Hydrogeology and Simulated Development of the Brackish Ground-Water Resources in Pinellas County, Florida

By Lari A. Knochenmus and T.H. Thompson

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
square foot (ft^2)	0.0929	square meter
foot squared per day (ft^2/d)	0.0929	meter squared per day
square foot per pound (ft^2/lb)	1.007×10^{-6}	square meter per Newton
gallon per minute (gal/min)	0.00006309	cubic meter per second
million gallons per day (Mgal/d)	0.4381	cubic meter per second
pound per square inch (lb/in^2)	6.895	kilopascal
pound per cubic foot (lb/ft^3)	0.0160	gram per cubic centimeter

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

Additional Abbreviations

milligrams per liter = mg/L
coefficient of determination = R^2

HYDROGEOLOGY AND SIMULATED DEVELOPMENT OF THE BRACKISH GROUND-WATER RESOURCES IN PINELLAS COUNTY, FLORIDA

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ABSTRACT

Pinellas County, in west-central Florida, is underlain by brackish ground water. Because of a growing demand for potable water in the area, evaluation of the potential for development of brackish ground water in the uppermost producing zone of the Floridan aquifer system (zone A) was needed. The focus of the study was to evaluate the availability of brackish ground water for development and to assess the changes in quality of the brackish ground water that might result from large and prolonged withdrawals in the area.

The findings of this study indicate that a sufficient quantity of ground water containing less than 4,000 milligrams per liter of dissolved solids can be obtained from zone A in much of the county. Also, areas are underlain by ground water containing less than 2,000 milligrams per liter of dissolved solids.

South-central Pinellas County has an abundant source of brackish water and development would be away from existing well fields and in an area of high demand for water. Although suitable well yields can be obtained in this area, the quality of the brackish ground water is subject to change as a result of upconing of deeper saline water associated with pumping.

A digital ground-water flow and solute-transport model incorporating the hydrologic and hydraulic characteristics of the aquifer in Pinellas County was used to simulate the changes in water quality that might occur at various pumping rates. The model indicated that pumping brackish water at rates of 350 gallons per minute or more would probably cause dissolved-solids concentrations to increase to greater than 4,000 milligrams per liter in less than 2 years. Thus, based on the limited amount of information available and model simulation, development of the brackish ground water in zone A appears impractical because of likely changes in water quality. However, a detailed investigation of aquifer characteristics at a particular site would allow a more definitive assessment of development potential.

INTRODUCTION

Historically, Pinellas County, and especially the city of St. Petersburg, has had difficulties supplying potable water from local sources. From 1903 to 1905, several wells were drilled in St. Petersburg. After less than 3 years of pumping, these wells became brackish, and St. Petersburg was forced to utilize an alternative source of water. Nearly all of the county is underlain by brackish ground water, and the potable resources available for public supply are limited. Complicating this natural phenomenon is the rapidly increasing population in the county, which requires an increasing water supply (Thompson, 1977).

Many parts of the county rely on water imported from Pasco and Hillsborough Counties. A proposed plan for alleviating this dependence on imported water is the development of the brackish waters in the Upper Floridan aquifer that would be made usable by reverse-osmosis processing to remove dissolved solids from locally supplied ground water. Reverse osmosis works by using pressure to force water through a membrane to remove dissolved solids, thus purifying the water. This process is practical only when dissolved-solids concentrations are less than 4,000 mg/L.

The U.S. Geological Survey, in cooperation with Pinellas County, began a study in May 1987 to assess the potential for development of brackish-water resources in Pinellas County. The study area is Pinellas County, which is a peninsula in west-central Florida bounded by Tampa Bay to the east and the Gulf of Mexico to the west (fig. 1).

Purpose and Scope

This report presents the results of a study (1) to assess the distribution, quantity, and quality of the ground water in Pinellas County; (2) to identify areas where the availability and quality of the ground water is suitable for the water to be used for low-pressure reverse-osmosis treatment; and

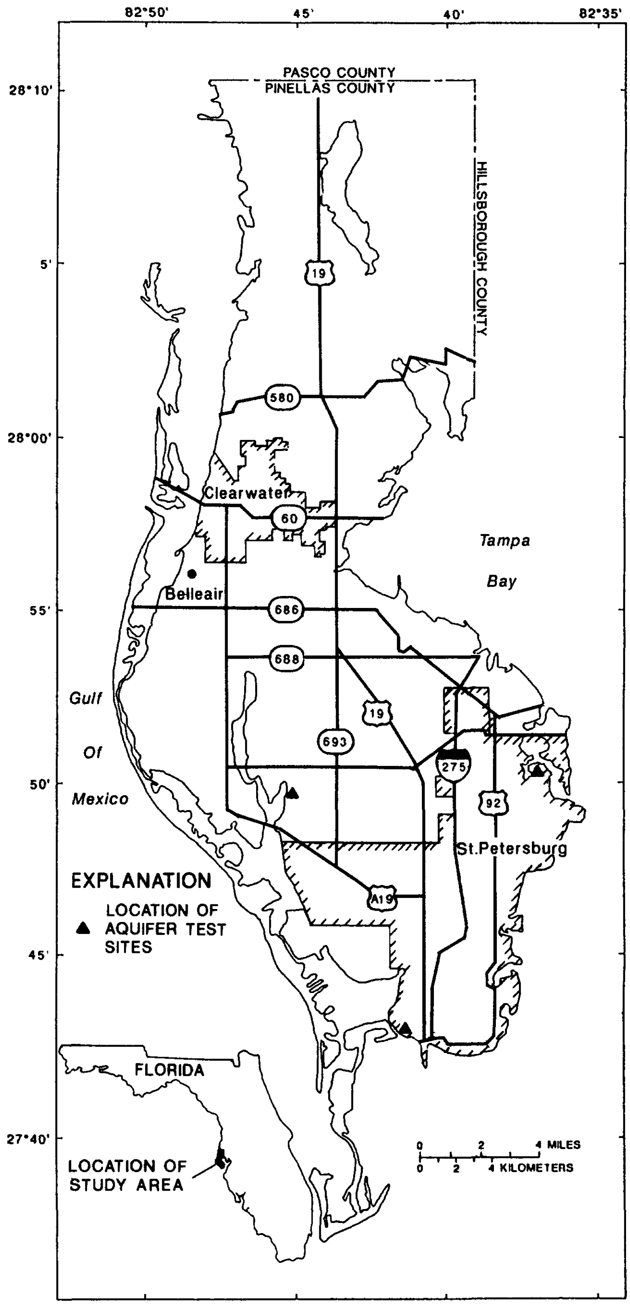


Figure 1. Location of study area.

(3) to estimate the effects of long-term pumping on the quality of the brackish ground water withdrawn from the aquifer. The quantification of the variables of aquifer thickness, confining unit thicknesses, hydrologic properties, matrix properties, and water chemistry was based on data from several sources. The information was compiled from lithologic well logs, geophysical well logs, aquifer-test data, and water-quality analyses from the files of the U.S. Geological Survey, the Southwest Florida Water Management District, and consultants' reports. In addition to the physical data available for interpretation, a ground-water solute-transport model, Heat and Solute Transport in Three-Dimensions (HST3D), developed by Kipp (1987), provided a means to define the changes in salinity that would be expected as a result of pumping water from the uppermost producing zone of the Upper Floridan aquifer.

The terminology used in this report to describe the water quality is (1) brackish water, which has a dissolved-solids concentration range of 1,000 to 10,000 mg/L, and (2) saline water, which has a dissolved-solids concentration range of 10,000 to 35,000 mg/L.

Physiographic and Geologic Setting

Pinellas County is part of the Gulf Coastal Lowlands physiographic region defined by White (1970). Structurally, Pinellas County is on the southwestern flank of the Peninsular Arch. Overlying the pre-Mesozoic igneous and metamorphic basement is a sequence of sedimentary units deposited during various transgressive and regressive events. Periods of emergence and erosion resulted in unconformable and gradational contacts between formations. The geologic history of Oligocene and younger-aged rocks, the units of interest in this study, is summarized briefly below. 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.

The Suwannee Limestone is the Oligocene unit in Pinellas County (fig. 2). The depositional environment during the Oligocene in peninsular Florida was shallow, warm, open marine waters. The Suwannee is a biogenic, predominantly foraminiferal packstone to grainstone, which is almost pure calcium carbonate. Mollusks and microfaunal remains are abundant. The formation consists of two distinct rock types. One is a cream to tan, crystalline, highly vuggy limestone with gastropod and pelecypod casts and molds. The other is a white to cream, finely pelletal limestone containing small foraminifera and micrite pellets bound in a micritic to finely crystalline limestone matrix (Miller, 1986).

Overlying the Suwannee Limestone is the Tampa Member of the Arcadia Formation, which is the lower Miocene unit of the Hawthorn Group (fig. 2). The Hawthorn Group consists of a complex sequence of lithologies. The diversity in lithology reflects the variety of depositional environments during this epoch. The environments of deposition include open-marine, shallow lagoonal, coastal, estuarine, and fluvial processes. The Hawthorn Group consists of carbonate, mixed carbonate and clastic, and clastic sequences that are heterogeneous and predominantly fine textured. The contact between the Tampa Member and the Suwannee Limestone is unconformable. The units are difficult to distinguish in the Tampa Bay area because the

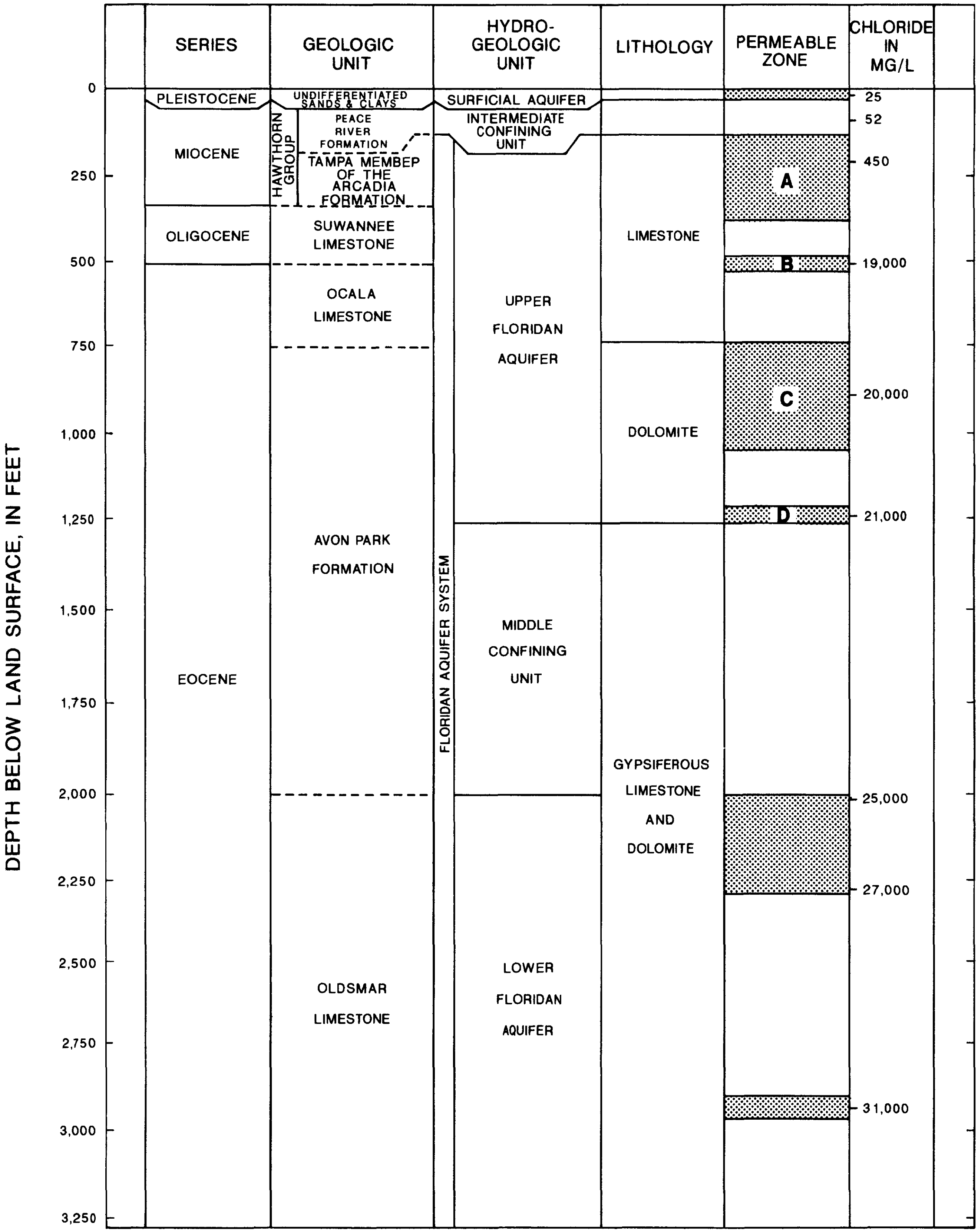


Figure 2. Generalized stratigraphic and hydrogeologic section, Pinellas County. (Modified from Hickey, 1982.)

