AN ASSESSMENT OF THE FLOW OF VARIABLE-SALINITY GROUND WATER IN THE MIDDLE CONFINING UNIT OF THE FLORIDAN AQUIFER SYSTEM, WEST-CENTRAL FLORIDA

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Abstract

The middle confining unit of the Floridan aquifer system of Tertiary age in west-central Florida underlies the freshwater-bearing Upper Floridan aquifer and consists of carbonate rocks with evaporite inclusions. It is present in the subsurface throughout west-central Florida, pinching out toward the east near the axis of peninsular Florida. The hydraulic conductivity of the upper part of the middle confining unit may be within the range from 0.01 to 0.1 foot per day. This range of hydraulic conductivity suggests that the unit is maybe more hydrogeologically analogous to a very fine-grained sandstone bed rather than analogous to a compact clay bed, as has been implicitly assumed in past literature. Mixing of a native brine with freshwater that has entered the unit is the probable cause of the variable-salinity ground water in the unit inland from the coast. An approximate linear temperature profile indicates that the vertical component of flow in the unit is small. At two widely separated sites with available data, freshwater development in the Upper Floridan aquifer has altered the magnitude of the vertical component of saline water velocity in the middle confining unit. These hydrogeologic characteristics and responses indicate that slow upward movement of variable-salinity ground water in the middle confining unit could result from the pumping of overlying freshwater in west-central Florida. Thus, saline water could enter the bottom of the Upper Floridan aquifer and slowly modify the freshwater resource during its development.

Agencies that develop and regulate the ground-water resource in west-central Florida could help safeguard the quality of fresh ground water in the Upper Floridan aquifer by minimizing and monitoring the vertical movement of saline ground water in and from the middle confining unit. A method for minimizing upward movement of the saline ground water would be to minimize drawdown at the top of the middle confining unit by pumping fresh ground water only from the uppermost permeable zones of the Upper Floridan aquifer. The vertical movement of saline ground water could be monitored by measuring pressure and water quality in a pair of observation wells with one well open to the middle confining unit and the other well open to the bottom of the Upper Floridan aquifer just above the top of the middle confining unit.

INTRODUCTION

Ground water from the Upper Floridan aquifer of Tertiary age is used for agricultural, industrial, and public supply purposes. This fresh ground water, however, is underlain by moderately saline to briny ground water that is characterized by relatively high chloride and sulfate concentrations. Inland from the coastal margin of the Gulf of Mexico, this variable-salinity ground water generally is found within the middle confining unit of the Floridan aquifer system. The presence of saline water at depth is of particular concern because, if it moves upward as a result of withdrawals of freshwater from the Upper Floridan aquifer, vertical encroachment of the saline water could limit ground-water development in west-central Florida.

The terms moderately saline and briny are from Robinove and others (1958) and represent dissolved-solids concentrations that range from 3,000 to more than 35,000 mg/L. Conceptual and numerical ground-water flow models of west-central Florida (Hutchinson and others, 1981; Wilson and Gerhart, 1982; Hutchinson, 1984; Ryder, 1985) have assumed that the middle confining unit is impermeable and acts hydraulically as a no-flow boundary. Such a view necessarily ignores the likelihood of vertical movement of saline water from the middle confining unit into the overlying fresh ground water. The objective of this report is to assess whether or not the moderately saline to briny ground water in the middle confining unit of the Floridan aquifer system is likely to move vertically into the overlying fresh ground water as a result of ground-water development in the Upper Floridan aquifer. This report, in other words, is a critical evaluation of the hypothesis that the middle confining unit acts hydraulically as a no-flow boundary.

Few hydrogeologic and water-quality data have been collected from the middle confining unit of the Floridan aquifer system in west-central Florida. Therefore, the hydrogeologic and water-quality descriptions in this report are approximate, but there are enough data to provide the basis for reasonable conclusions about the likelihood of vertical movement of saline ground water from the middle confining unit into the overlying fresh ground water of the Upper Floridan aquifer.

GEOLOGIC SETTING AND HYDROGEOLOGIC NOMENCLATURE

West-central Florida and the Southwest Florida Water Management District (fig. 1) are underlain by both a sequence of Cretaceous System and Tertiary System carbonate rocks and a sequence of Quaternary System carbonate and clastic rocks. These Cretaceous through Quaternary rocks range in thickness from about 4,000 feet in the northern part of the study area to more than 13,000 feet in the southern part and overlie a pre-Mesozoic basement complex of igneous and metamorphic rocks (Applin, 1951). The correlations between the stratigraphic and hydrogeologic units assumed in this report are shown in table 1. Because the bottom of the sub-Floridan confining unit lies relatively close to the top of the Cretaceous System, the top of the Cretaceous is a convenient horizon for separating rocks that are hydrogeologically significant in central Florida from those that are not. The altitude of the top of the Cretaceous System in central Florida (modified from Miller, 1986) is shown in figure 2. This surface ranges from about 2,000 feet below sea level in the northern part of the study area to about 6,000 feet below sea level in the southern part of the study area.

The hydrogeologic nomenclature used in this report follows that of the Southeastern Geological Society (1986) and Miller (1986). The Southeastern Geological Society (SEGS) nomenclature assumes that the presence or absence of either clay, anhydrite, or gypsum in strata can be used to distinguish relatively impermeable rocks (confining units) from relatively permeable rocks (aquifers). Four hydrogeologic units are identified in the SEGS nomenclature as the essential megascopic elements needed to describe the regional hydrogeologic framework of Florida. From uppermost to lowermost, as shown in table 1, these units are: (1) the surficial aquifer system composed mainly of sand; (2) the intermediate confining unit, or if this rock sequence has water-supply potential, the intermediate aquifer system. Both the confining unit and aquifer system are composed mainly of phosphatic sand, clay, and limestone; (3) the Floridan aquifer system (Miller, 1986) composed mainly of limestone and dolomite with some stratigraphic intervals that contain inclusions of anhydrite and gypsum; and (4) the sub-Floridan confining unit composed mainly of beds of anhydrite and dolomite. The concept of a hydrogeologic system was used by the Southeastern Geological Society for three of the four hydrogeologic units as a means of recognizing that each unit could be further subdivided depending upon the purpose of a particular investigation.

The middle confining unit of the Floridan aquifer system is defined in this report as the stratigraphic interval within the Floridan aquifer system that contains inclusions of anhydrite and gypsum. These strata are thought to be relatively impermeable and their identification provides a useful hydrogeologic refinement for conceptualizing regional ground-water flow within the Floridan aquifer system.

North-south (A-A′) and east-west (B-B′) sections that show the configuration of hydrogeologic units in west-central Florida are shown in figures 3 and 4, respectively. The lines of section A-A′ and B-B′ and locations of nine test-hole sites are shown in figure 1. Only two of the nine test wells used to construct the sections completely penetrate the Floridan aquifer system. Hydrogeologic units below the depth of the test wells at the remaining seven sites were approximated from resistivity logs of nearby (within 5-15 miles) oil test wells. The part of each hydrogeologic column that is interpreted from the oil test well resistivity logs is shown by dashed lines in figures 3 and 4. Resistivity logs were useful for hydrogeologic interpretations below the top of the middle confining unit because inclusions of anhydrite and gypsum and beds of anhydrite reduce effective porosity and thus increase formation resistivity. Resistivity logs were and should be used cautiously to establish the top of the middle confining unit in west-central Florida because of the presence of a low-porosity and permeable dolomite in the Upper Floridan aquifer that has a similar high-resistivity expression, as seen in logs of the middle confining unit.

