Descriptions of Anisotropy and Heterogeneity and Their Effect on Ground-Water Flow and Areas of Contribution to Public Supply Wells in a Karst Carbonate Aquifer System

United States
Geological
Survey
Water-Supply
Paper 2475

Prepared in cooperation with the Florida Department of Environmental Protection

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

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By LARI A. KNOCHENMUS and JAMES L. ROBINSON

Prepared in cooperation with the
Florida Department of Environmental Protection

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2475

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

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

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1996

For sale by the
U.S. Geological Survey
Branch of Information Services
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Denver, CO 80225–0286

Library of Congress Cataloging in Publication Data

By Knochenmus, Lari A., and Robinson, James L.
Descriptions of anisotropy and heterogeneity and their effect on ground-water flow and areas of contribution to public supply wells in a karst carbonate aquifer system
46 p. cm.—(U.S. Geological Survey Water-Supply Paper 2475)
QE12345 91–4303CIP
[151.7209792] ISBN 0-607-86216-5

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CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
	Flow	
million gallons per day (Mgal/d)	0.04381	cubic meters per day
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day
	Hydraulic conductivity	
foot per day per foot [(ft/d)/ft]	1.00	meter per day per meter

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

Acronyms

FDEP = Florida Department of Environmental Protection
MODFLOW = U.S. Geological Survey modular ground-water flow model
MODPATH = U.S. Geological Survey postprocessor particle tracker
NWHWRAP = Northwest Hillsborough Water Resources Assessment Project
ROMP = Regional observation monitoring well program
VCONT = Vertical conductance

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By Lari A. Knochenmus *and* James L. Robinson

Abstract

Delineation of areas of contribution to wells tapping a karst carbonate aquifer system can be extremely difficult using conventional approaches designed for isotropic and homogeneous aquifers, because ground-water flow tends to be through solution-enhanced conduits. Nonradial flow along preferential zones can result in inaccurate estimates of flow paths and traveltimes. Because of the large variability in factors affecting contributing areas and an imperfect understanding of how these factors can vary, the estimation of contributing areas is an approximation at best.

To better understand the effects of aquifer anisotropy and heterogeneity on areas of contribution, an exploratory modeling approach was used. MODFLOW, a numerical flow model, and MODPATH, a particle tracking program, were used to generate time-related areas of contribution for six hypothetical carbonate aquifer system types. The six types were conceptualized to approximate different types of aquifer anisotropy and heterogeneity. These include: (1) an isotropic and homogeneous single-layer system; (2) an anisotropic in a horizontal plane single-layer system; (3) a discrete vertically fractured single-layer system; (4) a multilayered system; (5) a doubly porous single-layer system; and (6) a vertically and horizontally interconnected heterogeneous system. The simulated aquifer anisotropy was 5:1 (K_{xx}/K_{yy}) determined from TENSOR2D results. The simulated discrete vertical fracture network represents locations inferred from mapped photolineaments. The simulated enhanced flow zones were determined from borehole video and geophysical logs. Areas of contribution were simulated for two prototype regions. The two prototypes were selected to be representative of the hydrologic diversity within the study area and were designated the Central Swamp and Lake Terrace regions.

Localized conditions in pumping, production well distribution, and aquifer transmissivity affect the size, shape, and orientation of areas of contribution to public supply wells. The simulated areas of contribution are 60 percent larger in the Central Swamp region where pumpage is more than double and transmissivity is about half that of the Lake Terrace region. Although these factors are important, this study focused on the effects from hydrogeologic factors common to karst carbonate aquifer systems.

This study indicates that the distribution and type of aquifer anisotropy and heterogeneity will affect the size, shape, and orientation of areas of contribution in a karst carbonate aquifer system. The size of the 50-year time-related areas of contribution ranged from 8.2 to 39.1 square miles in the Central Swamp region and from 4.0 to 18.3 square miles in the Lake Terrace region. Simulations showed that the size of areas of contribution is primarily affected by simulated withdrawal rates, effective porosity of the carbonate rock, and transmissivity. The shape and orientation of the simulated areas of contribution primarily result from aquifer anisotropy, well distribution, flow along solution-enhanced zones, and short-circuiting of flow through fracture networks.

Comparisons also were made between protection zones delineated using analytical models and areas of contribution delineated using numerical models. The size of the 5-year time-related protection zone in the Central Swamp region using an analytical model was almost twice as large as the numerically simulated area of contribution, and more than eight times larger than the numerically simulated area of contribution in the Lake Terrace region. The differences in size are primarily the result of how the flow field is approximated. The analytical method assumes only lateral flow to wells but numerical methods allow particles to move laterally and vertically. Additionally, multiple-well-interference effects resulting from the close proximity of several pumping wells cause individual capture zones to converge or diverge, depending on the difference in pumping rates and orientation among the wells. Such an interpretation is not available from analytical methods. The simulated distributions of aquifer anisotropy and heterogeneity, in this study, were highly conceptualized, but were based on plausible occurrences of anisotropy and heterogeneity inherent in carbonate aquifer systems.

INTRODUCTION

The 1986 Safe Drinking Water Act Amendments require States to establish wellhead protection programs to delineate protective areas (areas of contribution) around existing and future public supply wells and well fields. The contributing area includes the geographical extent from which ground-water flow is diverted to the pumping well (Morrissey, 1989, p. 7-8). Traditional strategies to protect ground-water resources have been through land-use regulation within a prescribed radial area around each well. At times, little regard has been given to localized hydrogeologic factors common to karstic aquifers that can affect the size, shape, and orientation of areas of contribution to supply wells. Public supply wells in karst carbonate aquifers are particularly vulnerable to contamination. This is because permeability in carbonate aquifers is enhanced by circulation of water and dissolution of rock, creating higher permeability along preferred flow paths.

Historically, carbonate aquifers have been treated as diffuse-flow aquifers, in that ground-water movement virtually follows Darcy's law. This assumption, although adequate for defining flow in regional ground-water studies, is inadequate for local studies based on the inaccuracies inherent in the conceptual model. For example, the effects of nonradial, non-Darcian flow due to preferential flow paths through enhanced secondary-porosity zones, such as fractures, is a complicating aspect for developing useful strategies for ground-water protection in carbonate terranes. Therefore, a better understanding of the effects of aquifer heterogeneity on the size, shape, and orientation of contributing areas to supply wells is needed to understand ground-water flow to pumped wells. In 1990, the U.S. Geological Survey, in cooperation with the Florida Department of Environmental Protection (FDEP), began a study to illustrate the effects of aquifer anisotropy and heterogeneity, inherent to karst carbonate aquifers, on the size, shape, and orientation of contributing areas around public supply wells and well fields.

Purpose and Scope

This report describes aquifer anisotropy and heterogeneity in a karst carbonate aquifer, how these heterogeneities affect ground-water flow, and their effect on the size, shape, and orientation of contributing areas to well fields. To evaluate how areas of contribution might be affected by aquifer anisotropy and heterogeneity, a study area in west-central Florida (fig. 1) underlain by the Floridan aquifer system was selected because adequate existing data were available. Within the study area, two prototype carbonate aquifer systems were defined for detailed study. The specific purposes of the report are to:

1. Describe the anisotropy and heterogeneity typical of a karst carbonate aquifer system.
2. Present effects of aquifer anisotropy and heterogeneity on ground-water flow.
3. Show the effects of aquifer anisotropy and heterogeneity on areas of contribution to supply wells.
4. Compare delineation of protection zones determined using analytical methods and areas of contribution determined using numerical methods.

Spatial distributions of aquifer anisotropy and heterogeneity, examined in this report, were based on the results of previous studies. Historical aquifer test data were used as input to a computer program, TENSOR2D (Maslia and Randolph, 1986), to identify the possible range in magnitude and direction of anisotropy (K_{xx}/K_{yy}) in a horizontal plane. Results of a photolineament study (Culbreath, 1988) were used to

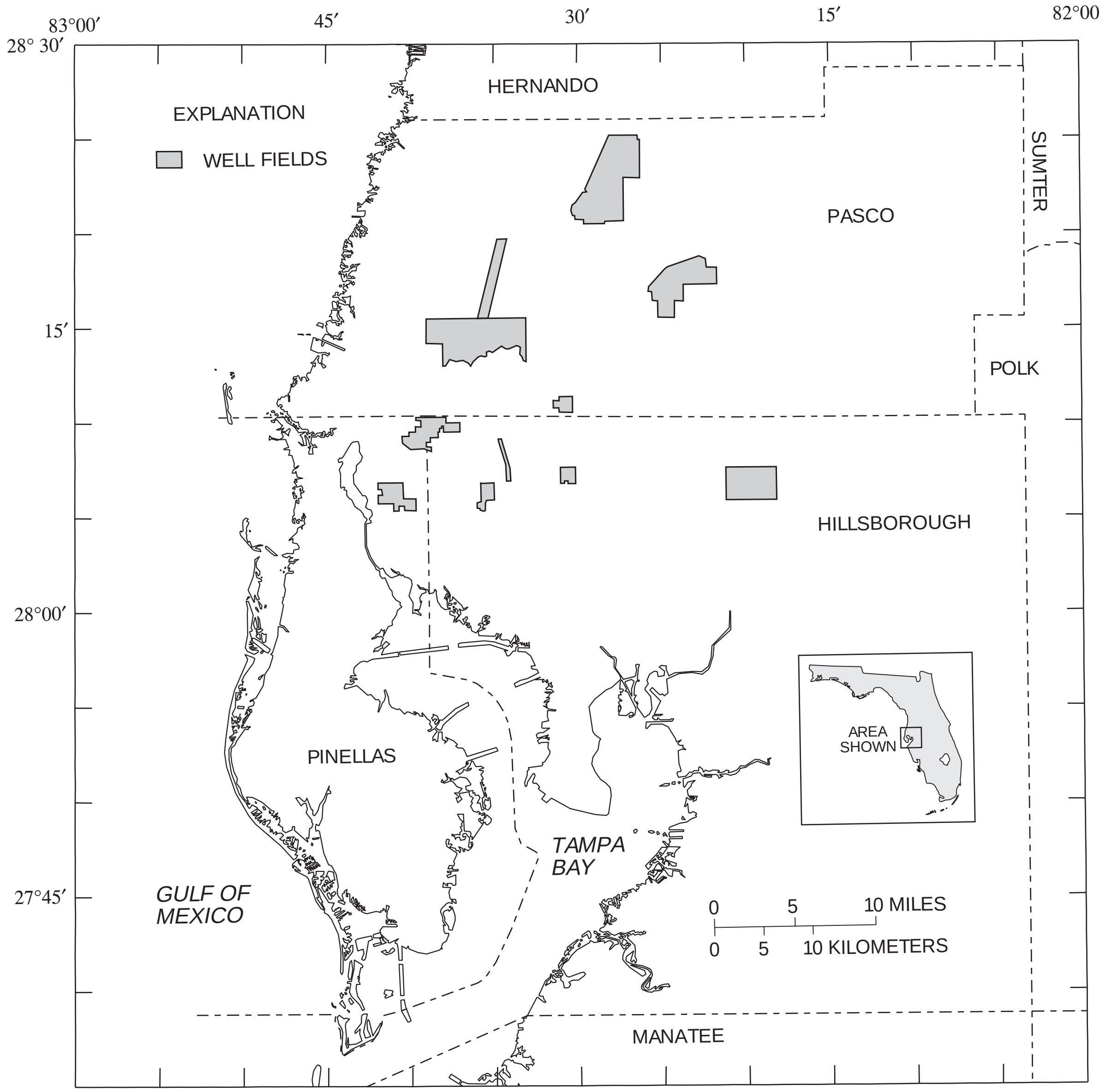


Figure 1. Location of the study area and well fields.

estimate locations of vertical fracture zones. Borehole video and geophysical logs were used to estimate locations of enhanced flow zones (Safko and Hickey, 1992). The data were then used to construct various hypothetical carbonate aquifer system types to be tested at two prototype regions, using the U.S. Geological Survey modular ground-water flow model (MODFLOW) and particle tracking program (MODPATH). This report is based on work done in west-central Florida, but the investigative techniques presented are applicable to similar hydrogeologic settings elsewhere.

Hydrogeology of the Upper Floridan Aquifer, a Typical Karst Carbonate Aquifer System

The most productive carbonate sequence in Florida and the southeastern Coastal Plain is the Floridan aquifer system, composed of limestones and dolomites with enhanced permeability caused by tectonic fracturing and karstification. These processes created secondary porosity, resulting in significant aquifer heterogeneity. Secondary porosity is defined in the Dictionary of Geologic Terms (Bates and Jackson, 1984) as porosity developed in rock after its deposition or emplacement through such processes as solution or fracturing. The mechanisms for secondary porosity development in the Upper Floridan aquifer system are mechanical fracturing and chemical dissolution.

Vertical fracturing in a carbonate aquifer system can occur from propagation of basement structures through the overlying carbonates in response to crustal flexing caused by earth tides (Blanchet, 1957). Surface lineaments have long been recognized as surface manifestations of underlying vertical to near-vertical zones of fracture concentrations (Lattman and Parizek, 1964). Previous investigators recognized the occurrence of fracture traces and surface lineaments in west-central Florida as systematic patterns and correlated these patterns to fractures observed in limestone outcrops (Vernon, 1951, p. 47-52). Culbreath (1988) investigated the correlation between surface lineaments and major faults in the crystalline basement rocks using gravity surface geophysical methods. The surface lineaments that had corresponding gravity anomalies were orthogonally and bimodally distributed, and their preferred orientation is between 45 and 55 degrees east and west of north (fig. 2). Culbreath (1988) hypothesized that geologic structures occurring in this preferred orientation are more likely to be manifested at the surface as lineaments because they parallel the stress fields associated with earth tides.

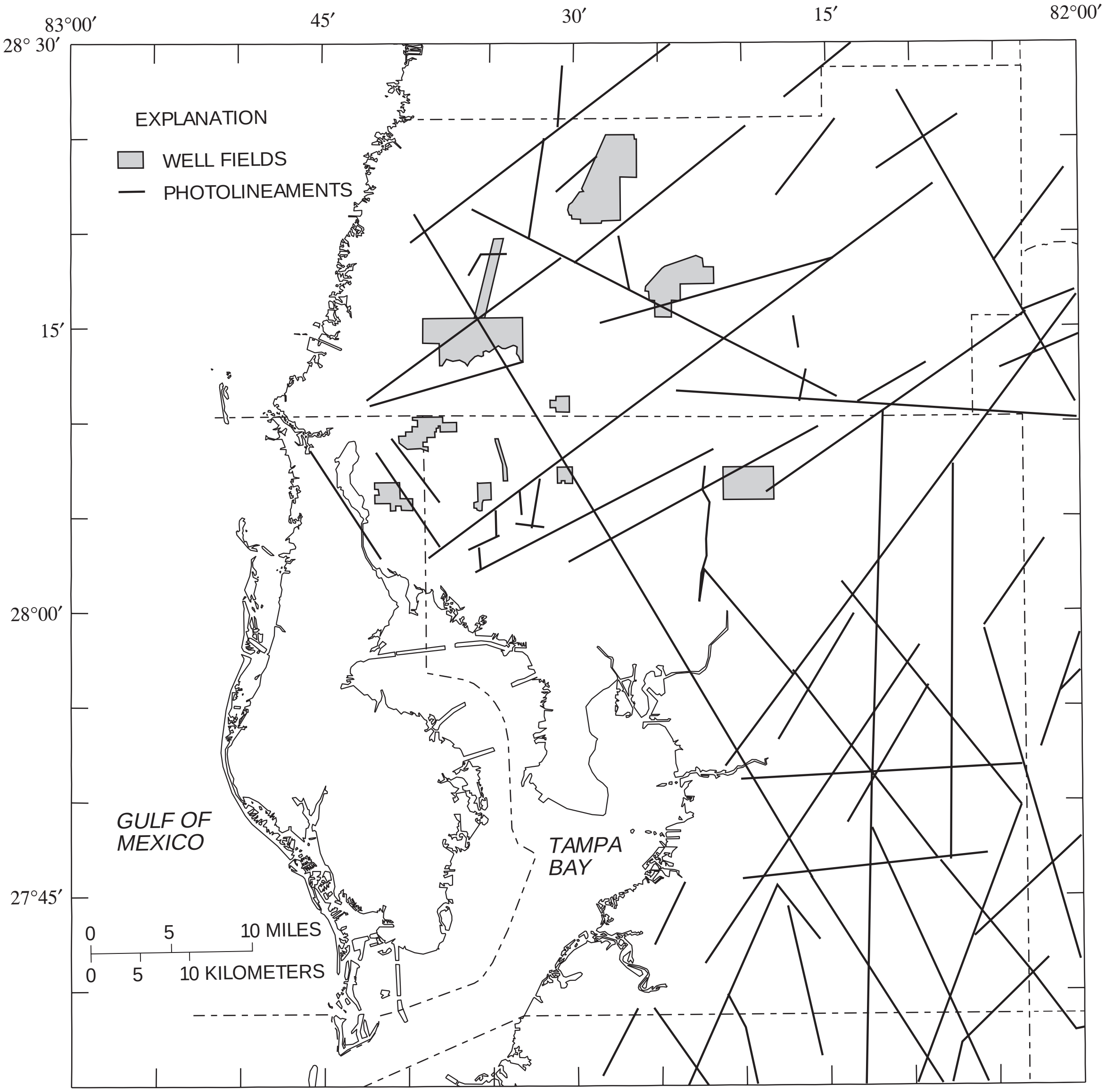


Figure 2. Location of photolineaments that have corresponding gravity anomalies. (Modified from Culbreath, 1988.)

In karst carbonate aquifer systems, fracture zones can be enlarged by chemical dissolution. Fractures channel ground-water flow along discrete paths, resulting in increased solution activity. Lattman and Parizek (1964) observed that karst features and associated highly transmissive zones are related to differential dissolution of the carbonate rock along linear fractures, faults, and joints in the rocks. Within the surface expressions of vertical to near-vertical fractures, narrow zones have been detected where porosity can be 10 to 100 times that of the intergranular matrix (Stewart and Wood, 1984). These narrow zones are highly heterogeneous discrete zones of increased vertical permeability within the carbonate aquifer system.

One mechanism for development of the heterogeneous layering of higher permeability zones in carbonate aquifer systems is chemical dissolution in response to changes in sea level. As water levels in the ocean rise and fall, base-levels change and subaerial karstification is cyclically renewed, creating various horizons of extensive secondary porosity development throughout the carbonate sequence. Chemical dissolution is most aggressive along zones of weakness in carbonate sequences. Horizontal zones of weakness tend to be at lithologic interfaces of differing types, at a specific lithologic boundary where a concentration of impurities such as sand, silt, and shell exists, and where cyclic changes such as laminations occur within a lithology. The lithologic heterogeneity within the Floridan aquifer system resulted from deposition in warm shallow seas over periods of geologic time where even slight changes in depositional conditions and diagenetic alterations resulted in textural and mineralogical changes described above. Vertical fracturing and heterogeneous layering of the carbonate rocks have resulted in variable horizontal and vertical permeabilities in the Upper Floridan aquifer (Williams, 1985). Subtle variations can affect porosity and permeability, resulting in a highly heterogeneous carbonate aquifer system.

Hydrogeologic Setting

The hydrogeologic framework in the study area comprises two aquifers, the clastic surficial aquifer system and the carbonate Floridan aquifer system that are separated by the intermediate confining unit (fig. 3). The Floridan aquifer system consists of the Upper and Lower Floridan aquifers that are separated by a middle confining unit (Miller, 1986). The middle confining unit and Lower Floridan aquifer generally contain saltwater in the study area. The Upper Floridan aquifer contains all or parts of the Avon Park Formation, the Ocala Group, the Suwannee Limestone, and the Tampa Member of the Arcadia Formation of the Hawthorn Group. In this report, the Tampa Member will be used to designate the Tampa Member of the Arcadia Formation of the Hawthorn Group. The formation names used in this report are based upon the geologic definitions of Scott (1988) and are the usage of the Florida Geological Survey.