environments of deposition were the same (warm, shallow, clear, open marine waters that covered most of western peninsular Florida). The Tampa Member is a white to light-gray, sandy, hard to soft, locally clayey, occasionally fossiliferous limestone that can contain phosphate and chert. Phosphate and clay percentages in the Tampa Member are lower in the Tampa Bay area than they are in other areas of west-central Florida.

Overlying the lower Miocene Tampa Member is the upper Miocene Peace River Formation of the Hawthorn Group (fig. 2). The Peace River Formation constitutes a low-permeability unit that acts as a confining unit in Pinellas County.

Overlying the Hawthorn Group is a sequence of undifferentiated sands and clays of post-Miocene age (fig. 2). The strata are divided into a basal sequence of marginal marine beds overlain by a series of sandy marine terrace deposits capped by thin aeolian sand deposits. The sequence consists of unconsolidated to poorly indurated clastic deposits that are dominated by quartz sand, shell, clay, and organic material (Gilboy, 1985).

The Suwannee Limestone, Hawthorn Group, and undifferentiated sands and clays of post-Miocene age represent deposits during a period of marine regression in peninsular Florida. Five major transgressive-regressive episodes occurred during the Pleistocene age (Gilboy, 1985). During regressive periods, Florida emerged from the sea, and influxes of clastic material were interbedded with the carbonates. The stratigraphy of Pinellas County reflects the regional geologic sequence of peninsular Florida.

HYDROGEOLOGY OF PARTS OF PINELLAS COUNTY

Ground water in Pinellas County occurs under water-table and confined conditions. Two aquifer systems are present: the surficial aquifer system and the Floridan aquifer system (fig. 2). The units are separated by the intermediate confining unit. Parker and others (1955) proposed the name Floridan aquifer as a collective term for the water-bearing limestone formations of Eocene, Oligocene, and Miocene age that act, more or less, as a single hydrologic unit. Terminology used in this report is based upon modifications made by Miller (1986) and by the Southeastern Geological Society (1986).

Surficial Aquifer System

The surficial aquifer system consists of undifferentiated sands and clays that vary in composition both laterally and vertically. The surficial aquifer is highly variable due to the nature of deposition affecting the physical characteristics of grain size, sorting, and thickness. These characteristics influence porosity and permeability, which, in turn, affect the ability of the unit to transmit water. The aquifer is not used as a potable-water source, but generally is used for lawn and garden irrigation.

The thickness of the surficial aquifer system ranges from 0 to 132 ft (fig. 3). Depth to the water table generally is less than 5 ft below land surface, but ranges from near 0 to more than 20 ft in some sand ridge areas. The depth to the water table fluctuates in response to recharge and pumping rates. Seasonal fluctuations are from 1 to 4 ft (Causseaux, 1985).

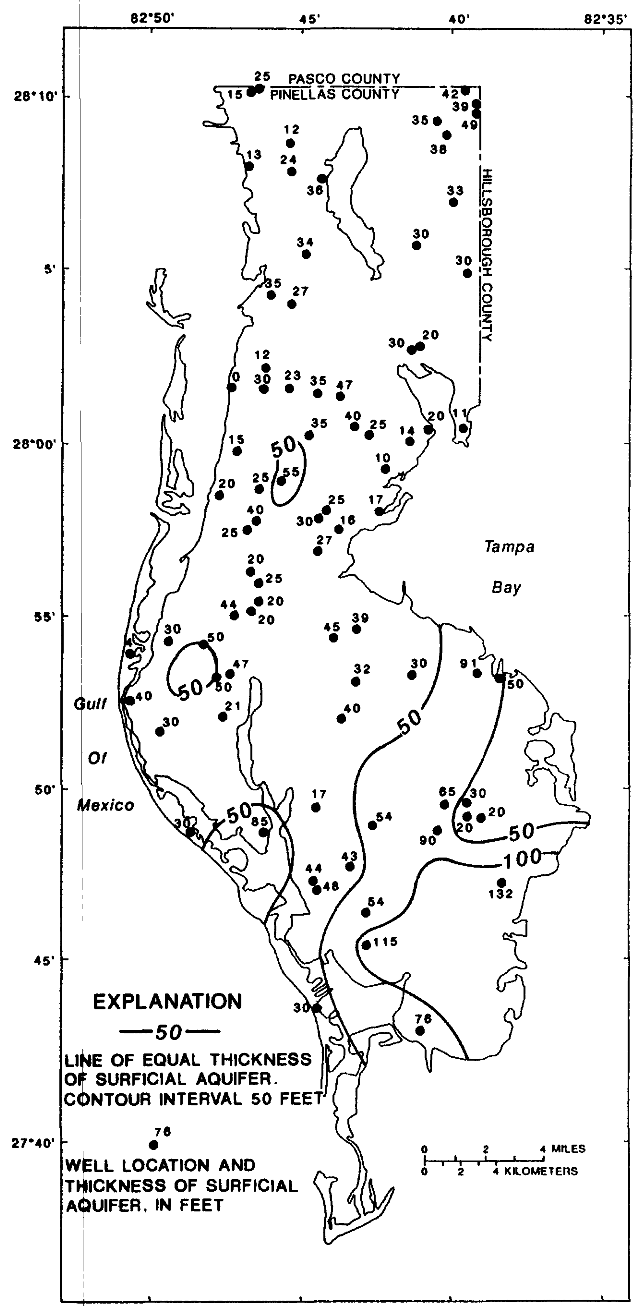


Figure 3. Thickness of the surficial aquifer system, Pinellas County.

The hydrologic properties of the surficial aquifer in Pinellas and northwestern Hillsborough Counties were determined during previous studies. Cherry and Brown (1974) and Sinclair (1974) reported that horizontal hydraulic conductivity ranged from 13 to 33 ft/d, and Sinclair (1974) and Hutchinson and Stewart (1978) reported that vertical hydraulic conductivity ranged from 0.36 to 13 ft/d. Four specific-yield determinations ranged from 33.7 to 37.6 percent (Sinclair, 1974), and two effective porosity determinations were 29.2 and 32.2 percent (Hutchinson and Stewart, 1978).

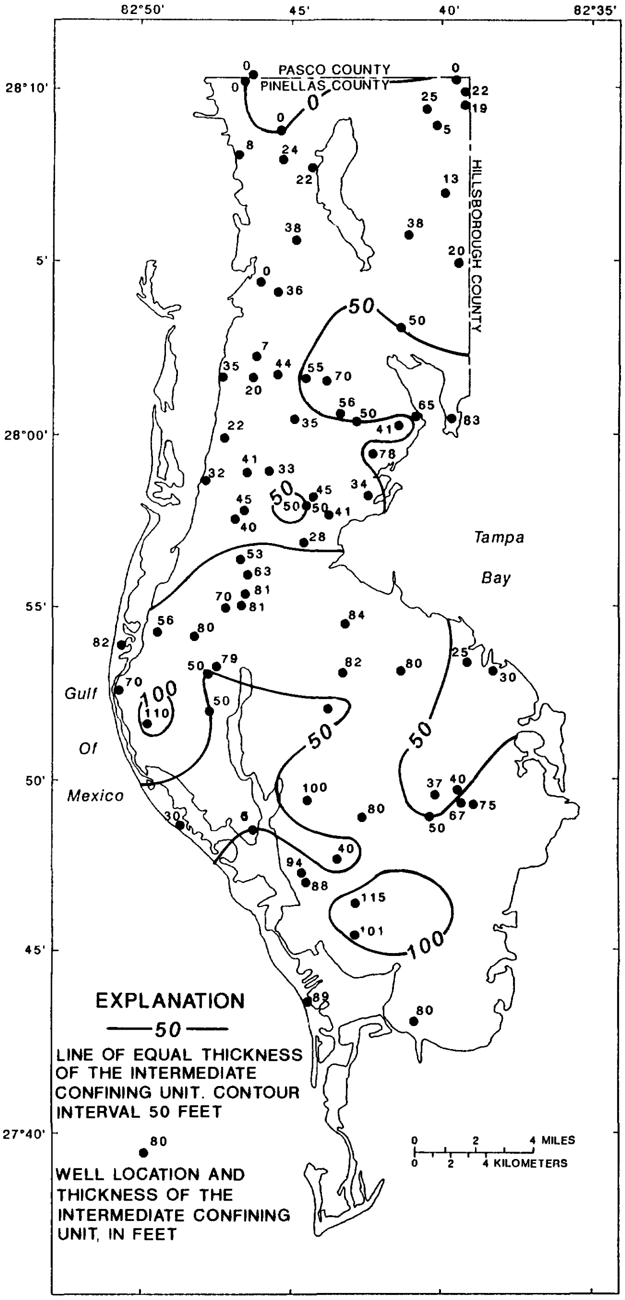


Figure 4. Thickness of the intermediate confining unit, Pinellas County.

Intermediate Confining Unit

The low-permeability intermediate confining unit lies between the surficial and Upper Floridan aquifers. The unit coincides with the Peace River Formation of the Hawthorn Group and consists of clastics and rare occurrences of low-permeability carbonates. The unit is heterogeneous with a diversity in lithology and variable thickness. These heterogeneities result in a wide range of hydraulic characteristics within the unit. The thickness of the intermediate confining unit is the difference between the depth to the base of the surficial aquifer and the depth to the top of the Upper Floridan aquifer. The unit pinches out in northern Pinellas County, with the thickness ranging from zero in the northern part of the county to 115 ft at one site in the southern part (fig. 4). Leakance values for the intermediate confining unit, as reported by Geraghty and Miller, Inc. (1976), Black, Crow and Eidness, Inc. (1978), Seaburn and Robertson, Inc. (1983), and M.P. Brown and Associates (1986), ranged from $1x10^{-3}$ to $1.5x10^{-2}$ day^{-1}.

Floridan Aquifer System

The Floridan aquifer system includes the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer (Miller, 1986). The top of the Upper Floridan aquifer is defined as the first occurrence of a persistent carbonate sequence. The base of the Upper Floridan aquifer is defined as the first occurrence of interbedded gypsum in the carbonates below a dark-brown, microcrystalline dolomite in the Avon Park Formation (Hickey, 1982). In Pinellas County, the top of the persistent carbonate sequence coincides with the top of the Tampa Member of the Arcadia Formation of the Hawthorn Group. This study is concerned only with the uppermost producing zone of the Upper Floridan aquifer and the overlying and underlying confining units, and further discussion will be restricted to these units.