HYDROGEOLOGIC CHARACTERISTICS OF THE MIDDLE CONFINING UNIT

The middle confining unit of the Floridan aquifer system is present within the Avon Park Formation of middle Eocene age and the Oldsmar Formation of lower Eocene age (table 1). The middle confining unit is composed of limestone, dolomitic limestone, and dolomite that contain inclusions of anhydrite and gypsum. These evaporite inclusions generally appear to be primary as they were apparently in place at the time of carbonate deposition (Stewart, 1966; Navoy, 1986). Observations of evaporite inclusions seen in borehole television surveys run in test holes in west-central Florida indicate that the evaporites were originally deposited as thin beds that were probably fragmented at the time of the resumption of carbonate deposition, and the fragments were then incorporated into the host carbonate rock as inclusions.

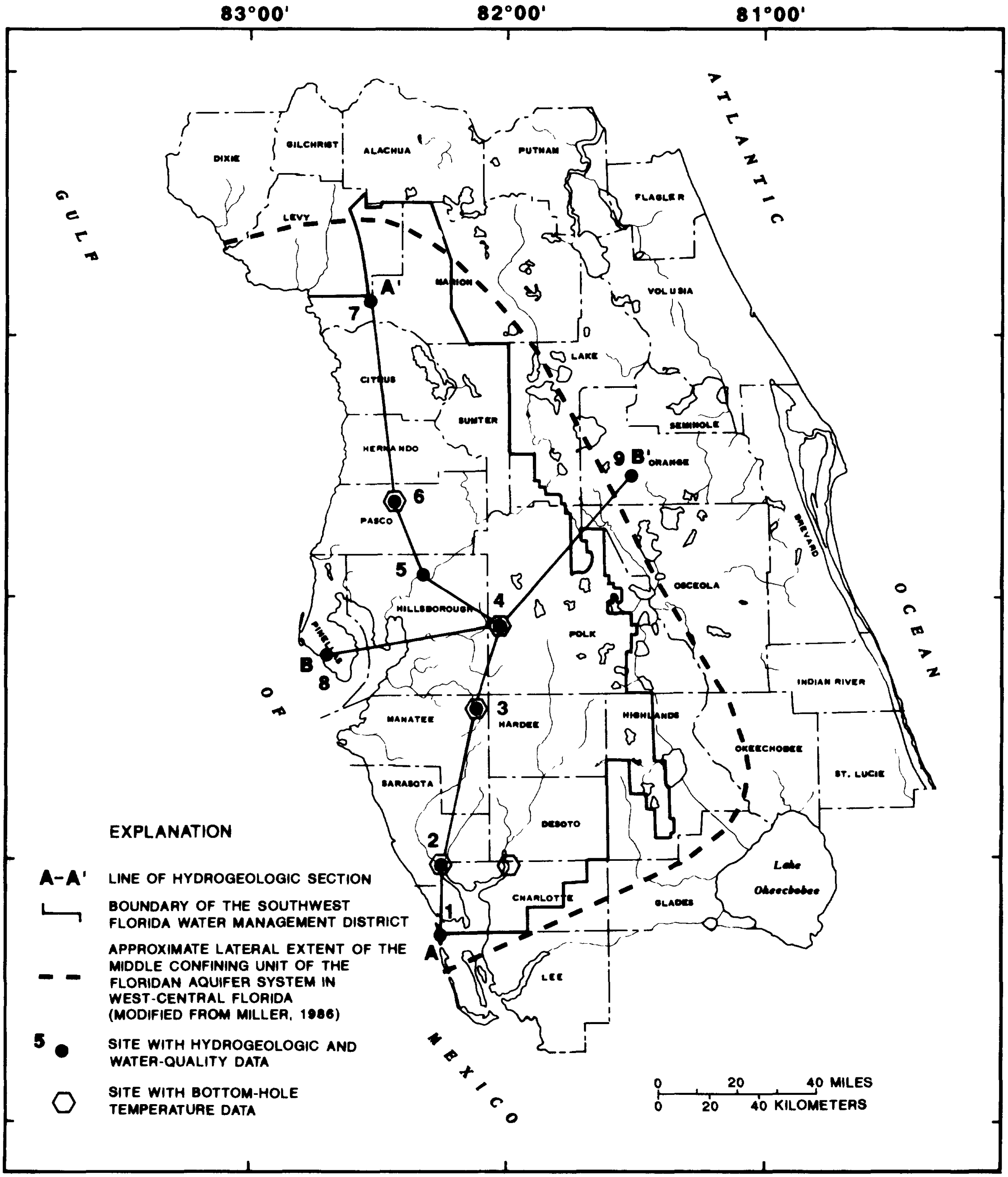

Figure 1. Location of test holes sites in west-central Florida. (Sections A-A′ and B-B′ are shown in figs. 3 and 4, respectively.)

Table 1. Stratigraphic and hydrogeologic units of west-central Florida
[Modified from Stringfield, 1966; Miller, 1986; Southeastern Geological Society, 1986]

Erathem	System	Series		Formation	Generalized lithology	Hydrogeologic units	
Cenozoic	Quaternary	Holocene and Pleistocene		Undifferentiated marine terrace and fluvial deposits	Sand and clay	Surficial aquifer system	
1.6 million years before present	Tertiary	Pliocene		Bone Valley Formation; Tamiami Formation	Sand, clay, and phosphate	Intermediate confining unit or intermediate aquifer system	
	Tertiary	Miocene		Hawthorn Formation	Phosphatic sand, clay, and limestone	Intermediate confining unit or intermediate aquifer system	
	Tertiary	Miocene		Tampa Limestone	Limestone	Floridan aquifer system	Upper
	Tertiary	Oligocene		Suwannee Formation	Limestone	Floridan aquifer system	Upper
	Tertiary	Eocene	Upper	Ocala Limestone	Limestone	Floridan aquifer system	Upper
	Tertiary	Eocene	Middle	Avon Park Formation	Dolomite and limestone	Floridan aquifer system	Upper
	Tertiary	Eocene	Middle	Avon Park Formation	Dolomite and limestone with some stratigraphic intervals containing inclusions of gypsum and anhydrite	Floridan aquifer system	Middle confining unit
	Tertiary	Eocene	Lower	Oldsmar Formation	Dolomite and limestone with some stratigraphic intervals containing inclusions of gypsum and anhydrite	Floridan aquifer system	Lower
66.4 million years before present	Tertiary	Paleocene		Cedar Keys Formation	Beds of anhydrite and dolomite	Sub-Floridan confining unit	
Mesozoic	Cretaceous	Undifferentiated for this report					