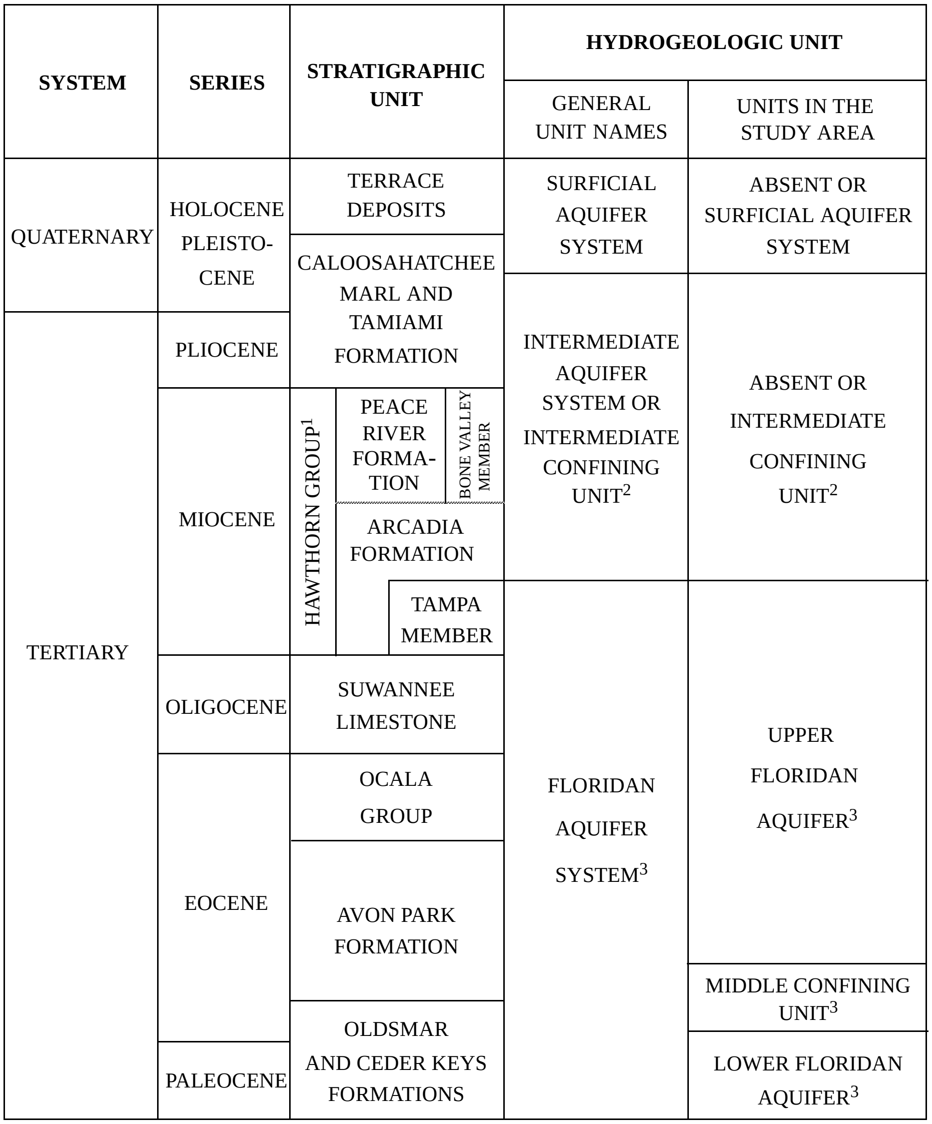
Transmissivity

In general, the majority of water supplied to municipal wells open to the entire Upper Floridan aquifer is from two 50- to 100-ft thick, areally persistent, highly fractured zones in the dolomitic section of the Avon Park Formation (Ryder, 1978; Ryder and others, 1980; CH2M Hill, 1990a,b). The overlying Ocala Group, Suwannee Limestone, and the Tampa Member, where present, also are characterized by discrete producing zones that occur locally and less predictably near formational contacts. Although most of the water is derived from discrete producing zones, the intergranular matrix of the Upper Floridan aquifer also is a source of ground water.

Transmissivity of the Upper Floridan aquifer is highly variable and ranges from 29,400 to 130,000 ft^2/d within the study area. This is a direct result of the anisotropic and heterogeneous nature of the aquifer. Transmissivities determined from aquifer tests for the Upper Floridan aquifer vary widely because: (1) some wells do not penetrate the highly permeable (fractured) dolomites in the Avon Park Formation, (2) the wells may or may not intersect locally occurring permeability zones related to secondary porosity, and (3) the highly heterogeneous and anisotropic nature of the carbonate aquifer system makes the application of standard methods of aquifer test analysis uncertain and the results questionable (Wolansky and Corral, 1985, p. 28). Table 1 lists the ranges in transmissivity in the study area as reported by other investigators and compiled by Bengtsson (1987).

Porosity

The following definitions, of different porosity types, are the terminology used in this report. The porosity classification in based on the size, shape, distribution, and volume of voids compared to the overall volume of rock. Porosity may be microscopic or macroscopic.



<table>
<tr><th rowspan="2">SYSTEM</th><th rowspan="2">SERIES</th><th rowspan="2" colspan="3">STRATIGRAPHIC UNIT</th><th colspan="2">HYDROGEOLOGIC UNIT</th></tr>
<tr><th>GENERAL UNIT NAMES</th><th>UNITS IN THE STUDY AREA</th></tr>
<tr><td rowspan="3">QUATERNARY</td><td rowspan="3">HOLOCENE
PLEISTOCENE</td><td colspan="3">TERRACE DEPOSITS</td><td rowspan="2">SURFICIAL AQUIFER SYSTEM</td><td rowspan="2">ABSENT OR SURFICIAL AQUIFER SYSTEM</td></tr>
<tr><td colspan="3" rowspan="3">CALOOSAHATCHEE MARL AND TAMIAMI FORMATION</td></tr>
<tr><td rowspan="4">INTERMEDIATE AQUIFER SYSTEM OR INTERMEDIATE CONFINING UNIT[2]</td><td rowspan="4">ABSENT OR INTERMEDIATE CONFINING UNIT[2]</td></tr>
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<tr><td colspan="2">TAMPA MEMBER</td><td rowspan="8">FLORIDAN AQUIFER SYSTEM[3]</td><td rowspan="4">UPPER FLORIDAN AQUIFER[3]</td></tr>
<tr><td>OLIGOCENE</td><td colspan="3">SUWANNEE LIMESTONE</td></tr>
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<tr><td rowspan="2">LOWER FLORIDAN AQUIFER[3]</td></tr>
<tr><td>PALEOCENE</td></tr>
</table>

[1] Based on nomenclature of Scott (1988).
[2] Based on nomenclature of Southeastern Geological Society (1986).
[3] Based on nomenclature of Miller (1986).

Figure 3. Hydrogeologic framework.

Microscopic porosity includes intercrystalline porosity, interstitial porosity, and microfissure porosity. Intercrystalline porosity is defined as the voids between mineral crystals. Interstitial porosity is defined as the voids between loose or poorly cemented granular material. Microfissure porosity is defined as the voids formed by microjoints, microfissures, and bedding and schistosity planes. Macroscopic or channel porosity is the porosity occurring as large fissures, conduits, and channels. In carbonate sequences, porosity is often a combination of microscopic and macroscopic porosity and therefore, two additional porosity types are defined. Rock porosity is defined as the porosity of unfissured blocks or volumes of rock. Massive or formation/aquifer scale porosity is defined as the combined porosity from both interstitial pores (rock porosity) and fissures (channel porosity) (LaMoreaux and others, 1984, p. 47). Effective porosity is defined as the amount of interconnected pore space available for fluid transmission (Lohman and others, 1972, p. 10).

Table 1. Ranges in transmissivity values by well field from aquifer test analyses

[ft^2/d, feet squared per day. Modified from Bengtsson (1987)]

Well Field	Transmissivity (ft^2/d)
Cross Bar Ranch	47,500 to 115,000
Cypress Creek	31,500 to 53,600 78,610
Starkey	[1]40,000 60,700
South Pasco	53,600 47,000 51,000 to 71,000
Eldridge Wilde	[1]33,000 34,400 to 58,800 35,500
East Lake	40,000
Cosme-Odessa	[1]53,500
Section 21	29,400 to 87,000 60,000 71,000
Morris Bridge	53,000 to 130,000 35,000 to 56,000

[1] Wells do not penetrate the major producing zones in the Avon Park Formation.

Some aquifers can be characterized by diffuse-flow where water moves more or less uniformly through the interconnected pore space of the rocks (rock porosity). Unconsolidated clastic aquifers are in this category. Karst carbonate aquifers can be characterized by conduit flow along irregularly distributed, solution-enlarged fissures (channel porosity) in combination with diffuse flow through the more uniformly distributed, interconnected pores (rock porosity). The Floridan aquifer system of west-central Florida is in this category (Vecchioli and others, 1989, p. 33)

Twenty-two core samples from four wells were selected for laboratory analysis of effective porosity to characterize the matrix properties of the Upper Floridan aquifer. The core samples were supplied by the Florida Geological Survey. Samples were selected as representative of a specific hydrogeologic unit within the study area. Laboratory analyses for effective porosity were completed by a commercial laboratory. The four wells from which cores were selected are ROMP 99 (Regional Observation Monitoring Well Program), ROMP TR12-3, ROMP TR14-2, and Brantley #1 (fig. 4). The effective porosity values, corresponding lithologic unit, and sample depths are listed in table 2. The average effective porosity values for the Tampa Member, Suwannee Limestone, and Ocala Group are 29, 36, and 38 percent, respectively. Cores were not selected for evaluating the effective porosity of the Avon Park Formation because of its highly fractured nature. A well-indurated core selected to be representative of the Avon Park Formation would disproportionately represent the least permeable zones. Additional effective porosity values, determined from cores from selected wells (fig. 4), in the proximity of the study area are listed in table 2.

Effective porosities typical of clastic aquifers reflect the interstitial porosity, which can be measured at the rock-core scale, whereas effective porosities typical of karst carbonate aquifers are massive porosities and reflect both rock porosity and channel porosity that cannot be satisfactorily measured at the rock-core scale. Generally, the effective porosity associated with fractured aquifers is much less than that of porous media aquifers. Therefore, the range of effective porosity values presented in this study include values associated with channel and interstitial porosity and represent the massive porosity of a karst carbonate aquifer system.

DESCRIPTIONS OF ANISOTROPY AND HETEROGENEITY IN THE STUDY AREA

Field data collected from wells in the study area indicate the presence of aquifer anisotropy and heterogeneity. Anisotropy and heterogeneity in carbonate aquifer systems is largely attributed to aquifer stratification, localized solution channeling, and discontinuous confining beds.

Anisotropy

Anisotropy is defined as the condition of having different properties in different directions (Bates and Jackson, 1984, p. 21). A fractured carbonate aquifer system can often be modeled as an anisotropic aquifer, because the permeability inherent in a carbonate aquifer can result from preferential dissolution of rock along fractures producing directional dependent aquifer properties. Experiments by Hushey and Crawford (1967) indicated that the overall permeability is greater when fractures are aligned with the predominant flow direction. Analytical solutions were developed for use in conjunction with aquifer test data to determine aquifer anisotropy and components of the anisotropic transmissivity tensor. These components define the principal directions of anisotropy corresponding to the

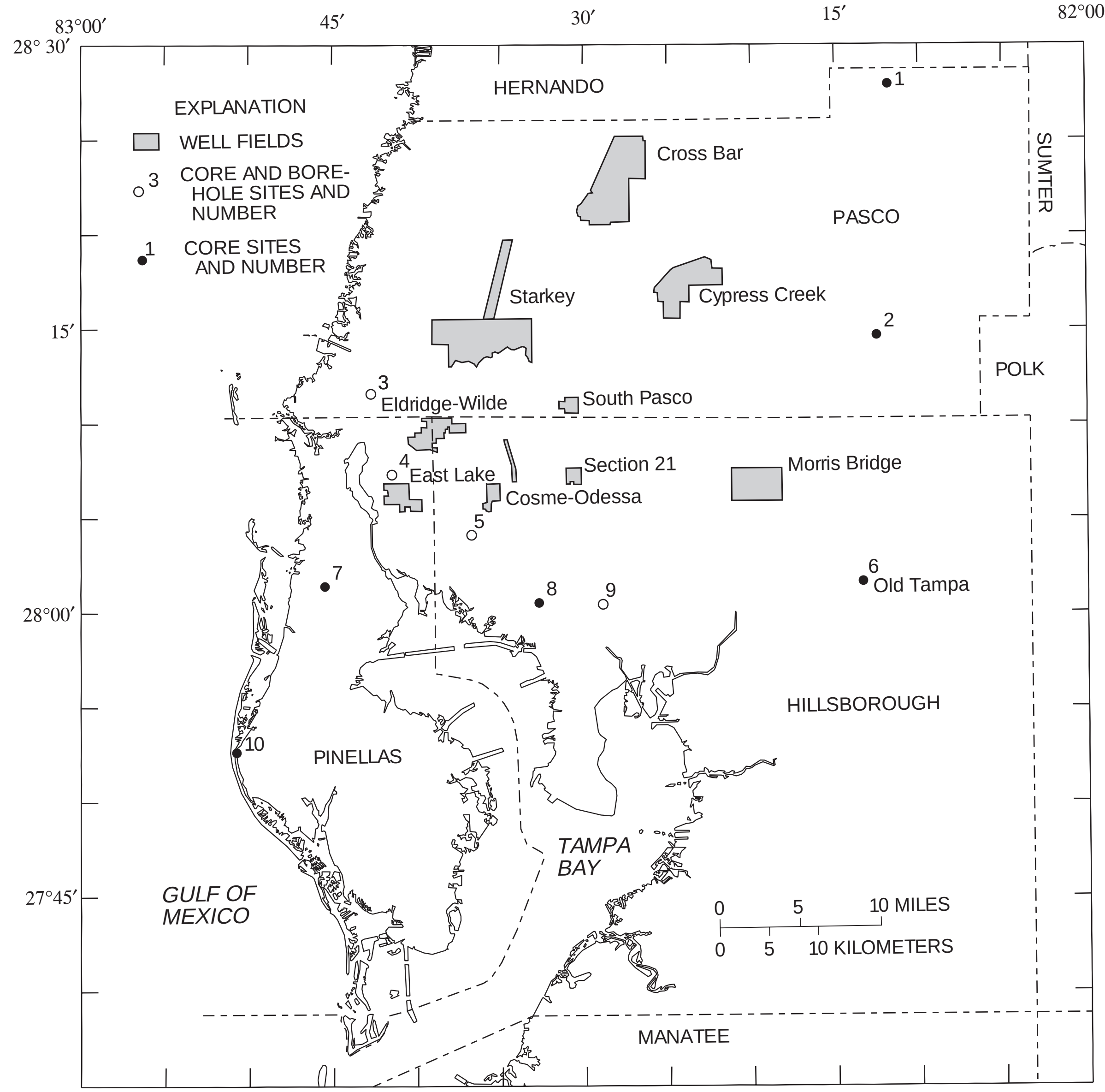


Figure 4. Location of the study area, well fields, and selected wells.

directions in space at which transmissivity (or hydraulic conductivity) attains its maximum and minimum values. The value of the ratio of the maximum and minimum transmissivities defines the magnitude of anisotropy. Based on indications of nonisotropic and nonhomogeneous porous-media ground-water flow, the TENSOR2D computer program (Maslia and Randolph, 1986) was used to evaluate the magnitude and direction of aquifer anisotropy. The TENSOR2D program automates the solution of hydraulic parameters and tensor components for an anisotropic aquifer using the Papadopulos method (1965). The rigorous application of the Papadopulos method requires data from a pumping well and a minimum of three observation wells. Transmissivities are determined for both the major ($T_{\varepsilon\varepsilon}$) and minor ($T_{\eta\eta}$) components of the anisotropic transmissivity tensor. Aquifer test data from wells, shown in figure 4, that tap a karst carbonate aquifer system were used as input to the program.

Aquifer test data sets for seven well fields within the study area were analyzed by using the TENSOR2D program. The results were highly variable within and among the well fields. In several instances, multiple wells were tested within the same well field, and TENSOR2D results did not indicate the same magnitude or direction of aquifer anisotropy; therefore, even at a local scale, the aquifer is not homogeneous, and the results were considered qualitative. Sometimes, the

Table 2. Laboratory analyses of effective porosity from rock cores from selected wells

[Locations shown on fig. 4]

Map number	County	Well name	Other name	Latitude longitude	Stratigraphic units	Sample depth (ft)	Effective porosity (percent)	Source
1	Pasco	—	W-16304	282756	Ocala	112	45	This study
				821149		172	36	
						214	34	
2	Pasco	Brantley 1	W-15957	281446	Suwannee	59	43	This study
				821225		80	34	
						129	39	
						141	27	
3	Pasco	NWHWRAP 3-D	—	281142	Ocala	348	37	CH2M Hill, (1990b)
				824241		388	38	
						438	39	
					Avon Park	1,051	12	
4	Pinellas	NWHWRAP 1-D	—	280923	Ocala	436	40	CH2M Hill (1990a)
				824123		452	27	
						490	34	
					Avon Park	1,155	11	
						1,174	24	
5	Hillsborough	NWHWRAP 4-D	—	280411	Ocala	425	45	CH2M Hill (1990b)
				823643		485	32	
						530	21	
					Avon Park	1,166	11	
6	Hillsborough	Tampa 19	—	280145	Suwannee	105	21	Robinson, 1995
				821324	Ocala	240	46	
7	Pinellas	ROMP TR14-2	W-15204	280132	Tampa	99	41	This study
				824528		137	21	
						203	30	
					Suwannee	232	30	
						273	42	
						397	39	
					Ocala	419	38	
						500	49	
						540	25	
8	Hillsborough	ROMP TR12-3	W-15494	280034	Tampa	106	29	This study
				823237		158	24	
					Suwannee	198	29	
						319	40	
						445	36	
					Ocala	491	48	
9	Hillsborough	NWHWRAP 2-D	—	280033	Ocala	404	44	CH2M Hill (1990b)
				822848		444	38	
						472	17	
					Avon Park	1,119	25	
						1,137	13	
10	Pinellas	McKay Creek	—	275241	Ocala	616	48	Hickey (1977)
				825039	Avon Park	892	20	
						957	7	
						1,028	2	

components of transmissivity could not be determined by using TENSOR2D analysis because of one or a combination of several possible factors: (1) the observation well distribution was insufficient to characterize the transmissivity tensor; (2) the assumptions of Papadopulos were violated because observation wells were too close together, too near the pumping well, or too far from the pumping well; and (3) the horizontal anisotropy did not adequately account for all of the variability in aquifer properties. The magnitude of aquifer anisotropy from the aquifer test data sets ranged from 2.5:1 to 25:1. Aquifer anisotropy for well fields increased toward the north, coinciding with a thinning of the confining materials. The average aquifer anisotropy from all TENSOR2D results was 5:1. The directions of apparent anisotropy ranged from 40 to 130 degrees and generally coincided with the orientation of the photolineaments. If the anisotropy is due to persistent fracture sets of relatively consistent orientation, it could be inferred that the principal directions are a result of fracture orientation. However, there is no guarantee that regional scale fractures would be indicative of density, persistence, and orientation of fractures at a local scale.

Layered Heterogeneity

Although the Floridan aquifer system is basically a vertically continuous sequence of generally permeable carbonates, extremely high permeabilities occur as discrete zones within the aquifer. Geophysical logs and borehole television surveys from regionally dispersed wells indicate that the aquifer system contains several highly permeable zones. These zones, which contribute most of the water to wells, generally conform to bedding planes and commonly contain enhanced secondary porosity caused by solution or fracturing and are separated by rocks of lower permeability that display relatively few secondary porosity features. Borehole television surveys have demonstrated that, in places, the Floridan aquifer system contains thin to moderately thick horizontal openings connected by nearly vertical fractures, some of which have been enlarged by chemical dissolution.

An approach that uses borehole data for characterizing secondary porosity of carbonate rocks was applied to this study. A detailed description of the methodology can be found in a report by Safko and Hickey (1992). Generally, the distribution of effective secondary porosity is determined from concurrent interpretation of lithologic logs, drillers' comments, borehole geophysical logs, and television surveys. The term "effective secondary porosity" is defined as observed secondary porosity from the borehole television surveys supported by interpretations of the caliper, pumping flowmeter, and pumping temperature logs, which indicates that the observed secondary porosity extends beyond the immediate vicinity of the borehole. Such secondary porosity features would be principally related to geologic processes rather than drilling activities (Safko and Hickey, 1992, p. 1).

Effective secondary porosity distributions in the study area were characterized in a general way from four test wells in northwest Hillsborough, northeast Pinellas, and southern Pasco Counties (fig. 4). The wells were constructed and tested under supervision of CH2M Hill as part of the Northwest Hillsborough Water Resources Assessment Project (NWHWRAP). The wells penetrate the entire thickness of the Upper Floridan aquifer. Figure 5 shows the lithologic, apparent secondary porosity, driller comments, caliper, pumping flowmeter, pumping temperature, and effective secondary porosity logs for each of the four wells. All logs, except the effective secondary porosity logs, were constructed from observed data. The apparent secondary porosity log was constructed from the television survey by classifying observed secondary porosity types for 10-ft segments of the borehole. Secondary porosity was classified into three types—vugs, cavities, and fractures—based on definitions proposed by Safko and Hickey, (1992). Cavity porosity designation was further restricted only to those zones in which the driller comment logs specified a bit drop. No bit drops were reported during the drilling of the NWHWRAP test holes; therefore, all observed cavities from the borehole television surveys (fig. 5, col. B) were interpreted as resulting from borehole collapse during the drilling process. The term "dredging" (fig. 5, col. B) refers to the removal of rock fragments from a borehole before drilling can continue. Dredging is required as a consequence of the collapse of poorly indurated lithologies during drilling and often results in enlargement of the borehole diameter. Miller (1986) states that the fractured nature of dolomite commonly causes chunks of dolomite to be dislodged during the drilling process. Corroborative data from pumping flowmeter and temperature logs were used to verify flow zones. Where appreciable flow enters the well, as indicated from flowmeter and temperature log response, apparent secondary porosity was considered to be effective secondary porosity.

