Regional Evaluation of the Hydrogeologic Framework, Hydraulic Properties, and Chemical Characteristics of the Intermediate Aquifer System Underlying Southern West-Central Florida

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Prepared in cooperation with the
Southwest Florida Water Management District

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Conversion Factors and Datums

Multiply	By	To obtain
square mile (mi^2)	2.590	square kilometer
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
foot per day per foot [(ft/d)/ft]	1.00	meter per day per meter
inch per year per foot [(in/yr)/ft]	83.33	millimeter per year per meter

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

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms and Additional Abbreviations

FGS	Florida Geological Survey
IQR	interquartile range
>	greater than
≥	greater than or equal to
<	less than
LPZ	lower permeable zone
ROMP	Regional Observation and Monitoring-well Program
SWFWMD	Southwest Florida Water Management District
SWUCA	Southern Water Use Caution Area
TR	SWFWMD ROMP transect wells
UPZ	upper permeable zone
USGS	U.S. Geological Survey

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Abstract

Three major aquifer systems—the surficial aquifer system, the intermediate aquifer system, and the Floridan aquifer system—are recognized in the approximately 5,100-square-mile southern west-central Florida study area. The principal source of freshwater for all uses is ground water supplied from the three aquifer systems. Ground water from the intermediate aquifer system is considered only moderately abundant compared to the Upper Floridan aquifer, but it is an important source of water where the Upper Floridan aquifer contains water too mineralized for most uses. In the study area, the potential ground-water resources of the intermediate aquifer system were evaluated by regionally assessing the vertical and lateral distribution of hydrogeologic, hydraulic, and chemical characteristics.

Although the intermediate aquifer system is considered a single entity, it is composed of multiple water-bearing zones separated by confining units. Deposition of a complex assemblage of carbonate and siliciclastic sediments during the late Oligocene to early Pliocene time resulted in discontinuities that are reflected in transitional and abrupt contacts between facies. Discontinuous facies produce water-bearing zones that may be locally well-connected or culminate abruptly. Changes in the depositional environment created the multilayered intermediate aquifer system that contains as many as three zones of enhanced water-bearing capacity. The water-bearing zones consist of indurated limestone and dolostone and in some places unindurated sand, gravel, and shell beds, and these zones are designated, in descending order, as Zone 1, Zone 2, and Zone 3. Zone 1 is thinnest (<80 feet thick) and is limited to <20 percent (southern part) of the study area. Zone 2, the only regionally extensive zone, is characterized by moderately low permeability. Zone 3 is found in about 50 percent of the study area, has the highest transmissivities, and generally is in good hydraulic connection with the underlying Upper Floridan aquifer. In parts of the study area, particularly in southwestern Hillsborough County and southeastern De Soto and Charlotte Counties, Zone 3 likely is contiguous with and part of the Upper Floridan aquifer.

Transmissivity of the intermediate aquifer system ranges over five orders of magnitude from about 1 to more than 40,000 feet squared per day (ft^2/d), but rarely exceeds 10,000 ft^2/d. The overall transmissivity of the intermediate aquifer system is substantially lower (2 to 3 orders of magnitude) than the underlying Upper Floridan aquifer. Transmissivity varies vertically among the zones within the intermediate aquifer system; Zone 2 has the lowest median transmissivity (700 ft^2/d), Zone 1 has a moderate median transmissivity (2,250 ft^2/d), and Zone 3 has the highest median transmissivity (3,400 ft^2/d). Additionally, the transmissivity varies geographically (from site to site) within a zone. Specifically, a region of relatively low transmissivity (<100 ft^2/d) throughout the vertical extent of the intermediate aquifer system is present in the central part of the study area. This low transmissivity region is encompassed by a larger region of moderately low transmissivity (<1,000 ft^2/d) that covers a large part of the study area.

Clay beds and fine-grained carbonates form the confining units between the water-bearing zones and are characterized by low leakance. Leakance through the intermediate aquifer system confining units ranges over 4 orders of magnitude from 4.2×10^{-7} to 6.0×10^{-3} foot per day per foot [(ft/d)/ft]. Despite

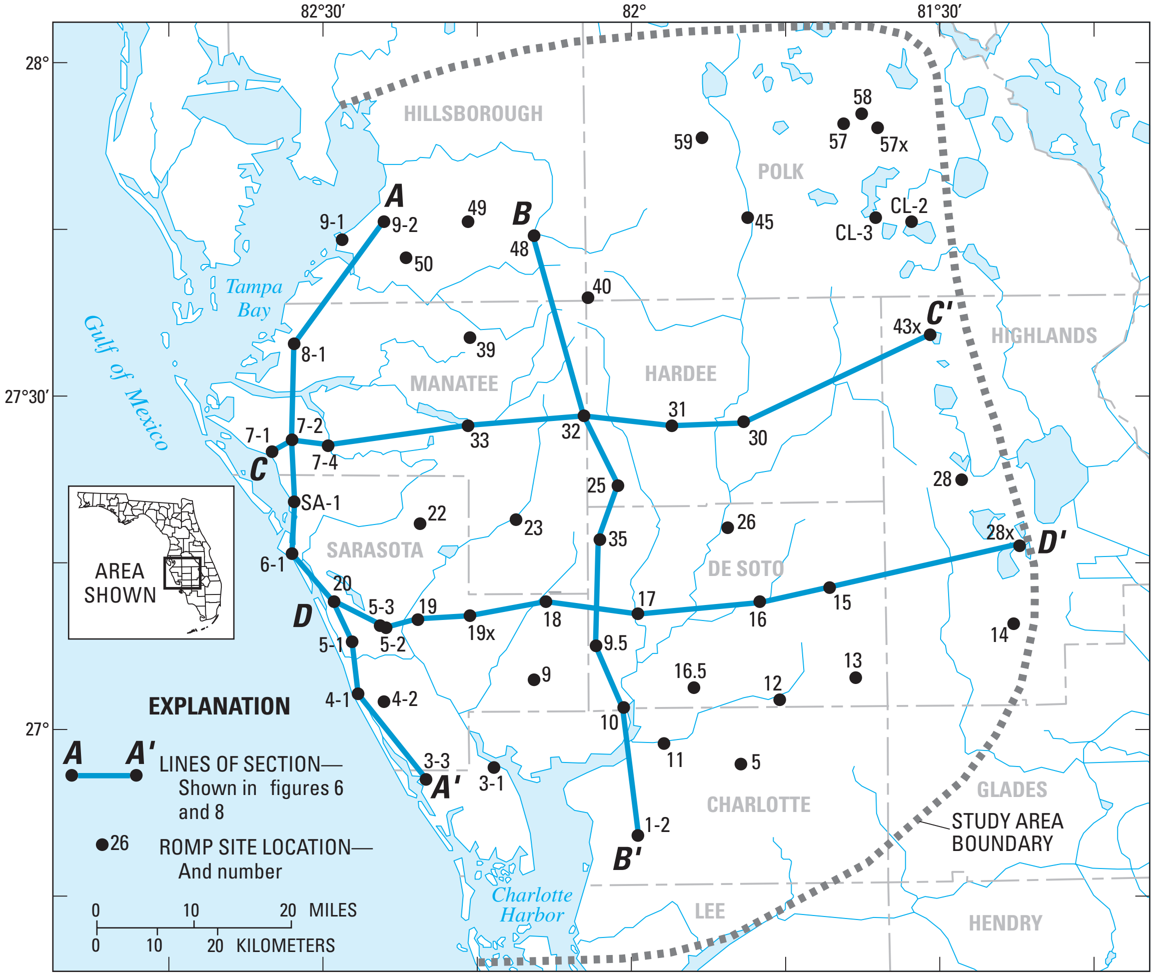
the large range, the geometric mean and median leakances of individual confining units are within the same order of magnitude, 10^{-5} (ft/d)/ft, which is 2 orders of magnitude less than the median leakance of the semiconfining unit within the Upper Floridan aquifer.

Major ion concentrations in water from the intermediate aquifer system, and throughout the ground-water flow system, generally increase with depth. The chemical composition of water in the intermediate aquifer system is more varied than the adjacent aquifers. This variation is related to the different types of minerals forming the aquifer matrix, and complex mixing with waters from adjacent aquifers. The dominant water type throughout the intermediate aquifer system is mixed-cation bicarbonate, typically with nearly equal concentrations of calcium and magnesium ions. At the southern extent of the study area, sodium-chloride type water is present throughout the intermediate aquifer system. Calcium-magnesium sulfate type water is present along the coastal margin from Tampa Bay to southern Sarasota County in Zone 3 and in two Zone 2 wells in west-central Sarasota County.

Differences in hydraulic head generally are greater between adjacent zones within the intermediate aquifer system than between the intermediate aquifer system and adjacent aquifers. Heads differences between Zone 1 and the surficial aquifer system range from -1 (downward) to 3 (upward) feet, and heads are nearly the same (<1 foot) between Zone 3 and the Upper Floridan aquifer in much of the study area. In contrast, head differences across the upper and lower groups of confining units of the intermediate aquifer system range from -48 to 14 feet and from -119 to 24 feet, respectively. These head differences among the zones indicate some degree of hydraulic separation between zones within the intermediate aquifer system.

Introduction

The southern half of the Southwest Florida Water Management District, encompassing a 5,100-square-mile area, includes all or parts of Hillsborough, Polk, Manatee, Hardee, Highlands, Sarasota, De Soto, and Charlotte Counties and is designated the Southern Water Use Caution Area (SWUCA; Southwest Florida Water Management District, 2004) (fig. 1). This area was designated a water-use caution area in 1992 when it was recognized that steadily increasing



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 1. Location of the study area, selected Regional Observation and Monitor-well Program (ROMP) sites, and lines of sections in southern west-central Florida.

ground-water withdrawals in response to growing demands from public supply, agriculture, mining, power generation, and recreational uses resulted in declines in aquifer heads causing saltwater intrusion in coastal areas, lowered lake levels in the upland areas, and reduced base flow in selected river reaches (Southwest Florida Water Management District, 2004; Beach and Chan, 2003). The principal source of freshwater for all uses is ground water supplied from three aquifers; the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer. In general, ground-water availability is low to moderate, moderate, and abundant from these three aquifers, respectively (Torres and others, 2001). Ground-water availability is geographically limited by the quantity or quality of water in each aquifer. In the coastal and southern parts of the SWUCA, the Upper Floridan aquifer contains water too mineralized for most uses so ground water from the surficial aquifer system and intermediate aquifer system is in greater demand (Knochenmus and Bowman, 1998; Torres and others, 2001).

The intermediate aquifer system is an important source of water in Sarasota and Charlotte Counties, and a potential but limited source of water in most of the SWUCA. Well yields are generally much less in the intermediate aquifer system than from the Upper Floridan aquifer (Duerr and others, 1988). To successfully and efficiently manage the ground-water resources of the intermediate aquifer system throughout the SWUCA, an investigation was initiated in 1999 by the U.S. Geological Survey (USGS) in cooperation with the Southwest Florida Water Management District (SWFWMD) to evaluate the available hydrologic data and assess the extent and interconnectedness of the intermediate aquifer system regionally. The study area excludes the northernmost extent of the SWUCA, where the intermediate aquifer is absent.

Purpose and Scope

This report provides an evaluation of the relation between the geologic and hydrogeologic framework, the occurrence of permeable and confining units, the vertical and lateral hydraulic properties, chemical characteristics, and the variations in the potential vertical flow direction and water-level changes among units within the intermediate aquifer system. Although the report focuses on the characteristics of the intermediate aquifer system, hydrologic data were evaluated from the overlying surficial aquifer system and underlying Upper Floridan aquifer to assess the interactions between the intermediate aquifer system and adjacent aquifers. A brief discussion of the adjacent aquifers is included in this report. Specifically, this report presents: (1) stratigraphic cross sections emphasizing the locations of clay beds and showing the lateral continuity of geologic and hydrogeologic units; (2) the spatial distribution of the hydraulic properties within the permeable and confining units in the intermediate aquifer system; (3) the spatial distribution of water-quality types; and (4) water-level differences that define the recharge and discharge areas of the aquifer system and degree of hydraulic connection. The primary source of data analyzed and presented in this report is from the SWFWMD Regional Observation and Monitor-well Program (ROMP). Additional data were compiled from USGS, SWFWMD, Florida Geological Survey (FGS), and consulting reports.

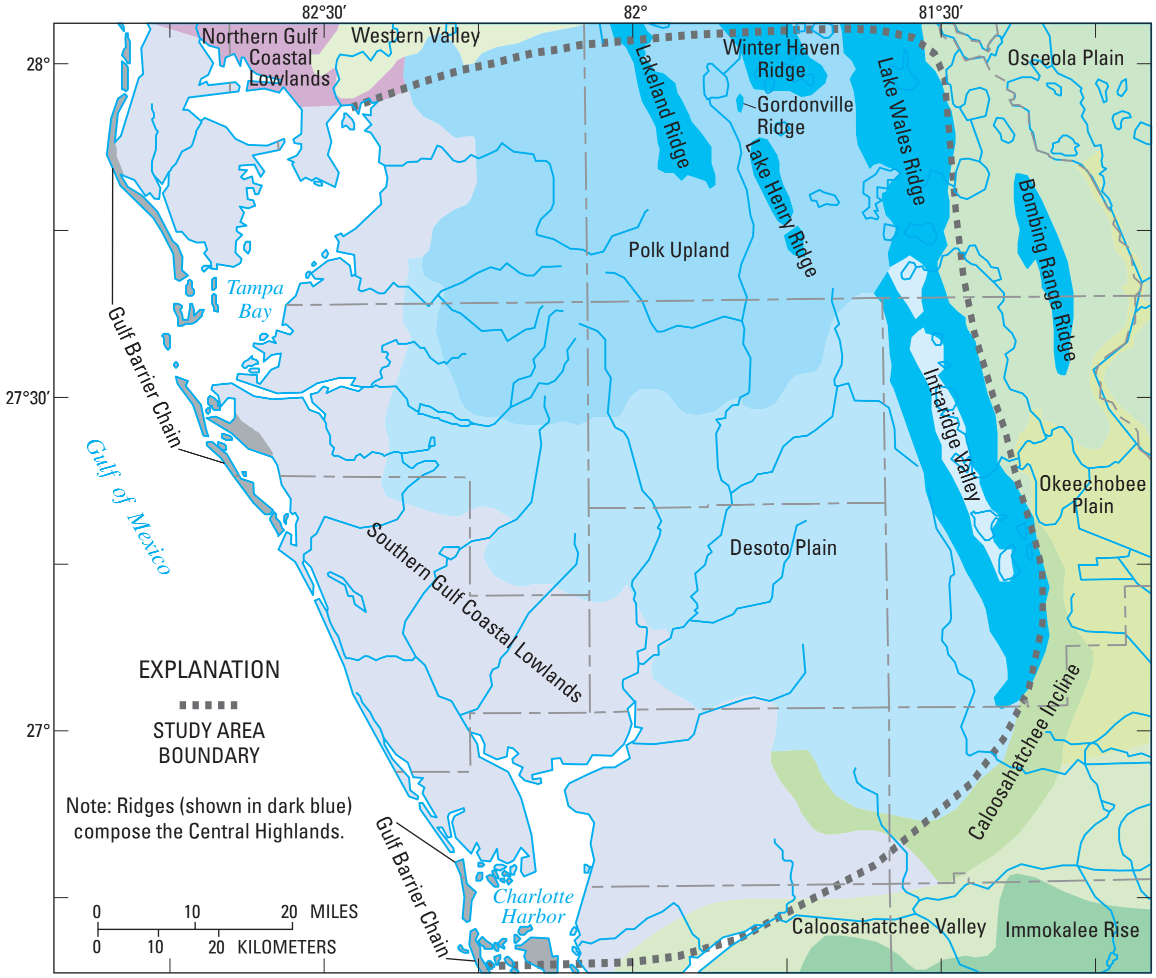
Description of the Study Area

The regional topography alternates between well-drained ridges and poorly drained lowlands. Ridges, the dominant landform, are remnant shoreline features (marine scarps) found throughout the State (Schmidt, 1997). The landforms result from depositional and erosional processes (Scott, 1992): altitudes range from about 0 to 250 feet (ft) above the National Geodetic Vertical Datum of 1929 (NGVD 1929), and most of the study area is a relatively flat plain (Carr and Alverson, 1959).

The physiographic features in the study area include the Central Highlands, Polk Upland, De Soto Plain, Southern Gulf Coastal Lowlands, and Gulf Barrier Chain (fig. 2; White, 1970). These features result from the reworking of geologic units by wind, ground water, and surface water over geologic time (Parker and others, 1955; Scott, 1992). The Central Highlands physiographic region includes the Winter Haven, Gordonville, Lakeland, Lake Henry, and Lake Wales Ridges (shaded dark blue in fig. 2). The Central Highlands region is an internally drained area of rapid recharge, and is prone to cover-collapse sinkhole development (Brooks, 1981). Land-surface altitudes range between 100 and 130 ft in the Polk Upland, which is a poorly drained plateau containing flatwoods, wetlands, and lakes (White, 1970; Brooks, 1981). Land-surface altitudes range from 30 to 100 ft in the De Soto Plain, which is a broad, gently sloping plain containing wet prairie, cypress swamps, and flatwoods drained by streams and sloughs (Brooks, 1981). Land-surface altitudes are <20 ft in the Southern Gulf Coastal Lowlands, which is bounded on the west by the Gulf of Mexico. The Southern Gulf Coastal Lowlands is a ground-water discharge area that is dominated by wet prairie and flatwoods vegetation, and includes the barrier beaches, barrier islands, spits, and overwash fans of recent origin (Brooks, 1981; Schmidt, 1997).

Hydrologic Data Sources

The primary sources of geologic, hydrologic, and chemical data were observation wells at ROMP sites; complimentary data were compiled from USGS and SWFWMD databases and reports. SWFWMD and FGS delineated the geologic framework, including lithologic descriptions and stratigraphic boundaries, using wire-line cores and cuttings retrieved during test-well drilling. SWFWMD personnel identified permeable zones and confining units based on changes



EXPLANATION

▪▪▪▪▪ STUDY AREA BOUNDARY

Note: Ridges (shown in dark blue) compose the Central Highlands.

Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 2. Physiography of the study area in southern west-central Florida (modified from White, 1970).

in the visual porosity, specific capacity, ground-water level, and water-quality characteristics observed during test-well drilling. Subsequent to test-well drilling, multiple observation wells were constructed, each of which was open to the most permeable strata within the surficial aquifer system, intermediate aquifer system, and Upper Floridan aquifer.

SWFWMD, USGS, and private consulting companies have conducted numerous aquifer tests at the ROMP sites. In 2000, SWFWMD recompiled and published the aquifer-test results. Most of the published transmissivity values were estimated using analytical techniques. In a concurrent USGS study, the hydraulic characteristics, including transmissivity and leakance, at selected ROMP sites were re-analyzed using numerical techniques (Yobbi and Halford, 2006).

Continuous water-level data from observation wells at ROMP sites were compiled from USGS and SWFWMD databases during 2000-2002. Water-level hydrographs were compared to determine the range in annual fluctuation, seasonal variation, and response to hydrologic stress. USGS personnel collected periodic water-level data to verify the accuracy of the continuous water-level data.

The water-quality characteristics of the aquifers were evaluated using major-ion data provided by SWFWMD. Data were collected in 2001 from selected observation wells at ROMP sites, and were used to characterize water types and to illustrate the spatial distribution of ionic species.

Acknowledgments

The author recognizes and is extremely grateful for the invaluable support of the cooperating agency, the Southwest Florida Water Management District. The author thanks the Resource Data Section of SWFWMD who provided the detailed hydrogeologic and water-quality data interpreted in this report. The hydrogeologic data are contained in ROMP reports listed separately in the selected references section of this report. Dave DeWitt graciously provided water-quality data. The continuous water-level data collected by SWFWMD were provided by the Hydrologic Data Section. The author also thanks Ron Basso and Mike Beach of the Hydrologic Evaluation Section of SWFWMD for their insightful and challenging debate as to the nature and extent of the intermediate aquifer system in west-central Florida.

Definitions and Terms

The clay beds shown on cross sections and the clay percentages shown on maps are distinct units that were noted as *clay* on lithologic logs. Clay percentages represent the ratio of the clay thickness to the total thickness of the Hawthorn Group. Entries on lithologic logs that included a clay component, but did not list clay as the primary component, were not used to calculate the thicknesses. An example of a lithologic unit excluded from the thickness calculation is a unit described as clayey sand.

An *aquifer* is a formation, group of formations, or part of a formation in the zone of saturation that is permeable enough to transmit usable quantities of water (Peek, 1958).

A *permeable unit* is an identifiable horizon of enhanced water-bearing capacity (Basso, 2002). Permeability is highly variable, thus, ranges of transmissivity, in feet squared per day (ft^2/d) are used to qualitatively define the relative permeability within the intermediate aquifer system:

- semiconfining unit: <0.1 ft^2/d.
- low permeability unit: ≥ 1 and <100 ft^2/d
- moderately low permeability unit: ≥ 100 and $<1,000$ ft^2/d
- moderate permeability unit: $\geq 1,000$ and $<10,000$ ft^2/d
- moderately high permeability unit: $\geq 10,000$ and $<100,000$ ft^2/d

Zone numbers used in this report are equivalent to PZ numbers used in reports by SWFWMD. *Zone 1* is equivalent to PZ1, *Zone 2* is equivalent to PZ2, and *Zone 3* is equivalent to PZ3.