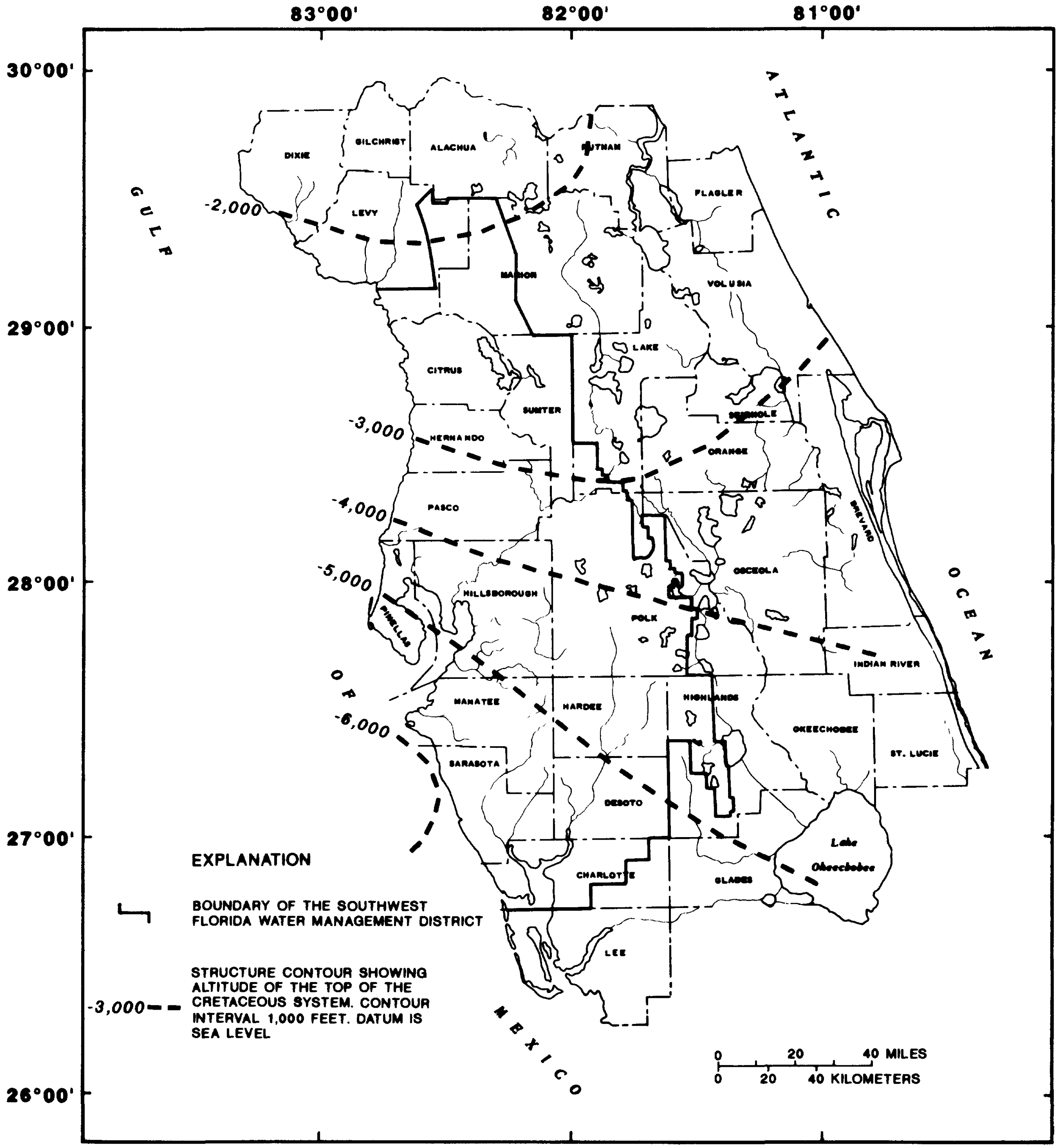

Figure 2. Top of the Cretaceous System in central Florida. (Modified from Miller, 1986)

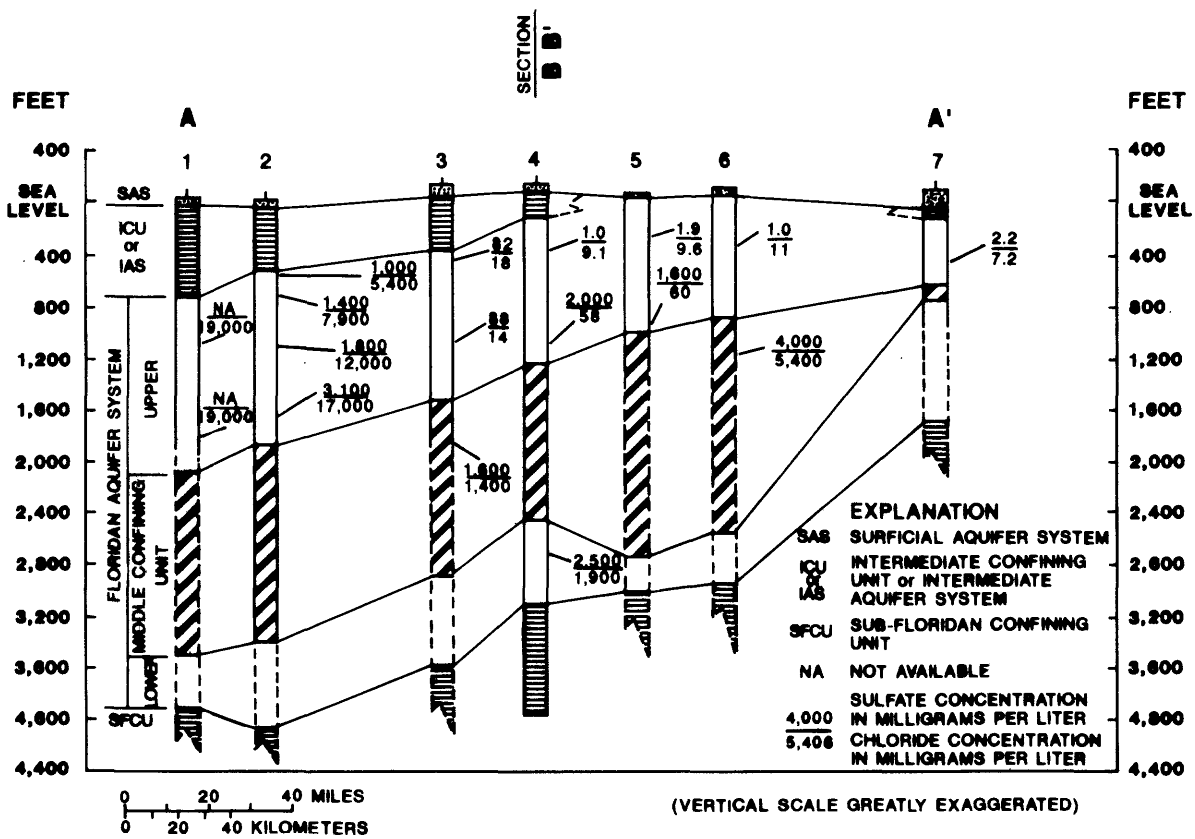

Figure 3. Hydrogeologic section A-A′ with sulfate and chloride concentrations in variable-salinity ground water at selected altitudes. (Location of section is shown in fig. 1.)