Zone A

In a previous investigation, Hickey (1982) subdivided the Upper Floridan aquifer into four permeable zones separated by semiconfining units. The zones were alphabetically labeled with increasing depth from A to D (fig. 2).

Zone A comprises the Tampa Member and the uppermost part of the Suwannee Limestone and is the shallowest and freshest of the producing zones. Zone A is the only feasible producing zone of brackish water in Pinellas County. The top of zone A coincides with the top of the Tampa Member in Pinellas County. The bottom of zone A occurs in the upper part of the Suwannee Limestone. Due to similar depositional environments, stratigraphic variation cannot be used consistently to delineate the bottom of zone A. Correlation between increased gamma-ray activity and the base of zone A was observed during previous studies in Pinellas County (Hickey, 1982).

On the basis of data compiled mostly from lithologic logs of the Florida Geological Survey, altitudes for the top of zone A range from sea level in northern Pinellas County to 192 ft below sea level in southern Pinellas County (fig. 5). Altitudes at the bottom of zone A (fig. 6) were determined from geophysical logs on file at the U.S. Geological Survey. The depth at which gamma-ray activity increased correlated with changes in both fluid conductivity and lithology. Zone A thickens toward the south and west and ranges in thickness from approximately 100 to 250 ft (fig. 7). Geraghty and Miller, Inc. (1976), Robertson and Mallory (1977), Black, Crow and Eidness, Inc. (1978), Hickey (1982), and M.P. Brown and Associates (1986) reported values of transmissivity for zone A that ranged from 2.2×10^4 to 3.5×10^4 ft^2/d and values of storativity that ranged from 4×10^{-4} to 8×10^{-4}. Porosity values of 0.26, 0.32, and 0.41 were estimated from geophysical logs (Hickey, 1982).

Semiconfining Unit Between Zones A and B

Underlying the uppermost permeable zone (zone A) in the Upper Floridan aquifer is the first of a series of semiconfining units that separate the permeable zones (fig. 2). These semiconfining units are composed of limestone, dolomitic limestone, and dolomite. The semiconfining units do not yield large quantities of water and are considered nonproducing zones in Pinellas County. The existence of these semiconfining units, especially above zone C, was determined during previous studies in Pinellas County (Hickey, 1982).

Cores taken from the carbonate semiconfining units indicate that closed fractures predominate and, therefore, primary porosity rather than secondary porosity controls permeability in the semiconfining units (Hickey, 1982). The degree and distribution of heterogeneities within the semiconfining unit underlying zone A are not known. Because of the depth and the poor quality of the water, the unit has not been developed and has not been studied in detail. The hydrologic properties of the semiconfining unit between zones A and B reported by Seaburn and Robertson, Inc. (1983), and M.P. Brown and Associates (1986) are 0.4 ft/d for horizontal hydraulic conductivity, 0.4 ft/d for vertical hydraulic conductivity, and 2.9×10^{-3} to $7 \times 10^{-3} day^{-1}$ for leakance. Hickey (1982) reported vertical hydraulic conductivities ranging from 1.3×10^{-3} to 2 ft/d. The value of 1.3×10^{-3} ft/d was determined from an aquifer test in northeast St. Petersburg where a higher percentage of clay occurred in the limestone matrix than at other sites in Pinellas County. The value of 2 ft/d was determined from a calibrated model where the head distribution generated by the model duplicated the actual head distribution.

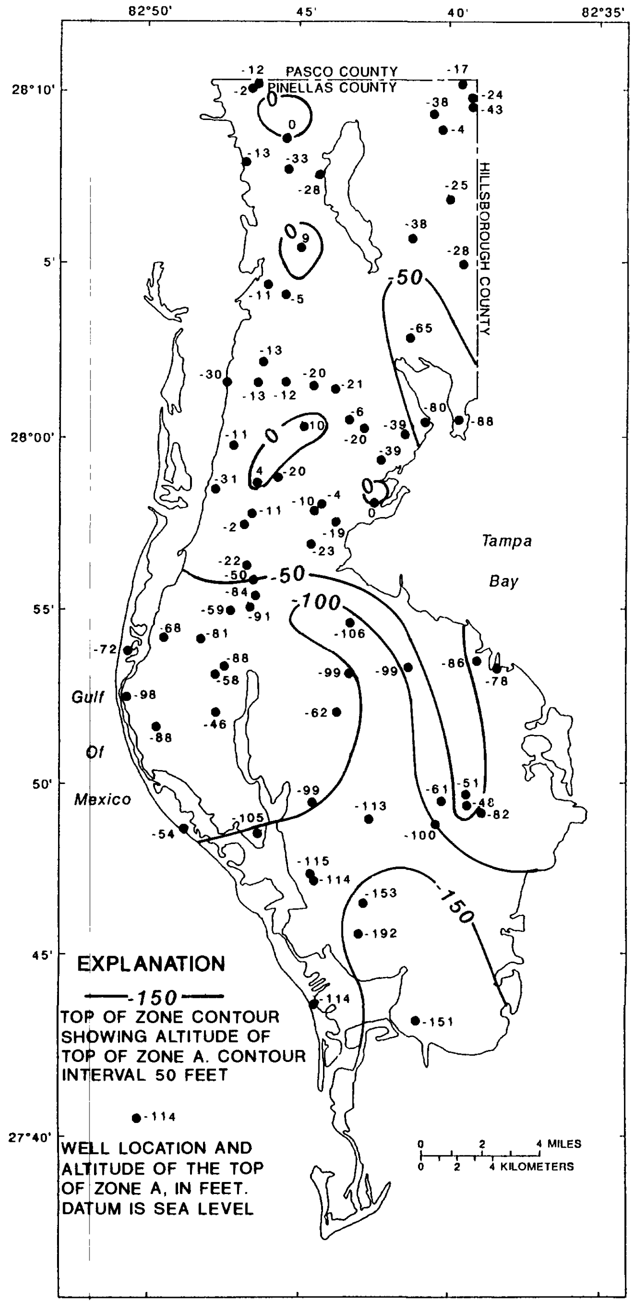


Figure 5. Top of permeable zone A of the Upper Floridan aquifer, Pinellas County.

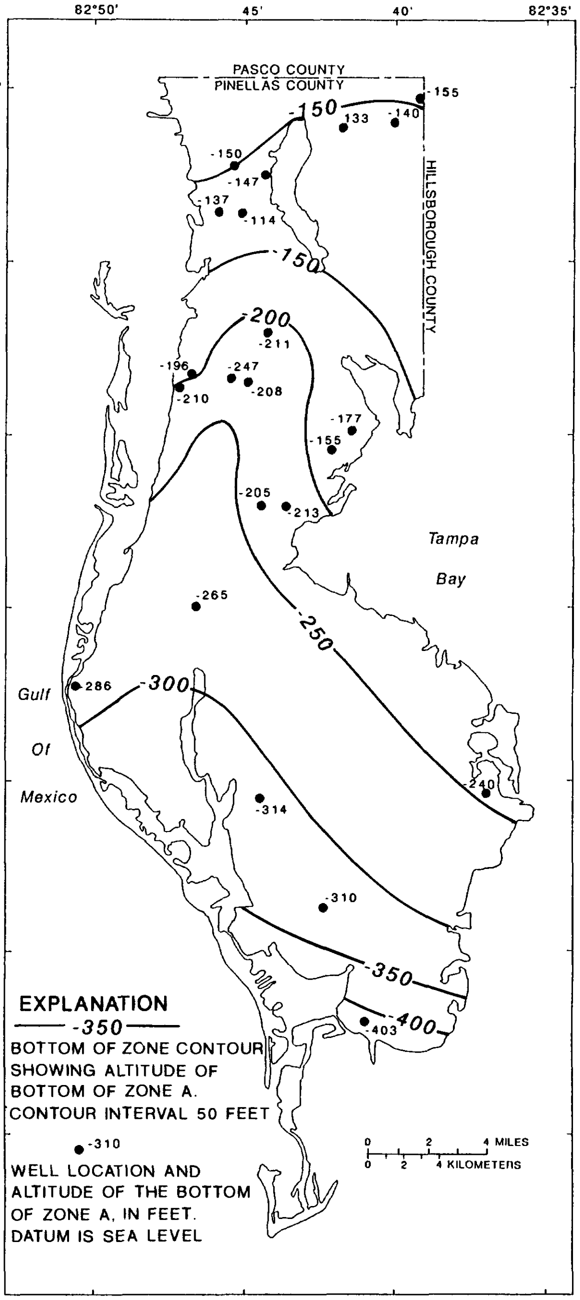


Figure 6. Bottom of permeable zone A of the Upper Floridan aquifer, Pinellas County.

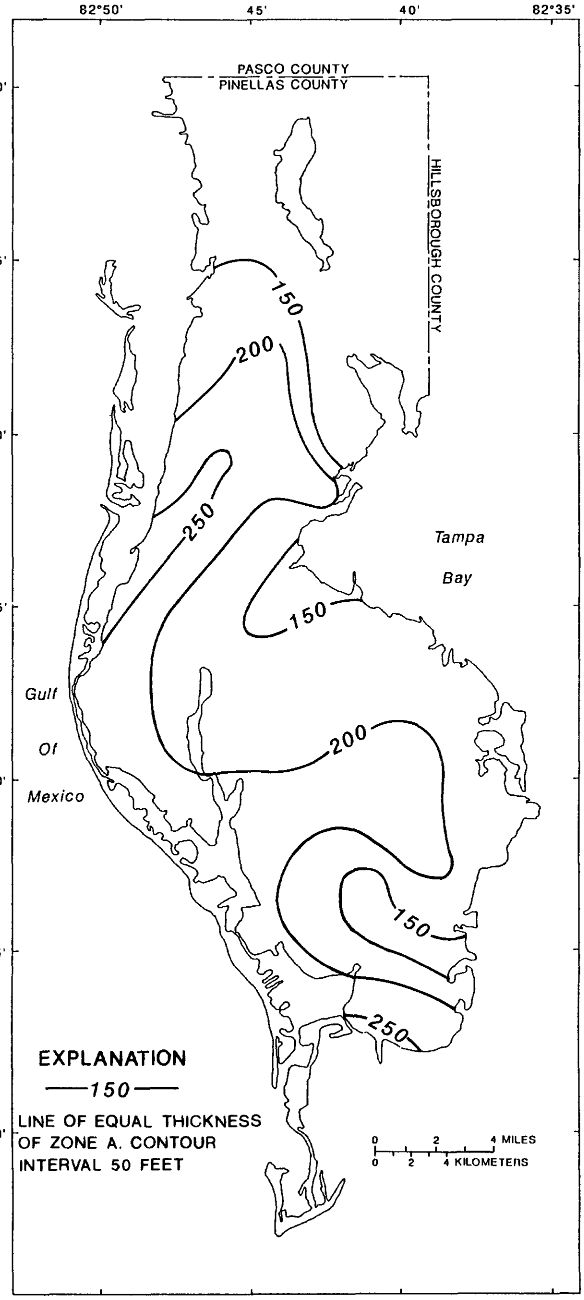


Figure 7. Thickness of permeable zone A of the Upper Floridan aquifer, Pinellas County.

Test results at southwest St. Petersburg and South Cross Bayou indicate that a value of less than 0.1 probably is not representative of general conditions in Pinellas County. Comparison of aquifer and laboratory tests indicate that the plausible range of vertical conductivities applicable to the semiconfining unit is 0.1 to 1 ft/d (Hickey, 1982).