Boxplots, a graphical display for summarizing data, illustrate the symmetry of a data set and provide a visual summary of the median, spread (interquartile range or box size), skewness (relative size of box halves), and presence of extreme values (outside and far-out values). The distance (or length of the line) to the last observation (largest and smallest) that is within 1.5 times the interquartile range is defined as the whisker length (Helsel and Hirsch, 1992).

The statistical terms used to summarize the hydraulic data include the mean, geometric mean, median, and interquartile range. The definitions of the statistical terms are from Helsel and Hirsch (1992).

- *Mean* is the average value within the sampled data set and is computed as the sum of the samples (observations) divided by the sample size.
- *Geometric mean* is the mean of the logarithms, transformed back to their original units. It is commonly reported for positively skewed data sets. For positively skewed data sets, the geometric mean is usually quite close to the median.
- *Median*, or 50th percentile, is the central value of the distribution when the data are ranked in order of magnitude, and is computed by first ranking the observations from smallest to largest and then selecting the data point that has an equal number of observations both above and below it.
- *Interquartile range* (IQR) measures the range of the central 50 percent of the data. The IQR is defined as the 75th (upper quartile) percentile minus the 25th (lower quartile) percentile, and is not influenced at all by the 25 percent of the data on either end of the range.

Water types are defined by their predominant cation and anion concentrations, expressed in milliequivalents per liter. For water to have a single cation/anion pair type, the cation and anion concentrations must exceed 50 percent of the total cation/anion concentration. Water samples containing cation and anion concentrations not exceeding 50 percent are defined as mixed-ion type waters (Hem, 1985). The water types used in this report are:

- Mixed-cation bicarbonate: no dominant cation species, commonly containing equal concentrations of calcium and magnesium with bicarbonate as the dominant anion
- Calcium-magnesium sulfate: typically containing about equal concentrations of calcium and magnesium with sulfate as the dominant anion
- Sodium chloride: both a single cation and anion species are dominant
- Mixed-ion: neither a dominant cation nor anion species, and ion combinations are highly variable

Major ion data, in milliequivalents per liter, were analyzed using a graphical method originated by Stiff (1951). *Stiff diagrams* have three parallel horizontal axes, bisected by a "zero" vertical axis. The cation (sodium, calcium, and magnesium) and anion (chloride, bicarbonate, and sulfate) data are plotted to the left and right of the vertical axis, respectively. Plotting of the data results in a six-sided polygon; the size and shape indicate the relative concentration and composition of the water sample (fig. 3).

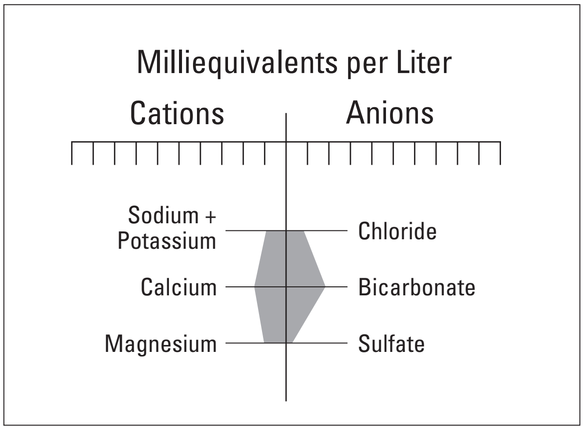


Figure 3. Representative Stiff diagram.

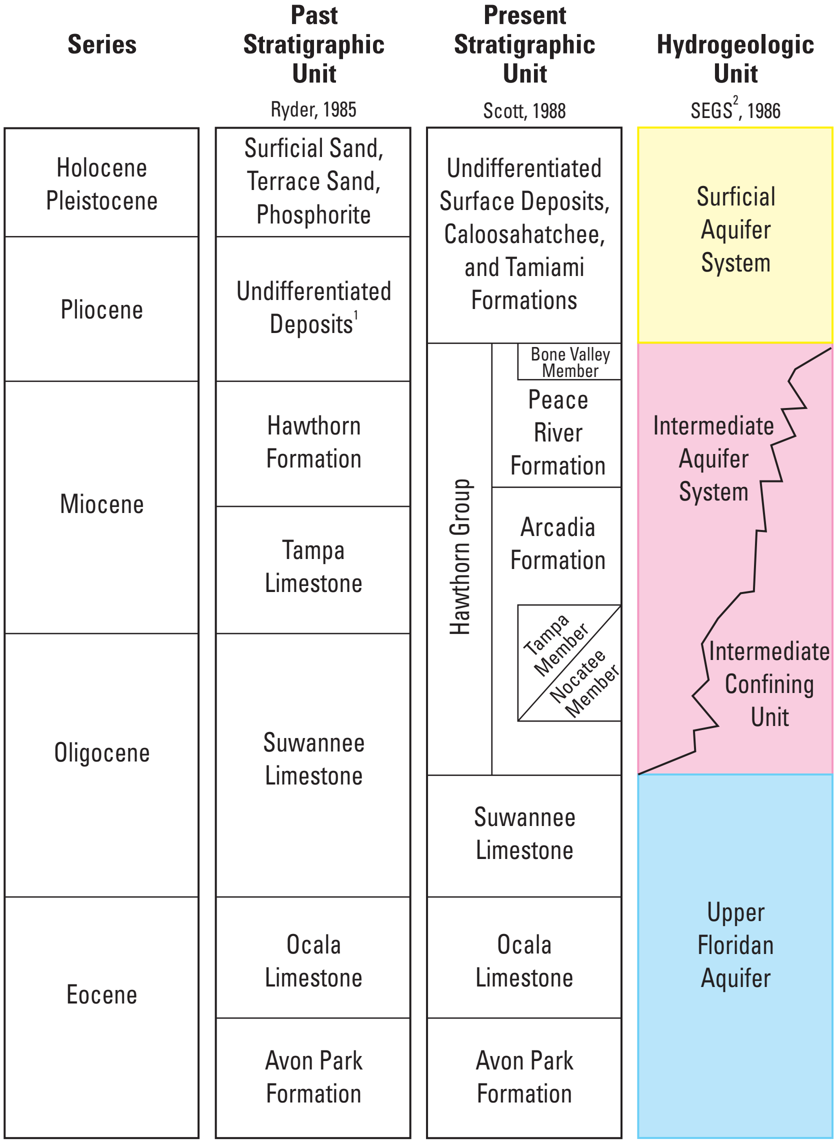
Geologic Framework

The geologic framework presented in this report is a departure from the framework presented in reports published before 1988. The stratigraphic names used in this report are based upon the geologic definitions of Scott (1988) that are used by the FGS. Changes in nomenclature resulted from the re-interpretation and refinement of the ages, names, and hierarchy of the stratigraphic units in Florida. Figure 4 shows the correlation between past and present stratigraphic nomenclature used in the study area. The chart illustrates the revisions in the ages, names, and hierarchy of units described in published reports up to Ryder (1985), and after the redefinition of the Hawthorn Group by Scott (1988). Earlier reports had the Tampa Limestone and Hawthorn Formation of equal stratigraphic status and had the Bone Valley Formation as part of the undifferentiated deposits. The current definition places all three of these units in the Hawthorn Group.

Depositional History

During the late Oliocene to early Pliocene, when the Hawthorn Group was deposited, frequent sea-level fluctuations spread a complex lithologic assemblage across the Florida Platform. In the study area, carbonates and siliciclastic sediments were deposited concurrently, with the sediment type varying geographically in the study area in relation to variations in the altitude of the sea-level stand (Randazzo, 1997). Geographically, more carbonate sediments were deposited in the southern and southwestern parts of the study area whereas siliciclastic sediments were deposited in the northern and eastern parts. In general, enhanced zones of permeability are found in the carbonate units within the Hawthorn Group. Carbonates also are more susceptible to post-depositional alteration such as dissolution and fracturing than siliciclastics, which can further increase permeability. Siliciclastic sediments such as well-sorted or coarse-grained sands may also produce water. Confining units are dominantly fine-grained siliciclastics like clays, and clay-size carbonates (mudstones) that hydraulically separate water-bearing zones within the intermediate aquifer system.

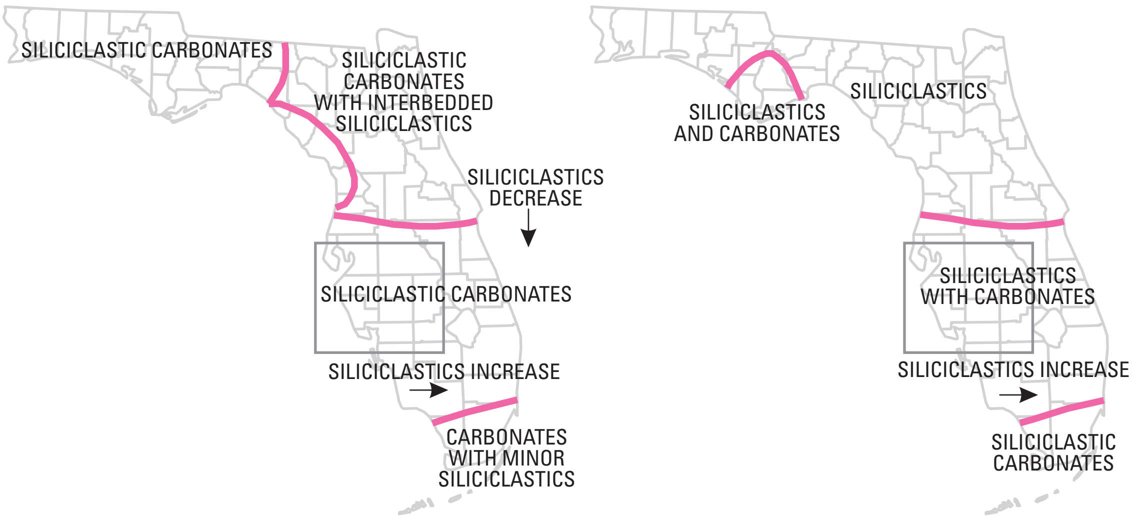
In the study area, the synchronous deposition of carbonate and siliciclastic sediments produced the highly heterogeneous Hawthorn Group, with both gradational (transitional) and abrupt contacts between facies (Missimer, 2002). Siliciclastic carbonate sediments were deposited during early Miocene time, with the siliciclastic content increasing eastward in the study area (fig. 5a). Siliciclastic sediments containing interbedded carbonate units were deposited during middle Miocene time (fig. 5b). Phosphate deposits were reworked and siliciclastic sedimentation was dominant in the study area during late Miocene time (fig. 5c). During Pliocene time, carbonate sedimentation resumed along the Gulf Coast margin south of Charlotte Harbor; contemporaneously, siliciclastic sedimentation dominated the area between Tampa Bay and Charlotte Harbor. In the western half of the peninsula north of Tampa Bay, a hiatus in deposition occurred (fig. 5d).



[1] Includes Caloosahatchee Marl, Bone Valley Formation, and Tamiami Formation

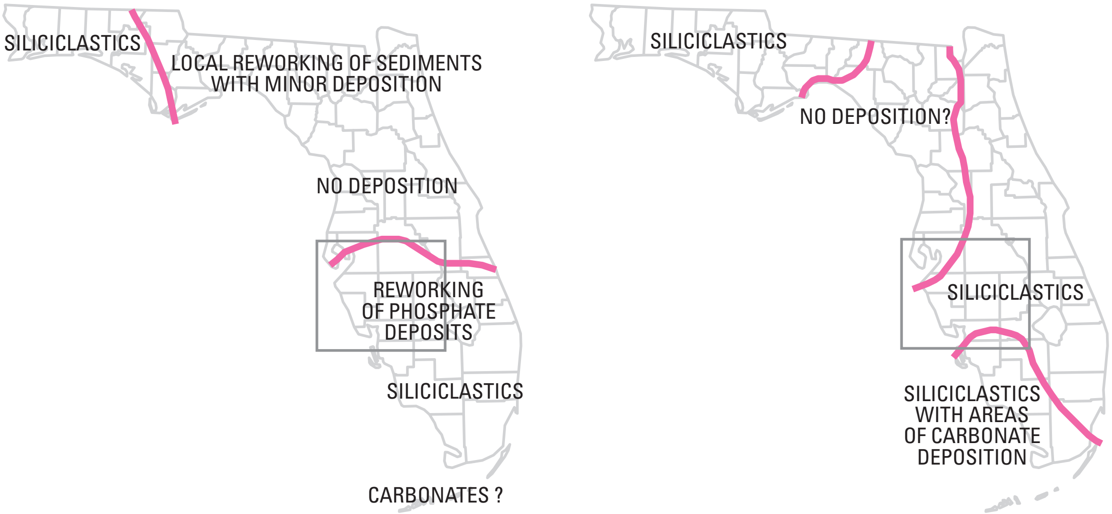
[2] SEGS, Southeastern Geological Society

Figure 4. Chart showing series, past and present stratigraphic unit nomenclature, and hydrogeologic units.



(A) Early Miocene Sediment Pattern

(B) Middle Miocene Sediment Pattern



(C) Late Miocene Sediment Pattern

(D) Pliocene Sediment Pattern

EXPLANATION

☐ MAP EXTENT—Shown in figure 1.

Figure 5. Early Miocene to Pliocene sediment patterns in Florida (modified from Scott, 1997).

Stratigraphy

To illustrate the occurrence and distribution of stratigraphic units in the study area, a series of stratigraphic sections were prepared. The thickness and depth of the stratigraphic units of interest vary in the study area (fig. 6; lines of section shown in fig. 1). General trends include (1) the stratigraphic units dip to the south, (2) the Suwannee Limestone and Hawthorn Group thin and are absent, in places, at the eastern extent of the study area, and (3) the undifferentiated surface deposits thicken substantially at the eastern extent of the study area. The stratigraphic units of interest are briefly described below and summarize geologic descriptions presented by Scott (1988, 1997) and Randazzo (1997).

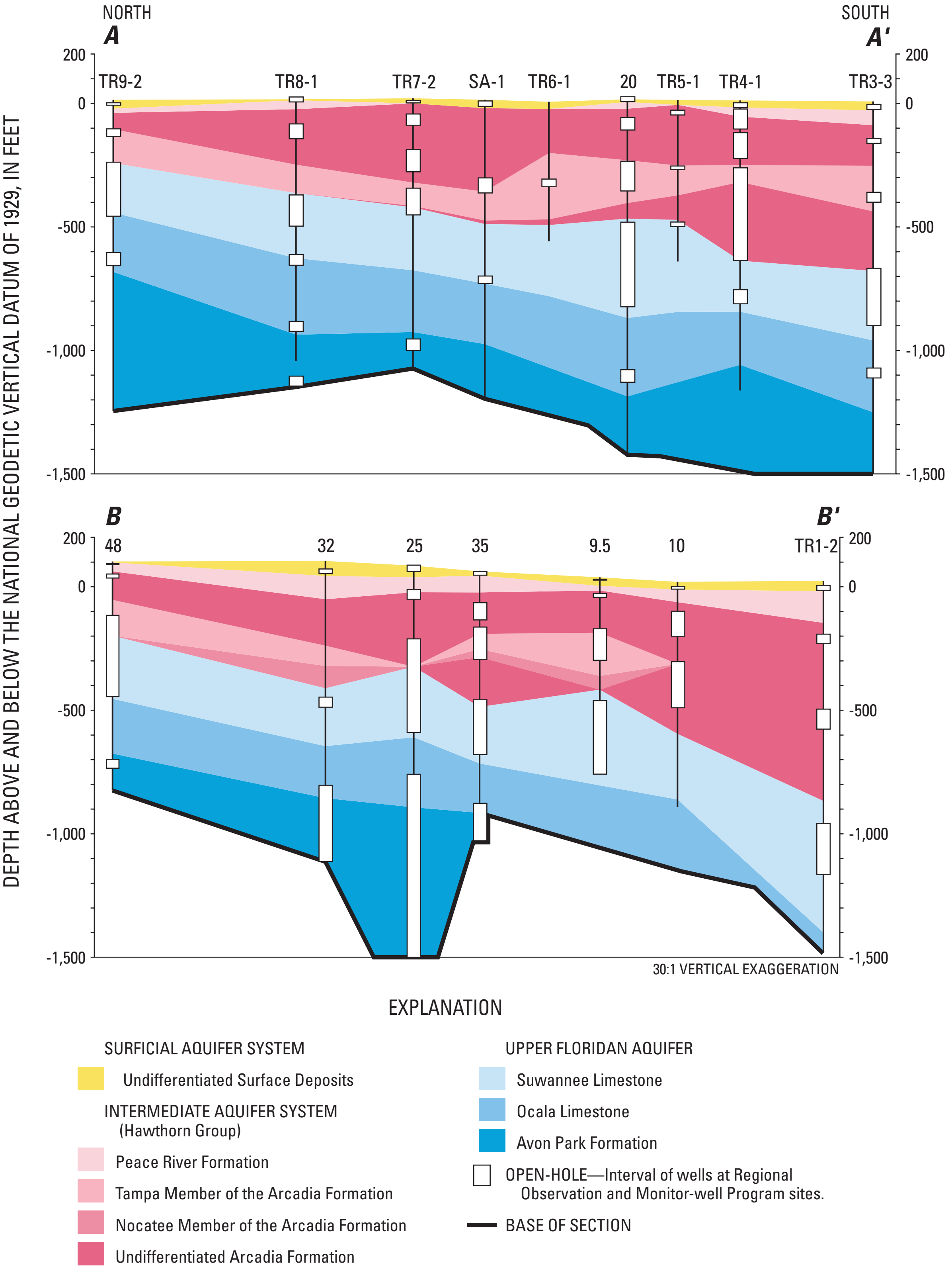


Figure 6. Stratigraphy, aquifer, and open-hole intervals of wells at selected Regional Observation and Monitor-well Program (ROMP) sites. The lines of section are shown in figure 1.

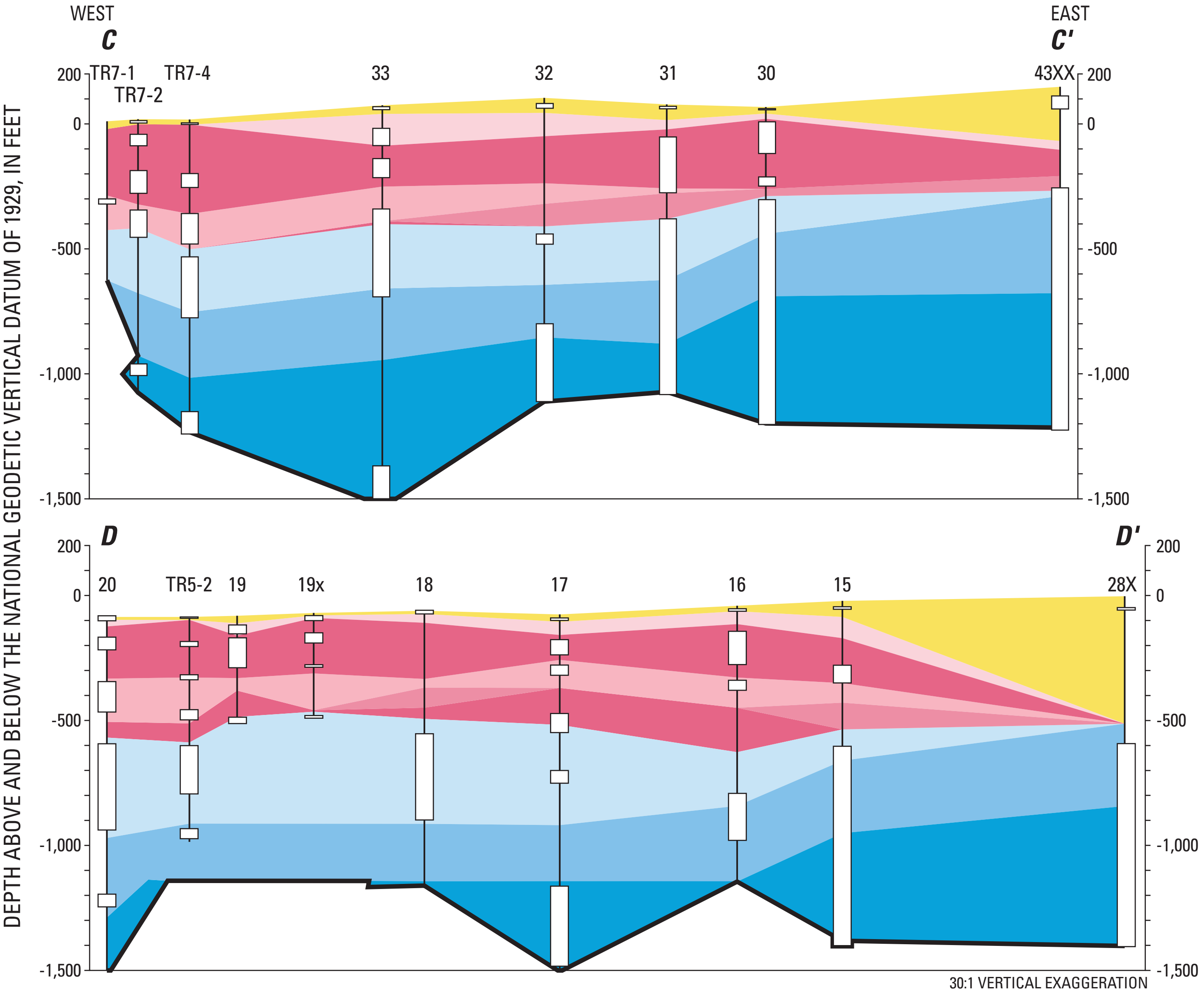


Figure 6. (Continued) Stratigraphy, aquifer, and open-hole intervals of wells at selected Regional Observation and Monitor-well Program (ROMP) sites. The lines of section are shown in figure 1.

