Numerical Simulation of Aquifer Tests, West-Central Florida

By Dann K. Yobbi and Keith J. Halford

Prepared in cooperation with the
Southwest Florida Water Management District

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Conversion Factors, Datums, Abbreviations, and Acronyms

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	0.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
	Flow rate	
foot per day (ft/d)	0.3048	meter per day
inch per year (in/yr)	25.4	millimeter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day
	Leakance	
gallon per minute per cubic foot [(gal/d)/ ft^3)]	0.09290	meter squared per meter
foot per day per foot [(ft/d)/ft] or, in reduced form (day^{-1})	1.0000	meter per day 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).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

ADDITIONAL ABBREVIATIONS

b	saturated thickness of unit
b'	confining-bed thickness
h_{km}	measured water level
h_{ks}	simulated water level
K	hydraulic conductivity
K'	vertical hydraulic conductivity
L	leakance
n	number of observations
r_i	radial distance to center of i th column
R^2	coefficient of determination
S	storativity
S_s	specific storage
S_y	specific yield
T	transmissivity
W_i	weighting factor

ACRONYMS

AVP	Avon Park Formation
CV	coefficient of variation
IAS	Intermediate aquifer system
ICU	Intermediate confining unit
MODFLOW	USGS modular three-dimensional ground-water flow model
MODOPTIM	computer program linking MODFLOW with an optimization routine
Z1	Intermediate aquifer system Zone 1
Z2	Intermediate aquifer system Zone 2
Z3	Intermediate aquifer system Zone 3
RCS	relative composite sensitivity
RMSE	root mean squared error
ROMP	Regional Observation Monitoring Program
SAS	Surficial aquifer system
S_s	sum-of-squares residuals
SUW	Suwannee Limestone
SWFWMD	Southwest Florida Water Management District
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey

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Abstract

This report presents the reinterpretation of 41 aquifer tests that were conducted from 1980 through 2004 at 13 sites in west-central Florida. The report is intended to expand upon the previous analyses of the Southwest Florida Water Management District by using numerical ground-water flow modeling and a method of automatic parameter estimation. Multiple aquifer tests of different hydrogeologic units at test sites are simulated with a single, radial axisymmetric numerical model that shifts between production wells for each stress period of a multiple aquifer test. The approach provides for better aquifer-test analysis of layered aquifer systems than separate interpretation of aquifer tests because more features of the ground-water system can be collectively simulated and constrained by the observations. Simulated hydraulic property values for aquifers and confining units are consistent with what is known about the aquifer systems at the various sites.

Introduction

In 1975, the Southwest Florida Water Management District (SWFWMD) began the Regional Observation and Monitoring-Well Program (ROMP) of test drilling and aquifer testing to increase their knowledge of the hydrogeologic system in west-central Florida. One of the objectives of this program was to assess the hydraulic properties of aquifers and confining units. The present monitoring program consists of many inland and coastal monitoring sites generally containing three to six wells. Aquifer testing provides the most realistic assessment of the hydraulic properties of the system and forms the foundation for determining the availability of ground water and the impact of withdrawals on future and existing users, and the environment.

Field-scale, vertical hydraulic conductivities of confining units in layered, multiple aquifer systems have been difficult to estimate. Multiple aquifer tests have been conducted at many of the ROMP sites; however, carefully controlled and successful aquifer tests are conducted with difficulty because the aquifer systems have a layered and nonuniform permeability distribution. Leakage between multiple aquifers is difficult to differentiate with analytical solutions and a single aquifer test. Vertical hydraulic conductivity estimates have been routinely discarded because leakage was not differentiated correctly.

Simulation of multiple aquifer-test data with a single radial axisymmetric numerical model of an entire hydrogeologic system provides an alternative method of determining hydraulic properties of multiple aquifers and confining units. Numerical modeling takes advantage of the geologic knowledge already developed for the systems, in combination with the data collected from one or more aquifer tests. The numerical simulations and results are considered more realistic for complex ground-water flow compared to analysis of independent tests using analytical methods because of the inherent limitations in applying analytical solutions derived for relatively simple hydrogeologic conditions to a complex system, and because more features of a complex ground-water system can be collectively simulated and constrained by observations.

As the demand for water in southwest Florida increases, more information is needed to efficiently develop and manage the ground-water flow system. A better understanding of the vertical and areal variability in hydraulic properties of the aquifer systems is essential for assessing ground-water availability.

Purpose and Scope

The primary purpose of this report is to present the results of the reinterpretation of 41 aquifer tests that were conducted from 1980 through 2004 at 13 sites in west-central Florida (fig. 1) using the U.S. Geological Survey (USGS) porous-media model MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). This report is intended to expand upon the previous analyses of SWFWMD by using axisymmetric numerical modeling and a method of automatic parameter estimation. This report describes the design, execution, and analyses of aquifer tests conducted at 13 areas in west-central Florida. The automatic, nonlinear optimization program, MODOPTIM (Halford, 1992), is used to calibrate the models to drawdown measured during aquifer tests conducted by the SWFWMD. Records of aquifer tests in the study area were reviewed and reanalyzed to provide estimates of hydraulic properties, primarily hydraulic conductivity and storativity of the aquifers and confining units. The report also contains information about the hydrogeologic conditions at the test sites, and the general testing procedure.

The modeling approach used in this study was developed to fill a need in west-central Florida. The results of this study have potential applicability in other settings across the Nation.

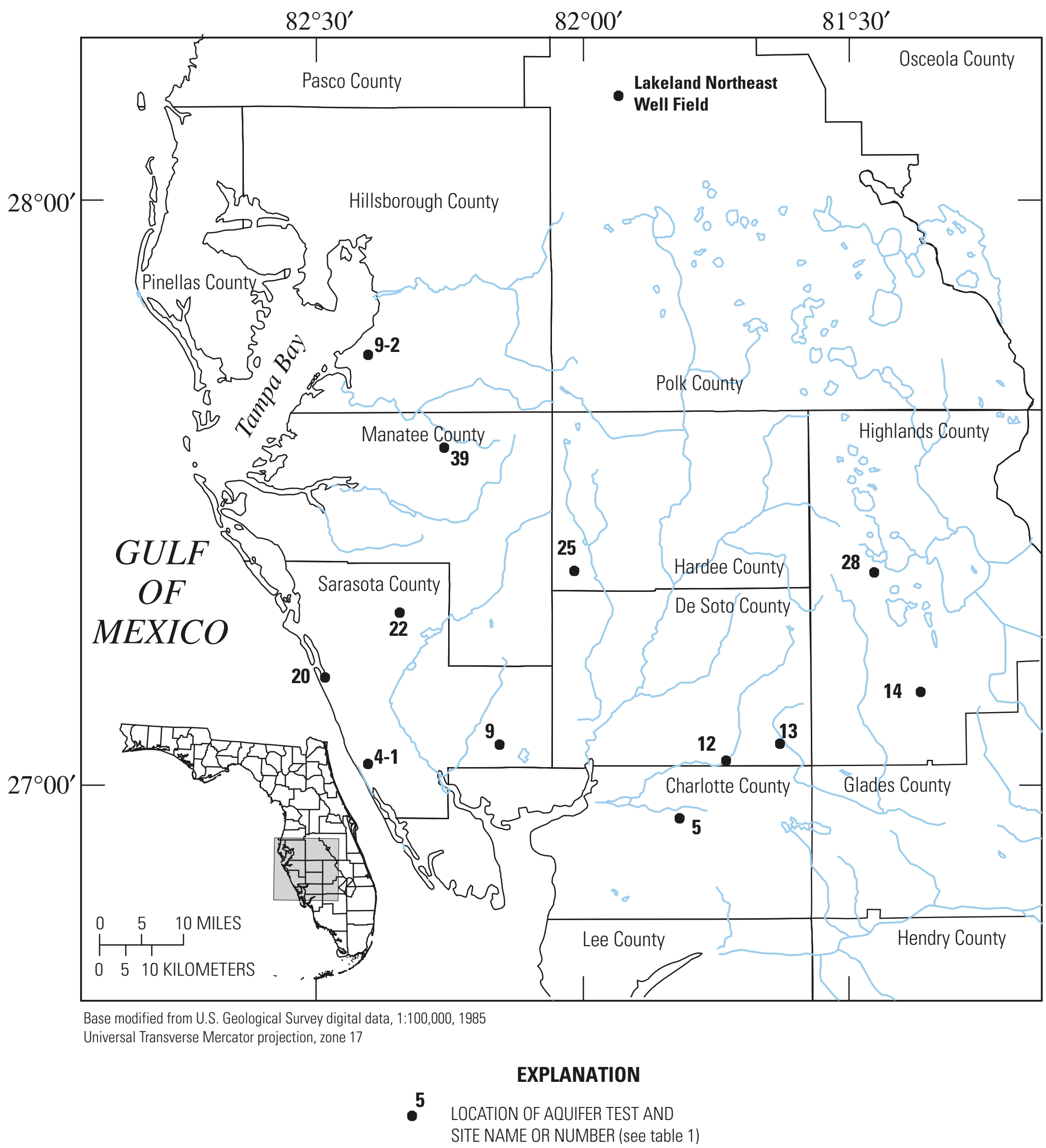


Figure 1. Location of aquifer-test sites in west-central Florida.

Acknowledgments

Special thanks are extended to Ted Gates at SWFWMD, who provided the necessary reports and electronic data files on aquifer tests in the study area. The authors also thank Ron Basso and Mark Barcelo at SWFWMD for their assistance and overwhelming support of this project. The discussion and analysis in this report were significantly improved by the thorough and insightful reviews given by Ed Weeks and Andy O´Reilly of the USGS, and Ron Basso, Michael Beach, and Jerry Mallams of SWFWMD.

Hydrogeologic Framework

The ground-water flow system can be characterized as a multi-aquifer system comprising permeable layers separated from each other by confining layers. Three aquifer systems are found in the study area—the surficial aquifer system, the intermediate aquifer system, and the Floridan aquifer system. The corresponding stratigraphic and hydrogeologic units underlying the study area are shown in figure 2. All deposits overlying the Hawthorn Group make up the surficial aquifer system. The deposits of the Hawthorn Group compose the intermediate aquifer system, and the underlying Oligocene and older carbonate rocks compose the Floridan aquifer system. The Floridan aquifer system consists of the Upper and Lower Floridan aquifers that are separated by a middle confining unit (Miller, 1986). The middle confining unit and the Lower Floridan aquifer in west-central Florida are saline and are not utilized for water supply. Each of these aquifer systems may include one or more water-producing zones separated by less permeable units.

The surficial aquifer system is the uppermost water-bearing formation and generally consists of undifferentiated clastic sediments. Because of the interbedded nature of the clastics composing the surficial aquifer system, more than one water-producing zone separated by beds of lower permeability may be present in this unit. The water-bearing capacity of the surficial aquifer system is largely dependent on the grain size, sorting, and saturated thickness of the sediments. Thickness of the surficial aquifer system varies widely over the study area and generally is less than 50 feet (ft), except in Highlands County, where the thickness can exceed 300 ft.

The intermediate aquifer system includes all rock units that lie between the overlying surficial aquifer system and underlying Upper Floridan aquifer, and generally coincides with the stratigraphic unit designated as the Hawthorn Group.

The intermediate aquifer system consists of (1) an upper sandy clay, clay, and marl confining unit that separates the upper permeable zones in the Peace River Formation from the surficial aquifer system; (2) a group of up to three water-producing zones (Zone 1, Zone 2, and Zone 3) separated by confining units and composed primarily of carbonate and sandy carbonate rocks (Peace River and Arcadia Formations); and (3) a lower sandy clay to clayey sand confining unit overlying the Upper Floridan aquifer (Nocatee Member or Undifferentiated Arcadia Formation) (Torres and others, 2001, and L.A. Knochenmus, U.S. Geological Survey, written commun., 2005). Thickness of the intermediate aquifer system ranges from less than 100 ft in southern Hillsborough County to more than 800 ft in southern Charlotte County.

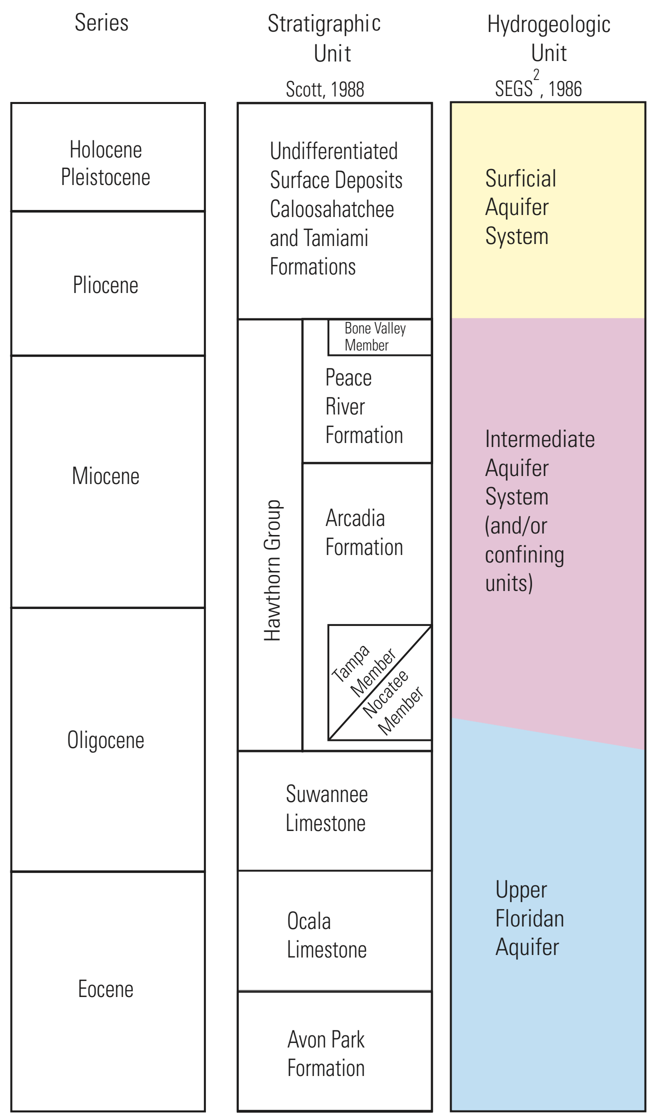


Figure 2. Stratigraphic and hydrogeologic units.

[2] SEGS, Southeastern Geological Society

The Upper Floridan aquifer is the lowermost fresh water-bearing formation and consists of a thick carbonate sequence that includes all or part of the Eocene- to Oligocene-age rocks. The Upper Floridan aquifer has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone at the study sites. A characteristic of the Upper Floridan aquifer is that in many places, zones of very high hydraulic conductivity exist within relatively small portions of the aquifer. The permeability of the Upper Floridan aquifer is very high in parts of the Avon Park Formation, somewhat lower in the Suwannee Limestone, and lowest in the Ocala Limestone. Thickness of the aquifer ranges from about 500 to 1,600 ft. The Suwannee Limestone typically forms the top of the aquifer in west-central Florida, which ranges in altitude from about zero to about 700 ft below NGVD 29 (Miller, 1986).

Definition of Terms

The hydraulic characteristics of aquifers and their overlying and underlying confining beds control the movement and storage of ground water. Aquifer tests, performed by pumping a well at a constant rate and observing the resulting changes in head in the aquifer system, are the most commonly used method for determination of aquifer hydraulic properties such as transmissivity (the ability of the aquifer to transmit water), storativity (the ability of the aquifer to store water), and leakance (the ability of the confining beds to transmit water vertically from an underlying or overlying source (Wolansky and Corral, 1985). For given values of hydraulic conductivity, the yield to a well is directly proportional to the saturated thickness of the aquifer. Alternatively, the yield into a well is directly dependent on the transmissivity (T) of the aquifer.

It is important to understand the meaning of common terms related to the hydraulic properties of aquifer systems. The basic definitions of selected properties are given below:

Hydraulic conductivity (K), expressed in foot per day (ft/d), is a measure of the capacity of a porous medium to transmit water. It is defined as the volume of water that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Transmissivity (T), expressed in foot squared per day (ft^2/d), is defined as the rate at which water can be transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity equals K * b, where K is hydraulic conductivity and b is saturated aquifer thickness.

Specific yield (S_y), dimensionless, is defined as the ratio of the volume of water that an unconfined aquifer will yield by gravity to a unit volume of the aquifer. Specific yield for confined aquifers cannot be determined because the aquifer material remains saturated during pumping.

Specific storage (S_s), expressed as 1/length, is the volume of water that is stored or released from the aquifer by the expansion of water and compression of the soil or rock. If the porous medium is incompressible, the compressibility of water would produce a specific storage of about 10^{-6} per foot times the porosity of the medium.

Storativity (S) or storage coefficient, is a dimensionless aquifer property defined by the volume of water that an aquifer releases from or takes into storage per unit surface area per unit change in head. The storage coefficient refers only to the confined parts of an aquifer and depends on the elasticity of the aquifer material and fluid. Storativity of confined aquifers typically ranges from 1.0E-5 to 1.0E-3 and is about 10^{-6} per foot of thickness (Lohman, 1979). The storativity in a confined aquifer is a product of S_s and saturated thickness of the aquifer. Storativity for an unconfined aquifer equals $S_y + S_s * b$. In unconfined aquifers, water is released primarily from compressive storage S_s during the early stage of a test. During the late stage of the test, water is released primarily from lowering of the water table, which is characterized by the specific yield, S_y. In unconfined aquifers, the storativity is virtually equivalent to the specific yield, which typically ranges from 0.01 to 0.3 (Freeze and Cherry, 1979) and equals the effective porosity or drainable pore space.

Leakance (L) or leakage coefficient, expressed in foot per day per foot (ft/d/ft), is defined by Hantush (1964) as the rate of flow that crosses through a horizontal unit area of a confining bed per unit of head difference per unit of time. Leakance equals K´/b´, where K´ and b´ are the vertical hydraulic conductivity and the thickness of the confining bed through which leakage occurs, respectively.

Numerical Simulation of Aquifer Tests

The USGS porous-media model code, MODFLOW (Harbaugh and McDonald, 1996), was used in an axisymmetric geometry mode with a single layer to simulate wells and ground-water flow. The grid consists of a series of cylindrical shells that are concentric to the center of pumping. The finite-difference expressions representing flow between grid cylinders are written in terms of radial distance from the center of the pumping well. Radial distance increases with increasing column indices and depth increases with increasing row indices. Hydraulic conductivities and storages of the i^{th} column are multiplied by $2\pi\, r_i$ to simulate radial flow where r_i is the distance from the outer edge of the first column to the center of the i^{th} column. Radial, axisymmetric flow has been simulated with MODFLOW by using a single row with many layers (Reilly and Harbaugh, 1993). A single MODFLOW layer is more convenient because input is defined easily, all conductances are computed within the Block-Centered Flow Package, and output is checked quickly (Halford and Yobbi, 2006).

Parameter estimation was facilitated by a parameter-estimation program (Halford, 1992). In this approach, differences between simulated drawdowns based on estimated hydraulic properties and measured (observed) drawdowns are minimized using a weighted sum of squares residuals (SS) based on a modified Gauss-Newton method (Gill and others, 1981). The SS is defined as:

$$SS\ (x) = \sum_{k=1}^{n} [w_i\ (h_{ks}-h_{km})]^2 \qquad (1)$$

where

w_i is the weighting factor;
h_{ks} is the k^{th} simulated water level, in feet;
h_{km} is the k^{th} measured water level, in feet; and
n is the number of measured water levels.

Weighted differences are used because unweighted sensitivities for hydraulic conductivity are roughly proportional to drawdown. Unweighted differences place more emphasis on matching drawdowns in nearby wells than distant wells even though measurable detection of any drawdown is equally important in nearby and distant wells. In this report, greater weights were applied to observations from distant wells and to observations from wells with fewer measurements during test periods. This was done so that the objective function would be influenced by these observations. Weights were estimated iteratively so that weighted sensitivities for a parameter would not be dominated by any one observation. All time-series water-level data from a well during an aquifer test were weighted uniformly.

Drawdowns also were weighted implicitly by subsampling the original time series data. Between 500 and 2,000 observations were reduced to about 100 observations so that the time series could be analyzed more quickly. Three periods; 0 to about 0.1 day (d), 0.1 to about 0.2 d, and 0.2 d to pump-off, were sampled uniformly. Fewer observations were sampled during the first 30 minutes to reduce the influence of wellbore storage effects in observation wells.

Although the SS serves as the objective function (measure of model fit), root-mean-squared error (RMSE) is reported instead because RMSE is more directly comparable to measured values and serves as a composite of the average and the standard deviation of a set of water-level comparisons (Halford, 1998). RMSE is related to the SS by:

$$RMSE = (SS/n)^{0.5} \qquad (2)$$

where

n is the number of water-level comparisons.

The first step in the parameter-estimation process is to perform one execution of the model to establish the initial differences (residuals) between simulated and measured water levels. The residuals are squared and summed to produce the sum-of-squares residuals objective function (eq. 1), which is used by the regression to measure model fit to the observations. In the next step, the sensitivity coefficients (derivatives of simulated water-level change with respect to parameter change) are calculated by the influence coefficient method (Yeh, 1986) using the initial model results. After the residuals and the sensitivities are calculated, a single parameter-estimation iteration is performed. The current arrays of sensitivity coefficients and residuals are used by a quasi-Newton procedure (Gill and others, 1981. p. 137) to compute the parameter change that should improve the model. The model is updated to reflect the latest parameter estimates and a new set of residuals is calculated. The entire process of changing a parameter in the model, calculating new residuals, and computing a new value for the parameter is continued iteratively until model error or model-error change is reduced to a specified level or until a specified number of iterations are made (Halford, 1992). Logs of the parameters are estimated because log-parameters are better behaved from a numerical perspective and because using logs prevent the actual parameter values from becoming negative during iterations.

Design of Models

The model structures are based on a simplified conceptualization of the ground-water flow system consisting of alternating high and low hydraulic conductivity beds. Wells and ground-water flow are simulated with a radial, axisymmetric geometry in a single layer. The aquifer system was idealized to consist of up to six high permeability zones (fig. 3) that were based on stratigraphic and hydrogeologic picks by field geologists. The formations were simulated as equivalent porous media. In this approach, the hydraulic conductivities used in the model represent the bulk properties of the fractured-rock formation. Water flux, which may pass through only the small fraction of the rock mass that is occupied by fractures, is simulated as if it were distributed throughout all parts of the formations. The base of the model coincides with the base of the Avon Park Formation, which is assumed to be impermeable. Changes in the wetted thickness of the aquifer were not simulated because the maximum drawdown near the water table was small relative to the thickness of the surficial aquifer system. All external boundaries were specified as no-flow.

Vertical discretization is coarse for aquifers and fine for confining units (fig. 3). Aquifers (producing zones) are defined with a primary row that simulates most of the thickness and two 0.01-ft-thick rows above and below the primary row. Creating separate rows for this transition simplifies interpretation of aquifer hydraulic property estimates. Surficial aquifer system aquifer tests are an exception. For these simulations, the surficial aquifer is defined with uniform properties but is more finely discretized into multiple rows to more accurately simulate drawdown. Confining units are defined with uniform hydraulic properties but are discretized variably into 20 rows or more to adequately simulate drawdown. Rows range in thickness from 1 to 10 percent of the total thickness of a confining unit with the thinnest rows being adjacent to the aquifer-confining unit contacts. Application of this design assumes that aquifers and confining units are flat-lying, homogeneous, and isotropic, which allows radial symmetry to shift between production wells as each test is analyzed.

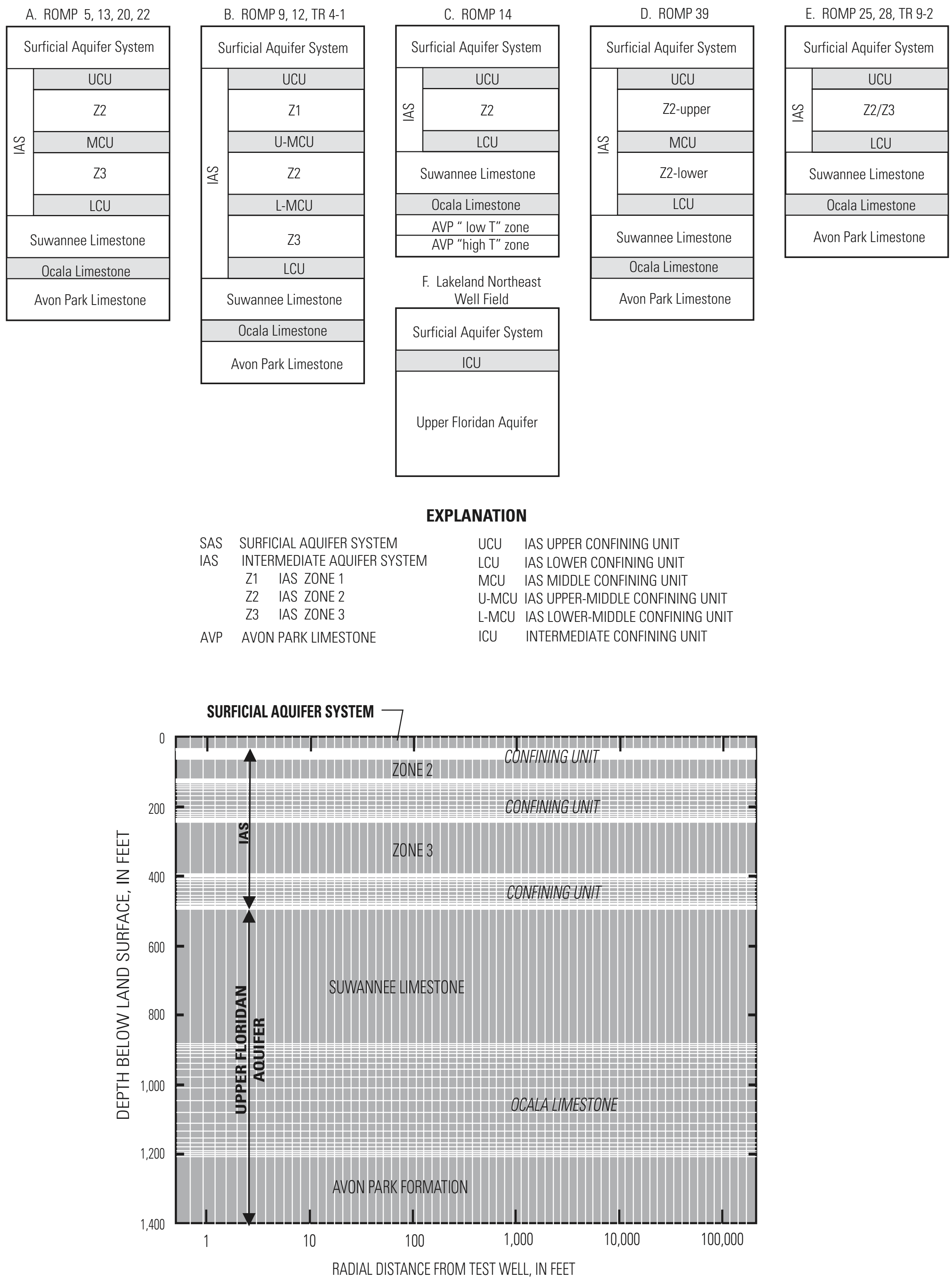


Figure 3. Hydrogeologic units and representative radial grid used for simulation of aquifer tests.

All aquifer tests were analyzed with a single, radial model that extends from land surface to the base of the hydrogeologic column. The models simulated all pumping events by using multiple stress periods. For example, drawdown during three aquifer tests within a hydrogeologic column would be simulated as a single MODFLOW run with three stress periods, where as drawdown during a single test would be simulated with one stress period. Recovery data were not considered in this analysis.

Conceptually, the center of the radial model shifts between production wells for each stress period of a multiple aquifer test. Elapsed time and off-site stresses between aquifer tests are not simulated and heads are initialized to zero at the beginning of each stress period. Each aquifer test was simulated with a 10-day stress period. Initial heads were set to zero and radial distances between a pumping well and observation wells changed at the start of each stress period. Stress-period lengths of 10 days were specified for convenience so drawdown observation time would be equivalent to elapsed time during each successive test plus a 10-day multiple.

For multiple tests, the models are calibrated by simultaneous simulation of drawdown. This procedure yields estimates of model parameters for the entire model using information from each test, but only one model, with one set of optimum parameters, is used by the model simulations. Simulating multiple aquifer tests with a single model facilitates parameter estimation because the hydrogeologic column is defined with a single, internally consistent set of hydraulic properties.

For each multiple aquifer test, the number of stressed intervals is limited by the number of aquifers in a hydrogeologic column. These assumptions primarily are imposed by data limitations, not MODFLOW. Each layer is assumed homogeneous and is characterized by a single value of horizontal hydraulic conductivity and specific storage.

Model Analysis

Essentially, the process of model calibration is the same using either an inverse model or the trial-and-error approach: parameter values and other aspects of the model are adjusted until the dependent variable (drawdown) match field observations. Significant advantages of using nonlinear least-squares regression are the ability to determine parameter values that produce the best match to field observations and the ability to quantify the quality of model calibration using statistical measures. Proper use of any parameter estimation algorithm, however, requires a certain amount of improvement also accomplished only by trail and error. Such adjustments involve, for example, selection of observations and weights assigned to these observations, which parameters to estimate, the proper selection of initial parameter estimates, and whether to use logarithmic parameter transformations.

The development of the models presented here for the analysis of aquifer tests was divided into four steps. First, well locations and construction records were determined for all wells. Locations of wells were defined in Cartesian coordinates and radial distances between the production well and observation wells were determined. Second, a selection was made of the drawdown suitable as input data, and drawdown estimates and data filtering were performed for each of the aquifer-test data sets. Third, the ground-water flow system was schematized in the numerical model. The schematization was based on the hydrogeologic framework using lithologic and geophysical logs, water levels, water quality, and hydraulic characteristics at each of the test sites. Stratigraphic units composing the geologic framework were based on stratigraphic picks by field geologists. Finally, initial hydraulic property estimates of the aquifers and confining units were made. Transmissivities of the aquifers were estimated initially with the Cooper-Jacob (1946) method because the solution is simple and can be solved graphically (Halford and Kuniansky, 2002). Drawdown in the pumping well was analyzed because drawdowns were greatest and the technique is particularly suitable to data for a production well. Aquifer storage, vertical hydraulic conductivity, and specific storage of adjacent confining units were estimated initially with a leaky aquifer solution, which also provides an estimate of transmissivity (Moench, 1985). Transmissivity estimates for the leaky aquifer solution were limited to values less than Cooper-Jacob estimates. The leaky aquifer solution was solved by optimization within a spreadsheet. Finally, parameter estimation was conducted.

Parameter estimation worked better when initial hydraulic conductivity estimates were within 1 to 2 orders of magnitude of the best estimates because the general shape of the measured drawdown curve was simulated. For example, the flattening of a drawdown curve is controlled by the hydraulic conductivity and specific storage of a confining unit (fig. 4). Parameter estimation will not be sensitive to changes in hydraulic conductivity and specific storage of a confining unit if the flattened section of the drawdown curve does not coincide initially with measured drawdowns.

In pumping wells, simulated and measured drawdown differences are compared after entry head losses have stabilized, which occurs about 15 to 30 minutes after pumping commences (fig. 5). Drawdown differences are matched because late-time changes are controlled by the hydraulic characteristics of the aquifer system, and not by well construction or partial-penetration effects. Fitting drawdown differences is equivalent to estimating the slope of drawdown as is done with a Cooper-Jacob analysis.

When background water-level data were available, observation-well responses were corrected for environment processes that were not influenced by pumping. Corrected water levels were constructed from several time series, including water levels in wells not influenced by pumping, a linear trend, and earth tide (Harrison, 1971). Corrected water levels in a well were fitted to measured water levels by adjusting the amplitude and phase of each time series. A best fit was obtained by minimizing the sum-of-squares difference between corrected and measured water levels. Latitude and

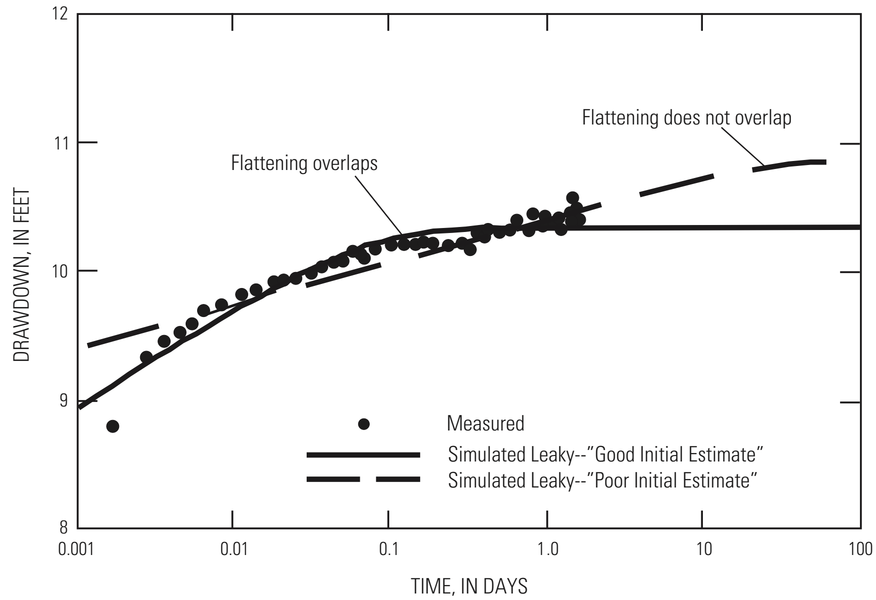


Figure 4. Effect of poor initial parameter estimates on model fit.