Zone B

Permeable zone B is composed of dolomite, dolomitic limestone, and limestone and probably includes the lower part of the Suwannee Limestone and the upper part of the Ocala Limestone. The top and bottom of the producing zone are defined by Hickey (1982) by the presence of dolomite and dolomitic limestone and by relatively high electrical resistivity.

The thickness of zone B ranges from 50 to 75 ft. Aquifer tests during an injection-well study in Pinellas County indicate that transmissivities in zone B are lower than in zone A (Hickey, 1982).

WATER-QUALITY DATA

The Pinellas County peninsula holds a lens of fresh ground water surrounded and underlain by saltwater in the Gulf of Mexico and Tampa Bay. The lens is maintained by recharge from rainfall. The hydrologic system is perturbed by pumping from municipal supply well fields, which causes lateral encroachment and upconing of saltwater. Saltwater encroachment, which results in increased salinity, occurs in aquifers in Pinellas County. Conservative mixing is the dominant process that causes increased salinity, rather than dissolution of matrix minerals that compose the aquifers (Hanshaw and Back, 1979). Characterization of the salinity is needed to assess the availability of brackish ground-water resources.

A statistical relation was developed to estimate dissolved-solids concentrations in historical ground-water samples for which only chloride concentrations had been analyzed. The U.S. Geological Survey's WATSTORE computer file was queried for water-quality data from wells that tap zone A and that represent a complete analysis, including major ions (table 1). Analyses for samples that met the initial criteria were further screened by comparing specific conductance with dissolved-solids concentration and by checking the ion balance. Thirty-three analyses were selected, and a simple linear relation was developed using the chloride and dissolved-solids concentrations (fig. 8).

A linear-regression analysis of dissolved-solids concentration as a function of chloride concentration resulted in the equation:

$$DS = 1.97 \bullet Cl + 327$$

Where DS and Cl are the dissolved-solids and chloride concentrations in milligrams per liter. The coefficient of determination (R^2) for the regression, which is a measure of the linear relation between the variables, was 97.3. The standard error of the estimate, which measures the possible miscalculation of a value for the dependent variable for a specific independent variable value based on the regression equation, was 230 mg/L.

The regression equation was used to estimate the dissolved-solids concentration in water at approximately 200 wells within Pinellas County for which only chloride data were available. The general distribution of estimated dissolved-solids concentrations in zone A, based on the regression analysis, is shown in figure 9. Concentrations are lowest in the northern and northeastern parts of the county and highest in coastal areas, particularly along the southern end of the peninsula. The area in the south-central part of the county, characterized by dissolved-solids concentrations less than 2,000 mg/L, appears to be suitable for development of brackish ground-water resources. There is a lateral buffer zone between the 2,000-mg/L area and areas of 4,000 mg/L, which is the upper limit of suitability for low-pressure reverse-osmosis treatment.

POTENTIAL FOR DEVELOPMENT OF BRACKISH GROUND-WATER RESOURCES

The purpose of describing the distribution of hydrogeologic units and water quality was to help identify areas where the quantity and quality of brackish ground water is suitable for development. The following criteria were used:

1. The brackish ground-water reservoir needs to be located away from existing well fields,
2. The brackish ground-water reservoir needs to be near population centers, and
3. The brackish ground-water reservoir needs to be able to yield sustained quantities of water with dissolved solids of less than 4,000 mg/L.

All well fields, except one, are at or north of Clearwater (fig. 10); there are no well fields in southern Pinellas County. Therefore, development of brackish ground water in southern Pinellas County would meet the first criterion. Southern Pinellas County, especially the city of St. Petersburg, is dependent on imported waters and would constitute a major consumer of the resource, thus meeting the second criterion.

Meeting the third criterion is more complex because it reflects geohydrologic data deficiencies and uncertainties. Areas where zone A is the thickest are in Clearwater, Belleair, and St. Petersburg (figs. 1 and 7); however, sufficient quantities of water, 5 to 10 Mgal/d can be pumped throughout the county. The intermediate confining unit is 50 to 115 ft thick in southern Pinellas County, but pinches out in northern Pinellas County (fig. 4). The disadvantage of a thick intermediate confining unit is the retardation of downward leakage of freshwater from the surficial aquifer; the advantage is the retardation of movement of contaminants from the land surface through the lithologic sequence.

Areas where downward leakage is indicated by positive head differences between the surficial aquifer system and the Upper Floridan aquifer delineate areas of recharge to zone A from the surficial aquifer system. Pumping-induced recharge from overlying freshwater would dilute the lateral or upward flow of saline water to the well. Figures 11 and 12 show differences between water levels in the surficial aquifer system and the Upper Floridan aquifer for wet and dry conditions. The differences are greatest in north-central Pinellas County.

Table 1. *Water-quality data for samples from selected wells in Pinellas County*

[ft, feet; mg/L, milligrams per liter; Ca, calcium; Mg, magnesium; Na, sodium; K, potassium; Cl, chloride; SO , sulfate; Alk, alkalinity; --, no data]

Site	Latitude-longitude	Well depth (ft)	Casing depth (ft)	Dis-solved solids (mg/L)	Ion concentration (mg/L)						
					Ca	Mg	Na	K	Cl	SO	Alk
NW Pinellas	2806310824551	93	--	5,730	260	180	1,700	45	3,000	470	140
McKay Creek	2752410825039	210	76	508	74	32	28	2	120	12	207
South Cross Bayou	2749290824435	251	250	969	160	47	110	13	450	60	159
Bear Creek	2746140824252	300	--	1,530	230	30	230	4	680	25	248
SW St. Petersburg	2742590824102	396	--	5,530	510	110	1,200	27	2,600	620	73
Sheraton BelAir	2742180824044	--	--	171	43	3	6	2	18	20	80
Eckerd College	2742470824109	325	200	4,140	360	130	560	17	1,400	430	162
Maximo Pres. Church	2742520824035	--	--	477	130	3	22	1	33	2	328
Boca Ciega H.S.	2745400824237	400	--	2,600	240	54	460	14	1,100	150	181
Royal Palm Court	2746060824226	285	185	1,030	150	27	89	5	310	41	194
Woodlawn Cemetery	2746070824253	153	92	760	120	19	45	4	180	18	201
White Cross Hosp.	2746130824318	--	--	784	130	22	57	4	230	22	196
2nd Ch. of Christ	2746160824304	270	--	967	140	24	76	5	290	29	191
Bishop Barry H.S.	2746530824318	220	--	664	120	21	47	5	180	14	230
Jim Winter	2748500823716	180	--	484	100	6	38	1	110	3	200
Stevens	2749060824359	198	135	1,000	130	33	86	1	290	25	215
Paradise Shores	2749070824505	240	--	902	120	36	48	11	240	16	217
Five Towns	2749160824458	300	--	786	110	32	41	10	180	32	207
Spangler	2749180824431	100	--	404	100	10	28	1	37	1	315
Butler	2750080824429	98	90	690	110	32	47	8	210	36	210
Hill	2752170825007	300	--	976	120	45	150	2	390	21	210
Hamlin	2752220825046	150	--	489	69	30	33	2	94	18	219
Indian Springs	2752380825042	160	90	412	59	29	22	1	71	8	208
G. Karg	2752390825037	125	--	424	58	29	21	1	64	3	219
Luce	2752450825013	300	--	369	57	21	26	7	5	74	130
Indian Rx Shop.	2752570825003	300	--	435	62	26	46	2	97	6	220
M.M. Domino	2753040825025	133	42	1,070	130	45	99	4	340	12	225
Liberty Baptist	2751350823819	115	--	906	170	8	100	1	340	4	190
Mills	2750290823804	115	--	531	140	7	22	2	66	20	300
Riviera Methodist	2749430823804	100	--	426	91	8	28	2	87	11	190
Neil	2749370823733	185	--	476	98	8	36	2	100	12	200
Roberts Comm.	2749020823904	115	--	470	96	9	28	1	91	8	190
Crisp Park	2748190823740	115	--	498	110	8	38	1	130	3	190

Water quality in zone A is the most critical factor because of the 4,000-mg/L dissolved-solids concentration limit for treatment by low-pressure reverse osmosis. Only a few wells in Pinellas County produce water in which the dissolved-solids concentrations are greater than 4,000 mg/L (fig. 9). Lowest concentrations are in northern Pinellas County, but moderately low concentrations predominate in the south-central part of the county. South-central Pinellas County met all the criteria and was selected for further investigation using a flow and solute-transport model to evaluate the effects of pumping on the quality of the brackish ground water.

SIMULATION OF THE EFFECTS OF DEVELOPMENT ON THE QUALITY OF GROUND WATER

Model Approach and Limitations

A digital model was used to simulate the change in water quality in response to pumping brackish water. Simulations were based on existing hydrologic data. The model was not calibrated because no data exist for comparison with the model results. The input data for the

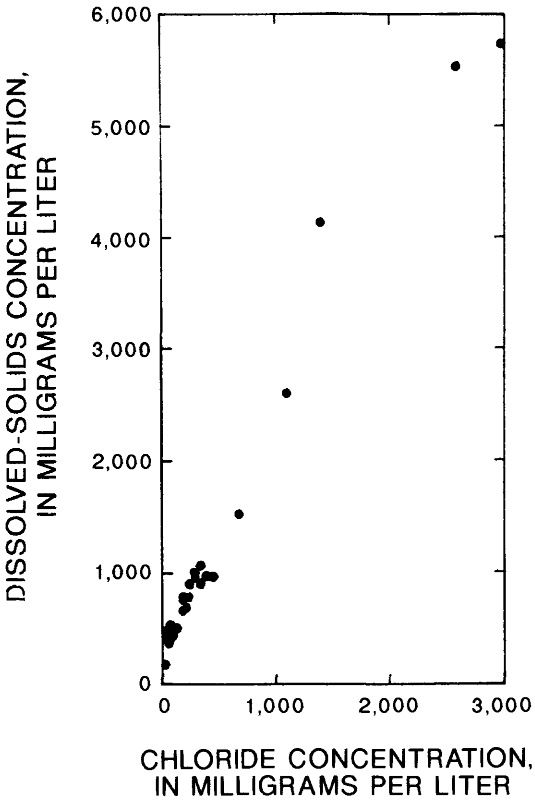


Figure 8. Relation between chloride and dissolved-solids concentrations in water from selected wells in Pinellas County.

model parameters are estimated values for the physical and chemical hydrogeologic characteristics that approximate realistic conditions. These characteristics were determined during a previous study (Hickey, 1982). The changes in solute concentrations, in reponse to pumping during the simulation, were then used as a measure of the potential for developing a brackish water supply. A sensitivity analysis was used as a means of testing whether a different but possible set of estimated values of model input parameters would affect the rate of changes in water quality resulting from large and prolonged ground-water withdrawals in the area.

Water-quality changes were simulated by the finite-difference model HST3D (Kipp, 1987), which solves partial-differential equations for ground-water flow and solute transport. This model has several advantages:

1. The model code has had the benefit of revisions, improvements, and corrections from previous transport codes;
2. The model contains a boundary type, the aquifer influence function, that minimizes computation time by eliminating excessive spatial discretization;
3. The model has several solution methods available; and
4. The model has free input format, which reduces input errors and format mismatch problems.