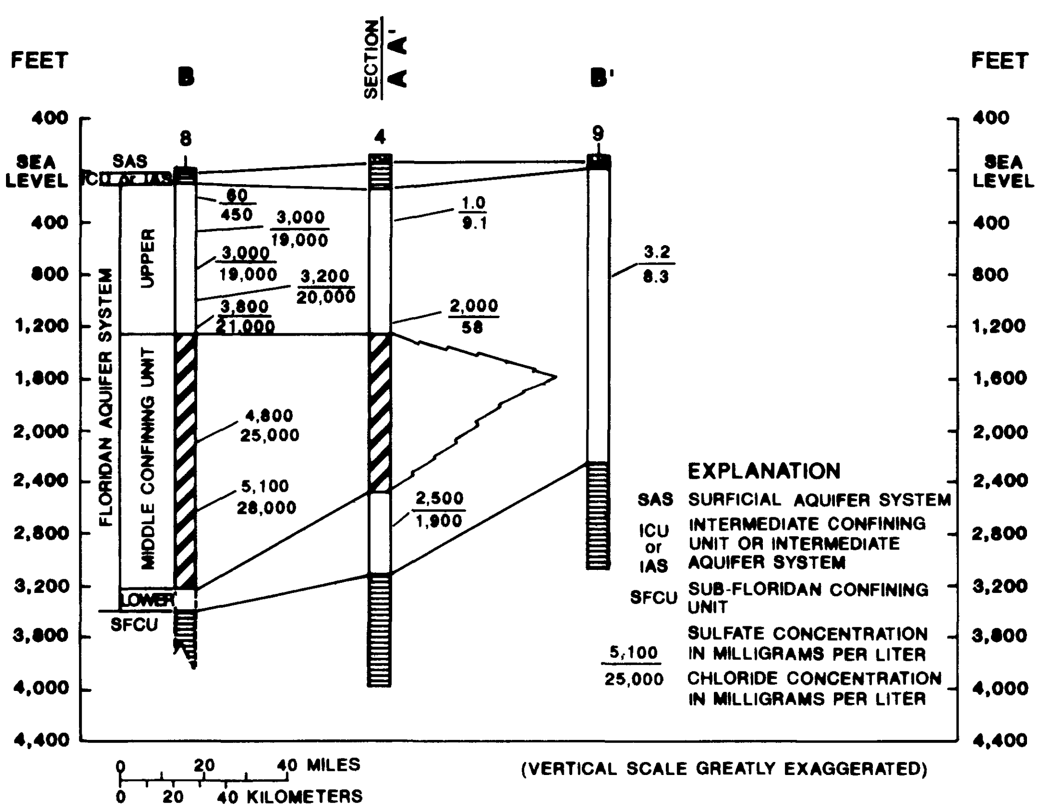

Figure 4. Hydrogeologic section B-B′ with sulfate and chloride concentrations in variable-salinity ground water at secleted altitudes. (Location of section is shown in fig. 1.)

The apparent thinness of the original evaporite beds implies that the beds had limited lateral extent, and thus, each narrow cluster of evaporite nodules would have limited lateral extent. Hydrogeologically, evaporite inclusions imply that the middle confining unit is less porous and less permeable than the overlying carbonate rocks of the Upper Floridan aquifer. Some secondary infilling of fractures and fossil casts by gypsum also is reported for the middle confining unit (Stewart, 1966; Navoy, 1986).

Stewart (1966) and Navoy (1986) state that some of the evaporite inclusions have a central core of anhydrite surrounded by gypsum. Consistent with this observation are results of X-ray diffraction analysis of an evaporite inclusion from the middle confining unit that underlies Pinellas County. Both gypsum and anhydrite were detected in the sample, but gypsum was predominant (Neil Plummer, U.S Geological Survey, written commun., 1988). Evaporite inclusions generally make up a relatively small fraction of the rocks that comprise the middle confining unit, seldom exceeding 10 to 30 percent of a given rock sample (Hickey, 1981; 1982; Navoy, 1986). The thickness of the middle confining unit, or the thickness of the carbonate rocks that contain evaporite inclusions, varies throughout the study area. The greatest variation occurs in the northern and eastern parts of the area. Figure 3 shows that evaporites occur in smaller intervals of the rock column toward the north, and thus, the middle confining unit thins abruptly between sites 6 and 7. Figure 4 shows that evaporite inclusions are absent from the rock column toward the east, and thus, the middle confining unit pinches out between sites 4 and 9. Slightly to the west of this pinchout of the middle confining unit is a dome in the potentiometric surface of the Upper Floridan aquifer that marks the highest heads in the Floridan aquifer system in peninsular Florida. This dome is commonly known as the "Polk City potentiometric high." The lateral extent of the middle confining unit in west-central Florida from Miller's (1986) middle confining unit II is shown in figure 1.

At site 3 (fig. 1), total porosity was estimated at selected depths by interpreting geophysical logs run in a test well (William F. Guyton and Associates, 1976). For the depths within the middle confining unit, total porosity was estimated to range from about 10 to 40 percent and to average about 30 percent. In a following section of this report which discusses vertical components of ground-water movement in the middle confining unit, effective porosity of the unit is assumed to be within the range from 10 to 30 percent.

Hydraulic conductivity near the top of the middle confining unit has been estimated at several locations in west-central Florida. Most of the available hydraulic conductivity estimates are from laboratory analysis of cores. Stewart (1966) reported four vertical hydraulic conductivities that ranged from 4.0×10^{-5} to 2.0 ft/d for cores taken about 10 miles north of site 4. Hickey (1981) reported three vertical hydraulic conductivities that ranged from 6.0×10^{-7} to 1.1 ft/d for cores taken about 5 miles south of site 8. Navoy (1986) reported 14 vertical hydraulic conductivities that ranged from 2.4×10^{-5} to 0.9 ft/d for cores taken about 20 miles northeast of site 4 and about at the center of the potentiometric dome mentioned above. Because of the probable small-scale heterogeneity in hydraulic conductivity caused by the evaporite inclusions, estimates from cores may not be representative of the bulk vertical hydraulic conductivity of the middle confining unit.

William F. Guyton and Associates (1976) reported a horizontal hydraulic conductivity on the order of 1 (gal/min)/ft^2 (0.1 ft/d) from a packer test on a 260-foot interval of the middle confining unit at site 3. Leggette, Brashears, and Graham, Inc. (1979) reported results from pumping tests that were run on two depth intervals, ranging from about 200 to 300 feet thick, of the middle confining unit during the drilling of an observation well at site 6. The horizontal hydraulic conductivity that was estimated from these tests was 0.3 (gal/min)/ft^2 (0.04 ft/d). William F. Guyton and Associates (1976) assumed that the evaporites in the middle confining unit were continuous and laterally extensive beds, and because of this, they assumed that the vertical component of hydraulic conductivity would be much lower than their reported horizontal value. Leggette, Brashears, and Graham, Inc. (1979), implicitly made the same assumption about the evaporites and, as a result, also assumed that the vertical component of hydraulic conductivity of the middle confining unit would be a small fraction of their reported horizontal value.

Because the evaporites in the middle confining unit occur mainly as nodules that are discontinuously distributed within narrow layers with limited lateral extent, the hydraulic conductivities estimated from the tests run at sites 3 and 6 may be applicable not only to the horizontal but also to the vertical direction. In other words, the vertical hydraulic conductivity of the middle confining unit rounded to the nearest order of magnitude may be within the range from 0.01 to 0.1 ft/d. Both the upper and lower limits of the estimated hydraulic conductivity range assumed for the middle confining unit are relatively small in comparison to the hydraulic conductivity of the overlying Upper Floridan aquifer, which commonly ranges from 50 to 1,000 ft/d (Ryder, 1985).