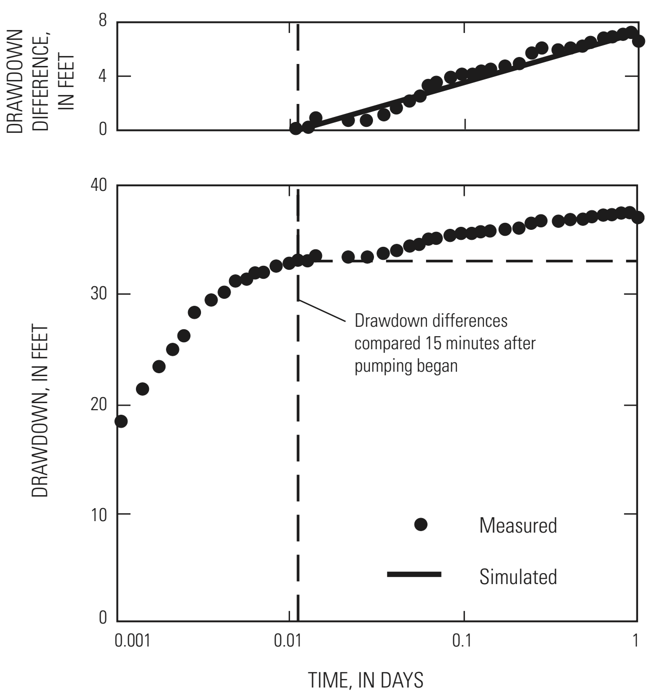


Figure 5. Effects of simulating drawdown in production wells after entry losses have stablized.

longitude of the aquifer-test location were used along with altitude to compute the theoretical earth tide. Drawdown estimates were exported to individual, tab-delimited ASCII files. A well name, starting date, and starting time were written to the header of each drawdown file, and measurement date and time were written with each elapsed time-drawdown pair to help trace spurious responses. Time-series analysis, data filtering, water-level correction, and drawdown estimation were performed within a spreadsheet.

As part of the regression, sensitivities for each estimated parameter are calculated. The magnitude of the main diagonal of the covariance matrix is a rough estimate of the sensitivity of the model to a parameter (Halford, 1998). Parameter sensitivity was reported in terms of the relative composite sensitivity (RCS), which is the square root of the main diagonal value divided by the maximum main diagonal for each parameter (Yobbi, 2000). The most sensitive parameter has a RCS value equal to 1.00 and a RCS value of less than 1 for all other estimated parameters. The larger the RCS, the more sensitive the model is to that parameter. RCS was used during calibration to decide what parameters to keep and exclude from the estimation process. Parameters with large RCS values are likely to be easily estimated by the regression; parameters with small RCS values may be more difficult to estimate.

Parameter sensitivity also was useful for comparing the reliability of each parameter within the same run of the inverse model because parameters with large RCS values contain more information and tend to have lower parameter uncertainty and smaller confidence intervals than parameters with small RCS values. Sensitivity of the final parameter values for hydraulic properties of the pumped intervals and confining units was subjectively assessed "high", "fair", and "low" based on RCS values. Parameters with larger RCS values exert greater control over the model simulation and have narrow confidence intervals relative to parameters with a smaller RCS. The parameters were ranked as follows:

- **High (RCS value greater than 0.1)**—Parameters rated "high" are the most sensitive, exerted the most control over the model solution, and were estimated the most reliably by the model compared to other parameters.
- **Fair (RCS value from 0.02 to 0.1)**—Parameters rated "fair" were moderately sensitive, exerted medium control over the model solution, and were estimated moderately reliably by the model compared to other parameters.

- **Low (RCS less than 0.02)**—Parameters rated "low" are the least sensitive, exerted the least control over the model solution, and were estimated the least reliably by the model compared to other parameters. In this circumstance, the available measurements used in the calibration did not provide enough information to constrain the parameter.

The analyses here are based on the assumption that measured water-level changes primarily are caused by pumping at the test well. Measured water-level changes also may be caused by recharge, drainage, pumping at other wells, air pressure fluctuations, and other processes. Generally, these water-level changes are small compared to those caused by test-well pumping; hence, errors in estimated hydraulic properties are correspondingly small. Some uncertainty in these estimated properties, however, is caused by the inability to accurately remove all antecedent and background water-level changes from available information.

An evaluation of the model fit between measured and simulated drawdown was made for the calibrated models using statistics and by visual inspections of the log-log graph of drawdown as a function of time since the start of pumping. Model error is defined as the sum of squares, unweighted residuals, where residuals are the differences between measured and simulated drawdown.

ROMP 5 Model

ROMP 5 is located at 26°56´44˝N and 81°48´29˝W in Charlotte County near the northern county line (fig. 6). Land surface altitude at the well site is about 40 ft above NGVD 29. Six permanent and two temporary wells ranging from 2 to 12 in. in diameter were completed at ROMP 5. The deepest well, MW6, was drilled to 1,400 ft below land surface.

Four aquifer tests were conducted from January-April 1997 at the ROMP 5 site to estimate the hydraulic properties of the surficial aquifer system (SAS), upper intermediate aquifer system (IAS-Zone 2), lower intermediate aquifer system (IAS-Zone 3), and the Suwannee Limestone producing zone (SUW) (table 1). A plan view and construction records of the production and observation wells for the aquifer tests conducted at the site are shown in figure 6. Figure 7 shows plots of the drawdown data used for analysis.

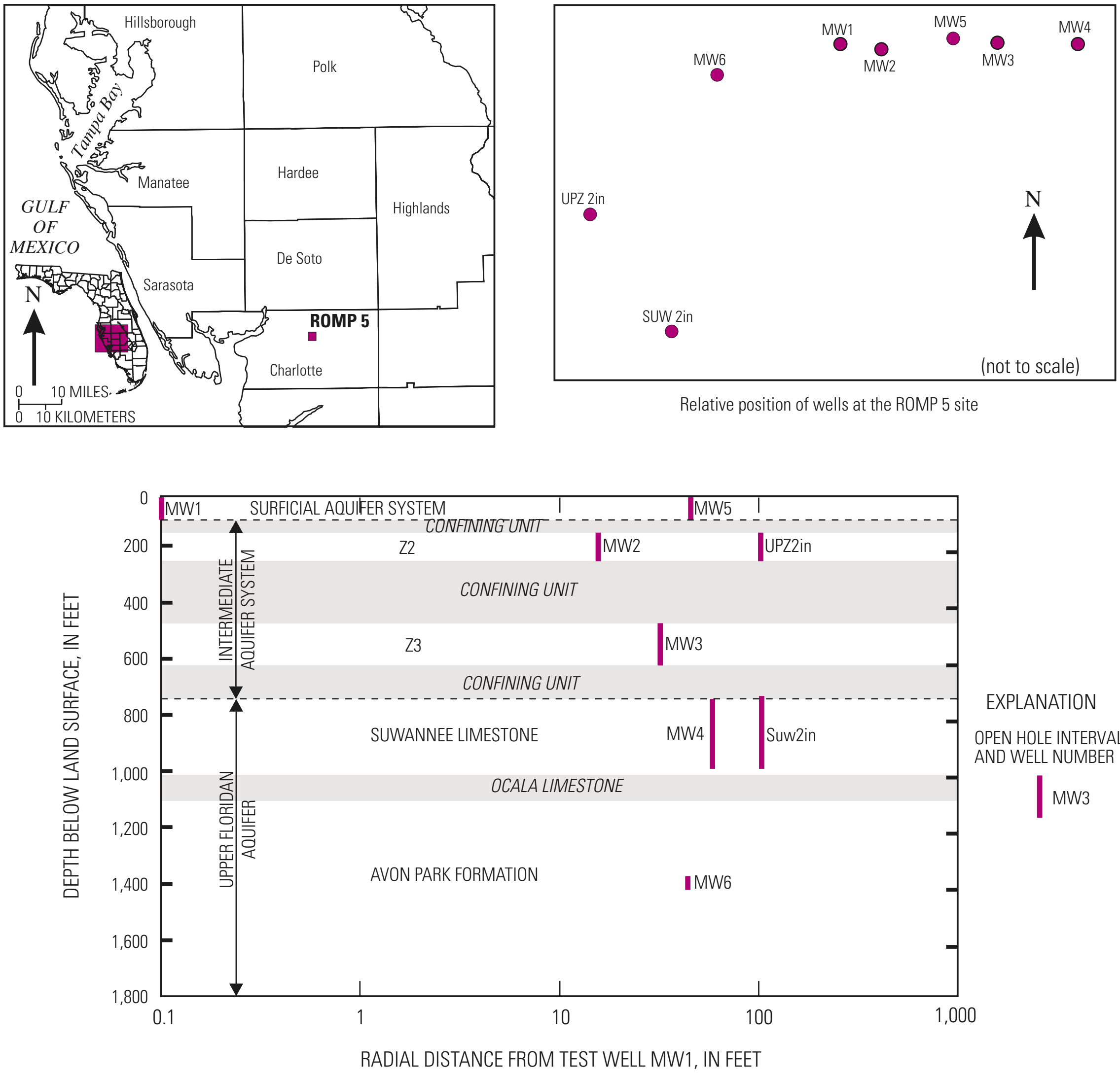
Table 1. Date, duration, and pumping rate for the aquifer performance tests.

[SAS, surficial aquifer system; Zones 1, 2, and 3 of the intermediate aquifer system are abbreviated as Z1, Z2, and Z3; SUW, Suwannee Limestone; AVP, Avon Park Formation; gal/min, gallons per minute]

Site	Interval Pumped	Start Date	Duration, in hours	Discharge, in gal/min
5	SAS	Jan-13-97	62.5	65
	Z2	Jan-6-97	37.5	237
	Z3	Apr-2-97	21.0	930
	SUW	Apr-9-97	24.0	349
9	SAS	Oct-28-96	48.0	75
	Z1	May-13-97	24.0	7.4
	Z2	May-15-97	24.0	42
	Z3	May-20-97	24.0	212
	SUW	May-28-97	24.0	1,020
12	SAS	Jul-22-97	31.4	21.4
	Z1	Aug-31-98	43.4	256
	Z2	Jul-13-98	46.4	47
	Z3	Jun-8-98	68.7	907
	SUW	May-12-98	56.9	730
	AVP	Nov-2-97	91.2	5,200
13	Z2	Dec-9-96	49.7	46
	Z3	Dec-2-96	51.7	230
	SUW	Nov-5-96	61.7	480
14	SAS	Jun-12-96	167.0	889
	Z2	Feb-7-95	52.2	14.6
	SUW	Jul-15-96	95.9	386
	AVP	Sep-30-96	117.9	1,651

Site	Interval Pumped	Start Date	Duration, in hours	Discharge, in gal/min
20	Z2	Dec-15-92	29.0	200
	Z3	Jul-29-92	28.0	400
	SUW	Jul-22-92	24.5	1,300
22	Z3	Apr-19-94	6.8	25
	SUW	Dec-14-93	36.7	1,065
	AVP	Apr-13-94	45.0	3,500
25	SUW	Dec-14-98	33.0	500
	AVP	May-4-99	72.0	4,700
28	SAS	Mar-21-93	20.0	400
	Z2	Feb-27-96	35.2	37
	SUW	Aug-19-96	83.4	150
	AVP	Feb-27-97	119.4	3,000
39	SUW	Feb-15-94	43.9	762
4-1	Z1	Feb-17-97	23.9	60
	Z2	Feb-7-97	24.4	60
	Z3	Jun-7-97	23.7	220
	SUW	Jun-13-97	24.0	1,080
9-2	AVP	Feb-4-91	53.0	1,098
[1]WF	SUW/AVP	Apr-30-03	287.8	3,000

[1]Lakeland Northeast Well Field.



Well name	Hydrogeologic unit	Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet)			
				MW1 (SAS)	MW2 (Z2)	MW3 (Z3)	MW4 (SUW)
		Surficial aquifer system (SAS)					
MW1	Undifferentiated surficial deposits	5/85	12		12.3	32.5	66.6
MW5	Undifferentiated surficial deposits	5/85	4	45.0	23.5	13.2	22.7
		Intermediate aquifer system					
MW2	Upper Arcadia zone (Z2)	130/230	8	12.0		21.1	54.3
UPZ 2in	Upper Arcadia zone (Z2)	130/230	2	102.5	93.0	127.8	150.6
MW3	Lower Arcadia zone (Z3)	450/600	12	32.2	21.2		35.4
		Upper Floridan aquifer					
MW4	Upper Floridan aquifer (SUW)	720/970	12	67.3	56.2	35.4	
SUW 2in	Upper Floridan aquifer (SUW)	710/970	2	103.8	110.6	120.3	137.8
MW6	Avon Park Formation	1,350/1,400	6	36.9	37.2	68.2	102.8

Figure 6. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 5 test site.

The four aquifer tests for the site are simulated as a single MODFLOW run with four 10-day stress periods, but, unlike standard MODFLOW runs, heads are reset to zero at the end of each stress period. Starting at t=0, pumping starts in the surficial aquifer system, with the aquifer test drawdowns that are to be matched specified at distances and in zones tabulated in the column headed MW1 in figure 6, with times extending from zero through the end of the drawdown phase of that test. For the second stress period, pumping is started in the IAS-Zone 2 after 10 days of simulation time, and drawdowns to be matched are specified beginning at 10 days plus the elapsed time since the start of the IAS-Zone 2 test at radial and vertical locations specified in the column headed MW2 in figure 6. For the third stress period, pumping is started in the IAS-Zone 3 after 20 days of simulation time, and drawdowns to be matched are specified beginning at 20 days plus the elapsed time since the start of the IAS-Zone 3 test at radial and vertical locations specified in the column headed MW3 in figure 6. For the fourth stress period, pumping is started in the Suwannee Limestone after 30 days of simulation time, and drawdowns to be matched are specified beginning at 30 days plus the elapsed time since the start of the IAS-Zone 1 test at radial and vertical locations specified in the column headed MW4 in figure 6. If recovery data also were analyzed, two stress periods would be needed for each aquifer test and heads would be set to zero after the second stress period, which simulated recovery.

Well MW1, tapping the surficial aquifer system, was pumped at a rate of 65 gal/min for 62.5 hours. Drawdown data measured in the pumped well (MW1), surficial aquifer system well MW5, and IAS-Zone1 well MW2 were used in the numerical analysis. Water levels in the production and observation wells began rising approximately 0.3 days into the pumping phase of the test as a result of heavy rainfall. During the drawdown phase of the aquifer test, the water level declined about 5 ft in the pumped well and about 1 ft in MW5. No decline in water level was estimated in IAS-Zone 1 observation well MW2 during the drawdown phase; however, during or shortly after the rainfall, water levels rose in the MW2 well indicating either a hydraulic connection with the surficial aquifer system or external stress.

Well MW2, tapping the upper producing zone of the intermediate aquifer system (IAS-Zone2), was pumped at a rate of 237 gal/min for 37.5 hours. Drawdown data measured in the pumped well (MW2), the surficial aquifer system well MW1, the IAS-Zone 2 well UPZ 2in, the IAS-Zone 3

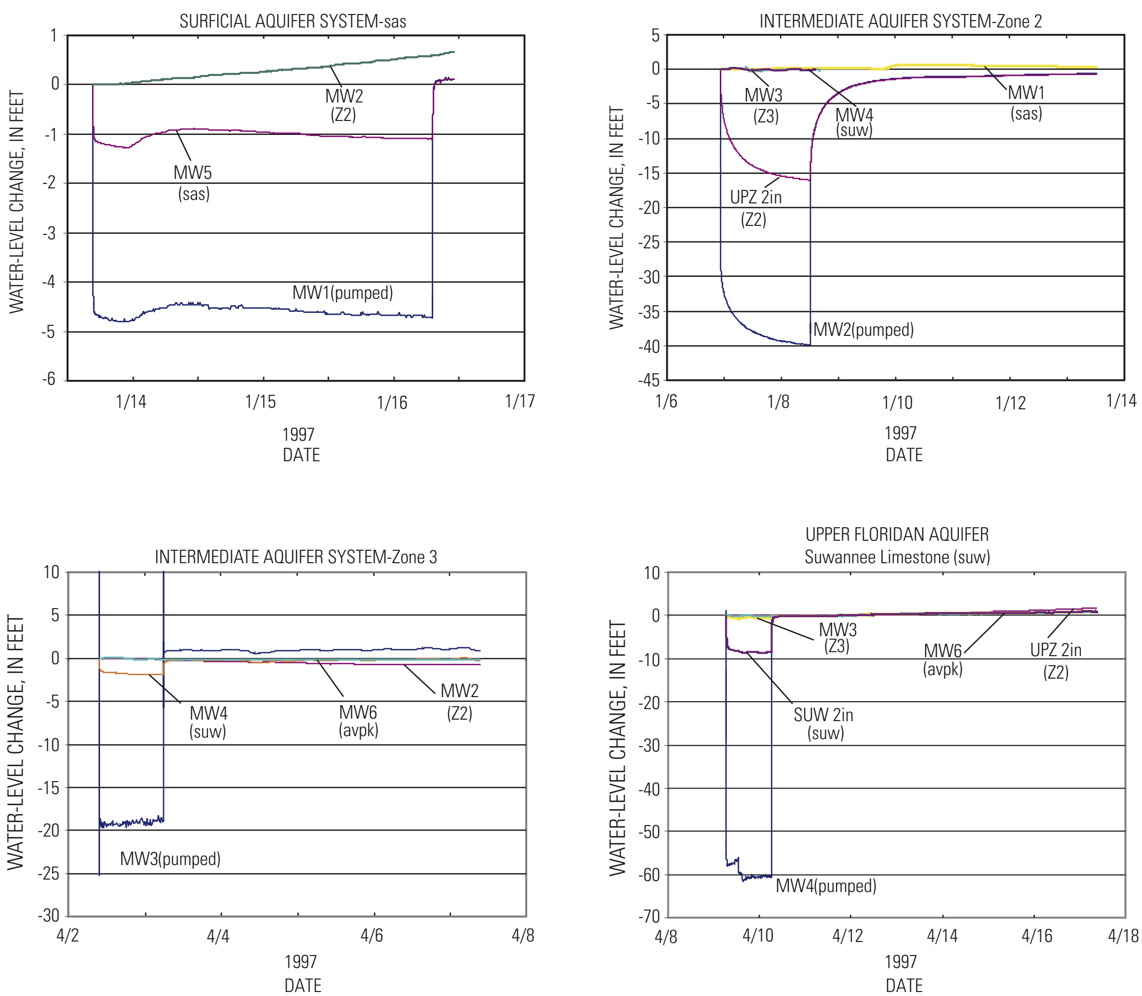


Figure 7. Water levels in selected wells during drawdown and recovery periods of the four aquifer tests conducted at the ROMP 5 test site.

well MW3, and the Suwannee Limestone well MW4 were used in the numerical analysis. Pumping of the IAS-Zone 2 began while the surficial aquifer system was recovering from a step-drawdown test conducted the same day. Throughout the pumping of the IAS-Zone 2, water levels in the surficial aquifer system rose, most likely in response to the step-test. Diurnal water-level fluctuations of about 0.2 ft were estimated in the Suwannee Limestone and IAS-Zone 3 observation wells. During the drawdown phase of the test, the water level declined about 40 ft in the pumped well and about 16 ft in the IAS-Zone 2 observation well UPZ 2in. No decline in water level was estimated in either the overlying surficial aquifer system well or in the underlying IAS-Zone 3 well or Suwannee Limestone well.

Well MW3, tapping the lower producing zone of the intermediate aquifer system (IAS-Zone 3), was pumped at a rate of 930 gal/min for 21 hours. Drawdown data measured in the pumped well (MW3), the IAS-Zone 2 well (MW2), the Suwannee Limestone well (MW4) and the Avon Park Formation well (MW6) were used in the numerical analysis. No observation well for the IAS-Zone 3 was constructed at this site. During the drawdown phase of the aquifer test, the water level declined about 19 ft in the pumped well and about 2 ft in the Suwannee Limestone well MW4, indicating hydraulic connection between IAS-Zone 3 and the Upper Floridan aquifer. No decline in water level was estimated in the overlying IAS-Zone 2 well (MW2) or in the underlying Avon Park Formation well (MW6).

Well MW4, tapping the Suwannee Limestone zone of the Upper Floridan aquifer, was pumped at a rate of 349 gal/min for about 24 hours. Water levels were measured in the pumped well and in all on-site observation wells during the aquifer test. All wells had diurnal water-level fluctuations of about 0.3 ft. During the drawdown phase of the aquifer test, the water level declined about 60 ft in the pumped well and about 9 ft in Suwannee Limestone well SUW-2in. A water level decline of about 0.7 ft was measured in the overlying IAS-Zone 3 well MW3. No decline was estimated in either the IAS-Zone 2 observation well or in the underlying Avon Park Formation observation well.

Aquifer-test data were analyzed by Gates (1997) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer tests and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP 5	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
Surficial aquifer system	2,780	33	no data
Intermediate aquifer system-Zone 2	1,390	14	2.1E-3
Intermediate aquifer system-Zone 3	2,970	20	no data
Upper Floridan aquifer-Suwannee Limestone	2,607	10	4.1E-1

Model Structure

The ROMP 5 model extended from the production wells to 200,000 ft away and from the water table to 1,776 ft below land surface. The numerical model consisted of 93 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 695 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column. Vertical discretization was finer across the confining units and the surficial aquifer system than across the other hydrogeologic units.

Five water-bearing units were simulated—the surficial aquifer system, IAS-Zone 1, IAS-Zone 3, Suwannee Limestone, and the Avon Park Formation; and four confining units—upper, middle, and lower confining units, and the Ocala Limestone (fig. 3A). The surficial aquifer system is about 84 ft thick underlying the ROMP 5 site (table 2). The intermediate aquifer system underlies the surficial aquifer and is about 613 ft thick, including two producing zones (IAS-Zone 2 and IAS-Zone 3) separated by three confining units. The Upper Floridan aquifer, the lowermost permeable hydrogeologic unit, is about 1,056 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 20 parameters. Lateral hydraulic conductivities of the four confining units and five aquifers compose nine of the parameters. Specific storage of the same hydrogeologic units make up nine more parameters. Vertical anisotropy and specific yield of the surficial aquifer make up the last two parameters. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all other units.

The simulated response in each hydrogeologic unit was sensitive not only to the hydraulic properties and initial conditions for the unit, but also to those of the other layers in the model, particularly the units representing the production zones. The fit of measured and simulated time-drawdown data is illustrated in figure 8. Simulated drawdowns matched measured drawdowns reasonably well during most aquifer tests with an average unweighted root-mean-squared error (RMSE) of 0.34 ft for the three tests. The fit for the IAS-Zone 3 test exhibited the poorest match between simulated and measured drawdown. One can see that the fit for early-time data is poorer than that for late-time data. In fact, no single set of values produced drawdown curves that fit all data. One should keep in mind that the log-log plot exaggerates

Table 2. Summary of estimated or assigned parameter values for water-bearing zones.

[SAS, surficial aquifer system; Zones 1, 2, and 3 are abbreviated as Z1, Z2, and Z3; SUW, Suwannee Limestone; AVP, Avon Park Limestone; ft/d, feet per day; ft^2/d, feet squared per day; bold numbers indicate pumped zones; --, not applicable]

Site	Lateral hydraulic conductivity, ft/d					
	SAS	Intermediate aquifer system			Upper Floridan aquifer	
		Z1	Z2	Z3	SUW	AVP
5	**23**	--	**17**	**98**	**10**	1,200
9	**790**	**1**	**5**	**22**	**16**	890
12	**13**	**100**	**5**	**184**	**27**	**1,500**
13	[1]3	--	**2**	**12**	**12**	780
14	**61**	--	**1**	--	**11**	**[3]15/100**
20	[1]10	--	**95**	**12**	**41**	670
22	[1]10	--	5	**2**	**31**	**300**
25	19	--	1	--	**19**	**400**
28	**44**	--	**6**	--	**1**	**46**
39	[1]10	--	[1]1	--	**28**	300
4-1	45	**3**	**12**	**11**	**34**	100
9-2	[1]10	--	--	[1]5	12	**99**
[1]WF	[1]30	--	--	--	**110**	

Site	[2]Transmissivity, ft^2/d					
	SAS	Intermediate aquifer system			Upper Floridan aquifer	
		Z1	Z2	Z3	SUW	AVP
5	**1,900**	--	**1,700**	**15,000**	**2,700**	830,000
9	**22,000**	**31**	**270**	**2,800**	**5,100**	760,000
12	**520**	**4,900**	**660**	**43,000**	**5,000**	**1,500,000**
13	60	--	**280**	**900**	**1,000**	780,000
14	**22,000**	--	30	--	**900**	**[3]7,400/30,000**
20	490	--	**5,200**	**1,800**	**16,000**	150,000
22	190	--	340	**200**	**8,100**	**220,000**
25	540	--	38	--	**6,900**	**330,000**
28	**10,000**	--	330	--	**170**	**59,000**
39	780	--	34	--	**9,200**	190,000
4-1	1,200	**190**	**1,200**	**4,300**	**7,100**	10,000
9-2	380	--	--	440	2,600	**56,000**
[1]WF	300	--	--	--	**85,000**	

Site	Coefficient of storage, 10^{-4}					
	SAS	Intermediate aquifer system			Upper Floridan aquifer	
		Z1	Z2	Z3	SUW	AVP
5	**1.4**	--	**3.1**	**0.3**	**0.8**	2.1
9	**0.4**	**3.7**	**0.5**	**8.3**	**3.8**	13.0
12	**0.8**	**0.1**	**6.6**	**0.2**	**1.9**	**7.7**
13	0.3	--	**0.9**	**0.5**	**2.3**	3.0
14	1.1	--	0.2	--	**100**	**[3]22/7.2**
20	0.1	--	**0.3**	**0.5**	**1.5**	2.0
22	0.3	--	1.0	**0.3**	**2.9**	13
25	0.9	--	0.6	--	**0.7**	**1.6**
28	**322**	--	6.5	--	**0.5**	**5.2**
39	1.2	--	0.5	--	**0.3**	9.3
4-1	5.5	**0.08**	**2.5**	**1.2**	**0.8**	1.6
9-2	0.6	--	--	1.3	0.6	**1.7**
[4]WF	0.2	--	--	--	**4.5**	

Site	Specific storage, 10^{-6}/ft					
	SAS	Intermediate aquifer system			Upper Floridan aquifer	
		Z1	Z2	Z3	SUW	AVP
5	**1.7**	--	**3.1**	**0.2**	**0.3**	0.3
9	**1.5**	**15.3**	**0.9**	**6.6**	**1.2**	1.5
12	**1.9**	**0.2**	**5.0**	**0.1**	**1.0**	**0.8**
13	[1]1.5	--	**0.6**	**0.6**	**3.1**	0.3
14	**0.3**	--	**0.3**	--	**130.0**	**[3]4.5/ [1]2.4**
20	[1]0.2	--	**0.6**	**0.3**	**0.4**	0.9
22	[1]1.5	--	1.5	**0.2**	**1.1**	**1.7**
25	[1]1.5	--	1.5	--	**0.2**	**0.2**
28	**140.0**	--	**10.9**	--	**0.4**	**0.4**
39	[1]1.5	--	[1]1.5	--	**0.1**	1.5
4-1	21.0	**0.1**	**2.4**	**0.3**	**0.4**	[1]1.5
9-2	[1]1.5	--	--	[1]1.5	0.3	**0.3**
[4]WF	1.9	--	--	--	**0.6**	

Site	Thickness of unit					
	Surficial aquifer system	Intermediate aquifer system			Upper Floridan Aquifer	
		Z1	Z2	Z3	SUW	AVP
5	**84**	--	**100**	**150**	**269**	696
9	**28**	**24**	**53**	**125**	**320**	851
12	**40**	**49**	**131**	**234**	**186**	**959**
13	**20**	--	**145**	**76**	**73**	996
14	**353**	--	**59**	--	**79**	**[3]485/300**
20	49	--	**55**	**151**	**387**	222
22	19	--	67	**131**	**265**	744
25	60	--	38	--	**370**	**824**
28	**230**	--	**60**	--	**121**	**1,290**
39	78	--	34	--	**331**	622
4-1	26	**76**	**103**	**390**	**207**	104
9-2	38	--	--	89	209	**563**
[4]WF	10	--	--	--	**755**	

[1]This value was specified and not estimated with the inverse model.

[2]Equals hydraulic conductivity times thickness of unit.

[3]First number is "low T zone" value and second number is "high T zone" value.

[4]Lakeland Northeast Well Field.

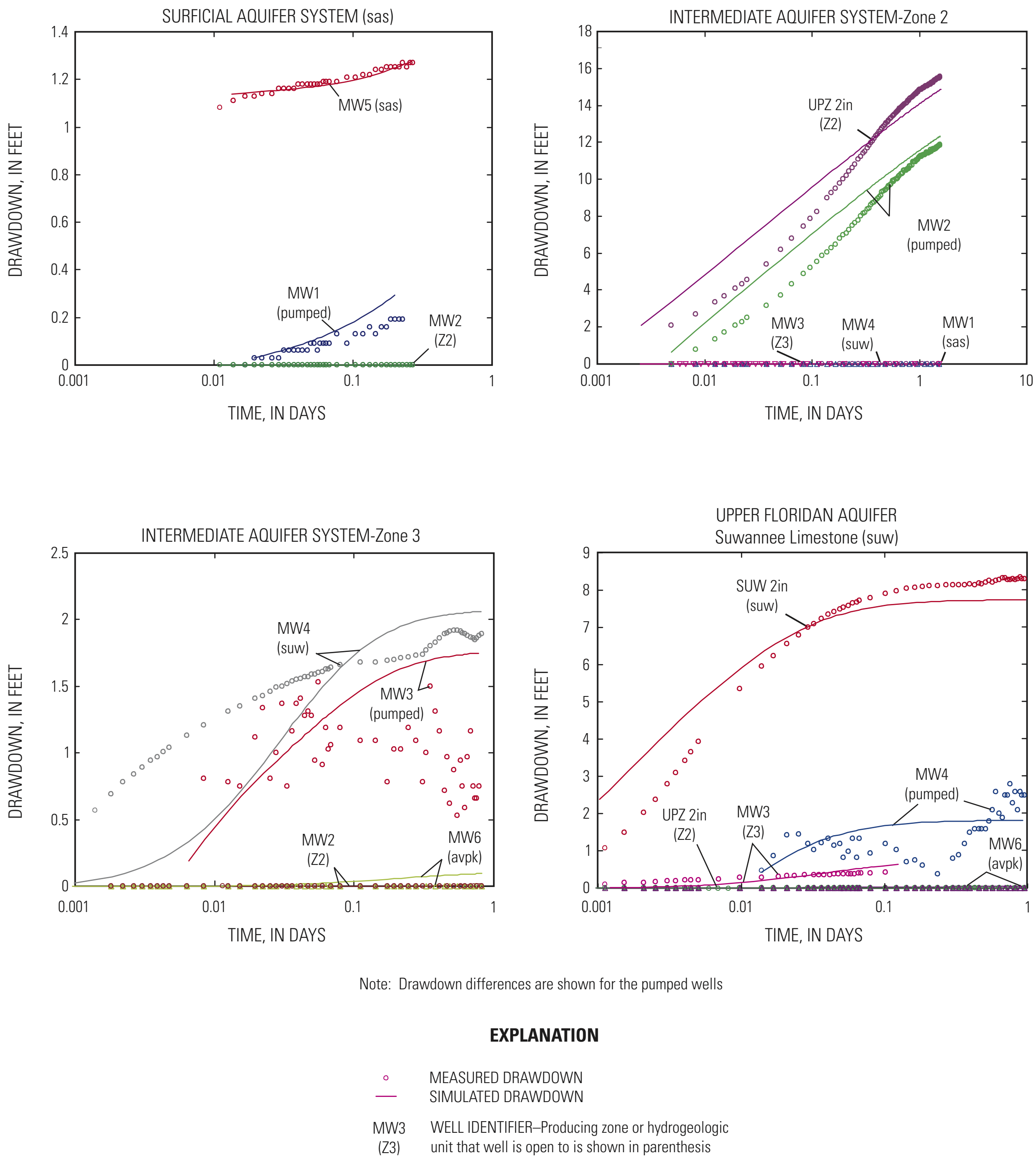


Figure 8. Simulated and measured drawdown for the four aquifer tests conducted at the ROMP 5 test site.

the lack of fit at early time, when drawdown is small. When viewed in the context of the entire drawdown data set, the lack of fit during early time is not severe. RMSE of individual aquifer tests ranged from 0.03 ft for the SAS to 0.53 ft for the IAS-Zone 2 (table 3). The estimated and assigned hydraulic properties and sensitivity assessment for the estimated parameters from this simulation are shown below (unpumped zone is italicized):

The resulting values of transmissivity are about the same as those derived from the analytical models, except for the IAS-Zone 3, where the simulated value is about 5 times greater than the analytical value. The resulting values of storativity range from about 1 to 3 orders of magnitude lower than the storativity values derived from the analytical models. Storativity values determined here are more physically plausible than those based on analytical results.

Hydrogeologic unit ROMP 5	T (ft^2/d)	K (ft/d)		K_z/K_h		S_y		Storage		
			[2]RCS rating		RCS rating		RCS rating	S	S_s (d^{-1})	RCS rating
Surficial aquifer system	1,900	23	high	0.19	high	0.18	high	1.4E-4	1.7E-6	low
IAS-Zone 2	1,700	17	high	[1]0.10				3.1E-4	3.1E-6	high
IAS-Zone 3	15,000	98	high	[1]0.10				3.0E-5	2.0E-7	low
UFA-Suwannee Limestone	2,700	10	high	[1]0.10				8.1E-5	3.0E-7	fair
UFA-Avon Park Formation	*83,000*	*1,200*	*low*	*[1]0.10*				*2.1E-4*	*3.0E-7*	*low*

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_s) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; K_z/K_h, vertical to horizontal anisotropy; S_y, specific yield. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

Table 3. Residual statistics for the aquifer test simulations.

[SAS, surficial aquifer system; RMSE, root mean square error; n, number of observations; ft, feet; SUW, Suwannee Limestone; AVP, Avon Park Formation; --, not applicable]

Site	SAS		Intermediate aquifer system						Upper Floridan aquifer			
			Zone 1		Zone 2		Zone 3		SUW		AVP	
	n	RMSE, ft	n	RMSE, ft	n	RMSE, ft	n	RMSE, ft	n	RMSE, ft	n	RMSE, ft
5	96	0.03	--	--	533	0.53	235	0.35	252	0.44	--	--
9	307	0.04	157	0.12	347	0.55	235	0.22	388	0.18	--	--
12	119	0.06	240	0.17	237	0.15	533	0.06	462	0.09	176	0.13
13	--	--	--	--	188	0.63	393	0.57	180	0.38	--	--
14	604	0.18	--	--	93	0.24	--	--	859	0.56	531	0.54
20	--	--	--	--	253	0.33	288	0.78	345	0.25	--	--
22	--	--	--	--	--	--	175	0.25	379	0.21	86	0.09
25	--	--	--	--	--	--	--	--	167	0.07	99	0.04
28	172	0.08	--	--	89	0.28	--	--	241	0.32	363	1.01
39	--	--	--	--	--	--	--	--	256	0.34	--	--
4-1	--	--	197	0.31	177	0.16	234	0.20	275	0.47	--	--
9-2	--	--	--	--	--	--	--	--	--	--	230	0.29
[1]WF	--	--	--	--	--	--	--	--	--	--	1,160	[2]0.33

[1]Lakeland Northeast Well Field.
[2]Upper Floridan aquifer test.