The Avon Park Formation, Ocala Limestone, and Suwannee Limestone were deposited in open-marine or restricted marine environments during middle Eocene through late Oligocene time (Randazzo, 1997). The Avon Park Formation is primarily composed of poorly to well-indurated fossiliferous limestone that has been pervasively dolomitized in places. The Avon Park Formation generally is thicker than either the Suwannee or Ocala Limestones. The depositional texture ranges from wackestones to mudstones, and fossil diversity is low.

The Ocala Limestone contains two distinct lithologic units; the lower unit is composed of partially dolomitized limestone and interbedded sucrosic dolostone, and the upper unit is composed of soft, poorly indurated, porous limestone. The Ocala Limestone ranges in thickness from 75 to 300 ft, the texture ranges from packstones to mudstones, and the fossil diversity is high.

The Suwannee Limestone is similar in composition and texture to the Ocala Limestone, particularly in the southwestern part of the study area, obscuring the boundary between the units. The Suwannee Limestone is composed of interbedded, sand-size limestone grains and calcareous mud. Near the base of the unit, the limestone may be dolomitized; near the top of the unit, quartz sand beds are present in parts of the study area. The Suwannee Limestone ranges in thickness from 0 to 500 ft; the limestone texture ranges from packstone to mudstone and is distinguishable from the Hawthorn Group by the lack of phosphate.

The Hawthorn Group was deposited during late Oligocene through early Pliocene time, which was characterized by a gradual shift from carbonate to siliciclastic deposition (Scott, 1997). Complicating the general lithologic shift were recurring cyclic episodes of transgressive/regressive sedimentation resulting in a heterogeneous mixture of shell, clay, silt, sand, and carbonate facies. Additionally, the Hawthorn Group contains phosphorite (phosphate mineral), palygorskite and sepiolite clays (magnesium-rich clays), and dolomitized limestone (magnesium-rich carbonates). Phosphate concentrations range from trace amounts to about 50 percent. The thickness of the Hawthorn Group ranges from 50 to 850 ft; the texture ranges from grainstones to mudstones.

The Hawthorn Group includes two formations—the basal Arcadia Formation contains predominantly carbonate sediments, and the overlying Peace River Formation contains a greater abundance of siliciclastic sediments. Generally, in the study area, the Arcadia Formation is substantially thicker than the Peace River Formation (fig. 6).

The Arcadia Formation, as described by Scott (1988), is more than 300 ft thick south of Hillsborough and Polk Counties and west of Highlands County. The unit thickens to more than 700 ft in Charlotte County (southern extent of study area) and thins to <50 ft at the northern and eastern extent of the study area. The Arcadia Formation contains two named members—the Tampa and the Nocatee Members. Where the Tampa and Nocatee Members cannot be identified, the Arcadia Formation is designated as the undifferentiated Arcadia Formation. The dominant lithology of the Arcadia Formation is dolomitic limestone containing varying amounts of quartz sand, clay, and phosphate grains. Beds of quartz sand, silt, and clay recur throughout the section. The phosphate content ranges from trace amounts to 25 percent, and averages 10 percent. The texture ranges from mudstone to wackestone.

The Nocatee Member of the Arcadia Formation is a predominantly siliciclastic unit, containing an interbedded sequence of quartz sand, clay, and carbonate facies. Clay beds are common. The limestone texture is wackestone. The unit ranges in thickness from 0 to 200 ft, is absent west of the Myakka River in central Sarasota County, and is thickest in southeastern De Soto County.

The Tampa Member of the Arcadia Formation is composed primarily of limestone with minor amounts of dolostone, sand, and clay (Scott, 1988). The Tampa Member is thickest (as much as 300 ft) along the coastal margin of the Gulf of Mexico and is absent east of the Peace River in Polk and Hardee Counties. Sand and clay beds are present sporadically within the section and are more common in the updip areas. Phosphate content is lower (<3 percent) than in other stratigraphic units in the Hawthorn Group and is the distinguishing characteristic identifying the Tampa Member. The texture ranges from mudstone to packstone, but the most common texture is wackestone.

The Peace River Formation overlies the Arcadia Formation. The stratigraphic boundary between the Arcadia and Peace River Formations is disconformable—in some areas, a chert and phosphate rubble zone delineates the formation boundary (Scott, 1988). The Peace River Formation is composed of >66 percent siliciclastics with minor carbonate sedimentation—the carbonate content increases with depth. Phosphate minerals and magnesium-rich clay beds are common. The Peace River Formation generally is thin (<50 ft thick) except in central Charlotte County where the unit is more than 250 ft thick. The Peace River Formation is absent in parts of Hillsborough, Pinellas, Manatee, De Soto, and Sarasota Counties. The Peace River Formation has one named member—the Bone Valley Member. The Bone Valley Member was not identified on lithologic logs from ROMP sites in the study area and consequently is not delineated on stratigraphic sections.

The stratigraphic units deposited during the Pliocene to Holocene are designated the “undifferentiated surface deposits” in the study area. The undifferentiated surface deposits generally are <50 ft thick, except at the eastern extent of the study area where the deposits are thicker than 200 ft. The undifferentiated surface deposits locally contain the Tamiami Formation and as many as three distinct lithologic units: (1) the Plio-Pleistocene shell beds, shelly, sandy, or silty marl, marl, and sandy limestone; (2) the Pleistocene yellow to orange quartz sand with interbedded clay and shell; and (3) the Holocene fine-grained quartz sand (Torres and others, 2001). In the study area, the Tamiami Formation is absent or thin (Jon Arthur, Florida Geological Survey, oral commun., 2000), and consists predominately of siliciclastic sediments (Missimer, 2002).

Hydrogeologic Framework

The stratigraphic units of varying permeability described above form three major hydrogeologic units—the surficial aquifer system, the intermediate aquifer system, and the Floridan aquifer system (figs. 4 and 6). The Floridan aquifer system consists of the Upper and Lower Floridan aquifers separated by the middle confining unit. The Lower Floridan aquifer contains highly mineralized water in west-central Florida. Only the Upper Floridan aquifer is described herein. In general, the aquifer systems are delineated along stratigraphic boundaries; however, near the northwestern and southern geographical extent of the study area, hydrogeologic units cross the stratigraphic boundaries. In general (1) the surficial aquifer system is equivalent to the undifferentiated surface deposits; (2) the intermediate aquifer system is equivalent to the Hawthorn Group; and (3) the Upper Floridan aquifer is equivalent to the carbonate sediments that form the Avon Park Formation, Ocala Limestone, and Suwannee Limestone. The top of the Upper Floridan aquifer generally corresponds to the upper surface of the Suwannee Limestone where it is present. Where carbonate units within the lower Hawthorn Group are contiguous with the Suwannee Limestone, the top of the aquifer is above the Suwannee Limestone. Where the Suwannee is absent (as in parts of Highlands County), the top of the aquifer coincides with the Ocala Limestone.

Evolution of Hydrogeologic Unit Nomenclature

Multiple permeable units within the aquifers have long been recognized and documented in published reports (Bishop, 1956; Peek, 1958; Menke and others, 1961; Stewart, 1966; Sproul and others, 1972; Sutcliffe, 1975; Joyner and Sutcliffe, 1976; Wilson, 1977; Brown, 1983). These early reports emphasized the hydrology of the Upper Floridan aquifer, and while permeable units above the top of the Upper Floridan aquifer were identified, neither a regional delineation nor hydrologic evaluation of these zones was the principal subject of these reports (Wolansky, 1983). Beginning in the mid-1980s, the permeable units within the strata that lie between the overlying surficial aquifer system and underlying Upper Floridan aquifer were collectively included in the intermediate aquifer system (Wolansky, 1983; Duerr and Wolansky, 1986; Duerr and others, 1988). The intermediate aquifer system was defined as an upper confining unit, a group of as many as three permeable units, and a lower confining unit (Duerr and others, 1988). The hydrogeologic unit nomenclature used in published reports included stratigraphic names, lithologic names, numbers, and general hierarchy such as "upper" or "lower." Recent reports use zone numbers (PZ1, PZ2, and PZ3) to designate the permeable units identified in the intermediate aquifer system (Barr, 1996; Torres and others, 2001; Basso, 2002; Beach and Chan, 2003). Figure 7 shows the published hydrogeologic unit designation, geographical extent of the investigation, and equivalent zone number used herein.

In this report, hydrogeologic unit *Zone 1* is equivalent to the "sandstone aquifer" (Sproul and others, 1972; Reese, 2000), "artesian zone 1" (Sutcliffe, 1975; Joyner and Sutcliffe, 1976), and is included in the "Tamiami-upper Hawthorn aquifer" (Wolansky, 1983; Duerr and Wolansky, 1986). Hydrogeologic unit Z*one 2* is equivalent to the "upper Hawthorn aquifer" (Sproul and others, 1972), "Tamiami-upper Hawthorn aquifer" (Brown, 1983; Wolansky, 1983; Duerr and Wolansky, 1986), "artesian zone 2" (Sutcliffe, 1975; Joyner and Sutcliffe, 1976), "mid-Hawthorn aquifer" (Reese, 2000), "uppermost artesian zone" (Stewart, 1966), "phosphorite unit" (Wilson, 1977), "shallow artesian aquifer" (Menke and others, 1961), and "permeable bed" (Peek, 1958). Hydrogeologic unit *Zone 3* is equivalent to the "lower Hawthorn-upper Tampa aquifer" (Wolansky, 1983; Duerr and Wolansky, 1986), "artesian zone 3" (Sutcliffe, 1975; Joyner and Sutcliffe, 1976), "secondary artesian aquifer" (Stewart, 1966), and "upper unit of the Floridan aquifer" (Wilson, 1977). Near the southeastern and northwestern extent of the study area, units previously called the "lower Hawthorn aquifer" and "Tampa producing zone," respectively, are included in the Upper Floridan aquifer (Menke and others, 1961; Sproul and others, 1972; Brown 1983; Reese, 2000).

Properties of the Aquifers Overlying and Underlying the Intermediate Aquifer System

Properties of the aquifers adjacent to the intermediate aquifer system, the overlying surficial aquifer system and underlying Upper Floridan aquifer, are briefly described herein because ground water exchanged among the aquifers varies in source, quality, and quantity. The quality of the water, the degree of interconnection, and potential for interaquifer leakage are important for gaining a complete understanding of the intermediate aquifer system.

Ground-water flow is not regionally extensive within the surficial aquifer system. In most of the study area, the water-producing capacity of the surficial aquifer system is limited by the saturated thickness (generally <50 ft) and by the degree of sediment sorting. The surficial aquifer system is used locally as a water supply in areas where the sand deposits thicken substantially beneath the Lake Wales Ridge, where the undifferentiated deposits are composed of predominantly shell and sand beds of moderate water-producing capacity, or where deeper aquifers are highly mineralized (Torres and others, 2001). Sand and shell beds thicken in coastal Manatee, Sarasota, and Charlotte Counties, and encircling Charlotte Harbor (Vacher and others, 1992; Torres and others, 2001). The surficial aquifer system is used for public water supply in southwestern Sarasota and coastal Charlotte Counties where deeper aquifers are highly mineralized. The hydraulic conductivity of the surficial aquifer system varies from 1 to 1,490 feet per day (ft/d), with a mean of 62, median of 27, and upper and lower quartiles of 13 and 51 ft/d, respectively (Beach and Chan, 2003). A single water type (calcium-bicarbonate) characterizes the surficial aquifer system at the eight ROMP sites in the study area (app. 1A-B).

The Upper Floridan aquifer is a confined aquifer throughout the study area. The top of the aquifer dips to the south from about NGVD 1929 in central Polk County to $>1{,}000$ ft below NGVD 1929 in southern Charlotte County, whereas thickness varies from about 1,000 to more than 1,400 ft. In the study area, the Upper Floridan aquifer consists of three hydrogeologic units—the moderately permeable packstone unit of the Suwannee Limestone (UPZ); the semiconfining mudstone unit of the Ocala Limestone, and the highly permeable fractured crystalline dolostone in the Avon Park Formation (LPZ) (Basso, 2002; Beach and Chan, 2003). The transmissivity of the Upper Floridan aquifer generally exceeds 10,000 and can be $>1{,}000{,}000$ ft^2/d (Southwest Florida Water Management District, 2000). Transmissivities of the Suwannee Limestone range from 1,400 to 290,000 ft^2/d; with a mean of 17,000, median of 15,000, and lower and upper quartiles of 7,800 and 37,000 ft^2/d, respectively (Beach and Chan, 2003). Transmissivities of the Avon Park Formation range from 4,900 to 1,600,000 ft^2/d, with a mean of 110,000, median of 100,000, and lower and upper quartiles of 54,000 and 260,000 ft^2/d, respectively (Southwest Florida Water Management District, 2000; Beach and Chan, 2003).

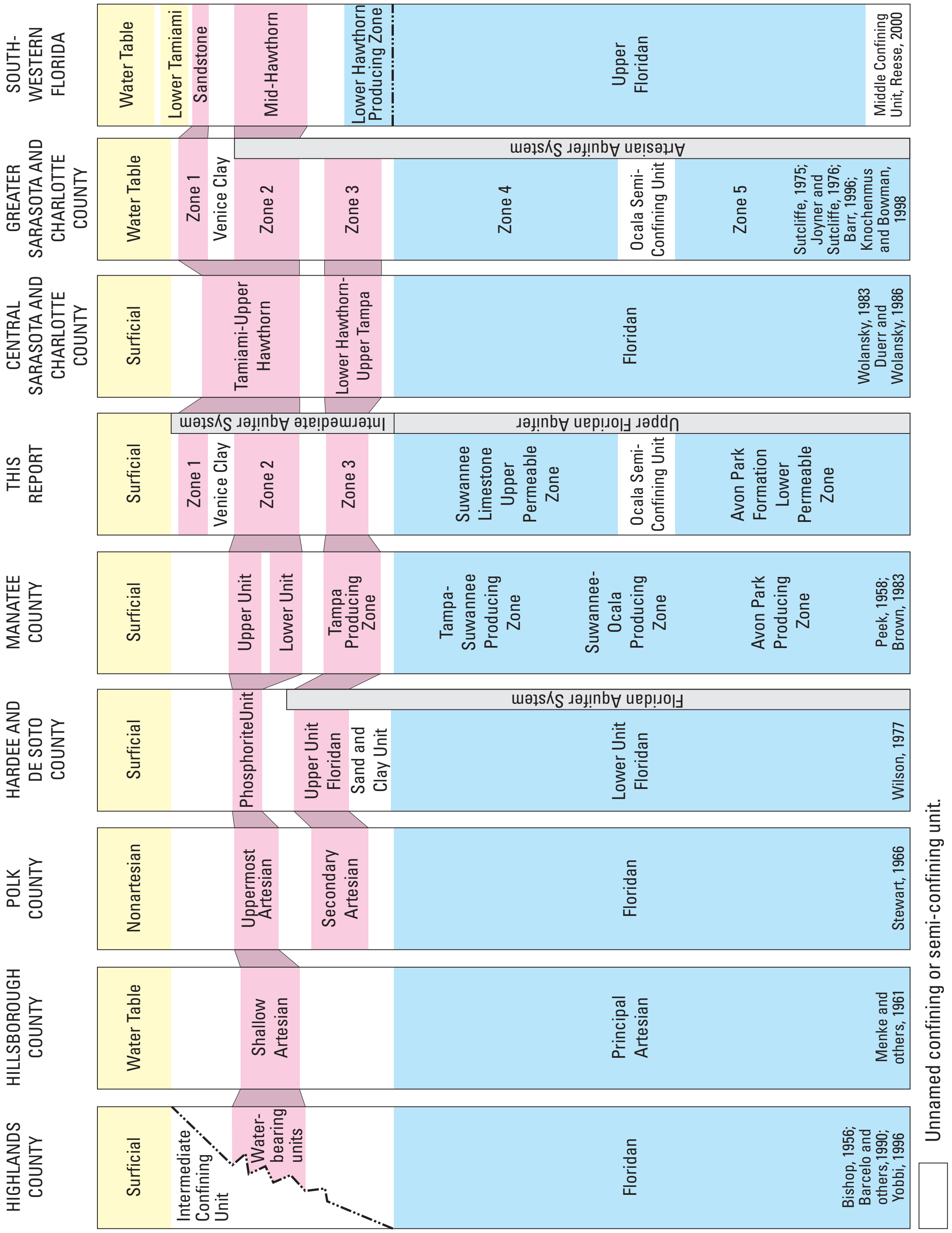


Figure 7. Hydrogeologic units in this study compared with those in previous reports.

The concentration of major ions is generally higher in water from the Upper Floridan aquifer than from the intermediate aquifer system in the study area (app. 1A-B). The chemical composition of water in the Upper Floridan aquifer evolves along regional flow paths from mixed-cation bicarbonate to calcium-magnesium sulfate to sodium-chloride type water (Plummer, 1977; Sacks and Tihansky, 1996). Half of the samples from the Upper Floridan aquifer in the study area contain calcium-magnesium sulfate type water. Mixed-ion type water is present at ROMP sites in coastal Hillsborough County and at selected ROMP sites (13, 14, and 16.5) in southeastern De Soto and southwestern Highlands Counties.

Intermediate Aquifer System

The intermediate aquifer system generally is coincident with the Hawthorn Group and underlies most of the study area. The heterogeneous lithologic composition of the Hawthorn Group results in a hydrogeologic unit that is best characterized as thin permeable units in a predominantly fine-grained clayey matrix. As a single entity, the intermediate aquifer system is characterized as a system with substantially lower permeability than the underlying Upper Floridan aquifer, and is often classified as a confining or semiconfining unit (Basso, 2002).

The intermediate aquifer system ranges in thickness from <100 ft in southern Hillsborough and central Polk County to more than 800 ft in southern Charlotte County (Duerr and others, 1988), (table 1). The number of permeable units increases as the intermediate aquifer system thickens. The permeable units are of limited vertical extent and are present at variable depths (fig. 8). Within the intermediate aquifer system, there is considerable hydraulic and chemical variability among the three vertically stratified water-bearing zones.

Variations in hydraulic and chemical properties of permeable units reflect the original texture and composition of sediments and post-depositional processes such as dolomitization, recrystallization, fracturing, and dissolution (Knochenmus and Bowman, 1998; Torres and others, 2001). The reported transmissivities of water-bearing zones in the intermediate aquifer system vary over 5 orders of magnitude, from about 1 to more than 40,000 ft^2/d. This wide range is because permeable units are (1) thin, (2) absent in places where clay beds dominate, and (3) vary with lithology and solution development within the carbonate sediments rather than with thickness (Wolansky, 1983; Knochenmus and Bowman, 1998; Southwest Florida Water Management District, 2000; Basso, 2002). Transmissivity values are listed by zone in table 2.

Table 1. Regional Observation Monitioring-well Program (ROMP) well indentification, site characteristics, construction information, and zone specification.

[USGS site ID, base ID and does not include the 2-digit sequence number assigned to each well. FGS, Florida Geological Survey; LSD, land surface datum, in feet above NGVD29; thickness, total thickness of the Hawthorn Group; casing, casing depth below NGVD29; depth, well depth below NGVD29; zone 3*, well open to zone 3 and the Upper Floridan aquifer; %, percent; *, Venice clay present; x, zone at site; -- absent; ND, no data]

ROMP name	USGS Site ID	FGS ID	LSD	Thick-ness	Clay %	Venice Clay	Zone 1	Casing	Depth	Zone 2	Casing	Depth	Zone 3	Casing	Depth	Zone 3*	Casing	Depth
5	2656440814833	16913	40	642	43	*	--	--	--	x	-90	-190	x	-410	-560			
9	2704320820857	17056	25	518	23	--	x	-15	-40	x	-97	-140	x	-169	-295			
9.5	2707370820251	17597	38	420	12	--	x	-23	-39	--	--	--	x	-167	-293			
10	2701520820028	12684	9	583	0	--	--	--	--	x	-101	-201	x	-294	-479			
11	2658370815611	30013	13	ND	ND	--	--	--	--	x	-207	-332	--	--	--			
12	2702250814433	16578	41	667	13	--	x	-16	-69	x	-239	-368	x	-464	-664			
13	2704180813658	17392	60	492	20	--	--	--	--	x	-222	-357	x	-450	-532			
14	2708580812111	17001	145	282	61	--	--	--	--	x	-315	-376	--	--	--			
15	2712320813922	15801	79	365	75	--	--	--	--	x	-181	-251	--	--	--			
16	2711150814627	50001	60	564	17	--	--	--	--	x	-45	-176	x	-240	-280			
16.5	2703400815302	18116	40	535	34	*	x	-16	-50	--	--	--	x	-307	-421			
17	2710260815836	15303	25	413	10	--	--	--	--	x	-75	-135	x	-175	-215	x	-370	-445
18	2711370820748	14383	40	420	9	*	--	--	--	--	--	--	--	--	--			
19x	2710210821516	14717	31	385	6	--	x	-49	-90	x	-177	-190	--	--	--			
19	2709590822030	14787	20	375	19	--	--	--	--	x	-67	-185	--	--	--			
20	2711370822845	17087	15	472	19	*	--	--	--	x	-60	-110	x	-235	-355			
22	2718130822013	16783	35	339	42	*	--	--	--	x	-60	-90	x	-195	-255			
23	2719060821124	14382	60	505	13	*	--	--	--	x	-115	-190	x	-244	-314			
25	2721590820025	17608	85	361	19	--	--	--	--	x	-20	-60	--	--	--	x	-215	-591
26	2717570814930	14878	75	500	48	--	--	--	--	x	-65	-105	x	-180	-355			

Table 1. (Continued) Regional Observation Monitioring-well Program (ROMP) well indentification, site characteristics, construction information, and zone specification.

