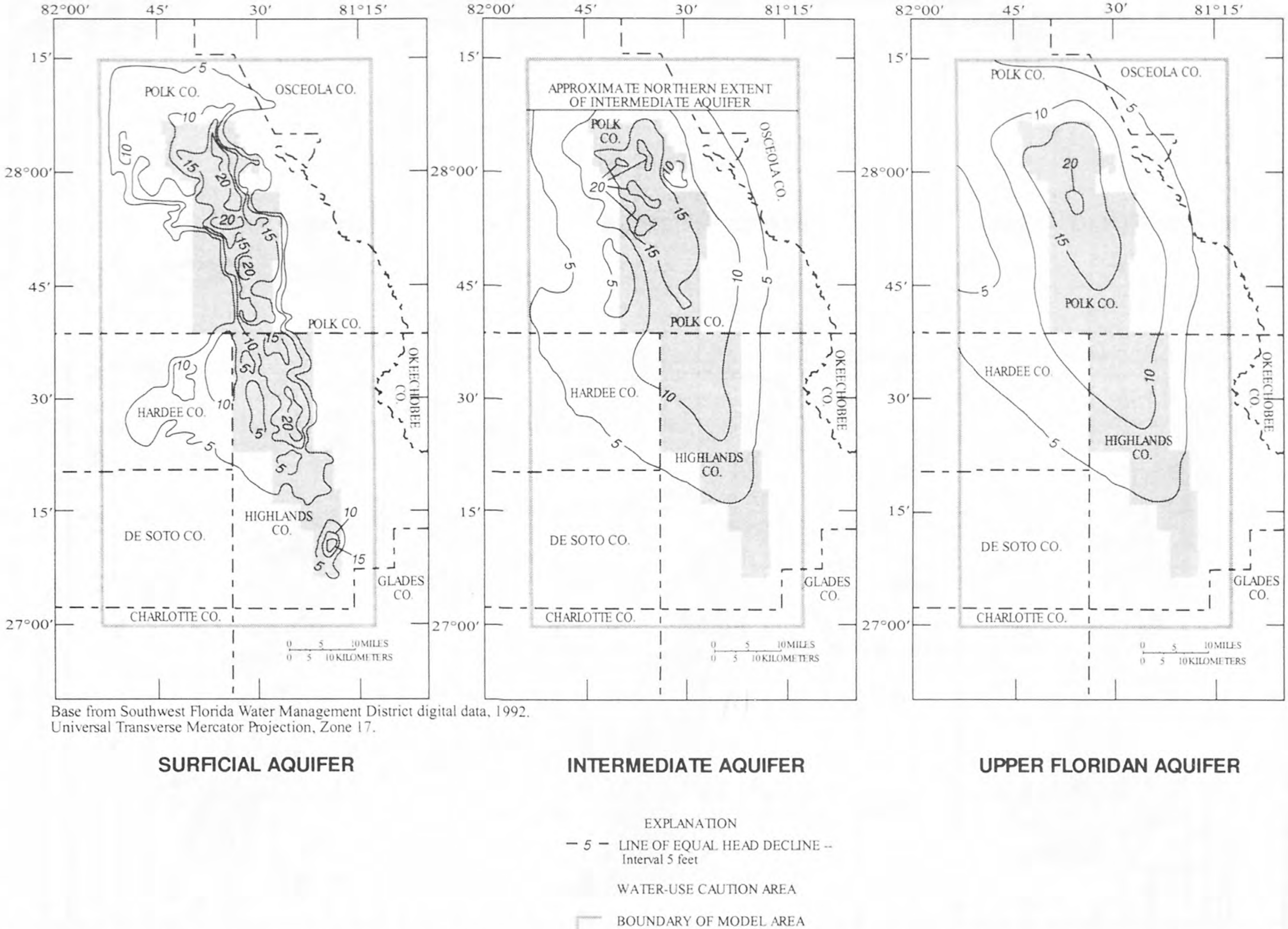


Figure 54. Simulated decline of September 1989 heads in the surficial aquifer, the intermediate aquifer, and the Upper Floridan aquifer at the end of September 2009 as a result of the continuation of present (1990 water year) permitted ground-wster withdrawals of 506 million gallons per day.

In addition to the large head changes due to increased pumpage, large changes in the volumetric flow rates are predicted to occur. The most significant changes in flow rates include: (1) increase in the lateral boundary inflow and the volume of water removed from storage in May 2009, and (2) decrease in lateral boundary outflow and increase in the volume of water returned to storage in September 2009.

Predicted head declines for selected sites for the two 20-year model simulation periods are shown in figure 55. ROMP 57 (Floridan and Hawthorn) and ROMP CL3 NRSD wells are located in Polk County within the WUCA near the centers of the resultant depressions produced by the development alternatives; ROMP 43 Floridan, ROMP 28 Floridan, and Bairs Den wells are located within the WUCA near the southern periphery of the resultant depression in Highlands County; ROMP 26 (Shallow, Hawthorn, and Avon Park) and Rowell wells are located outside of the WUCA near the western periphery of the resultant depression in De Soto and Hardee Counties, respectively. These plots approximate the predicted hydrographs for the observation wells located at the corresponding sites.