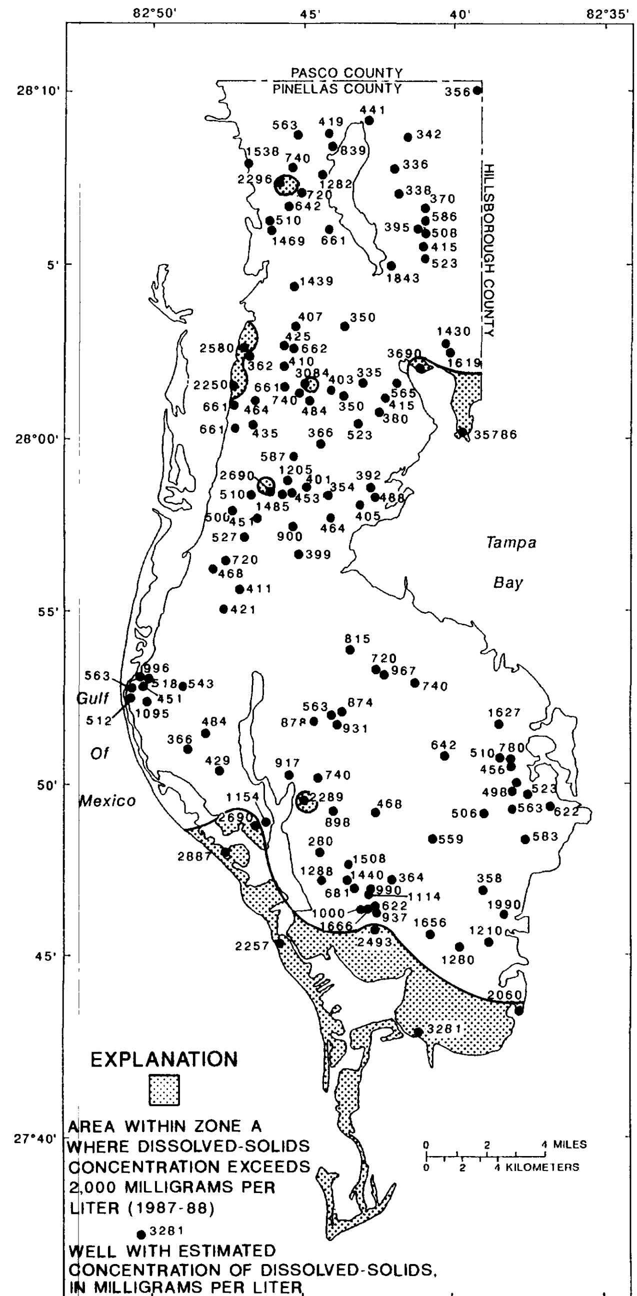


Figure 9. Estimated concentration of dissolved solids in water from selected wells open to permeable zone A of the Upper Floridan aquifer, Pinellas County.

An axisymmetric radial-flow model with cylindrical coordinates was constructed on the premise that water-quality changes will occur faster because of vertical movement of dissolved solids than because of lateral movement. A hydrogeologic region was simulated about a well that fully penetrates zone A. Boundary conditions were assumed, and hydraulic and transport properties were estimated for each cell in a point-distributed grid.

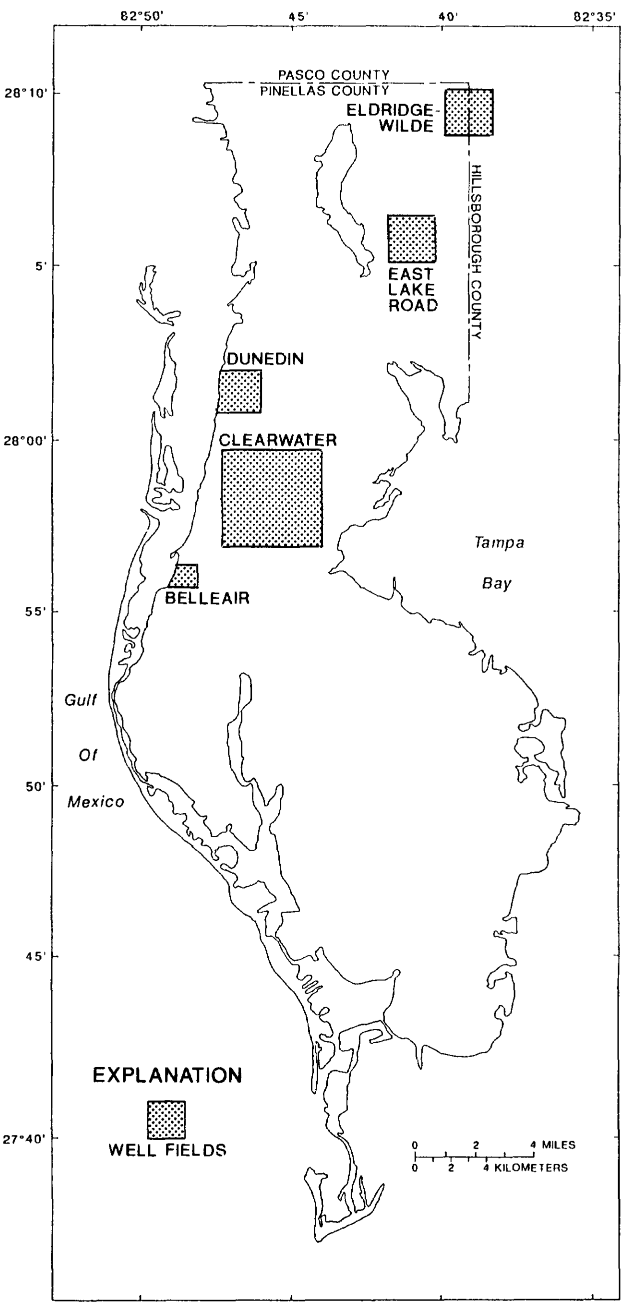


Figure 10. Location of well fields in Pinellas County.

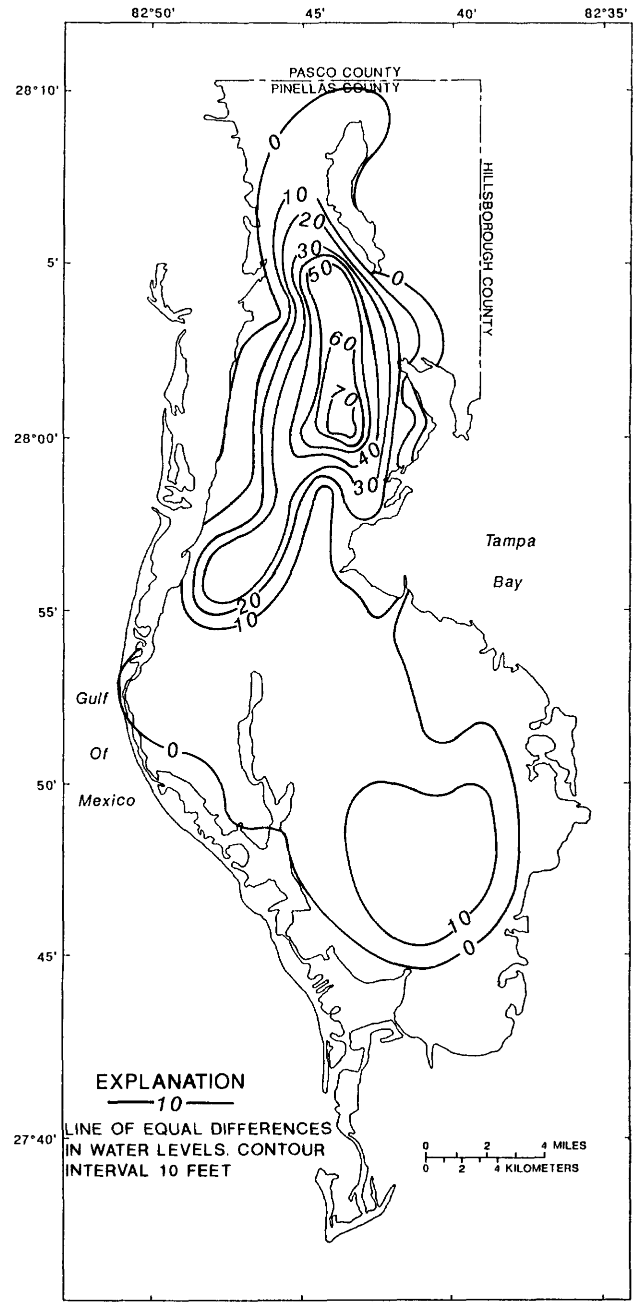


Figure 11. Differences in water levels in wells completed in the surficial aquifer system and the Upper Floridan aquifer, September 1981 (wet-season conditions).

The initial phase of the modeling exercise was the selection of the solution method or finite-difference option that allowed convergence, exhibited stability, and minimized numerical diffusion. The second phase was the sensitivity analysis, during which input parameters were varied over their likely range of values.

The model is discretized both spatially (fig. 13) and temporally. The top of the model grid coincides with the base of the surficial aquifer, and the bottom coincides with the base of the semiconfining unit between zones A and B. The spatial discretization is 98 variably spaced vertical columns and 18 evenly spaced horizontal rows. The model dimensions are 3,000 horizontal ft and 425 vertical ft. Radial spacing expands logarithmically from 0.14 ft at the well up to a maximum of 50 ft.

Temporal discretization is achieved interactively by choosing a maximum time-step that does not introduce numerical error. Minimum and maximum time increments were selected. The actual time increment used for each iteration is automatically selected by the model, within the specified range, to minimize the number of time steps required for convergence.

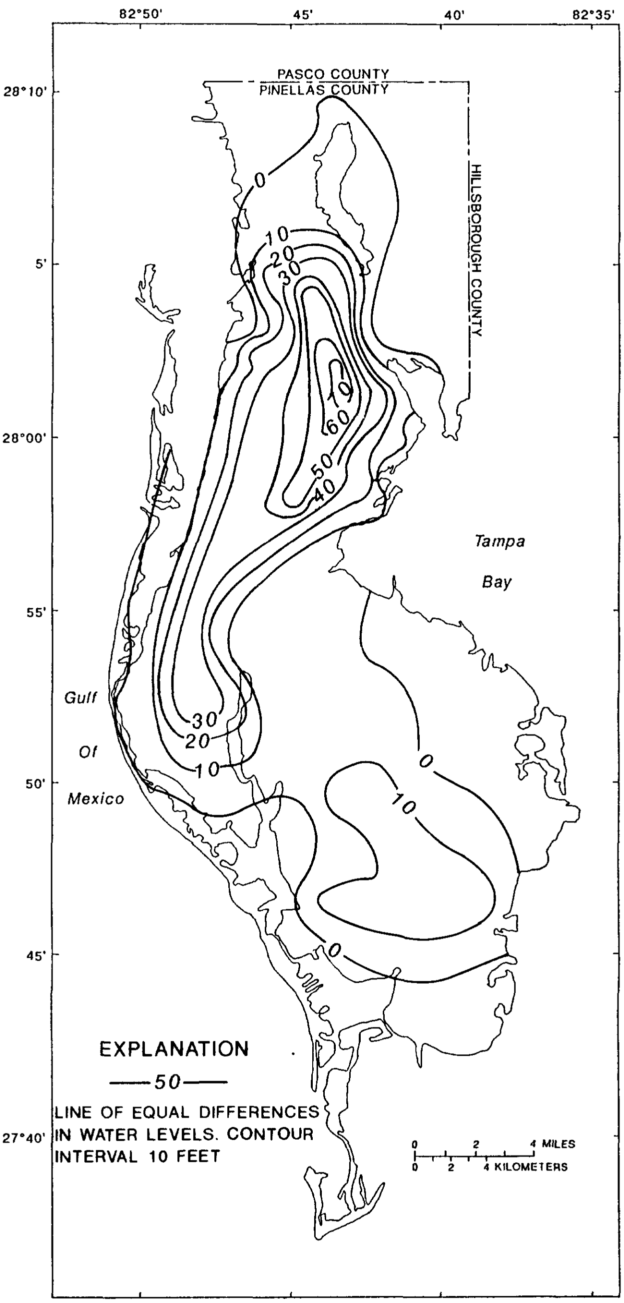


Figure 12. Differences in water levels in wells completed in the surficial aquifer system and the Upper Floridan aquifer, May 1982 (dry-season conditions).