Hydraulic conductivity of the pumped zones and specific storage of IAS-Zone 2 was resolved with high confidence (high sensitivity), while specific storage of the surficial aquifer system and IAS-Zone 3 was resolved with low confidence (low sensitivity) and are the most uncertain of the aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP 5	Leakance (ft/d/ft)	K_Z (ft/d)		$^5K_Z/K_h$	Specific storage (d^{-1})	
			[4]RCS rating			RCS rating
[1]Upper	2.4E-5	1.1E-3	low	0.1	2.0E-7	low
[2]Middle	1.6E-5	3.5E-3	low	0.1	2.0E-7	low
[3]Lower	4.2E-3	5.0E-1	fair	0.1	2.0E-7	low
Ocala Limestone	1.5E-3	1.4E-1	fair	0.1	3.0E-7	low

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_Z) by the appropriate thickness; K_Z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 2. [2]Confining unit between IAS-Zone 2 and IAS-Zone 3. [3]Confining unit between IAS-Zone 3 and Suwannee Limestone. [4]Relative scaled sensitivity. [5]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the lower confining unit and the Ocala Limestone were resolved with moderate confidence whereas vertical hydraulic conductivity of the upper and lower confining units and specific storages of the confining units were resolved with low confidence and are the most uncertain of the confining unit parameters.

Relative composite sensitivity (RCS) values for the estimated and assigned parameters are shown in figure 9 and appendix 1. Generally, the model was most sensitive to hydraulic conductivity of the pumped zones and least sensitive to specific storage of the confining units. Sensitivity is highest for the hydraulic conductivity of IAS-Zone 2 and lowest for specific storage of the upper confining unit. The model was insensitive to vertical hydraulic conductivity of the upper and confining units, resulting in little influence of these parameters on overall model performance. Part of the reason for this may the lack of drawdown across these confining units when the adjacent aquifers were pumped.

ROMP 9 Model

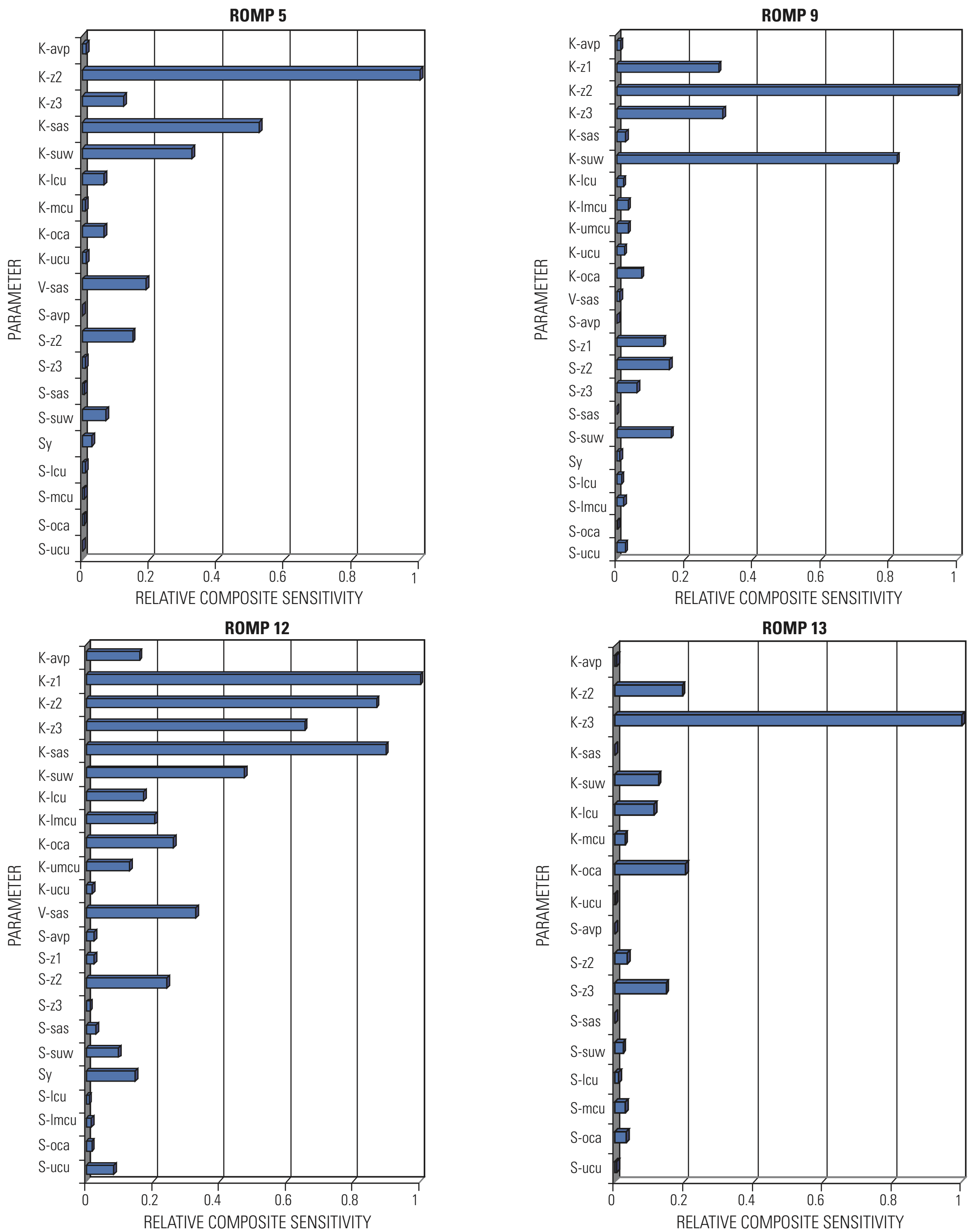
ROMP 9 is located at 27°04´32˝N and 82°08´57˝W in Sarasota County near the southeastern county line (fig. 10). Land surface altitude at the well site is about 25 ft above NGVD 29. Seven permanent and nine temporary wells ranging from 2 to 12 in. in diameter were completed at ROMP 9. The deepest well, MW6, was drilled to 1,230 ft below land surface.

Five aquifer tests were conducted from October 1996 through May 1997 at the ROMP 9 site to estimate the hydraulic properties of the surficial aquifer system (SAS), upper intermediate aquifer system (IAS-Zone 1), middle intermediate aquifer system (IAS-Zone 2), lower intermediate aquifer system (IAS-Zone 3), and the Suwannee Limestone (table 1). A plan view and construction records of the production and observation wells for the aquifer tests are shown in figure 10. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 11 shows plots of the drawdown data used for analysis.

Well MW1, tapping the surficial aquifer system, was pumped at a rate of 75 gal/min for 48 hours. Prior to this test, a preliminary test was run for a total of 240 minutes at a pumping rate of 42 gal/min. Drawdown data measured in the pumped well (MW1), the surficial aquifer system wells OW7 and OW11, and IAS-Zone 1 well MW2, were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 1.6 ft in the pumped well, about 0.4 ft in well OW7, and about 0.1 ft in well OW11. During the drawdown phase of the test, a water-level decline of about 0.02 ft was estimated in the IAS-Zone 1 observation well, indicating a possible hydraulic connection with the underlying IAS-Zone 1. No decline in water level was estimated in the underlying IAS-Zone 2 well MW3.

Well MW2, tapping the upper producing zone of the intermediate aquifer system (IAS-Zone 1), was pumped at a rate of 7.4 gal/min for 24 hours. Drawdown data measured in the pumped well (MW2), IAS-Zone 1 well OW8, IAS-Zone 2 well MW3, IAS-Zone 3 well MW4, and Suwannee Limestone well MW5 were used in the numerical analysis. Diurnal water-level fluctuations of about 0.1 ft were estimated in the surficial aquifer system and IAS-Zone 2 observation wells. During the drawdown phase of the aquifer test, the water level declined about 19 ft in the pumped well and about 10 ft in the IAS-Zone 1 observation well OW8. No decline in water level was estimated in either the overlying surficial aquifer system well or in the underlying IAS-Zone 2, IAS-Zone 3, or Suwannee Limestone wells.

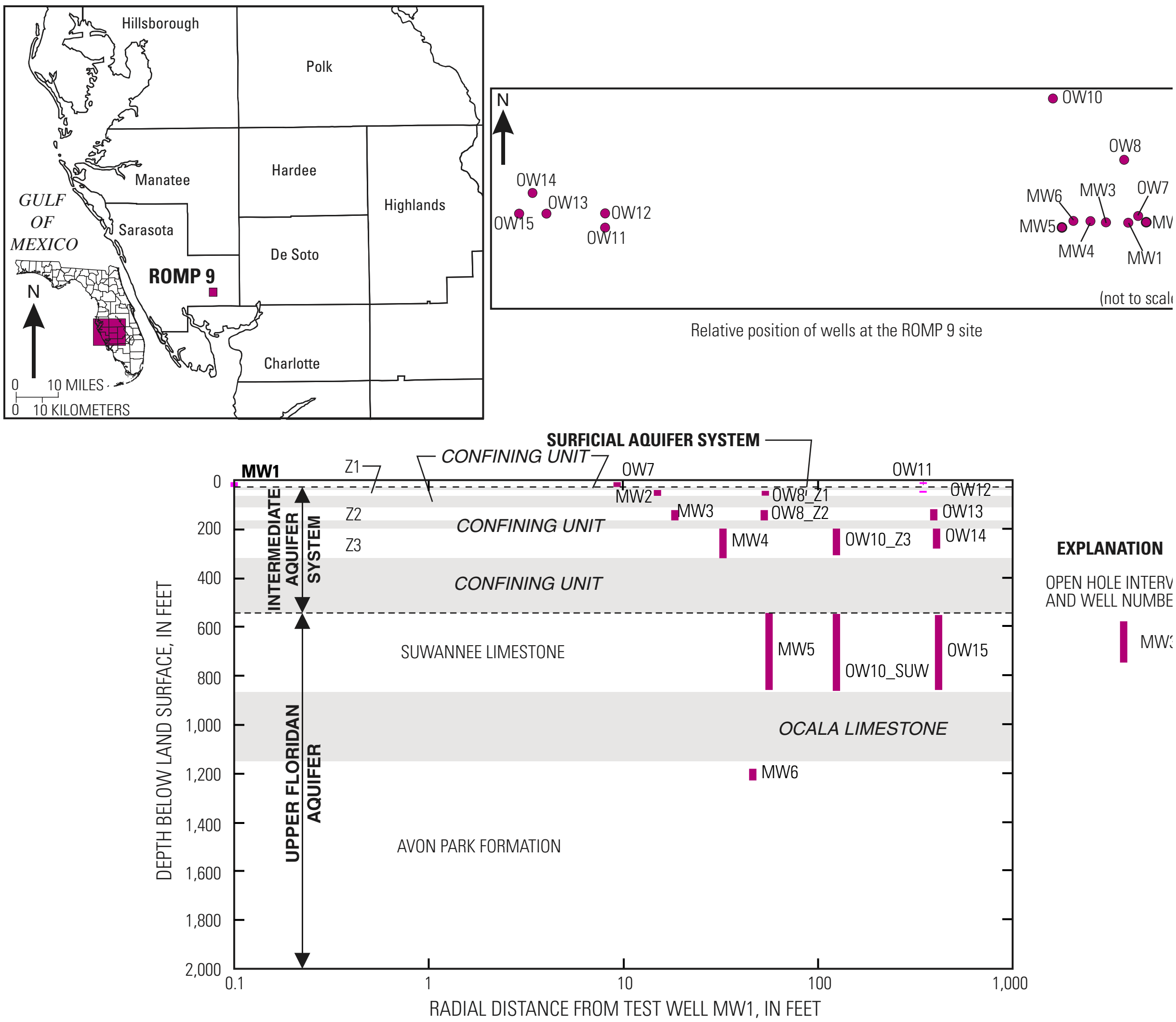
Well MW3, tapping the middle producing zone of the intermediate aquifer system (IAS-Zone 2), was pumped at a rate of 42 gal/min for 24 hours. Drawdown data measured in the pumped well (MW3), IAS-Zone 2 wells OW8 and OW13, IAS-Zone 1 well OW8, and IAS-Zone 3 well MW4 were used



Parameter Abbreviations

[K, hydraulic conductivity; S, specific storage; Sy, specific yield; V, vertical anisotropy; sas, surficial aquifer system; ias, intermediate aquifer system; z1, ias Zone 1; z2, ias Zone 2; z3, ias Zone 3; suw, Suwannee Limestone; avp, Avon Park Limestone; ucu, confining unit between sas and ias; umcu, confining unit between z1 and z2; lmcu, confining unit between z2 and z3; mcu, confining unit between z1/2 and z3; lcu, confining unit between z3 and suw; V, vertical anisotropy]

Figure 9. Relative composite sensitivity for final parameter values for ROMP 5, 9, 12, and 13.



Well name	Stratigraphic Unit		Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet) MW1 (SAS)	MW2 (Z1)	MW3 (Z2)	MW4 (Z3)	MW5 (SUW)
			Surficial aquifer system (SAS)						
MW1	Undifferentiated surficial deposits		7/27	4		15.0	19.0	32.1	57.1
OW7	Undifferentiated surficial deposits		7/27	2	9.2	9.4	26.5	39.2	64.6
OW11	Undifferentiated surficial deposits		8/13	2	448.0	463.0	429.0	416.0	391.0
			Intermediate aquifer system						
MW2	Peace River Formation	(Z1)	40/65	6	15.0		34.0	47.0	72.1
OW8	Peace River Formation	(Z1)	42/63	2	55.1	56.9	56.3	60.4	79.2
OW12	Peace River Formation	(Z1)	42/52	2	448.1	463.1	429.1	416.1	392.2
MW3	Upper Arcadia Formation	(Z2)	122/165	8	19.0	34.0		13.0	38.2
OW8	Upper Arcadia Formation	(Z2)	122/164	2	55.1	56.9	56.3	60.4	79.2
OW13	Upper Arcadia Formation	(Z2)	120/184	2	497.1	512.0	478.1	465.0	440.1
MW4	Lower Arcadia Formation	(Z3)	190/320	12	32.1	47.0	13.0		25.5
OW10	Lower Arcadia Formation	(Z3)	193/309	2	125.2	132.8	115.6	110.0	110.3
OW14	Lower Arcadia Formation	(Z3)	190/280	2	509.7	524.6	490.6	477.6	452.9
			Upper Floridan aquifer						
MW5	Suwannee Limestone	(SUW)	545/860	12	57.1	72.1	38.2	25.5	
OW10	Suwannee Limestone	(SUW)	547/863	2	125.2	132.8	115.6	110.0	110.3
OW15	Suwannee Limestone	(SUW)	550/860	2	521.1	536.0	502.0	489.0	464.1
MW6	Avon Park Formation		1,180/1,230	6	47.0	62.0	28.0	15.0	11.2

Figure 10. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 9 test site.

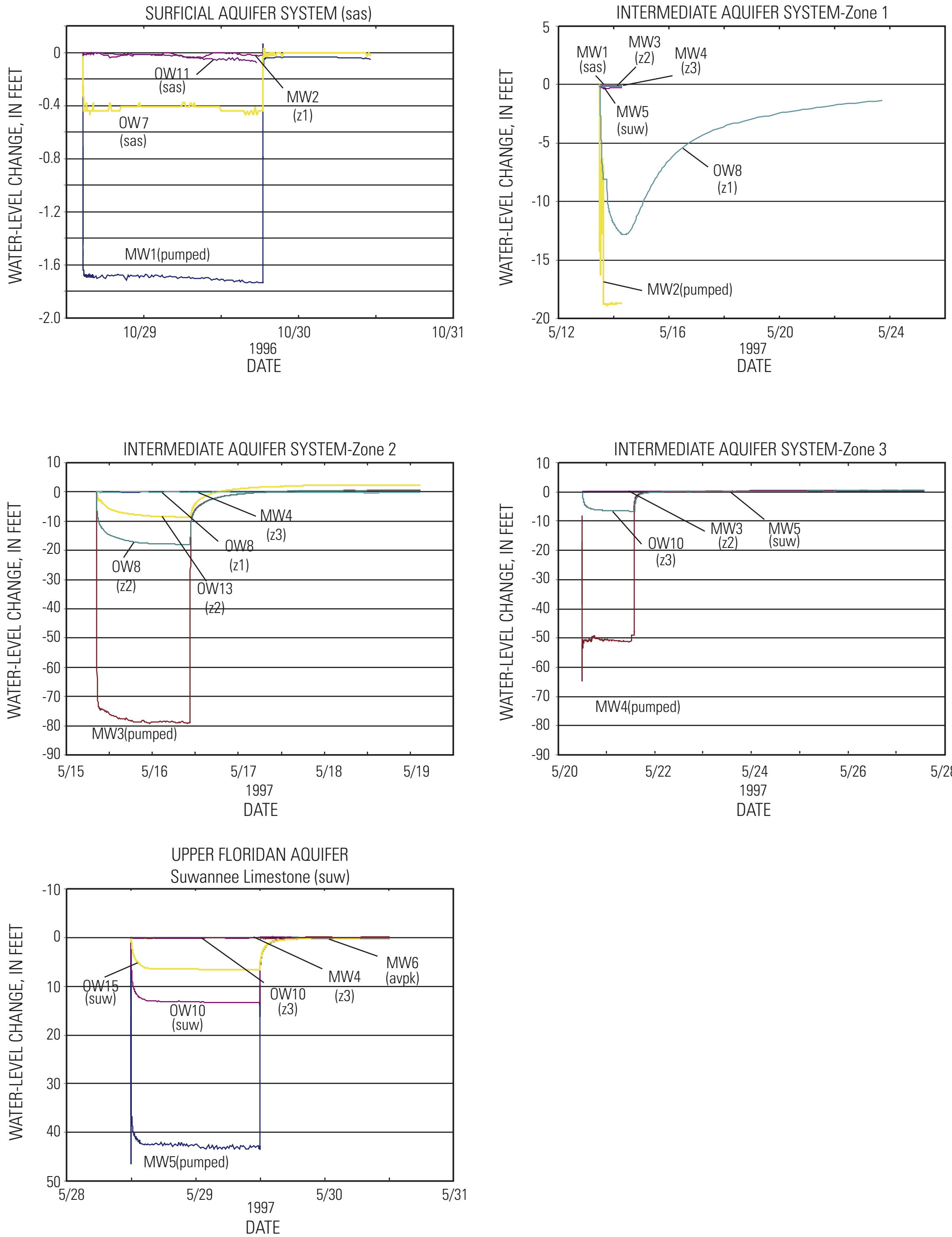


Figure 11. Water levels in selected wells during drawdown and recovery periods of the five aquifer tests conducted at the ROMP 9 test site.

in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 80 ft in the pumped well, about 20 ft in the IAS-Zone 2 well OW8, and about 10 ft in the IAS-Zone 2 well OW13. Diurnal water-level fluctuations of about 0.2 ft were estimated in the IAS-Zone 3 and Suwannee Limestone observation wells. A decline of about 0.6 ft was estimated in the IAS-Zone 1 well, but no decline in water level was estimated in the underlying IAS-Zone 3 or Suwannee Limestone wells.

Well MW4, tapping the lower producing zone of the intermediate aquifer system (IAS-Zone 3), was pumped at a rate of 212 gal/min for 24 hours. Drawdown data measured in the pumped well (MW4), IAS-Zone 3 well OW10, IAS-Zone 2 well MW3, and Suwannee Limestone well MW5 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 50 ft in the pumped well and about 6 ft in IAS-Zone 3 well OW10. No decline was estimated in the overlying Zone 2 or underlying Suwannee Limestone wells.

Well MW5, tapping the Suwannee Limestone zone of the Upper Floridan aquifer, was pumped at a rate of 1,020 gal/min for about 24 hours. Drawdown data measured in the pumped well (MW5), Suwannee Limestone wells OW10 and OW 15, IAS-Zone 3 well OW10 and MW4, and Avon Park Formation well MW6 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 45 ft in the pumped well, about 13 ft in the Suwannee Limestone well OW10, and about 7 ft in the Suwannee Limestone OW15 well. No decline in water level was estimated in either the overlying IAS-Zone 3 well or in the underlying Avon Park Formation well. Diurnal water-level fluctuations of about 0.2 ft were observed in the IAS-Zone 3, IAS-Zone 2, and Suwannee Limestone observation wells.

Aquifer test data were analyzed by Thompson (1997) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer tests and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP 9	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
Surficial aquifer system	32,900	1,200	1.8E-4
IAS-Zone 1	47	2	--
IAS-Zone 2	246	5	2.6E-4
IAS-Zone 3	708	6	1.1E-3
UFA-Suwannee Limestone	6,374	20	2.8E-4

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; -- no data]

Model Structure

The ROMP 9 model extended from the production wells to 200,000 ft away and from the water table to 2,000 ft below land surface. The numerical model consisted of 116 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 695 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column.

Six water-bearing units were simulated—the surficial aquifer system, IAS-Zone 1, IAS-Zone 2, IAS-Zone 3, Suwannee Limestone, and the Avon Park Formation; and five confining units—upper, upper-middle, lower-middle, lower confining units, and the Ocala Limestone (fig. 3B). The surficial aquifer system is about 28 ft thick at the ROMP 9 site (table 2). The intermediate aquifer system underlies the surficial aquifer system and is about 517 ft thick, including three producing zones (IAS-Zone 1, IAS-Zone 2, and IAS-Zone 3) separated by three confining units. The Upper Floridan aquifer, the lowermost permeable aquifer, is about 1,455 ft thick and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 20 parameters. Lateral hydraulic conductivities of the five confining units and six producing zones make up 11 of the parameters. Specific storage of four of the five producing zones and three of the five confining units make up seven more parameters. Vertical anisotropy and specific yield of the surficial aquifer system make up the last two parameters. Specific storage of the two shallowest confining units was defined with a single parameter because their lithology was similar and the parameters were highly correlated. Specific storage of the surficial aquifer system, Ocala Limestone, and the Avon Park Formation was assigned a value of 1.5 E-6 ft^{-1} because of parameter insensitivity. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all other units.

Simulated drawdowns matched measured drawdowns reasonably well during most aquifer tests with an average unweighted root-mean-squared error (RMSE) of 0.22 ft for the five tests. The fit of measured and simulated time-drawdown data is illustrated in figure 12. RMSE of individual aquifer tests ranged from 0.04 ft for the surficial aquifer system to 0.55 ft for the IAS-Zone 2 (table 3). The estimated and assigned hydraulic properties and sensitivity rating for the estimated parameters from this simulation are shown below (unpumped zone is italicized):

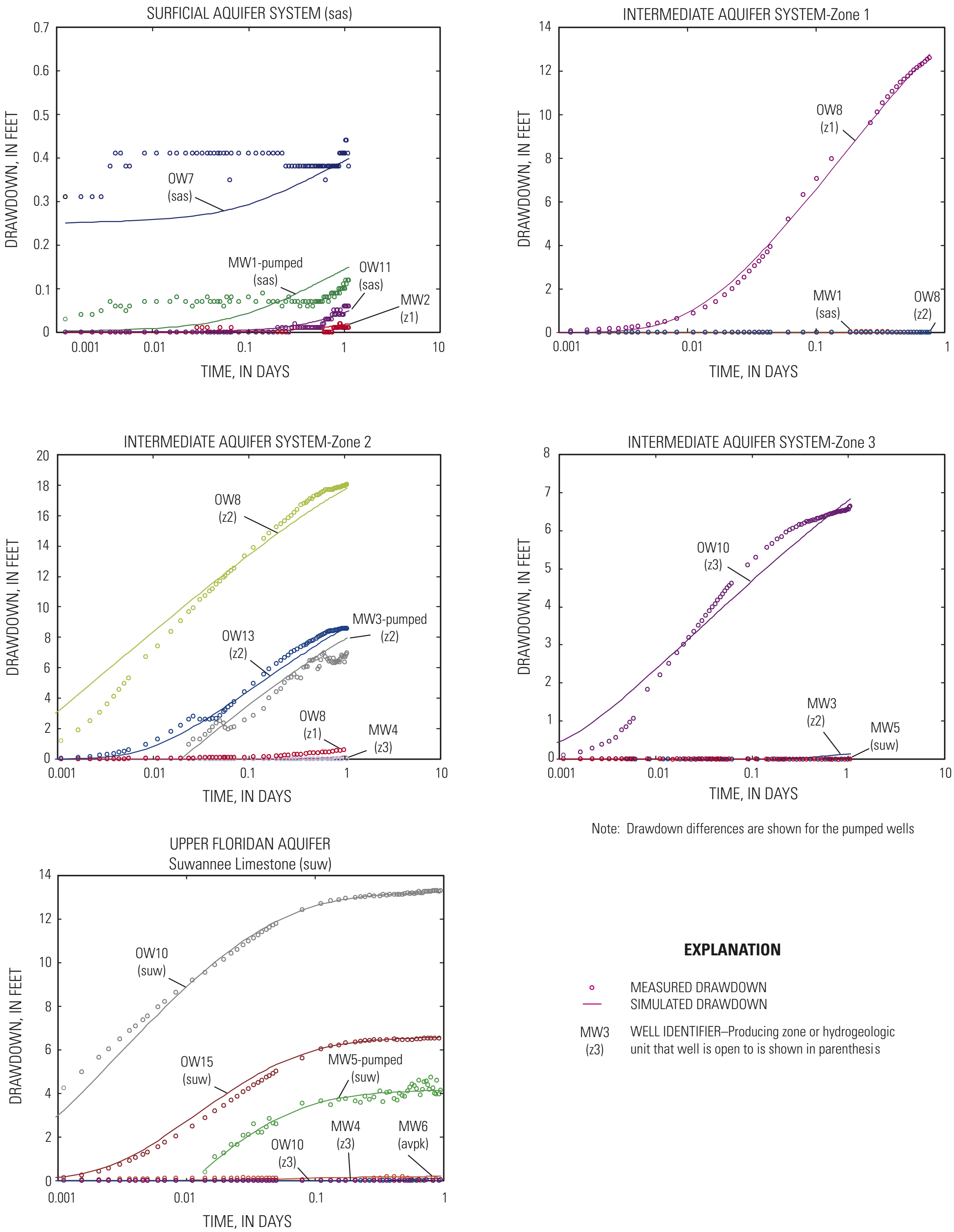


Figure 12. Simulated and measured drawdown for the five aquifer tests conducted at the ROMP 9 test site.

Hydrogeologic unit ROMP 9	T (ft^2/d)	K (ft/d)		K_z/K_h		S_y		Storage		
			[2]RCS rating		RCS rating		RCS rating	S	S_s (d^{-1})	RCS rating
Surficial aquifer system	22,000	790	fair	0.04	low	0.22	low	4.2E-5	[1]1.5E-6	
IAS-Zone 1	31	1	high	[1]0.10				3.7E-4	1.5E-5	high
IAS-Zone 2	270	5	high	[1]0.10				4.8E-5	9.0E-7	high
IAS-Zone 3	2,800	22	high	[1]0.10				8.3E-4	6.6E-6	fair
UFA-Suwannee Limestone	5,100	16	high	[1]0.10				3.8E-4	1.2E-6	high
UFA-Avon Park Formation	*760,000*	*890*	*low*	*[1]0.10*				*[1]1.3E-3*	*[1]1.5E-6*	

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_s) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; K_z/K_h, vertical to horizontal anisotropy; S_y, specific yield. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

The resulting values of transmissivity are about the same as those derived from the analytical models, except for the IAS-Zone 3, where the simulated value is about 4 times greater, and the surficial aquifer system, where the simulated value is about 50 percent lower. The resulting values of storativity are about an order of magnitude less than those derived from the analytical models.

Hydraulic conductivity of the pumped zones and specific storage of IAS-Zone 1, IAS-Zone 2, and the Suwannee Limestone were resolved with high confidence. Hydraulic conductivity of the surficial aquifer system and specific storage IAS-Zone 3 were resolved with moderate confidence. Hydraulic conductivity of the unpumped Avon Park Formation, and vertical anisotropy and specific yield of the surficial aquifer system were resolved with low confidence and are the most uncertain of the aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP 9	Leakance (ft/d/ft)	K_z (ft/d)		[6]K_z/K_h	Specific storage (d^{-1})	
			[5]RCS rating			RCS rating
[1]Upper	1.4E-4	1.7E-3	fair	0.1	8.0E-7	fair
[2]Upper-Middle	1.7E-5	8.0E-4	fair	0.1	8.0E-7	fair
[3]Lower-Middle	2.0E-5	6.0E-4	fair	0.1	1.1E-6	fair
[4]Lower	1.7E-4	3.9E-2	low	0.1	3.3.E-6	low
Ocala Limestone	1.6E-2	4.5E+00	fair	0.1	1.6E-5	low

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_z) by the appropriate thickness; K_z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 1. [2]Confining unit between IAS-Zone 1 and IAS-Zone 2. [3]Confining unit between IAS-Zone 2 and IAS-Zone 3. [4]Confining unit between IAS-Zone 3 and Suwannee Limestone. [5]Relative scaled sensitivity. [6]This parameter was assigned and not estimated with the inverse model]

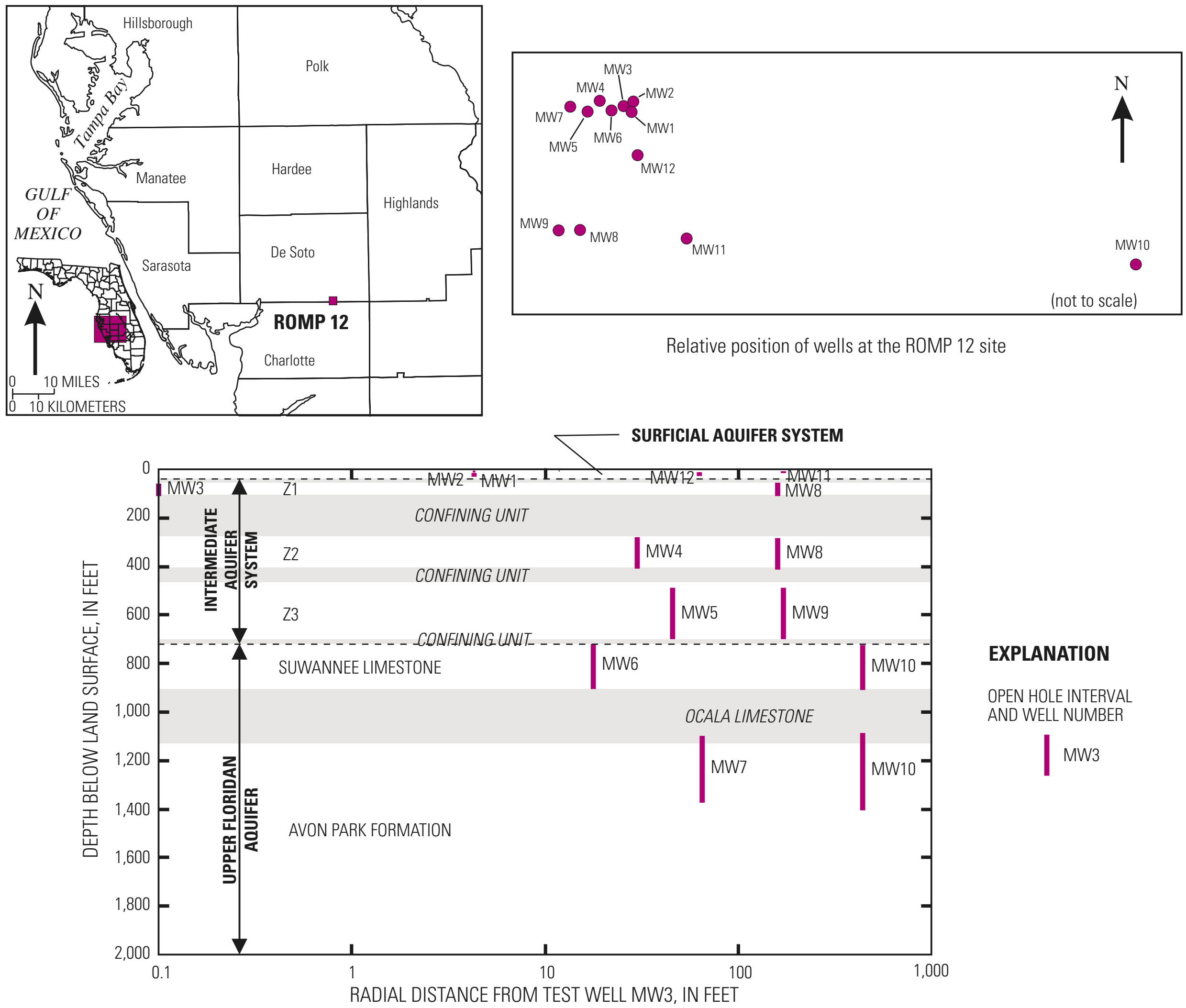
Vertical hydraulic conductivity of the upper, upper-middle, and lower-middle confining units, and the Ocala Limestone and specific storage of the upper, upper-middle, and lower-middle confining units were resolved with moderate confidence. Hydraulic conductivity of the lower confining unit and specific storage of the lower confining unit and the Ocala Limestone was resolved with low confidence and are the most uncertain of the confining unit parameters.

Relative composite sensitivity (RCS) values for the estimated and assigned parameters are shown in figure 9 and appendix 1. Generally, the model was most sensitive to hydraulic conductivity of the pumped zones and the least sensitive to specific storage of the confining units. Sensitivity is highest for the hydraulic conductivity of IAS-Zone 2 and lowest for specific storage of the surficial aquifer system. The reason for the model´s insensitivity to hydraulic conductivity of the lower confining unit and Avon Park Formation is that no drawdown was observed across confining units when neighboring layers were pumped.

ROMP 12 Model

ROMP 12 is located at 27°26´28˝N and 81°44´32˝W in De Soto County near the southern county line (fig. 13). Land surface altitude at the well site is about 41 ft above NGVD 29. Seven permanent and seven temporary wells ranging from 2 to 12 in. in diameter were completed at ROMP 12. The deepest well, MW10, was drilled to 1,405 ft below land surface.

Six aquifer tests were conducted from July 1997 through August 1998 at the ROMP 12 site to estimate the hydraulic properties of the surficial aquifer system (SAS), the upper intermediate aquifer system (IAS-Zone 1), the middle intermediate aquifer system (IAS-Zone 2), the lower intermediate aquifer system (IAS-Zone 3), the Suwannee Limestone), and the Avon Park Formation (table 1). A plan view and construction records of the production and observation wells for the aquifer tests are shown in figure 13. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 14 shows plots of the drawdown data used for analysis.