The general trend of the hydrographs for the two development alternatives, particularly within the WUCA, is one of continually declining heads at gradually decreasing rates of decline. The sawtoothed pattern exhibited by these predicted head declines results from the seasonal variation in irrigation pumpage. During nonirrigation months aquifer heads partially recover from the effects produced by pumping during the previous irrigations months. The recovery pattern is generally the same for both simulations, however, the decline in yearly peak values indicates that discharge from pumpage exceeded the rate of recharge during the simulation. Aquifer heads will asymptotically approach values appropriate to the establishment of a new steady-state flow system.

In summary, simulation of the two development alternatives resulted in head declines, reduced net lateral boundary outflow, and reduced ground-water discharge to streams. Aquifer-head declines are predicted to mostly occur in the high recharge areas of the WUCA. The extent and magnitude of head declines and the rate of reduction of natural discharge will depend on the net pumping rate, the degree of confinement that exists between aquifers (leakance), and the availability of recharge. The rate of leakage from the surficial aquifer will be limited by the head difference between aquifers and the hydraulic conductivity of the confining units while the head difference between aquifers will be limited primarily to the net pumping rate. Pumping at greater rates produced greater declines. The general trend within the WUCA is one of continually declining aquifer heads at a gradually decreasing rate of decline. Pumping induces leakage from the overlying surficial aquifer and reduces discharge to it, thereby lowering the water table. Initially, most of the water that would be discharged from the aquifer system by pumpage would be derived from water held in storage within the aquifer system, and withdrawal of this water would be accompanied by the development and growth of cones of depression. As the head decline increases, an increasing fraction of the water discharged by wells would be derived from the surficial aquifer, through downward leakage primarily in areas of high recharge. Eventually most or all of the water that is discharged by pumpage may be supplied by water from storage in lakes and in the surficial aquifer. Because lakes are hydraulically connected to the surficial aquifer, the level of lakes within the WUCA are predicted to decline substantially as a result of current or future pumpage and a continuation of 1990 hydrologic conditions. It is important to note that the simulations show that a system of steady-state flow was not established within the WUCA at the end of the two 20-year simulation periods and equilibrium conditions within the WUCA were being met at a much slower and less complete rate when compared to most areas outside of the WUCA.

Appraisal of Model Results

This computer model represents a simplification of the ground-water flow system in the Lake Wales Ridge and adjacent areas. The hydrogeologic system was conceptualized, the hydraulic properties identified and estimated, and transformed into the mathematical analog. The model offers approximate solutions to differential equations that define the system, and, because it is an approximation, the model has a limited capability to simulate the natural system in detail. For this reason, caution is advised when interpreting model results.

The accuracy of the model is dependant on the assumptions and approximations in the finite-difference calibration, the distribution and quality of the data, and how well the model simulated the ground-water flow system under present-day conditions.