Effective secondary porosity for each of the NWHWRAP wells are described below. Effective secondary porosity for NWHWRAP site 1-D (fig. 5) is characterized by vug porosity from 425 to 485 ft and by large vugs intersected by high angle fractures from 585 to 675 ft and at 816 ft. Because borehole television survey data were not available for the bottom 379 ft of the borehole, the secondary porosity could not be characterized for the flow zone from 1,085 to 1,187 ft. Effective secondary porosity for NWHWRAP site 2-D (fig. 5) is characterized by fracture porosity from 262 to 272 ft and from 312 to 332 ft and by large vugs intersected by high angle fractures from 700 to 822 ft, from 942 to 982 ft, and from 992 to 1,072 ft. Effective secondary porosity for NWHWRAP site 3-D (fig. 5) is characterized by fracture porosity from 198 to 218 ft, from 558 to 638 ft, and from 828 to 878 ft and by large vugs intersected by high angle fractures from 638 to 768 ft and from 890 to 1,018 ft. Because borehole television survey data were not available for the interval from 258 to 558 ft, secondary porosity could not be characterized for the flow zone from 290 to 320 ft and from 405 to 455 ft. Effective secondary porosity for NWHWRAP site 4-D (fig. 5) is characterized by vug and fracture porosity from 309 to 405 ft. Because borehole television survey data were not available for the bottom 389 ft, the secondary porosity could not be characterized for the flow zone from 990 to 1,120 ft. The effective secondary porosity interpretations are shown in figure 5, column G, and are interpreted to be distributed spatially and interconnected beyond the vicinity of the borehole and to be the result of geologic processes. The secondary porosity types associated with the prominent flow zones are probably intersections of near vertical fractures with horizontal planes of weakness that have been enlarged by solution.

Analysis of the distribution of the effective secondary porosity indicates that the Upper Floridan aquifer is a layered aquifer system. In general, the producing zones occur near lithologic contacts where horizontal zones of weakness tend to occur. The majority of water enters the borehole from the fractured dolomitic units of the Avon Park Formation. Dolomite beds tend to be severely fractured along zones of weakness. The types of secondary porosity are different in the limestone and dolomite sequences (fig. 5, col. B), possibly the result of the response of different lithologies to stress. Limestone is ductile and the apparent secondary porosity types tends to be vugs and cavities. Because of less induration in the limestone, drilling processes can create cavities from washouts. Dolomite is harder and more brittle and the apparent secondary porosity type tends to be fractures.

Prototype Regions

Within the study area, two prototype carbonate aquifer systems were characterized for detailed analysis. The hydrogeologic framework of these two prototypes represent the end-members of the hydrologic diversity in the study area and were designated the Central Swamp and Lake Terrace regions. The names of these regions were derived from the physiographic units where they are located. The physiographic units north of Tampa Bay are shown in figure 6. Each physiographic unit encompasses one or more well fields. The hydrogeologic framework and aquifer characteristics for the Central Swamp and Lake Terrace regions are those for the Cypress Creek and Cosme-Odessa well fields, respectively.

Descriptions of the hydrogeologic framework and aquifer characteristics of the prototype regions are based on existing data compiled from previous studies by the U.S. Geological Survey, the Southwest Florida Water Management District, the Florida Geological Survey, and private consulting firms. The hydrogeologic framework is composed of two aquifer systems separated by the intermediate confining unit. Aquifer heterogeneity, including vertical fracture zones and horizontal enhanced flow zones, has been observed in both the Central Swamp and Lake Terrace regions. The vertical fracture network is based on the actual locations identified by Culbreath (1988). Horizontal layering of the Upper Floridan aquifer in the Central Swamp and Lake Terrace regions is supported by drillers' logs, specific-capacity data, and borehole geophysical logs for selected wells in the regions. Locations of selected wells (fig. 7) and generalized hydrogeologic sections constructed from well data (figs. 8 and 9) show the observed distribution of aquifer heterogeneity.

There are several hydrologic differences between the two prototype regions. Topography in the Central Swamp region is flat and swampy, and land surface ranges from 60 to 70 ft above sea level. In the Lake Terrace region, land surface ranges from 10 to 70 ft above sea level. The surficial aquifer system is 25 ft thick or less in the Central Swamp region and ranges from 50 to 100 ft in the Lake Terrace region. In the Central Swamp and Lake Terrace region, the intermediate confining unit ranges from 25 to 50 ft thick and 25 ft or less, respectively. The Upper Floridan aquifer is about 900 and 1,125 ft thick, respectively. The Central

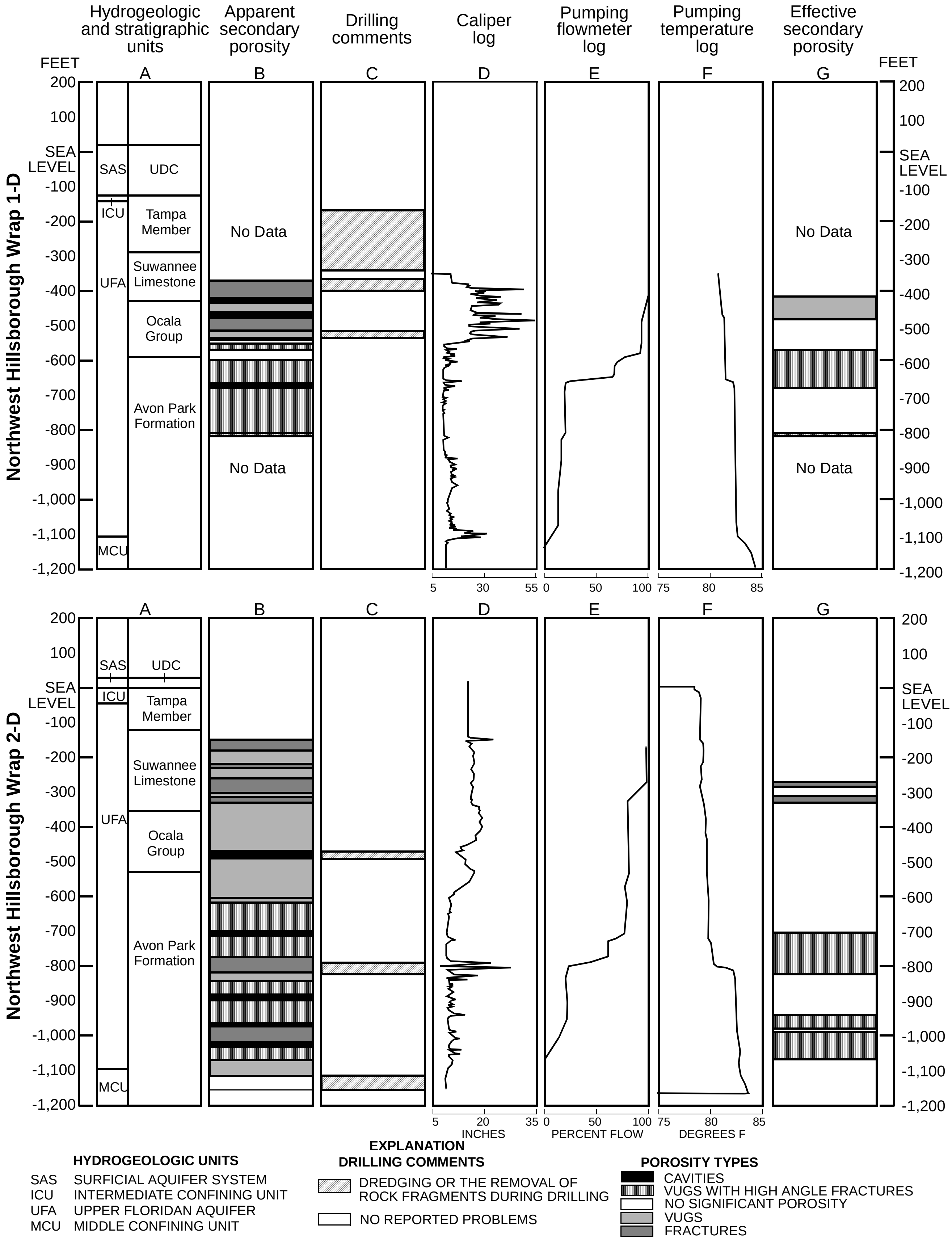


Figure 5. Comprehensive borehole interpretation for the Northwest Hillsborough Water Resources Assessment Project: sites 1-D, 2-D, 3-D, and 4-D.

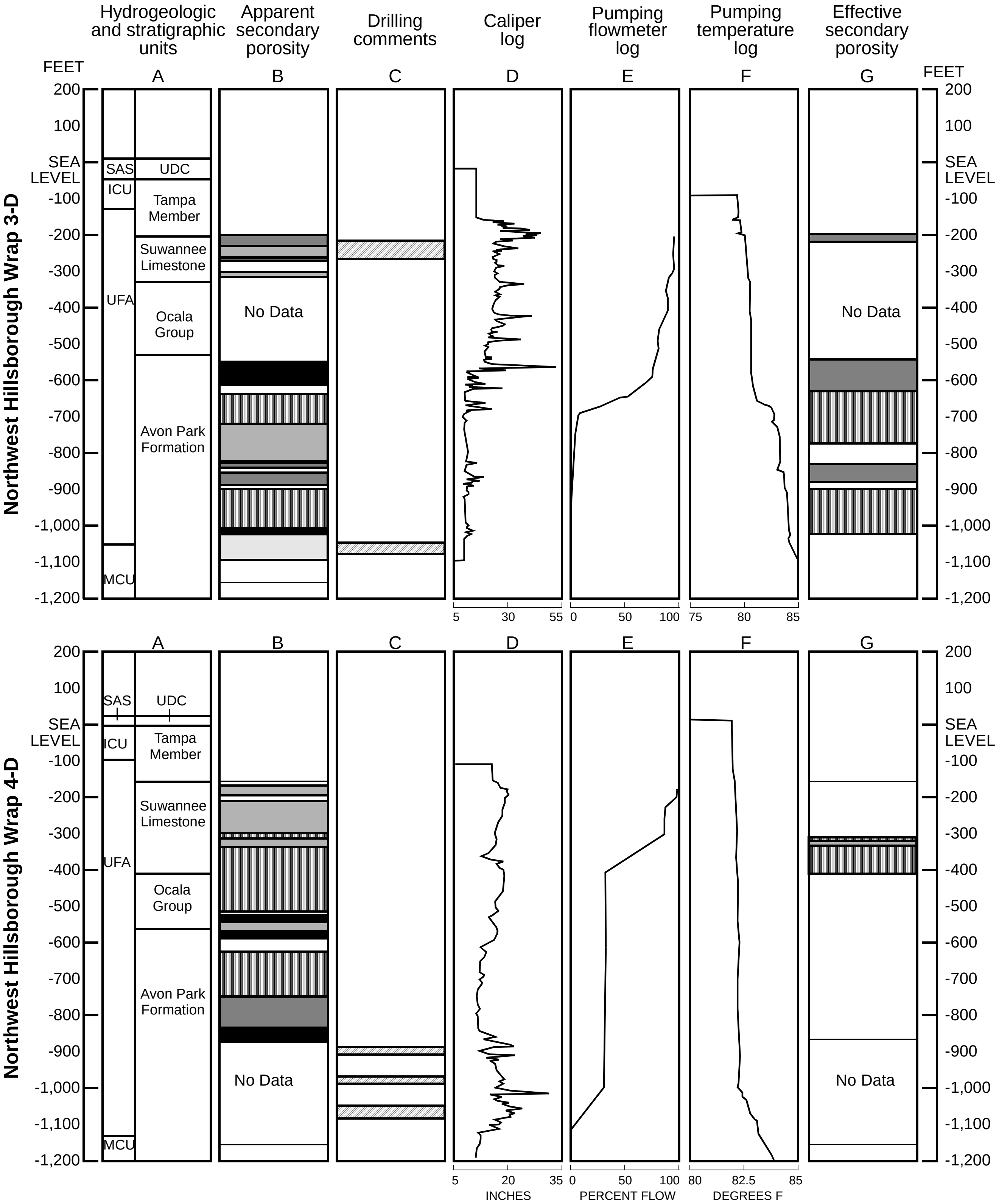


Figure 5. (Continued) Comprehensive borehole interpretation for the Northwest Hillsborough Water Resources Assessment Project: sites 1-D, 2-D, 3-D, and 4-D.

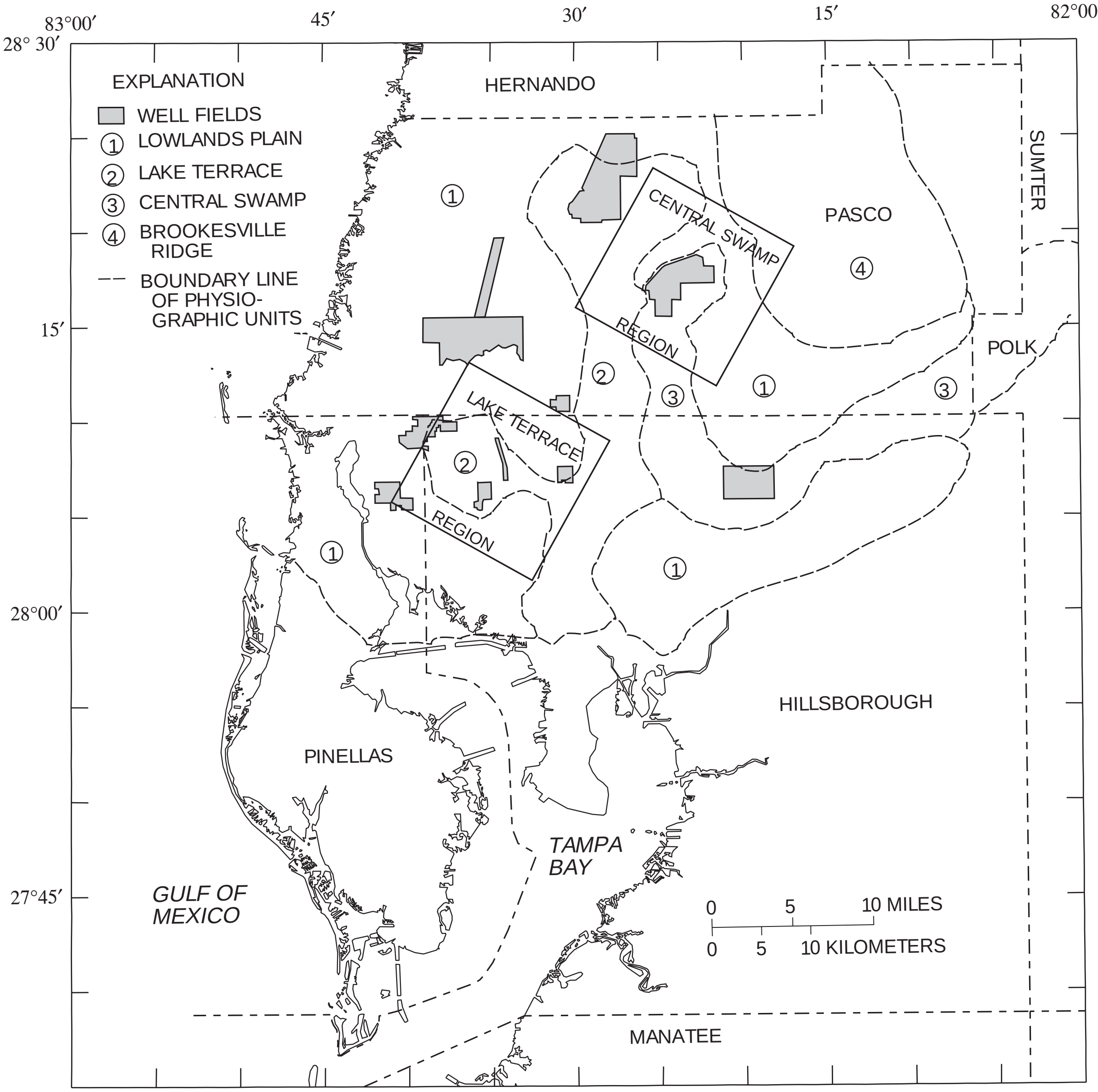


Figure 6. Physiographic units and regions.

Swamp and Lake Terrace regions are in zone 2 and zone 4 of sinkhole types classified by Sinclair and others (1985). Zone 2 is characterized by bare or thinly covered limestone where sinkhole development is rare. Zone 4 is characterized by a 25- to 100-ft thick clastic cover where sinkholes are numerous. Layering of the secondary porosity zones in the Central Swamp region is highly variable (fig. 8). Ryder (1978) states that, in the vicinity of Cypress Creek well field, movement of ground water is primarily along solution-enhanced joints and fractures, and water enters the well from discrete flow intervals.

Two major water-bearing zones occur in the dolomitic zone of the Avon Park Formation. The Tampa Member, Suwannee Limestone, and Ocala Group can contain solution-enhanced permeable zones that generally occur near formational contacts. In the Lake Terrace region, specific-capacity data from wells in the vicinity of the Cosme-Odessa well field, indicate the existence of three flow zones. These enhanced flow zones are at depths from 360 to 420 ft, from 780 to 840 ft, and from 1,000 to 1,155 ft below sea level. Borehole interpretation methods indicate an effective secondary porosity zone from 290 to 390 ft (fig. 9).

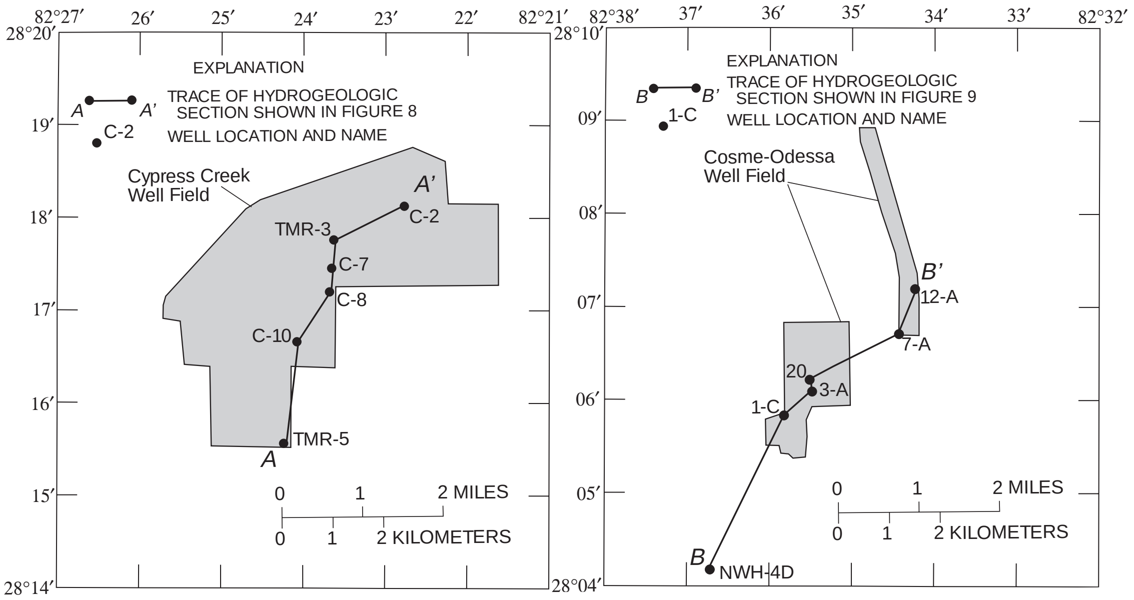


Figure 7. Location of selected wells used for the hydrogeologic sections *A-A′* across the Cypress Creek well field and *B-B′* across the Cosme-Odessa well field.