Well name	Stratigraphic Unit		Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet)					
					MW12 (SAS)	MW3 (Z1)	MW4 (Z2)	MW5 (Z3)	MW6 (SUW)	MW7 (AvPk)
Surficial aquifer system (SAS)										
MW1	Undifferentiated surficial deposits		2/5	4	52.0	6.4	36.4	51.5	20.0	72.1
MW2	Undifferentiated surficial deposits		12/27	4	60.0	6.4	36.9	53.5	22.0	74.4
MW11	Undifferentiated surficial deposits		8/15	2	114.0	167.4	193.3	179.0	167.1	195.5
MW12	Undifferentiated surficial deposits		13/28	4		60.8	78.1	78.1	60.9	97.7
Intermediate aquifer system										
MW3	Peace River Formation	(Z1)	60/110	8	60.8		31.3	47.4	15.9	60.4
MW8	Peace River Formation	(Z1)	55/110	2	111.4	138.0	136.0	140.2	145.9	146.6
MW4	Upper Arcadia Formation	(Z2)	280/409	8	78.1	31.3		17.6	16.6	29.2
MW8	Upper Arcadia Formation	(Z2)	285/414	2	111.4	138.0	136.0	115.5	121.8	128.2
MW5	Lower Arcadia Formation	(Z3)	487/710	8	78.4	47.4	17.6		31.6	15.0
MW9	Lower Arcadia Formation	(Z3)	490/705	2	128.5	166.7	160.8	120.0	130.1	123.0
Upper Floridan aquifer										
MW6	Suwannee Limestone	(SUW)	720/905	8	60.9	15.8	16.6	31.5		45.0
MW10	Suwannee Limestone	(SUW)	725/909	3	411.8	442.1	471.2	481.3	457.0	500.0
MW7	Avon Park Formation	(AvPk)	1,100/1,373	12	97.7	60.4	29.5	15.0	45.0	
MW10	Avon Park Formation	(AvPk)	1,085/1,405	6	411.8	442.1	471.2	481.3	457.0	500.0

Figure 13. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 12 test site.

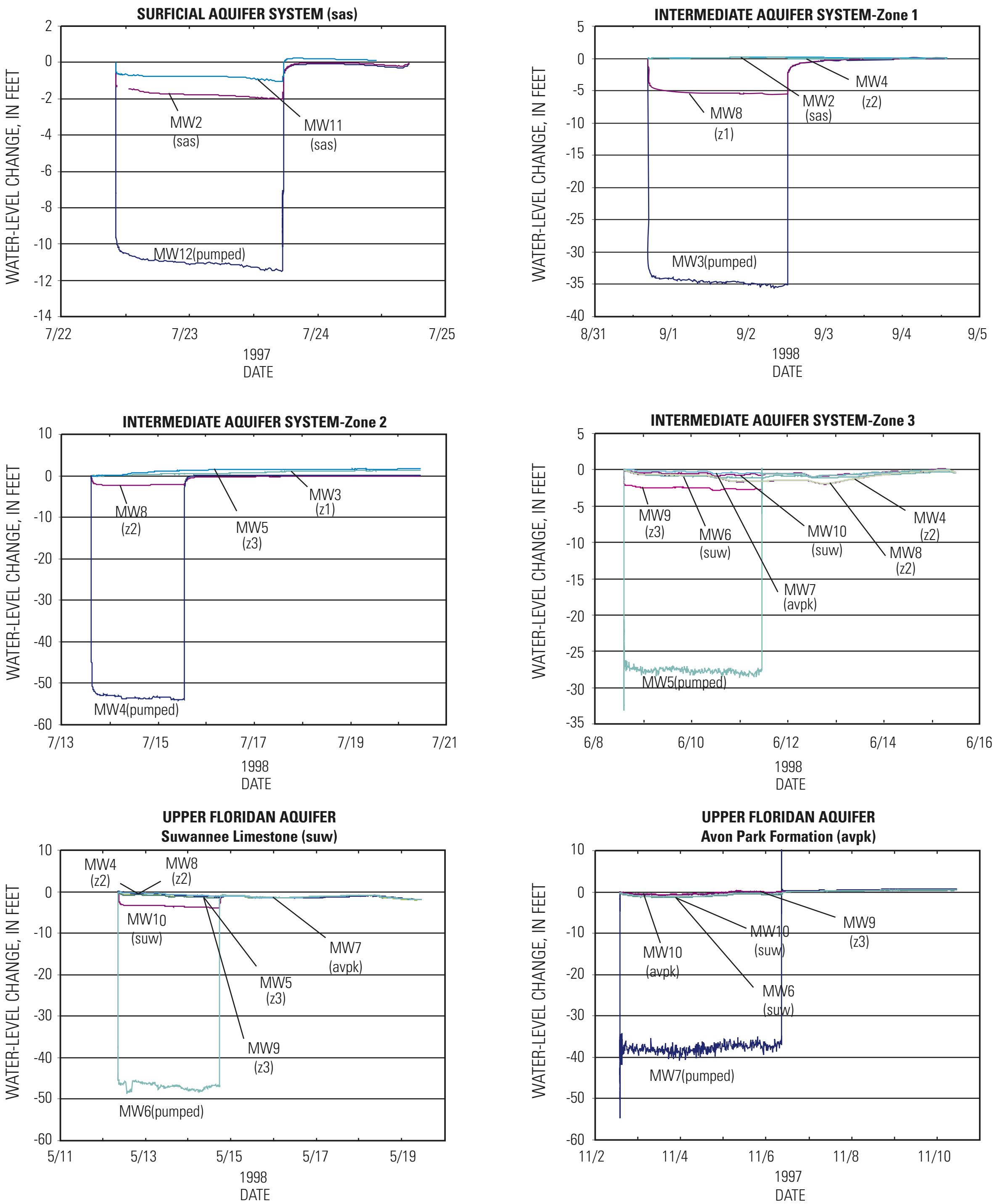


Figure 14. Water levels in selected wells during drawdown and recovery periods of the six aquifer tests conducted at the ROMP 12 test site.

Well MW12, tapping the lower surficial aquifer system, was pumped at a rate of 21.4 gal/min for 31.4 hours. Drawdown data measured in the pumped well MW12 and surficial aquifer system wells MW2 and MW 11 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 11 ft in the pumped well, about 2 ft in surficial aquifer system well MW2, and about 1 ft in surficial aquifer system well MW11. No decline in water level was estimated in the underlying IAS-Zone 1 observation well (MW3) during the drawdown phase.

Well MW3, tapping the upper permeable zone of the intermediate aquifer system (IAS-Zone 1), was pumped at a rate of 256 gal/min for 43.4 hours. Drawdown data measured in the pumped well (MW3), IAS-Zone 1 well MW8, surficial aquifer system well MW2, and IAS-Zone 2 well MW4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 35 ft in the pumped well and about 6 ft in IAS-Zone 1 observation well MW8.

Well MW4, tapping the middle permeable zone of the intermediate aquifer system (IAS-Zone 2), was pumped at a rate of 47 gal/min for 46.4 hours. Drawdown data measured in pumped well (MW4), IAS-Zone 2 well (MW8), IAS-Zone 3 (MW5) and IAS-Zone 1 well (MW3) were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 54 ft in the pumped well and about 2 ft in IAS-Zone 2 well MW8. No decline in water level was estimated in the overlying IAS-Zone 1 well or in the underlying IAS-Zone 3 well; however, after about 1 day, water levels started to rise in all observation wells indicating an external stress.

Well MW5, tapping the lower permeable zone of the intermediate aquifer system (IAS-Zone 3), was pumped at a rate of 907 gal/min for 68.7 hours. Drawdown data measured in IAS-Zone 3 well MW9, IAS-Zone 2 wells MW4 and MW8, Suwannee Limestone wells MW6 and MW10, and Avon Park Formation well MW7 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 28 ft in the pumped well and about 3 ft in the IAS- Zone 3 observation well MW9. Water level declines of about 0.7 ft in the IAS-Zone 2 wells and about 0.5 ft in the Suwannee Limestone were estimated, indicating hydraulic connection with the overlying IAS-Zone 2 and the underlying Suwannee Limestone. All wells had diurnal water-level fluctuations of about 0.2 ft.

Well MW6, tapping the Suwannee Limestone producing zone of the Upper Floridan aquifer, was pumped at a rate of 730 gal/min for about 56.9 hours. Drawdown data measured in Suwannee Limestone well MW10, IAS-Zone 2 wells MW4 and MW8, IAS-Zone 3 wells MW5 and MW9, and Avon Park Formation well MW7 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 48 ft in the pumped well and about 4 ft in the Suwannee Limestone well MW10. Water-level declines of about 0.5 ft in the IAS-Zone 3 well and about 0.2 ft in the IAS-Zone 2 well were measured. No decline was estimated in either the IAS-Zone 1 observation well or in the Avon Park Formation observation well. Regional water-level declines of about 1 ft were estimated in the IAS wells during the pumping phase of the test. Additionally, all wells have diurnal water-level fluctuations of about 0.2 ft.

Well MW7, tapping the Avon Park Formation producing zone of the Upper Floridan aquifer, was pumped at a rate of 5,200 gal/min for about 91.2 hours. Drawdown data measured in Avon Park Formation well MW10, IAS-Zone 3 well MW9, and Suwannee Limestone wells MW6 and MW10 were used in the numerical analysis. Wells had diurnal water-level fluctuations of about 0.1 to 0.5 ft. Water levels in the production and observation wells began rising approximately 10 hours and 30 hours into the pumping phase of the test, respectively, as a result of changes in regional stresses in the area. Consequently, only the first 10 hours of the test were simulated. During the drawdown phase of the aquifer test, the water level declined about 39 ft in the pumped well and about 0.5 ft in the Avon Park Formation well MW10 well. Water-level declines of about 0.5 ft in the IAS-Zone 3 well and about 0.5 ft in Suwannee Limestone wells were measured.

Aquifer test data were analyzed by Clayton (1999) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer tests and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP 12	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
Surficial aquifer system	752	19	2.5E-4
IAS-Zone 1	5,550	113	4.8E-5
IAS-Zone 2	1,210	9	2.9E-4
IAS-Zone 3	42,600	182	8.1E-5
UFA-Suwannee Limestone	7,060	38	3.9E-4
UFA-Avon Park Formation	1,640,000	1,710	8.0E-4

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer]

Model Structure

The ROMP 12 model extended from the production wells to 200,000 ft away and from the water table to 2,090 ft below land surface. The numerical model consisted of 135 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 959 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column. Vertical discretization was finer across the confining units and the surficial aquifer system than across the other hydrogeologic units.

Six water-bearing units were simulated—the surficial aquifer system, IAS- Zone 1, IAS- Zone 2, IAS- Zone 3, Suwannee Limestone, and the Avon Park Formation; and five confining units—upper, upper-middle, lower-middle, and lower confining units, and the Ocala Limestone (fig. 3B). The surficial aquifer system is about 40 ft thick at the ROMP 12 site (table 2). The intermediate aquifer system underlies the surficial aquifer and is about 679 ft thick, including three producing zones (IAS-Zone 1, IAS-Zone 2, and IAS-Zone 3) separated by four confining units. The Upper Floridan aquifer, the lowermost permeable zone, is about 1,371 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 23 parameters. Lateral hydraulic conductivities of the five confining units and six producing zones make up 11 of the parameters. Specific storage of the two shallowest confining units was solved with a single parameter because their lithology was similar and the parameters were highly correlated. Specific storage of the remaining hydrogeologic units make up nine more parameters. Vertical anisotropy and specific yield of the surficial aquifer make up the last two parameters. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all other units.

Simulated drawdowns matched measured drawdowns reasonably well during most aquifer tests with an average unweighted root-mean-squared error (RMSE) of 0.11 ft for the six tests (table 3). The fit of measured and simulated time-drawdown data is illustrated in figure 15. The fit for the Avon Park Formation test exhibited the poorest match between simulated and measured drawdown. Model simulated changes do not parallel the observed drawdown hydrograph during the late phase of the test. It is believed that the poor match is associated with anisotropy of the aquifer system and unknown stresses in the area. RMSE of individual aquifer tests ranged from 0.06 ft for the SAS to 0.17 ft for IAS-Zone 1 (table 3). The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below:

Hydrogeologic unit ROMP 12	T (ft^2/d)	K (ft/d)		K_z/K_h		S_y		Storage		
			[2]RCS rating		RCS rating		RCS rating	S	S_s (d^{-1})	RCS rating
Surficial aquifer system	520	13	high	0.02	high	0.04	high	7.6E-5	1.9E-6	fair
IAS-Zone 1	4,900	100	high	[1]0.1				9.8E-6	2.0E-7	fair
IAS-Zone 2	660	5	high	[1]0.1				6.6E-4	5.0E-6	high
IAS-Zone 3	43,000	184	high	[1]0.1				2.3E-5	1.0E-7	low
UFA-Suwannee Limestone	5,000	27	high	[1]0.1				1.9E-4	1.0E-6	fair
UFA-Avon Park Formation	1,500,000	1,518	high	[1]0.1				7.7E-4	8.0E-7	fair

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_s) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; K_z/K_h, vertical to horizontal anisotropy; S_y, specific yield. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

The resulting values of transmissivity are about the same as the transmissivity derived from the analytical models, except for the IAS-Zone 2, where the simulated value is 50 percent less. The resulting values of storativity differed up to an order of magnitude from those derived from analytical models, with most model results providing smaller values.

Hydraulic conductivity of the pumped zones and specific storage of IAS-Zone 2 was resolved with high confidence. Specific storage of the surficial aquifer system, IAS-Zone 1, the Suwannee Limestone, and Avon Park Formation were resolved with moderate confidence. Specific storage of IAS-Zone 3 was resolved with low confidence and is the most uncertain of the aquifer parameters.

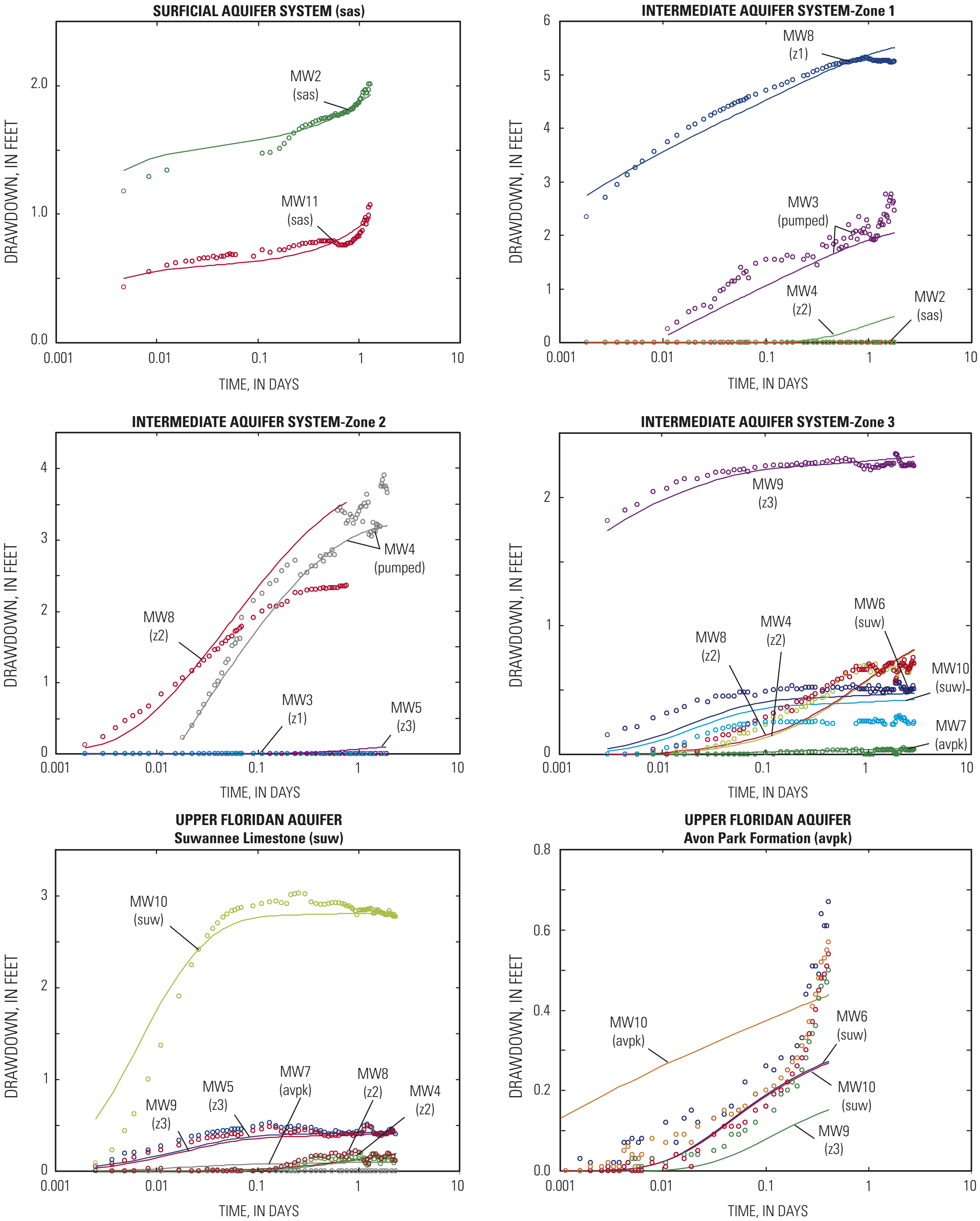
The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP 12	Leakance (ft/d/ft)	K_z (ft/d)		[6]K_z/K_h	Specific storage (d^{-1})	
			[5]RCS rating			RCS rating
[1]Upper	4.6E-4	7.9E-4	low	0.1	3.0E-6	fair
[2]Upper-Middle	2.9E-4	4.9E-2	high	0.1	3.0E-6	fair
[3]Lower-Middle	1.1E-3	6.5E-2	high	0.1	1.9E-6	low
[4]Lower	6.0E-3	1.2E-1	high	0.1	1.7E-6	low
Ocala Limestone	9.7E-3	2.2E+00	high	0.1	1.1E-6	low

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_Z) by the appropriate thickness; K_Z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 1. [2]Confining unit between IAS-Zone 1 and IAS-Zone 2. [3]Confining unit between IAS-Zone 2 and IAS-Zone 3. [4]Confining unit between IAS Zone 3 and Suwannee Limestone. [5]Relative scaled sensitivity. [6]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the upper-middle, lower-middle, and lower confining units, and the Ocala Limestone was resolved with high confidence. Hydraulic conductivity of the upper confining unit and specific storage of the lower-middle and lower confining units and the Ocala Limestone were resolved with low confidence and are the most uncertain of the confining unit parameters.

Relative composite sensitivity (RCS) values for the estimated and assigned parameters are shown in figure 9 and appendix 1. Overall, the model is most sensitive to hydraulic conductivity of the aquifers and least sensitive to specific storage of the confining units. Sensitivity is highest for the



Note: Drawdown differences are shown for the pumped wells

EXPLANATION

∘	MEASURED DRAWDOWN	MW3 (z3)	WELL IDENTIFIER–Producing zone or hydrogeologic unit that well is open to is shown in parenthesis
—	SIMULATED DRAWDOWN		

Figure 15. Simulated and measured drawdown for the six aquifer tests conducted at the ROMP 12 test site.

hydraulic conductivity of IAS-Zone 1 and lowest for specific storage of the lower confining unit. The model was insensitive to hydraulic conductivity of the upper confining unit and specific storage of the Ocala Limestone, lower-middle confining unit, IAS-Zone 3, and the lower confining unit, resulting in little influence of these parameters on overall model performance.

ROMP 13 Model

ROMP 13 is located at 27°04´17˝N and 81°36´57˝W in De Soto County near the southeastern county line (fig. 16). Land surface altitude at the well site is about 60 ft above NGVD 29. Five permanent and four temporary wells ranging from 2 to 8 in. in diameter were completed at ROMP 13. The deepest well, MW5, was drilled to 1,600 ft below land surface.

Three aquifer tests were conducted from November-December 1996 at the ROMP 13 site to estimate the hydraulic properties of the upper intermediate aquifer system (IAS-Zone 2), the lower intermediate aquifer system (IAS-Zone 3), and the Suwannee Limestone (table 1). A plan view and construction records of the production and observation wells for the aquifer tests are shown in figure 16. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 17 shows plots of the drawdown data used for analysis.

Well MW2, tapping the uppermost producing zone of the intermediate aquifer system (IAS-Zone 2), was pumped at a rate of 46 gal/min for 49.7 hours. Drawdown data measured in the pumped well (MW2), IAS-Zone 2 well (MW7), and IAS-Zone 3 wells (MW3 and MW7) were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 52 ft in the pumped well and about 13 ft in IAS-Zone 2 well MW7. No water-level declines were estimated in any of the other monitor wells; however, diurnal water-level fluctuations of about 0.1 ft were recorded in the Suwannee Limestone and the Avon Park Formation wells.

Well MW3, tapping the lowermost producing zone of the intermediate aquifer system (IAS-Zone 3), was pumped at a rate of 230 gal/min for 51.7 hours. Drawdown data measured in the pumped well (MW3), IAS-Zone 3 well MW7, IAS-Zone 2 well MW2, and Suwannee Limestone well MW4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 48 ft in the pumped well and about 25 ft in IAS-Zone 3 observation well MW7. No drawdown was estimated in the overlying IAS-Zone 2 well MW2 or the underlying Suwannee Limestone well MW4. There were two sudden and substantial declines in water level during both the pumping and recovery phase in the Suwannee Limestone zone that was attributed to nearby pumping (Baldini, 1999). Regional water-level declines of about 0.5 ft were estimated in the IAS-Zone 2 MW7well and in the Suwannee Limestone MW4 well during the pumping phase of the test.

Well MW4, tapping the Suwannee Limestone producing zone of the Upper Floridan aquifer, was pumped at a rate of 480 gal/min for about 61.7 hours. Drawdown data measured in the pumped well (MW4), the Suwannee Limestone well MW8, the IAS-Zone 3 well MW7, and the Avon Park Formation well MW5 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 141 ft in the pumped well, about 18 ft in the Suwannee Limestone well MW8 well, and about 0.2 ft in the Avon Park Formation well MW5. No water-level decline was estimated in the IAS-Zone 3 well MW7; however, regional water-level declines of about 0.5 ft were estimated in the IAS-Zone 2 well, the IAS-Zone 3, and in the Avon Park Formation wells during the pumping phase of the test.

Aquifer test data were analyzed by Baldini (1999) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer tests and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

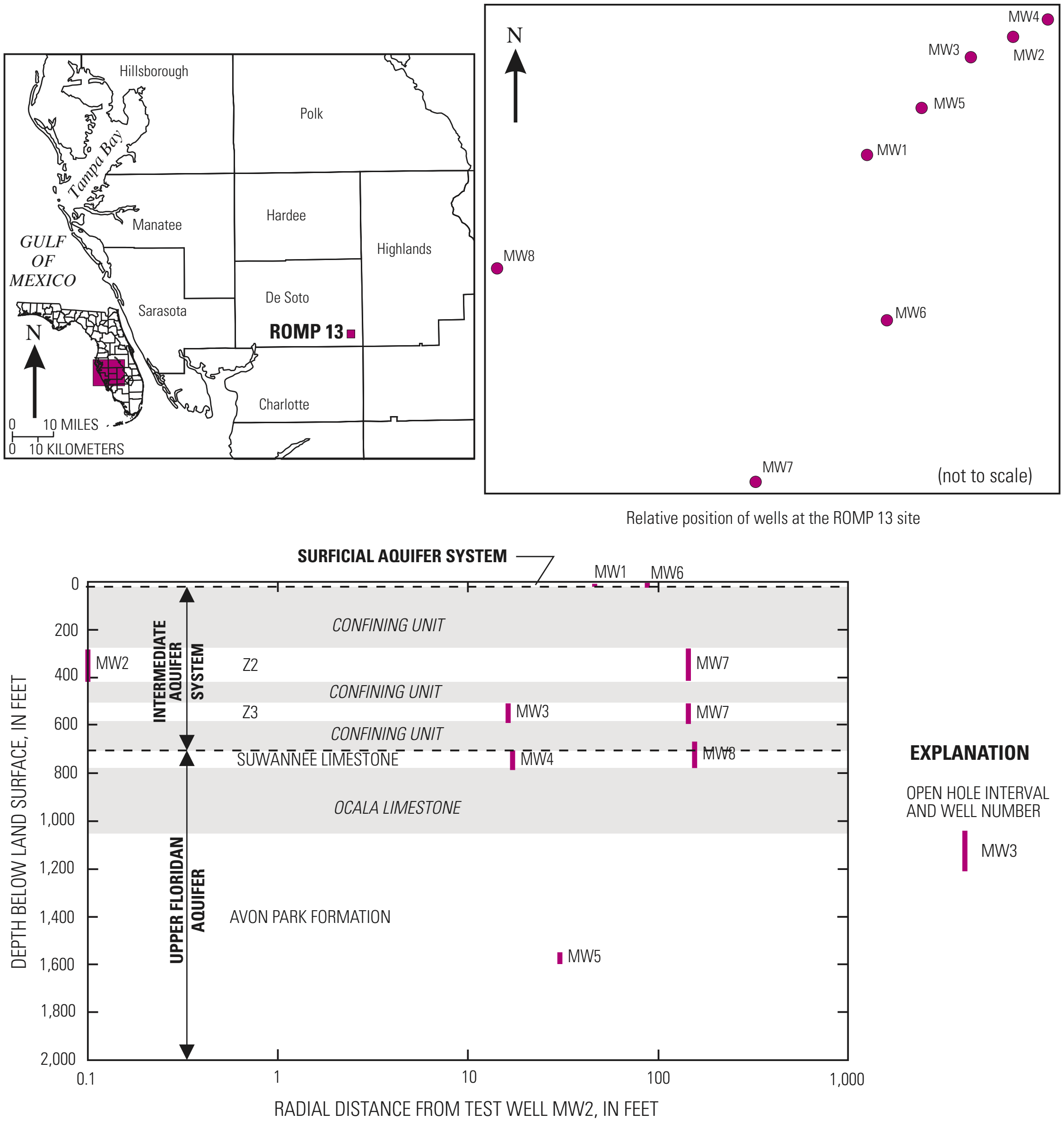
Hydrogeologic unit ROMP 13	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
IAS-Zone 2	258	2	7.6E-5
IAS-Zone 3	766	10	1.2E-4
UFA-Suwannee Limestone	2,350	32	8.6E-2

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer]

Model Structure

The ROMP 13 model extended from the production wells to 200,000 ft away and from the water table to 2,050 ft below land surface. The numerical model consisted of 93 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 996 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column. Vertical discretization was finer across the confining units and the surficial aquifer system than across the other hydrogeologic units.

Five water-bearing units were simulated—the surficial aquifer system, IAS-Zone 2, IAS-Zone 3, Suwannee Limestone, and the Avon Park Formation; and four confining units—upper, middle, and lower confining units, and the Ocala Limestone (fig. 3A). The surficial aquifer system is about 20 ft thick at the ROMP 13 site. The intermediate aquifer system underlies the surficial aquifer and is about 700 ft thick, including two producing zones (IAS-Zone 2, and IAS-Zone 3) separated by three confining units. The Upper Floridan aquifer, the lowermost permeable zone, is about 1,340 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.



Well name	Stratigraphic Unit	Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet)		
				MW2 (Z2)	MW3 (Z3)	MW4 (SUW)
		Surficial aquifer system (SAS)				
MW1	Undifferentiated surficial deposits	7/23	4	54.4	44.0	71.0
MW6	Undifferentiated surficial deposits	5/24	4	98.3	86.5	111.1
		Intermediate aquifer system				
MW2	Upper Arcadia Formation (Z2)	282/417	8		13.9	13.7
MW7	Upper Arcadia Formation (Z2)	280/415	2	158.2	145.7	171.3
MW3	Lower Arcadia Formation (Z3)	510/592	8	13.5		27.1
MW7	Lower Arcadia Formation (Z3)	410/595	2	158.2	145.7	171.3
		Upper Floridan aquifer				
MW4	Suwannee Limestone (SUW)	671/786	6	13.7	27.5	
MW8	Suwannee Limestone (SUW)	725/909	2	161.8	148.1	175.3
MW5	Avon Park Formation	1,550/1,600	6	32.1	18.9	45.8

Figure 16. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 13 test site.

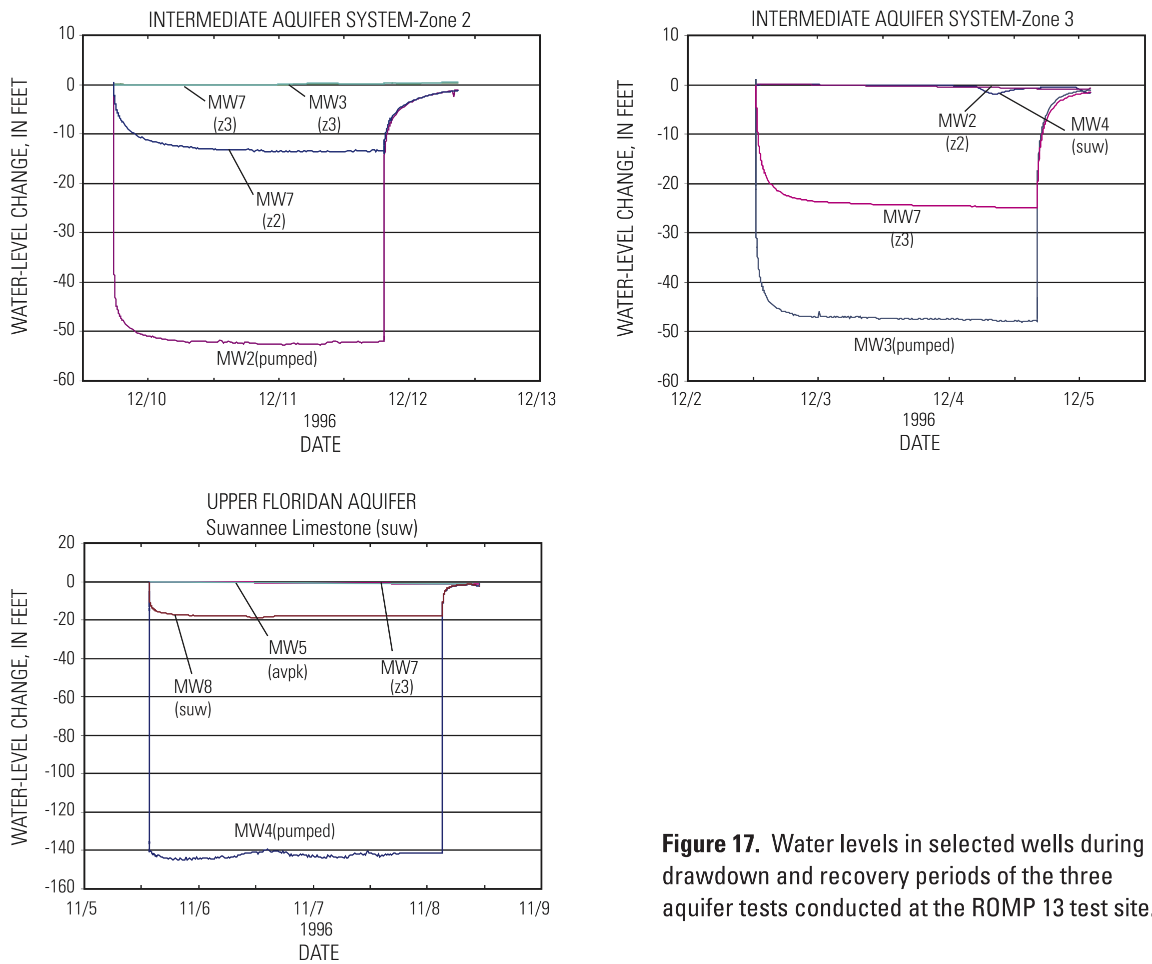


Figure 17. Water levels in selected wells during drawdown and recovery periods of the three aquifer tests conducted at the ROMP 13 test site.

Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 16 parameters. Lateral hydraulic conductivities of the four confining units and four of the five aquifers (IAS-Zone 2, IAS-Zone 3, Suwannee Limestone and Avon Park Formation) make up eight of the parameters. Hydraulic conductivity and specific storage of the surficial aquifer system were assigned a value of 3 ft/d and 1.5E-6 d^{-1}, respectively, because of parameter insensitivity. Specific storage of the other hydrogeologic units make up eight more parameters. Vertical hydraulic conductivity was assigned uniformly as 0.1 of horizontal hydraulic conductivity in all units.

Simulated drawdowns matched measured drawdowns satisfactorily with an average root-mean-squared error (RMSE) of 0.50 ft for the three tests. The fit of measured and simulated time-drawdown data is illustrated in figure 18. RMSE of individual aquifer tests ranged from 0.38 ft for the Suwannee Limestone test to 0.63 ft for the IAS- Zone 2 test (table 3). One can see that the fit for early-time data is poorer than the fit for late-time data for the IAS- Zone 3 test. Once again, keep in mind that the log-log plot exaggerates the lack of fit at early time, when the drawdowns are small.