An assumption that is commonly made when simulating ground-water flow in the Floridan aquifer system in west-central Florida (Hutchinson and others, 1981; Wilson and Gerhart, 1982; Hutchinson, 1984; Ryder, 1985) is that the middle confining unit is impermeable and hydraulically acts as a no-flow boundary. The range of vertical hydraulic conductivity mentioned above, 0.01 to 0.1 ft/d, leads to the interpretation that this assumption may be inappropriate. The middle confining unit may be more hydrogeologically analogous to a very fine-grained sandstone bed rather than analogous to a compact clay bed, as is implicitly assumed by treating the unit as a no-flow boundary.

Consistent with the above estimated range of vertical hydraulic conductivity for the middle confining unit is a comparison between water-level measurements taken from the Upper Floridan aquifer and from the middle confining unit at sites 3 and 6. Water levels in wells that tap the Upper Floridan aquifer at sites 3 and 6 vary over a greater range than water levels in wells that tap the middle confining unit. For example, water levels from the Upper Floridan aquifer at site 6 varied during the period of record by about 13 feet, and water levels from the middle confining unit at a depth of 240 feet below its top varied by about 2 feet (fig. 5). The ratio of the water-level variation in the middle confining unit to the water-level variation in the Upper Floridan aquifer at site 6 is 0.15. At site 3, this ratio is 0.03 and is relatively small, in part, probably because the observation well tapping the moderately saline ground water was never developed.

Bottom-hole temperatures measured at selected altitudes in test wells that tap rocks generally between the top of the middle confining unit and above the bottom of the sub-Floridan confining unit are shown in figure 6. These temperature data are from five sites in west-central Florida (fig. 1). Seven of the 10 temperatures shown in figure 6 were measured in test wells drilled by the air-reverse rotary method; 3 were measured in test wells drilled by the mud-rotary method.

With the exception of one temperature measurement at about 4,850 feet below sea level from a mud-rotary drilled hole, all of the temperature data in figure 6 were used and fitted to a straight line. The approximate linear-temperature profile for the middle confining unit in figure 6 has temperature increasing downward; a least-squares estimate of slope, or geothermal gradient of 1.3 °F/100 feet; a coefficient of determination (R^2) of 0.98; and a standard error of estimate of 1.8 °F. The occurrence

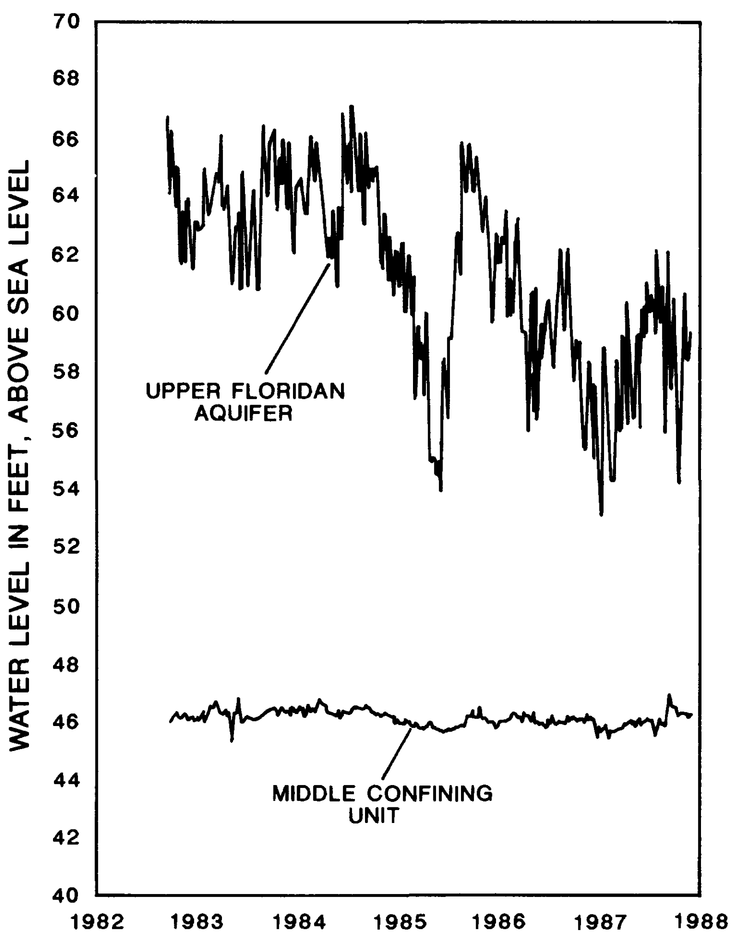

Figure 5. Altitude of water levels in observation wells at site 6.