Boundary Conditions

The extent of the modeled area, confined by hypothetical boundaries, represents the region that might be affected by an ideal, fully penetrating well that pumps 1 Mgal/d for 10 years. The idealized well penetrates zone A and is open from 100 to 300 ft below sea level. Underlying zone A is a semiconfining unit, so defined because its hydraulic conductivity is two orders of magnitude less than that of the production zone. The top and bottom of the model are specified pressure boundaries because the producing zones are very permeable relative to the entire Floridan aquifer system. Pressure on the upper boundary is set at 10.83 lb/in^2, equivalent to the pressure exerted from an overlying 25-ft column of freshwater presumed to exist in the overlying surficial aquifer system. Pressure on the lower boundary is 196.67 lb/in^2, equivalent to the pressure exerted from a 450-ft column of freshwater and saltwater presumed to exist in the overlying formations. The left boundary is the pumped well in zone A. No-flow conditions were established for the confining units above and below the well. The right boundary is defined by a transient flow, aquifer-influence function (AIF) that utilizes the Carter-Tracy approximation (Kipp, 1987) to compute flow rates between the inner, discretized aquifer region and a larger outer region where aquifer properties are only generally known. The primary benefit of using the AIF boundary condition is the reduction in simulated area size. This option reduces the computer storage and computation time needed to reach a stable solution.

Input Parameters

Model input parameters were compiled from information gathered during previous studies in Pinellas County. The input parameters are typical values for hydrologic and matrix properties derived from aquifer tests, laboratory tests on cores, and geophysical log interpretations. Fluid property input parameters are the standard published values for freshwater and seawater. Input data for well definition are discharge rates and construction information. All three layers are isotropic.

Matrix Properties.--Matrix characteristics are defined for each of the hydrogeologic layers in the model (fig. 13 and table 2). The layers are numbered as follows: (1) the semiconfining unit below zone A, (2) permeable zone A, and (3) the intermediate confining unit (fig. 13). The matrix parameters are intrinsic permeability, effective porosity, matrix compressibility, longitudinal dispersivity, and transverse dispersivity (table 2). Intrinsic permeability was calculated from values of hydraulic conductivity given by Hickey (1982), with the conversion factors from Freeze and Cherry (1979, p. 29). Values of hydraulic conductivity and compressibility were determined from aquifer tests and laboratory tests of samples collected during previous studies in Pinellas County; values for porosity were estimated from geophysical logs. Longitudinal and transverse dispersivity values were based on criteria for discretization stability described in Voss (1984, p. 50-55).

each cell in layer 2 with a range in values from zero (no flow) to one (equivalent flow across total cell length). A fully penetrating well has a well-completion factor of one for each cell in layer 2. The flow from a well is a negative number.

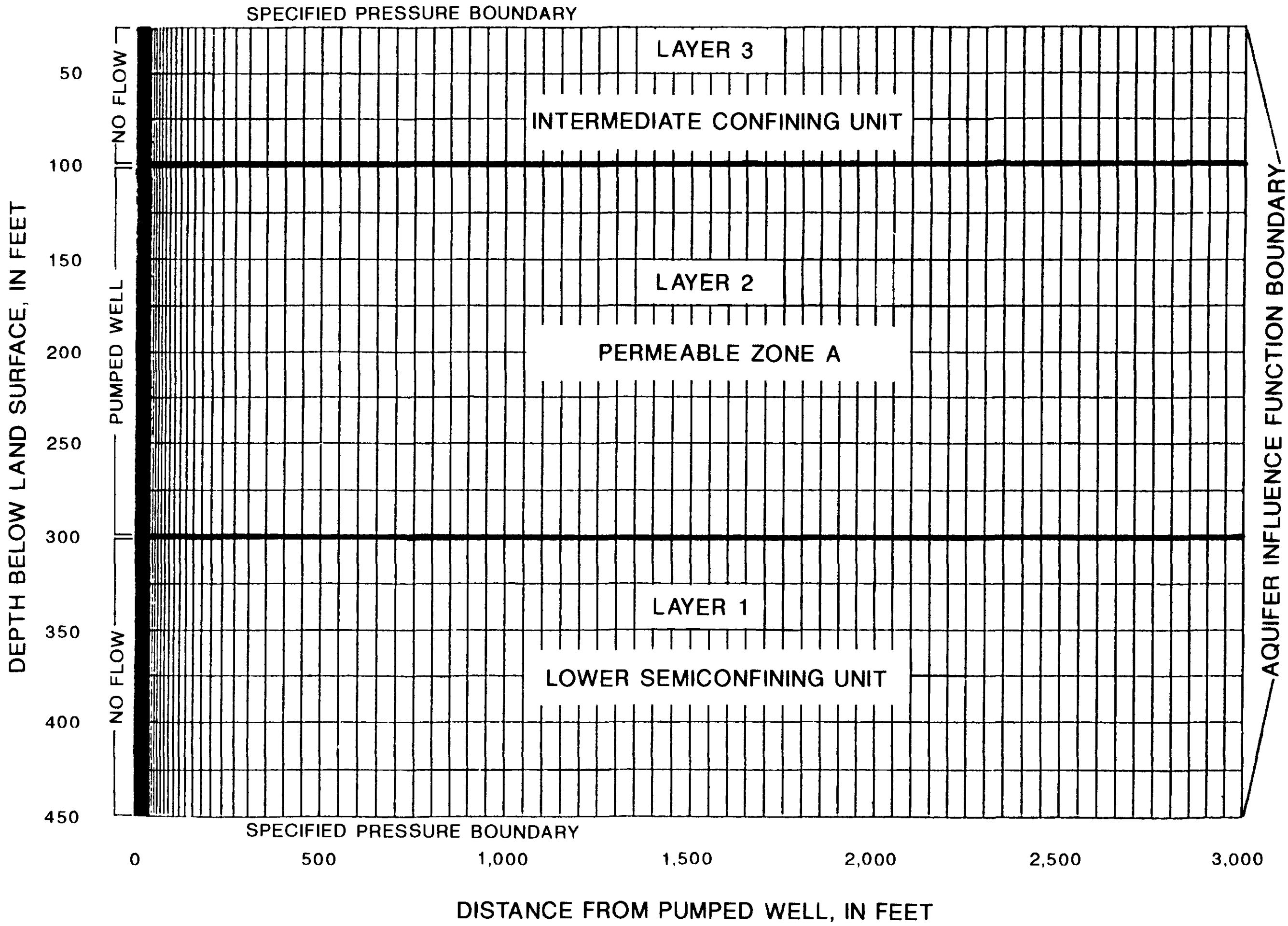


Figure 13. Model grid of 18 rows and 98 columns with boundary conditions.

Fluid Properties.--Characteristics of water in the aquifer include density, viscosity, compressibility, molecular diffusivity, and dissolved-solids concentrations expressed as scaled-solute mass fraction. The data are listed in table 3 by layers. Layer 1 contains high solute-concentration waters. Layers 2 and 3 contain fresher waters. The scaled-solute mass fraction is a dimensionless relative solute-concentration term. Zero is equivalent to 35,000 mg/L, and 1 is equivalent to 0 mg/L dissolved-solids concentration.

Well Information.--In the model, the well occurs in the first column of the grid. The open-hole interval of the well is defined in terms of row numbers. The open-hole length of a fully penetrating well is 200 ft. The model distributes the total flow from the pumped well among the cells on the basis of cell location, hydraulic conductivity, and well-completion factor. The well-completion factor defines the behavior for

The dissolved-solids concentration of the discharge water was calculated by averaging the concentrations of the individual cells in the open-hole section (layer 2). Observation wells are simulated by defining a single open cell at which pressure and concentration can be observed at specified depths and times.

Finite-Difference Methods

Selection of the appropriate finite-difference method for the hydrologic condition being simulated is necessary to obtain a stable solution. Numerical diffusion due to truncation error and oscillation due to instability can be controlled partly by the choice of the finite-differencing method. The various options are described in detail by Kipp (1987). The centered-in-space (CIS) and centered-in-time

Table 2. *Matrix properties*

[ft^2, square foot; ft^2/lb, square foot per pound]

Parameter	Layer 1	Layer 2	Layer 3
Intrinsic permeability) (ft^2)	3.877^{-15}	6.247^{-10}	3.877^{-12}
Porosity	.30	.30	.30
Matrix compressibility (ft^2/lb)	1.6^{-10}	1.6^{-10}	1.6^{-10}
Longitudinal dispersivity (feet)	12.5	12.5	12.5
Transverse dispersivity (feet)	2.50	2.50	2.50

Table 3. *Fluid properties*

[lb/ft^3, pound per cubic foot; ft^2/lb, square foot per pound; ft^2/d, foot squared per day]

Parameter	Layer 1	Layer 2	Layer 3
Specific weight (lb/ft^3)	64.0	62.4	62.4
Viscosity (centipoise)	.9039	.9500	.9500
Fluid compressibility (ft^2/lb)	3.3^{-6}	3.3^{-6}	3.3^{-6}
Molecular diffusivity (ft^2/d)	8.75^{-7}	8.75^{-7}	8.75^{-7}
Scaled solute mass fraction	.3	.999	.999

(CIT) difference methods have no truncation error, but stability problems arise when the ratio of time step to grid size is too large. Backward-in-space (BIS) and backward-in-time (BIT) difference methods always produce a stable solution, but numerical diffusion may produce error in results. A CIS and BIT difference scheme removes spatial truncation errors, but results can still be unstable if spatial discretization and dispersivity guidelines are not met. Use of the BIS and CIT options removes temporal truncation errors, but results can be unstable if the ratio of time step to grid size is too large.

To eliminate numerical diffusion of model results, the CIS and CIT finite-difference equations were used. However, a stable solution could not be achieved by this method. A stable solution would have guaranteed the validity of the model results. When using time steps of a fraction of a day or larger, divergent oscillations were apparent in the pressures and solute concentrations, and the model would exceed the number of allowable iterations per run. When a very small time step was selected (0.0001 day), temporal oscillations were not apparent; however, the computer time needed to simulate even a few hours was excessive. Use of such a small time step required exorbitant computer storage and computation time to do a 10-year simulation. Consequently, BIS and BIT difference methods were used for all subsequent runs. When using these solution methods, results were stable, temporal oscillations were eliminated, and numerical diffusion was not evident.

Model Results and Sensitivity Analysis

The model simulation based on the typical input parameters indicated that dissolved-solids concentration exceeded 4,000 mg/L in less than 2 years. Because dissolved-solids concentration is the critical parameter for this study, model results are exhibited as change in concentration with time in response to pumping (fig. 14). No field data are available for comparison with model results. Therefore, the sensitivity analysis was used both for indicating which parameters substantially affect model results and for evaluating a variety of pumping rates and well-construction strategies that reflect the potential for development of brackish water.

The sensitivity of the simulated dissolved-solids concentration of pumped water to model input was determined by methodically varying the parameters over a range of values representative of Pinellas County. Input parameter values that greatly affect model results might incorrectly estimate the water-quality changes in response to pumping brackish water from zone A. All parameters that have a significant effect on model results must be based upon the best possible data available or represent the most probable value.