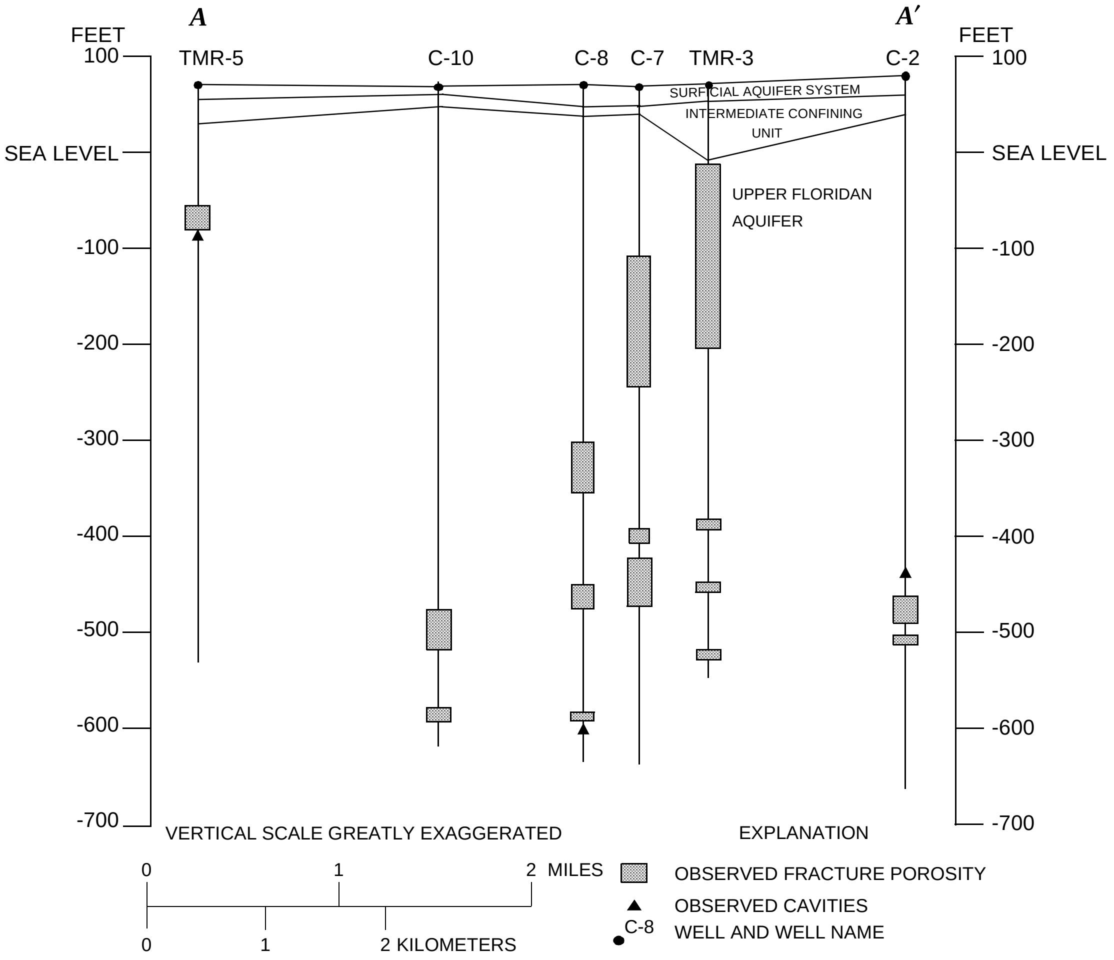


Figure 8. Generalized hydrogeologic section *A-A′*, showing vertical distribution of observed secondary porosity across the Cypress Creek well field.

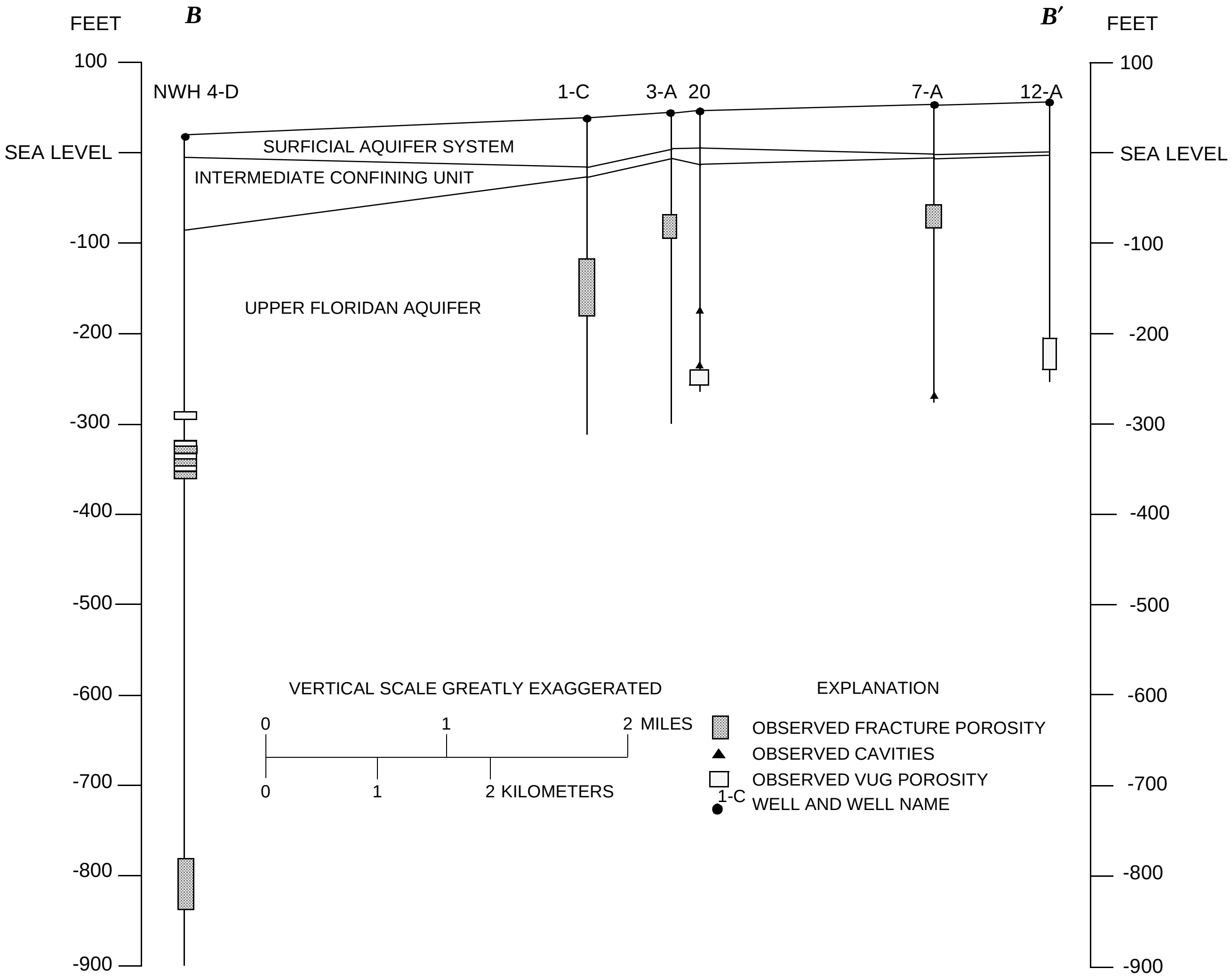


Figure 9. Generalized hydrogeologic section *B-B′*, showing vertical distribution of observed secondary porosity across the Cosme-Odessa well field.

A highly fractured zone from 980 to 1,130 ft is indicated by the caliper log. Pumping temperature logs indicate borehole flow from 1,000 to 1,030 ft (CH2M Hill, 1990a,b).

Generally, the depth interval from 425 to 780 feet within the Ocala Group has lower permeability and acts as a semiconfining unit within the Upper Floridan aquifer. Permeable zones overlie and underlie this zone. As shown in figures 8 and 9, the sources of water to wells, in both the Central Swamp and Lake Terrace regions, are derived from multiple, vertically spaced, and discrete permeable zones.

HYPOTHETICAL CARBONATE AQUIFER SYSTEMS

Observations of anisotropy and heterogeneity, based on field data, in the Central Swamp and Lake Terrace regions led to the development of six hypothetical carbonate aquifer systems. These systems were conceptualized to illustrate generalized types of carbonate aquifer systems. The systems were developed to incorporate increasingly complex representations of aquifer anisotropy and heterogeneity. In addition, an isotropic and homogeneous carbonate aquifer system was developed for comparison with the more complex carbonate aquifer systems.

The first carbonate aquifer system is that of a single isotropic and homogeneous unit, where aquifer properties are uniform (fig. 10, case 1).

The second carbonate aquifer system incorporates horizontal anisotropy (fig. 10, case 2) where aquifer properties differ by direction. The anisotropy was found to vary from site to site. This is most likely caused by the orthogonal distribution of the fracture network.

The third carbonate aquifer system includes a fully penetrating vertical fracture network in a single layer carbonate unit (fig. 10, case 3). The fracture network is based on the work of Culbreath (1988). Fractures in carbonate aquifer systems can behave as impermeable barriers to flow or as highly permeable conduits for flow (Stewart and Wood, 1984). Both impermeable and highly permeable fractures are known to occur in the Upper Floridan aquifer system.

The fourth carbonate aquifer system includes heterogeneous layering of hydraulic properties as a result of carbonate dissolution, thereby creating enhanced flow zones (fig. 10, cases 4a and 4b). Case 4a shows the layering of the carbonate aquifer system by using lithostratigraphic boundaries. Field data indicates that these units have different hydraulic properties. Case 4b shows the redistribution of layers by further defining the relatively thin flow zones found within specific lithostratigraphic units. Enhanced flow zones in carbonate terranes are indicated from specific-capacity data, borehole geophysical logs, and drillers' logs.

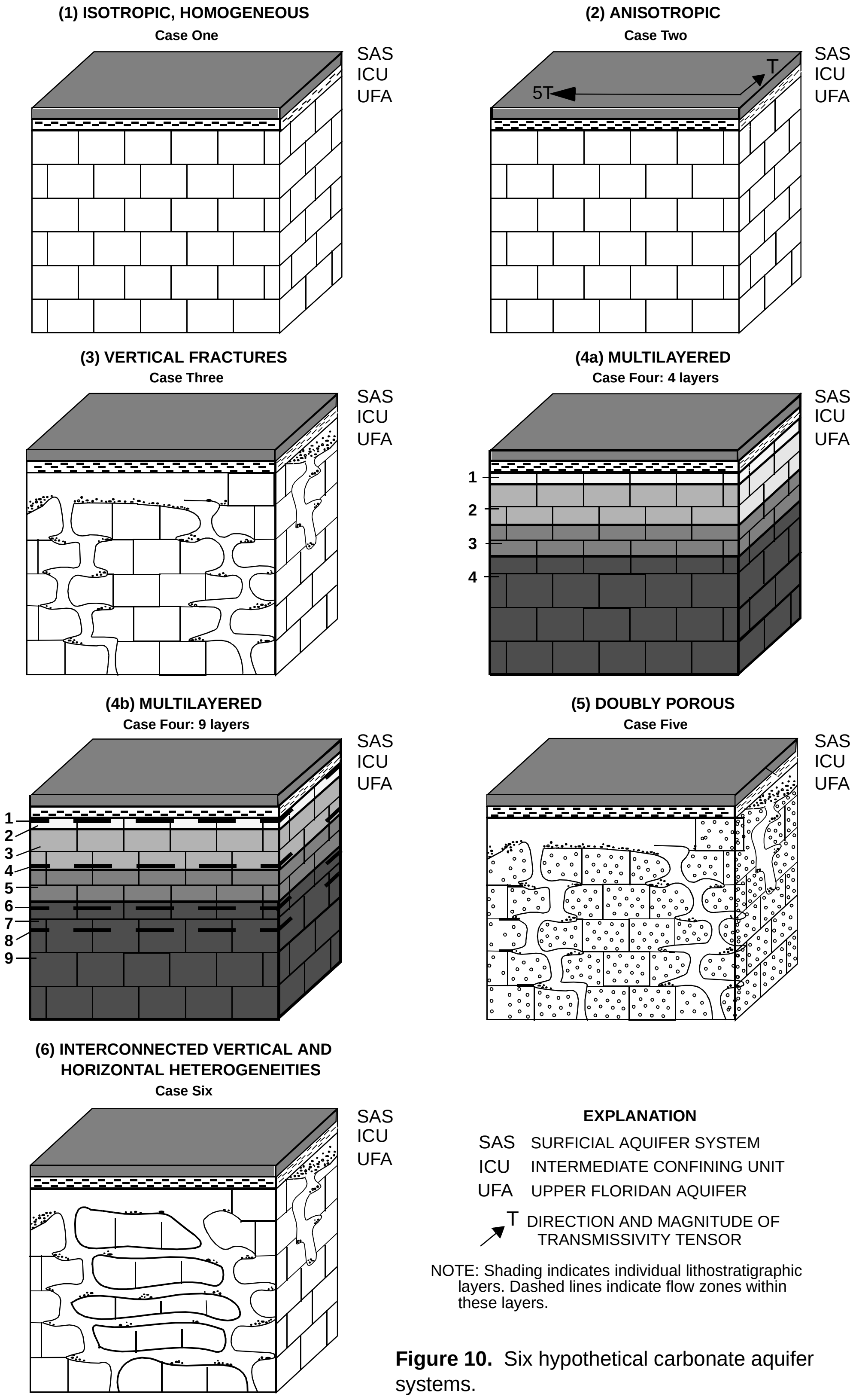
The fifth carbonate aquifer system was that of a doubly porous system (fig. 10, case 5). In a double porous system, the aquifer porosity consists of two types, the postdepositional secondary porosity, such as fractures and solution channels and the syndepositional primary porosity of the intergranular matrix, both having distinctive characteristics. Two coexisting porosities and hydraulic conductivities are recognized: those of lower storage capacity (low porosity) and higher hydraulic conductivity (permeability) of the fracture dominated rock volumes, and those of higher storage capacity (high porosity) and lower hydraulic conductivity (permeability) of the unfractured rock volumes. Field evidence supports this double porosity behavior. The core data suggests that primary porosity is significant; however, borehole geophysical log and television survey interpretations indicate that appreciable flow enters the well along discrete zones characterized by secondary porosity features. Transmissivity values determined from aquifer test analysis within a single well field vary significantly. The highest calculated transmissivities are probably from areas where the pumped well intersected fractured (secondary porosity) zones. Both secondary and primary porosity contribute to the total porosity in the aquifer; however, if movement of water within pores isolated from solution channels were insignificant relative to movement within the solution channels, then transmissivity and effective porosity values would be ascribed to the flow properties and channel porosity volume of the solution conduits. Channel porosity volume relative to the total rock volume is typically much less than the measured 30 percent from core samples.

The sixth carbonate aquifer system (fig. 10, case 6) combines the effects of both the enhanced vertical interconnection between hydrogeologic layer and the horizontal, solution-enhanced flow zones.

EFFECTS OF AQUIFER ANISOTROPY AND HETEROGENEITY ON GROUND-WATER FLOW

Aquifer anisotropy and heterogeneity, inherent in carbonate aquifer systems, can affect both the direction and velocity of ground-water flow. Fluid flow in karst carbonate aquifers can be highly variable and difficult to measure or predict with a reasonable degree of certainty, because flow regimes can range from almost entirely diffuse to predominantly conduit flow. Over brief periods of time, where small volumes of the aquifer are tested, such as during aquifer testing, a carbonate aquifer system might be dominated by flow in fractures. Yet, with longer periods of time, a larger volume of the aquifer is tested and the overall flow might tend to behave as if it were an equivalent porous medium. A karst carbonate aquifer system might behave as an equivalent porous medium when the secondary porosity features are numerous and spatially interconnected such that the aquifer effectively assumes hydraulic characteristics of a porous medium. Additionally, the volume of aquifer material tested or scale of the problem determines how heterogeneities must be taken into account in evaluating the flow system. Although Darcian flow assumptions might be acceptable for estimating the general head gradient, the average linear velocities might be inaccurate due to the directional dependence and strong discontinuity of fractures.

The influence of aquifer anisotropy and heterogeneity on the movement of ground water often can be inferred from aquifer and tracer test data and from



EXPLANATION

SAS	SURFICIAL AQUIFER SYSTEM
ICU	INTERMEDIATE CONFINING UNIT
UFA	UPPER FLORIDAN AQUIFER
↗ T	DIRECTION AND MAGNITUDE OF TRANSMISSIVITY TENSOR

NOTE: Shading indicates individual lithostratigraphic layers. Dashed lines indicate flow zones within these layers.

Figure 10. Six hypothetical carbonate aquifer systems.

borehole geophysical logs. Aquifer test data for the Upper Floridan aquifer have been collected by the U.S. Geological Survey, local and State agencies, and private consultants. Selected aquifer tests conducted from 1952 to 1976 were analyzed and presented in a report by Wolansky and Corral (1985). The purpose of that study was to obtain a probable range of values of transmissivity, storage coefficient or specific yield, and leakance for the surficial aquifer system, the intermediate confining unit, and the Upper Floridan aquifer. In several instances, analyses of aquifer test data from the Upper Floridan aquifer system provided ambiguous results and were excluded from the report. These aquifer tests, which indicated a wide variation in hydraulic properties at a site, as determined by inconsistent responses in several observation wells, indicated that the basic assumptions of the analytical solutions were not entirely met. The authors surmise that heterogeneity, anisotropy, and hydrologic boundaries may be responsible for the apparent variation in aquifer properties (Wolansky and Corral, 1985, p. 27).

Tracer tests were performed at the Old Tampa well field in 1992 (fig. 4). Rapid fluid flow between widely separated wells was observed, indicating that flow is through conduits rather than through porous media (Robinson, 1995). Prior to tracer test initiation, tracer arrival time of 46 days was calculated based on porous media flow assumptions, a distance between wells of 200 ft and a porosity of 25 percent. Initial tracer arrival occurred after 4 hours, a second arrival occurred after 36 days, and a peak concentration occurred after 48 days. The bimodal distribution of tracer arrival suggests that the porous media assumptions are not strictly obeyed in the aquifer. Conclusions from the reports by Wolansky and Corral (1985) and Robinson (1995) are that aquifer and tracer test data indicate that the hydraulic response of the carbonate aquifer system to stresses in west-central Florida deviates from isotropic and homogeneous porous media behavior. These assumptions are used for most area of contribution calculations.

MODEL DESIGN AND SIMULATION OF THE PROTOTYPE CENTRAL SWAMP AND LAKE TERRACE REGIONS

A finite-difference flow model was used to evaluate the effects of simulated aquifer anisotropy and heterogeneity on areas of contribution to supply wells in the Central Swamp and Lake Terrace regions. The models are highly conceptual and were not calibrated because of the hypothetical nature of the simulation and because no data exists for comparison with the model results. The analysis implemented an exploratory modeling approach where models are constructed to simulate a wide range of possible solutions. It is used to better understand a system filled with hydrologic uncertainties. This modeling approach permitted many combinations of aquifer anisotropy and heterogeneity types to be simulated. To compare the effects of aquifer anisotropy and heterogeneity on contributing areas, particle tracking was used to delineate the size, shape and orientation of these areas. Contributing area analysis delineates the two-dimensional surface area that corresponds to the area of influence of a pumping well. The area of influence of a pumping well is the area around a well where captured water balances well discharge. The carbonate aquifer system types were simulated by emphasizing anisotropy and heterogeneity typical of karst carbonate terranes.

The models selected to analyze ground-water flow in the study area are the U.S. Geological Survey MODFLOW program (McDonald and Harbaugh, 1984) and MODPATH program (Pollock, 1988). MODFLOW is a three-dimensional, finite-difference flow model. The flow fields generated by MODFLOW are used as input to MODPATH. The MODPATH program is a post-processing, particle-tracking program designed for use with output from flow simulations obtained using MODFLOW. MODPATH is used to delineate pathlines and position of particles at specific time intervals within the simulated flow system. Pathlines and particles can be tracked forward (in the direction of future locations) or backward (in the direction of past locations) from specified model cells.

MODFLOW and MODPATH numerical models were used to generate time-related areas of contribution in the Central Swamp and Lake Terrace regions and were each simulated as the six hypothetical carbonate aquifer system discussed in a previous section of the report. Particles were backtracked from simulated well locations toward the recharge areas to delineate pathlines along which ground-water would flow toward the well. The areal extent of the simulated pathlines defines the approximate area of capture from which the well field draws its water. If the hydrologic system is at equilibrium, the resulting particle paths delineate the total capture zone. Lengths of pathlines are proportional to ground-water flow velocity. Velocities increase as particles approach the simulated wells and is indicated by progressively longer spacing between positions of particles plotted along pathlines.

Boundary Conditions and Grid Design

The two prototype regions were assigned identical boundary conditions and model size so that comparisons between the regions were similarly constrained. Although the boundary conditions do not correspond to natural hydrologic boundaries, if the model area were sufficiently large such that effects of simulated well field pumping would not cause measurable head changes at the boundaries, constant-head boundaries could then be used (Bush, 1978). This criterion was used to define the location of the lateral, hypothetical boundaries for the Central Swamp and Lake Terrace regions. The procedure used to determine this area was to utilize the MODPATH program to evaluate the configuration of particle paths delineating sources of water to well fields. MODPATH was used in conjunction with a calibrated flow model (Fretwell, 1988), that coincides with the study area of this project. The area around each well field encompassed by the pathlines was used as general guidelines for locating the lateral boundaries beyond which well field pumping effects are minimized. An adequate model extent of 100-mi^2 was selected and the lateral boundaries were specified as constant-head boundaries. The upper boundary condition, the water table, was also assigned a specified head. The lower boundary condition was designated a no-flow boundary and represents the hydrologic boundary between the Upper Floridan aquifer and the middle confining unit. Discretization of the 100-mi^2 model area created 1,600, 1/16-mi^2 uniform grid blocks per layer. Both the Central Swamp and Lake Terrace regions were assigned equivalent boundary condition types and discretizations (fig. 11) and these conditions were not changed during simulation. The main objective of the digital simulation was to illustrate how the incorporation of conceptualized distributions of aquifer anisotropy and heterogeneity effect the size, shape, and orientation of areas of contribution to supply wells. The areas of contribution for this study are based on a “traveltime” distance, not on a capture zone defined by a potentiometric surface; therefore, a gradient for neither the water table nor pumped aquifer was simulated.