[USGS site ID, base ID and does not include the 2-digit sequence number assigned to each well. FGS, Florida Geological Survey; LSD, land surface datum, in feet above NGVD29; thickness, total thickness of the Hawthorn Group; casing, casing depth below NGVD29; depth, well depth below NGVD29; zone 3*, well open to zone 3 and the Upper Floridan aquifer; %, percent; *, Venice clay present; x, zone at site; -- absent; ND, no data]

ROMP name	USGS Site ID	FGS ID	LSD	Thick-ness	Clay %	Venice Clay	Zone 1	Casing	Depth	Zone 2	Casing	Depth	Zone 3	Casing	Depth	Zone 3*	Casing	Depth
28	2722070812604	17000	84	191	ND	--	--	--	--	x	-286	-346	--	--	--			
28x	2715590812023	17418	105	--	--	--	--	--	--	--	--	--	--	--	--			
30	2727280814747	15648	67	330	42	--	--	--	--	x	12	-113	x	-213	-249			
31	2727140815459	13514	78	396	33	--	--	--	--	--	--	--	x	-52	-272			
32	2728140820348	16257	104	454	53	--	--	--	--	--	--	--	--	--	--			
33	2727280821530	16784	74	441	19	--	--	--	--	x	-21	-89				x	-330	-676
33[a]	2727280821530	16784	74	441	19	--	--	--	--	x	-141	-216	--	--	--			
35	2717050820221	18117	65	530	24	--	--	--	--	x	-55	-124	x	-165	-295			
39	2735210821505	16740	125	466	28	--	--	--	--	x	-5	-80	--	--	--			
40	2738510820315	30003	140	375	53	--	--	--	--	x	64	-40	--	--	--			
43X	2736160812848	14884	148	ND	ND	--	--	--	--	--	--	--	--	--	--			
45	2745470814709	14385	122	285	41	--	--	--	--	--	--	--	x	12	-70			
48	2744270820837	14386	102	197	53	--	--	--	--	x	57	41	--	--	--	x	-113	-439
49	2745460821514	14888	130	330	43	--	--	--	--	--	--	--	x	-100	-160			
50	2742400822127	13517	50	260	0	--	--	--	--	--	--	--	--	--	--	x	-150	-512
57	2754110813720	14883	128	85	70	--	--	--	--	x	33	-12	--	--	--			
57x	2753480813357	16309	197	54	ND	--	--	--	--	x	6	-12	--	--	--			
58	2755070813537	16307	142	--	--	--	--	--	--	--	--	--	--	--	--			
59	2753140815142	12640	119	140	35	--	--	--	--	x	69	5	--	--	--			
59[a]	2753140815142	12640	119	140	35	--	--	--	--	x	-3	-23	--	--	--			
TR1-2	2650260815854	15289	24	847	27	--	--	--	--	x	-195	-231	x	-496	-576			
TR3-1	2656380821307	15332	7	574	11	*	x	-48	-68	x	-133	-153	x	-243	-263			
TR3-1[a]	2656380821307	15332	7	574	11	*	--	--	--	--	--	--	x	-373	-393			
TR3-3	2655310821948	15683	6	650	16	*	--	--	--	x	-149	-169	x	-364	-404			
TR4-1	2703260822627	17488	5	620	7	*	x	-25	-107	x	-116	-219	x	-262	-627			
TR4-2	2702400822357	14871	15	437	7	*	--	--	--	--	--	--	--	--	--	x	-445	-460
TR5-1	2708080822705	15168	12	465	13	*	x	-28	-47	--	--	--	x	-263	-277			
TR5-2	2709190822342	15636	15	490	15	*	--	--	--	x	-85	-105	x	-230	-250			
TR5-2[a]	2709190822342	15636	15	490	15	*	--	--	--	--	--	--	x	-345	-385			
TR5-3	2709350822411	un-known	15	ND	ND	--	--	--	--	x	-48	-125	--	--	--			
TR6-1	2716010823305	14882	5	491	13	*	--	--	--	--	--	--	x	-295	-310			
TR7-1	2725100823457	15166	10	404	27	*	--	--	--	--	--	--	x	-310	-330			
TR7-2	2726120823301	17057	19	420	11	*	--	--	--	x	-41	-86	x	-338	-446			
TR7-2[a]	2726120823301	17057	19	420	11	*	--	--	--	x	-181	-271	--	--	--			
TR7-4	2725390822920	16303	17	499	29	*	--	--	--	x	-196	-251	x	-363	-483			
TR8-1	2734580823247	15826	15	376	39	--	--	--	--	x	-85	-145	--	--	--			
TR9-1	2744210822754	13515	4	214	0	--	--	--	--	--	--	--	x	-120	-284			
TR9-2	2745540822338	16618	13	220	4	--	--	--	--	--	--	--	x	-105	-135			
CL-2	2745220813039	15938	82	235	17	--	--	--	--	x	-248	-264	--	--	--			
CL-3	2745450813425	16306	123	130	ND	--	--	--	--	x	-74	-148	--	--	--			
SA-1	2720490823245	17452	13	468	26	--	--	--	--	--	--	--	x	-315	-375			

[a] More than 1 well in a zone at a ROMP site.

The chemical composition of water in aquifers is controlled by the mineralogy and solubility of aquifer material, the time of residence in the aquifer, and mixing of water from adjacent aquifers with differing compositions. The chemical composition of water is highly variable in the intermediate aquifer system because of the greater variety of minerals composing the intermediate aquifer system, and mixtures with water from the underlying Upper Floridan aquifer and overlying surficial aquifer system. Differences in composition result from the abundance of clay, phosphorite, and dolomite in the intermediate aquifer system (Sacks and Tihansky, 1996). Four ground-water quality types (water types), defined in terms of cation and anion concentrations, are present in the intermediate aquifer system in the study area—mixed-cation bicarbonate, calcium-magnesium sulfate, sodium chloride, and mixed ion. The water-quality data are listed and the major ion compositions are exhibited as pie charts in appendixes 1A and 1B.

Permeable Units

The wells at the ROMP sites were constructed to penetrate the most permeable strata in the underlying aquifers. Identification of horizons of enhanced permeability was based predominantly on visual inspection of rock cores, and was corroborated by water-level and water-quality changes and specific-capacity data collected during test drilling. Permeable units were assigned zone numbers based on a naming convention begun by Sutcliffe (1975), furthered by Barr (1996), and currently used in reports published by SWFWMD. In this report, the vertically stratified permeable units in the intermediate aquifer system are designated (in descending order) as Zone 1, Zone 2, and Zone 3 (table 1).

Zone 1

The uppermost permeable unit (Zone 1) of the intermediate aquifer system has been described in the southern and southwestern parts of the study area, underlying all of Sarasota, Charlotte, and Lee Counties, and parts of Manatee and De Soto Counties (fig. 9). Zone 1 generally is found above the confining unit called the *Venice Clay,* which is found in southern Manatee County, throughout Sarasota County, in eastern Charlotte County, and in western De Soto County (Sutcliffe, 1975; Wedderburn and others, 1982; Barr, 1996; Reese, 2000). Zone 1 is best recognized and mapped in southern Sarasota and coastal Charlotte Counties (Joyner and Sutcliffe, 1976; Sutcliffe and Thompson, 1983; Barr, 1996; Basso, 2002). Zone 1 is used for irrigation in the eastern part of Charlotte County, underlies central Sarasota, and extends into northern Lee County (Sutcliffe, 1975). Zone 1 also has been described at ROMP sites 9, 12, and 17, located in eastern Sarasota, southern De Soto, and western De Soto Counties, respectively (Torres and others, 2001). Compared to recent studies by SWFWMD (Basso, 2002; Beach and Chan, 2003), this study delineates a larger extent for Zone 1 that is consistent with the extent delineated in earlier studies.

Zone 1 is composed of discontinuous limestone, dolostone, sand, gravel, and shell beds located in the unconsolidated sediments within the Peace River Formation and uppermost Arcadia Formation in areas of the SWUCA, where it is present (Torres and others, 2001; Basso, 2002). Zone 1 is <80 ft thick (Beach and Chan, 2003). Zone 1 is >50 ft thick in central Charlotte County (Barr, 1996), and found at depths ranging from 55 to 148 ft below land surface (Sutcliffe, 1975). In the study area, the Zone 1 wells found at eight ROMP sites are completed above the Venice Clay at depths of <150 ft (fig. 9a). South of the study area in Lee County, Zone 1 is 50 to 100 ft thick at depths ranging from 60 to more than 170 ft below land surface (Wedderburn and others, 1982; Reese, 2000).

Transmissivity values are reported for 14 sites in Zone 1 in the study area, and range from about 50 to 8,700 ft^2/d (fig. 9b; table 2). The mean, geometric mean, median, lower, and upper quartile values are about 3,300, 1,600, 2,200, 1,100, and 5,500 ft^2/d, respectively. The most common transmissivities are in the moderate permeability range, in the thousands of feet squared per day

Multiple water types with relatively low ionic concentrations are present in Zone 1 (fig. 9c). The ionic composition and concentration of water samples in Zone 1 are indicated by the shape and size of the Stiff diagrams. Mixed-cation bicarbonate type water is present in southern De Soto County (ROMP sites 9.5, 16.5 and 12). Sodium-chloride type water is present in southern Sarasota County (ROMP sites TR4-1 and 9). Mixed-ion type water is present at ROMP site 19x in central Sarasota County. A water sample with anomalously high ionic concentration was collected from the well at the ROMP TR4-1 site. This site is located in southern Sarasota County on a spit surrounded by the Gulf of Mexico. The ionic composition and concentration indicate that this zone is hydraulically connected to the Gulf of Mexico and has been locally inundated by seawater (De Haven and Jones, 1996; fig. 9c; and app. 1A-B).

Zone 2

The middle permeable unit of the intermediate aquifer system (Zone 2) is composed of dolomite and limestone units within the upper Arcadia Formation (Torres and others, 2001; Basso, 2002). Zone 2 generally is above the Tampa Member and is hydraulically separated from adjacent zones by clay beds (Beach and Chan, 2003). Zone 2 is present over most of the study area, south of southern Hillsborough County and central Polk County (Basso, 2002) and west of central Highlands County (fig. 10a). At the northern and eastern extent of Zone 2, permeable units are discontinuous, but the unit also is locally present in low-lying areas west of the Lake Wales Ridge in Highlands County (Bishop, 1956) and in Hillsborough County (Menke and others, 1961). In the study area, Zone 2 wells are found at 38 ROMP sites (fig. 10a; table 1).

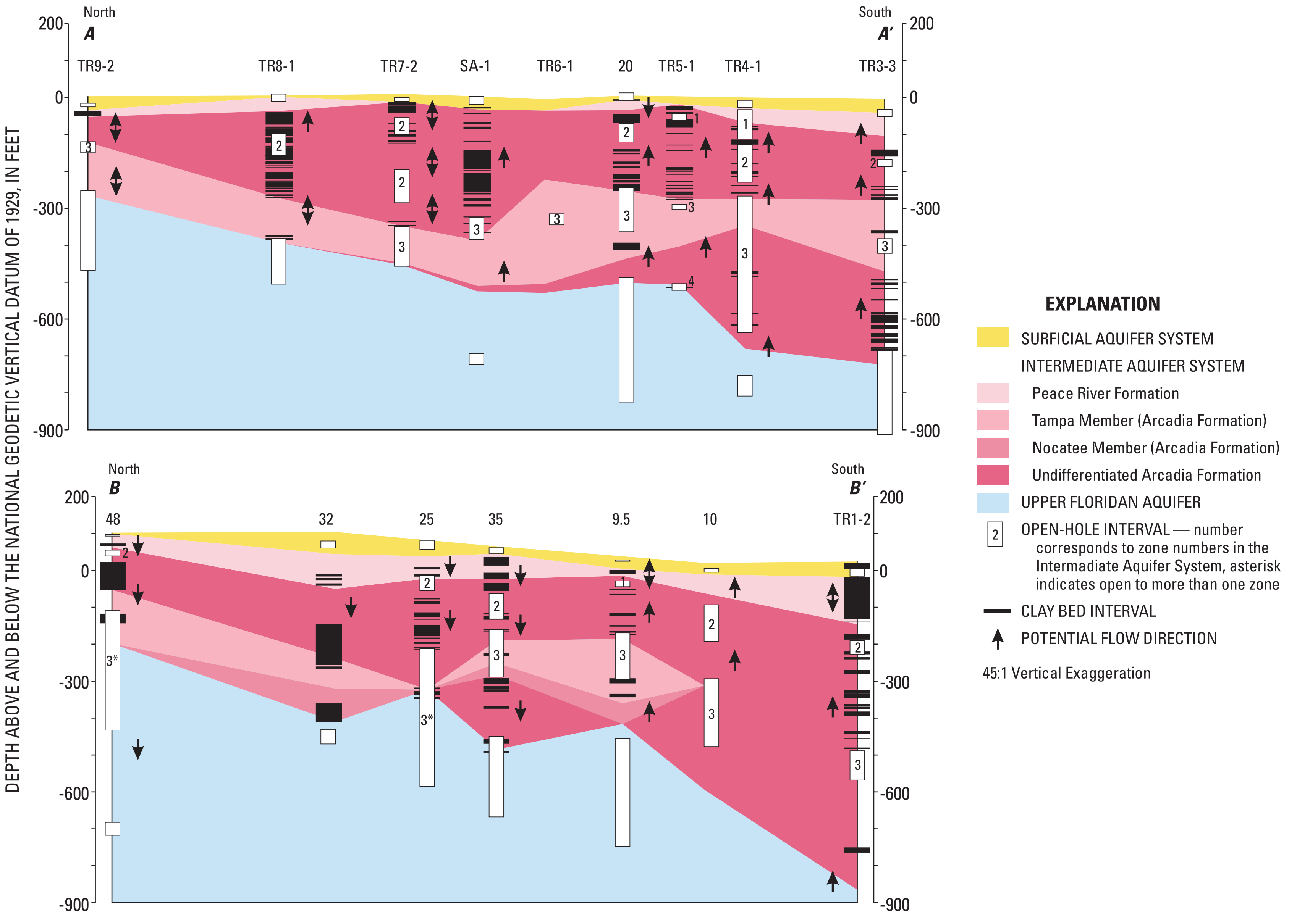


Figure 8. Stratigraphy, aquifer, open-hole interval, clay beds, and potential flow direction at selected Regional Observation and Monitor-well Program sites. (Locations of sections shown on figure 1.)

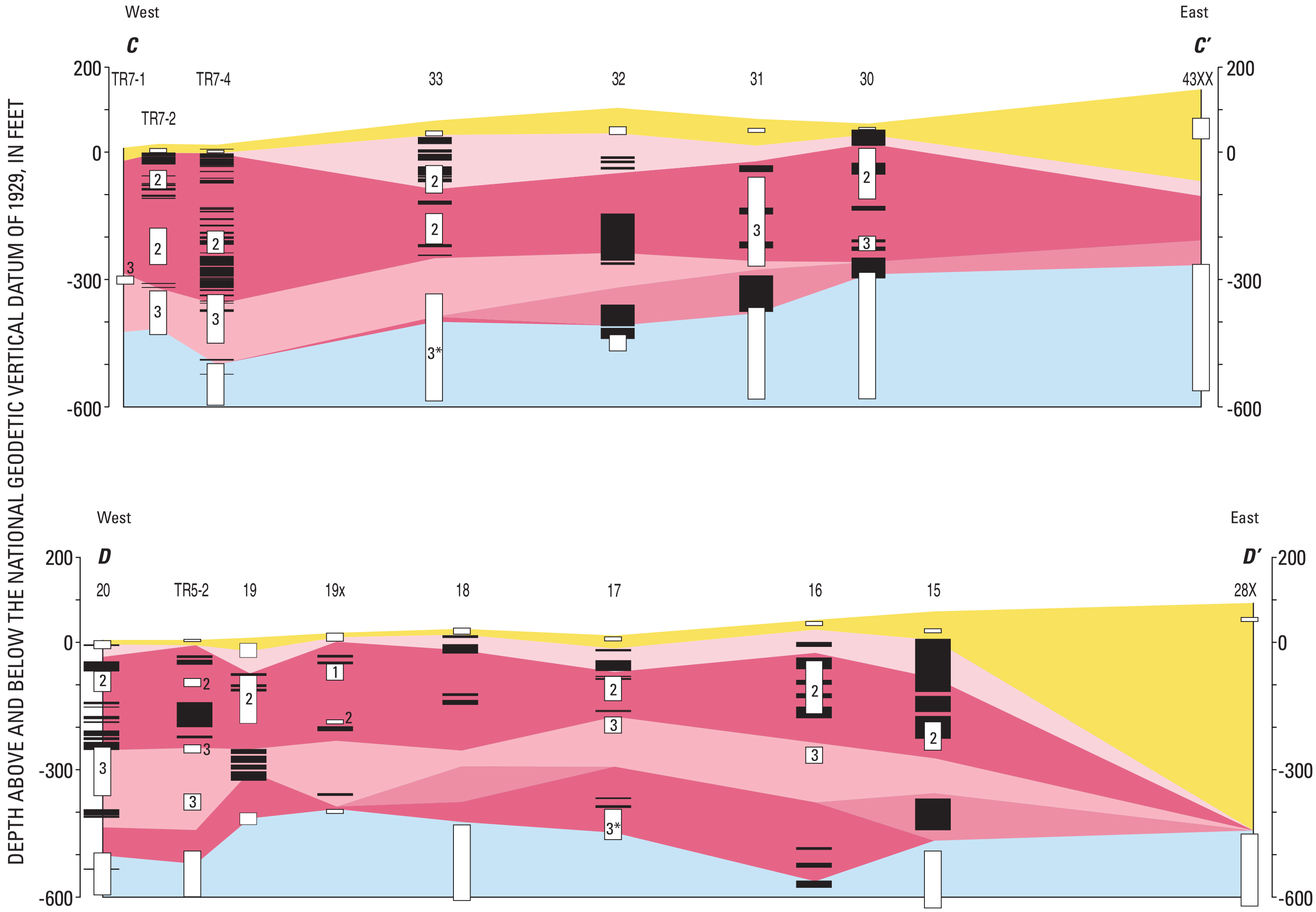


Figure 8. (Continued) Stratigraphy, aquifer, open-hole interval, clay beds, and potential flow direction at selected Regional Observation and Monitor-well Program sites. (Locations of sections shown on figure 1.)

Table 2. Transmissivity values for the intermediate aquifer system.