The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below (unpumped zones are italicized):

Hydrogeologic unit ROMP 13	T (ft^2/d)	K (ft/d)		[1]K_z/K_h	Storage		
			[2]RCS rating		S	S_S (d^{-1})	RCS rating
Surficial aquifer system	*1,900*	*[1]3*		*0.1*	*3.0E-5*	*[1]1.5E-6*	
IAS-Zone 2	280	2	high	0.1	8.7E-5	6.0E-7	fair
IAS-Zone 3	900	12	high	0.1	4.6E-5	6.0E-7	high
UFA-Suwannee Limestone	1,000	12	high	0.1	2.3E-4	3.1E-6	fair
Avon Park Formation	*780,000*	*780*	*low*	*0.1*	*3.0E-4*	*3.0E-7*	*low*

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_S) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

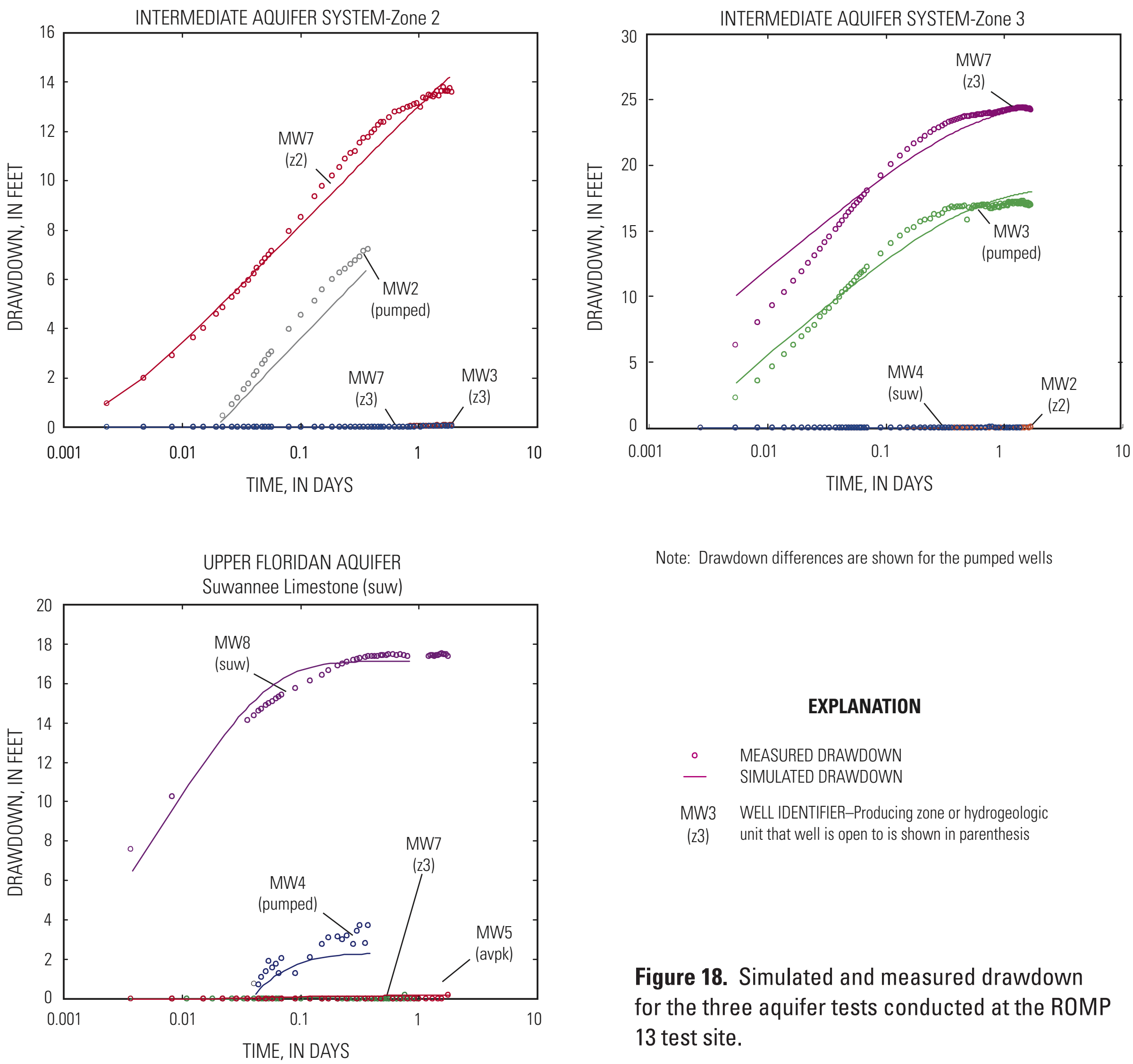


Figure 18. Simulated and measured drawdown for the three aquifer tests conducted at the ROMP 13 test site.

The resulting values of transmissivity are about the same as those derived from the analytical models, except for the Suwannee Limestone, where the simulated value is about 50 percent less. The resulting values of storativity are within a factor of 3 of those derived from the analytical models, except for the Suwannee Limestone, for which model results are about 3 orders of magnitude lower.

Hydraulic conductivity of the pumped zones and specific storage of IAS-Zone 3 were resolved with high confidence. Specific storage of the IAS-Zone 2 and the Suwannee Limestone was resolved with moderate confidence. Hydraulic conductivity and specific storage of the unpumped Avon Park Formation were resolved with low confidence and are the most uncertain of the estimated aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP 13	Leakance (ft/d/ft)	K_z (ft/d)		[5]K_z/K_h	Specific storage (d^{-1})	
			[4]RCS rating			RCS rating
[1]Upper	2.2E-6	5.7E-4	low	0.1	3.0E-6	fair
[2]Middle	1.3E-6	1.1E-4	fair	0.1	1.9E-6	low
[3]Lower	9.8E-6	1.2E-3	high	0.1	1.7E-6	low
Ocala Limestone	2.0E-3	5.5E-1	high	0.1	1.1E-6	low

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_Z) by the appropriate thickness; K_Z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 2. [2]Confining unit between IAS-Zone 2 and IAS-Zone 3. [3]Confining unit between IAS-Zone 3 and Suwannee Limestone. [4]Relative scaled sensitivity. [5]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the lower confining unit and the Ocala Limestone were resolved with high confidence. Hydraulic conductivity of the middle confining unit and specific storage of the middle confining unit and the Ocala Limestone was resolved with moderate confidence. Hydraulic conductivity of the upper confining unit and specific storage of the upper and lower confining units were resolved with low confidence and are the most uncertain of the confining unit parameters.

Relative composite sensitivity (RCS) values for the estimated and assigned parameters are shown in figure 9 and appendix 1. Sensitivity is highest for hydraulic conductivity of the pumped zones and about equally low for specific storage of the pumped zones and the confining units. Sensitivity is highest for the hydraulic conductivity of IAS-Zone 3 and is lowest for specific storage of the surficial aquifer system. The model was insensitive to hydraulic conductivity of the unpumped zones (surficial aquifer system and the Avon Park Formation) and the upper confining unit, and specific storage of the upper and lower confining units and the surficial aquifer system, resulting in little influence of these parameters on overall model performance.

ROMP 14 Model

ROMP 14 is located at 27°08´58˝N and 81°21´11˝W in the south-central portion of Highlands County (fig. 19). Land surface altitude at the well site is about 145 ft above NGVD 29. Four permanent and 12 temporary wells ranging from 2 to 12 in. in diameter were completed at ROMP 14. The deepest well, MW11, was drilled to 1,674 ft below land surface.

Four aquifer tests were conducted from February 1995 through September 1996 at the ROMP 14 site to estimate the hydraulic properties of the surficial aquifer system, the intermediate aquifer system (IAS-Zone 2), the Suwannee Limestone, and the Avon Park Formation (table 1). A plan view and construction records of the production and observation wells for the aquifer tests are shown in figure 19. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 20 shows plots of the drawdown data used for analysis.

Well MW4, tapping the surficial aquifer system, was pumped at a rate of 889 gal/min for 167 hours. Drawdown data measured in the surficial aquifer system wells MW5, MW6, and MW7; and in the upper confining unit well MW8b were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 39 ft in the pumped well and about 6 ft in MW5, about 5 ft in MW6, and about 4 ft in MW7. No decline in water level was estimated in the IAS observation well.

Well MW3, tapping Zone 2 of the intermediate aquifer system, was pumped at a rate of 14.6 gal/min for 52.2 hours. The pumping rate decreased during the first 320 minutes from about 18 to 13 gal/min at which time the pumping rate was increased to about 15 gal/min for the remainder of the test. Drawdown data measured in the pumped well (MW3), IAS Zone 2 well MW10, and Suwannee Limestone well MW2 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 110 ft in the pumped well and about 47 ft in the IAS observation well MW10. No decline in water level was estimated in the underlying Suwannee Limestone well.

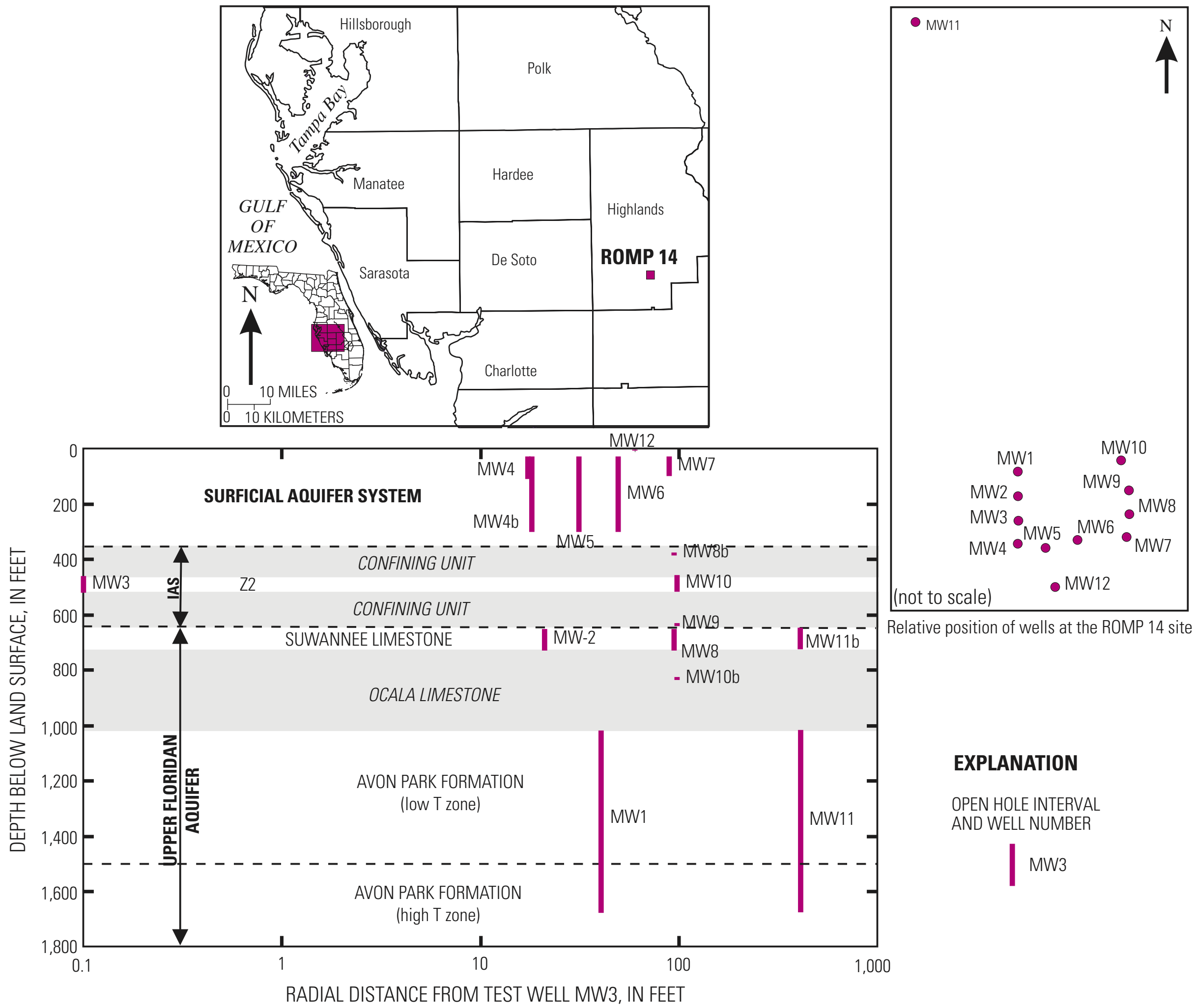
Well MW2, tapping the Suwannee Limestone zone of the Upper Floridan aquifer, was pumped at a rate of 386 gal/min for 95.9 hours. Drawdown data measured in the pumped well (MW2), Suwannee Limestone wells MW8 and MW11b, and intermediate aquifer system well MW10, Ocala Limestone well MW10b, and Avon Park Formation well MW11 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 76 ft in the pumped well, about 29 ft in the Suwannee Limestone well MW8, and about 2 ft in the Suwannee Limestone well MW11b. No decline in water level was estimated in the overlying intermediate aquifer system well or in the underlying Avon Park Formation well.

Well MW1, tapping the Avon Park Formation of the Upper Floridan aquifer, was pumped at a rate of 1,651 gal/min for about 117.9 hours. Drawdown data measured in the pumped well (MW1), Avon Park Formation well (MW11), and Suwannee Limestone wells MW2 and MW8 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 105 ft in the pumped well while no drawdown was measured in the Avon Park Formation well 451 feet from the pumped well. The lack of drawdown in the Avon Park observation well (MW11) may be due to either well construction or boundary conditions existing between the pumped and observation well in the fractured dolostone (Clayton, 1998). Because of poor water quality below 1,700 ft below land surface, the production well was constructed to a total depth of 1,670 ft and not open to the lower part of the “high transmissivity” zone. A water-level decline of about 0.3 ft was estimated in the Suwannee Limestone observation wells (MW2 and MW8).

Aquifer test data were analyzed by Clayton (1998) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifers and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP 14	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
Surficial aquifer system	16,300	46	1.3E-3
IAS-Zone 2	31	<1	2.5E-3
UFA-Suwannee Limestone	6,570	83	9.9E-4
UFA-Avon Park Formation	7,580	16	2.2E-5

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; <, less than]



Well name	Stratigraphic Unit	Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet) MW4 (SAS)	MW3 (Z2)	MW2 (SUW)	MW1 (AvPk)
		Surficial aquifer system (SAS)					
MW4	Undifferentiated surficial deposits	30/110	2		18.0	39.0	59.0
MW4b	Undifferentiated surficial deposits	30/300	12		18.0	39.0	59.0
MW5	Undifferentiated surficial deposits	30/300	2	24.4	31.3	47.2	64.7
MW6	Undifferentiated surficial deposits	30/300	2	47.5	49.5	58.8	72.1
MW7	Undifferentiated surficial deposits	30/100	2	88.9	89.6	94.5	102.7
MW12	Undifferentiated surficial deposits	5/8	2	45.4	60.3	79.1	97.5
		Intermediate aquifer system (IAS)					
MW8b	Arcadia Formation (upper confining unit)	375/385	2	97.2	94.7	95.9	100. 7
MW3	Middle Arcadia Formation (Z2)	460/521	8	18.2		21.0	40.8
MW10	Middle Arcadia Formation (Z2)	457/517	8	108.6	98.2	88.8	83.8
MW9	Arcadia Formation (lower confining unit)	630/640	2	104.0	97.9	94.5	95.2
		Upper Floridan aquifer					
MW2	Suwannee Limestone (SUW)	650/730	8	39.2	21.0		19.8
MW8	Suwannee Limestone (SUW)	650/730	2	97.2	94.7	95.7	100.6
MW11b	Suwannee Limestone (SUW)	650/737	8	508.5	490.6	471.0	451.0
MW10b	Ocala Limestone (confining unit)	826/836	2	108.6	98.2	88.8	83.8
MW1	Avon Park Formation (AvPk)	1,003/1,670	10	59.0	40.8	19.8	
MW11	Avon Park Formation (AvPk)	1,015/1,674	8	508.5	490.6	471.0	451.0

Figure 19. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 14 test site.

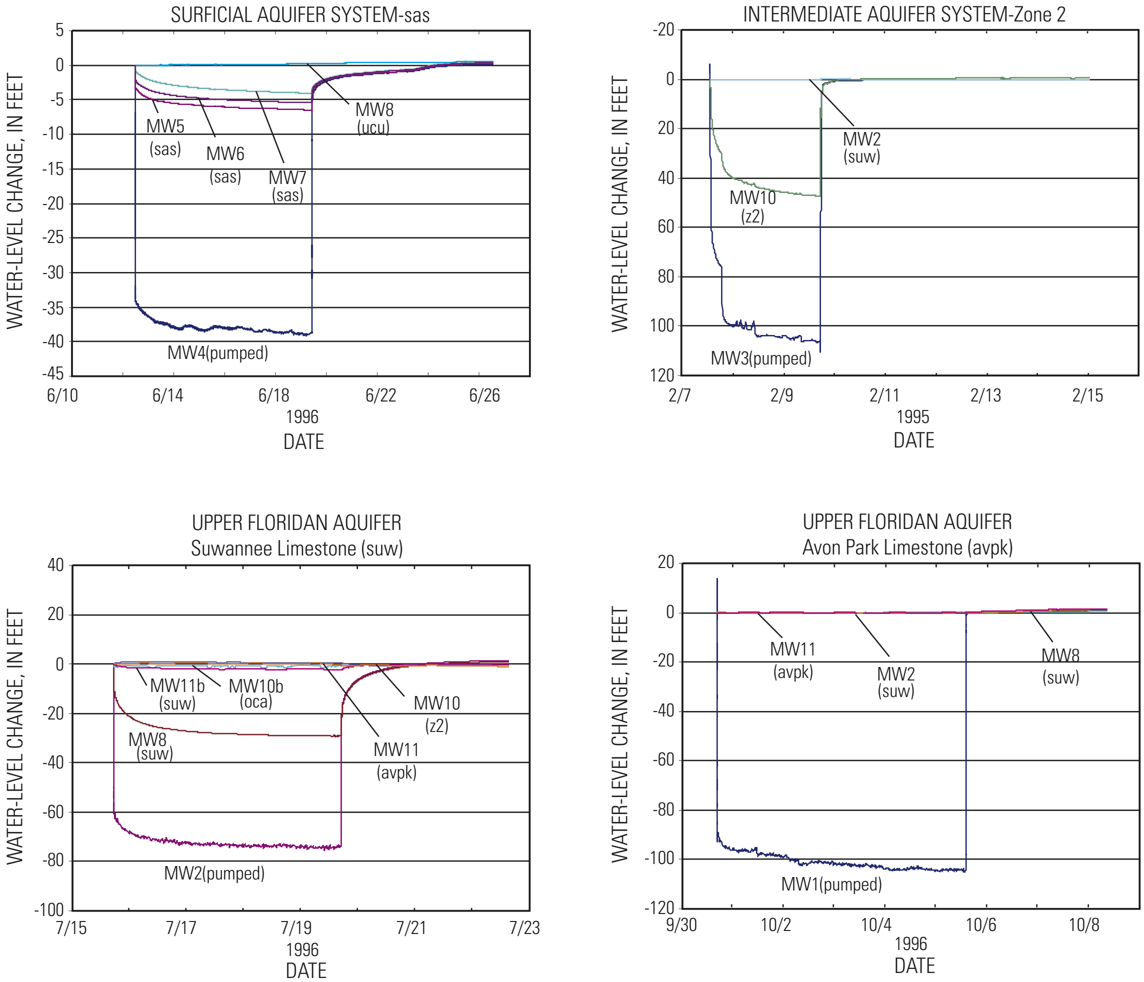


Figure 20. Water levels in selected wells during drawdown and recovery periods of the four aquifer tests conducted at the ROMP 14 test site.

Model Structure

The ROMP 14 model extended from the production wells to 200,000 ft away and from the water table to 1,804 ft below land surface. The numerical model consisted of 110 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 1,000 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column. Vertical discretization was finer across the confining units, the surficial aquifer system, and the Avon Park Formation than across the Suwannee Limestone.

Five water-bearing units were simulated—the surficial aquifer system, IAS-Zone 2, Suwannee Limestone, upper Avon Park Formation, and lower Avon Park Formation; and three confining units—upper and lower confining units, and the Ocala Limestone (fig. 3C). The surficial aquifer system is about 353 ft thick at the ROMP 14 site (table 2). The intermediate aquifer system underlies the surficial aquifer and is about 292 ft thick. Two confining units and one “minor” producing zone (IAS-Zone 2) were found within the intermediate aquifer system at the ROMP 14 site. The Upper Floridan aquifer, the lowermost permeable aquifer, is about 1,150 ft thick and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone. The Avon Park Formation was subdivided into “low” and “high” transmissivity units to better characterize the nonfractured and fractured nature of the unit. The upper unit (low T) is about 485 ft thick and the lower unit (high T) is about 300 ft thick. This subdivision was needed because aquifer test results indicated too little vertical interconnection within the formation to analyze the unit as a single hydrologic unit.

Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 17 parameters. Lateral hydraulic conductivities of the three confining units and four producing zones make up seven of the parameters. Specific storage of the same hydrogeologic units make up seven more parameters. Vertical anisotropy and specific yield of the surficial aquifer system and vertical anisotropy of the ”low T” zone of the Avon Park Formation make up the last three parameters. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all other units. Hydraulic conductivity and specific storage of the “high T” zone of the Avon Park Formation were assigned values of 100 ft/d and 2.4E-6 d-1, respectively.

Relatively good fits were achieved between simulated drawdowns and measured drawdowns with an average unweighted root-mean-squared error (RMSE) of 0.38 ft for the four tests. The fit of measured and simulated time-drawdown data is illustrated in figure 21. RMSE of individual aquifer tests ranged from 0.18 ft for the surficial aquifer system test to 0.56 ft for the Suwannee Limestone test (table 3). The fit for the early-time data for well MW5 for the surficial aquifer system test and for well MW11b for the Suwannee Limestone test is poor. Overall, the fit for early-time data is poorer than the fit for late-time data. A good fit was achieved for all wells for the IAS-Zone 2 test. When reviewed in the context of the entire set of drawdown data, the lack of fit during early time is not severe. The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below:

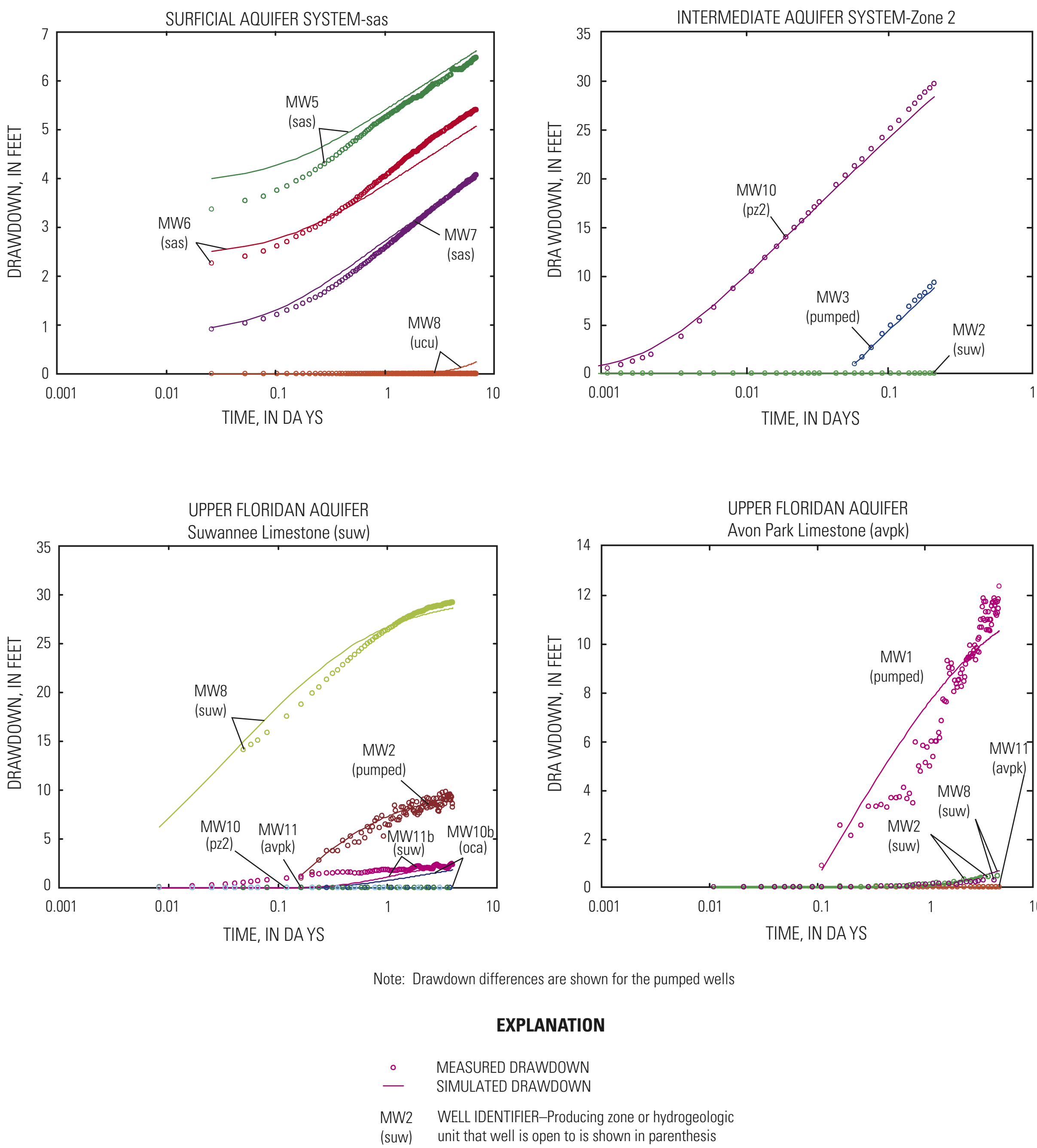


Figure 21. Simulated and measured drawdown for the four aquifer tests conducted at the ROMP 14 test site.

Hydrogeologic unit ROMP 14	T (ft^2/d)	K (ft/d)		K_z/K_h		S_y		Storage		
			[2]RCS rating		RCS rating		RCS rating	S	S_s (d^{-1})	RCS rating
Surficial aquifer system	22,000	61	high	0.50	low	0.10	high	1.1E-4	3.0E-7	low
IAS-Zone 2	30	<1	high	[1]0.10				1.8E-5	3.0E-7	high
UFA-Suwannee Limestone	900	11	high	[1]0.10				1.0E-2	1.3E-4	high
UFA-AVP (low T zone)	7,400	15	high	0.001	fair			2.2E-3	4.5E-6	fair
UFA-AVP (high T zone)	30,000	[1]100		[1]0.10				7.2E-4	[1]2.4E-6	

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_s) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; AVP Avon Park Limestone; K_z/K_h, vertical to horizontal anisotropy; S_y, specific yield; <, less than. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

The resulting values of transmissivity are about the same as those derived from the analytical models, except for the Suwannee Limestone zone, for which model results were about 7 times less. The resulting values of storativity were about 2 orders of magnitude more than those derived from the analytical models, except IAS-Zone 2, for which model results were about 2 orders of magnitude greater. The simulated value of specific storage for the Suwannee Limestone is unrealistic.

Hydraulic conductivity of the pumped zones, specific yield of the surficial aquifer system, and specific storage of IAS-Zone 2 and the Suwannee Limestone were resolved with high confidence. Vertical anisotropy and specific storage of the Avon Park Formation "low T" zone were resolved with moderate confidence. Vertical anisotropy and specific storage of the surficial aquifer system were resolved with low confidence and are the most uncertain of the aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP 14	Leakance (ft/d/ft)	K_z (ft/d)		[4]K_z/K_h	Specific storage (d^{-1})	
			[3]RCS rating			RCS rating
[1]Upper	5.8E-7	6.1E-5	fair	0.1	3.1E-6	fair
[2]Lower	4.3E-7	5.5E-5	fair	0.1	3.1E-6	low
Ocala Limestone	7.8E-3	2.3E+0	high	0.1	2.1E-4	fair

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_z) by the appropriate thickness; K_z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 2. [2]Confining unit between IAS-Zone 2 and Suwannee Limestone. [3]Relative scaled sensitivity. [4]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the Ocala Limestone was resolved with high confidence. Hydraulic conductivity of the upper and lower confining units and specific storage of the upper and Ocala Limestone were resolved with moderate confidence.

Relative composite sensitivity (RCS) values for the estimated and assigned parameters are shown in figure 22 and appendix 1. Generally, the model was most sensitive to hydraulic conductivity of the pumped zones and least sensitive to specific storage of the confining units. Sensitivity was highest for the hydraulic conductivity of the Suwannee Limestone and lowest for specific storage of the "low T" zone of the Avon Park Formation. The model was insensitive to specific storage of the lower confining unit, the surficial aquifer system, and the "high T" zone of the Avon Park Formation, and to vertical anisotropy of the surficial aquifer system, resulting in little influence of these parameters on overall model performance.

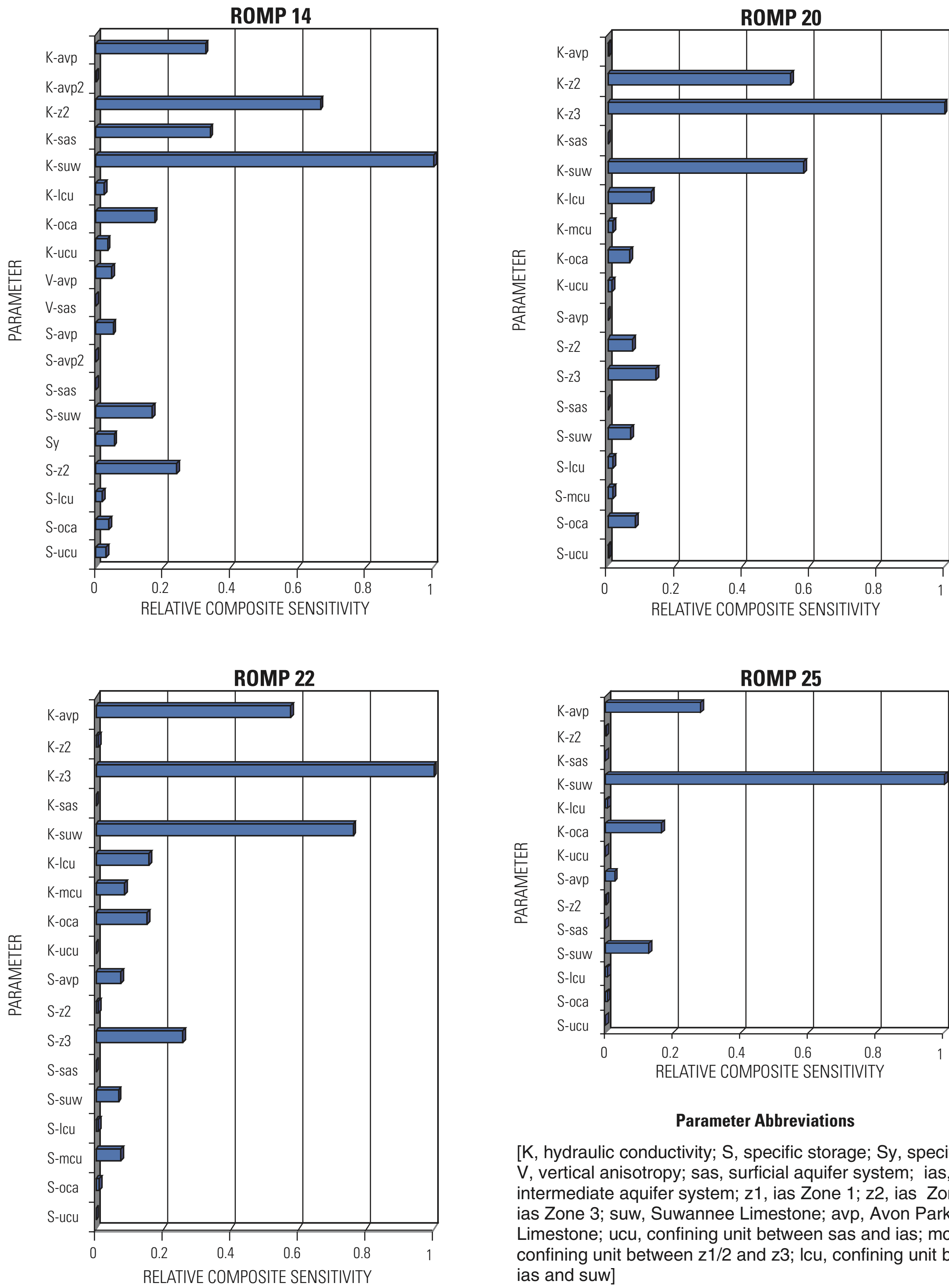
ROMP 20 Model

ROMP 20 is located at 27°11´37˝N and 82°28´45˝W in west-central Sarasota County near the Gulf of Mexico (fig. 23). Land surface altitude at the well site is about 15 ft above NGVD 29. Five permanent and five temporary wells ranging from 2 to 12 in. in diameter were completed at ROMP 20. The deepest well, MW8, was drilled to 1,150 ft below land surface.

Three aquifer tests were conducted from July-December 1992 at the ROMP 20 site to estimate the hydraulic properties of the upper intermediate aquifer system (IAS-Zone 2), the lower intermediate aquifer system (IAS-Zone 3) and the Suwannee Limestone. A plan view and construction records of the production and observation wells are shown in figure 23. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 24 shows plots of the drawdown data used for analysis.

Well MW2, tapping IAS-Zone 2, was pumped at a rate of 200 gal/min for 29 hours. Drawdown data measured in the pumped well (MW2), IAS-Zone 2 well MW7, SAS well MW2, IAS-Zone 3 well MW3, and Suwannee Limestone well MW4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 50 ft in the pumped well, about 5 ft in IAS-Zone 2 well MW7, and about 0.3 ft in the IAS-Zone 3 well MW3. No decline in water level was estimated in the SAS and Suwannee Limestone observation wells during the drawdown phase.