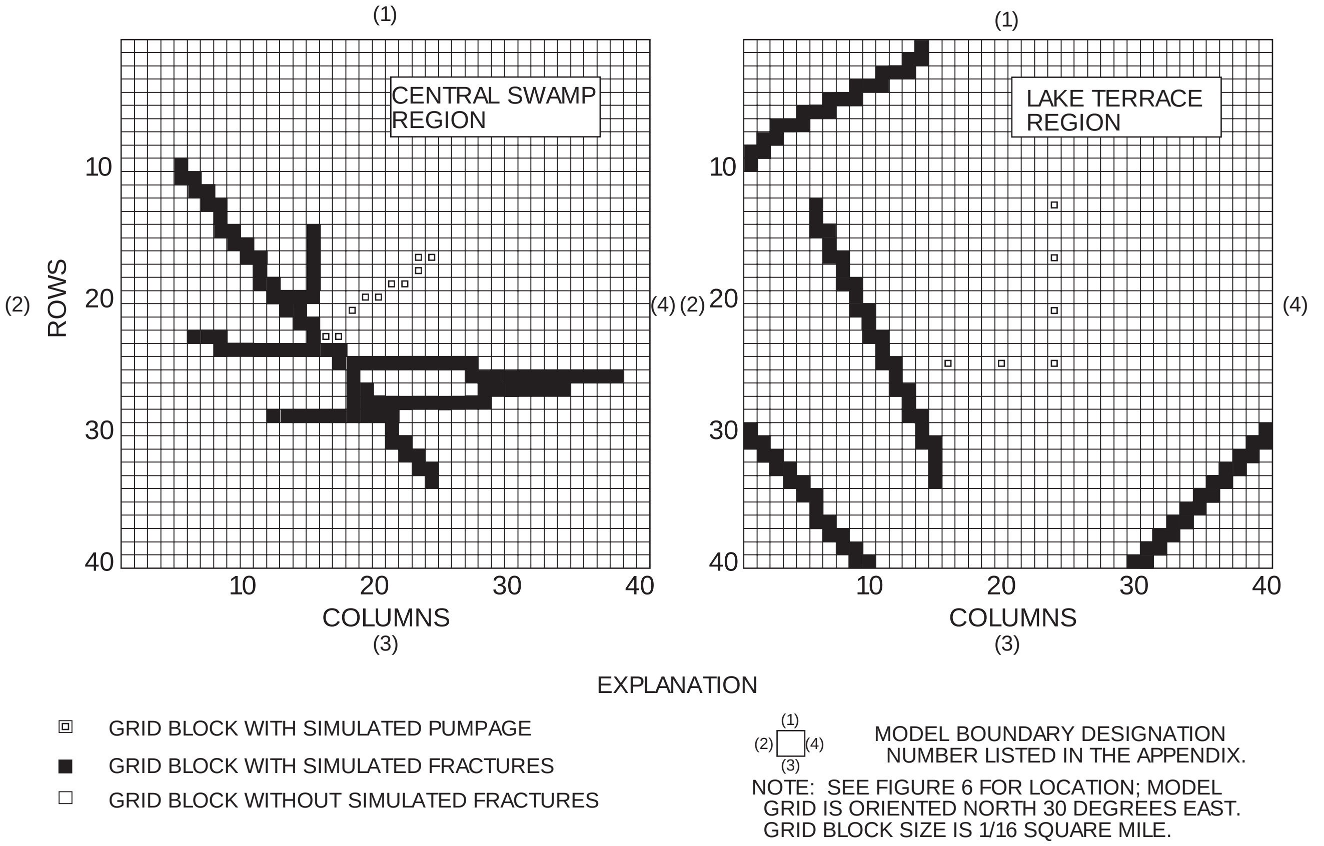


Figure 11. Model grid of 40 rows and 40 columns per layer, showing grid blocks, simulated fractures, and wells in the Central Swamp and Lake Terrace regions.

Model Input Parameters

The quasi-three-dimensional flow systems of the Central Swamp and Lake Terrace regions were constructed to include an unconfined aquifer system (surficial aquifer system) and a confined aquifer system (Upper Floridan aquifer) separated by a confining unit (intermediate confining unit). Model input parameters were compiled from data gathered during previous investigations and are defined for each of the hypothetical carbonate aquifer system types in the following sections of the report. The input parameters were derived from specific capacity tests, aquifer tests, laboratory core analyses, surface and borehole geophysical log data, and calibrated model information (Hutchinson, 1984; Bengtsson, 1987; Fretwell, 1988). Input data for the regions for each of the carbonate aquifer system types are shown in figures 12 and 13.

Simulated pumpage are 30 and 13 Mgal/d, which are the withdrawals used in previously calibrated models for the Cypress Creek and Cosme-Odessa well fields, respectively (Hutchinson, 1984; Fretwell, 1988). Well locations and grid distributed pumpage approximates the configuration of the Cypress Creek and Cosme-Odessa production wells (fig. 11).

Case 1: Isotropic and Homogeneous Single-Layer System

The input data selected for simulating an isotropic, homogeneous, single-layer, carbonate aquifer system for the Central Swamp and Lake Terrace regions are described below. The transmissivity values selected for simulation of the Central Swamp and Lake Terrace regions are 30,000 and 57,000 ft^2/d, respectively. Reported transmissivities in the vicinity of these regions are listed in table 1.

The thickness of the aquifer penetrated by test wells in the Central Swamp region for which transmissivity values are reported is 700 ft. Even though these wells are not fully penetrating, the major water-bearing zones designated by Ryder (1978) have been penetrated. Therefore, the reported transmissivity values should be considered representative of the Upper Floridan aquifer in the region. Reported transmissivity values from published calibrated models for the Cypress Creek well field ranged from 26,000 to 41,000 ft^2/d (Fretwell, 1988) and from 31,500 to 53,600 ft^2/d (Ryder, 1978).

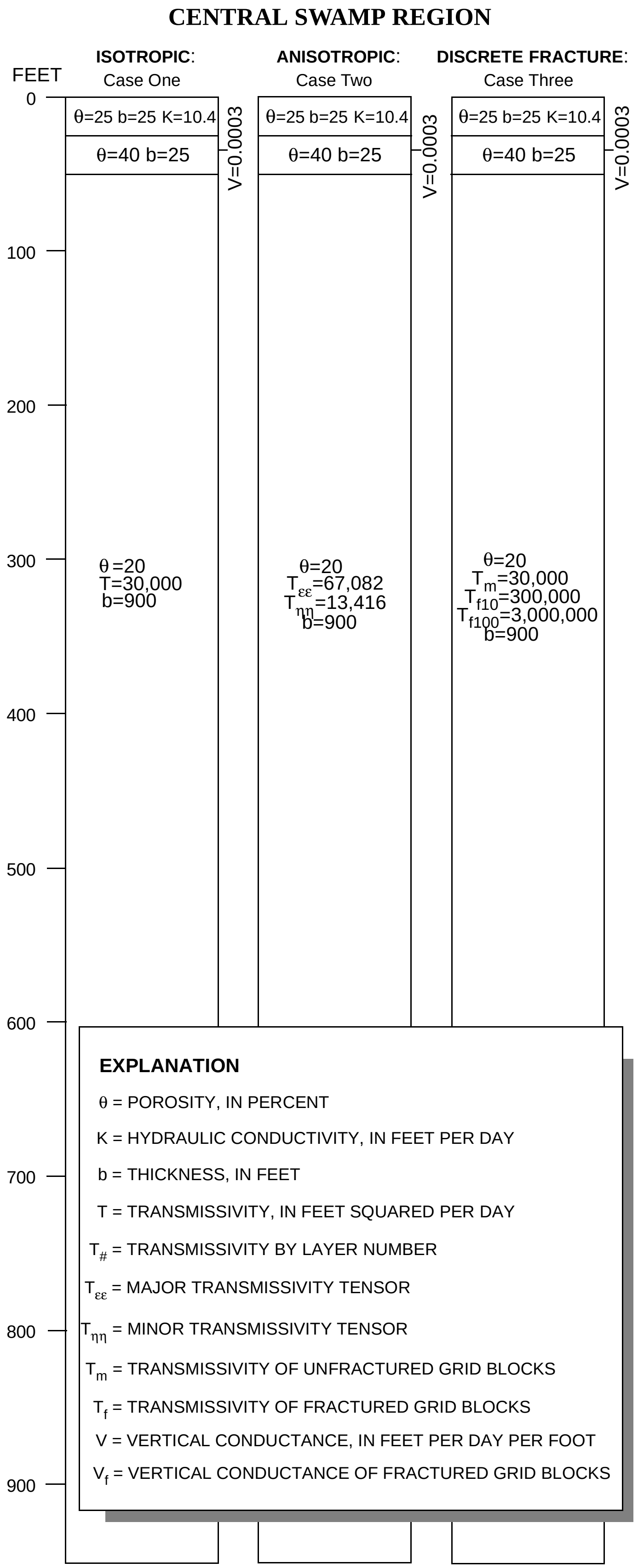


Figure 12. Distribution of input data for the Central Swamp region for the hypothetical carbonate aquifer systems.

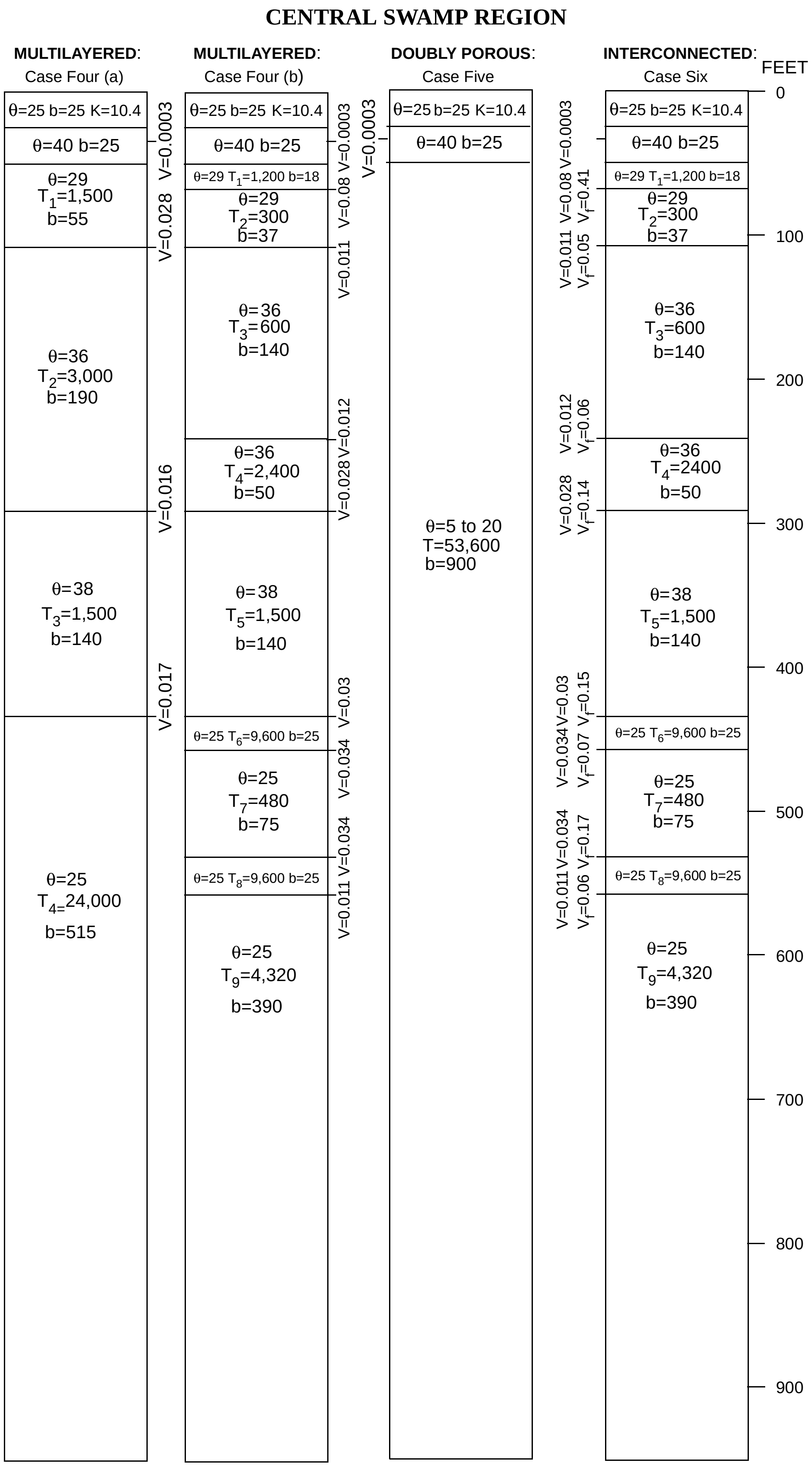


Figure 12. (Continued) Distribution of input data for the Central Swamp region for the hypothetical carbonate aquifer systems.

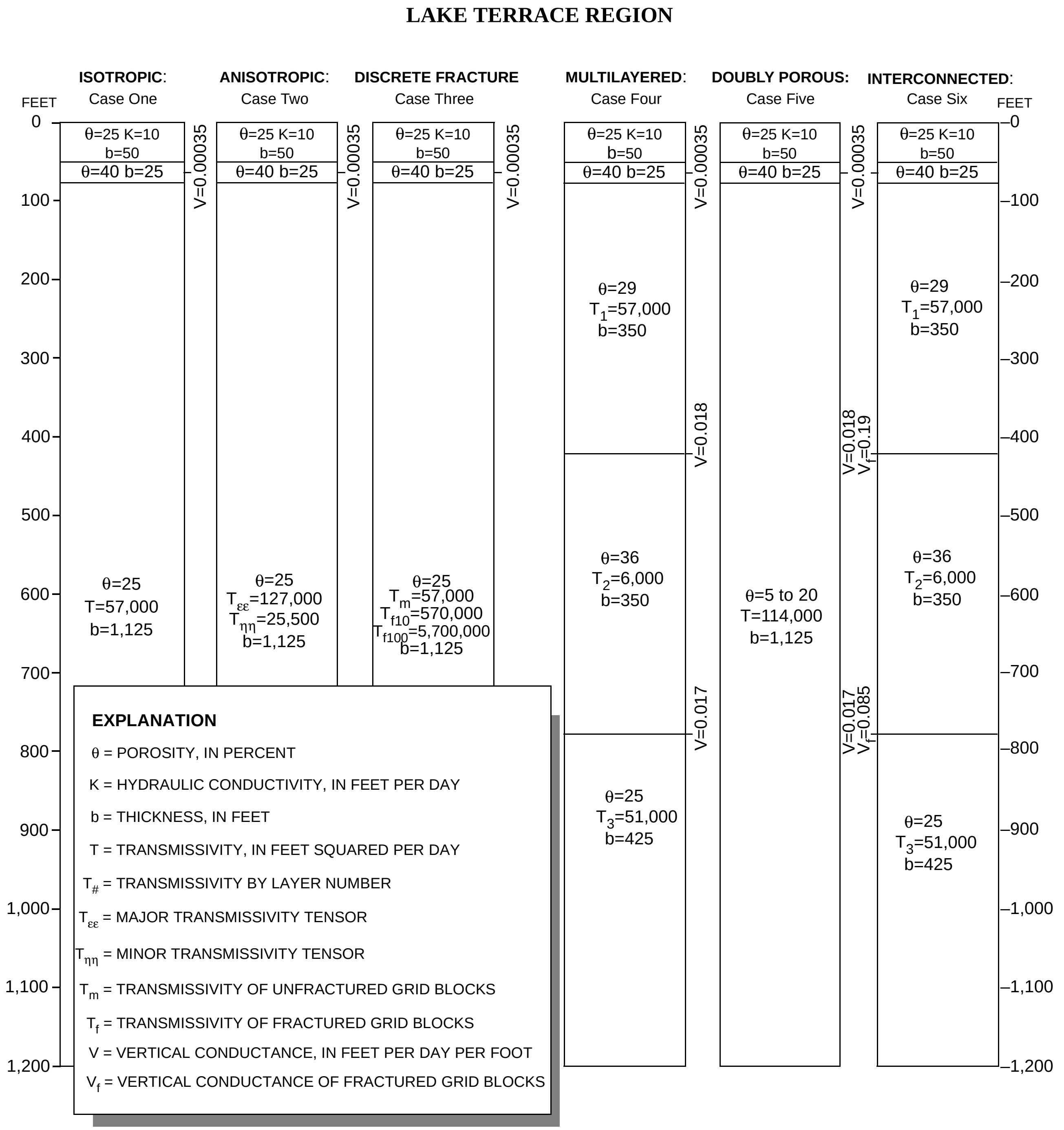


Figure 13. Distribution of input data for the Lake Terrace region for the hypothetical carbonate aquifer systems.

Reported transmissivities from published calibrated models for the Cosme-Odessa well field are 57,000 ft^2/d (Hutchinson, 1984; Bengtsson, 1987) and 66,000 ft^2/d (Fretwell, 1988). However, the aquifer thickness penetrated by the test wells in the Lake Terrace region for which transmissivity values are reported ranges from 200 to 600 ft and represents only 18 to 53 percent of the estimated 1,125-ft total thickness of the Upper Floridan aquifer in the region. Reported transmissivity values should be considered a minimum for the Upper Floridan aquifer in the Lake Terrace region.

The effective porosity values selected for simulation in the Central Swamp and Lake Terrace regions are 20 and 25 percent, respectively. These values are representative of the rock or primary porosity of the Upper Floridan aquifer system.

Case 2: Anisotropy in a Horizontal Plane for a Single-Layer System

The transmissivity values for an anisotropic carbonate aquifer system in the Central Swamp and Lake Terrace regions were computed by assuming an anisotropy ratio of 5:1 and effective transmissivities (T_e) of 30,000 and 57,000 ft^2/d, respectively. The term “effective transmissivity” is defined as the average of the transmissivities in the two principal directions corresponding to the greatest and least preferred flow directions. These directions defined the principal transmissivity tensors. The selected anisotropy ratio is the average of the TENSOR2D results from aquifer tests in west-central Florida. Anisotropy was simulated by using the MODFLOW program with two transmissivity tensors designated $T_{\varepsilon\varepsilon}$ and $T_{\eta\eta}$, which are the maximum and minimum transmissivities, respectively. The equation used to compute the transmissivity tensors is:

$$T_e = (T_{\varepsilon\varepsilon} \text{ x } T_{\eta\eta})^{1/2}.$$

Maximum transmissivities probably coincide with fracture locations. Because the fractures are orthogonally distributed, two possible orientations of maximum transmissivity are possible. Therefore, the maximum transmissivity tensor was independently simulated, first along rows and then along columns. The input values for the maximum and minimum transmissivities are about 67,000 and 13,400 ft^2/d in the Central Swamp region and 127,500 and 25,500 ft^2/d in the Lake Terrace region.

Case 3: Discrete, Vertically Fractured, Single-Layer System

Simulation of a carbonate aquifer system with discrete, fully penetrating, permeable vertical fractures was approximated by incorporating differing permeabilities for the fractured and unfractured grid blocks. The influence of permeable vertical fractures in a carbonate aquifer system can be grossly approximated by enhancing the transmissive properties of the fractures. Studies have indicated that fracture permeability may be 10 to 100 times greater than unfractured rock permeability (Stewart and Wood, 1984). Fractures can act as conduits for flow as well as barriers to flow. Both types, conduits and barriers, have been observed in the Upper Floridan aquifer in west-central Florida (Wood and Stewart, 1985). Fractures that are barriers to flow have been recrystallized or filled in with clastic material and are simulated as no-flow grid blocks. Fractures that are conduits for flow are simulated by increasing the transmissivity in the fractures grid blocks relative to the unfractured blocks. The fracture locations in the Central Swamp and Lake Terrace regions, based on the work of Culbreath (1988), are shown in figure 11. The simulated fracture-influenced transmissivity values for the Central Swamp and Lake Terrace regions range from 300,000 to 3,000,000 ft^2/d and 570,000 to 5,700,000 ft^2/d, and the simulated porosities are 20 and 25 percent, respectively. The transmissivity and porosity selected for simulation of the unfractured part of the aquifer in the Central Swamp and Lake Terrace regions are 30,000 ft^2/d and 20 percent and 57,000 ft^2/d and 25 percent, respectively. These transmissivity values fall within the range of published data for west-central Florida. The porosity values are average values from core samples from this study and published reports in west-central Florida.

Case 4: Multilayered System

Carbonate aquifer systems with multiple layers of differing hydraulic properties was simulated by subdividing the single layer aquifer into separate lithostratigraphic units. In addition, discrete flow zones occur within these lithostratigraphic units. Data indicate that, in the study area, the Upper Floridan aquifer contains multiple, thin, flow zones that supply most of the water to wells. The occurrence of flow zones are at varying depths but are generally associated with locations of lithologic contacts. The layered carbonate aquifer system in the Central Swamp region was simulated, both as a four- and nine-layer system on the basis of specific-capacity data and the work of Ryder (1978). The layered carbonate aquifer system in the Lake Terrace region was simulated as a three-layer system.