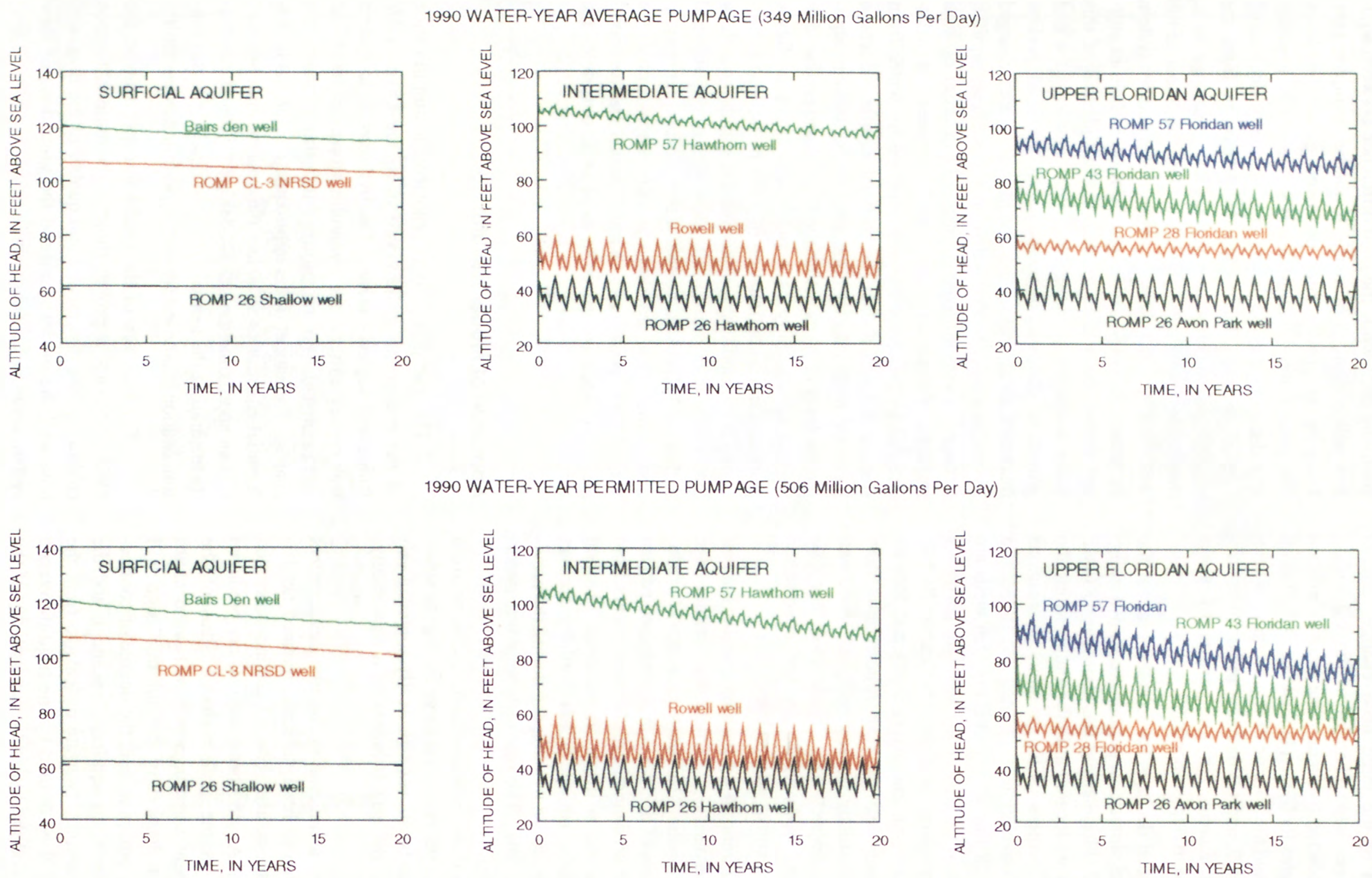


Figure 55. Projected hydrographs of selected sites in the Lake Wales Ridge area for the two 20-year development alternative simulations.

Several simplifying assumptions and limitations were necessary in the simulation and conceptualization of the flow system:

1. It was assumed that fractures and solution openings, through which water flows in the intermediate and Upper Floridan aquifers, could be represented as a porous medium and that Darcy's law was applicable at a regional scale. This assumption may be reasonable because the model grid spacing is in miles.
2. The model simulation also assumed steady-state conditions in September 1989. Whether or not current ground-water discharge is in equilibrium with current recharge is unknown; however, the rapid achievement of equilibrium in the Upper Floridan aquifer following cessation of pumping tends to support this assumption.
3. The effect of pumping large quantities of water near the model-grid boundary may not be depicted accurately because of inaccuracies in boundary assumptions. However, the model boundaries were selected sufficiently far away from the WUCA to minimize errors within the WUCA.
4. The constant-head boundary around the perimeter of the surficial aquifer system could lead to errors in heads near the boundary because it tends to minimize the drawdown near the boundary.
5. The scale of the model limits the capability of the model to provide detailed analysis of local flow effects within the 1 mi^2 blocks and only partially accounts for ground-water flow between the surficial aquifer and lakes and streams. However, it is probably not possible to accurately simulate ground-water flow at a smaller scale than about 1 mi^2 in this karstic terrain with models that assume equivalent porous media flow such as McDonald-Harbaugh. All these limitations may serve to introduce errors in calibration and in predicted head change.

Tests of the model's sensitivity to changes in hydraulic properties have indicated that there is no unique set of input data. The model could be calibrated over a rather broad range of values for most hydrogeologic characteristics of the simulated ground-water system. One of the least known and most important parameters is the vertical leakance of the confining units. This parameter along with the difference in head between aquifers controls movement of water between aquifers. Vertical leakance values were refined on the basis of ground-water levels, distribution and amount of recharge, and the distribution and amount of discharge. Increasing recharge in the simulation resulted in a corresponding increase in discharge and a proportional increase in vertical leakage values. Thus the vertical leakance values determined by simulation include an uncertainty equal to the uncertainty of the estimated recharge. The reliability of the valuation also is related to how well the model simulated the ground-water flow system under present-day (1990) conditions. The model was calibrated by simulating aquifer heads measured at individual wells and lakes for four different stress periods, under steady-state and transient conditions. Calibrations were made for seasons when withdrawals were lowest and aquifer heads were highest and for seasons when withdrawals were highest and aquifer heads were lowest. In some areas, simulated heads were much higher or lower than observed heads. These differences were acceptable as long as they could be accounted for by the amount of data available to determine how closely the measured data can be reproduced by simulation. Overall, a good agreement was obtained between simulated and measured heads, and the simulation results seem to adequately represent conditions in the aquifer system.

The calibration process often can be of value in improving the modeler's understanding of the functioning of the system being modeled. In this study it was noted that:

1. Calibration of the model was achieved with very little manipulation of the transmissivity distributions for the intermediate aquifer and for the Upper Floridan aquifer that were derived from aquifer tests and regional models. This indicates that the values from these sources reasonably define transmissivity in the physical system.
2. Significant adjustments in vertical leakance values were required to calibrate the model. This indicates that leakage in the area is quite variable, perhaps more variable than is indicated by aquifer tests.
3. The surface-water/ground-water interaction for both streams and lakes were poorly simulated. This indicates that the connection between the streams and lakes with the surficial aquifer cannot be considered direct on a regional scale.

This model is not unique and many combinations of aquifer properties and recharge-discharge distributions can produce the same results. However, model-derived aquifer properties, as a result of extensive calibration simulations, were within realistic limits based on available field data. Despite this deficiency, this model is presently the best available tool for analyzing the regional flow of ground water and for evaluating the long-term effects of large-scale ground-water withdrawals within the WUCA and adjacent areas.

SUMMARY AND CONCLUSIONS

The 750-mi^2 area of the Lake Wales Ridge in central Polk and western Highlands Counties, Florida, is an upland recharge area that contains many sinkhole lakes. The regional decline of lake levels has prompted several studies in the area. This study was designed to gain a better understanding of the ground-water flow system in the Lake Wales Ridge and adjacent areas and how pumping affects aquifer water levels.