Sensitivity analyses were performed to evaluate the response of solute-concentration distributions to variations in pumping rates, finite differencing methods, and porous media properties. Figure 14 defines the input parameter values for each model simulation and shows the results of the model runs and sensitivity tests. Each model simulation is specified by a variable name. The graphs show variations in the dissolved-solids concentration for the pumped water over time for each of the parameters tested.

Solute Concentration Distribution

The simulated dissolved-solids concentrations ranged from 0 to 35,000 mg/L. The initial conditions simulated were 35,000 mg/L for the semiconfining unit (layer 1) and 0 mg/L for permeable zone A and the intermediate confining unit (layers 2 and 3, respectively). The dissolved-solids concentration limit for this study is 4,000 mg/L. Model simulations indicated that a dissolved-solids concentration of 4,000 mg/L would be exceeded in approximately 3 months under initial conditions (fig. 14A). Accordingly, initial dissolved-solids concentrations were judged to be too conservative and not representative of realistic conditions. Next, a dissolved-solids concentration of approximately 25,000 mg/L was selected for layer 1 based on water-quality analyses from previous studies in Pinellas County. A dissolved-solids concentration of 35 mg/L was selected for the freshwater layers. The simulated dissolved-solids concentration of 4,000 mg/L at the well was exceeded in less than 1 year (fig. 14A). Dissolved-solids concentrations of 35 and 25,000 mg/L were used for all subsequent sensitivity runs.

Pumping Rates

Various pumping rates were tested to determine if any withdrawal rate could be simulated to provide sufficient quantities of water for development and not exceed the maximum dissolved-solids concentration limit of 4,000 mg/L. The pumping rates simulated were 694 gal/min (1 Mgal/d), 500 gal/min, and 350 gal/min. For all three rates, the dissolved-solids concentration limit was exceeded in 2 years or less. At the minimum simulated pumping rate of 350 gal/min, dissolved-solids concentration limits were exceeded in approximately 2 years. At the maximum simulated rate of 1 Mgal/d, dissolved-solids concentrations were exceeded in less than 1 year (fig. 14B). For all subsequent sensitivity runs, a pumping rate of 1 Mgal/d was used in the simulation.

Hydraulic Conductivity of the Lower Semiconfining Unit

The effects of hydraulic conductivity in the semiconfining unit (layer 1) on the dissolved-solids concentration were assessed with sensitivity analyses. Sensitivity to changes in hydraulic conductivity of the other units did not affect model results. The hydraulic conductivity of layers 2 and 3 in Pinellas County is well known. Values determined from aquifer and laboratory tests are consistent. The characteristics of the lower semiconfining unit are not well documented because no test wells have been drilled into this poor quality water unit. Understanding the influence of this unit's characteristics on model results, however, is important because it is the primary source of saline water. The rate of upward migration of the saline water is critical in the determination of the long-term availability of brackish water for development.

Model results indicate that the rate of upward movement of saline water is sensitive to changes in the hydraulic conductivity of layer 1. The hydraulic conductivity values simulated were $1.3x10^{-3}$, 0.1, 1, and 2 ft/d based on a previous study in Pinellas County (Hickey, 1982). The model-simulated values of dissolved-solids concentrations in pumped water using 2, 1, and 0.1 ft/d all exceeded 4,000 mg/L within 5 years (fig. 14C). In a model simulation using a hydraulic conductivity of $1.3x10^{-3}$ ft/d, the concentration did not exceed 4,000 mg/L even after 60 years. Rather, dissolved-solids concentrations oscillated between 2,200 and 3,700 mg/L. The oscillations did not converge in time, indicating a stability problem with the solution method. The value of $1.3x10^{-3}$ ft/d is probably unrealistically low according to John J. Hickey (U.S. Geological Survey, oral commun., 1988). Both hydraulic conductivity values of 0.1 and 1 ft/d were used in subsequent sensitivity runs.

Intermediate Confining Unit Thickness

Between the surficial aquifer system and the Upper Floridan aquifer is a low-permeability unit referred to as the intermediate confining unit (layer 3). Its maximum observed thickness in Pinellas County is 115 ft, and it pinches out in northern Pinellas County (fig. 4). Model simulations were made that estimate the effect of the thickness of the intermediate confining unit on the dissolved-solids concentration. The modeled thickness in Pinellas County for the intermediate confining unit is 75 ft. Simulated thicknesses in the sensitivity analyses ranged from 0 to 50 ft. The surficial aquifer system was only simulated in one model run because of its limited use as a potable resource and recharge source. Model results indicate that, when the thickness of layer 3 is 25 ft, the dissolved-solids concentration exceeds 4,000 mg/L after only 0.10 year of pumping (fig. 14D).

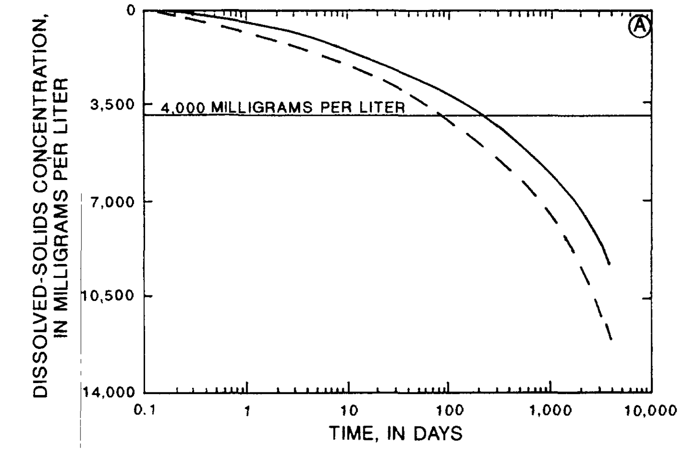
A simulation with the absence of the intermediate confining unit allowed direct recharge from the surficial aquifer system into the underlying Upper Floridan aquifer. In this simulation, the dissolved-solids concentration did not exceed the 4,000-mg/L limit after 10 years of pumping. In fact, the water became slightly fresher. This hydrogeologic condition represents only a minor area of Pinellas County, and these areas have already been developed.

Porosity

Sensitivity to values for porosity in layer 2 was tested by using values of 0.15 and 0.45 to bracket a probable value of 0.30. A porosity of 0.05 also was tested because this is the value used for conduit flow in limestones for well-head protection (Vecchioli and others, 1989). Permeability and porosity control the velocity of solute movement. When porosity increases while permeability is constant, velocity decreases. Simulated dissolved-solids concentration is sensitive to changes in porosity in layer 2. When porosity equals 15, 30, and 45 percent, the simulated dissolved-solids concentration exceeds 4,000 mg/L in 0.5, 3, and 5 years (fig. 14E, F).

		Model input parameters								
Figure	Symbol	HCond	Pump	DS1	DS2	Phi	LDisp	TDisp	ICU	PPENT
14A	——— — —	1	1MGD	35,000 25,000	0 35	0.30	12.5	2.5	75	100
14B	——— — — —··—	1	1MGD 500GPM 350GPM	25,000	35	0.30	12.5	2.5	75	100
14C	—··— x——x ——— — —	1 2 0.1 0.0013	1MGD	25,000	35	0.30	12.5	2.5	75	100
14D	——— ·——· x——x -- ——	1	1MGD	25,000	35	0.30	12.5	2.5	75 50 25 0	100
14E	——— x——x -- ——	1	1MGD	25,000	35	0.30 0.15 0.45	12.5	2.5	75	100
14F	——— —··— x——x	0.1	1MGD	25,000	35	0.30 0.15 0.45	12.5	2.5	75	100
14G	———	1	1MGD	25,000	35	0.30	12.5 18.75 6.25	2.5 3.75 1.25	75	100
	·——·	0.1					12.5 18.75 6.25	2.5 3.75 1.25		
14H	——— ·——· x——x	1	1MGD	25,000	35	0.30	12.5	2.5	75	100 75 50

HCond - hydraulic conductivity, in feet per day.
Pump - pumping rate.
DS1 - dissolved-solids concentration, in milligrams per liter.
DS2 - dissolved-solids concentration, in milligrams per liter for layer 2 and 3.
Phi - porosity.
LDisp - longitudinal dispersivity, in feet.
TDisp - transverse dispersivity, in feet.
ICU - thickness of the intermediate confining unit, in feet.
PPENT - percent penetration of well in layer 2.
The horizontal line at a concentration of 4,000 mg/L represents the maximum dissolved-solids concentration suitable for reverse-osmosis treatment.
MGD - million gallons per day; GPM - gallons per minute.



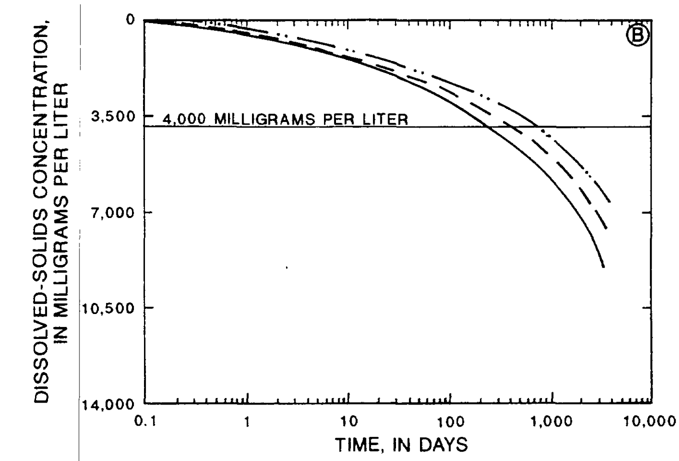


Figure 14. Sensitivity of the simulated dissolved-solids concentration in pumped waters to changes in model input parameters.

Dispersivity

Dispersivity is a scale-dependent parameter that controls dispersion of the solute. The typical model had a 4 to 1 ratio of grid length to longitudinal dispersivity and a 10 to 1 ratio for transverse dispersivity. The initial input values were 12.5 ft for longitudinal dispersivity and 2.50 ft for transverse dispersivity. In the sensitivity analysis, longitudinal and transverse dispersivities were varied independently by 50 percent. Changes in the transverse and longitudinal dispersivities did not affect the concentration distribution. At either extreme, the dissolved-solids concentration in pumped water exceeded 4,000 mg/L after approximately 2 to 3 years (fig. 14G). Vertical and lateral migration of the solute does not appear to be highly sensitive to dispersivity.

Boundary Conditions

Use of the AIF boundary condition described by Kipp (1987, p. 134) allows the radial distance of the modeled area to remain small. The initial radial distance used for model simulations was 6,000 ft. The concentrations, pressures, and head distributions for simulations with radial distances of 6,000 and 3,000 ft were virtually the same at the AIF boundary for both simulations. Based on this observation and similar model results from a study in west-central Florida (Hutchinson, 1991), radial expansions and reductions were not tested further, and the same grid distribution and total radial distance were used as in the west-central Florida study. Hutchinson's (1991) HST3D model simulations indicated that increasing the radial distance did not produce a noticeable change in the dissolved-solids concentration.

Partially Penetrating Wells

Several well-completion designs were simulated to quantify the effects of partial penetration. The rate of water-quality change was expected to decrease by pumping partially penetrating wells rather than fully penetrating wells because a buffer zone of fresher water would exist between the pumped zone and the underlying poor quality water. The simulated well penetrations ranged from 50 to 100 percent. The 50-percent penetration well is open to the upper 100 ft of layer 2.