The four-layer aquifer system in the Central Swamp region was simulated by redistributing aquifer properties by lithostratigraphic unit based on the assumption, supported by physical data, that the lithostratigraphic units do not equally supply water to wells. The four layers of the carbonate aquifer system represent the lithostratigraphic units of the Tampa Member, Suwannee Limestone, Ocala Group, and Avon Park Formation. These lithostratigraphic units are 55, 190, 140, and 515 ft thick and contribute 5, 10, 5, and 80 percent of the flow, respectively. Multilayered models of differing hydraulic characteristics require vertical-conductance data (VCONT) that define the interaction between layers. VCONT is a calculated input parameter and is defined as the vertical hydraulic conductivity divided by the thickness from one layer to the next lower layer (McDonald and Harbaugh, 1984, p. 155). The simulated ratio of horizontal to vertical hydraulic conductivity is 5:1. This ratio falls within the range of published values determined from core analyses. Porosities were assigned to each layer based on effective porosities determined from core analyses for specific lithostratigraphic units of the carbonate aquifer system. Input values are shown in figure 12.

A nine-layer aquifer system in the Central Swamp region was simulated also because, within these distinct lithostratigraphic units, discrete flow zones occur that supply most of the water to wells. Aquifer properties were redistributed by assuming that 80 percent of the flow in each lithostratigraphic unit, with the exception of the Ocala Group, was derived from the discrete flow zones. The Ocala Group tends to behave as a semiconfining unit within the study area. The lithostratigraphic units were relayered to incorporate the discrete flow zones. The location and thickness of the flow zones in the Tampa Member, Suwannee Limestone, and Avon Park Formation generally conform to descriptions by Ryder (1978). The Tampa Member has an 18-ft-thick flow zone that supplies 80 percent of the flow from the unit. The flow zone occurs near the contact with the intermediate confining unit. The remaining 37 ft of the Tampa Member supplies the remaining 20 percent of the flow from the unit. The Suwannee Limestone has a 50-ft thick flow zone that supplies 80 percent of the flow from the unit. The flow zone occurs near the contact with the underlying Ocala Group. The remaining 150 ft of the Suwannee Limestone supplies 20 percent of the flow from the unit. The Ocala Group was simulated without a discrete flow zone and the entire 140-ft thickness supplies 5 percent of the total water to the well. Two discrete flow zones, each with a thickness of 25 ft, were simulated in the Avon Park Formation. The combined flow supplied from the Avon Park Formation to wells from the two zones is equivalent to 80 percent of the flow from the unit. The flow was equally divided between them. The remaining 20 percent of flow from the unit was attributed to the two less permeable, unfractured units separating the producing zones. Input values are shown in figure 12.

The VCONT values simulated for the nine-layer carbonate aquifer system are a calculated parameter (McDonald and Harbaugh, 1984, p. 155). The porosities were assigned by lithostratigraphic unit as described for the four-layer model. Although the nine-layer model is highly conceptualized, many authors have alluded to the heterogeneous layering observed.

A three-layer aquifer system in the Lake Terrace region was simulated. Specific-capacity data and borehole geophysical log interpretations for the NWHWRAP test well 4-D (CH2M Hill, 1990b) indicate that, in the vicinity of the Lake Terrace region, the Upper Floridan aquifer contains two units of high permeability that are separated by a unit of low permeability. Pumping flowmeter logs from the test well indicate that slightly more than half of the flow enters the well from the upper 300 ft of the carbonate aquifer, and most of the remaining flow enters the well from the lower 300 ft. Based on the discussion of well penetration depth, published transmissivity values of 57,000 and 51,000 ft^2/d were used to characterize the upper and lower producing zones, respectively. The selected horizontal to vertical hydraulic conductivity ratio is 5:1. The input values for VCONT are a calculated parameter. Porosities were assigned to each layer based on average effective porosities determined by core analysis for specific lithostratigraphic units. Input values are shown in figure 13.

Case 5: Doubly Porous, Single-Layer System

Doubly porous systems consist of two media: the high porosity, low permeability of the unfractured parts of the aquifer; and the low porosity, and high permeability of the fractured parts of the aquifer. Generally, fluid transmission occurs through the fractures; therefore, a doubly porous aquifer system can be approximated by using porous media models and by increasing the effective transmissivity (permeability) and by decreasing the effective porosity (Gordon, 1986). The rationale of increasing the overall transmissivity in the simulation is because fractures transmit the water and typically have higher transmissivities than unfractured parts of the aquifer. The rationale for decreasing the porosity in the simulation is because, in an aquifer system consisting of both primary and secondary porosity, fluid flow tends to be through the secondary porosity solution features which make up only a small part of the total aquifer porosity. Therefore, the rate of fluid movement can be more accurately estimated by using a porosity value only associated with the conduits.
The doubly porous carbonate aquifer system was approximated by simulating the aquifer as a single layer with a higher transmissivity and lower porosity value for both the Central Swamp and Lake Terrace regions. The transmissivity value selected for the Central Swamp region is the largest transmissivity value determined from aquifer test analyses. The transmissivity value selected for the Lake Terrace region is

equivalent to the total transmissivity of the multilayered model. The wide range of effective porosities is measured in carbonate aquifer systems, and the effective porosity that is solely related to the volume of the fractures is unknown. Therefore, a range of porosities was tested. Input values are shown in figures 12 and 13.

Case 6: Vertically and Horizontally Interconnected Heterogeneous System

The carbonate aquifer system incorporating vertical fracture zones and horizontal, solution-enhanced conduits, was simulated to investigate the effects of a hypothetically distributed, three-dimensional heterogeneity. The distribution of transmissivity values for the Central Swamp and Lake Terrace regions is identical to the distribution used to simulated the multilayered aquifer system, thereby incorporating horizontal, solution-enhanced flow zones. Vertical fractures were simulated by increasing the vertical hydraulic conductivity in fractured blocks relative to the unfractured blocks to simulate the enhanced connectivity between layers. The calculated VCONT values used in the layered model were used to simulate the unfractured blocks. The calculated VCONT values for the fractured blocks were simulated as being five times as permeable as the unfractured blocks, thereby short-circuiting the porous media flow. The term “short-circuiting” is used to describe the interconnection between fractures enhancing fluid movement. This short circuiting was observed at the Old Tampa well field (Robinson, 1995). The effective porosity values are those used for the layered model. Input values are shown in figures 12 and 13.

Simulated Areas of Contribution to Supply Wells, Using Particle Tracking Techniques

Ground-water flow was modeled by using particle tracking techniques to derive the area contributing water to supply wells. The area around each well encompassed by pathlines defines the approximate area of contribution that supplies water to pumping wells. Areas of contribution were delineated for the hypothetical carbonate aquifer systems by placing particles within the grid block containing wells and by running the MODPATH program in the backward-tracking mode. Particle locations were plotted at 10-year intervals and terminated after 50 years. Particle locations were also plotted for a 5-year delineation of the area of contribution. The particle paths were plotted in plane and cross-sectional view. Plane view particle paths were used to estimate time-related areas of contribution to supply wells for the Central Swamp and Lake Terrace regions. Plane views were created by projecting all of the particle paths onto a two-dimensional slice and, therefore, represents the composite area of contribution for the entire thickness of the simulated regions. The extent of the particle paths represents the maximum area from which water is supplied to the wells. Cross-sectional view particle paths are presented to show the effects of aquifer heterogeneity on the vertical flow fields. Cross-sectional views were created by projecting particle paths for supply wells located along a specified row onto that particular row. Therefore, particle paths in the cross section and in the plane view cannot be readily correlated. The sizes of the simulated areas of contribution are those for 50- and 5-year time-related areas.

The Central Swamp Region

The size, shape, and orientation of the areas of contribution in the Central Swamp region for the hypothetical carbonate aquifer systems were delineated by seeding cells containing production wells with particles and by analyzing the flow path patterns in plane view (fig. 14). In addition, boundary fluxes were calculated using the computer program ZONEBUDGET. ZONEBUDGET can be used to calculate the subregional water budgets using results from MODFLOW (Harbaugh, 1990). The appendix contains a list of inflow percentages from each of the constant-head boundaries. Inflow from the constant-head water table ranged from 58 to 81 percent. A brief discussion of the ZONEBUDGET results is included in the discussion of the individual cases.

Case 1.—The isotropic, homogeneous single-layer carbonate aquifer system has a 12.7-mi^2 area of contribution in the shape of an elongated oval. The orientation is slightly northeast-southwest, roughly following the supply well orientation. The ZONEBUDGET results for Case 1 indicates that about 75 percent of the boundary inflow is derived from the water table. The lateral boundaries contribute varying percentages ranging from 5.5 to 7 percent. The differences among percentages derived from the individual lateral boundaries is probably the result of well locations relative to the boundaries.

Cases 2A and 2B.—The simulated areas of contribution are approximately 12.4 mi^2 for the anisotropic, single-layer, carbonate aquifer system. The shape and orientation are elliptical and elongated in the direction of the maximum transmissivity tensor. The ZONEBUDGET results for Cases 2A and 2B indicate that about 63 percent of the boundary inflow is derived from the water table. This is 12 percent less than in the isotropic case (Case 1) and is probably the result of enhanced direction-dependent lateral transmissivity in the pumped aquifer. The combined inflow from the lateral boundaries normal to the maximum transmissivity tensor contribute about 35 percent.

Case 3A.—The simulated area of contribution is approximately 8.2 mi^2 for the impermeable, discrete, fractured, carbonate aquifer system. The shape is roughly circular and without apparent orientation. The shift to a more circular area of contribution is probably due to the flow field attenuation at the fracture network and greater velocities of the particles not intersecting fractures. The ZONEBUDGET results for Case 3A indicates that about 81 percent of the boundary inflow is derived from the water table. This is 6 percent more than in the isotropic case and is probably the result of the flow field attenuation by the simulated impermeable fractures in the pumped aquifer. Lateral inflow is contributed almost exclusively from lateral boundaries 1 and 4, which are located away from the impermeable fracture blocks.

Cases 3B and 3C.—The simulated areas of contribution for the permeable, discrete, fractured, carbonate aquifer system ranged from 10.7 to 12.1 mi^2. The size of the area of contribution for various values of fracture-influenced transmissivity is not greatly affected; but, as the ratio of transmissivities in the fractured and unfractured blocks increases, particle paths deviate from radial flow. Particles travel two to three times farther in the simulated fractured blocks than in the unfractured blocks. The ZONEBUDGET results for Cases 3B and 3C indicate that about 69 and 63 percent of the boundary inflow is derived from the water table, respectively. This is 6 and 12 percent less than in the isotropic case and is probably the result of enhanced transmissivity of the simulated permeable fractures. The lateral boundaries closest to the fractured blocks contribute a greater percentage, and this percentage increases as the ratio of transmissivities in the fractured to unfractured blocks is increased.

Case 4A.—The simulated area of contribution for the four-layer carbonate aquifer system is the same size (12.7 mi^2), shape, and orientation as the simulated area of contribution for the Case 1 model. This indicates that the distribution of transmissivity values by layer does not affect the composite area of contribution to supply wells. However, these alterations do affect the individual particle paths. The vertical component of flow is enhanced by simulating a layered aquifer system with variable hydraulic properties. The ZONEBUDGET results for Case 4A indicates that about 72.5 percent of the boundary inflow is derived from the water table. The lateral boundaries contribute varying percentages ranging between 5.6 and 7.5 percent.

Case 4B.—The simulated area of contribution for the nine-layer carbonate aquifer system is 23.0 mi^2. The shape is irregular, but roughly circular. There appears to be no preferred orientation. This hypothetical carbonate aquifer system incorporated discrete producing zones of higher permeability. The particle paths are horizontal in the permeable zones and more vertical in the lower permeability layers. The particles travel four times farther in these zones, generating a larger composite area of contribution. The ZONEBUDGET results for Case 4B indicates that about 75 percent of the boundary inflow is derived from the water table and is nearly equivalent to the isotropic case. The lack of preferred orientation of the composite area of contribution is supported by the budget results because nearly equivalent percentages are contributed from each of the lateral boundaries.

Case 5.—The simulated area of contribution for the doubly porous, carbonate aquifer system are 12.7, 16.0, and 39.1 mi^2 for porosities of 20, 10, and 5 percent, respectively. The area of contribution for the doubly porous model with an effective porosity of 20 percent is not shown in figure 14 because it is identical to Case 1. The doubly porous model with an effective porosity of 5 percent is almost circular in shape.
No orientation was evident. The ZONEBUDGET results for Case 5 when using a 5 percent porosity indicates that about 57 percent of the boundary inflow is derived from the water table. This is 18 percent less than in the isotropic case and is probably the result of the higher simulated transmissivity in the pumped aquifer. The lack of preferred orientation of the area of contribution is supported by the budget results because nearly equivalent percentages are contributed from each of the lateral boundaries.

Case 6.—The simulated area of contribution for the vertically and horizontally interconnected heterogeneous carbonate aquifer system is 23.6 mi^2.

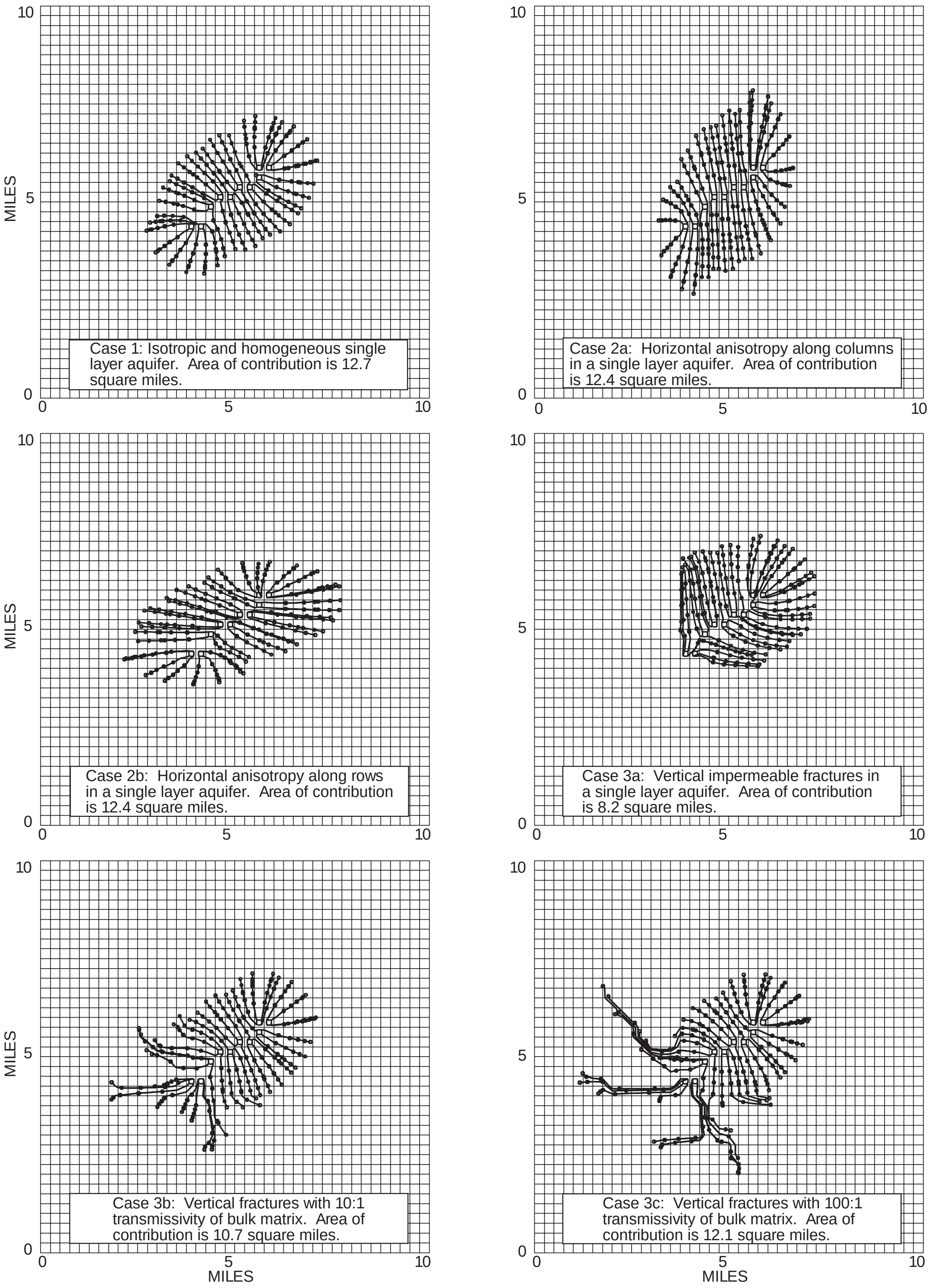


Figure 14. Fifty-year time-related area of contribution for the hypothetical carbonate aquifer systems in the Central Swamp region.

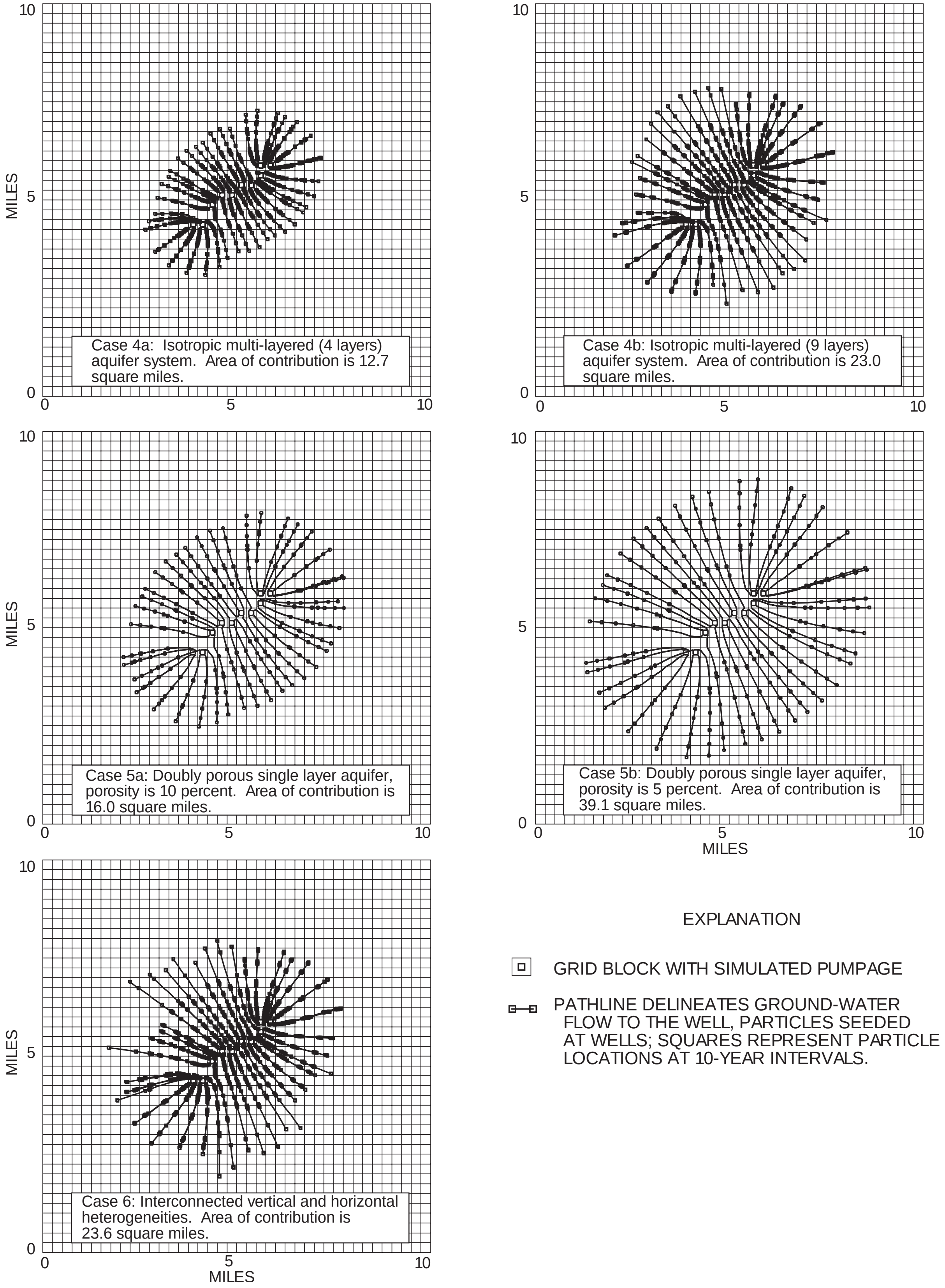


Figure 14. (Continued) Fifty-year time-related area of contribution for the hypothetical carbonate aquifer systems in the Central Swamp region.