The sediments underlying the study area form a multi-aquifer system consisting of a water-table aquifer and an underlying sequence of two confined aquifers and intervening confining units. The principal hydrogeologic units underlying the study area include the surficial aquifer, the intermediate aquifer and confining units, and the Floridan aquifer system.

The surficial aquifer is composed of clastic deposits that range in thickness from about 10 to 300 feet. The most important function of the surficial aquifer is to store water. The surficial aquifer is the major source of recharge to the underlying aquifers.

The intermediate aquifer and confining units are composed of Miocene and younger age clastic sediments interbedded with carbonates. The thickness of the aquifer system varies widely and ranges from 0 to more than 500 ft. Transmissivity of the permeable units of the aquifer system is generally less than 13,000 ft^2/d. The leakage coefficients range from 1.0×10^{-6} to 1.0×10^{-3} (ft/d)/ft for the upper confining unit and from 1.0×10^{-6} to 1.3×10^{-4} (ft/d)/ft for the lower confining unit.

The Floridan aquifer system consists of a thick, hydraulically connected sequence of Tertiary-age carbonate rocks. The system consists of the Upper Floridan aquifer, the middle confining unit, and the Lower Floridan aquifer. The freshwater flow system is limited to the Upper Floridan aquifer in the study area because the middle confining unit and the Lower Floridan aquifer generally contain saltwater. The thickness of the Upper Floridan aquifer ranges from about 1,200 to 1,400 feet. Transmissivities of the Upper Floridan aquifer range from about 10,300 to 270,000 ft^2/d based on aquifer tests, whereas transmissivities based on model simulations range from 12,000 to 400,000 ft^2/d. The storage coefficient of the Upper Floridan aquifer ranges from about 1.8×10^{-2} to about 3.1×10^{-4} based on aquifer tests.

A total of about 401 Mgal/d of freshwater was withdrawn from the aquifer system in calendar year 1990, mostly for agricultural, industrial and public supply pumpage. The Upper Floridan aquifer is the major source of water supply in the modeled area and supplies more than 30 times the amount of water from within the surficial or intermediate aquifers. The primary use of ground-water in the area is for agriculture and accounts for 275 Mgal/d. Mining is the second largest user of ground-water and accounts for 60 Mgal/d. Withdrawals for public supply average about 48 Mgal/d.

Ground-water levels fluctuate seasonally with highest levels generally in September at the end of the wet season, and lowest levels generally in May at the end of the dry season. Seasonal fluctuations are generally less than 5 feet in the surficial aquifer and generally less than 30 feet in the intermediate and Upper Floridan aquifers. Water-level declines are caused by pumpage for agriculture and mining. In areas where pumpage for irrigation is small, water levels seldom vary more than 10 feet seasonally. Well hydrographs indicate a general downward trend in annual peaks and an increase in the range between seasonal low- and high-water levels during the late 1960's and early 1970's. Long-term declines in lake levels also have occurred. Lakes located at higher altitude on the Lake Wales Ridge generally have experienced larger water-level fluctuations than lakes located at lower altitudes.

The Lake Wales Ridge hydrologic system can be generalized as follows. Water moves downward from the surficial aquifer to the intermediate aquifer and the Upper Floridan aquifer in the central area, primarily under the ridges, with minor flow under the flatlands. Ground water then flows laterally away from the central area and downgradient to discharge areas to the west, east, and south. Local movement of ground water is to nearby streams and lakes.

Ground-water flow within the surficial aquifer is predominantly towards major streams and lakes. Ground-water flow in the intermediate and Upper Floridan aquifers is generally west towards the Peace River and east towards the Kissimmee River. The general configuration and head gradients of the potentiometric surfaces of the intermediate and Upper Floridian aquifer between seasons is similar; however, the potentiometric contours in May compared to September of each year are shifted inland.

Downward leakage from the surficial aquifer to the underlying confined aquifers occurs in most ridge and upland areas; upward leakage occurs along valleys of major streams.

A quasi-three-dimensional, finite-difference computer model of the ground-water flow system was constructed. The model was initially calibrated in a steady-state simulation in which simulated heads were within 10 feet of observed or estimated ground-water levels. Simulation of ground-water discharge to streams was poor, probably due to the scale of the model and because measured streamflow does not represent natural conditions.

Simulated water-budget computations for the September 1989 steady-state model run shows that about 49 percent of ground-water discharge was lateral boundary flow, about 26 percent was pumpage, about 14 percent was streamflow, and about 11 percent was diffuse upward seepage to wetlands. Leakage from the surficial aquifer into the intermediate aquifer was simulated at about 378 Mgal/d. Downward leakage was equivalent to about 2.3 inches per year over the modeled area.

Sensitivity tests conducted during calibration of the steady-state model indicated that simulated heads are generally more sensitive to decreases in parameter values than to increases in parameter values. The model calibrations are very sensitive to changes in transmissivities of the Upper Floridan aquifer, net recharge/discharge and pumpage. The model calibrations is comparatively insensitive to changes in transmissivity of the intermediate aquifer, hydraulic conductivity of the surficial aquifer, and river-bed conductances.