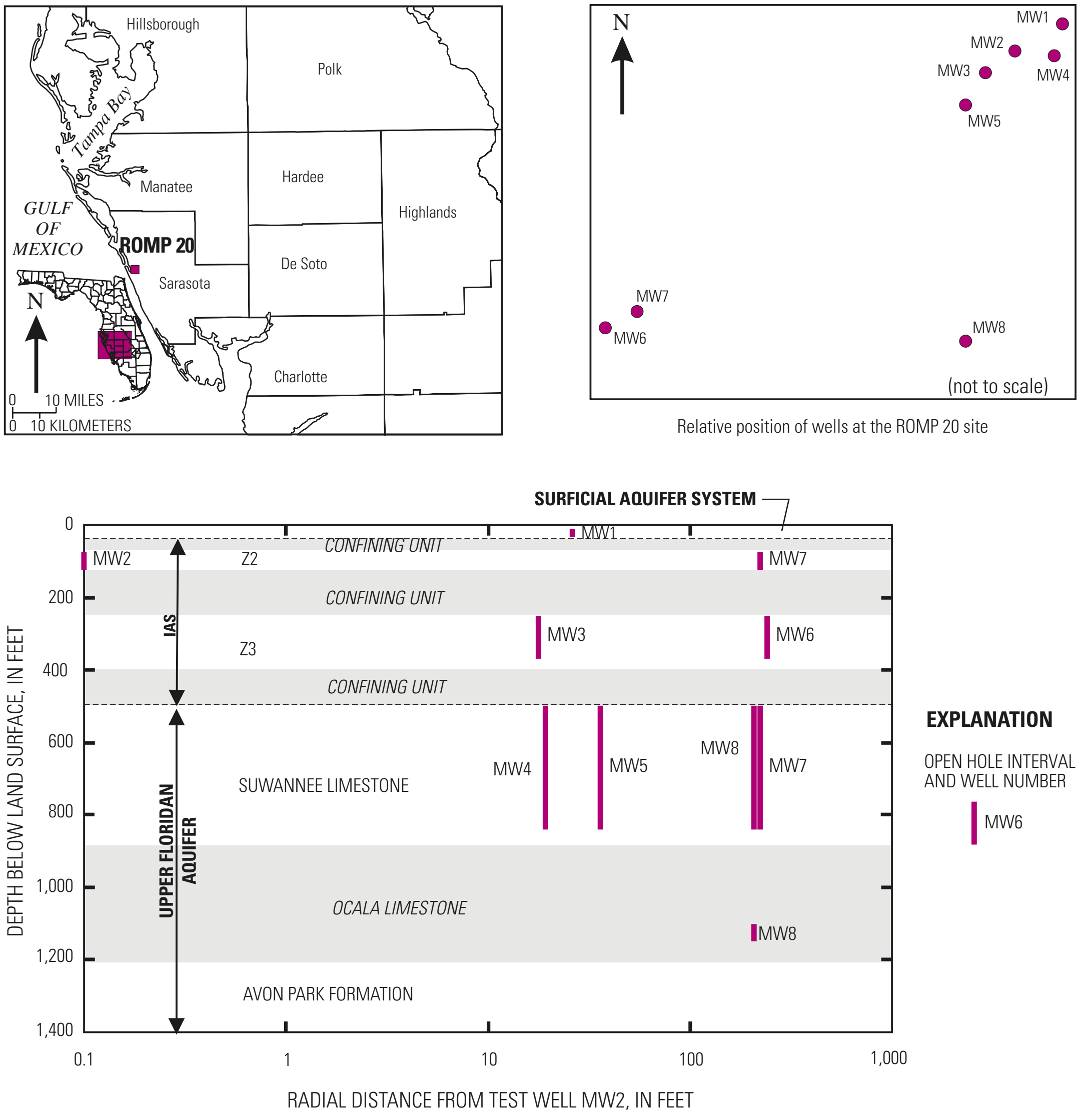
Well MW3, tapping IAS-Zone 3, was pumped at a rate of 400 gal/min for 28 hours. Drawdown data measured in the pumped well (MW3), IAS-Zone 3 well MW6, IAS-Zone 2



Parameter Abbreviations

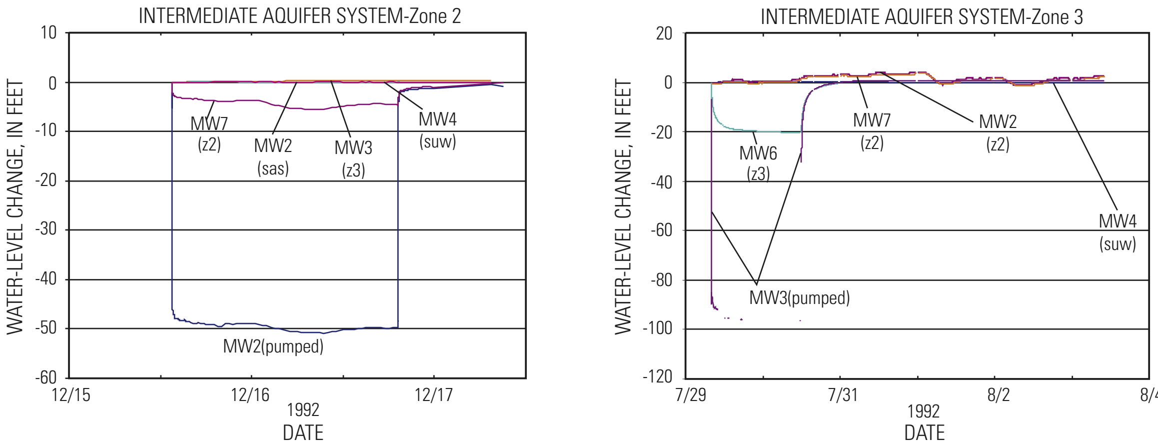
[K, hydraulic conductivity; S, specific storage; Sy, specific yield; V, vertical anisotropy; sas, surficial aquifer system; ias, intermediate aquifer system; z1, ias Zone 1; z2, ias Zone 2; z3, ias Zone 3; suw, Suwannee Limestone; avp, Avon Park Limestone; ucu, confining unit between sas and ias; mcu, confining unit between z1/2 and z3; lcu, confining unit between ias and suw]

Figure 22. Relative composite sensitivity for final parameter values for ROMP 14, 20, 22, and 25.



Well name	Stratigraphic Unit		Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet)		
					MW2 (Z2)	MW3 (Z3)	MW4 (SUW)
			Surficial aquifer system				
MW1	Undifferentiated surficial deposits		12/32	6	26.1	43.9	15.4
			Intermediate aquifer system (IAS)				
MW2	Upper Arcadia Formation	(Z2)	75/125	8		17.9	19.3
MW7	Upper Arcadia Formation	(Z2)	75/125	2	223.2	205.3	237.9
MW3	Lower Arcadia Formation	(Z3)	250/370	12	17.9		34.5
MW6	Lower Arcadia Formation	(Z3)	250/370	2	240.6	222.7	255.3
			Upper Floridan aquifer				
MW4	Suwannee Limestone	(SUW)	500/840	12	19.3	34.5	
MW5	Suwannee Limestone	(SUW)	500/840	2	36.0	18.8	49.6
MW7	Suwannee Limestone	(SUW)	500/840	6	223.1	205.2	237.7
MW8	Suwannee Limestone	(SUW)	500/840	2	150.0	136.0	152.0
MW8	Ocala Limestone	(OCA)	1,100/1,150	2	150.0	136.0	152.0

Figure 23. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 20 test site.



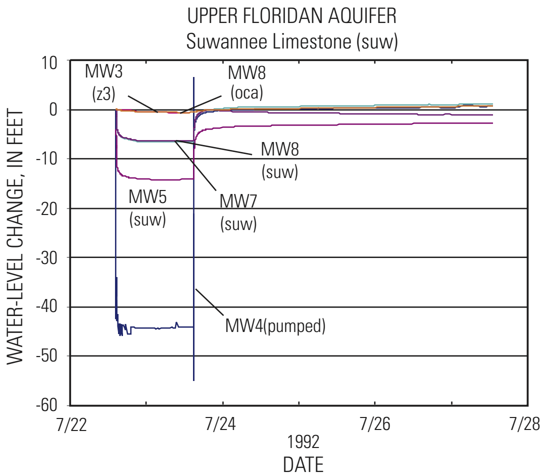


Figure 24. Water levels in selected wells during drawdown and recovery periods of the three aquifer tests conducted at the ROMP 20 test site.

wells MW2 and MW7, and Suwannee Limestone well MW4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 95 ft in the pumped well, about 20 ft in the IAS-Zone 3 observation well MW6, and about 0.3 ft in the Suwannee Limestone well MW4. No decline in water level was estimated in either of the overlying IAS-Zone 1 wells, but about 0.3 ft of drawdown was induced in IAS-Zone 3 by pumping IAS-Zone 2 zone.

Well MW4, tapping the Suwannee Limestone of the Upper Floridan aquifer, was pumped at a rate of 1,300 gal/min for 24.5 hours. Drawdown data measured in the Suwannee Limestone wells MW5, MW7, and MW8; IAS-Zone 3 well MW3; and Ocala Limestone well MW8 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 45 ft in the Suwannee Limestone pumped well MW4 and about 15 ft in the Suwannee Limestone well MW5, about 6 ft in the Suwannee Limestone well MW7, and about 6 ft in the Suwannee Limestone well MW8. Water-level declines of about 0.6 ft were estimated in the overlying IAS-Zone 3 well MW3 and about 0.6 ft in the underlying Ocala Limestone well MW8. No decline in water level was estimated in the overlying IAS-Zone 1 wells or in the underlying Avon Park Formation wells.

Aquifer test data were analyzed by DeWitt and Thompson (1997) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer tests and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP 20	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
IAS-Zone 2	1,900	35	6.0E-5
IAS-Zone 3	1,500	10	7.0E-5
UFA-Suwannee Limestone	19,100	49	9.1E-4

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer]

Model Structure

The model extended from the production wells to 200,000 ft away and from the water table to 1,430 ft below land surface. The numerical model consisted of 93 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 387 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column. Vertical discretization was variable and finer across the confining units than across the other hydrogeologic units.

Five water-bearing units were simulated—the surficial aquifer system, IAS-Zone 2, IAS-Zone 3, Suwannee Limestone, and Avon Park Formation; and four confining units—upper, middle, and lower confining units, and the Ocala Limestone (fig. 3A). The surficial aquifer system is about 49 ft thick at the ROMP 20 site (table 2). The intermediate aquifer system underlies the surficial aquifer and is about 450 ft thick, including three confining units and two producing zones (IAS-Zone 2 and IAS-Zone 3). The Upper Floridan aquifer, the lowermost permeable aquifer, is about 993 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 16 parameters. Lateral hydraulic conductivities of the four confining units and four aquifers (IAS-Zone 2, IAS-Zone 3, Suwannee Limestone, and Avon Park Formation) make up eight of the parameters. Specific storage of the same hydrogeologic units make up eight more parameters. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all units. Lateral hydraulic conductivity and specific storage for the surficial aquifer system was specified in the model because sufficient information was not available in the observations to independently determine their values. Hydraulic conductivity and specific storage of the surficial aquifer system were assigned values of 10 ft/d and 2.0E-5 d-1, respectively.

Simulated drawdowns matched measured drawdowns favorably with an average unweighted root-mean-squared error (RMSE) of 0.46 ft for the three tests. The fit of measured and simulated time-drawdown data is illustrated in figure 25. RMSE of individual aquifer tests ranged from 0.25 ft for the Suwannee Limestone test to 0.78 ft for the IAS-Zone 3 test (table 3). The fit for the late time data for wells MW3, MW7 and MW1 do not parallel the observed hydrographs

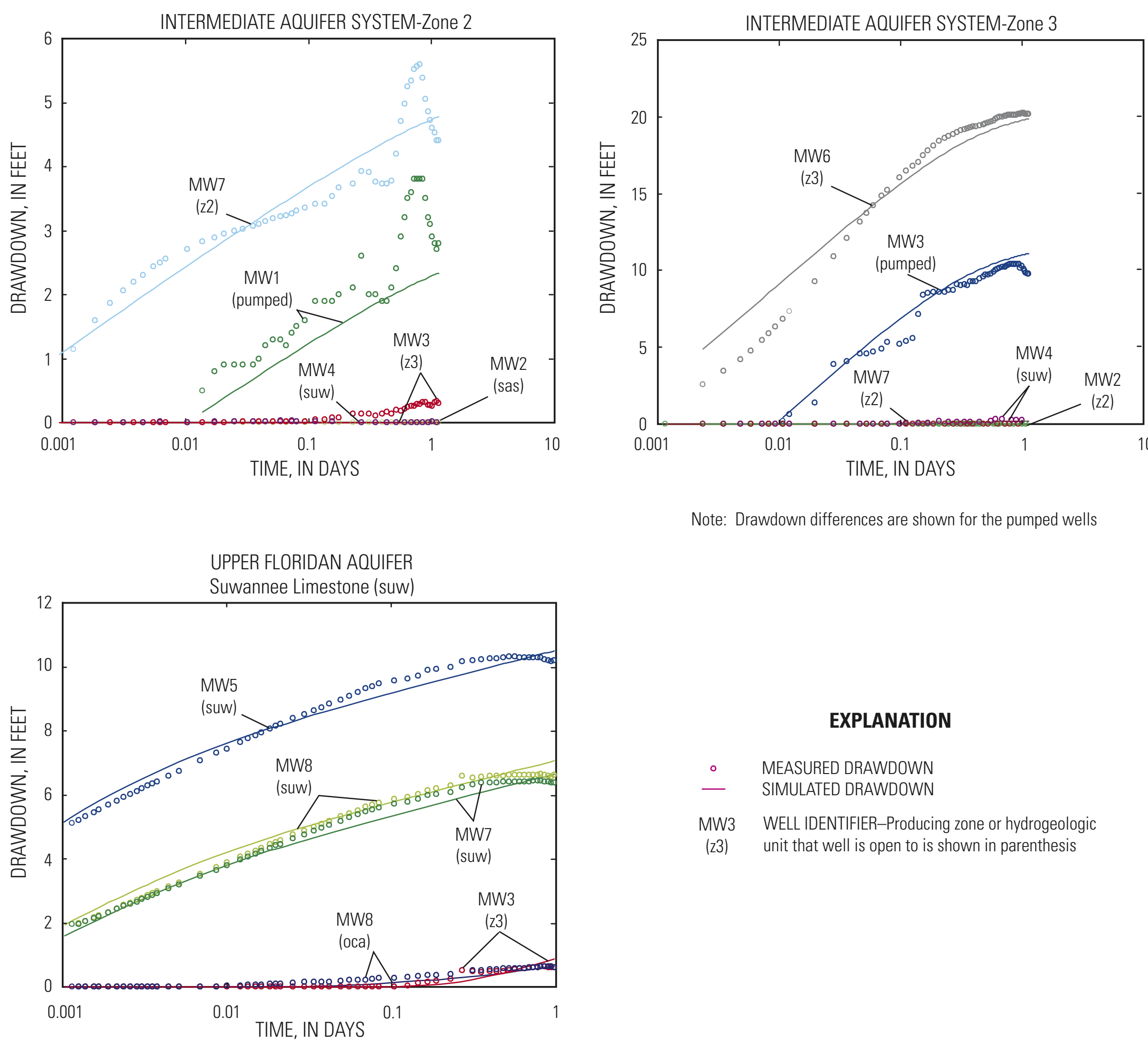


Figure 25. Simulated and measured drawdown for the three aquifer tests conducted at the ROMP 20 test site.

for the IAS-Zone 2 test. Water levels in these wells appear to be influenced by pumping from other wells near the test site. The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below (unpumped zones are italicized):

Hydrogeologic unit ROMP 20	T (ft^2/d)	K (ft/d)		$^1K_z/K_h$	Storage		
			[2]RCS rating		S	S_s (d^{-1})	RCS rating
Surficial aquifer system	*490*	*[1]10*		0.10	*1.0E-5*	*[1]2.0E-7*	
IAS-Zone 2	5,200	95	high	0.10	3.3E-5	6.0E-7	fair
IAS-Zone 3	1,800	12	high	0.10	4.5E-5	3.0E-7	high
UFA-Suwannee Limestone	16,000	41	high	0.10	1.5E-4	4.0E-7	fair
UFA-Avon Park Formation	*150,000*	*670*	*low*	0.10	*2.0E-4*	*9.0E-7*	*low*

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_S) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

The resulting values of transmissivity are about the same as those derived from the analytical models, except for IAS-Zone 2 where the simulated value is about 3 times larger. The resulting values of storativity are about 2 to 5 times lower than those derived from the analytical models.

Hydraulic conductivity of the pumped zones and specific storage of IAS-Zone 3 were resolved with high confidence. Specific storage of IAS-Zone 2 and the Suwannee Limestone was resolved with moderate confidence. Hydraulic conductivity and specific storage of the unpumped Avon Park Formation were resolved with low confidence and are the most uncertain of the estimated aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP 20	Leakance (ft/d/ft)	K_z (ft/d)		$^5K_z/K_h$	Specific storage (d^{-1})	
			[4]RCS rating			RCS rating
[1]Upper	1.3E-5	2.7E-4	low	0.1	3.0E-7	low
[2]Middle	4.4E-6	5.4E-4	low	0.1	5.0E-7	low
[3]Lower	8.9E-5	8.8E-3	high	0.1	2.0E-7	low
Ocala Limestone	1.0E-3	3.4E-1	fair	0.1	1.2E-5	fair

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_Z) by the appropriate thickness; K_Z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 2. [2]Confining unit between IAS-Zone 2 and IAS-Zone 3. [3]Confining unit between IAS-Zone 3 and Suwannee Limestone. [4]Relative scaled sensitivity. [5]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the lower confining unit was resolved with high confidence. Hydraulic conductivity and specific storage of the Ocala Limestone were resolved with moderate confidence. Hydraulic conductivity and specific storage of the upper and lower confining units, and specific storage of the lower confining unit were resolved with low confidence and are the most uncertain of the estimated confining unit parameters.

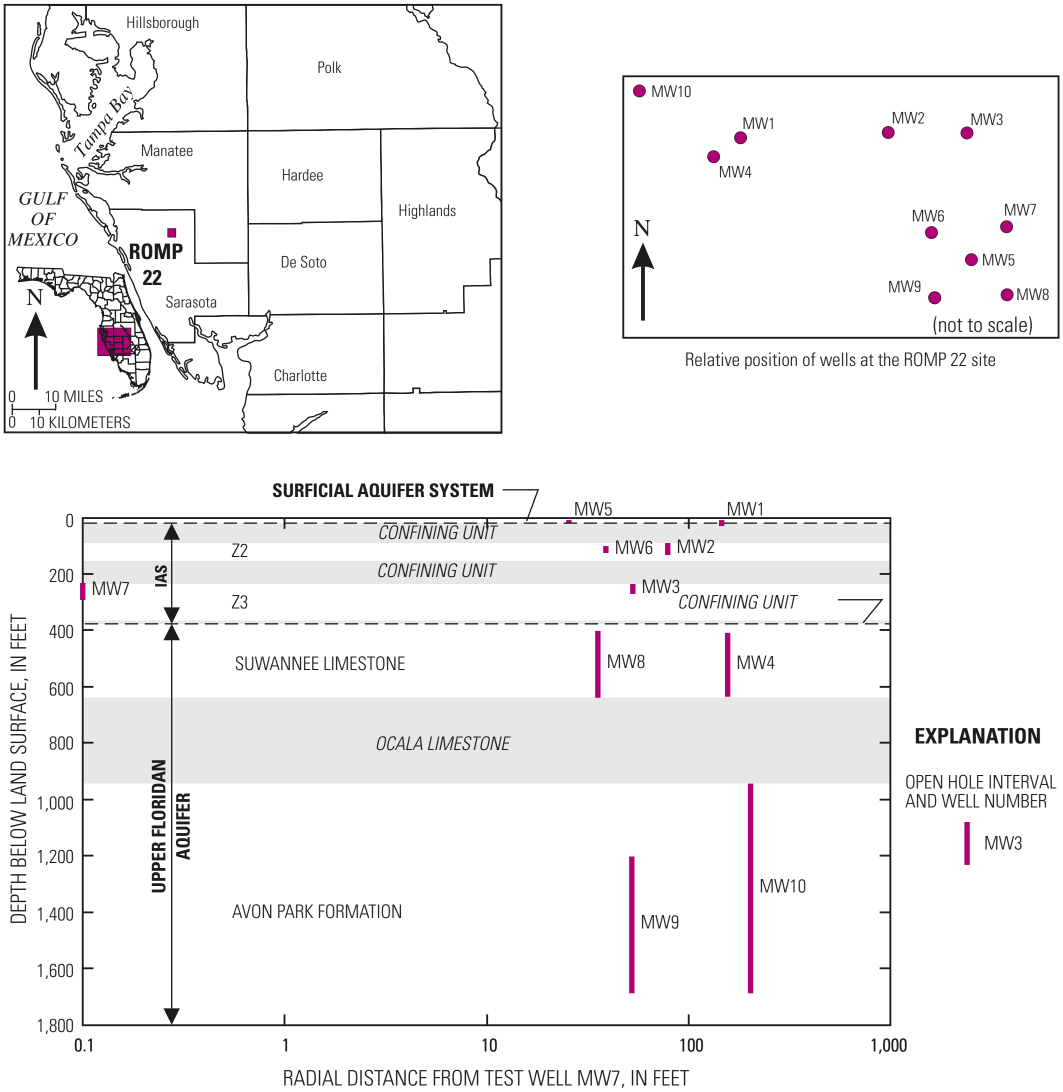
Relative composite sensitivity (RCS) values for the estimated and assigned parameters are shown in figure 22 and appendix 1. Generally, the model was most sensitive to hydraulic conductivity of the pumped zones and the least sensitive to specific storage of the confining units. Sensitivity is highest for the hydraulic conductivity of IAS-Zone 3 and lowest for specific storage of the unpumped surficial aquifer system. The model´s insensitivity to hydraulic conductivity of the middle confining unit, upper confining unit, surficial aquifer system, and Avon Park Formation is because no drawdown was observed across confining units when neighboring layers were pumped, resulting in little influence of these parameters on overall model performance.

ROMP 22 Model

ROMP 22 is located at 27°18´13˝N and 82°20´12˝W in north-central Sarasota County (fig. 26). Land surface altitude at the well site is about 36 ft above NGVD 29. Five permanent and five temporary wells ranging from 2 to 18 in. in diameter were completed at ROMP 22. The deepest well, MW10, was drilled to 1,685 ft below land surface.

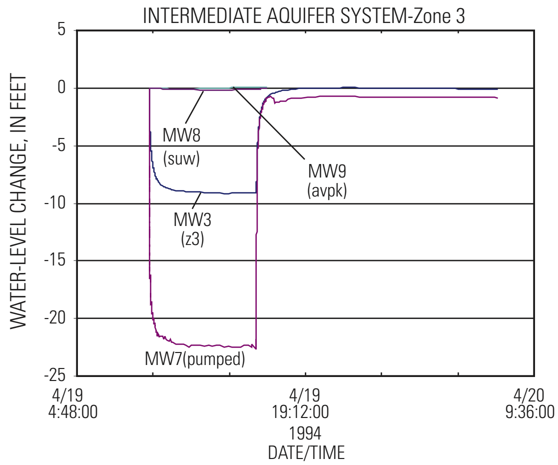
Three aquifer tests were conducted from December 1993 through April 1994 at the ROMP 22 site to estimate the hydraulic properties of the lower intermediate aquifer system (IAS-Zone 3), the Suwannee Limestone, and the Avon Park Formation (table 1). A plan view and construction records of the production and observation wells for the aquifer tests are shown in figure 26. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 27 shows plots of the drawdown data used for analysis.

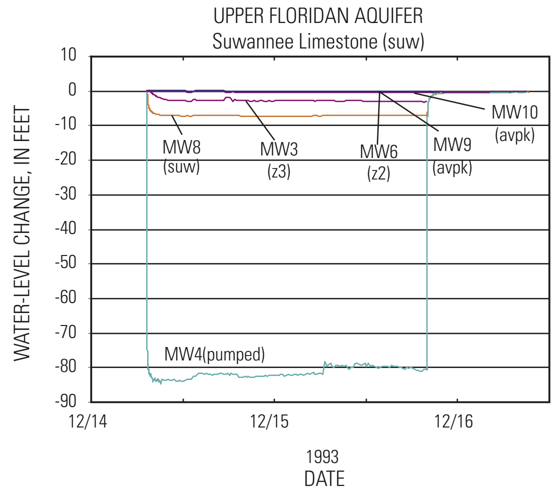
Well MW7, tapping IAS-Zone 3, was pumped at a rate of 25 gal/min for 6.8 hours. Drawdown data measured in the pumped well (MW7), IAS-Zone 3 well MW3, Suwannee Limestone well MW8, and Avon Park Formation well MW9 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 23 ft in the pumped well and about 9 ft in IAS-Zone 3 well MW3. Water-level declines of about 0.2 ft were estimated in the underlying Suwannee Limestone well MW8, indicating a hydraulic connection with the underlying Suwannee Limestone. No decline in water level was estimated in the overlying IAS-Zone 2 well during the drawdown phase.



Well name	Stratigraphic Unit	Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet)		
				MW7 (Z3)	MW4 (SUW)	MW10 (AvPk)
Surficial aquifer system (SAS)						
MW1	Undifferentiated surficial deposits	6/28	6	146.0	17.0	57.7
MW5	Undifferentiated surficial deposits	6/18	6	25.5	143.3	192.5
Intermediate aquifer system (IAS)						
MW2	Upper Arcadia Formation (Z2)	90/132	2	78.8	91.6	131.0
MW6	Upper Arcadia Formation (Z2)	110/125	6	39.2	119.9	168.5
MW3	Lower Arcadia Formation (Z3)	235/270	2	52.9	132.9	172.2
MW7	Lower Arcadia Formation (Z3)	230/290	6		156.7	203.5
Upper Floridan aquifer						
MW4	Suwannee Limestone (SUW)	409/635	12	156.7		51.4
MW8	Suwannee Limestone (SUW)	400/637	6	35.5	168.5	218.4
MW9	Avon Park Formation (AvPk)	1,200/1,660	6	52.6	136.5	187.4
MW10	Avon Park Formation (AvPk)	940/1,685	18	203.5	51.4	

Figure 26. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 22 test site.





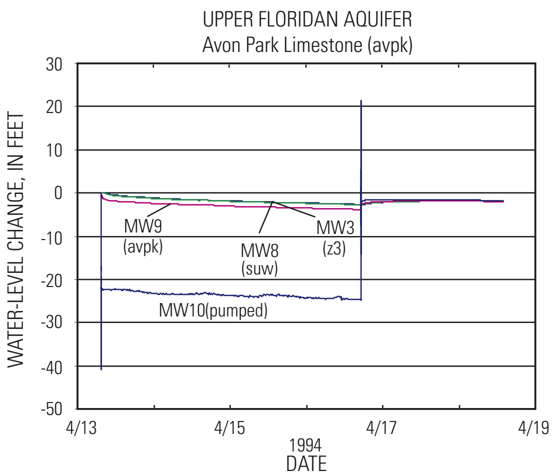


Figure 27. Water levels in selected wells during drawdown and recovery periods of the three aquifer tests conducted at the ROMP 22 test site.

Well MW4, tapping the Suwannee Limestone of the Upper Floridan aquifer, was pumped at a rate of 1,065 gal/min for 36.7 hours. Drawdown data measured in the pumped well (MW4), Suwannee Limestone well MW8, IAS-Zone 3 well MW3, IAS-Zone 2 well MW6, and Avon Park Formation wells MW9 and MW10 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 83 ft in the pumped well and about 7 ft in Suwannee Limestone observation well MW8. Water-level declines of about 3 ft in the IAS-Zone 3 well MW3 and about 0.2 ft in the Avon Park Formation wells were estimated, indicating hydraulic connection with the overlying and underlying zones.

Well MW10, tapping the Avon Park Formation of the Upper Floridan aquifer, was pumped at a rate of 3,500 gal/min for 45 hours. Drawdown data measured in the Avon Park Formation well MW9, Suwannee Limestone well MW8, and IAS-Zone 3 well MW3 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 24 ft in the pumped well (MW10) and about 2 ft in the Avon Park Formation well MW9. Water-level declines of about 0.7 ft were estimated in the overlying Suwannee Limestone well MW3, indicating hydraulic connection with the overlying zone.

Aquifer test data were analyzed by Thompson and DeWitt (1995) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer test and hydraulic conductivity values dericed for aquifer thinesses equavalant to this report are as follows:

Hydrogeologic unit ROMP 22	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
IAS-Zone 3	120	1	7.4E-5
UFA-Suwannee Limestone	12,000	45	4.0E-4
UFA-Avon Park Formation	250,000	336	1.5E-3

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer]

Model Structure

The model extended from the production wells to 200,000 ft away and from the water table to 1,685 ft below land surface. The numerical model consisted of 93 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 744 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column.

Vertical discretization was finer across the confining units, the surficial aquifer system, and the Avon Park Formation than across the other hydrogeologic units.

Five water-bearing units were simulated—the surficial aquifer system, IAS-Zone 2, IAS-Zone 3, Suwannee Limestone, and Avon Park Formation; and four confining units—upper, middle, and lower confining units, and the Ocala Limestone (fig. 3A). The surficial aquifer system is about 19 ft thick underlying the ROMP 22 site (table 2). The intermediate aquifer system underlies the surficial aquifer and is about 355 ft thick, including two producing zones (IAS-Zone 2 and IAS-Zone 3) separated by three confining units. The Upper Floridan aquifer, the lowermost permeable aquifer, is about 1,300 ft thick, and has two major water-bearing zones—Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

Aquifer-Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 14 parameters. Lateral hydraulic conductivities of three confining units (middle and lower confining units and Ocala Limestone) and four producing zones (IAS-Zone 2, IAS-Zone 3, Suwannee Limestone, and Avon Park Formation) make up seven of the parameters. Specific storage of the same hydrogeologic units make up seven more parameters. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all units. Lateral hydraulic conductivity and specific storage for the surficial aquifer system and the upper confining unit were specified in the model because sufficient information was not available in the observations to independently determine their values. Hydraulic conductivity and specific storage of the surficial aquifer system were assigned values of 10 ft/d and 1.52E-6 d^{-1}, respectively. Hydraulic conductivity and specific storage of the upper confining unit were assigned values of 0.001 ft/d and 1.5E-6 d^{-1}, respectively.

Simulated drawdowns matched measured drawdowns favorably with an average unweighted root-mean-squared error (RMSE) of 0.18 ft for the three tests. The fit of measured and simulated time-drawdown data is illustrated in figure 28. RMSE of individual aquifer tests ranged from 0.09 ft for the Avon Park Formation test to 0.25 ft for the IAS-Zone 3 test (table 3). The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below (unpumped zones are italicized):

Hydrogeologic unit ROMP 22	T (ft^2/d)	K (ft/d)		[1]K_z/K_h	Storage		
			[2]RCS rating		S	S_s (d^{-1})	RCS rating
Surficial aquifer system	*190*	*[1]10*		*0.1*	*2.9E-5*	*[1]1.5E-6*	
IAS-Zone 2	*340*	*5*	*low*	*0.1*	*1.0E-4*	*1.5E-6*	*low*
IAS-Zone 3	200	2	high	0.1	2.6E-5	6.0E-7	high
UFA-Suwannee Limestone	8,100	31	high	0.1	2.9E-4	3.0E-7	fair
UFA-Avon Park Formation	220,000	299	high	0.1	1.3E-3	4.0E-7	fair

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_s) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

The resulting values of transmissivity are similar to those derived from the analytical models. The resulting values of storativity are about the same to about 3 times lower than those derived from the analytical models.

Hydraulic conductivity of the pumped zones and specific storage of IAS-Zone 3 were resolved with high confidence. Specific storage of the Suwannee Limestone and Avon Park Formation was resolve with moderate confidence. Hydraulic conductivity and specific storage of the unpumped IAS-Zone 2 were resolved with low confidence and are the most uncertain of the estimated aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP 22	Leakance (ft/d/ft)	K_z (ft/d)		[5]K_z/K_h	Specific storage (d^{-1})	
			[4]RCS rating			RCS rating
[1]Upper	1.5E-5	[4]1.0E-3		0.1	[5]1.5E-6	
[2]Middle	3.2E-5	2.5E-3	fair	0.1	9.0E-5	fair
[3]Lower	8.5E-4	8.5E-3	high	0.1	5.0E-5	low
Ocala Limestone	1.7E-2	5.2E+00	high	0.1	6.0E-5	low

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_Z) by the appropriate thickness; K_Z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 2. [2]Confining unit between IAS-Zone 2 and IAS-Zone 3. [3]Confining unit between IAS-Zone 3 and Suwannee Limestone. [4]Relative scaled sensitivity. [5]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the lower confining unit and Ocala Limestone were resolved with high confidence. Hydraulic conductivity and specific storage of the middle confining unit were resolved with moderate confidence. Specific storage of the lower confining unit and the Ocala Limestone was resolved with low confidence and these are the most uncertain of the estimated confining unit parameters.