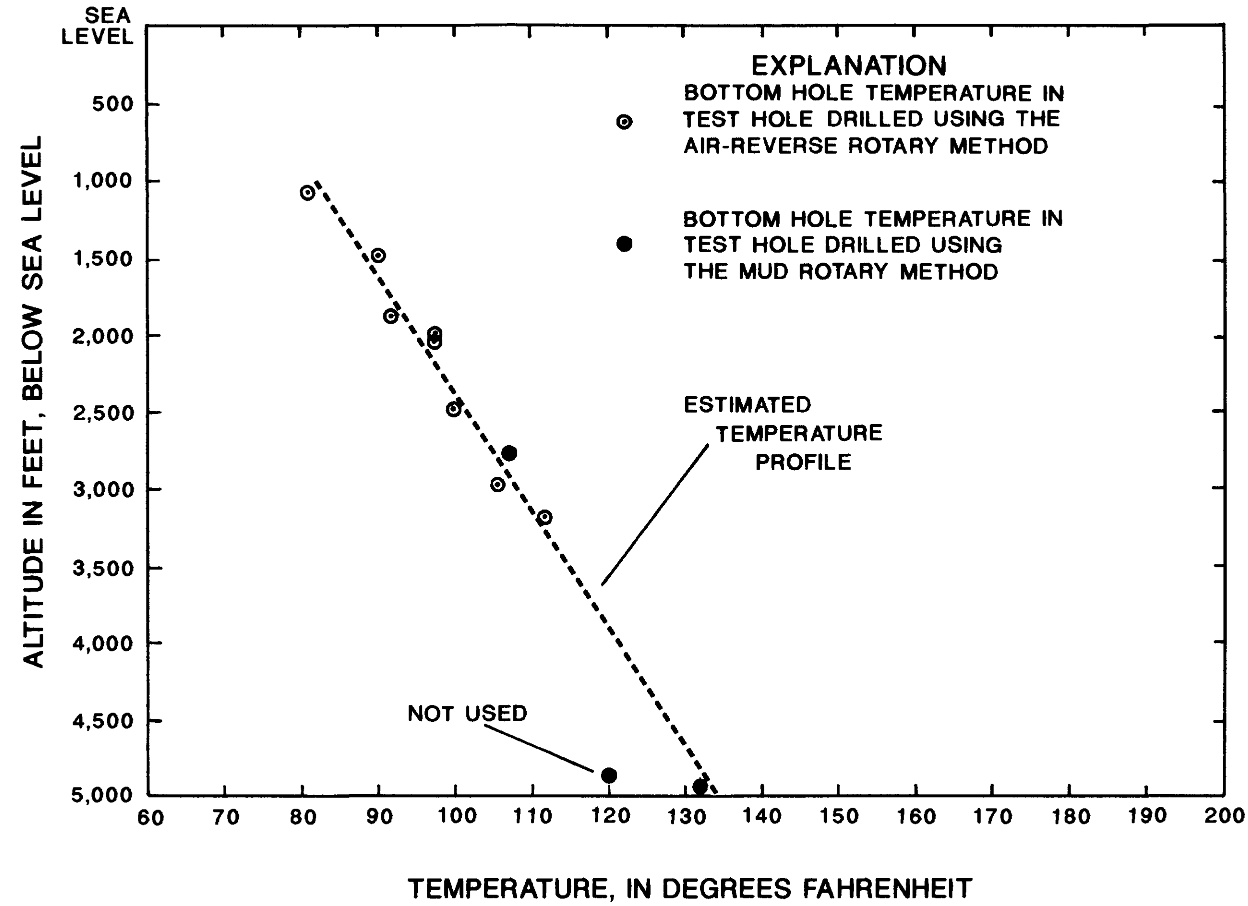

Figure 6. Bottom hole temperatures at altitudes below the top of the middle confining unit in west-central Florida. (Locations of sites with temperature data are shown in fig. 1.)

of an approximate linear-temperature profile indicates that the vertical component of the overall ground-water movement inferred from the chloride-concentration distribution in the middle confining unit, discussed below, is very slow (Bredehoeft and Papadopulos, 1965).

The geothermal gradient estimated between the top of the middle confining unit and the bottom of the sub-Floridan confining unit is similar to the mean geothermal gradient estimated in a deep test well (King and Simmons, 1972) about 10 miles east of site 9. This deep test well was open to an interval of Cretaceous rocks about 2,000 feet below the bottom of the sub-Floridan confining unit. A brine with about four times the dissolved-solids concentration of seawater was found at a comparable depth at site 9. The mean geothermal gradient in the interval between 5,000 and 5,600 feet below sea level, based upon measurements by King and Simmons (1972), was 1.3 °F/100 feet, the same value estimated for the middle confining unit in west-central Florida.

WATER-QUALITY CHARACTERISTICS OF VARIABLE-SALINITY GROUND WATER IN THE MIDDLE CONFINING UNIT

Sulfate and chloride concentrations in the variable-salinity ground water at selected altitudes in the middle confining unit and also in the Upper Floridan aquifer are shown in figures 3 and 4. In the Upper Floridan aquifer, chloride concentrations similar to that of seawater occur at site 1 (fig. 3) and site 8 (fig. 4). Chloride concentrations in the Upper Floridan aquifer decrease inland between sites 1 and 2 (fig. 3) and increase with depth at sites 2 and 8. The spatial distribution of chloride concentration in the Upper Floridan aquifer at sites 1, 2, and 8 shows the presence of a saltwater-freshwater transition zone. The major source of chloride ions is probably the Gulf of Mexico. Near the bottom of the Upper Floridan aquifer at site 8 (fig. 4), however, a chloride concentration of 21,000 mg/L, which is higher than that of seawater and thus implies a seawater and brine mixture, suggests upward movement of brine from the underlying middle confining unit. Vertical components of ground-water velocity estimated at site 3 in the middle confining unit, and discussed below, suggest that an upward component of flow is present in the middle confining unit south of Tampa Bay at a distance tens of miles inland from the coastal margin. The widening of the saltwater-freshwater transition zone in the lower part of the Upper Floridan aquifer south of the Tampa Bay area (Hickey, 1981, fig. 15; Wilson, 1982, fig. 7) may be partly explained by the upward flow of saline water from the middle confining unit.

Relatively small sulfate and chloride concentrations are present in ground water near the top of the Upper Floridan aquifer at sites 4 through 7 (fig. 3) and at site 9 (fig. 4). These inland sites are in regions identified as areas of recharge to the Upper Floridan aquifer (Ryder, 1985). As would be expected for such areas, sulfate and chloride concentrations in the ground water are similar to those in precipitation (Irwin and Kirkland, 1980).

Near the bottom of the Upper Floridan aquifer, just above the top of the middle confining unit at sites 4 and 5 (fig. 3), relatively large sulfate concentrations occur along with chloride concentrations that are elevated with respect to those of the shallower ground water. This zone of high sulfate concentrations is more than 70 feet thick at site 5 and more than 120 feet thick at site 4. Ground water that has a specific conductance similar to that of the high sulfate concentration water at sites 4 and 5 is present at site 3 (fig. 3) in a zone about 170 feet thick just above the top of the middle confining unit (William F. Guyton and Associates, 1976).

Two hypotheses may explain the origin of the high sulfate concentrations found near the bottom of the Upper Floridan aquifer at sites 4 and 5. One possible source of the sulfate is the solution of evaporites at the top of the middle confining unit. The other possible source is upward movement of water that contains high sulfate concentrations from the middle confining unit into the bottom of the Upper Floridan aquifer. Whatever the source of the sulfate, subsequent hydrodynamic dispersion along and perpendicular to the paths of ground-water flow near the bottom of the Upper Floridan aquifer would account for the observed sulfate distribution. The sulfate-to-chloride millimole-per-liter ratio in water from the high sulfate concentration zone in the bottom of the Upper Floridan aquifer at site 4 is 13 and at site 5 the ratio is 10. The ratios in water from the middle confining unit at sites 3 and 6 are 0.4 and 0.3, respectively. A comparison of these ratios suggests there is little, if any, upward movement of water from the middle confining unit into the bottom of the Upper Floridan aquifer at sites 4 and 5, as would be expected in recharge areas. Thus, the origin of the high sulfate concentrations at the bottom of the Upper Floridan aquifer at sites 4 and 5 is probably from the solution of evaporite at the top of the middle confining unit.

Brine occurs in the middle confining unit at site 8 (fig. 4). This brine has a chloride concentration that ranges from 25,000 to 28,000 mg/L, about 1.3 to 1.4 times the chloride concentration of seawater. The occurrence of both evaporite inclusions and brine at site 8 is geologically consistent and provides the basis for hypothesizing that the pore water in those parts of the middle confining unit with evaporites originally may have been such a brine. The measured density of the brine at site 8 ranges from about 1.03 to 1.04 g/mL (Hickey, 1979). Chloride concentrations that are less than the concentrations in the brine, and similar to the concentrations within the saltwater-freshwater transition zone in the coastal margin of the Upper Floridan aquifer, occur in the middle confining unit at sites 3 and 6, inland from site 8 (fig. 3). At site 3, the chloride concentration and density of water from the middle confining unit are 1,600 and 1.004 g/mL, respectively; at site 6, the chloride concentration and density of water from the middle confining unit are 4,000 and 1.011 g/mL, respectively.

The chloride concentrations and densities at sites 3 and 6 in comparison to site 8 strongly imply that water with relatively low chloride concentration and density (freshwater) historically has moved across the boundaries of the middle confining unit. Movement of freshwater across the boundaries of the unit probably started soon after the Florida carbonate platform emerged above sea level and fresh ground water derived from rainfall began circulating within the platform. Inland from the coast, in areas of recharge to the Upper Floridan aquifer, fresh ground water probably is presently moving downward into the middle confining unit across its uppermost boundary. In the coastal margin of west-central Florida, the presence of a brine in the middle confining unit and a chloride concentration of 21,000 mg/L in the bottom of the Upper Floridan aquifer at site 8 imply that upward movement of brine from the middle confining unit into the bottom of the Upper Floridan aquifer probably occurs. Mixing of a native brine with freshwater that has entered the unit is the probable cause of the variable-salinity ground water inland from the coast.