The calibrated hydraulic parameters were further tested by a transient simulation that involved matching observed or estimated heads for May 1990 and September 1990, and by comparing simulated water-level hydrographs with observed water-level hydrographs on a monthly basis. Overall, observed heads agreed reasonably well with heads simulated by the model. In most instances, differences could be accounted for by reasonable ranges of errors in the input parameters.

Simulated water-budget computations for the May 1990 transient model period shows that about 86 percent of ground water was discharge by ET, about 11 percent was discharge by pumpage, and about 3 percent was discharge across lateral boundaries. Most of the water pumped was derived from an increase in downward leakage and from a decrease in lateral boundary flow. Leakage into the Upper Floridan aquifer increased about 54 percent and net boundary flow decreased about 47 percent during the irrigation season (September 1989 to May 1990).

Sensitivity analysis indicated that the transient model was most sensitive to changes in net recharge/discharge and pumpage, particularly increased net recharge/discharge. Storage coefficients for the intermediate and Upper Floridan aquifer are significantly less important because high transmissivities allow rapid head changes throughout the confined regional system.

A final test of the model was made using a transient simulation for the period October 1988 through September 1989. Results indicate that there is a reasonable match between model-simulated and observed heads, however, the May 1989 transient calibration has greater error and deviation than the May 1990 calibration result.

The calibrated flow model was used to evaluate the short-term effects of 1990 water year pumpage (120 to 486 Mgal/d) on the September 1989 ground-water flow system. Five one-year simulations were made to assess the effects of different pumping alternatives. Simulation of removing all pumpage from the model area during the 1990 water year indicated a maximum head rise of about 2 feet in the surficial aquifer, about 12 feet in the intermediate aquifer, and about 16 feet in the Upper Floridan aquifer. The high-rate recharge areas along the Lake Wales Ridge are most affected by pumping. The simulation in which there was no pumpage for agriculture resulted in a maximum recovery of about 2.0 feet in each aquifer. The effects of agriculture pumpage on the confined aquifer are small whereas the effects of pumping on the surficial aquifer are relatively large.

The simulation in which there was no industrial and mining use in 1990 water year resulted in a maximum recovery of less than 0.5 feet in the surficial aquifer, about 10 feet in the intermediate aquifer, and about 14 feet in the Upper Floridan aquifer. The phosphate mining area of southwest Polk County was most affected by industrial pumpage. The simulated effect of no public supply pumpage is a maximum recovery of about 0.5 feet in the surficial aquifer, about 4 feet in the intermediate aquifer, and about 10 feet in the Upper Floridan aquifer. The simulated effects of no pumpage for public supply are greatest near the larger municipalities. Simulation of no regional pumping outside the WUCA during the 1990 water year indicated maximum recoveries of less than 2 feet within the WUCA.

The calibrated flow model also was used to evaluate the effects of long-term pumping on heads in the aquifer system. Two 20-year model simulations were run: (1) continuation of 1990 water year hydrologic conditions and pumping rates (349 Mgal/d), and (2) continuation of 1990 water year hydrologic conditions and increased pumpage (506 Mgal/d). Simulation of continued 1990 water year hydrologic conditions and pumping for 20 years indicated that head declines of more than 10 feet might be expected in each aquifer in the northern part of the WUCA. Simulation of increased ground-water pumpage (by 45 percent) for 20 years indicated maximum head declines exceeding 23 feet in each aquifer in the northern part of the WUCA. Because lakes are hydraulically connected to the surficial aquifer, the level of lakes within the WUCA could decline substantially as a result of present or future pumping and a continuation of 1990 hydrologic conditions. These relatively large head declines were accompanied by decreased simulated lateral boundary outflow of about 40 percent and decreased simulated water discharge to rivers by about 32 percent. A condition of steady state was not established at the end of the two 20-year simulation periods and equilibrium conditions were being met at a much slower and less complete rate within the WUCA when compared with most areas outside of the WUCA.

In this study it was noted that; (1) calibration of the model was achieved with very little manipulation of the transmissivity distributions for the intermediate aquifer and the Upper Floridan aquifer, (2) significant adjustments in vertical leakance values were needed to calibrate the model, and (3) the surface-water/ground-water interaction for both streams and lakes were poorly simulated.

The computer model is based on a simplified conceptual model of the ground-water flow system in the study area. The mathematical solution was an approximate solution to the differential equations that define the ground-water flow system. For this reason, caution is advised when interpreting model results. Model-derived properties, however, resulted from extensive calibration simulations and are within realistic limits.

SELECTED REFERENCES

Adams, D.B. and Stoker, Y.E., 1985, Hydrology of Lake Placid and adjacent areas, Highlands County, Florida: U.S. Geological Survey Water-Resources Investigations Report 84-4149, 1 sheet.

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

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

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

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

Barr, G.L., 1992, Ground-water contamination potential and quality in Polk County, Florida: U.S. Geological Survey Water-Resources Investigations Report 92-4086, 92 p.

Barcelo, M.D., Slonena, D.L., Camp, S.C., and Watson, J.D, 1990, Ridge II, A hydrogeologic investigation of the Lake Wales Ridge: Southwest Florida Water Management District, 121 p.

Belles, R.G., and Martin, E.H., 1985, Hydrology of Lake June-in-Winter, Highlands County, south-central Florida: U.S. Geological Survey Water-Resources Investigations Report 84-4303, 1 sheet.