The shape is irregular, especially in the vicinity of the simulated fracture network. The ZONEBUDGET results for Case 6 indicate that boundary inflows are nearly the same as for Case 4B. This indicates that enhanced lateral flow zones in the pumped aquifer control the source of boundary inflow to a greater extent than enhanced vertical interconnection between flow zones even though the shape of the area of contribution is affected by these simulated vertical fractures.

Figure 15 is included in the report to show the effects of aquifer heterogeneity in cross section. The cross-section view is along row 20 in the Central Swamp region and particle paths are projected onto a two-dimensional slice corresponding to row 20. Particles were seeded in each well in row 20, and all wells were pumped during simulation. The projection can be misleading in that particles that do not travel in the specified row are projected onto that row. However, the figure does present the vertical flow deviations not readily discernible in plane view. The vertical flow deviations shown in figure 15 are discussed in terms of observed variations for the particular row.

Case 1.—The particle paths are evenly spaced and become more vertical near the top of the simulated carbonate aquifer system.

Cases 2A and 2B.—The predominant direction of aquifer anisotropy is readily apparent. By using the cross-section projection along a row, lateral spread of pathlines is small when flow is predominantly along columns and large when flow is predominantly along rows.

Cases 3A, 3B, and 3C.—Discrete fracture networks influence the lateral spread of pathlines by limiting pathline length when intersecting closed fractures and increasing lateral spread in the direction of high permeability fractures.

Case 4A.—Simulation of a multilayered aquifer system with contrasting hydraulic properties had a pronounced effect on flowlines and simulated particle paths. The particles tend to move more horizontally in permeability layers and more vertically in low permeability layers.

Case 4B.—Simulation of discrete producing zones has an even more pronounced effect because of the greater contrasts in hydraulic properties among the hydrologic units. Flow is predominantly horizontal in the enhanced flow zones and nearly vertical in the less permeable zones.

Cases 5A and 5B.—Selection of simulated porosity affects the lateral spread of pathlines. The lower the porosity the larger the spread.

Case 6.— The distribution of pathlines in the cross section does not appear to be affected by enhanced vertical connectivity between zones and is identical to case 4B.

All of the hydrogeologic factors tested had some effect on the simulated flow fields that defined the areas of contribution in the Central Swamp region. Generally, the simulated areas of contribution represent a composite area that results from pumping interference among supply wells. Well orientation, distribution, and pumping rates have an underlying effect on the size, shape, and orientation of the areas of contribution. Differing types of simulated aquifer anisotropy and heterogeneity affected the areas of contribution in a variety of ways. The size of the simulated areas of contribution is mostly affected by heterogeneous layering of aquifer properties and the selection of effective porosity. The shape of simulated areas of contribution to supply wells is mostly affected by the location of the discrete fracture network, and the orientation of simulated areas of contribution is mostly affected by aquifer anisotropy.

The Lake Terrace Region

The size, shape, and orientation of the areas of contribution in the Lake Terrace region for the hypothetical carbonate aquifer systems were delineated by seeding cells containing production wells with particles and by analyzing the flow path patterns in plane view (fig. 16). In addition, boundary fluxes were calculated by using the computer program ZONEBUDGET. ZONEBUDGET can be used to calculate the subregional water budgets using results from MODFLOW (Harbaugh, 1990). The appendix contains a list of inflow percentages from each of the constant-head boundaries. Inflow from the constant-head water table ranged from 38 to 65 percent. A brief discussion of the ZONEBUDGET results among the various cases is included in the discussion of the individual cases.

Case 1.—The isotropic, homogeneous, single-layer, carbonate aquifer system has a 4.0-mi^2 area of contribution. The shape and orientation that were delineated are roughly radial particle paths surrounding an individual grid block containing wells. The combined areas of contribution for the well field roughly follow the orientation of the supply wells. The ZONE

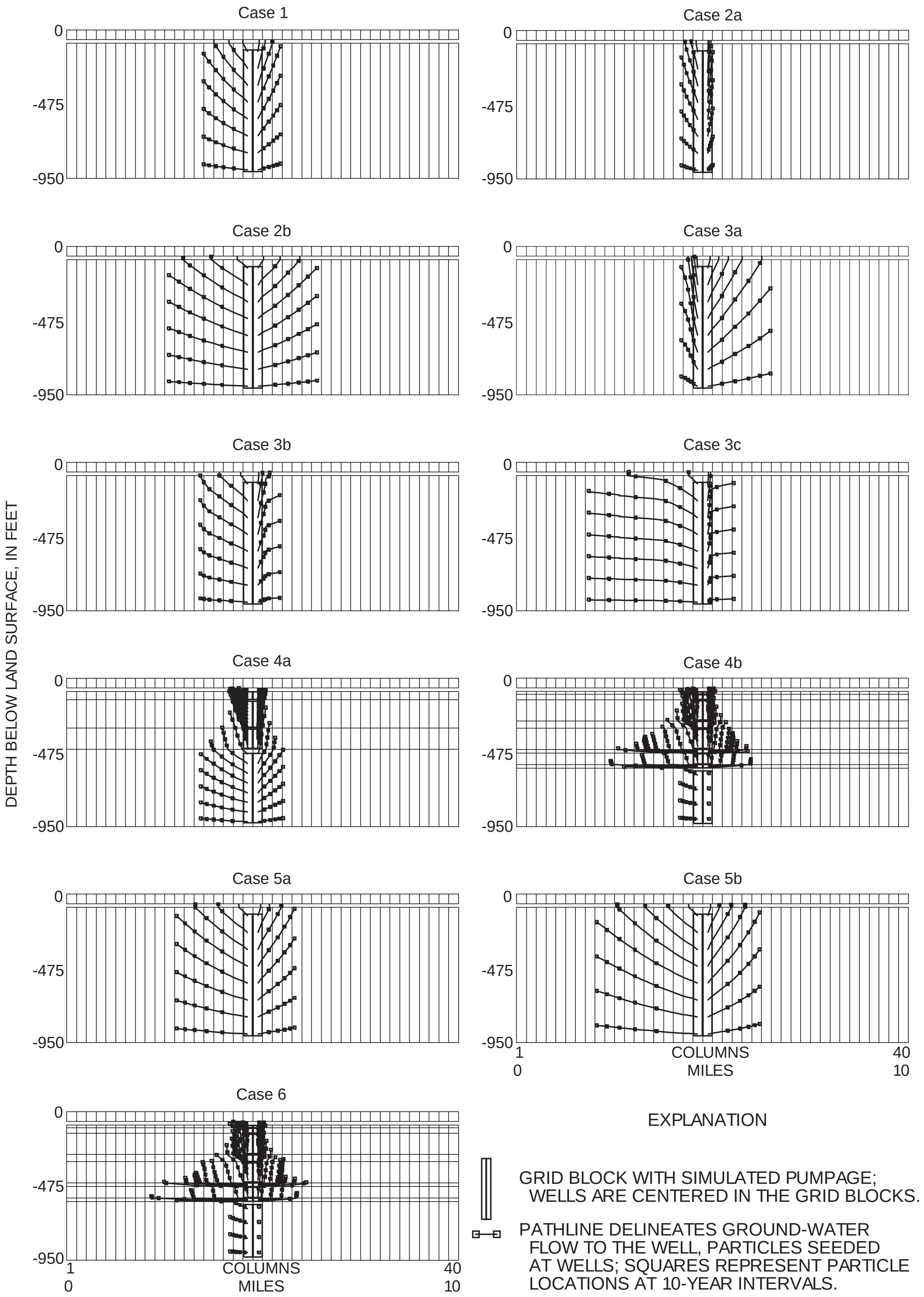
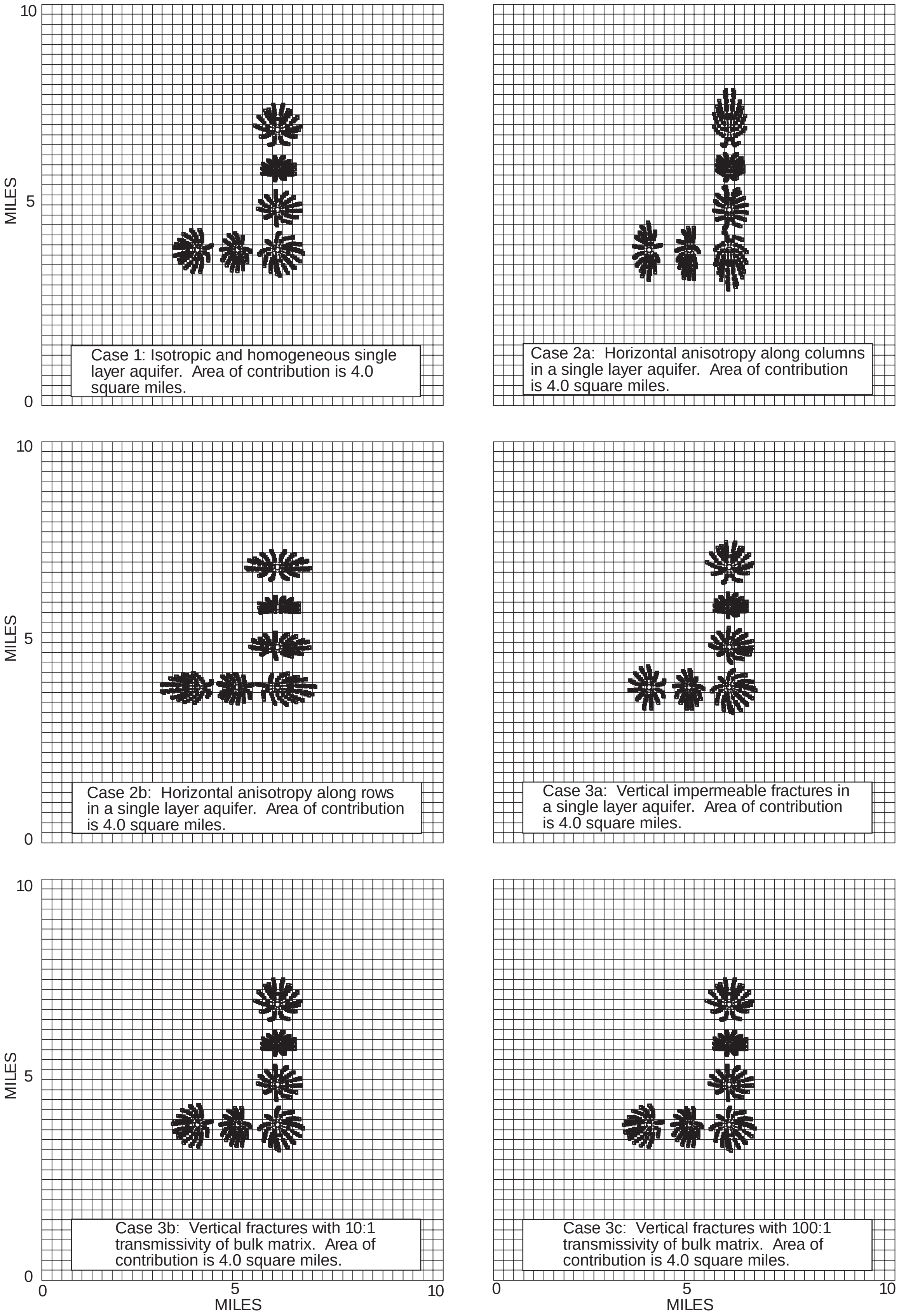


Figure 15. Fifty-year traveltimes for particles projected onto a two-dimensional slice corresponding to row 20 for the hypothetical carbonate aquifer systems in the Central Swamp region.



Case 1: Isotropic and homogeneous single layer aquifer. Area of contribution is 4.0 square miles.

Case 2a: Horizontal anisotropy along columns in a single layer aquifer. Area of contribution is 4.0 square miles.

Case 2b: Horizontal anisotropy along rows in a single layer aquifer. Area of contribution is 4.0 square miles.

Case 3a: Vertical impermeable fractures in a single layer aquifer. Area of contribution is 4.0 square miles.

Case 3b: Vertical fractures with 10:1 transmissivity of bulk matrix. Area of contribution is 4.0 square miles.

Case 3c: Vertical fractures with 100:1 transmissivity of bulk matrix. Area of contribution is 4.0 square miles.

Figure 16. Fifty-year time-related areas of contribution for the hypothetical carbonate aquifer systems in the Lake Terrace region.

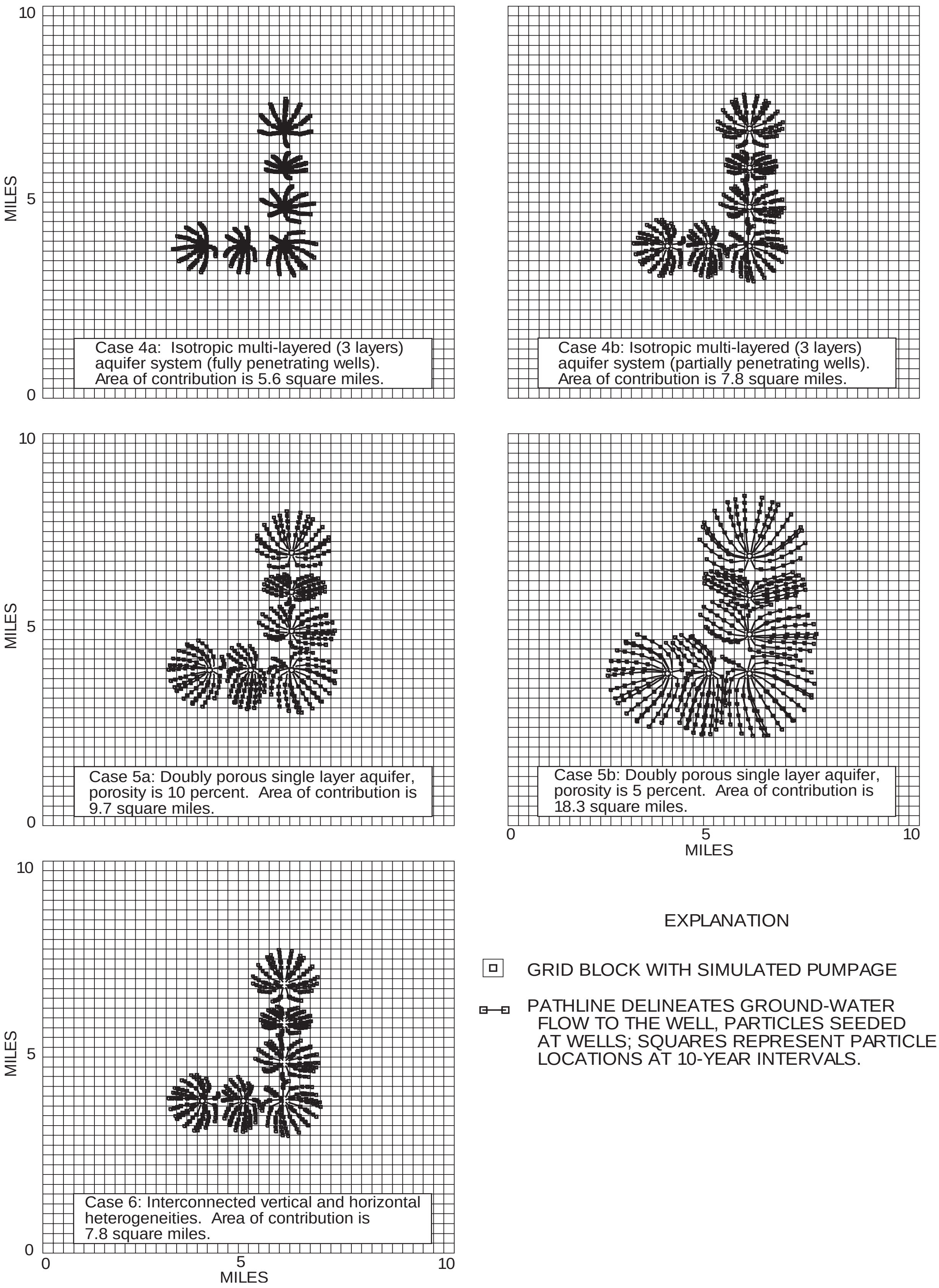


Figure 16. (Continued) Fifty-year time-related areas of contribution for the hypothetical carbonate aquifer systems in the Lake Terrace region.

BUDGET results for Case 1 indicate that about 58 percent of the boundary inflow is derived from the water table. The lateral boundaries contribute varying percentages ranging between 8 and 12 percent. The differences among percentages derived from the individual lateral boundaries is probably the result of well locations relative to the boundaries.

Cases 2A and 2B.—The anisotropic, single-layer, carbonate aquifer system also has a 4.0 mi^2 area of contribution. The shape and orientation of particle paths are elliptical and elongated in the direction of the maximum transmissivity tensor. The ZONEBUDGET results for Cases 2A and 2B indicate that about 48 percent of the boundary inflow is derived from the water table. This is 10 percent less than in the isotropic case (Case 1) and is probably the result of enhanced direction-dependent lateral transmissivity in the pumped aquifer. The combined inflow from the lateral boundaries normal to the maximum transmissivity tensor contribute 50 percent.

Cases 3A, 3B, and 3C.—Neither the simulated impermeable nor permeable, fractured, single-layer, carbonate aquifer system affected the size, shape, or orientation of the simulated areas of contribution. The 50-year particle paths do not intersect the simulated fracture locations. The area of contribution is the same as for Case 1. Whereas simulated fracture locations did not affect the size, shape, or orientation of the areas of contribution, the ZONEBUDGET results were affected. The ZONEBUDGET results for Case 3A indicate that about 66 percent of the boundary inflow is derived from the water table. This is 8 percent more than in the isotropic case and is probably the result of the flow field attenuation by the simulated fractures in the pumped aquifer. A combined lateral inflow of about 32 percent is almost equally contributed from boundaries 1, 3, and 4. Lateral boundary 2 contributes only about 2 percent. This is probably due to the close proximity of an impermeable fracture to the wells. The ZONEBUDGET results for Case 3B and 3C indicate that about 56 and 55 percent of the boundary inflow is derived from the water table, respectively. This is 2 and 3 percent less than in the isotropic case and is probably the result of the enhanced transmissivity of the simulated permeable fractures; however, the lateral inflow is not significantly increased because the fractures blocks are located distant from the pumped wells. The greatest increase in contribution between impermeable and permeable fracture simulations is from lateral boundary 2.

Case 4.—Two scenarios of well construction, fully and partially penetrating, were simulated in the multilayered carbonate aquifer system. The simulated areas of contribution for the fully and partially penetrating wells tapping a multilayered carbonate aquifer system are 5.6 and 7.8 mi^2, respectively. The general shape and orientation is the same as for the previous cases. The difference between the sizes in areas for case 4A and 4B is the result of greater well interference, as exhibited by the particle paths in case 4B. The representation of the partial penetrating wells coincide with actual well depths in the Cosme-Odessa well field. The ZONEBUDGET results for Cases 4A and 4B indicate that between 38 and 40 percent of the boundary inflow is derived from the water table and is nearly 20 percent less than in the isotropic case. The effects of partial penetration did not substantially change inflow from the water table (<2 percent). Inflow from the lateral boundaries for Case 4A ranges from about 13 to 18 percent and in Case 4B from about 12 to 17 percent.

Cases 5A, 5B, and 5C.—The simulated areas of contribution for the doubly porous carbonate aquifer system with an effective porosity of 20 and 10 percent are 5.6 and 9.7 mi^2, respectively. The simulated areas of contribution for the doubly porous carbonate aquifer system with an effective porosity of 5 percent is 18.3 mi^2. As the simulated effective porosity decreased, the area of contribution increased. The composite shape and orientation are similar but the particle paths around individual wells are less radial due to competition among the wells. The area of contribution for 20 percent porosity is not shown in figure 16. The ZONEBUDGET results for Case 5 when using a 5 percent porosity indicate that about 38 percent of the boundary inflow is derived from the water table. This is 20 percent less than in the isotropic case and is probably the result of the higher simulated transmissivity in the pumped aquifer.

Case 6.—The simulated areas of contribution for the fully and partially penetrating wells tapping an vertically and horizontally interconnected heterogeneous, carbonate aquifer system are 5.6 and 7.8 mi^2, respectively. The simulated areas of contribution are nearly identical to Case 4; therefore, only the partially penetrating well simulation is shown in figure 16. The enhanced vertical connection between layers in the simulated fractured grid blocks did not affect the areas of contribution. The ZONEBUDGET results for Case 6 indicate that boundary inflows are nearly the same as for Case 4B. This indicates that enhanced lateral flow zones in the pumped aquifer control the source of boundary inflow to a greater extent than enhanced vertical interconnection between flow zones even though the shape of the area of contribution is affected by these simulated vertical fractures.

Figure 17 is included in the report to show the effects of aquifer heterogeneity in cross section. The cross-section view is along row 25 in the Lake Terrace region and particle paths are projected onto a two-dimensional slice corresponding to row 25. Slight variations in the flow fields can be observed that are not readily apparent in plane view.

Case 1.—The particle paths are evenly spaced and become more vertical near the top of the simulated carbonate aquifer system.

Cases 2A and 2B.—The predominant direction of anisotropy is readily apparent. The lateral spread of pathlines is small when flow is predominantly along columns and large when flow is predominantly along rows.