[All values in feet squared per day; --, indicates absent; SWFWMD, Southwest Florida Water Management District]

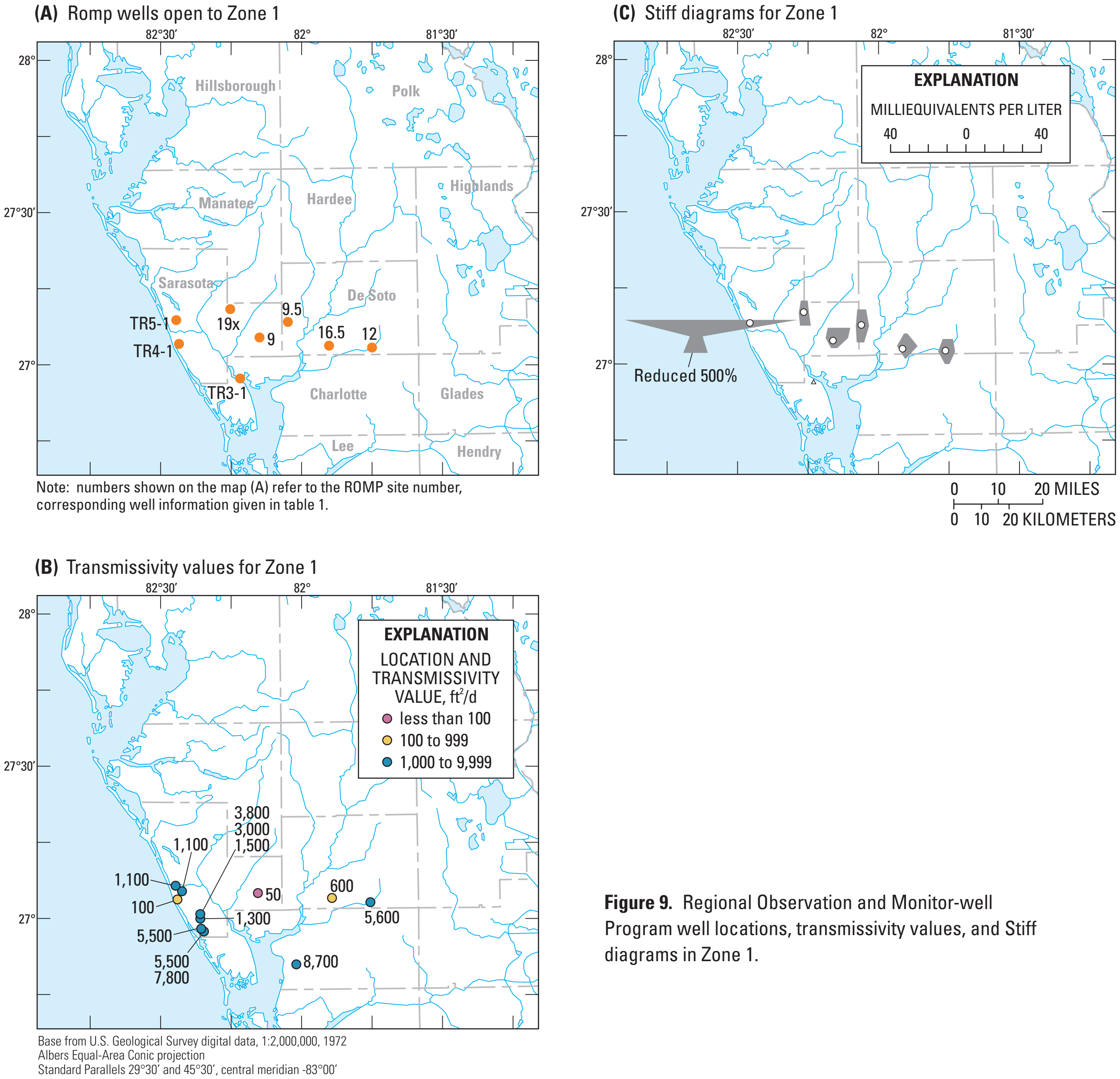
ROMP data only				Non-ROMP data from SWFWMD (2000)					
Well name	Zone 1	Zone 2	Zone 3	Well ID[a]	Zone 1	Well ID[a]	Zone 2	Well ID[a]	Zone 3
ROMP 5	--	1,400	3,000	40	1,100	1	700	5	600
ROMP 9	50	200	700	43	1,100	3	200	9	400
ROMP 9.5	--	--	9,900	51	3,000	4	700	14	13,000
ROMP 12	5,600	1,200	43,000	51	3,800	6	2,600	15	200
ROMP 13	--	300	800	51	1,500	7a	300	19	200
ROMP 14	--	30	--	52	1,300	7b	300	21	10,000
ROMP 16.5	600	--	4,900	53	5,500	8	300	23	400
ROMP 17	--	[b]20	[b]60	55	7,800	10	1,400	25	5,800
ROMP 18	--	2,100	--	55	5,500	11	5,000	28	2,000
ROMP 20	--	1,800	1,700	61	8,700	17	200	32	13,000
ROMP 22	--	--	100			20	8,800	35	8,000
ROMP 23	--	[b]3,600	[b]60			27	700	39	13,000
ROMP 25	--	1	--			32	5,300	40	15,000
ROMP 28	--	200	--			33	1,200	44	15,000
ROMP 30	--	[b]100	--			36	2,700	46	5,600
ROMP 33	--	[b]100	[b]20			40	800	50	2,900
ROMP 35	--	[c]3	[c]200			41	500	55	8,200
ROMP TR4-1	100	1,300	3,800			42	700	56	15,000
ROMP TR5-2	--	5,000	10,000			43	800	57	5,300
ROMP TR7-4	--	--	2,700			43	500	58	6,800
						45	400	59	3,000
						46	300		
						48	700		
						49	200		
						57	4,200		
						60	1,000		
						61	2,400		

Zones	Transmissivity statistics for all wells				
	Mean	Geometric mean	Median	Lower quartile	Upper quartile
Zone 1	3,261	1,629	2,250	1,100	5,500
Zone 2	1,401	520	700	200	1,800
Zone 3	6,232	2,090	3,400	500	9,950
All zones	3,551	1,058	1,300	300	5,000

[a] Data from SWFWMD (2000); cells without footnotes are from this source.

[b] Data from Stephanie Hertz, SWFWMD, written commun. (2001).

[c] Data from J.J. LaRoche, ROMP 35 Final Report (2004).


(A) Romp wells open to Zone 1

Note: numbers shown on the map (A) refer to the ROMP site number, corresponding well information given in table 1.

(B) Transmissivity values for Zone 1

Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

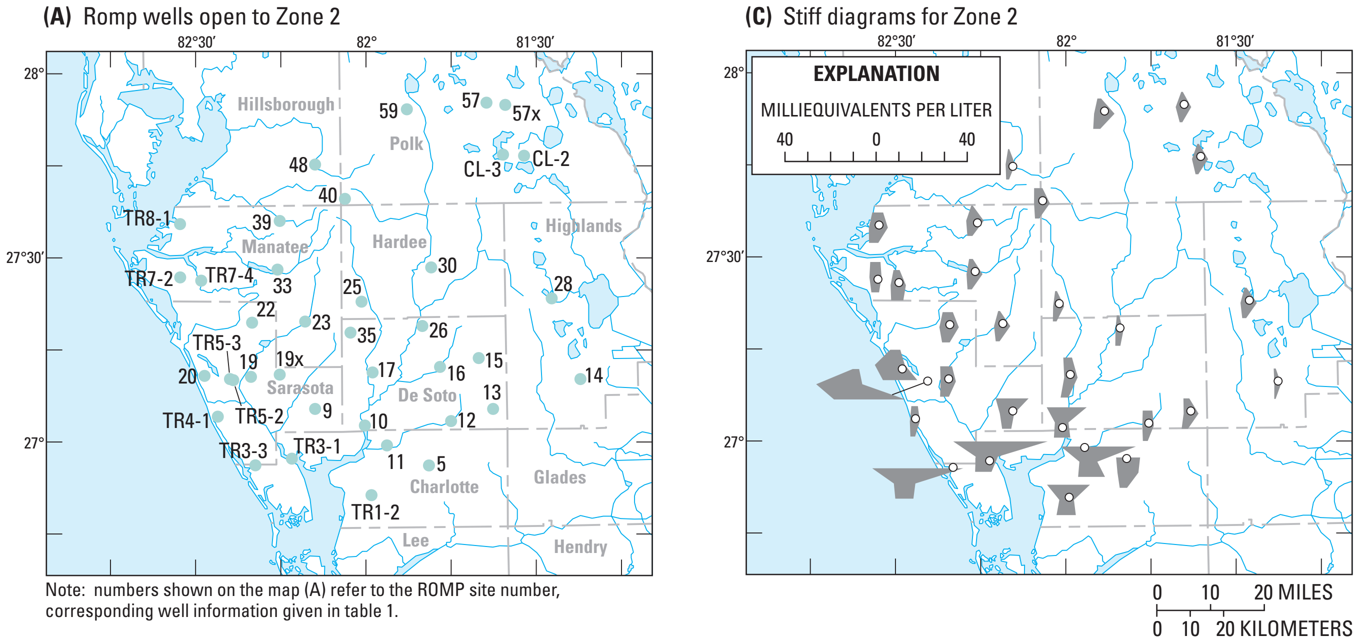
(C) Stiff diagrams for Zone 1

Figure 9. Regional Observation and Monitor-well Program well locations, transmissivity values, and Stiff diagrams in Zone 1.

The thickness of Zone 2 ranges from <20 to about 200 ft, and typically is <100 ft in the study area (Duerr and Wolansky, 1986; Barr, 1996; Knochenmus and Bowman, 1998; Beach and Chan, 2003). In Lee County, south of the study area, Zone 2 rarely is thicker than 80 ft and it terminates near the southern county line (Reese, 2000). Depths below land surface to Zone 2 generally increase to the south from about 25 ft (northern sites) to more than 200 ft (southern sites). Depths of wells open to this zone are 30 to 75 ft in central Polk County (Stewart, 1966), average 40 and 65 ft in Hardee and northern De Soto Counties, respectively (Wilson, 1977), and range from about 25 to more than 200 ft in Manatee County (Peek, 1958), from 90 to 280 ft in Sarasota County (Duerr and Wolansky, 1986; Knochenmus and Bowman, 1998), and from 120 to 360 ft in Charlotte County (Sutcliffe, 1975).

Transmissivity values for Zone 2 are reported for 43 wells in the study area and range from 1 to 8,800 ft^2/d (fig. 10b) (Southwest Florida Water Management District, 2000; Beach and Chan, 2003). The mean, geometric mean, median, lower, and upper quartile values are about 1,400, 520, 700, 200, and 1,800 ft^2/d, respectively. The most frequently reported transmissivities (more than 50 percent) are in the low permeability range, in the hundreds of feet squared per day.

Multiple water types are present in Zone 2 (app. 1A-B). The ionic composition and concentration of water samples in Zone 2, indicated by the shape and size of the Stiff diagrams, are shown in figure 10c. Mixed-cation bicarbonate type water is present at two-thirds of the ROMP sites, has relatively low ionic concentrations, and is located everywhere but in southern and coastal Sarasota County and Charlotte

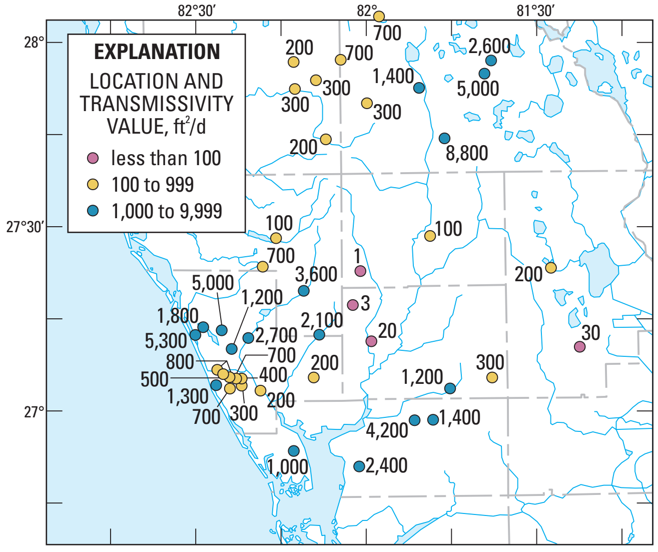


(A) Romp wells open to Zone 2

(C) Stiff diagrams for Zone 2

Note: numbers shown on the map (A) refer to the ROMP site number, corresponding well information given in table 1.

(B) Transmissivity values for Zone 2



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 10. Regional Observation and Monitor-well Program well locations, transmissivity values, and Stiff diagrams in Zone 2.

County. Calcium-magnesium sulfate type water is present at two coastal sites in Sarasota County (ROMP 20 and TR 5-2). Sodium chloride type water is present in southern Sarasota County and Charlotte County (ROMP sites TR1-2, TR3-1, TR3-3, 5, 9, 10, and 11). Mixed-ion type water is present at ROMP TR7-2 site in coastal Manatee County.

Zone 3

The third and lowermost permeable unit of the intermediate aquifer system (Zone 3) is composed of limestone and varying amounts of dolostone and siliciclastics sediments within the Tampa or Nocatee Members of the Arcadia Formation (Torres and others, 2001; Basso, 2002). Where the named members of the Arcadia Formation are absent, Zone 3 is present in the lower undifferentiated Arcadia Formation.

Zone 3 is present over a smaller part of the study area than Zone 2, and is present south of Hillsborough and Polk Counties (Basso, 2002), west of Highlands County, and north of west-central Charlotte County (fig. 11a). At five sites (ROMP TR4-2, 25, 33, 48, and 50), wells are open to both Zone 3 of the intermediate aquifer system and the Suwannee Limestone of the Upper Floridan aquifer. Zone 3 is up to 300 ft thick and typically is > 100 ft thick (Barr, 1996; Knochenmus and Bowman, 1998; Beach and Chan, 2003). Depths below land surface of wells open to Zone 3 generally increase to the south from about 150 ft (northern sites) to over 600 ft (southern sites). Zone 3 is hydraulically connected to the Upper Floridan aquifer at the northwestern and southern extent of the study area (Sutcliffe, 1975; Reese,

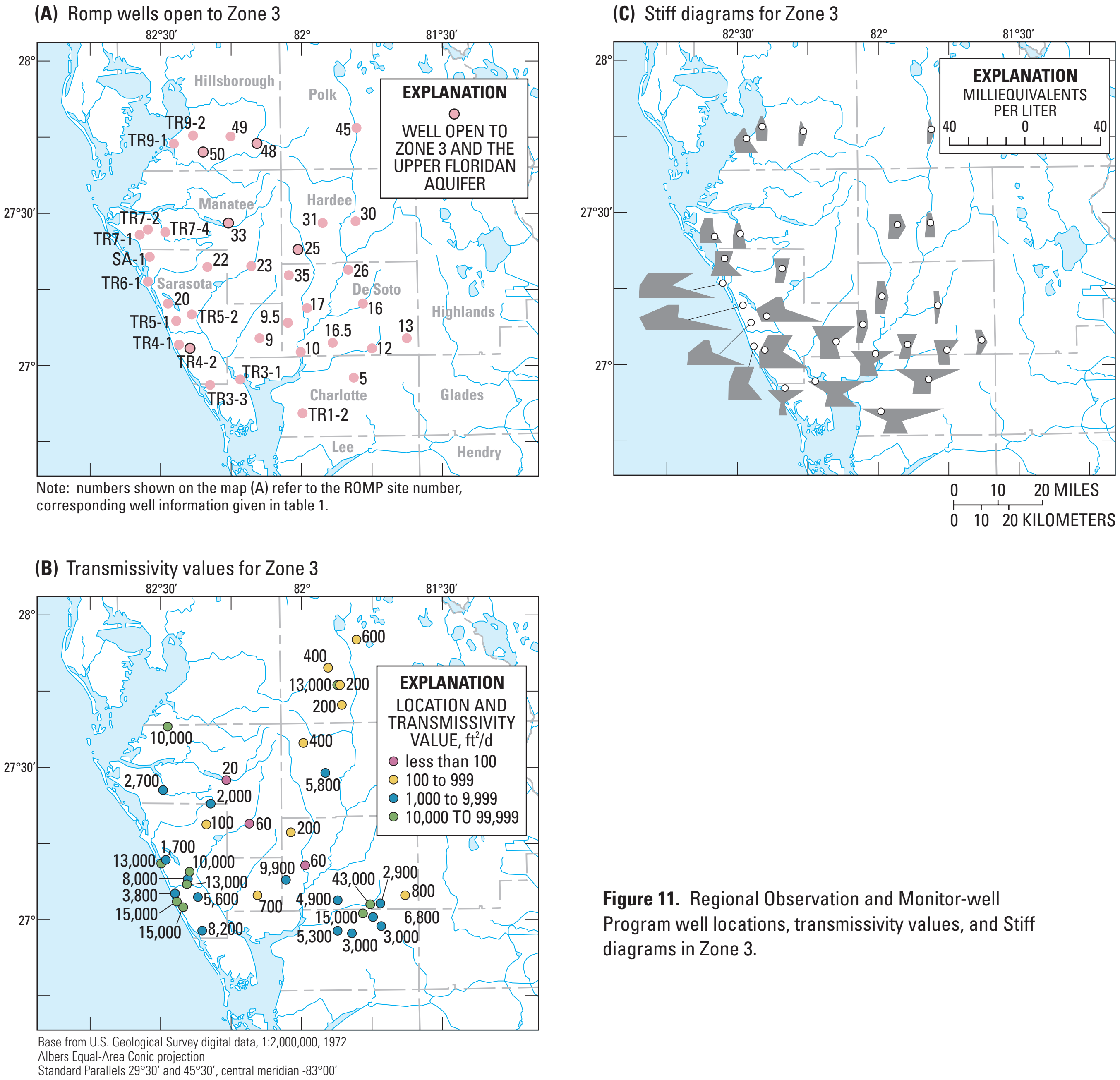


Figure 11. Regional Observation and Monitor-well Program well locations, transmissivity values, and Stiff diagrams in Zone 3.

2000; Basso, 2002). Depth below land surface of wells open to this zone ranges from 130 to 300 ft in Hardee County, from 130 to 400 ft in De Soto County (Wilson, 1977), from 280 to 440 ft in Sarasota County, and from 350 to 400 ft in Charlotte County (Sutcliffe, 1975; Knochenmus and Bowman, 1998; Reese, 2000).

Transmissivity values for Zone 3 are reported for 36 sites in the study area, and range from 20 to 43,000 ft^2/d (Southwest Florida Water Management District, 2000; Beach and Chan, 2003). Of the three permeable zones in the intermediate aquifer system, only Zone 3 has values exceeding 10,000 ft^2/d (fig. 11b). The mean, geometric mean, median, lower, and upper quartile values are about 6,200, 2,100, 3,400, 500, and 9,900 ft^2/d, respectively. The most frequently reported transmissivities are in the moderate permeability range, in the thousands of feet squared per day, however, nearly equal numbers of reported transmissivities are in the hundreds and tens of thousands of feet squared per day.

Multiple water types also are present in Zone 3 at selected ROMP sites (fig. 11c). The water types are about equally split among mixed-cation bicarbonate, calcium-magnesium sulfate, and sodium chloride. The ionic composition and concentration of water samples are indicated by the shape and size of the Stiff diagrams. Mixed-cation bicarbonate type water is present at seven inland ROMP sites (9.5, 13, 16, 17, 30, 31, 45, and 49) located in south central Hillsborough, Polk, Hardee, and most of De Soto Counties. Calcium-magnesium sulfate type water is present at nine coastal Manatee and Sarasota County

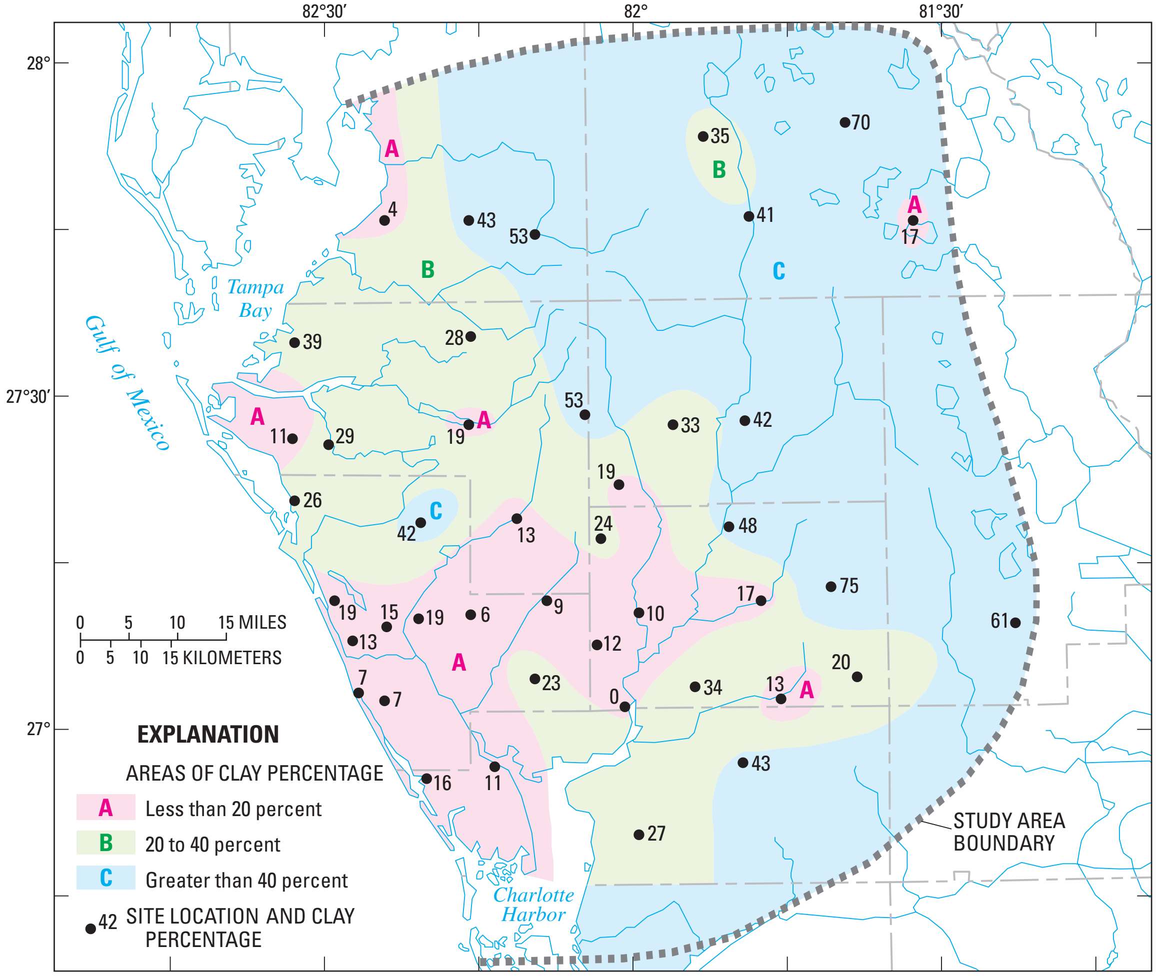
ROMP sites (TR 4-1, 4-2, 5-1, 5-2, 6-1, 7-2, 7-4, SA-1, and 20). Sodium chloride type water is present at eight ROMP sites (TR1-2, TR3-1, TR3-3, 5, 9, 10, and 12) in Charlotte and southern De Soto Counties. Mixed-ion type water is present at three ROMP sites (TR9-2, 22, and 30) in coastal Hillsborough, eastern Sarasota, and central Hardee Counties.

Confining Units

In most of the study area, confining units restrict, to varying degrees, the vertical movement of water between permeable units. The confining units consist of sandy and silty clays as well as mudstones and dolosilts that hydraulically separate the permeable units within the intermediate aquifer system, and isolate the intermediate aquifer system from the adjacent aquifers. Although the confining units impede the movement of water between zones, the units are leaky and water moves across them depending on hydraulic head differences and the relative permeability of the units.