Bengtsson, T., 1987, Development and documentation of a transient quasi-three-dimensional, finite-difference model of the tri-county well-field area: Southwest Florida Water Management District, 95 p.

Bishop, E.W., 1956, Geology and ground-water resources of Highlands County,

Florida: Florida Geological Survey Report of Investigations 15, 115 p.

Bradburry, K.R., Kartos, L.F., and Richters, D.F., 1978, Hydrology and limnology of Crooked Lake near Babson Park, Florida: Brooksville, Florida, Southwest Florida Water Management District, 47 p.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-C, 80 p.

Cooke, C.W., 1945, Geology of Florida: Florida Geological Survey Bulletin 29, 339 p.

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 90-4101, 46 p.

Duerr, A.D., Hunn, J.D., Leweling, B.R. and Trommer, J.T., 1988, Geohydrology and 1985 water withdrawals for the aquifer systems in southwest Florida, with emphasis on the intermediate aquifer system: U.S. Geological Survey Water-Resources Investigations Report 87-4259, 115 p.

Durbin, Timothy J., 1978, Calibration of a mathematical model of the Antelope Valley ground-water basin, California: U.S. Geological Survey Water-Supply Paper 2046, 51 p.

Fretwell, J.D., 1988, Water resources and effects of ground-water development in Pasco County, Florida: U.S. Geological Survey Water-Resources Investigations Report 87-4188, 209 p.

Geraghty and Miller, Inc., 1979, Basic data framework of the Highlands Ridge hydrologic investigation: Consultant's report prepared for and in the files of the Peace River Basin Board of the Southwest Florida Water Management District, 27 p.

Geraghty and Miller, Inc., 1980, Highlands Ridge hydrologic investigation: Consultant's report prepared for and in the files of the Peace River Basin Board of the Southwest Florida Water Management District, 142 p.

Grubb, H.F., and Rutledge, A.T., 1979, Long-term water-supply potential, Green Swamp area, Florida: U.S. Geological Survey Water-Resources Investigations 78-99, 76 p.

Hammett, K.M., 1981, Hydrologic description of Lake Jackson, Sebring, Florida: U.S. Geological Survey Open-File Report 81-494, 1 sheet.

Hammett, K.M., 1990, Land use, water use, streamflow characteristics, and water-quality characteristics of the Charlotte Harbor inflow area, Florida: U.S. Geological Survey Water Supply Paper 2359, 64 p.

Hickey, J.J., 1984, Field testing the hypothesis of Darcian flow through a carbonate aquifer: Ground Water, v. 22, no. 5, 544-547 p.

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

Hughes, G.H., 1974, Water-level fluctuations of lakes in Florida: Florida Bureau of Geology Map Series 62, 1 sheet.

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.

Hutchinson, C.B., 1984, Hydrogeology of well-field areas near Tampa, Florida, phase 2--development and documentation of a quasi-three-dimensional finite-difference model for simulation of steady-state ground-water flow: U.S. Geological Survey Water-Resources Investigations Report 84-4002, 174 p.

Jones, K., 1978, Hydrogeology of the Lake Buffum area: Brooksville, Florida, Southwest Florida Water Management District, 10 p.

Kaufman, M.I., 1967, Hydrologic effects of ground-water pumpage in the Peace and Alafia River basins, Florida, 1934-1965: Florida Geological Survey Report of Investigations 49, 32 p.

Knochenmus, L.A., 1990a, Potentiometric surface of the intermediate aquifer system, west-central Florida, May 1990: U.S. Geological Survey Open-File Report 90-555. 1 sheet.

Knochenmus, L.A., 1990b, Potentiometric surface of the Upper Floridan aquifer, west-central Florida, May 1990: U.S. Geological Survey Open-File Report 90-556, 1 sheet.

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

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

Kohout, F.A., and Meyer, F.W., 1959, Hydrologic features of the Lake Istokpoga and Lake Placid areas, Highlands County, Florida: Florida Geological Survey Report of Investigations 19, 73 p.

Lee, T.M., and Swancar, Amy, 1994, Influence of evaporation, ground water, and uncertainty in the hydrologic budget of Lake Lucerne, a seepage lake in Polk County, Florida: U.S. Geological Survey Open-File Report 93-26.

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

Maslia, M.L., and Hayes, L.R., 1988, Hydrogeology and simulated effects of ground-water development of the Floridan aquifer system, southwest Georgia, northwest Florida, and southernmost Alabama: U.S. Geological Survey Professional Paper 1403-H, 71 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.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Water-Supply Paper 1403-B, 91 p.

Planert, Michael and Aucott, W.R., 1985, Water supply potential of the Floridan aquifer in Osceola, Eastern Orange, and southwestern Brevard Counties, Florida: U.S. Geological Survey Water-Resources Investigations Report 84-4135, 69 p.

Pride, R.W., Meyer, F.W., and Cherry, R.N., 1966, Hydrology of Green Swamp area in central Florida: Florida Geological Survey Report of Investigations 42, 137 p.

Robertson, A.F., 1973, Hydrologic conditions in the Lakeland Ridge are of Polk County, Florida: Florida Bureau of Geology Report of Investigations 64, 54 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 Report 81-54, 61 p.

Ryder, P.D., 1985, Hydrology of the Floridan aquifer system in west-central Florida: U.S. Geological Survey Water-Supply Paper 1503-F, 63 p.