Relative composite sensitivity (RCS) values for the assigned and estimated parameters are shown in figure 22 and appendix 1. The model was most sensitive to hydraulic

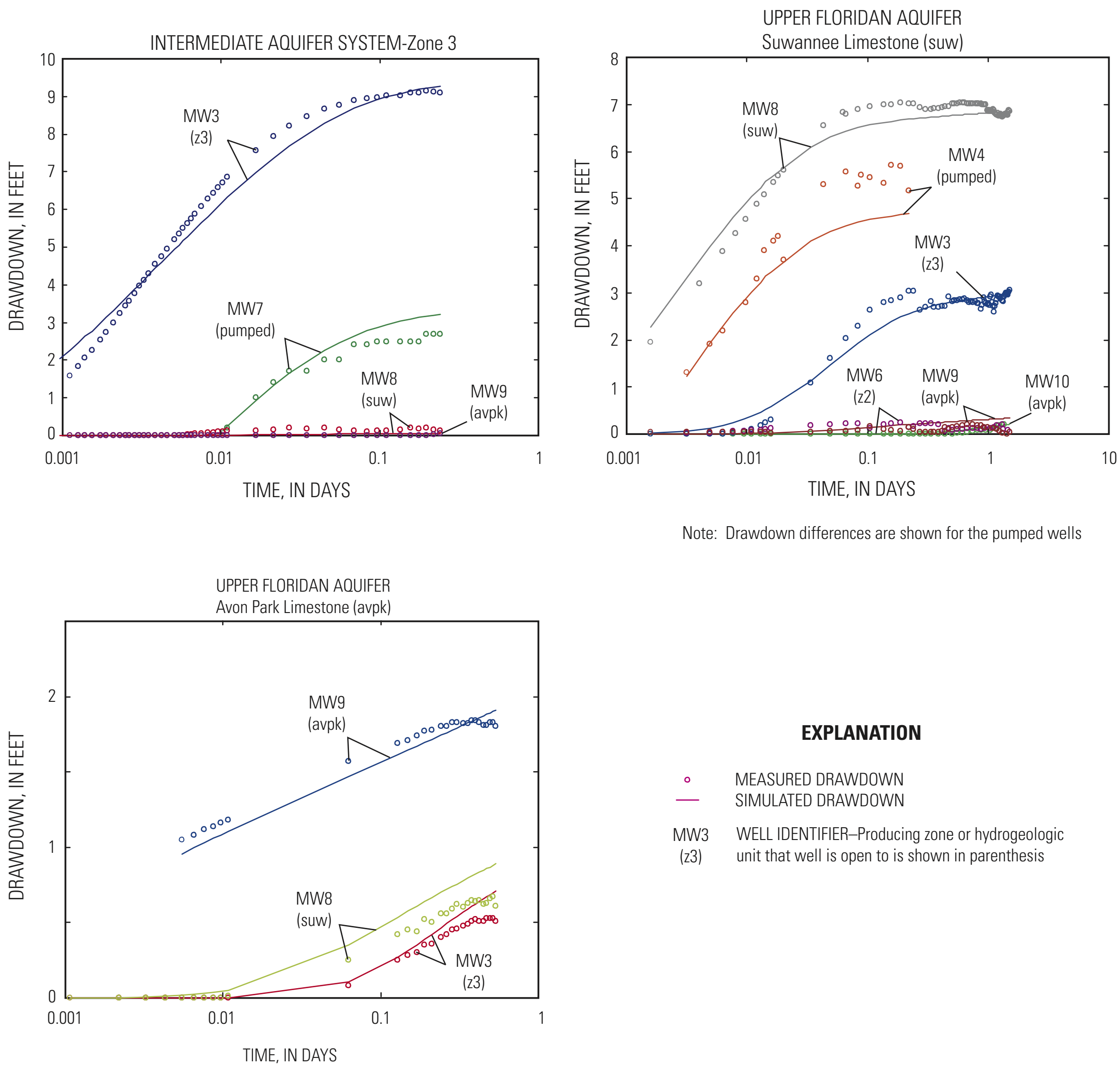


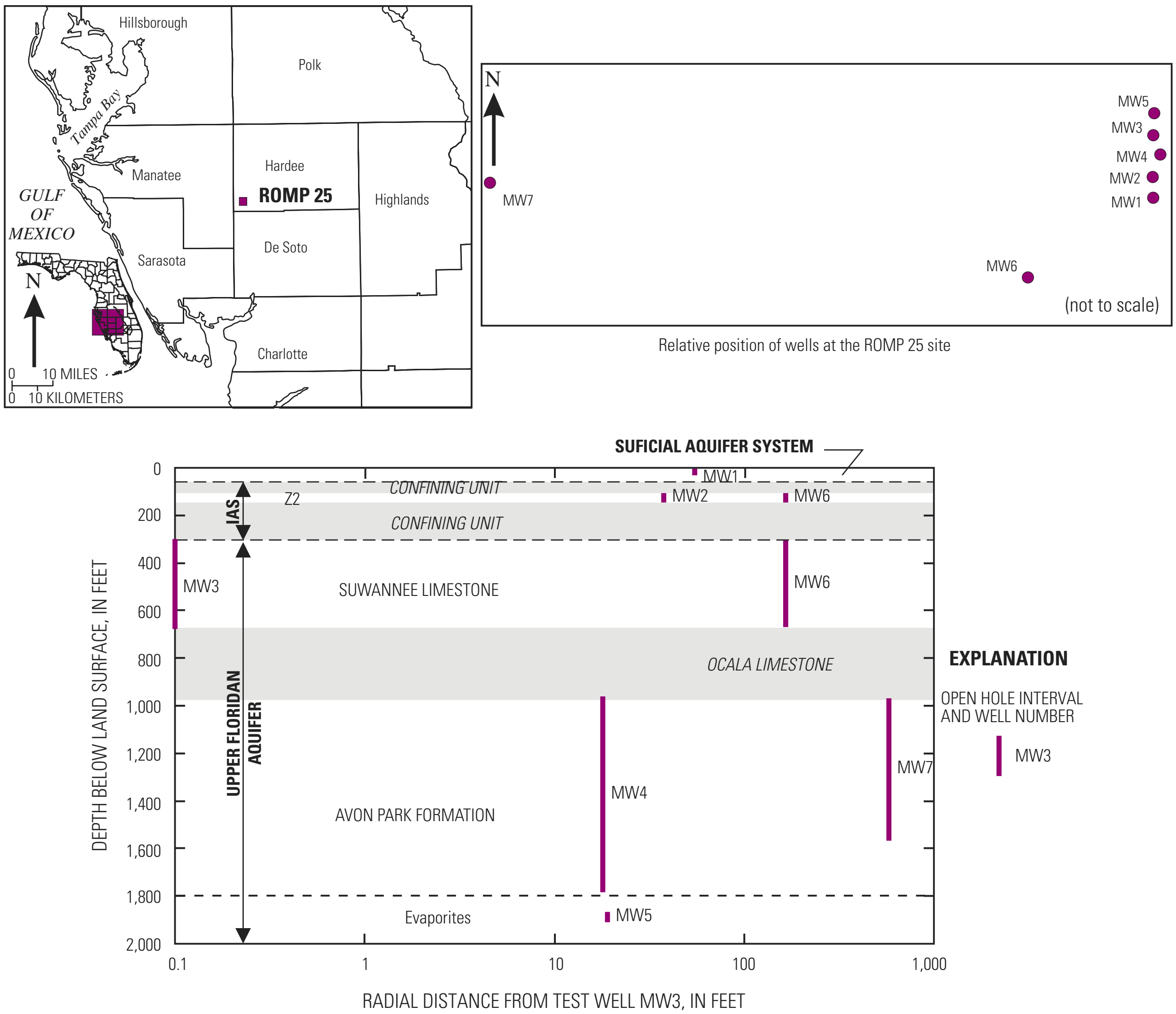
Figure 28. Simulated and measured drawdown for the three aquifer tests conducted at the ROMP 22 test site.

conductivity of the pumped zones and least sensitive to specific storage of the confining units. Sensitivity is highest for the hydraulic conductivity of IAS-Zone 3 and lowest for hydraulic conductivity of the surficial aquifer system. The model was insensitive to specific storage of the upper confining unit, the lower confining unit, and the Ocala Limestone, specific storage of IAS-Zone 2 and the surficial aquifer system, and hydraulic conductivity of the upper confining unit, IAS-Zone 2, and the surficial aquifer system, resulting in little influence of these parameters on overall model performance.

ROMP 25 Model

ROMP 25 is located at 27°21´59˝N and 82°00´25˝W in southwest Hardee County (fig. 29). Land surface altitude at the well site is about 85 ft above NGVD 29. Five permanent and three temporary wells ranging from 2 to 18 in. in diameter were completed at ROMP 25. The deepest well, MW5, was drilled to 1,911 ft below land surface.

Two aquifer tests were conducted from December 1998 through May 1999 at the ROMP 25 site to estimate the hydraulic properties of the Suwannee Limestone and the Avon Park Formation. Short-term aquifer tests also were performed on the surficial aquifer system and IAS-Zone 2 but were not numerically simulated because of the brief length of the tests.



Well name	Stratigraphic Unit		Casing depth/ Well depth (feet)	Casing diameter (Inches)	Distance from production well (feet) MW3 (SUW)	MW4 (AvPk)
			Surficial aquifer system (SAS)			
MW1	Undifferentiated surficial deposits		5/30	4	50.5	31.4
			Intermediate aquifer system (IAS)			
MW2	Upper Arcadia Formation	(Z2)	105/145	8	15.7	15.9
MW6	Upper Arcadia Formation	(Z2)	105/145	2	160.0	158.7
			Upper Floridan aquifer			
MW3	Suwannee Limestone	(SUW)	300/676	12		23.0
MW6	Suwannee Limestone	(SUW)	305/668	2	160.0	158.7
MW4	Avon Park Formation	(AvPk)	960/1,785	18	23.0	
MW7	Avon Park Formation	(AvPk)	970/1,568	2	494.0	500.0
MW5	Avon Park Formation	(AvPk)	1,866/1,911	6	19.1	41.5

Figure 29. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 25 test site.

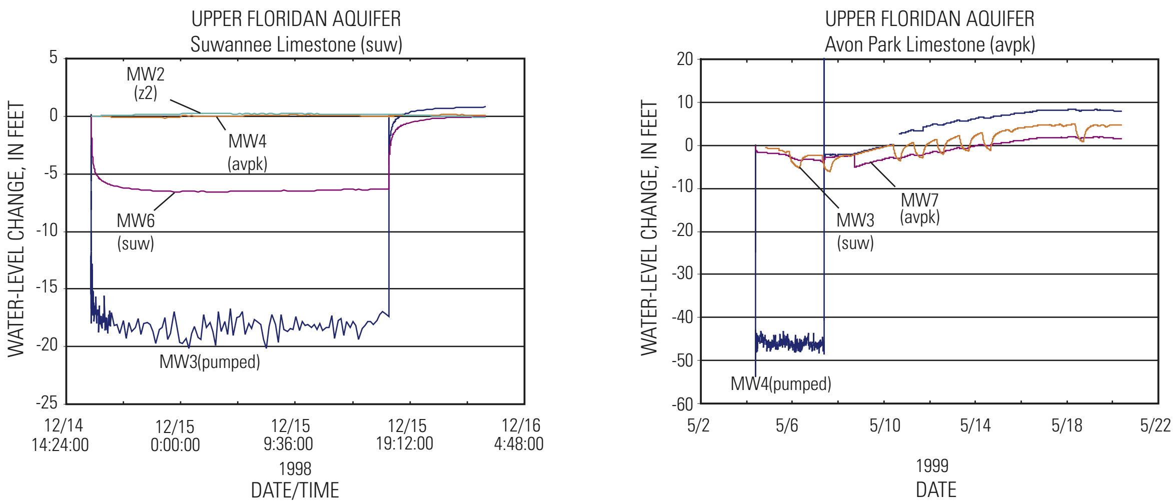


Figure 30. Water levels in selected wells during drawdown and recovery periods of the two aquifer tests conducted at the ROMP 25 test site.

A plan view and construction records of the production and observation wells for the aquifer tests are shown in figure 29. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 30 shows plots of the drawdown data used for analysis.

Well MW3, tapping the Suwannee Limestone zone of the Upper Floridan aquifer, was pumped at a rate of 500 gal/min for 33 hours. Drawdown data measured in the pumped well (MW3), Suwannee Limestone well MW6, IAS-Zone 2 well MW2, and Avon Park Formation well MW4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 18 ft in the pumped well (MW3) and about 7 ft in the Suwannee Limestone observation well MW6. No water-level declines in the IAS-Zone 2 well MW2 or in the Avon Park Formation well were estimated.

Well MW4, tapping the Avon Park Formation of the Upper Floridan aquifer, was pumped at a rate of 4,700 gal/min for 72 hours. Drawdown data measured in the Avon Park Formation well MW4, Avon Park Formation well MW7, and Suwannee Limestone well MW3 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 45 ft in the pumped well (MW4) and about 2 ft in the Avon Park Formation well MW3. Water-level declines of about 5 ft were estimated in the overlying Suwannee Limestone well MW8; however, offsite stresses were responsible for most of the decline. The water-level drawdown data have been corrected using regression analysis to account for the regional water-level trend and offsite stresses. Therefore, only the data after 0.6 day of the test were used in the simulation.

Aquifer test data were analyzed by Gates (2000) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer tests, including the short-term tests not simulated, and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP 25	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
Surficial aquifer system	273	5	--
IAS-Zone 2	0.5	0.01	--
UFA-Suwannee Limestone	7,800	21	1.0E-4
UFA-Avon Park Formation	320,000	388	2.9E-4

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; -- no data]

Model Structure

The model extended from the production wells to 200,000 ft away and from the water table to 1,800 ft below land surface. The numerical model consisted of 70 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 714 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column.

Four water-bearing units were simulated—the surficial aquifer system, IAS-Zone 2, Suwannee Limestone, and Avon Park Formation; and three confining units—upper and lower confining units, and the Ocala Limestone (fig. 3C). The surficial aquifer system is about 60 ft thick underlying the ROMP 25 site (table 2). The intermediate aquifer system underlies the surficial aquifer system and is about 245 ft thick at the study site, including one producing zone (IAS-Zone 2) separated by two confining units. The Upper Floridan aquifer, the lowermost permeable aquifer, is about 1,385 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

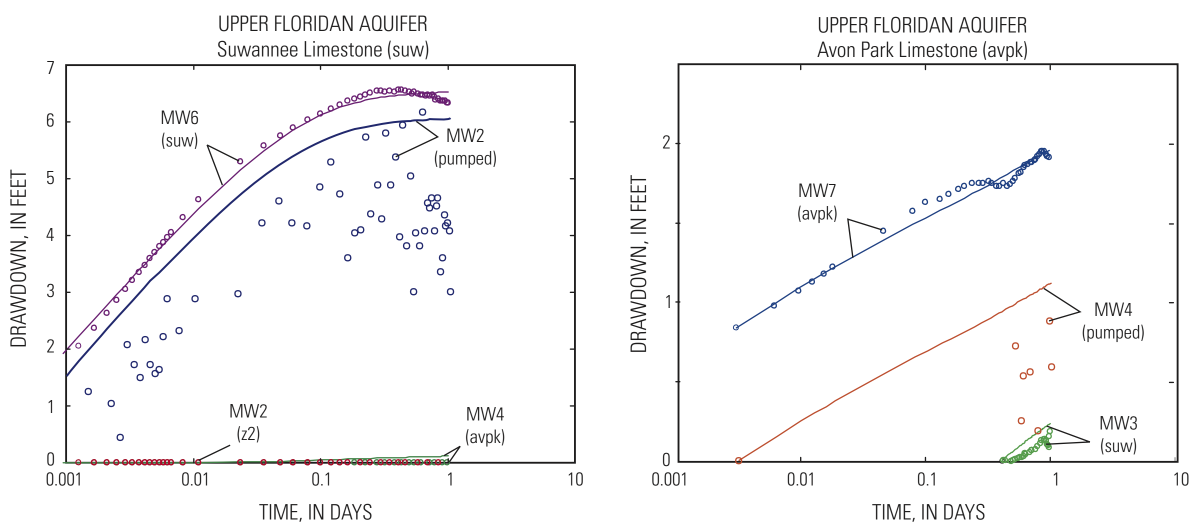
Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 10 parameters. Lateral hydraulic conductivities of the lower confining unit and Ocala Limestone, and the lower three producing zones (IAS-Zone 2, Suwannee Limestone, and Avon Park Formation) make up five of the parameters. Specific storage of the same hydrogeologic units make up five more parameters. Lateral hydraulic conductivity and specific storage for the surficial aquifer system and the upper confining unit were specified in the model because sufficient information was not available in the observations to independently determine their values. Additionally, vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all units.

Simulated drawdowns matched measured drawdowns favorably with an average unweighted root-mean-squared error (RMSE) of 0.06 ft for the two tests. The fit of measured and simulated time-drawdown data is illustrated in figure 31. RMSE of individual aquifer tests ranged from 0.04 ft for the Avon Park Formation test to 0.07 ft for the Suwannee Limestone test (table 3). The estimated and assigned hydraulic properties and sensitivity rating for the estimated parameters from this simulation are shown below (unpumped zones are italicized):

Hydrogeologic unit ROMP 25	T (ft^2/d)	K (ft/d)		[1]K_z/K_h	Storage		
			[2]RCS rating		S	S_S (d^{-1})	RCS rating
Surficial aquifer system	*540*	*[1]9*		*0.1*	*9.0E-5*	*[1]1.5E-6*	
IAS-Zone 2	*38*	*1*	*low*	*0.1*	*5.7E-5*	1.5E-6	*low*
UFA-Suwannee Limestone	6,900	19	high	0.1	7.4E-5	2.0E-7	high
UFA-Avon Park Formation	330,000	400	high	0.1	1.6E-4	2.0E-7	fair

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_S) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]



Note: Drawdown differences are shown for the pumped wells

EXPLANATION

MEASURED DRAWDOWN
SIMULATED DRAWDOWN

MW2 (z2) WELL IDENTIFIER–Producing zone or hydrogeologic unit that well is open to is shown in parenthesis

Figure 31. Simulated and measured drawdown for the two aquifer tests conducted at the ROMP 25 test site.

The resulting values of transmissivity and storativity are about the same as those derived from the analytical models.

Hydraulic conductivity of the pumped zones and specific storage of the Suwannee Limestone were resolved with high confidence. Specific storage of the Avon Park Limestone was resolved with moderate confidence. Hydraulic conductivity and specific storage of the unpumped IAS-Zone 2 were resolved with low confidence and are the most uncertain of the estimated aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP 25	Leakance (ft/d/ft)	K_Z (ft/d)		$^4K_Z/K_h$	Specific storage (d^{-1})	
			^{3}RCS rating			RCS rating
[1]Upper	1.1E-5	[4]5.0E-4		0.1	[4]1.5E-6	
[2]Lower	8.1E-6	1.3E-3	low	0.1	4.0E-5	low
Ocala Limestone	9.6E-4	2.9E-1	high	0.1	1.0E-5	low

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_Z) by the appropriate thickness; K_Z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 2. [2]Confining unit between IAS-Zone 2 and Suwannee Limestone. [3]Relative scaled sensitivity. [4]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the Ocala Limestone was resolved with high confidence where as hydraulic conductivity and specific storage for the lower confining unit and specific storage of the Ocala Limestone were resolved with low confidence and are the most uncertain of the estimate confining unit parameters.

Relative composite sensitivity (RCS) values for the assigned and estimated parameters are shown in figure 22 and appendix 1. The model was most sensitive to hydraulic conductivity of the pumped zones and least sensitive to specific storage of the confining units. Sensitivity is highest for the hydraulic conductivity of the Suwannee Limestone and lowest for hydraulic conductivity of the IAS-Zone 2. The model was insensitive to specific storage of the lower and upper confining units, the Ocala Limestone, the surficial aquifer system, and IAS-Zone 2, and hydraulic conductivity of the lower and upper confining units, the surficial aquifer system, and IAS-Zone 2, resulting in little influence of these parameters on overall model performance.

ROMP 28 Model

ROMP 28 is located at 27°22´07˝N and 81°26´04˝W in west-central Highlands County (fig. 32). Land surface altitude at the well site is about 84 ft above NGVD 29. Sixteen permanent wells ranging from 2 to 12 in. in diameter were completed at ROMP 28. The deepest well, MW6, was drilled to 2,103 ft below land surface.

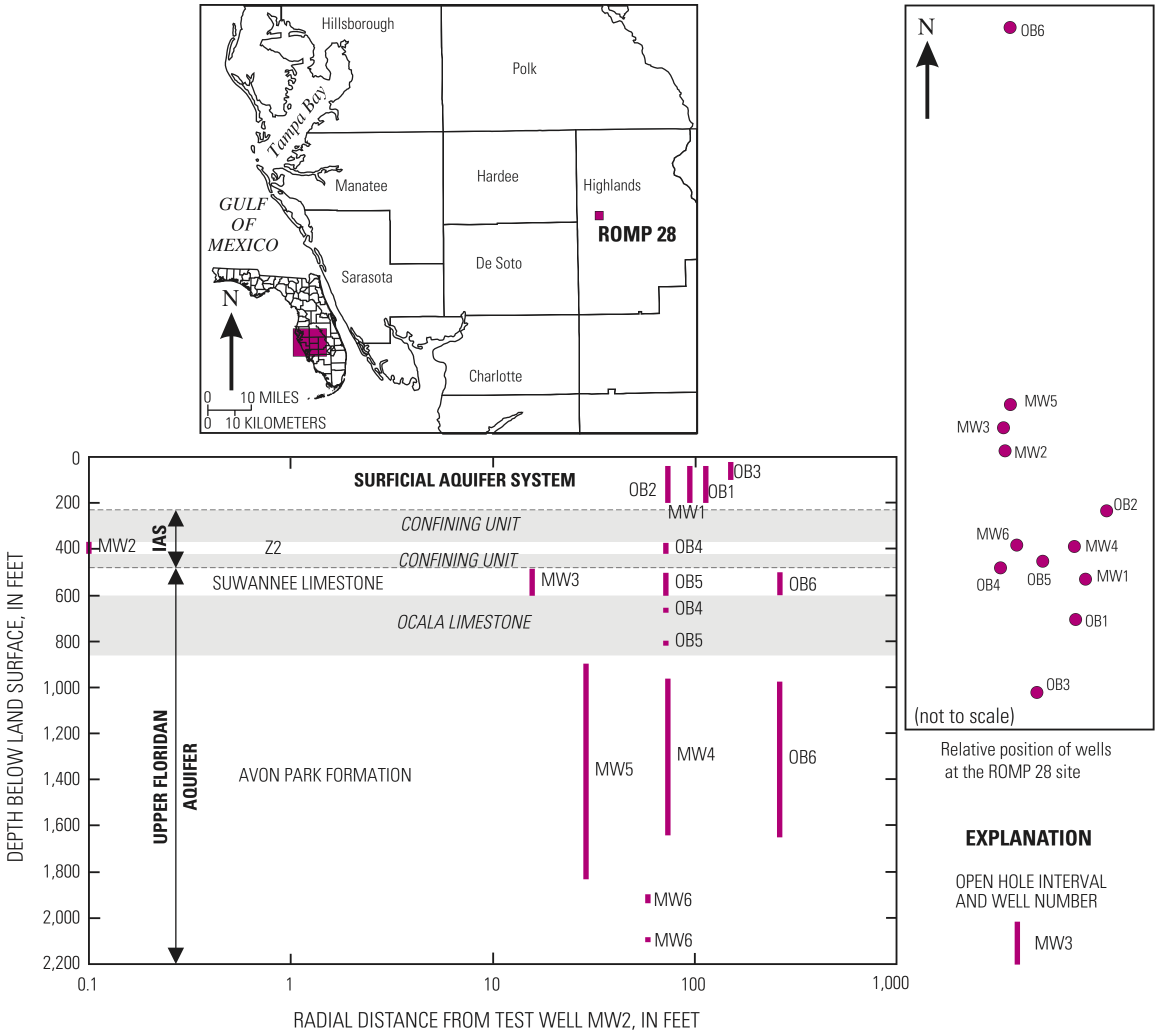
Four aquifer tests were conducted from March 1993 through February 1997 at the ROMP 28 site to estimate the hydraulic properties of the surficial aquifer system (SAS), the intermediate aquifer system (IAS), the Suwannee Limestone, and the Avon Park Formation (table 1). A plan view and construction records of the production and observation wells for the aquifer tests are shown in figure 32. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 33 shows plots of the drawdown data used for analysis.

Well MW1, tapping the surficial aquifer system, was pumped at a rate of 400 gal/min for 20 hours. Drawdown data measured in the surficial aquifer system wells OB1, OB2, and OB3 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 50 ft in the pumped well (MW1), about 4 ft in OB1, about 3 ft in OB2, and about 2 ft in OB3.

Well MW2, tapping Zone 2 of the intermediate aquifer system, was pumped at a rate of 37 gal/min for 35.2 hours. Drawdown data measured in the pumped well (MW2), IAS well OB4, surficial aquifer system well MW1, and Suwannee Limestone well MW3 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 85 ft in the pumped well and about 7 ft in the IAS observation well OB4. No decline in water level was estimated in either the overlying surficial aquifer system well or in the underlying Suwannee Limestone well.

Well MW3, tapping the Suwannee Limestone of the Upper Floridan aquifer, was pumped at a rate of 150 gal/min for 83.4 hours. Drawdown data measured in the pumped well MW3, the Ocala Limestone well OB4, Suwannee Limestone wells OB5 and OB6, and IAS wells MW2 and OB4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 140 ft in the pumped well (MW3), about 35 ft in the Suwannee Limestone well OB5, about 8 ft in the Suwannee Limestone well OB6, and about 0.7 ft in IAS wells MW2 and OB4. No decline in water level was estimated in the underlying Avon Park Formation wells; however, a 20-ft decline was estimated in the Ocala Limestone well OB4.

Well MW5, tapping the Avon Park Formation of the Upper Floridan aquifer, was pumped at a rate of 3,000 gal/min for about 119.4 hours. Drawdown data measured in the pumped well MW5, Avon Park Formation wells MW4 and OB6, Suwannee Limestone wells MW3, OB5, and OB6, and Ocala Limestone well OB4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 35 ft in the pumped well (MW5), about 9 ft in Avon Park Formation well MW4, and about 8 ft in Avon Park Formation well OB6. Water-level declines were estimated to be about 5 ft in Suwannee Limestone wells (OB6, OB5, andMW3), about 7 ft in the Ocala Limestone well OB4, and about 3 ft in the IAS wells MW2 and OB4, indicating hydraulic connection with overlying zones.



Well name	Stratigraphic Unit	Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet) MW1 (SAS)	MW2 (Z2)	MW3 (SUW)	MW5 (AvPk)
	Surficial aquifer system (SAS)						
MW1	Undifferentiated surficial deposits	40/200	12		99.5	119.4	123.0
OB1	Undifferentiated surficial deposits	40/200	2	19.5	116.2	136.6	140.3
OB2	Undifferentiated surficial deposits	40/200	2	49.5	79.4	95.0	95.5
OB3	Undifferentiated surficial deposits	20/100	2	74.0	158.5	178.7	183.5
	Intermediate aquifer system (IAS)						
MW2	Arcadia Formation (Z2)	370/420	8	99.5		20.5	25.5
OB4	Arcadia Formation (Z2)	372/422	2	38.8	78.2	98.7	103.4
	Upper Floridan aquifer						
MW3	Suwannee Limestone (SUW)	485/600	8	119.4	20.2		7.5
OB5	Suwannee Limestone (SUW)	502/602	2	21.5	79.3	99.5	103.2
OB6	Suwannee Limestone (SUW)	494/594	2	730.5	614.0	594.0	589.1
OB4	Ocala Limestone (confining unit)	652/678	2	38.8	78.2	98.7	103.4
OB5	Ocala Limestone (confining unit)	797/817	2	21.5	79.3	99.5	103.2
MW4	Avon Park Formation (AvPk)	960/1,642	11	19.8	80.6	100.9	103.1
MW5	Avon Park Formation	897/1,830	8	123.0	25.5	7.5	
MW6	Avon Park Formation (evaporite)	1,935/1,897	2	32.5	73.8	94.4	98.5
MW6	Avon Park Formation (evaporite)	2,083/2,103	2	32.5	73.8	94.4	98.5
OB6	Avon Park Formation	973/1,650	3	730.5	614.0	594.0	589.1

Figure 32. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 28 test site.

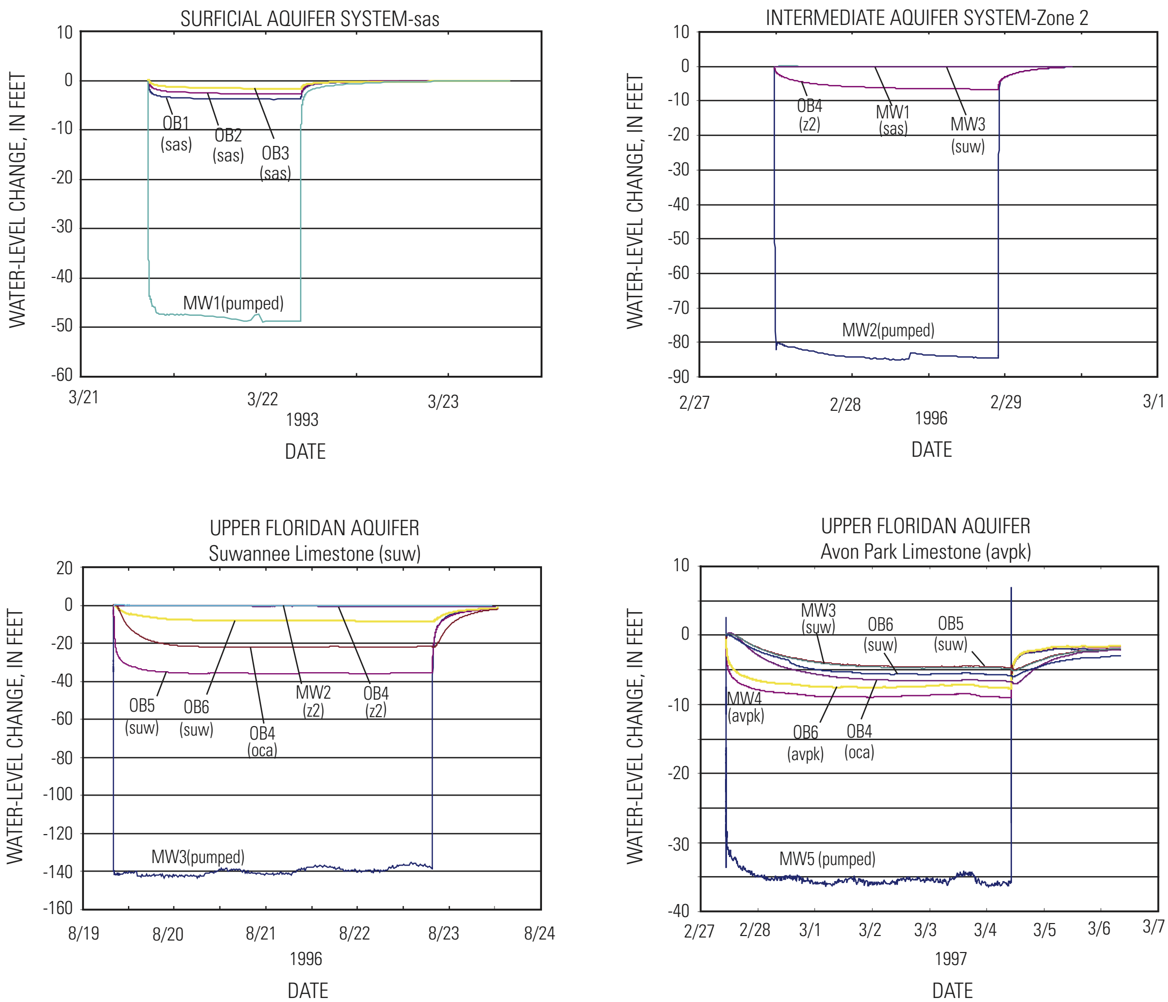


Figure 33. Water levels in selected wells during drawdown and recovery periods of the four aquifer tests conducted at the ROMP 28 test site.

Aquifer test data were analyzed by DeWitt (Southwest Florida Water Management District, written commun., 2003) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer tests and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP 28	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
Surficial aquifer system	6,900	30	--
IAS-Zone 2	162	3	2.4E-4
UFA-Suwannee Limestone	330	3	1.9E-4
UFA-Avon Park Formation	53,000	41	1.2E-3

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; -- no data]

Model Structure

The model extended from the production wells to 200,000 ft away and from the water table to 2,103 ft below land surface. The numerical model consisted of 92 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 1,243 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column. Vertical discretization was finer across the confining units and the surficial aquifer system than across the other hydrogeologic units.

Four water-bearing units were simulated—the surficial aquifer system, intermediate confining unit, Suwannee Limestone, and the Avon Park Formation; and three confining units—upper and lower confining units, and the Ocala

Limestone (fig. 3C). The surficial aquifer system is about 230 ft thick underlying the ROMP 28 site (table 2). The intermediate confining unit underlies the surficial aquifer and is about 249 ft thick, including two confining units and a slightly more permeable zone (Z2). The Upper Floridan aquifer is the lowermost permeable aquifer and is about 1,623 ft thick. The Upper Floridan aquifer has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 15 parameters. Lateral hydraulic conductivities of the three confining units and four producing zones make up seven of the parameters. Specific storage of the same hydrogeologic units make up seven more parameters. Specific yield of the surficial aquifer system is the last parameter. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all units.

Simulated drawdowns matched measured drawdowns reasonably well with an average unweighted root-mean-squared error (RMSE) of 0.42 ft (table 3) for the four tests. The fit of measured and simulated time-drawdown data is illustrated in figure 34. The Avon Park Formation test exhibited the poorest match between simulated and measured values. The simulated drawdown for shallow intervals (Suwannee Limestone and Ocala wells) was greater than measured for early time and less for late time. This departure may be associated with horizontal anisotropy of the aquifer system that is not adequately represented in this model. RMSE of individual aquifer tests ranged from 0.08 ft for the surficial aquifer system test to 1.01 ft for the Avon Park Formation test. The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below:

Hydrogeologic unit ROMP 28	T (ft^2/d)	K (ft/d)		[1]K_z/K_h	S_y		Storage		
			[2]RCS rating			RCS rating	S	S_s (d^{-1})	RCS rating
Surficial aquifer system	10,000	44	high	0.1	0.24	low	3.2E-2	1.4E-4	high
IAS-Zone 2	300	6	high	0.1			6.5E-4	1.1E-5	fair
UFA-Suwannee Limestone	170	1	high	0.1			4.8E-5	4.0E-7	high
UFA-Avon Park Formation	59,000	46	high	0.1			5.2E-4	4.0E-7	fair

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_s) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; S_y, specific yield. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

The resulting values of transmissivity are slightly higher than those derived from the analytical models, and values of storativity are about 2 to 4 times lower than those derived from the analytical models. The simulated specific storage value for the surficial aquifer system, however, is unrealistic.

Hydraulic conductivity of the pumped zones and specific storage of the surficial aquifer system and the Suwannee Limestone were resolved with high confidence. Specific storage in IAS-Zone 2 and the Suwannee Limestone was resolved with moderate confidence. Specific yield of the surficial aquifer was resolved with low confidence and is the most uncertain of the estimated aquifer parameters.

The estimated hydraulic properties and sensitivity rating for the confining units from this simulation are:

Confining unit ROMP 28	Leakance (ft/d/ft)	K_z (ft/d)		[4]K_z/K_h	Specific storage (d^{-1})	
			[3]RCS rating			RCS rating
[1]Upper	7.9E-4	1.1E-1	fair	0.1	1.1E-5	fair
[2]Lower	2.2E-5	1.1E-3	fair	0.1	6.0E-5	low
Ocala Limestone	3.7E-3	9.5E-1	high	0.1	1.0E-5	fair

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_Z) by the appropriate thickness; K_Z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 2. [2]Confining unit between IAS-Zone 2 and Suwannee Limestone. [3]Relative scaled sensitivity. [4]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the Ocala Limestone was resolved with high confidence. Hydraulic conductivity of the upper and lower confining units and specific storage of the upper and lower confining unit and the Ocala Limestone were resolved with moderate confidence and are the most uncertain of the confining unit parameters.

Relative composite sensitivity (RCS) values for the estimated parameters are shown in figure 35 and appendix 1. The model was most sensitive to hydraulic conductivity of the pumped zones and least sensitive to specific storage of the confining units. Sensitivity was highest for the hydraulic conductivity of the Suwannee Limestone and lowest for specific storage of the lower confining unit. The model was insensitive to specific storage of the lower confining unit and specific yield of the surficial aquifer system, resulting in little influence of these parameters on overall model performance.