Cases 3A, 3B, and 3C.—Particle paths closest to the simulated impermeable fracture network (Case 3A) reflect slight effects from the no-flow grid blocks by becoming more vertical. Slight variations in the flow field as represented by particle paths (case 3B and 3C) are the result of location and permeability of the discrete fracture network, but, because the fracture network is not intersected directly, effects are minimal.

Case 4A and 4B.—Layering and well penetration affect the flow field by creating variations in fluid movement direction and velocity. The lateral spread of particles is small in the simulated semiconfining unit relative to the more permeable units (Case 4A). When only the upper producing zone is being stressed, flow paths are predominantly horizontal in the high permeability layers and vertical in the low permeability layer (Case 4B). The flow velocities vary by layer due to differing effective porosities and permeabilities.

Case 5.—Selection of simulated porosity affects the lateral spread of pathlines. The lower the porosity, the larger the spread, which results in competition for flow among wells.

Case 6.—The particle paths are identical to those for Case 4. The fracture network is not intersected and, therefore, has little effect on particle paths.

In the Lake Terrace region, the hydrogeologic factors tested affected the areas of contribution to supply wells. The well distribution, orientation, and pumping rates resulted in the distinct shape of the areas of contribution. Pumping interference is minimal, and each well is characterized by an individual contributing area for isotropic, homogeneous conditions (Case 1). Incorporation of aquifer anisotropy and heterogeneity does affect the size, shape, and orientation of areas of contribution, but not as dramatically as expected. The size of the simulated areas of contribution is mostly affected by heterogeneous layering of aquifer properties (Cases 4 and 6) and by the selection of effective porosity (Case 5). The shape of simulated areas of contribution is mostly affected by well orientation and distribution, and the orientation is mostly affected by aquifer anisotropy (Case 2).

Comparisons Between Simulated Areas of Contribution in the Central Swamp and Lake Terrace Regions

The simulated areas of contribution for the prototype regions were compared to illustrate the effects of withdrawal rates, well distribution, and hydrogeologic differences on size, shape, and orientation of the areas. The major difference between the simulated areas of contribution in the Central Swamp and Lake Terrace regions is size. Generally, the simulated areas of contribution are about 60 percent larger in the Central Swamp region where the pumping rate is more than double and transmissivity is about half that of the Lake Terrace region. However, the difference in contributing area size between the two regions was not constant for all the hypothetical carbonate aquifer systems simulated. The largest difference in simulated contributing area size between the Central Swamp and Lake Terrace regions was 64 percent, a result of the simulation of the vertically and horizontally interconnected heterogeneities (Case 6). The smallest difference in contributing area size between the regions was 31 percent, a result of the simulation of a multilayered system (Case 4).

The shapes of the simulated areas of contribution in the Lake Terrace region are predominantly controlled by well location and distribution and generally follow the outline of supply wells at the Cosme-Odessa well field. The shapes of simulated areas of contribution in the Central Swamp region are primarily affected by locations of simulated fracture networks. The larger the ratio of fracture to bulk matrix permeability, the more linear the flow field becomes. The shapes of particle paths for the multilayered carbonate aquifer system in the Central Swamp region were irregular, rosette-shaped areas of contribution because of the variability in flow direction and velocity between high

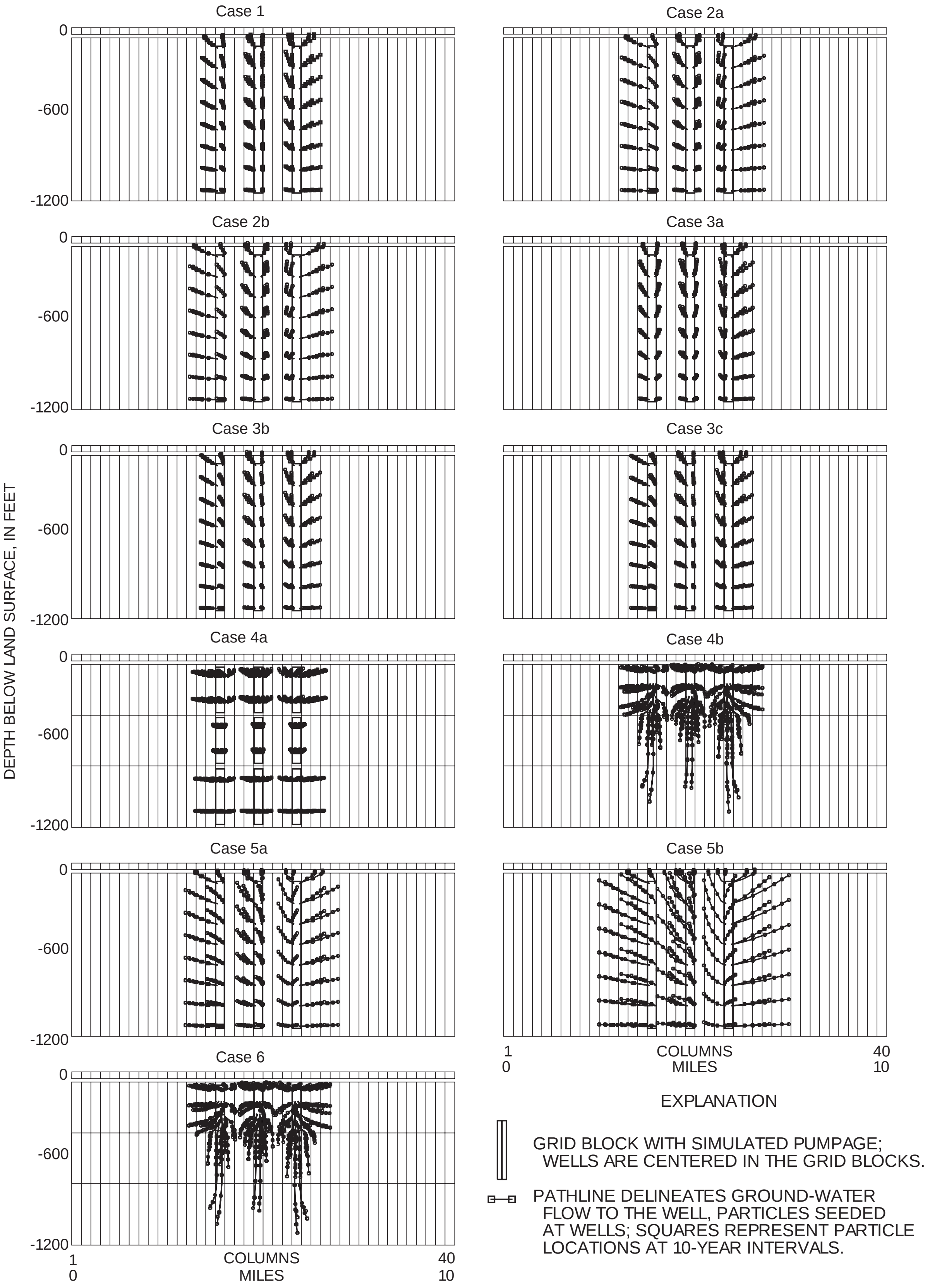


Figure 17. Fifty-year traveltimes for particles projected onto a two-dimensional slice corresponding to row 25 for the hypothetical carbonate aquifer systems in the Lake Terrace region.

and low permeability layers. The shapes of the areas of contribution for simulations incorporating aquifer anisotropy in both regions are elongated ellipses. Aquifer anisotropy has similar effects on the orientation of simulated areas of contribution in the Central Swamp and Lake Terrace regions. The orientation of these areas of contribution is controlled by the maximum transmissivity tensor. In the Central Swamp region, orientation of particle paths is affected by the fracture network. Flow deviates from radial to linear paths once the fracture network is intersected. The 50-year traveltimes in the Lake Terrace region are unaffected by the simulated fracture network, because the 50-year traveltimes of particle paths do not intersect the discrete fracture network. The first particles just reach the fracture network after 100 years.

Simulations incorporating generalized representations of nonisotropic and nonhomogeneous aquifer behavior including anisotropy, vertical fractures, and multiple layers do affect the size, shape, and orientation of areas of contribution. Therefore, local-scale heterogeneities should be considered when delineating areas of contribution for karst carbonate aquifer systems.

COMPARISON OF NUMERICAL SIMULATION RESULTS WITH RESULTS USING ANALYTICAL METHODS

Major differences in the methodology between analytical and numerical delineation of protection zones to supply wells result from the strict limiting assumptions when implementing analytical techniques. Analytical models are typically one-dimensional. Consequently, three-dimensional aquifer anisotropy and heterogeneity cannot be incorporated. The numerical models developed for this study were designed to approximate varying degrees of aquifer anisotropy and heterogeneity.

Vecchioli and others (1989) used a radial, volumetric displacement, analytical method to delineate protection zones at well fields in the Upper Floridan aquifer in west-central Florida. The analytical method used was based on equations derived from Darcy’s law and assumes uniform, radial flow. A porosity of 5 percent was selected for the analysis. The selection of a 5 percent porosity value is based on the characterization of the Upper Floridan aquifer system as a doubly porous system having both primary and secondary porosity. Fluid flow tends to be through the solution features (secondary porosity) which make up only a small part of the total porosity. Therefore, the rate of fluid movement can be more accurately estimated by using a porosity value only associated with the conduits. Protection zones were delineated for a specified traveltime of 5 years, flow was assumed to be lateral in the aquifer, and the aquifer thickness was taken equal to the well penetration. Where the protection zones overlapped, composite protection zones were delineated. Limitations of the analytical method include the inability to incorporate the natural slope of the potentiometric surface, complex hydrologic boundaries, and variations in porosity and aquifer thickness (Vecchioli and others, 1989, p. 33).

The numerical model that most closely approximates the conditions used in the analytical model is the doubly porous model when using an aquifer porosity of 5 percent (Case 5). To make comparisons with the analytically derived protection zones, 5-year time related areas of contribution were numerically simulated for the Central Swamp and Lake Terrace regions. The numerically simulated contributing areas for the two regions and the analytically delineated protection zones for the Cypress Creek and Cosme-Odessa well fields (from Vecchioli and others, 1989) are shown in figure 18.

The areas of contribution that were delineated using numerical methods are different in both shape and size from protection zones that were delineated using analytical methods. The protection zones that were delineated for the Cypress Creek and Cosme-Odessa well fields using the analytical model are 7.85 and 8.24 mi^2, respectively. The contributing areas that were delineated for the Central Swamp and Lake Terrace regions are about 4 and 1 mi^2, respectively. This discrepancy in size can be the result of various factors. The most critical factor is that the analytically derived protection zone size was determined for a 5-year lateral traveltime, which does not correspond to a 5-year traveltime for seeded particles because particles can move both laterally and vertically. Some of the assumptions of analytical methods that may affect the size, shape, and orientation of delineated protection zones are that ground-water flow to wells is uniform and that the aquifer is bounded by nonleaky confining beds. The assumption of uniform, radial flow is only approximated near the well bore and the deviation from radial flow increases as the distance from the well is increased. The assumption of nonleaky confining beds is a poor assumption, because relatively few confined

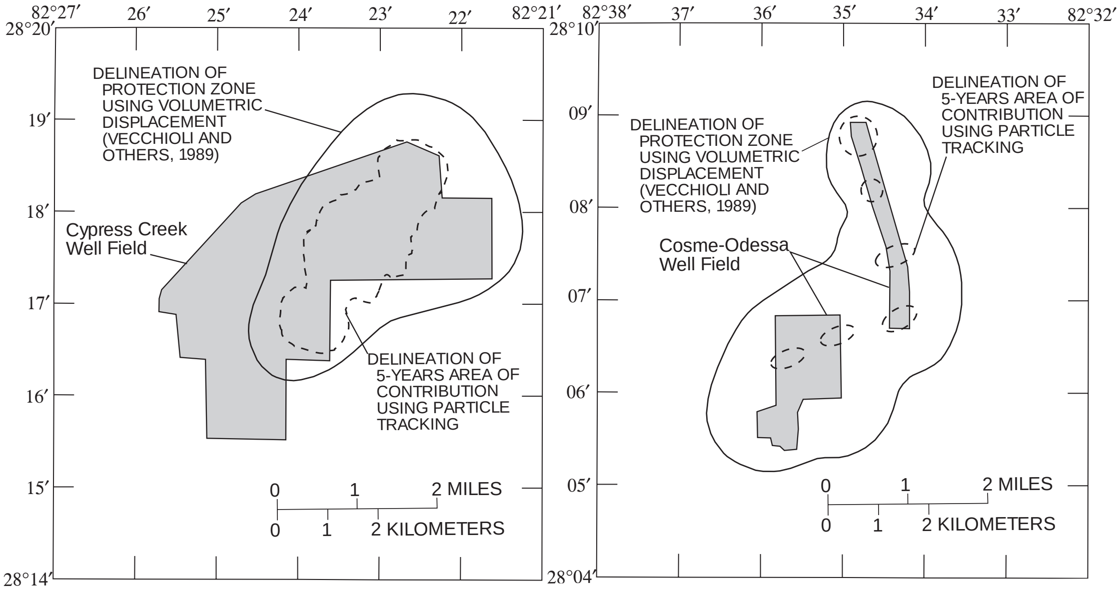


Figure 18. Delineation of protection zones using analytical methods, and areas of contribution using numerical methods for the Central Swamp and Lake Terrace regions.

aquifers do not receive water from adjacent beds. In addition the analytically derived protection zones do not account for changes in the flow field caused by changes in the local hydraulic gradient in response to pumping.

Numerical models should be more accurate than analytical models simply because greater aquifer complexities can be incorporated in the model. However, these numerical models are hypothetical in that distributions and behaviors of aquifer heterogeneities are not well understood. The analytically derived protection zones are very conservative when compared with the contributing areas delineated by numerical modeling.

SUMMARY AND CONCLUSIONS

The highly permeable, karst carbonate Floridan aquifer system underlies Florida and much of the southeastern Coastal Plain and is a principal source of drinking water. Public supply wells in karst carbonate aquifers are particularly vulnerable to contamination. Estimation of areas of contribution in karst carbonate aquifers can be extremely difficult, because permeability in carbonate aquifers is greatly enhanced by dissolution of rock, which creates an uneven distribution of permeability along preferred flow paths.

Traditional strategies to protect ground-water resources have been through land-use regulation within a prescribed radial area around supply wells. Hydrogeologic factors operating at a site that may affect the size, shape, and orientation of areas of contribution to supply wells often are not considered. Ground-water flow to wells in karst carbonate aquifer systems tends to be through solution-enhanced conduits. Nonradial flow along preferential zones can result in inaccurate estimations of flow paths and traveltimes. A better understanding of the effects of aquifer heterogeneity on flow fields is needed to protect the ground-water resources.

The influence of aquifer anisotropy and heterogeneity on the movement of ground water can often be inferred from aquifer and tracer test data. Evaluation of aquifer test, tracer test, and borehole geophysical log data available for the study area indicate various nonuniform flow conditions. Based on field evidence of nonuniform flow, six hypothetical carbonate aquifer systems were conceptualized. These conceptualized systems were designed to approximate anisotropic and heterogeneous aquifer behavior and to evaluate how incorporation of aquifer anisotropy and heterogeneity may affect the size, shape, and orientation of areas of contribution.

Although many hydrogeologic factors affect the estimation of contributing areas to well fields, this report focused primarily on the effects of aquifer heterogeneity and anisotropy on the size, shape, and orientation of the simulated areas. The method used to estimate contributing areas was a three-dimensional numerical flow model and particle tracking subroutine used as a postprocessor. MODFLOW and MODPATH numerical models were used to generate time-related areas of contribution for six carbonate aquifer system types. These include: an isotropic and homogeneous single-layer system; an anisotropic in a horizontal plane single-layer system; a discrete vertically fractured single-layer system; a multilayered system; a doubly porous single-layer system; and a vertically and horizontally interconnected heterogeneous system. The simulated aquifer anisotropy was 5:1 and was determined from TENSOR2D results. The simulated vertical discrete fracture network represents locations of photolineaments. The simulated enhanced flow zones were determined from borehole video and geophysical logs. The hypothetical carbonate aquifer systems were simulated for two prototype regions. The two regions, Central Swamp and Lake Terrace, were selected to be representative of the hydrologic diversity within the study area.

The simulated distributions of aquifer heterogeneity and anisotropy are highly conceptualized, but are based on plausible carbonate aquifer heterogeneities observed in west-central Florida that are typical of carbonate aquifers everywhere. This study indicates that the distribution and nature of aquifer heterogeneities will affect the size, shape, and orientation of areas of contribution in a karst carbonate aquifer system. The size of the 50-year time-related areas of contribution ranged from 8.2 to 39.1 square miles in the Central Swamp region. The size of the 50-year time-related areas of contribution ranged from 4.0 to 18.3 square miles in the Lake Terrace regions. The differences in size between the regions are primarily the results of variability in withdrawal rates, well distribution, and aquifer transmissivity. The simulated areas of contribution are 60 percent larger in the Central Swamp region where pumpage is more than double and transmissivity is about half that of the Lake Terrace region. Simulations showed that the size of areas of contribution is primarily affected by simulated withdrawal rates, effective porosity of the carbonate rock, and transmissivity. The shape and orientation of the simulated areas of contribution primarily result from aquifer anisotropy, well distribution, flow along solution-enhanced zones, and short-circuiting of flow through fracture networks. Flow velocities and particle path length respond to withdrawal rates, simulated effective porosity, short-circuiting of flow by fractures, and effective transmissivity.

Results of simulations incorporating aquifer heterogeneity indicate that oversimplification of the flow system may result in erroneous definition of flow fields. For example, aquifer anisotropy typical of many carbonate aquifers creates elliptical flow fields. Circular protection zones do not adequately characterize the elliptical areas of contribution. Also, areas of contribution were larger when the carbonate aquifer system was simulated as a multilayered system with discrete flow zones. This type of carbonate aquifer system is observed in west-central Florida. Simulated areas of contribution are significantly influenced by the choice of effective porosity. However, accurate, quantitative values of effective porosity in a carbonate aquifer system like the Upper Floridan aquifer are extremely difficult to measure.

Although the effective porosity from core analyses can characterize the primary porosity of the Upper Floridan aquifer, fluid flow tends to be through solution features that make up only a small part of the total porosity. The inclusion of a vertical fracture network may or may not affect the delineation of areas of contribution. In the Lake Terrace region, the simulated fractures had little effect on the short term (50-year) area of contribution. In the Central Swamp region, the simulated fractures have a large effect, because the simulated flow field intersected these fractures. Flow in fractures is linear rather than radial and velocities increase. Areas of contribution are difficult to precisely determine where a high degree of aquifer anisotropy and heterogeneity exists. The anisotropies and heterogeneities were simulated to show their possible effects on the size, shape, and orientation of areas of contribution.

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APPENDIX

Boundary Fluxes Calculated by Using the ZONEBUDGET Computer Program for the Central Swamp and Lake Terrace Regions

Appendix. Boundary fluxes calculated using ZONEBUDGET computer program for the Central Swamp and Lake Terrace regions

Central Swamp			Lake Terrace		
Case Number	**Boundary Designation**	**Inflow (percent)**	**Case Number**	**Boundary Designation**	**Inflow (percent)**
1	Water Table	74.7	1	Water Table	58.0
	1	7.0		1	11.0
	2	6.6		2	8.0
	3	5.5		3	11.0
	4	6.2		4	12.0
2a	Water Table	63.8	2a	Water Table	48.1
	1	18.5		1	24.0
	2	0.9		2	0.9
	3	16.0		3	26.0
	4	6.2		4	1.0
2b	Water Table	63.4	2b	Water Table	48.0
	1	1.0		1	2.0
	2	18.0		2	21.0
	3	0.6		3	2.0
	4	17.0		4	27.0
3a	Water Table	81.0	3a	Water Table	66.0
	1	10.0		1	10.0
	2	1.0		2	2.0
	3	0.0		3	10.0
	4	8.0		4	12.0
3b	Water Table	69.3	3b	Water Table	56.0
	1	6.5		1	11.0
	2	9.2		2	9.0
	3	6.8		3	12.0
	4	8.2		4	12.0
3c	Water Table	63.2	3c	Water Table	55.0
	1	6.5		1	10.0
	2	11.5		2	11.0
	3	7.0		3	12.0
	4	11.8		4	12.0
4a	Water Table	72.5	4a	Water Table	37.8
	1	7.5		1	14.8
	2	6.8		2	12.6
	3	5.6		3	16.9
	4	6.8		4	17.9
4b	Water Table	74.4	4b	Water Table	39.8
	1	6.6		1	14.8
	2	6.4		2	11.6
	3	6.2		3	15.9
	4	6.4		4	17.4
5c	Water Table	57.0	5c	Water Table	38.0
	1	12.0		1	16.0
	2	11.0		2	12.0
	3	10.0		3	17.0
	4	10.0		4	17.0
6	Water Table	74.5	6b	Water Table	38.0
	1	6.6		1	14.8
	2	6.3		2	11.6
	3	6.2		3	15.9
	4	6.4		4	17.9

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations, as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases for quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

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