Clay Beds

The degree of hydraulic connection between permeable zones is related to the presence and thickness of clay beds within the Hawthorn Group. Clay beds, described in lithologic logs, make up 0 to 75 percent of the sediments in the Hawthorn Group; the clay content generally increases to the north and east (fig. 12). At about 70 percent of the ROMP sites, the clay beds in the Hawthorn Group make up <25 percent of the lithology; however, even at small percentages, clays lower the permeability. The clay beds are heterogeneously distributed both laterally and vertically and range in thickness from about 2 ft (stringer) to more than 100 ft (fig. 8). Clay beds that are distributed throughout the Hawthorn Group tend to lower the overall permeability, resulting in a hydrogeologic unit that is best described as a confining or semiconfining unit separating the overlying surficial aquifer system and underlying Upper Floridan aquifer. In general, the clay content is lowest in the Tampa Member, and higher in the Peace River Formation, the Nocatee Member, and undifferentiated Arcadia Formation.



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 12. Percentage of clay in the Hawthorn Group sediments.

Leakance Across Confining Units

In general, confining units have low hydraulic conductivity and transmit water at a very slow rate. Over a large area of contact and sufficient time, however, confining units can contribute substantially to the recharge of aquifers (De Weist, 1965). Leakance is the hydraulic property that quantifies the potential for confining units to transmit water vertically from an underlying or overlying aquifer (Wolansky and Corral, 1985). In the study area, leakance was estimated between adjacent aquifers and zones at 12 ROMP sites. Leakance values of the confining units within the intermediate aquifer system that were determined, numerically spans 4 orders of magnitude—4.3x10^{-7} to 6.0x10^{-3} (ft/d)/ft, (Yobbi and Halford, 2006) (table 3). Leakance of confining units ranges from 4.6x10^{-5} to 1.1x10^{-4} (ft/d)/ft for the units separating the surficial aquifer system from Zone 1; 7.1x10^{-6} to 2.9x10^{-4} (ft/d)/ft for the units separating Zone 1 from Zone 2; 1.3x10^{-6} to 1.1x10^{-3} (ft/d)/ft for the units separating Zone 2 from Zone 3, and 1.1x10^{-6} to 6.0x10^{-3} (ft/d)/ft for the units separating Zone 3 from the Upper Floridan aquifer (table 3). The spatial and vertical distribution of leakance for each confining unit evaluated in the study area is shown in figure 13. No apparent pattern, such as increasing/decreasing with depth or location, is observed in the vertical distribution of leakance (fig. 13a).

Table 3. Leakance values at selected Regional Observation and Monitor-well Program (ROMP) sites.

[All values in foot per day per foot]

ROMP name	Upper confining unit[a]		Upper-middle confining unit[b]		Lower-middle confining unit[c]		Middle confining unit[d]		Lower confining unit[e]		Ocala semiconfining unit[f]	
5	2.4x10^{-5}	SAS–2					1.6x10^{-5}	Zone 2–3	4.2x10^{-3}	Zone 3–UFA	1.5x10^{-3}	UPZ–LPZ
9	1.4x10^{-4}	SAS–1	1.7x10^{-5}	Zone 1–2	2.0x10^{-5}	Zone 2–3			1.7x10^{-4}	Zone 3–UFA	1.6x10^{-2}	UPZ–LPZ
12	4.6x10^{-5}	SAS–1	2.9x10^{-4}	Zone 1–2	1.1x10^{-3}	Zone 2–3			6.0x10^{-3}	Zone 3–UFA	9.7x10^{-3}	UPZ–LPZ
13	2.2x10^{-6}	SAS–2					1.3x10^{-6}	Zone 2–3	9.8x10^{-6}	Zone 3–UFA	2.0x10^{-3}	UPZ–LPZ
14	5.8x10^{-7}	SAS–2							4.3x10^{-7}	Zone 2–UFA	7.8x10^{-3}	UPZ–LPZ
20	1.3x10^{-5}	SAS–2					4.4x10^{-6}	Zone 2–3	8.9x10^{-5}	Zone 3–UFA	1.0x10^{-3}	UPZ–LPZ
22	1.5x10^{-5}	SAS–2					3.2x10^{-5}	Zone 2–3	8.5x10^{-4}	Zone 3–UFA	1.7x10^{-2}	UPZ–LPZ
25	1.1x10^{-5}	SAS–2							8.1x10^{-6}	Zone 2–UFA	9.6x10^{-4}	UPZ–LPZ
28	7.9x10^{-4}	SAS–2							2.2x10^{-5}	Zone 2–UFA	3.7x10^{-3}	UPZ–LPZ
39	1.0x10^{-5}	SAS–2					2.4x10^{-5}	Zone 2–2[g]	7.8x10^{-7}	Zone 2–UFA	7.7x10^{-5}	UPZ–LPZ
TR4-1	1.1x10^{-4}	SAS–1	7.1x10^{-6}	Zone 1–2	6.5x10^{-5}	Zone 2–3			6.3x10^{-4}	Zone 3–UFA	6.0x10^{-3}	UPZ–LPZ
TR9-2	2.9x10^{-6}	SAS–3							1.1x10^{-6}	Zone 3–UFA	7.6x10^{-4}	UPZ–LPZ

	Upper group[h]	Lower group[i]	Ocala[f]
Mean	9.9x10^{-5}	1.1x10^{-4}	5.5x10^{-3}
Geometric Mean	2.0x10^{-5}	1.2x10^{-5}	2.6x10^{-3}
Median	1.5x10^{-5}	1.8x10^{-5}	2.8x10^{-3}
Minimum	5.8x10^{-7}	4.3x10^{-7}	7.7x10^{-5}
Maximum	7.9x10^{-4}	1.1x10^{-3}	1.7x10^{-2}

[a] Upper confining unit separates the surficial aquifer system (SAS) and the uppermost Zone (1 or 2) in the intermediate aquifer system.

[b] Upper-middle confining unit separates Zone 1 from Zone 2.

[c] Lower-middle confining unit separates Zone 2 and Zone 3.

[d] Middle confining unit separates Zone 1 or Zone 2 from Zone 3.

[e] Lower confining unit separates lowermost Zone (2 or 3) from the upper permeable zone of the Upper Floridan aquifer (UFA).

[f] Ocala semiconfining unit separates the upper (UPZ) and lower permeable zones (LPZ) of the Upper Floridan aquifer.

[g] Zone 2 to 2 confining unit separates zones both designated 2.

[h] Upper group includes all confining units above Zone 2.

[i] Lower group includes all confining units below Zone 2.

(A) Leakance, in foot per day per foot across confining units separating permeable units

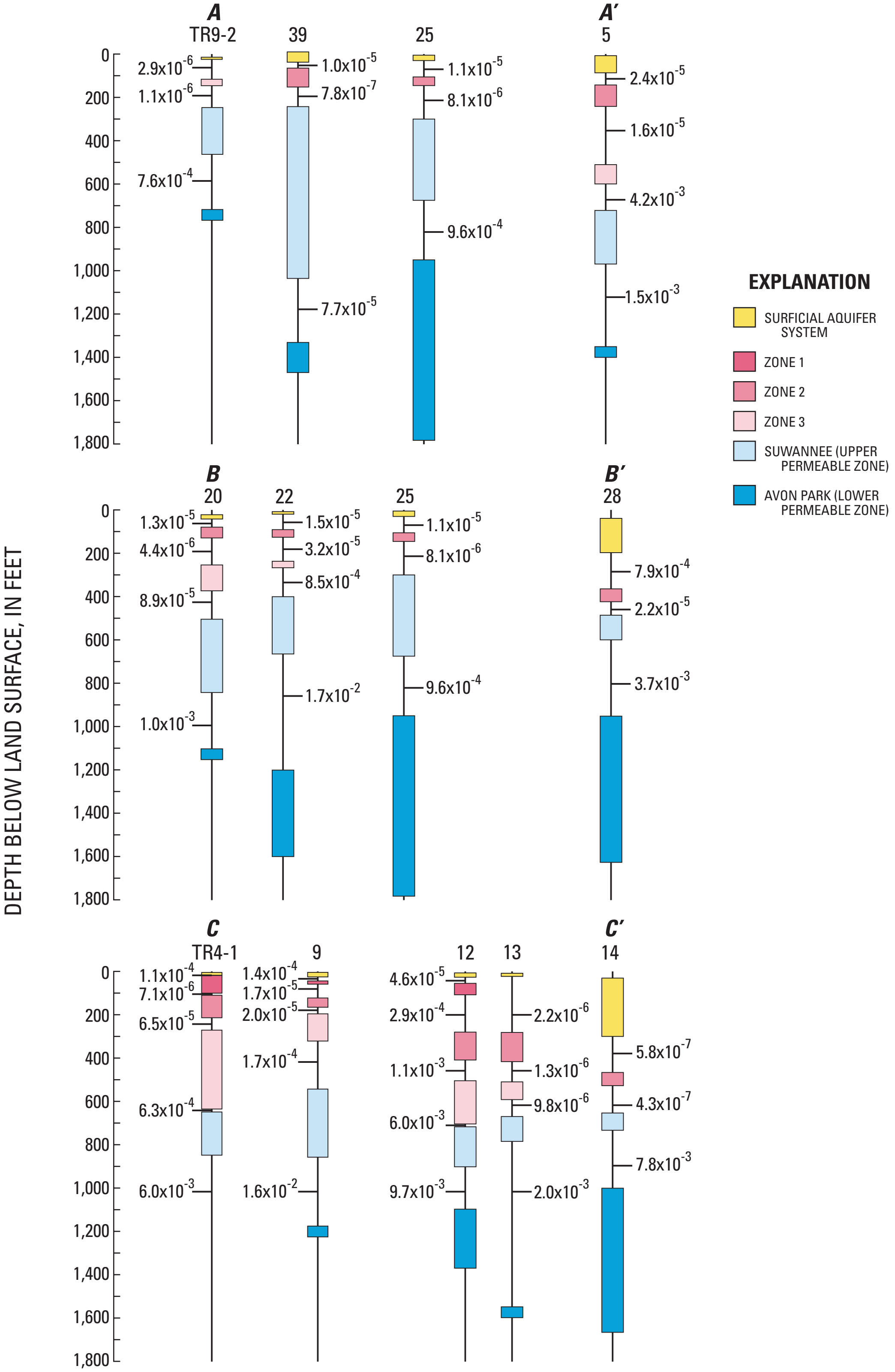
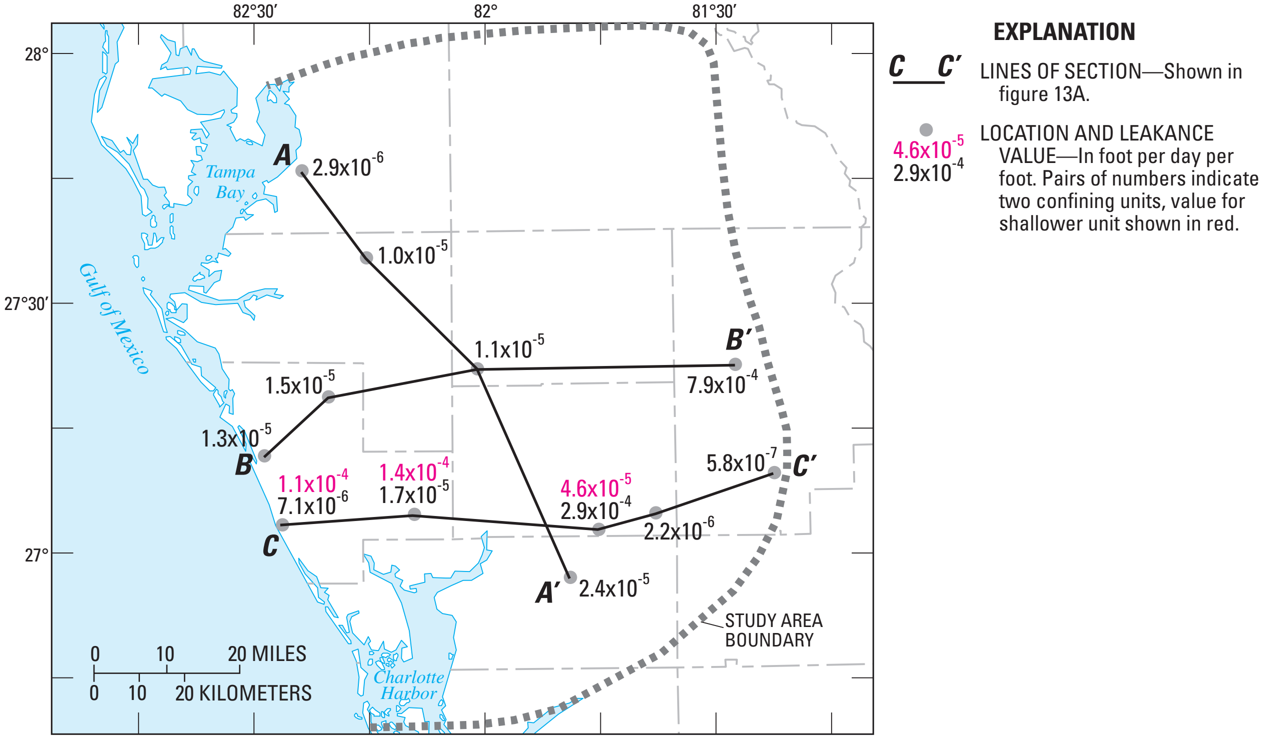
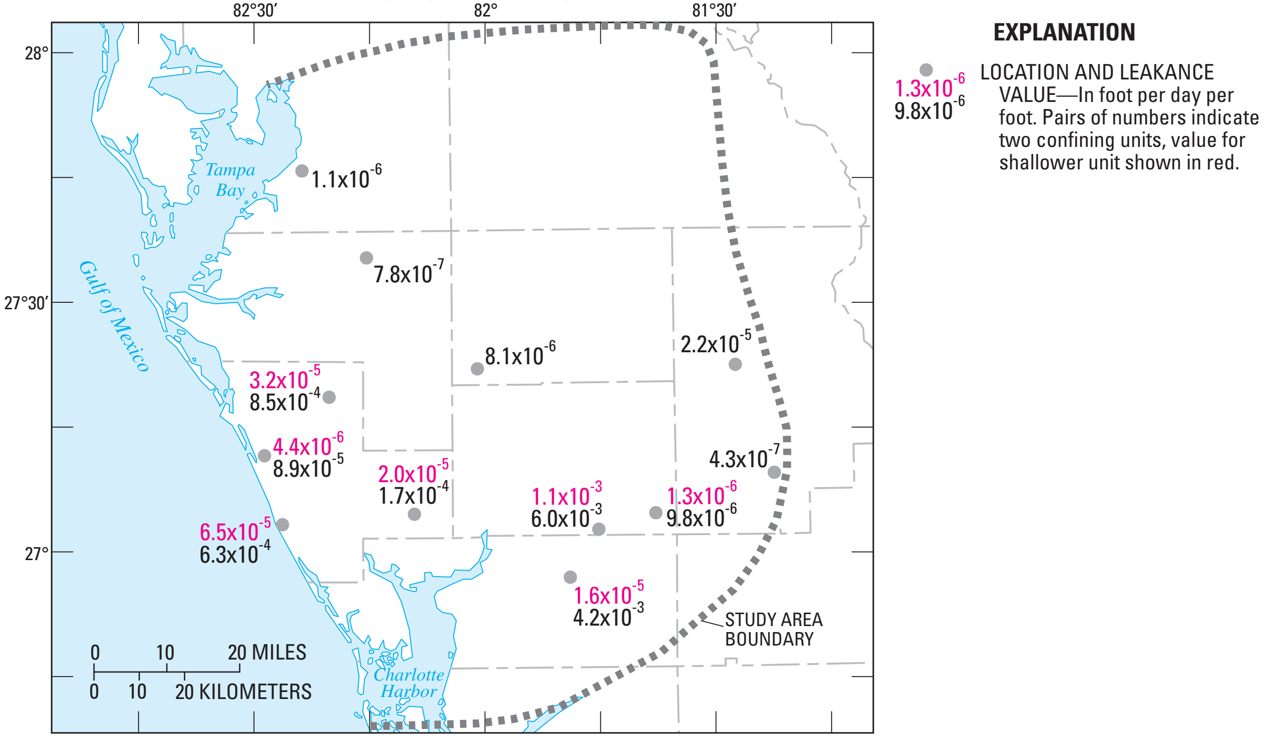


Figure 13. Leakance values, in foot per day per foot, shown on sections and maps at selected Regional Observation and Monitor-well Program sites.

(B) Leakance across the upper group of confining units–(above Zone 2)



(C) Leakance across the lower group of confining units–(below Zone 2)



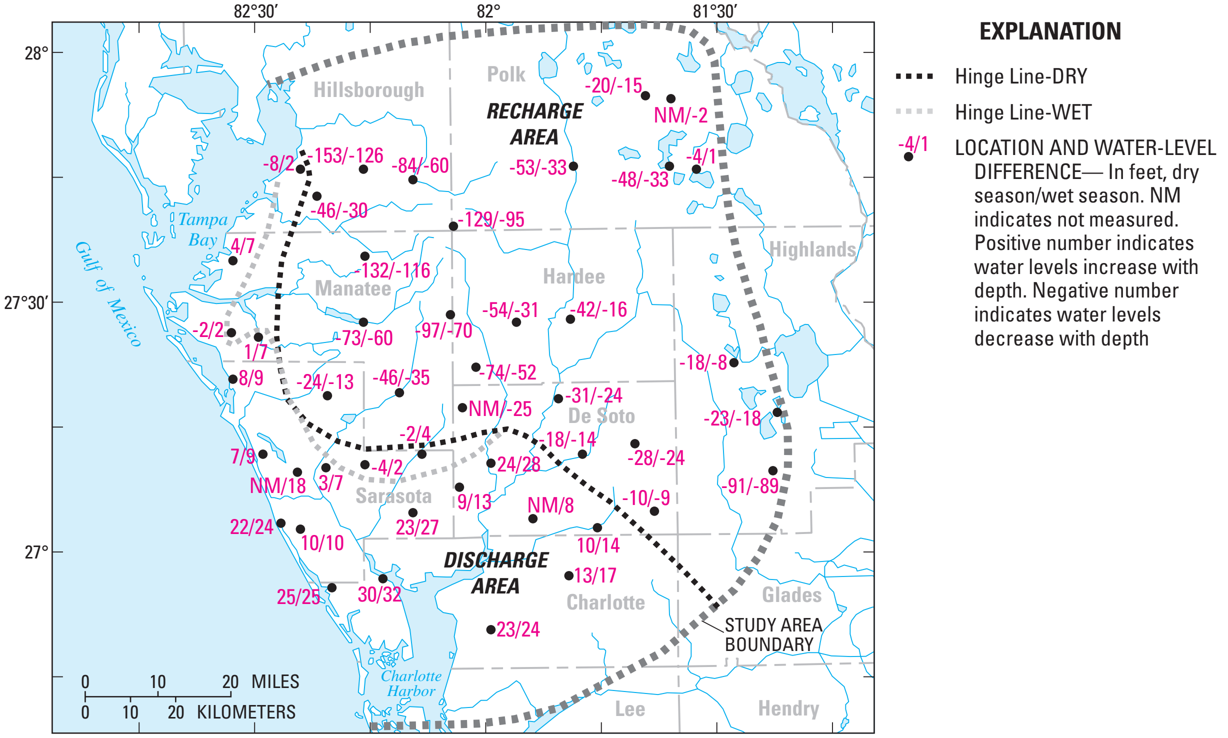
Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 13. (Continued) Leakance values, in foot per day per foot, shown on sections and maps at selected Regional Observation and Monitor-well Program sites.

The apparent randomness of the leakance values is due in part to the limited geographical extent of Zone 1, and overall good hydraulic connection between Zone 3 and the Upper Floridan aquifer. Zone 2, however, typically is hydraulically separated from the adjacent aquifers; therefore it was deemed appropriate to evaluate leakance in terms of an *upper* and *lower* group of confining units. The upper group includes any and all intermediate aquifer system confining units above Zone 2; the lower group includes any and all intermediate aquifer system confining units below Zone 2, multiple leakance values listed for a site indicate the presence of more than one confining unit within the upper or lower group (figs. 13b,c). Leakance values for the upper group range from 5.8x10^{-7} to 7.9x10^{-4} (ft/d)/ft and values for the lower group range from 4.3x10^{-7} to 1.1x10^{-3} (ft/d)/ft. The mean, geometric mean, and median values for the upper group are 9.9x10^{-5}, 2.0x10^{-5}, and 1.5x10^{-5} (ft/d)/ft; and for the lower group are 1.1x10^{-4}, 1.2x10^{-5}, and 1.8x10^{-5} (ft/d)/ft, respectively (table 3). Despite the large overall range in leakance, the most frequent values for both groups of confining units within the intermediate aquifer system are about the same order of magnitude (10^{-5}), which is about 2 orders of magnitude lower than the semiconfining unit (Ocala) separating the upper permeable zone (UPZ; Suwannee Limestone) from the lower permeable zone (LPZ; Avon Park Formation) in the Upper Floridan aquifer (table 3; fig. 13a).