Shaw, J.E., and Trost, S.M., 1984, Hydrogeology of the Kissimmee planning area, South Florida Water Management District: South Florida Water Management District Technical Publication 84-1, part 1-text, 235 p.

Shupe, M.G., 1987, A three-dimensional simulation of the ground-water flow system of south-central Florida: Master's thesis, College of Arts and Sciences, Ohio University, 557 p.

Southwest Florida Water Management District, 1987, Aquifer characteristics within the Southwest Florida Water Management District: Brooksville, Florida, 30 p.

Southwest Florida Water Management District, 1989-90, Summary of hydrologic conditions: Brooksville, Florida (published monthly).

Southwest Florida Water Management District, 1993, Eastern Tampa Bay water-resources assessment project: Brooksville, Florida.

Stewart, H. G., 1966, Ground-water resources of Polk County, Florida: Florida Geological Survey Report of Investigations 44, 170 p.

Stringfield, V.T., 1966, Artesian water in the Tertiary limestone in the southeastern states: U.S. Geological Survey Professional Paper 517, 226 p.

Swancar, Amy, and Hutchinson, C.B., 1992, Chemical and isotopic composition and potential for contamination of water in the Upper Floridan aquifer, west-central Florida, 1986-89: U.S. Geological Survey Open-File Report 92-47, 47 p.

Tibbals, C.H., 1981, Computer simulation of the steady-state flow system of the Tertiary limestone (Floridan) aquifer system in east-central Florida: U.S. Geological Survey Water-Resource Investigations, 81-681, 31 p.

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

Visher, F.N., and Hughes, G.H., 1975, The difference between rainfall and potential evaporation in Florida (2d ed.): Florida Bureau of Geology Map Series 32.

White, K.E., and Sloto, R.A., 1991, Base flow frequency characteristics of selected Pennsylvania streams: U.S. Geological Survey Water-Resources Investigations Report 90-4160.

White, W.A., 1970, The geomorphology of the Florida peninsula: Florida Bureau of Geology Bulletin 51, 164 p.

Wilson, W.E., 1977, Ground-water resources of De Soto and Hardee Counties, Florida: Florida Geological Survey Report of Investigations 82, 102 p.

Wilson, W.E., and Gerhart, J.M. 1980, Simulated effects of ground-water development in the potentiometric surface of the Floridan aquifer, west-central Florida: U.S. Geological Survey Professional Paper 1217, 83 p.

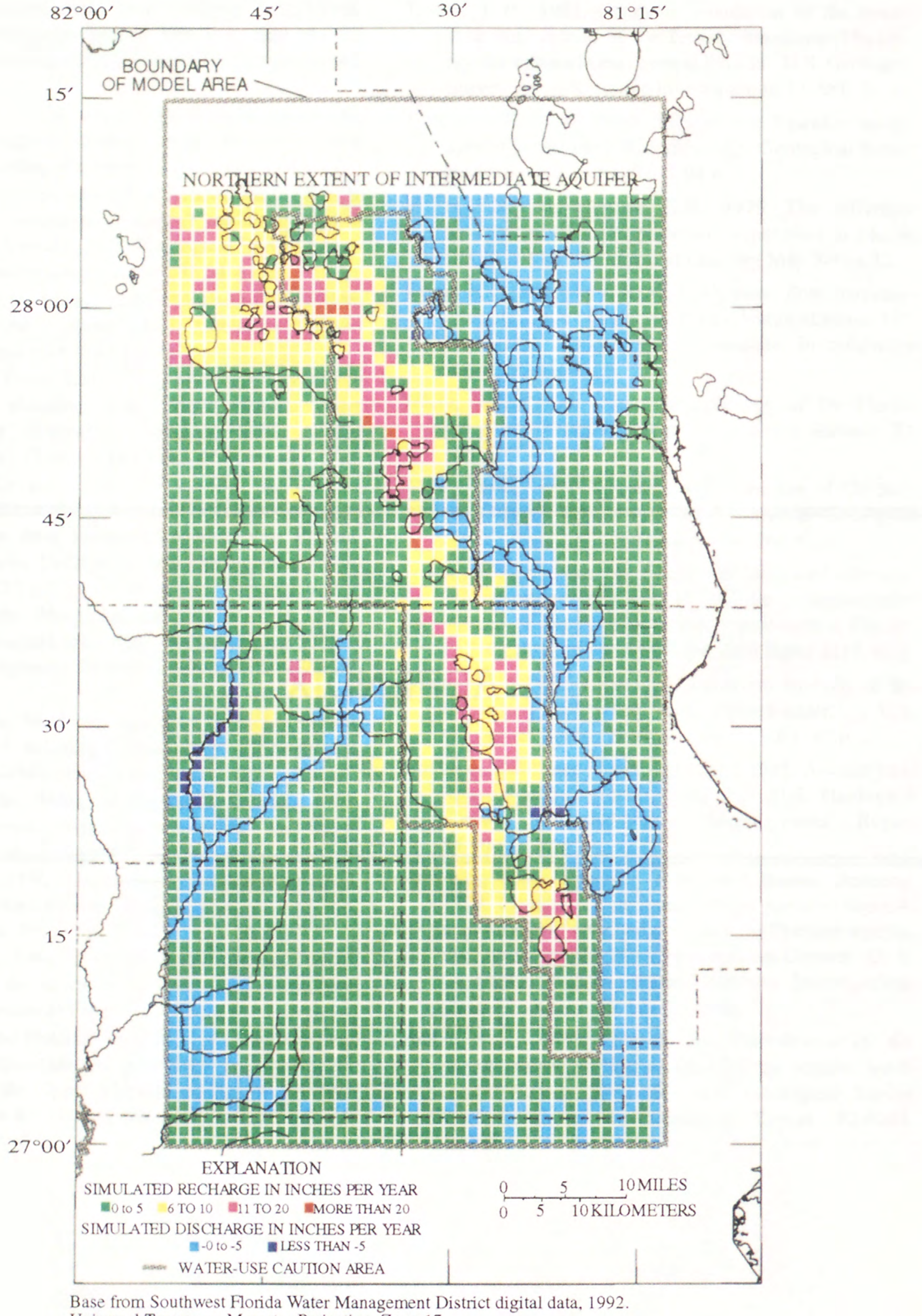
Winter, T.C., 1976, Numerical simulation analysis of the interaction of lakes and ground-water: U.S. Geological Survey Profession paper 1001, 45 p.