Water-quality data from observation wells and production wells located in two well fields, which tap the uppermost permeable zones of the Upper Floridan aquifer, have shown no trends since each field began operation. Site 5 is about in the middle of the Morris Bridge well field. This well field started operation in 1982. Sulfate and chloride concentration data have been collected at the site since 1978. The 40-foot sampling interval in the observation well at the site is open near the bottom of the Upper Floridan aquifer. The base of the sampling interval is about 30 feet above the top of the middle confining unit. From 1982 to 1987, an average of about 14 Mgal/d was pumped from the well field. All of the production wells tap the Upper Floridan aquifer to an average depth of about 500 feet above the top of the middle confining unit. From 1978 to 1987, no trends were discerned in the sulfate and chloride concentration data from site 5. (Water-quality data are in the files of the U.S. Geological Survey, Tampa, Fla.)

Site 6 is within the Cross Bar Ranch well field. This well field started operation in 1980. The production wells adjacent to the observation well at site 6 tap the Upper Floridan aquifer to an average depth of about 300 feet above the top of the middle confining unit. From 1980 to 1987, an average of about 14 Mgal/d was pumped from the well field. No trends were discerned in the sulfate and chloride concentration data from the production wells adjacent to site 6 between 1980 and 1987. (Water-quality data are in the files of the West Coast Regional Water Supply Authority, Clearwater, Fla.)

VERTICAL GROUND-WATER FLOW IN THE MIDDLE CONFINING UNIT

Ground-water flow probably occurs naturally in the middle confining unit and apparently has influenced the chemical quality of ground water in the Upper Floridan aquifer in the vicinity of the coastal margin. As inferred from the temperature profile mentioned in the hydrogeologic discussion, however, the vertical component of ground-water flow in the unit is very small. These interpretations are based upon data that indirectly reflect the long-term and regional history of ground-water flow in the middle confining unit of the Floridan aquifer system. What follows is a discussion of ground-water flow at specific locations in the middle confining unit that is based upon data directly related to vertical flow at sites 3 and 6.

Sites 3 and 6 each have a pair of observation wells. One well at each site is open to an interval in the Upper Floridan aquifer and the other is open to an interval within the middle confining unit. Water-level data, collected on a regular basis from these wells, are available for site 3 for the period from 1975-76 and for site 6 for the period from 1982 to 1987. In order to calculate the vertical velocity of ground water in the middle confining unit at these two sites, estimates of ground-water density and pressure at specific depths are required. Also, it is assumed that ground-water flow in the Upper Floridan aquifer is horizontal and that a barotropic field exists in the middle confining unit. A barotropic field represents conditions in which ground-water density increases only vertically downward and surfaces of equal ground-water density are coincident with surfaces of equal pressure.

The vertical component of velocity (v_z) in the middle confining unit, assuming a barotropic field, can be estimated by

$$v_z = -\frac{K}{\phi}\left[\frac{\Delta P/\Delta z}{\bar{\rho}g} + 1\right] \qquad (1)$$

where

- K is hydraulic conductivity, in feet per day (L/T);
- ϕ is effective porosity, dimensionless;
- $\Delta P/\Delta z$ is the approximate vertical component of the pressure gradient, in pounds per cubic foot, between two vertically separated points of calculated pressure (F/L^3);
- ΔP is the pressure difference, in pounds per square foot (F/L^2);
- Δz is the vertical distance between calculated pressures, in feet (L); and
- $\bar{\rho}g$ is the mean specific weight of ground water, in pounds per cubic foot, between two vertically separated points of calculated pressure (F/L^3).

Site 3 is in a region where intensive ground-water development of the Upper Floridan aquifer has taken place since the 1960's. At site 3 during 1975-76, the average water level in the observation well open to the middle confining unit was about 50 feet above sea level, whereas the average water level in the observation well open to the Upper Floridan aquifer was about 25 feet above sea level (William F. Guyton and Associates, 1976, fig. 22). For predevelopment conditions, the average water level in the Upper Floridan aquifer at site 3 was estimated at about 58 feet above sea level (Johnston and others, 1980). These water levels were used to estimate pressures at selected altitudes at site 3.

The difference between pressures that were calculated at the top of the middle confining unit (1,550 feet below sea level) and at the base of the casing in the middle confining unit (1,830 feet below sea level) for predevelopment conditions is $\Delta P = -18{,}000\ lb/ft^2$ and for development conditions (1975-76) is $\Delta P = -21{,}000\ lb/ft^2$. The mean density of ground water in the interval between the points of calculated pressures is unknown for predevelopment and development conditions, but should be within the range from 0.998 to 1.004 g/mL, which is the range of water densities from the two observation wells. After adjusting these densities for field temperature and pressure conditions, the mean specific weight of water ($\bar{\rho}g$) in the interval between 1,550 and 1,830 feet below sea level (Δz = 280 feet) should be within the range from 62.2 to 62.6 lb/ft^3.

Assuming that effective porosity is within the range from 10 to 30 percent, hydraulic conductivity is within the range from 0.01 to 0.1 ft/d, and using the site 3 estimates of ΔP, Δz, and $\bar{\rho}g$, the vertical component of ground-water velocity in the middle confining unit can be calculated for predevelopment and development conditions at site 3 by applying equation 1. For predevelopment conditions, the vertical component of ground-water velocity in the middle confining unit is calculated to be within the range from 0.0009 to 0.03 ft/d. For development conditions, the vertical component of ground-water velocity is calculated to be within the range from 0.007 to 0.2 ft/d. The implied positive sign for the predevelopment and development velocities indicates that flow was upward within the middle confining unit during both circumstances. The influence of ground-water development on the vertical component of velocity in the middle confining unit at site 3 is shown by the seven to eight times increase in upward velocity as a result of development.

Site 6 is within the Cross Bar Ranch municipal well field that started pumping ground water from the Upper Floridan aquifer in 1980. At site 6, the average water level from 1982 to 1987 in the observation well open to the middle confining unit was 46.1 feet above sea level, and the average water level was 58.3 feet above sea level from April 1986 to December 1987 in the observation well that is open to the Upper Floridan aquifer. Figure 5 shows the water-level measurements that were used to calculate these averages. For predevelopment conditions during October and September 1979, the average water level in the observation well open to the Upper Floridan aquifer was about 66.2 feet above sea level (Leggette, Brashears, and Graham, Inc., 1979). These water levels were used to estimate pressures at selected altitudes as was done for site 3.

The difference between pressures that were calculated at the top of the middle confining unit (900 feet below sea level) and at the top of the sand and gravel packed screened interval of the middle confining unit observation well (1,140 feet below sea level) for predevelopment conditions is ΔP = -14,500 lb/ft^2 and for development conditions from April 1986 to December 1987 is ΔP = -15,000 lb/ft^2. The mean density of ground water in the interval between the points of calculated pressure is unknown for predevelopment and development conditions, but should be within the range from 0.998 to 1.011 g/mL, which is the range of water densities from the two observation wells. After adjusting density for field temperature and pressure conditions, the mean specific weight of water ($\bar{\rho}g$) in the interval between 900 and 1,140 feet below sea level (Δz = 240 feet) should be within the range from 62.3 to 63.0 lb/ft^3.