Hydraulic Head Differences

Differences between hydraulic heads of aquifers in the study area were used to characterize recharge and discharge areas, to illustrate the magnitude and direction of vertical flow, and to qualitatively assess the degree of interconnection between permeable units. The magnitude of the head differences at a particular site reflects the degree of confinement between the aquifers and zones, and is related to the lithologic composition and thickness of the confining units. Thicker and hydraulically tighter confining units typically result in greater head differences and reduced hydraulic connection between zones. Small differences indicate good hydraulic connection and larger differences indicate greater hydraulic separation. Head differences between permeable units create the potential for vertical ground-water flow across confining units (Wilson, 1977). In 2001, head differences varied from as much as -153 ft (downward head difference) in the recharge area to more than 30 ft (upward head difference) in the discharge area (fig. 14; app. 2A (April) and app. 2B (October)). The transition from recharge to discharge conditions is abrupt, and is delineated by a *hinge line*, a boundary line separating recharge areas from discharge areas (Freeze and Cherry, 1979). The hinge line divides De Soto County, passes through east central Sarasota County, and parallels the coast in Sarasota, Manatee, and Hillsborough Counties (fig. 14). The hinge line moved slightly south in Sarasota County between the dry and wet



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 14. Recharge and discharge areas and magnitude of water-level differences between the surficial aquifer system and the Upper Floridan aquifer during the wet and dry seasons, 2001.

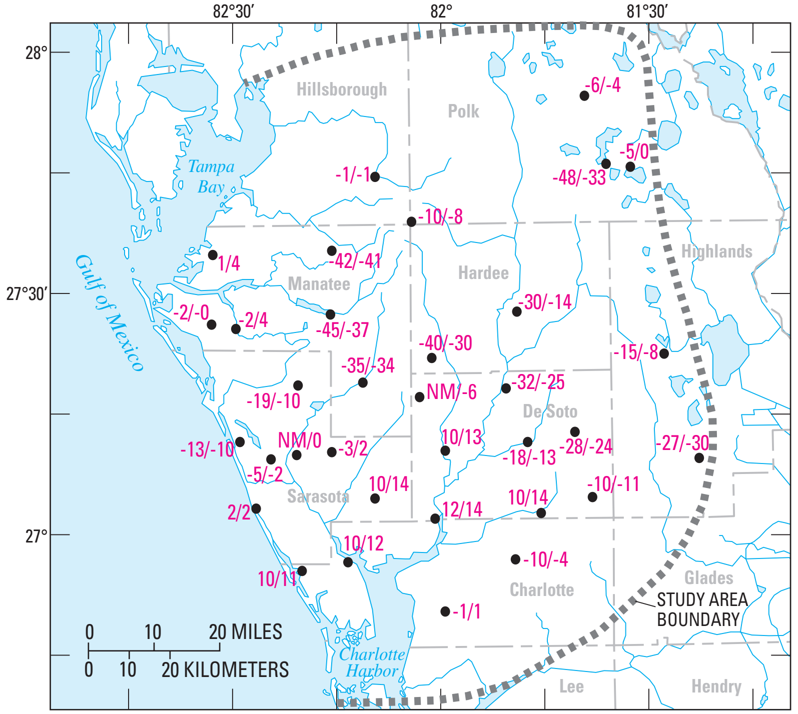
seasons in 2001. Water-level differences and potential flow directions between zones in wells that are located close to the hinge line alternate seasonally between discharge and recharge conditions.

Hydraulic heads differ among zones within the intermediate aquifer system and between these zones and adjacent aquifers. Generally, head differences are greater across the intermediate aquifer system than between the intermediate aquifer system and adjacent aquifers. In the small part of the study area where Zone 1 is found, head differences between Zone 1 and the surficial aquifer system range from -1 to 3 ft. Additionally, heads are nearly the same (<1 ft) between Zone 3 and the Upper Floridan aquifer, except in coastal Charlotte and Sarasota Counties where the differences range from 2 to 10 ft (ROMP sites TR3-1, TR3-3, TR4-1, TR5-1, TR5-2, 20, and SA-1) and inland sites where differences range from <-1 to -5 ft (ROMP sites 9.5, 17, 30, 31, 45, and 49) (app. 2A-B). Total head differences between the surficial aquifer system and the Upper Floridan aquifer range from -153 to 30 ft, and head differences between the intermediate aquifer system and adjacent aquifers are within plus or minus 5 ft. Therefore, the large remainder of these differences in head is found between adjacent zones within the intermediate aquifer system.

Because of the absence of Zones 1 and 3 in parts of the study area, differences in hydraulic head across the intermediate aquifer system were evaluated by separating the confining units into an upper and lower group of units. Differences in hydraulic head across the upper group of units were defined by water-level differences between the surficial aquifer system and Zone 2 during 2001. Differences in hydraulic head across the lower group of units were defined by water-level differences between Zone 2 and the Upper Floridan aquifer during 2001. Water-level differences between the surficial aquifer system and Zone 2 ranged from about -48 to 14 ft, and water-level differences between Zone 2 and the Upper Floridan aquifer ranged from -119 to 24 ft (fig. 15). In the discharge area (Charlotte, most of Sarasota, and coastal Manatee and Hillsborough Counties), upward head differences between Zone 2 and the Upper Floridan aquifer are greatest. With a few exceptions, downward head differences between the surficial aquifer system and Zone 2 are greatest in the recharge area.

Water levels in aquifers in southwest Florida follow a natural cyclic pattern of seasonal fluctuation, typically rising during the summer wet season (when the rate of recharge exceeds the rate of discharge) and falling to the lowest levels in the spring dry season (when the rate of discharge exceeds the rate of recharge). The magnitude of fluctuation in water

(A) Water-level difference between the surficial aquifer system and Zone 2 of the intermediate aquifer system.



EXPLANATION

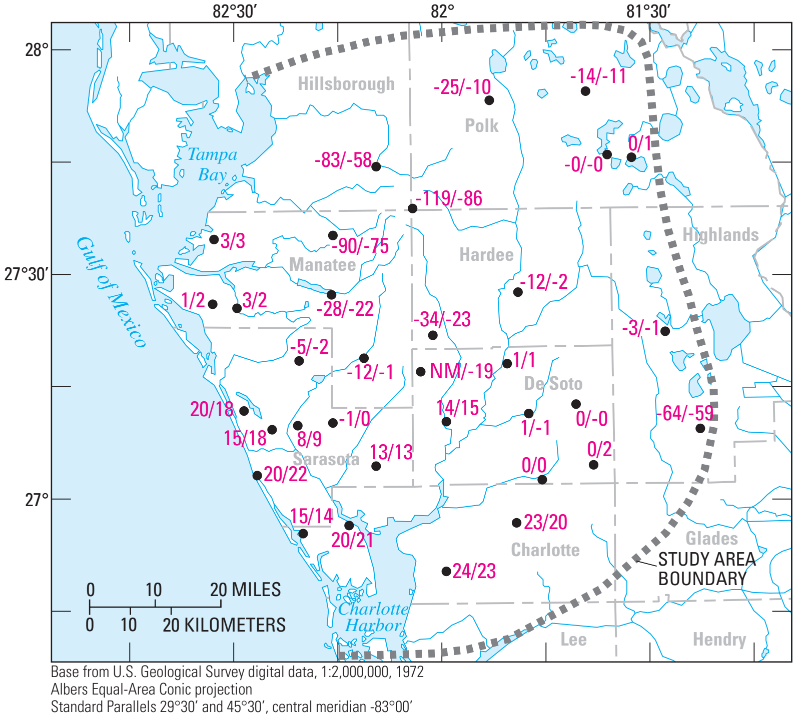
-5/0 ● LOCATION AND WATER-LEVEL DIFFERENCE— In feet, dry season/wet season. NM indicates not measured. Positive number indicates water levels increase with depth. Negative number indicates water levels decrease with depth

NOTE: Values of -0 indicate that the difference was less than 0 but not greater than -0.5 feet.

Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 15. Water-level differences during the wet and dry seasons, 2001.

(B) Water-level difference between Zone 2 of the intermediate aquifer system and the Upper Floridan aquifer.



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

EXPLANATION

● 0/1 LOCATION AND WATER-LEVEL DIFFERENCE— In feet, dry season/wet season. NM indicates not measured. Positive number indicates water levels increase with depth. Negative number indicates water levels decrease with depth

NOTE: Values of -0 indicate that the difference was less than 0 but not greater than -0.5 feet.

Figure 15. (Continued) Water-level differences during the wet and dry seasons, 2001.

levels can vary greatly from season to season and from year to year in response to varying climatic conditions. Additionally, the magnitude and timing of seasonal water-level fluctuations may vary in different aquifers in the same geographic area, depending on the sources of recharge to and discharge from the aquifers and the hydraulic properties of each (Taylor and Alley, 2001). Water levels in wells at most of the ROMP sites also are affected by nearby pumping. The withdrawal of ground water by pumping is the most important human activity that alters the volume of water in storage, the rate of discharge from aquifers, and the direction of flow both horizontally and vertically (Taylor and Alley, 2001). Declines in ground-water levels can alter the potential flow direction among zones within the intermediate aquifer system and between the intermediate aquifer system and adjacent aquifers. Temporary changes in vertical flow direction likely result from localized heavy but short-lived pumping conditions; whereas widespread, long-term ground-water pumping can lead to persistent ground-water level declines and gradient changes, creating new recharge areas within the aquifer system (Galloway and others, 1999). Ranges in the annual water-level fluctuation, seasonal variations, and cumulative effects of short-term and long-term hydrologic stresses in the aquifers throughout the study area are exhibited on hydrographs of water levels from nested wells (fig. 16).

Changes in the potential vertical flow direction were observed at 14 ROMP sites in the study area (fig. 16a). Under ambient (nonpumping) conditions, 13 of the 14 sites are in the discharge area and heads increase with depth. Under stressed (pumping) conditions, changes in the vertical head distribution range in duration from less than a day (temporary), to short-term (seasonal), to long-term (year-round). Changes may affect the entire ground-water system or only certain zones at a site. Ground-water development is primarily from the upper intermediate aquifer system (Zones 1 and/or 2) in the southern part of the study area, coincident with the occurrence of poor quality water in the deeper zones (Sutcliffe, 1975).

Potential vertical ground-water flow patterns, based on water-level differences in cluster wells, can be grouped into five categories: (1) decreasing water levels with depth (downward flow potential); (2) increasing water levels with depth (upward flow potential); (3) water levels that are lower in the upper intermediate aquifer system (Zones 1 or 2) than in adjacent aquifers (both upward and downward flow potential); (4) unstressed water levels that increase with depth (upward flow potential) but under temporary stressed conditions water levels are lowered in the upper intermediate aquifer system (upward and downward flow potential); and (5) water levels that alternate seasonally between increasing water levels with depth during the wet season and decreasing water levels with depth during the dry season (upward and downward flow potential throughout the entire ground-water flow system) (fig. 16a).

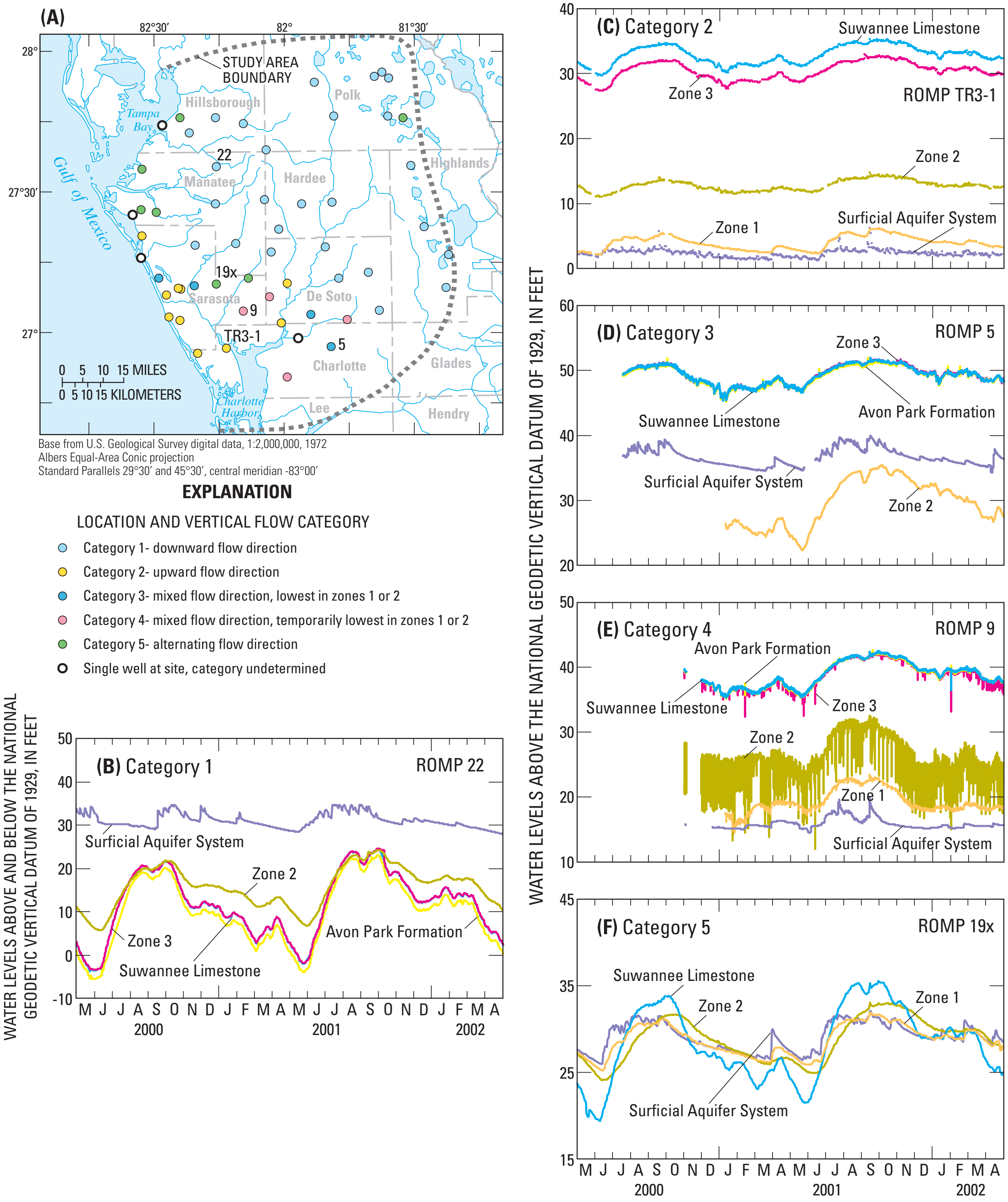


Figure 16. Flow potential category and representative water-level hydrographs.

The ROMP 22 site is an example of the first category, where water levels decrease with well penetration depth (fig. 16b; table 1). Water-level differences among wells vary seasonally in that differences are typically lower during the late summer (lower recharge potential) and higher during the late spring (higher recharge potential). A persistent water-level difference of about 2 ft is observed within the Upper Floridan aquifer, between the Suwannee and Avon Park wells, but no measurable difference is observed between the Suwannee and Zone 3 wells. Zone 2 is hydraulically separated from the surficial aquifer system, and the water-level difference between the wells in these two zones is as much as 20 ft. During unstressed periods (wet season), heads are nearly identical within zones of the intermediate aquifer. During stressed periods (dry season), however, heads are about 10 ft lower in Zone 3 than in Zone 2.

The ROMP TR3-1 site is an example of the second category, where water levels increase with well penetration depth (fig. 16c). Head differences at this site are smaller between the intermediate aquifer system and adjacent aquifers (2 ft or less) compared to head differences between zones within the intermediate aquifer system (10 ft between Zones 1 and 2, and 15 ft between Zones 2 and 3). In May and June, water levels are about the same in Zone 1 and surficial aquifer system wells. Water-level fluctuations are similar in all of the wells, so differences and potentials for upward flow are about the same throughout the year.

The ROMP 5 site is an example of the third category, where water levels are lowest year-round in the Zone 2 well (about 20 ft lower than levels in the Suwannee, Avon Park, and Zone 3 wells) (fig. 16d). Water levels are the same in Suwannee, Avon Park, and Zone 3 wells. Water-level differences between the Zone 2 and surficial aquifer system wells annually fluctuate, ranging from 3 to 10 ft and averaging about 5 ft. Thus, during 2000-2002, there was the potential for both upward and downward flow from adjacent aquifers into Zone 2.

The ROMP 9 site is an example of the fourth category, an area where the potential for upward flow exists during unstressed conditions, but during stress conditions, water levels are temporarily lower in the intermediate aquifer system than in the surficial aquifer system. At this site, water levels are about 20 ft higher in the Suwannee and Avon Park wells than in the surficial aquifer system well (fig. 16e). This 20-ft water-level difference essentially occurs within the intermediate aquifer system, with nearly equivalent differences between the Zones 3 and 2 wells, and between the Zones 2 and 1 wells (about 10 ft, respectively). During pumping periods, however, water levels in the Zone 2 well may temporarily decline below the levels in the Zone 1 well and occasionally below levels in the surficial aquifer system as well. Thus, during momentary pumping periods in 2000-2002, there was the potential for both upward and downward flow from adjacent zones (Zones 1 and 3) and aquifers (surficial aquifer system and Upper Floridan aquifer) into Zone 2.

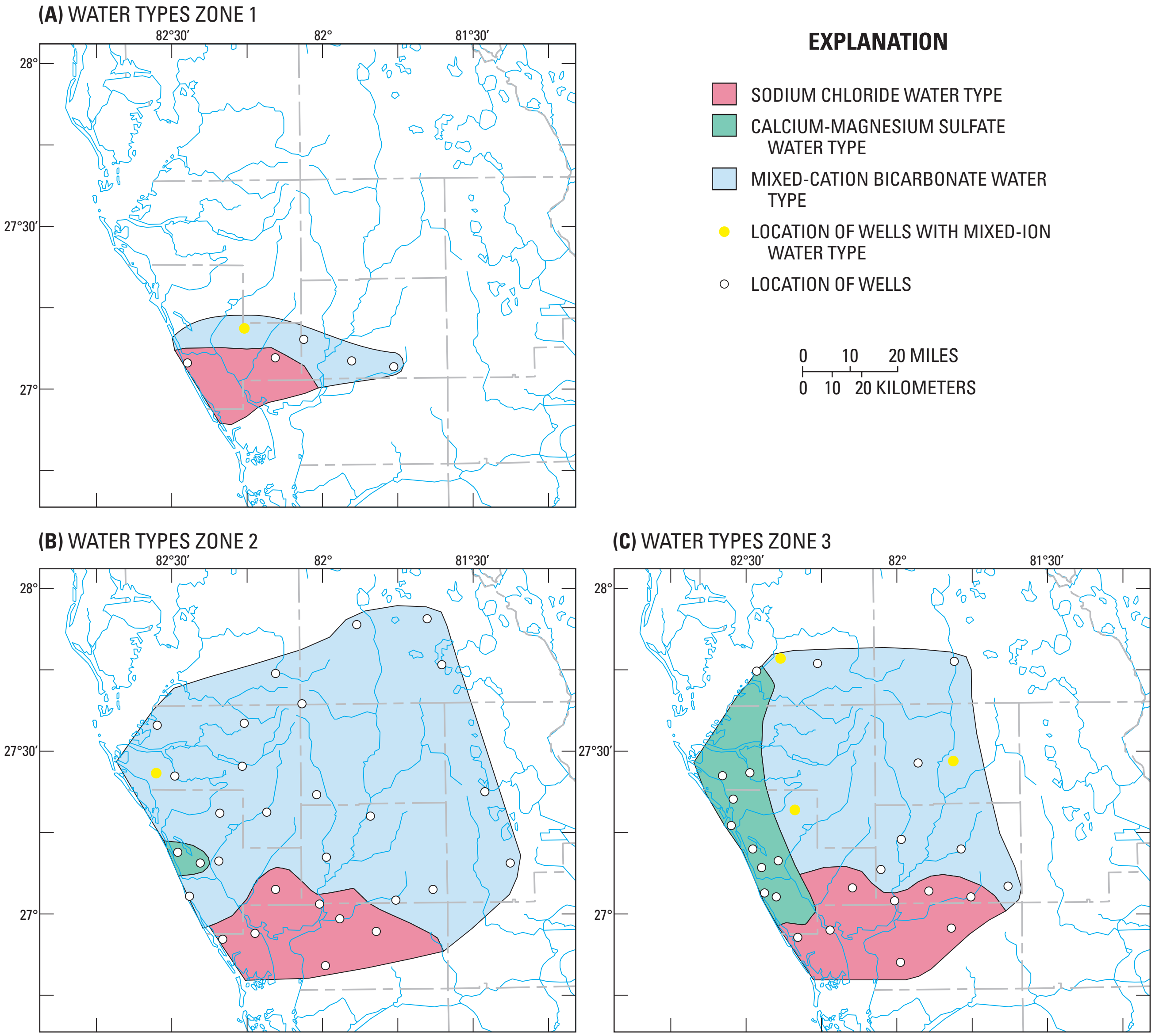
The ROMP 19X site is an example of the fifth category, where both upward and downward flow potential occurs. Water levels increase with well penetration depth by the end of wet season (September and October), decrease with well penetration depth by the end of the dry season (April and May), and are mixed during the rest of the year (fig. 16f). The mixed gradients result from the timing of seasonal water-level fluctuations (maximums and minimums) among the aquifers. Annually, water-level differences between the wells penetrating the Upper Floridan aquifer and the surficial aquifer system vary from -4 to 3 ft. Most of the time, water levels are nearly the same in the surficial aquifer system and Zone 1 wells. During the winter (January and February), water levels are nearly the same throughout the intermediate aquifer system, in the surficial aquifer system, and occasionally in the Upper Floridan aquifer.

In general, the magnitude of the water-level differences among wells at a particular site reflects the degree of confinement between the aquifers and zones, and is related to the lithologic composition and thickness of the confining units. Thicker and hydraulically tighter confining units typically result in greater water-level differences and reduced hydraulic connection between zones. Small differences indicate good hydraulic connection and larger differences indicate greater hydraulic separation.