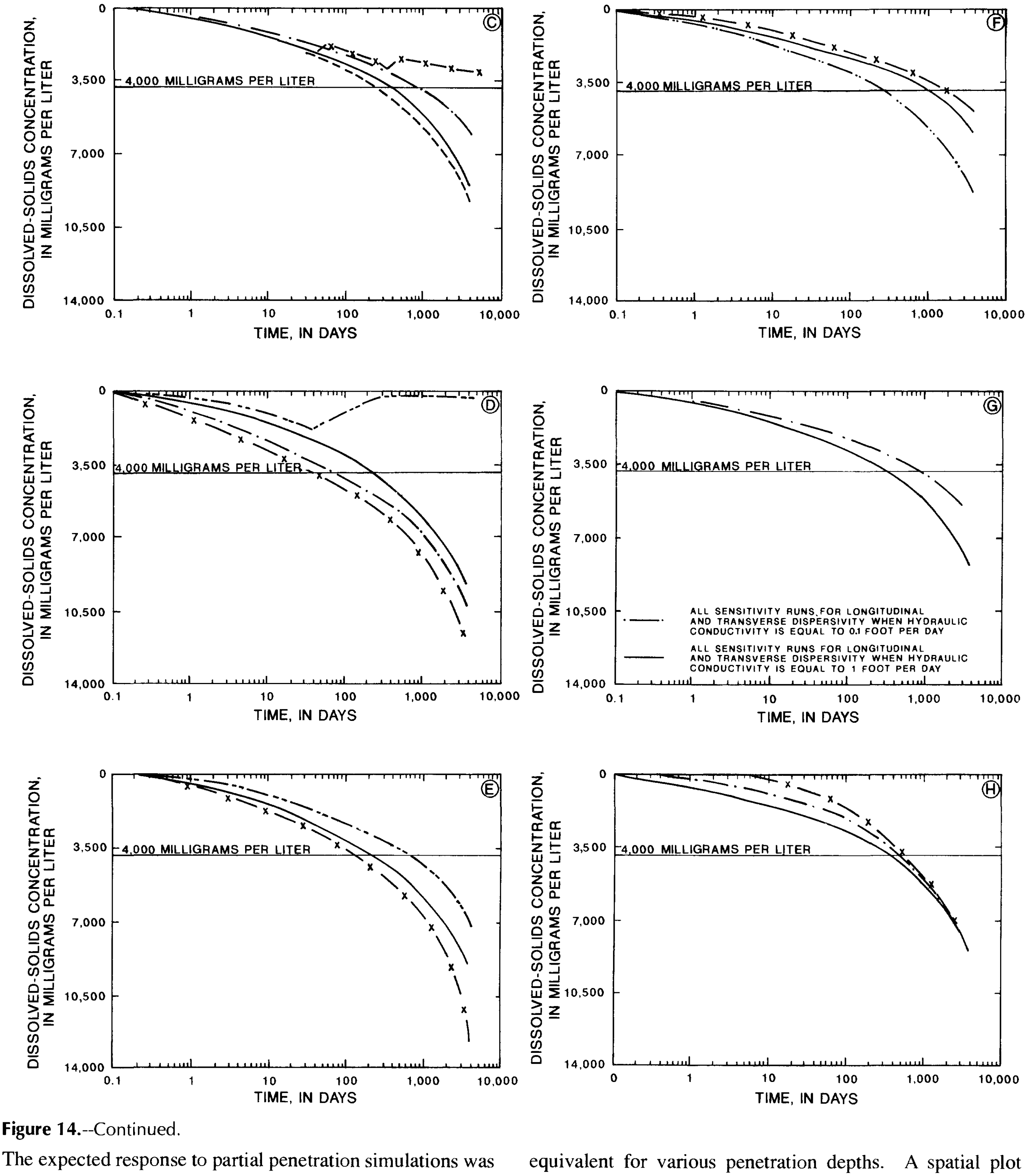


Figure 14.--Continued.

The expected response to partial penetration simulations was the retardation of water-quality changes because the open-hole interval would be 100 ft above the poor water zone. Dissolved-solids concentrations were plotted to show temporal and spatial trends. The temporal plot shows the dissolved-solids concentration trend over a 10-year period for several well-construction scenarios (fig. 14H). Simulations indicate that partial penetration does retard water-quality changes, but, after 1 year, the water-quality change is equivalent for various penetration depths. A spatial plot shows the relation of dissolved-solids concentrations to distance from the pumped well (fig. 15). Concentration values after 10 years of pumping were contoured for penetrations of 50, 75, and 100 percent. The figure indicates that changes in water quality occur radially and with depth. The average dissolved-solids concentration for pumped waters, due to mixing, is approximately equivalent for all percentages of well penetration.

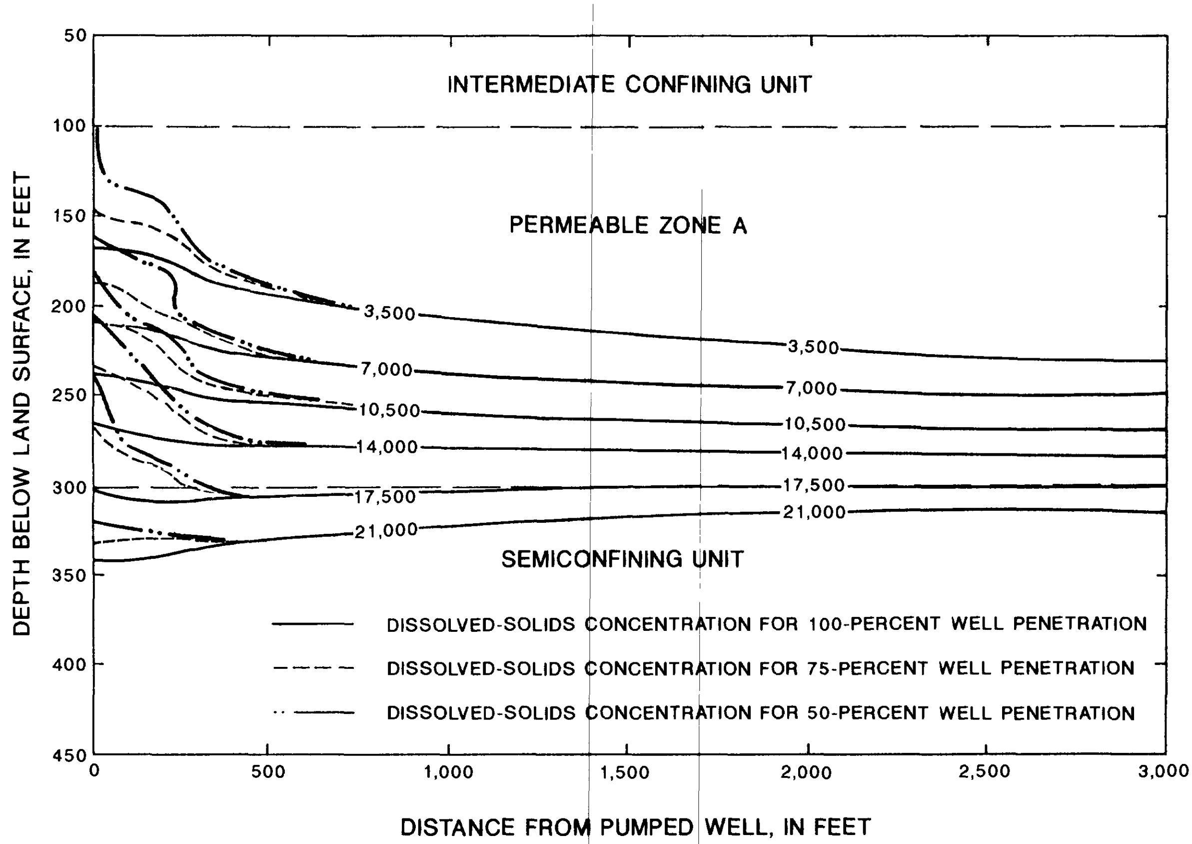


Figure 15. Distribution of dissolved-solids concentration, in milligrams per liter, for partially penetrating wells after 10 years of pumping.

Temporal and spatial plots indicate that the rate of water-quality change cannot be decreased by pumping partially penetrating wells instead of fully penetrating wells. This is due to the departure from radial flow in a partially penetrating well. Pumping partially penetrating wells produces a significant vertical component of flow. Water from layer 1 moves upward along curved flowlines to reach the well. As a result of the pumping, the equilibrium between saltwater and freshwater is disrupted and the interface rises toward the well. The upward migration of saline water from layer 1 contaminates the partially penetrating well so that the maximum dissolved-solids concentration limit of 4,000 mg/L is exceeded in about the same time as for a fully penetrating well.

FEASIBILITY OF DEVELOPING THE BRACKISH GROUND-WATER RESOURCES

The model described in this report was not calibrated due to the limited field data and because no appreciable development of brackish ground water has occurred in Pinellas County. Therefore, results of the pumping simulations are to be regarded as speculative. On the basis of the model simulation results, however, development of the brackish ground water appears impractical.

The limited hydrologic information, both physical and chemical, for the semiconfining unit underlying zone A leaves some uncertainties about the accuracy of the model results and results of the study. If the hydraulic conductivity of the semiconfining unit is substantially smaller than that being modeled, the upward leakage of saline water would be retarded. Likewise, if the hydraulic conductivity of the intermediate confining layer is greater than the value assumed in the model, a significant quantity of freshwater would be drawn from the surficial aquifer. This would increase the anticipated availability of brackish water. A detailed investigation of aquifer characteristics at a particular site, including test drilling and aquifer testing of the semiconfining unit below zone A, would allow a more definitive assessment of the feasibility for brackish ground-water development in Pinellas County.

SUMMARY AND CONCLUSIONS

Pinellas County, in west-central Florida, is underlain by brackish water and has only limited potable-water resources available for public supply. However, brackish water with concentrations of dissolved solids less than 4,000 mg/L can be treated for public supply using a reverse-osmosis process.

The potential for development of brackish ground-water resources in Pinellas County was evaluated by the U.S. Geological Survey, in cooperation with Pinellas County.

All ground water in the Upper Floridan aquifer in Pinellas County contains concentrations of chloride and dissolved solids that exceed the Florida Department of Environmental Regulation drinking water standards of 250 and 500 mg/L, respectively. However, brackish water with dissolved-solids concentrations of 4,000 mg/L or less is present in the uppermost part of the Upper Floridan aquifer (zone A) throughout most of Pinellas County, and, therefore, zone A was selected for further study.

The evaluation of brackish water with dissolved solids of less than 4,000 mg/L included determining areas where sufficient quantities of such water were available and determining areas of potential development that would be distant from operating well fields but yet near population centers. Based on these criteria, south-central Pinellas County appears to have a sufficient quantity of brackish ground water (less than 4,000 mg/L of dissolved solids) available for development. However, further study of the effects of pumping on the quality of brackish water is needed.

A numerical model that has the capability to simulate heat and solute transport in addition to ground-water flow using numerical equations was used to simulate water-quality changes in zone A during pumping from an idealized section based upon known or plausible values of geologic properties for Pinellas County. Three layers were simulated, including the intermediate confining unit, permeable zone A, and the semiconfining unit that separates permeable zones A and B. The types of boundary conditions used in the model include specified pressure, no flow, known flux, and aquifer-influence function. The backward-in-space and backward-in-time finite-difference method was used. The results were similar to other finite-differencing methods tested, and oscillation problems generally were eliminated with this numerical solution method. Several pumping and well-penetration schemes were simulated. Sensitivity tests were used to indicate the parameters that produced the greatest variability in simulation results. The model was most sensitive to changes in hydraulic conductivity. Results of 24 model-sensitivity simulations indicate that the dissolved-solids concentration of water from a well being pumped at 350 gal/min or greater from zone A (layer 2) will increase to greater than 4,000 mg/L in less than 2 years. Thus, on the basis of the limited amount of available information and model simulation of the hydrogeologic system, development of the brackish ground water in Pinellas County appears impractical because of likely changes in water quality.

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