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.

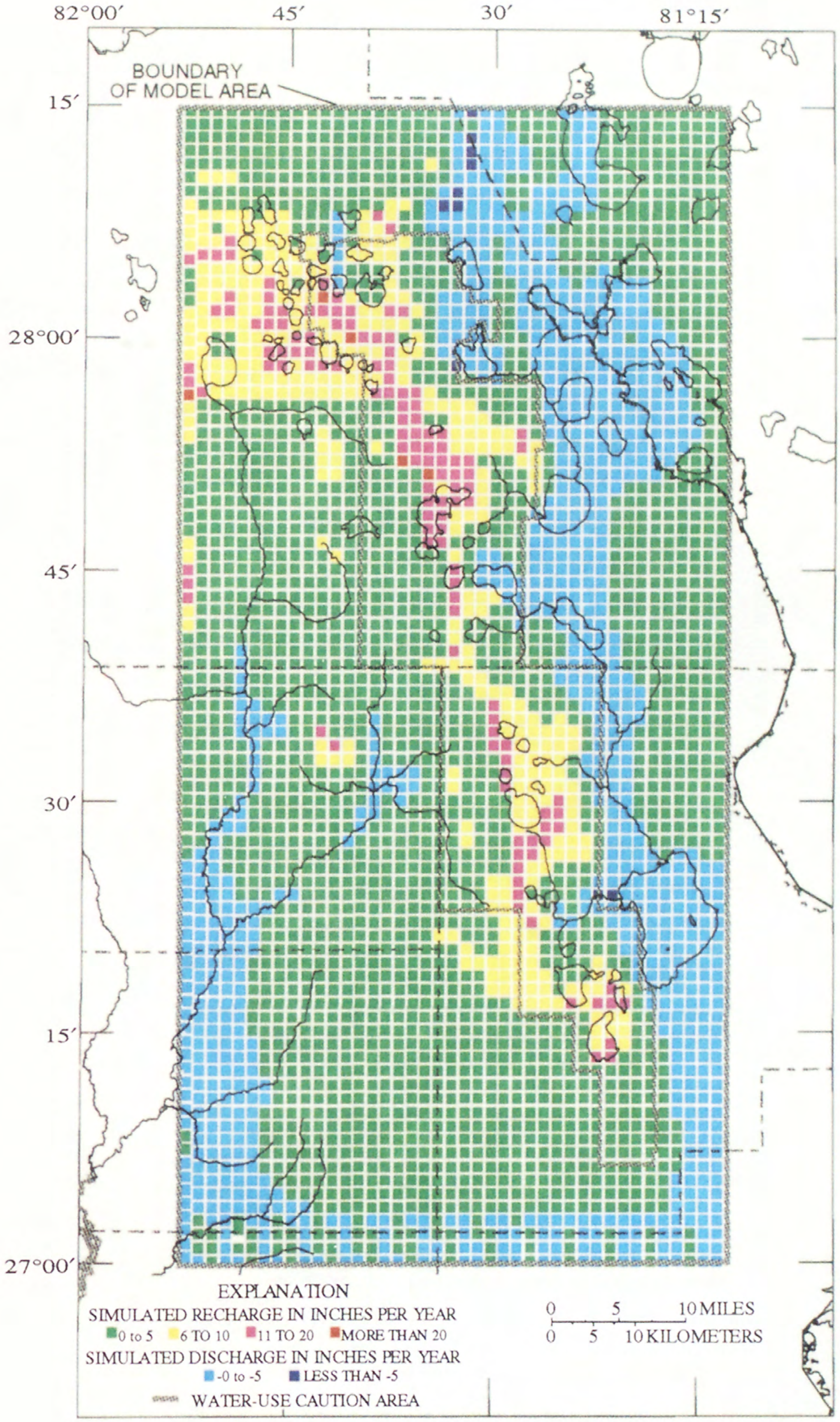
Yobbi., D.K., 1983, Trends and fluctuations in the potentiometric surface of the Floridan aquifer, west-central Florida, 1961-80: U.S. Geological Survey Water-Resources Investigations Report 82-4086, 1sheet.

APPENDIX



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 56. Simulated leakage rates through the upper confining unit, September 1989.



Base from Southwest Florida Water Management District digital data, 1992.
Universal Transverse Mercator Projection, Zone 17.

Figure 57. Simulated leakage rates through the lower confining unit, September 1989.

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