Regional Evaluation of the Intermediate Aquifer System

A regional evaluation of the chemical characteristics, hydraulic properties, head gradients, and water-level responses is presented below. Comparisons among zones, particularly the distribution of the hydraulic properties and chemical characteristics, indicate that the study area can be separated into interrelated subgroups (subregions with similar characteristics) regardless of the intermediate aquifer system zone.

Comparison of the chemical composition of water among the zones indicates the lack of a distinct geochemical signature that characterizes individual zones. In contrast, the geographic distribution of water types in all zones is similar (fig. 17). Sodium chloride type water is present in the southernmost part of the study area in all zones, with the likely source of sodium and chloride from relict saltwater from past marine inundations during periods of high sea level stand that has not been flushed from the aquifers (DeHaven and Jones, 1996). Calcium-magnesium sulfate type water is present along the coastal margin from Tampa Bay to southern Sarasota


(A) WATER TYPES ZONE 1

(B) WATER TYPES ZONE 2

(C) WATER TYPES ZONE 3

Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 17. Distribution of water types in Zones 1, 2, and 3.

County, with the likely source of magnesium and sulfate from upwelling of sulfate-rich waters from the Upper Floridan aquifer (Sacks and Tihansky, 1996). Mixed-cation bicarbonate type water is present in the inland areas, and is the predominant water type within the intermediate aquifer system, with the likely source of magnesium and calcium from the dolomitic aquifer matrix.

The overall permeability in the intermediate aquifer system is best characterized as low to moderately low. Comparisons of the hydraulic characteristics among the zones were made using standard boxplots of the transmissivity data available from 93 wells. Of the 93 wells, 15 percent (14 wells), 45 percent (43 wells), and 39 percent (36 wells) were open to Zones 1, 2, and 3, respectively (fig. 18). The data sets are similar in the following ways; each of the boxplots shows (1) a median line that is closer to the lower quartile than the upper, indicating a greater number of low values, and (2) the taller top box halves and significantly longer upper whiskers indicate a right-skewed distribution (fig. 18). Right-skewed distributions are the most commonly occurring shape for water-resources data (Helsel and Hirsch, 1992).

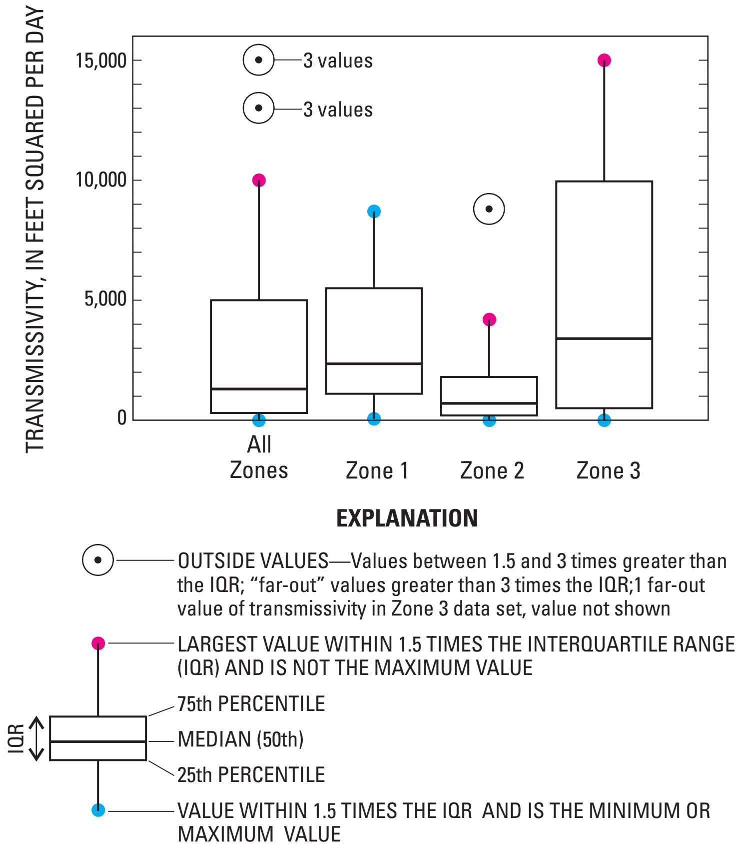


Figure 18. Box plots of transmissivity.

The statistically defined differences among the zones can be seen in the variations in the median values and interquartile ranges. Zone 2 is the least transmissive with the lowest median value, which is less than half the Zone 1 value. The median transmissivity for Zone 3 is highest, with a value twice as large as the value for Zone 1 and more than four times the value for Zone 2. The spread of the data is smallest for Zone 2, medium for Zone 1, and largest for Zone 3. Zone 2 has a single outside value of transmissivity (value between 1.5 and 3 times the interquartile range) and Zone 3 has a single far-out value of transmissivity (value beyond 3 times the interquartile range). When all zones are combined, there are seven transmissivity outliers (six outside values and one far-out value).

The permeability distribution within each zone was mapped, creating *permeability subregions* that were defined using ranges of transmissivity (fig. 19). Zone 1 underlies the smallest part of the study area and is present in southwestern Manatee and De Soto Counties and most of Sarasota and Charlotte Counties (fig. 19a). Transmissivities are between 1,000 and 10,000 ft^2/d, except at three isolated sites. Data are lacking for almost half of the area; where data are available, Zone 1 is characterized as moderately permeable (fig. 19a).

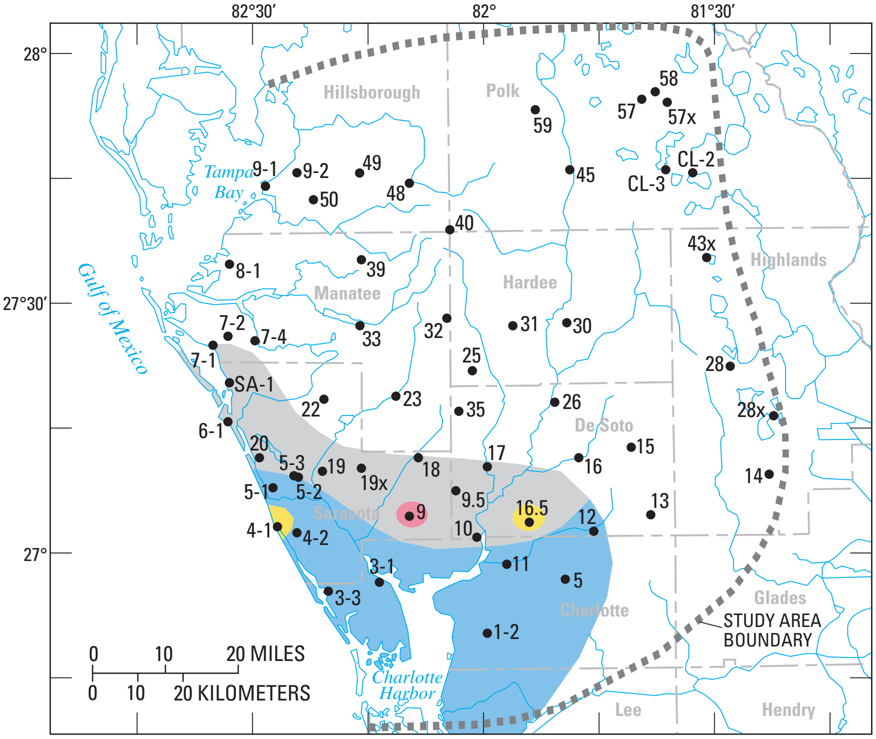
Of the three zones, Zone 2 underlies the largest part of the study area. More than half of the study area has transmissivities in Zone 2 that are moderately low, ranging from 100 to $<1,000$ ft^2/d. Three regions within Zone 2 have transmissivities between 1,000 and 10,000 ft^2/d and are characterized as moderately permeable (blue areas in fig. 19b). A larger region that has moderately low permeability separates these three smaller regions. A region of low permeability (transmissivity ranging from 1 to <100 ft^2/d) is located in the central part of the study area.

Zone 3 underlies the southern half of Manatee County, south central Polk County, all of Sarasota County and most of Hardee, De Soto, and Charlotte Counties. In eastern De Soto, southeastern Charlotte, western Hillsborough, and northwestern Manatee Counties, the carbonate strata of the lower Arcadia Formation and the Suwannee Limestone are contiguous and Zone 3 is included in the Upper Floridan aquifer rather than the intermediate aquifer system (Reese, 2000; Basso, 2002). The permeability of Zone 3 in the intermediate aquifer system ranges from low to moderately high; lowest transmissivities are present in the central part, transmissivities are highest near the coast in southwestern Sarasota County, and moderate transmissivities predominate in the coastal and southern parts of the study area (fig. 19c).

More noticeable than variations within zones, however, is the geographical distribution of transmissivity resulting from the lithologic variability and differences in the depositional environment in the study area. More carbonate sediments where deposited in the southern and southwestern parts of the study area where transmissivity is higher, whereas siliciclastic sediments were deposited throughout the rest of the study area where transmissivity is lower. Specifically, a region of relatively low transmissivity (<100 ft^2/d) throughout the vertical extent of the intermediate aquifer system is present in the central part of the study area encompassed by a larger region of moderately low permeability ($<1,000$ ft^2/d) that covers a large part of the study area. Therefore, permeability subregions based on ranges of transmissivity can be defined geographically for the intermediate aquifer system regardless of zone.

Water-level differences reflect the degree of confinement between aquifers and zones, well location with respect to the regional ground-water flow system (recharge/discharge), and ground-water withdrawals. Thicker and hydraulically tighter confining units typically result in greater head differences and reduced hydraulic connection between zones. Markedly thinner or absent confining units result in nonexistent or small water-level differences and indicate good hydraulic connection. The following water-level characteristics were noted in the study area. Water-level differences are equivalent or nearly so between surficial aquifer system and Zone 1 wells, and between Zone 3 and Upper Floridan aquifer wells. Water levels in Zone 2 wells typically are distinct from levels measured in adjacent zones at a site. The recharge area (decreasing water levels with well penetration depth) encompasses more than 70 percent of the study area. Water levels alternate seasonally between increasing and decreasing water levels with depth along the hinge line separating the discharge and recharge areas. Ground-water withdrawals from Zones 1 and 2 in the southern part of the study area have lowered levels in these zones, causing recharge to the intermediate aquifer system from both the surficial aquifer system and the Upper Floridan aquifer.

(A) ZONE 1



EXPLANATION

▨ NO DATA

🟥 LOW PERMEABILITY—Transmissivity is less than 100 feet squared per day

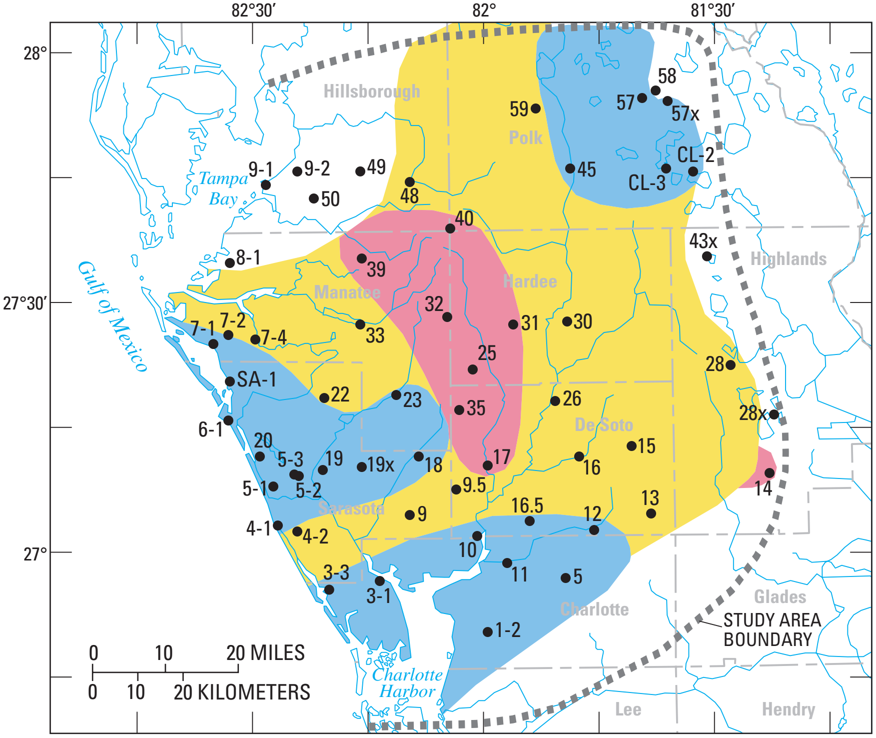
🟨 MODERATELY LOW PERMEABILITY—Transmissivity is greater than 100 and less than 1,000 feet squared per day

🟦 MODERATE PERMEABILITY—Transmissivity is greater than 1,000 and less than 10,000 feet squared per day

🟩 MODERATELY HIGH PERMEABILITY—Transmissivity is greater than 10,000 and less than 100,000 feet squared per day

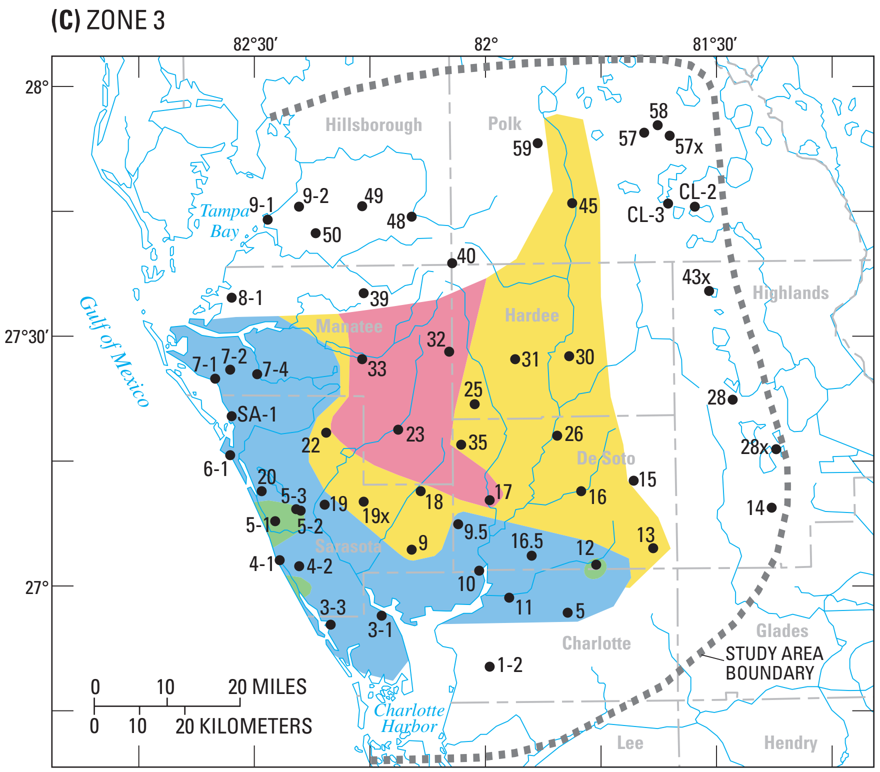
14● ROMP SITE LOCATION AND NUMBER

(B) ZONE 2



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 19. Permeability subregions and transmissivity ranges in Zones 1, 2, and 3.



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30′ and 45°30′, central meridian -83°00′

Figure 19. (Continued) Permeability subregions and transmissivity ranges in Zones 1, 2, and 3.

Summary

Whereas the intermediate aquifer system is considered a single entity that generally coincides with the Hawthorn Group stratigraphic unit, it is composed of multiple water-bearing zones separated by confining units. Deposition of a complex assemblage of carbonate and siliciclastic sediments during the late Oligocene to early Pliocene time resulted in discontinuities that are reflected in transitional and abrupt contacts between facies. Discontinuous facies produce water-bearing zones that may be locally well-connected or culminate abruptly. Changes in the depositional environment created a multilayered system with as many as three zones of enhanced water-bearing capacity. At the extremities of the study area, the Hawthorn Group is missing or composed of fine grain sediments that lack permeable units. In parts of the study area where the Hawthorn Group lacks permeable units, it behaves hydraulically as a confining unit rather than an aquifer system and is often referred to as the intermediate confining unit.

The lithologic composition of the Hawthorn Group, especially the presence of clay beds, controls lateral and vertical ground-water flow and influences the hydraulic connectivity between water-bearing zones in the intermediate aquifer system. The zones are designated, in descending order, Zone 1, Zone 2, and Zone 3. Zone 1 is thinnest (<80 ft thick) and limited to the southern part (<20 percent) of the study area. Zone 2 is the found throughout most of the study area but has moderately low transmissivity. Zone 3 is found south of central Manatee and southern Polk County (about 50 percent of the study area), has the highest transmissivities, and generally is in good hydraulic connection with the underlying Upper Floridan aquifer. In parts of the study area, particularly in southwestern Hillsborough County and southeastern De Soto and Charlotte Counties, the carbonates that compose Zone 3 are contiguous with the Upper Floridan aquifer and function as a single hydrogeologic unit.

Transmissivity of the intermediate aquifer system ranges over 5 orders of magnitude, from about 1 to more than 40,000 ft^2/d, but rarely exceeds 10,000 ft^2/d. The overall transmissivity of the intermediate aquifer system is substantially lower (2 to 3 orders of magnitude) than the underlying Upper Floridan aquifer. Transmissivity varies vertically among the zones within the intermediate aquifer system and geographically (from site to site) within a zone. Both the median value and interquartile range of transmissivity values are statistically different among the zones, and samples are not normally distributed. All transmissivity values are skewed to the right towards higher transmissivity values. Zone 2 has the lowest median transmissivity (700 ft^2/d) and the smallest interquartile range, Zone 1 has a moderate median transmissivity (2,250 ft^2/d) and interquartile range, and Zone 3 has the highest median transmissivity (3,400 ft^2/d) and interquartile range.

More noticeable than variations within zones, however, is the geographical distribution of transmissivity resulting from the lithologic variability and differences in the depositional environment in the study area. Permeability subregions based on ranges of transmissivity can be defined geographically for the intermediate aquifer system regardless of zone. Specifically, throughout the vertical extent of the intermediate aquifer system the highest permeability (thousands to tens of thousands feet squared per day) is present in the southwestern part of the study area corresponding to areas with greater carbonate deposition. A region of relatively low transmissivity (<100 ft^2/d) is present in the central part of the study area encompassed by a larger region of moderately low permeability ($<1,000$ ft^2/d) that covers a large part of the study area. Areas of lower transmissivity correspond to greater siliciclastic deposition.

Clay beds and fine-grained carbonates form the confining units separating the water-bearing zones, influence the hydraulic connectivity, and control the vertical exchange of water between aquifers and zones. The potential for the vertical flow of water across confining units is defined as leakance. Leakance through the intermediate aquifer system confining units ranges over 4 orders of magnitude from 4.2×10^{-7} to 6.0×10^{-3} (ft/d)/ft. Despite the large range, the geometric mean and median leakance are within the same order of magnitude, 10^{-5} (ft/d)/ft, and 2 orders of magnitude less than the median leakance of the semiconfining unit within the Upper Floridan aquifer. The geometric mean and median values of leakance are within the same order of magnitude (10^{-5}) for both the upper and lower groups of confining units, which is about 2 orders of magnitude lower than the leakance of the semiconfining unit within the Upper Floridan aquifer. There is no apparent pattern in the leakance data for the intermediate aquifer system, such as increasing or decreasing leakance with depth or location.

Concentrations of major ions generally increase with depth both in the intermediate aquifer system and throughout the ground-water flow system. The chemical composition of water in zones of the intermediate aquifer system lacks a distinct geochemical signature characterizing an individual zone, and overall is more varied than the adjacent aquifers. This variation is related to the types of minerals forming the aquifer matrix, and complex mixing of waters from adjacent aquifers. The dominant water type throughout the intermediate aquifer system is mixed-cation bicarbonate, typically with nearly equal concentrations of calcium and magnesium ions. The mixed-cation bicarbonate type water is the most prevalent type in the intermediate aquifer system. Sodium chloride type water is present in the southernmost part of the study area in all zones. The source of the sodium and chloride is relict seawater emplaced during past marine inundations that has not been flushed from the aquifers. Calcium-magnesium sulfate type water is present along the coastal margin from Tampa Bay to southern Sarasota County in Zone 3 and at two Zone 2 wells in west-central Sarasota County. The source of the magnesium and sulfate is upwelling from the Upper Floridan aquifer.

Differences in hydraulic head generally are greater between adjacent zones within the intermediate aquifer system than between the adjacent aquifers. Heads differences between Zone 1 and the surficial aquifer system range from -1 to 3 ft, and heads are nearly the same (<1 ft) between Zone 3 and the Upper Floridan aquifer except at seven sites in coastal Charlotte and Sarasota Counties and six inland sites. Whereas head differences across the upper (between the surficial aquifer system and Zone 2) and lower (between Zone 2 and the Upper Floridan aquifer) groups of confining unit of the intermediate aquifer system range from -48 to 14 ft and from -119 to 24 ft, respectively. Larger head differences indicate hydraulic separation of zones within the intermediate aquifer compared to between the intermediate aquifer system and adjacent aquifers.

In general, the overall permeability of the intermediate aquifer system is low relative to the Upper Floridan aquifer, permeability and water-quality contrasts can be defined geographically regardless of zone, and Zone 2 is the most hydraulically isolated and spatially extensive water-bearing unit in the study area.

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