Assuming that effective porosity is within the range from 10 to 30 percent, hydraulic conductivity is within the range from 0.01 to 0.1 ft/d, and using the site 6 estimates of ΔP, Δz, and $\bar{\rho}g$, the vertical component of velocity in the middle confining unit also can be calculated for predevelopment and development conditions at site 6 by using equation 1. For predevelopment conditions, the vertical component of ground-water velocity is calculated to be within the range from -0.001 to -0.03 ft/d. For development conditions, the vertical component of ground-water velocity is calculated to be within the range from -0.0003 to -0.003 ft/d. The negative sign of the predevelopment and development velocities indicates that flow was downward within the middle confining unit during both circumstances. The influence of ground-water development on the vertical component of velocity in the middle confining unit at site 6 is shown by the 3 to 10 times decrease in downward velocity as a result of development. By assuming zero vertical velocity, equation 1 indicates that a further decline in average water level of only about 2 feet in the Upper Floridan aquifer would cause vertical flow in the middle confining unit to reverse and be directed upward at the location of the two observation wells.

SUMMARY AND CONCLUSIONS

The middle confining unit of the Floridan aquifer system of Tertiary age underlies the freshwater-bearing Upper Floridan aquifer and consists of carbonate rocks that contain evaporite inclusions. Because evaporite inclusions reduce effective porosity, their presence implies that the middle confining unit is less porous and less permeable than the overlying carbonate rocks of the Upper Floridan aquifer. The middle confining unit is present in the subsurface throughout west-central Florida, but pinches out toward the east near the axis of peninsular Florida.

Hydraulic conductivity of the upper part of the middle confining unit may be within the range of 0.01 to 0.1 ft/d. This range of hydraulic conductivity suggests that the middle confining unit is maybe more hydrogeologically analogous to a very fine-grained sandstone bed rather than analogous to a compact clay bed, as has been implicitly assumed in past hydrogeologic literature dealing with west-central Florida. Consistent with the estimated range of hydraulic conductivity are water levels in wells tapping depths more than 240 feet below the top of the middle confining unit that show measureable variations in response to ground-water development in the Upper Floridan aquifer.

The middle confining unit contains moderately saline to briny ground water. Mixing of native brine with freshwater that has entered the unit is the probable cause of the variable-salinity ground water in the unit inland from the coast. An approximate linear temperature profile indicates that vertical components of flow in the unit are small. At two widely separated sites with available data, freshwater development in the Upper Floridan aquifer has altered the magnitude of the vertical component of ground-water velocity in the middle confining unit. Chemical characteristics of water from two well fields pumping ground water from the uppermost permeable zones of the Upper Floridan aquifer, however, have shown no trends after several years of operation.

The above summary of hydrogeologic characteristics and responses indicates that variable-salinity ground water in the middle confining unit could move slowly upward into the bottom of the overlying Upper Floridan aquifer as a result of freshwater development in west-central Florida. Because the vertical rate of saline-water movement and subsequent degradation of freshwater in the bottom of the Upper Floridan aquifer will be controlled by local hydrogeologic and pumping conditions, it cannot be precisely predicted. Based upon available data, however, it could take in excess of several years after beginning ground-water development of the

Upper Floridan aquifer before water-quality changes would begin to occur.

Agencies that develop and regulate the ground-water resource in west-central Florida could help safeguard the quality of fresh ground water in the Upper Floridan aquifer by minimizing and monitoring vertical movement of saline ground water from the middle confining unit. A method for minimizing upward movement of saline water would be to minimize drawdown at the top of the middle confining unit by pumping fresh ground water from only the uppermost permeable zones of the Upper Floridan aquifer. This is already a common practice and one that should be continued when new well fields are constructed in west-central Florida. A method for monitoring the vertical movement of saline water and any resulting chemical changes to water in the Upper Floridan aquifer at a site would be to measure pressure and water quality in a pair of observation wells with one well open to the middle confining unit and the other well open to the bottom of the Upper Floridan aquifer just above the top of the middle confining unit.

SELECTED REFERENCES

Applin, P.L., 1951, Preliminary report on buried pre-Mesozoic rocks in Florida and adjacent states: U.S. Geological Survey Circular 91, 28 p.

Bredehoeft, J.D., and Papadopulos, I.S., 1965, Rates of vertical ground-water movement estimated from the Earth's thermal profile: Water Resources Research, v. 1, no. 2, p. 325-328.

Hickey, J.J., 1979, Hydrogeologic data for the South Cross Bayou subsurface-injection test site, Pinellas County, Florida: U.S. Geological Survey Open File Report 78-575, 87 p.

——— 1981, Hydrogeology, estimated impact, and regional well monitoring of effects of subsurface wastewater injection, Tampa Bay area, Florida: U.S. Geological Survey Water-Resources Investigations 80-118, 40 p.

——— 1982, Hydrogeology and results of injection tests at waste-injection test sites in Pinellas County, Florida: U.S. Geological Survey Water-Supply Paper 2183, 42 p.

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

Hutchinson, C.B., Johnson, D.M., and Gerhart, J.M., 1981, Hydrology of well-field areas near Tampa, Florida, phase 1—development and documentation of a two-dimensional finite-difference model for simulation of steady-state ground-water flow: U.S. Geological Survey Open-File Report 81-630, 129 p.

Irwin, G.A., and Kirkland, R.T., 1980, Chemical and physical characteristics of precipitation at selected sites in Florida: U.S. Geological Survey Water-Resources Investigations 80-81, 70 p.

Johnston, R.H., Krause, R.E., Meyer, F.W., Ryder, P.D., Tibbals, C.H., and Hunn, J.D., 1980, Estimated potentiometric surface for the Tertiary limestone aquifer system, southeastern United States, prior to development: U.S. Geological Survey Open-File Report 80-406, 1 sheet.

King, W., and Simmons, G., 1972, Heat flow near Orlando, Florida, and Uvalde, Texas, determined from well cuttings: Geothermius, v. 1, p. 133-139.

Leggette, Brashears, and Graham, Inc., 1979, Construction and testing of the deep water-quality well B-1: Consultant's report prepared for and in the files of the West Coast Regional Water Supply Authority, Clearwater, Fla.

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

Navoy, A.S., 1986, Hydrogeologic data from a 2,000-foot deep core hole at Polk City, Green Swamp area, central Florida: U.S. Geological Survey Water-Resources Investigations Report 84-4257, 31 p.

Robinove, C.J., Langford, R.H., and Brookhart, J.W., 1958, Saline-water resources of North Dakota: U.S. Geological Survey Water-Supply Paper 1616, 132 p.

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

Southeastern Geological Society, 1986, Hydrogeological units of Florida: Florida Geological Survey Special Publication 28, 8 p.

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

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

William F. Guyton and Associates, 1976, Hydraulic and water quality: Consultant's report prepared for Swift Agricultural Chemical Corporation in files of the Southwest Florida Water Management District, Brooksville.

Wilson, W.E., 1982, Estimated effects of projected ground-water withdrawals on movement of the saltwater front in the Floridan aquifer, 1976-2000, west-central Florida: U.S. Geological Survey Water-Supply Paper 2189, 24 p.

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