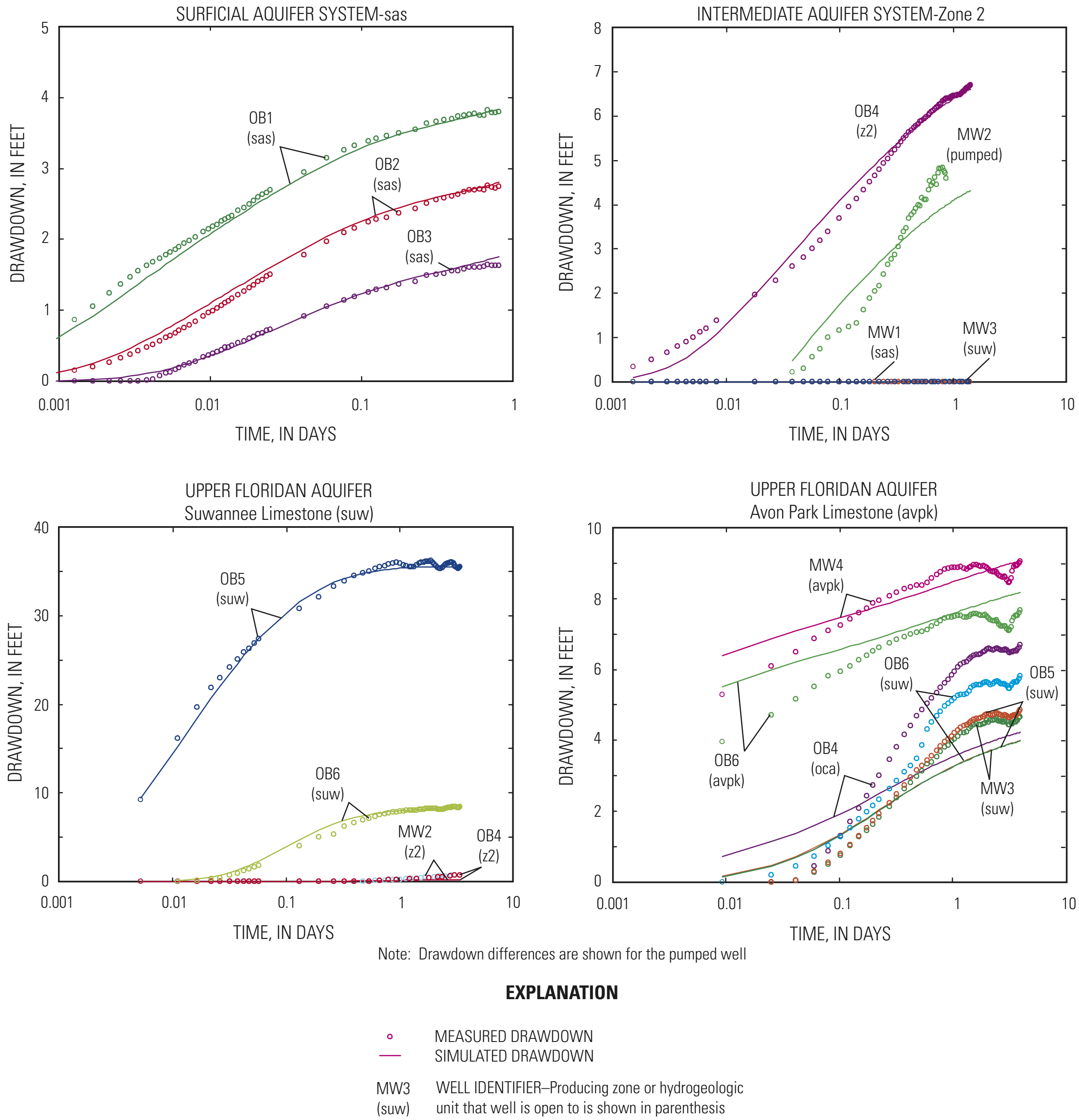
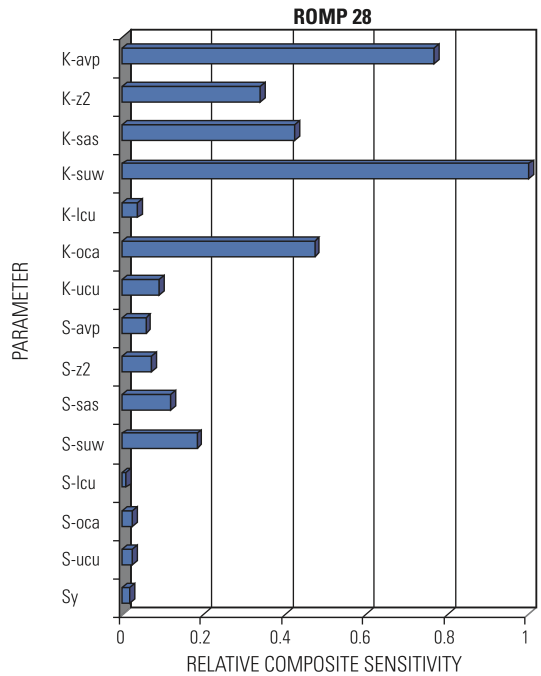
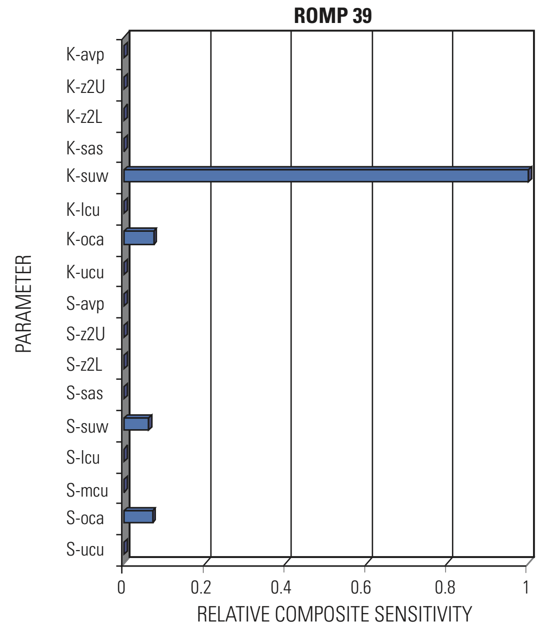
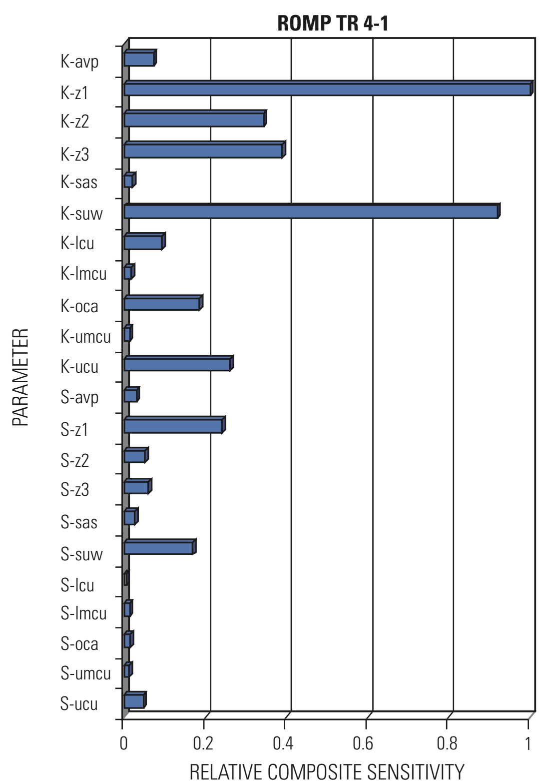
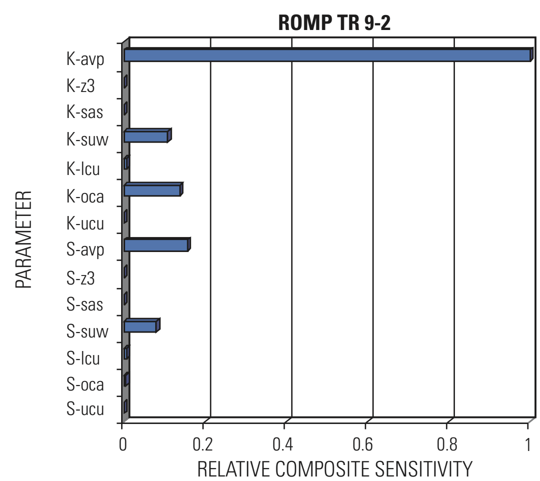


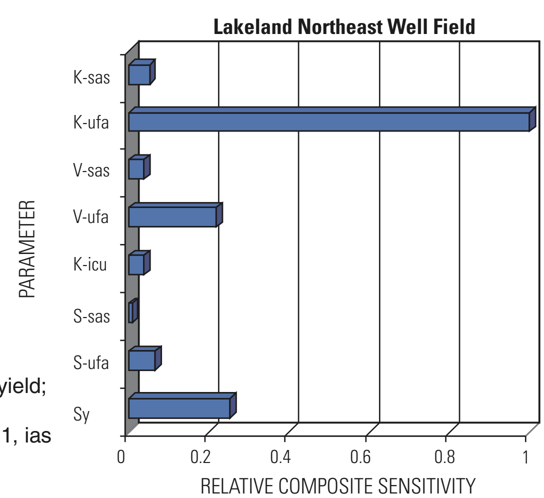
Figure 34. Simulated and measured drawdown for the four aquifer tests conducted at the ROMP 28 test site.











Parameter Abbreviations

[K, hydraulic conductivity; S, specific storage; Sy, specific yield; V, vertical anisotropy; sas, surficial aquifer system; ias, intermediate aquifer system; ufa, Upper Floridan aquifer; z1, ias Zone 1; z2, ias Zone 2; z3, ias Zone 3; suw, Suwannee Limestone; avp, Avon Park Limestone; icu, intermediate confining unit; ucu, confining unit between sas and ias; umcu, confining unit between z1 and z2; lmcu, confining unit between z2 and z3; lcu, confining unit between ias and suw]

Figure 35. Relative composite sensitivity for final parameter values for ROMP 28, 39, TR 4-1, TR 9-2, and Lakeland Northeast Well Field.

ROMP 39 Model

ROMP 39 is located at 27°35´21˝N and 82°15´05˝W in north-central Manatee County (fig. 36). Land surface altitude at the well site is about 125 ft above NGVD 29. Four permanent wells and one temporary well ranging from 4 to 12 in. in diameter were completed at ROMP 39. The deepest well, MW4, was drilled to 1,120 ft below land surface.

A single aquifer test was conducted in February 1994 at the ROMP 39 site to estimate the hydraulic properties of the Suwannee Limestone. A plan view and construction records of the production and observation wells are shown in figure 36. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 37 shows a plot of the drawdown data used for analysis.

The Suwannee Limestone zone of the Upper Floridan aquifer was pumped at a rate of 762 gal/min for 43.9 hours. Drawdown data measured in the pumped well (MW5), Suwannee Limestone well MW3, IAS-Zone 2 well MW2, and Avon Park Formation well MW4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 55 ft in the pumped well (MW5) and about 9 ft in the Suwannee Limestone observation well MW3. No water-level declines in the IAS-Zone 2 well MW2 or in the Avon Park Formation well were estimated.

Aquifer test data were analyzed by Clayton (1994) using analytical techniques. Average transmissivity and storativity values reported for the aquifer test and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP 39	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
UFA-Suwannee Limestone	12,000	36	1.6E-4

[UFA, Upper Floridan aquifer]

Model Structure

The model extended from the production well to 200,000 ft away and from the water table to 1,627 ft below land surface. The numerical model consisted of 93 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 662 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column.

Four water-bearing units were simulated—the surficial aquifer system, IAS-Zone 2, Suwannee Limestone, and Avon Park Formation; and four confining units—upper, middle, and lower confining units, and the Ocala Limestone (fig. 3D). The surficial aquifer system is about 78 ft thick underlying the ROMP 39 site (table 2). The intermediate aquifer system underlies the surficial aquifer and is about 310 ft thick at the study site, including two minor producing zones separated by three confining units. The Upper Floridan aquifer, the lowermost permeable aquifer, is about 1,240 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone. At this site, the Tamper Member is included as part of the Suwannee Limestone water-bearing zone.

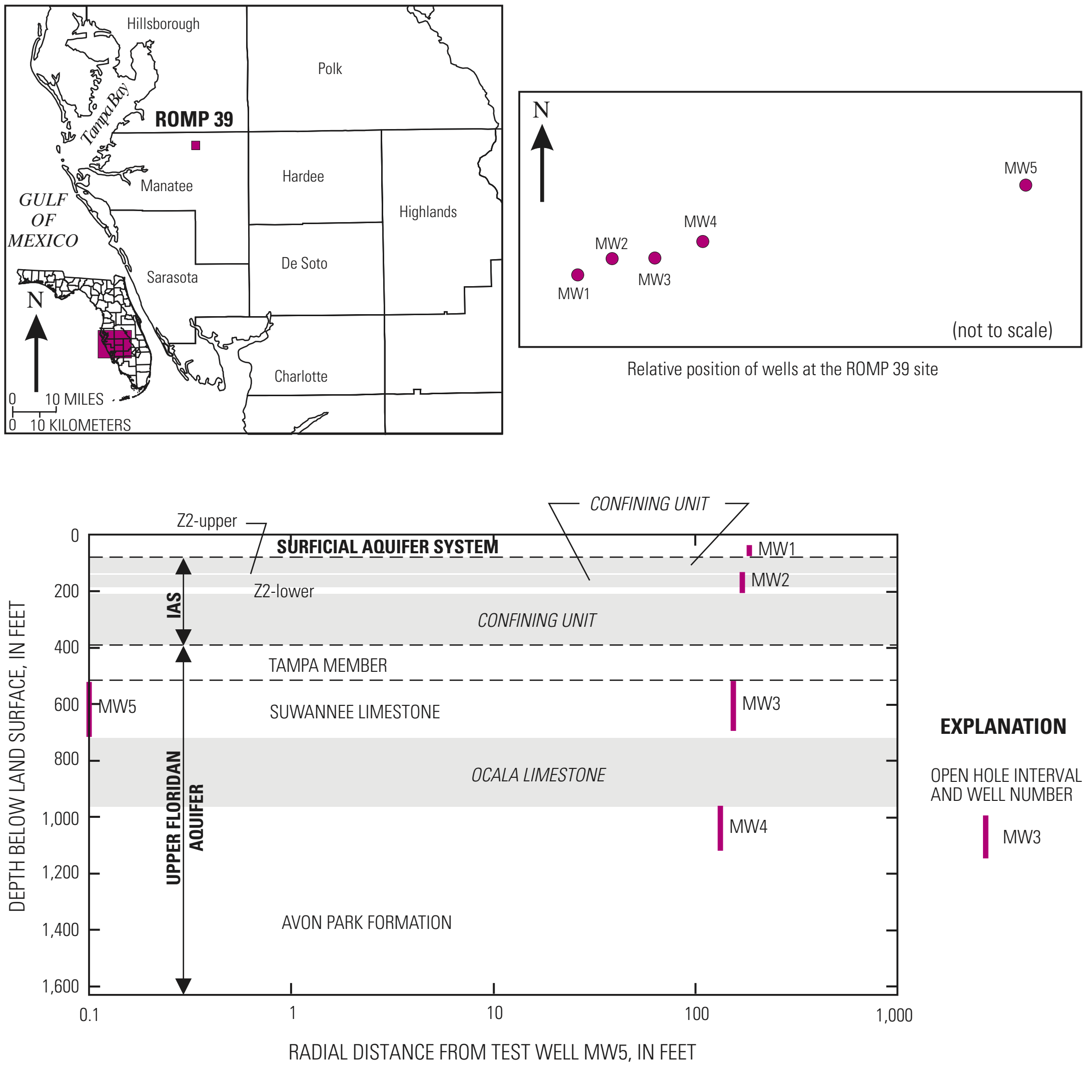
Aquifer-Test Simulation

Differences between simulated and measured drawdowns were minimized by estimating six parameters. Lateral hydraulic conductivities of two confining units (lower confining unit and the Ocala Limestone) and one producing zone (Suwannee Limestone) make up three of the parameters. Specific storage of the same hydrogeologic units make up three more parameters. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity in all units. Lateral conductivity and specific storages of the surficial aquifer system, the IAS-Zone 2-upper, IAS-Zone 2-lower, the Avon Park Formation, and the upper and middle confining units were specified in the model because sufficient information was not available in the observations to independently determine their values.

Simulated drawdowns matched measured drawdowns favorably with an unweighted root-mean-squared error (RMSE) of 0.34 ft (table 3). The fit of measured and simulated time-drawdown data is illustrated in figure 38. The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below (unpumped zones are italicized):

Hydrogeologic unit ROMP 39	T (ft^2/d)	K (ft/d)		[1]K_z/K_h	Storage		
			[2]RCS rating		S	S_s (d^{-1})	RCS rating
Surficial aquifer system	*780*	*[1]10*		*0.1*	*1.2E-4*	*[1]1.5E-6*	
IAS-Zone 2 Upper	*9*	*[1]1*		*0.1*	*3.9E-4*	*[1]1.5E-6*	
IAS-Zone 2 Lower	*25*	*[1]1*		*0.1*	*3.3E-5*	*[1]1.5E-6*	
UFA-Suwannee Limestone	9,200	28	high	0.1	3.3E-5	1.0E-7	fair
UFA-Avon Park Formation	*190,000*	*[1]300*		*0.1*	*9.3E-4*	*[1]1.5E-6*	

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit was determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_s) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]



Well name	Stratigraphic Unit		Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet) MW5 (SUW)
Surficial aquifer system					
MW1	Undifferentiated surficial deposits		35/75	4	183
Intermediate aquifer system (IAS)					
MW2	Peace River/ Arcadia Fm	(Z2)	130/205	6	169
Upper Floridan aquifer					
MW3	Suwannee Limestone	(SUW)	516/696	8	155
MW5	Suwannee Limestone	(SUW)	520/714	12	
MW4	Avon Park Formation	(AvPk)	960/1,120	6	138

Figure 36. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP 39 test site.

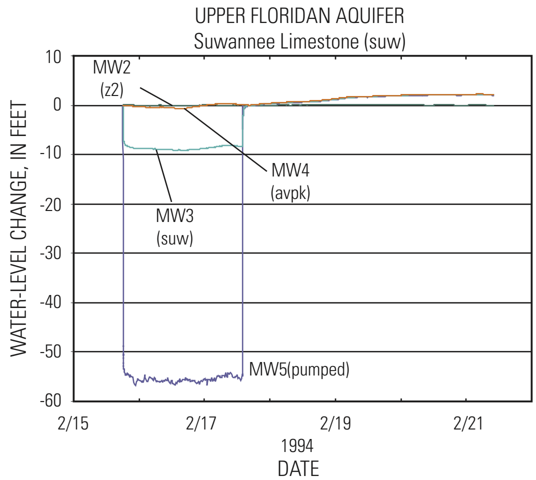


Figure 37. Water levels in selected wells during drawdown and recovery periods of the Suwannee Limestone aquifer test conducted at the ROMP 39 test site.

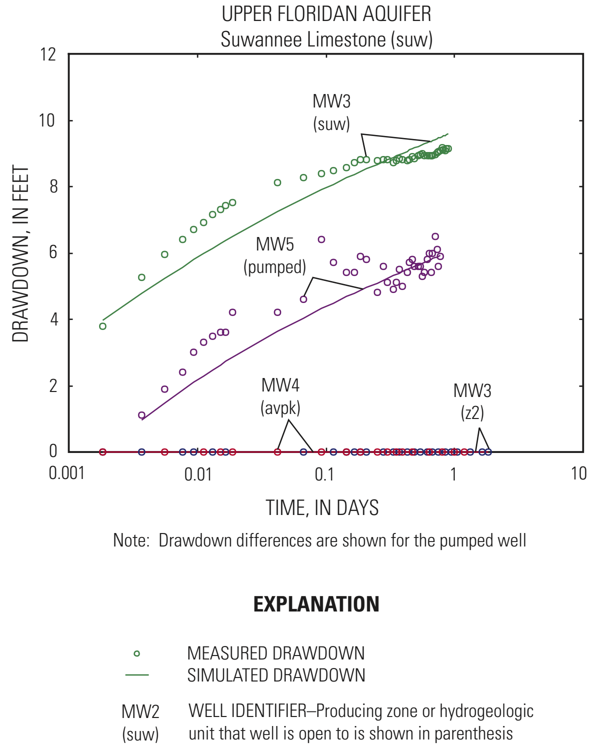


Figure 38. Simulated and measured drawdown for the Suwannee Limestone aquifer test conducted at the ROMP 39 test site.

The resulting value of transmissivity is slightly lower than that derived from the analytical model, and the storativity value is 20 percent of the analytical value.

Hydraulic conductivity of the pumped zone was resolved with high confidence and specific storage of the pumped zone was resolved with moderate confidence.

The estimated or assigned hydraulic properties and sensitivity ratings for the estimated confining units from this simulation are:

Confining unit ROMP 39	Leakance (ft/d/ft)	K_z (ft/d)	[4]RCS rating	[5]K_z/K_h	Specific storage (d^{-1})	RCS rating
[1]Upper	1.0E-5	[5]1.0E-3		0.1	[5]1.5E-6	
[2]Middle	2.4E-5	[5]1.0E-3		0.1	[5]1.5E-6	
[3]Lower	7.8E-7	1.4E-4	low	0.1	1.0E-7	low
Ocala Limestone	7.7E-5	1.9E-2	fair	0.1	2.0E-7	fair

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_z) by the appropriate thickness; K_z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 2 upper. [2]Confining unit between IAS-Zone 2 upper and IAS-Zone 2 lower. [3]Confining unit between IAS-Zone 2 lower and Suwannee Limestone. [4]Relative scaled sensitivity. [5]This parameter was assigned and not estimated with the inverse model]

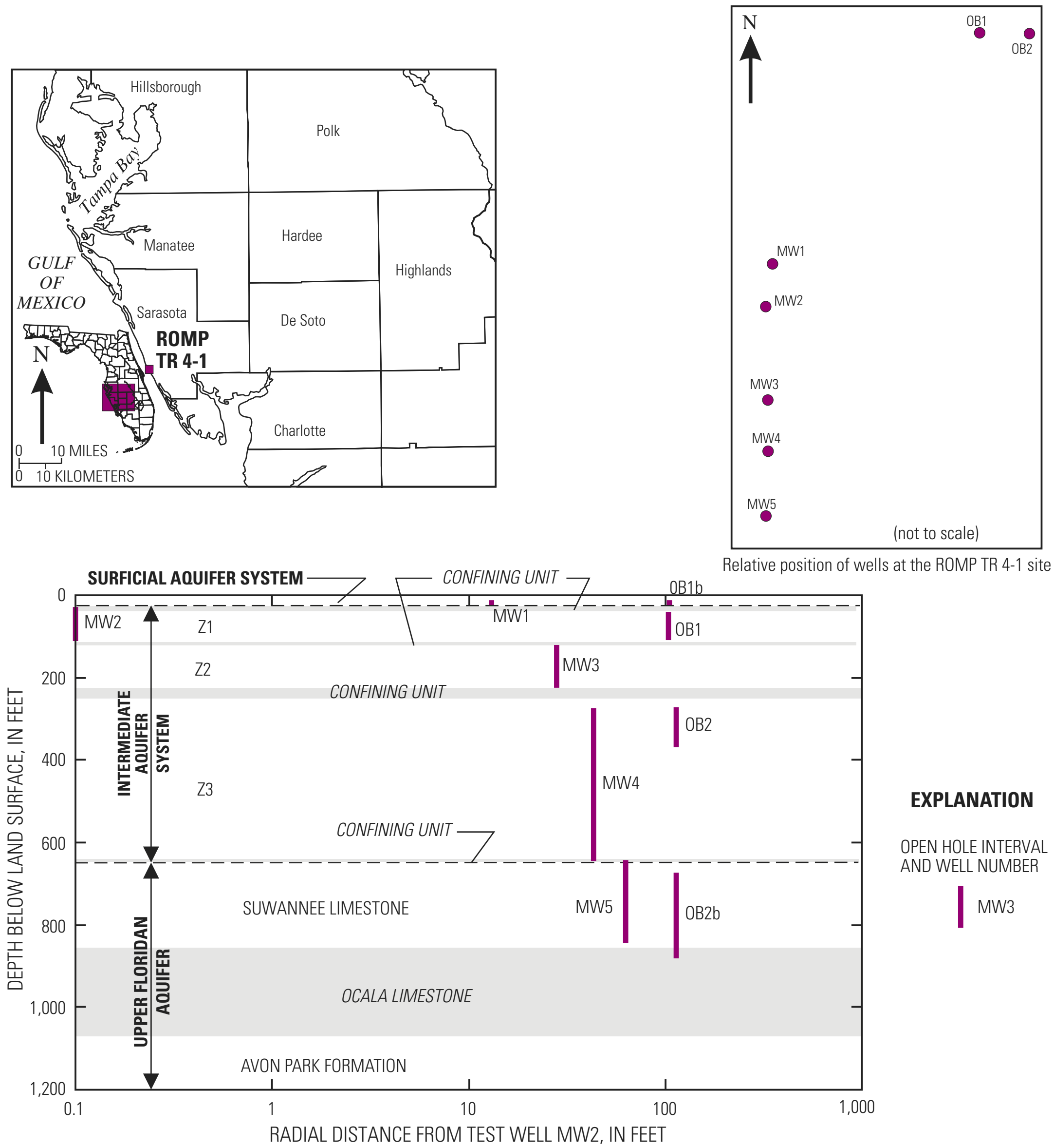
Vertical hydraulic conductivity and specific storage of the Ocala Limestone were resolved with moderate confidence. Vertical hydraulic conductivity and specific storage of the lower confining unit were resolved with low confidence and are the most uncertain of the estimated confining unit parameters.

Relative composite sensitivity (RCS) values for the assigned and estimated parameters are shown in figure 35 and appendix 1. The model is highly sensitive to hydraulic conductivity of the Suwannee Limestone, and moderately sensitive to vertical hydraulic conductivity and specific storage of the Ocala Limestone and specific storage of the Suwannee Limestone. The model was insensitive to all other parameters, resulting in little influence of these parameters on overall model performance.

ROMP TR 4-1 Model

ROMP TR 4-1 is located at 27°03´26˝N and 82°26´27˝W in southwest Sarasota County near the Gulf of Mexico (fig. 39). Land surface altitude at the well site is about 10 ft above NGVD 29. Five permanent and four temporary wells ranging from 1 to 12 in. in diameter were completed at ROMP TR 4-1. The deepest well, OB2, was drilled to 880 ft below land surface.

Four aquifer tests were conducted from February-June 1997 at the ROMP TR 4-1 site to estimate the hydraulic properties of the upper intermediate aquifer system (IAS-Zone 1), middle intermediate aquifer system (IAS-Zone 2), lower intermediate aquifer system (IAS-Zone 3), and Suwannee Limestone (table 1). A plan view and construction records of the production and observation wells for the aquifer tests are shown in figure 39. Water levels were measured continuously



Well name	Stratigraphic Unit	Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet) MW2 (Z1)	MW3 (Z2)	MW4 (Z3)	MW5 (SUW)
		Surficial aquifer system (SAS)					
MW1	Undifferentiated surficial deposits	12/23	6	14.2	33.3	48.8	73.5
OB1	Undifferentiated surficial deposits	11/23	4	104.3	127.1	140.7	158.8
		Intermediate aquifer system					
MW2	Peace River Formation (Z1)	30/110	6		19.1	34.4	59.4
OB1	Peace River Formation (Z1)	41/108	2	104.3	127.1	140.7	158.8
MW3	Upper Arcadia Formation (Z2)	120/224	8	19.2		15.5	40.4
MW4	Lower Arcadia Formation (Z3)	275/645	8	34.5	15.5		24.9
OB2	Lower Arcadia Formation (Z3)	271/369	1	113.9	135.0	147.8	165.1
		Upper Floridan aquifer					
MW5	Suwannee Limestone (SUW)	643/844	12	59.3	40.3	24.9	
OB2	Suwannee Limestone (SUW)	674/880	3	113.9	135.0	147.8	165.1

Figure 39. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP TR 4-1 test site.

in multiple wells for withdrawal and recovery periods of the tests. Figure 40 shows plots of the drawdown data used for analysis.

Well MW2, tapping the upper permeable zone of the intermediate aquifer system (IAS-Zone 1), was pumped at a rate of 60 gal/min for 23.9 hours. Drawdown data measured in the pumped well (MW2), surficial aquifer system well MW1, and IAS-Zone 2 well MW3 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 33 ft in the pumped well (MW2) and about 0.9 ft in the surficial aquifer system well MW1, indicating hydraulic connection with the overlying surficial aquifer system. No decline in water level was estimated in the underlying IAS-Zone 2 well.

Well MW3, tapping the middle permeable zone of the intermediate aquifer system (IAS-Zone 2), was pumped at a rate of 60 gal/min for 24.4 hours. Drawdown data measured in the pumped well (MW3), IAS-Zone 2 well OB1, and IAS-Zone 1 well MW2 were used in the numerical analysis. Diurnal water-level fluctuations of about 0.5 ft were estimated in IAS-Zone 1 and IAS-Zone 2 observation wells. During the drawdown phase of the aquifer test, the water level declined about 9 ft in the pumped well (MW3) and about 5 ft in the IAS-Zone 2 observation well OB1. No decline in water level was estimated in the overlying IAS-Zone 1 or surficial aquifer system wells.

Well MW4, tapping the lower permeable zone of the intermediate aquifer system (IAS-Zone 3), was pumped at a rate of 220 gal/min for 23.7 hours. Drawdown data measured in the pumped well (MW4), IAS-Zone 3 well OB2, IAS-Zone 2 well OB1, and Suwannee Limestone well MW5 were used in the numerical analysis. Diurnal water-level fluctuations of about 1 ft were estimated in the IAS-Zone 2, IAS-Zone 3, and Suwannee Limestone observation wells. During the drawdown phase of the aquifer test, the water level declined about 11 ft in the pumped well (MW4), about 5 ft in the IAS-Zone 3 well OB2, and about 0.6 ft in the Suwannee Limestone well MW5. No decline in water level was estimated in the overlying IAS-Zone 2 well.

Well MW5, tapping the Suwannee Limestone zone of the Upper Floridan aquifer, was pumped at a rate of 1,080 gal/min for about 24 hours. Drawdown data measured in the

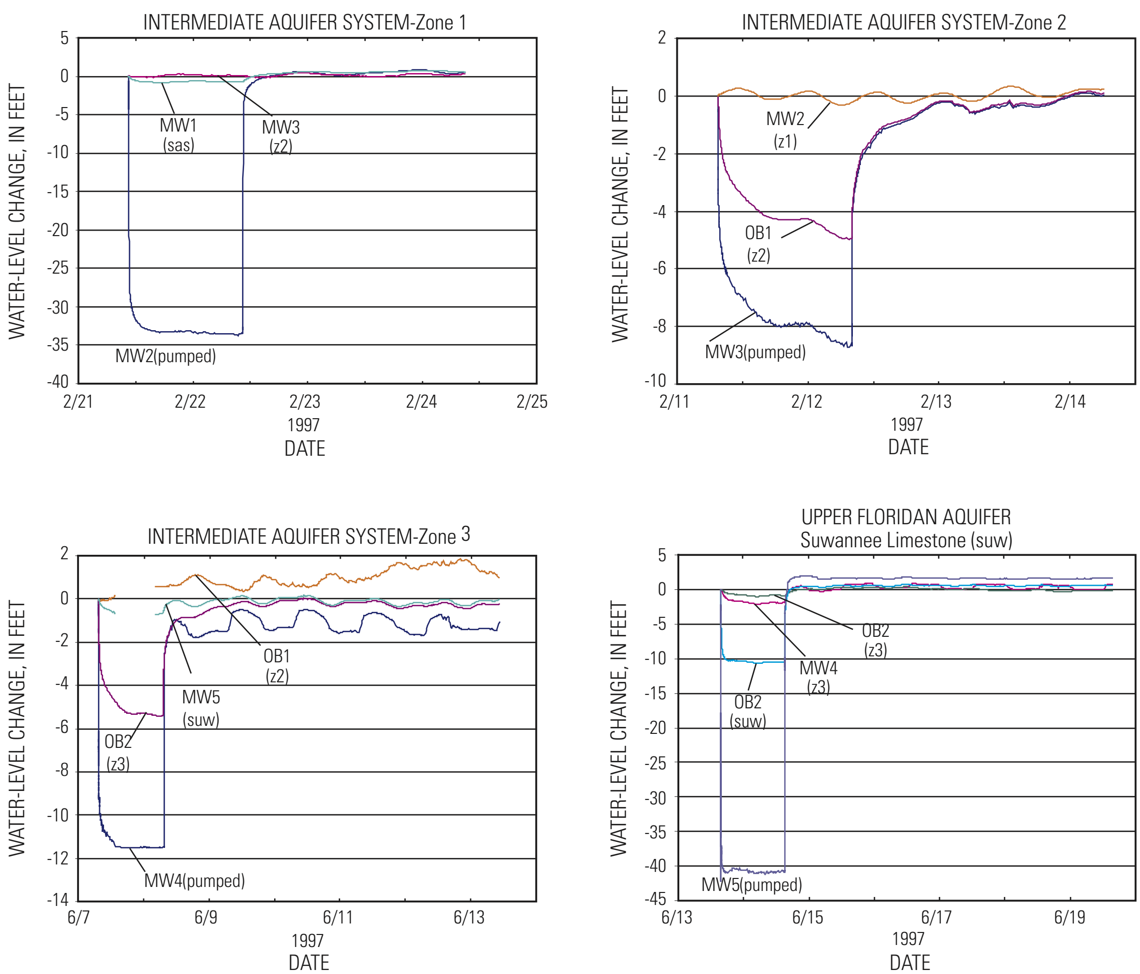


Figure 40. Water levels in selected wells during drawdown and recovery periods of the four aquifer tests conducted at the ROMP TR 4-1 test site.

pumped well (MW5), Suwannee Limestone well OB2, and IAS-Zone 3 wells OB2 and MW4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 40 ft in the pumped well (MW5) and about 10 ft in the Suwannee Limestone well OB2. Water-level declines of about 2 ft and 1.5 ft were estimated in the IAS-Zone 3 wells (MW4 and OB2), respectively, indicating hydraulic connection with the overlying IAS-Zone 3 zone.

Aquifer test data were analyzed by Thompson and others (2000) using analytical techniques. Average transmissivity and storativity values reported for each of the aquifer tests and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP TR 4-1	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
IAS-Zone 1	110	1	1.3E-2
IAS-Zone 2	1,300	13	1.7E-4
IAS-Zone 3	3,800	10	1.4E-3
UFA-Suwannee Limestone	7,800	38	3.6E-1

[IAS, intermediate aquifer system; UFA, Upper Floridan aquifer]

Model Structure

The model extended from the production wells to 200,000 ft away and from the water table to 1,174 ft below land surface. The numerical model consisted of 116 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 390 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column.

Six water-bearing units were simulated—the surficial aquifer system, IAS-Zone 1, IAS-Zone 2, IAS-Zone 3, Suwannee Limestone, and the Avon Park Formation; and five confining units—upper, upper-middle, lower-middle, and lower confining units, and the Ocala Limestone (fig. 3B). The surficial aquifer system is about 26 ft thick underlying the ROMP TR 4-1 site (table 2). The intermediate aquifer system underlies the surficial aquifer and is about 622 ft thick at the study site, including three producing zones (IAS-Zone 1, IAS-Zone 2, and IAS-Zone 3) separated by three confining units. The Upper Floridan aquifer, the lowermost permeable aquifer, is about 526 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

Aquifer Tests Simulation

Differences between simulated and measured drawdowns were minimized by estimating 20 parameters. Lateral hydraulic conductivities of the five confining units and five upper producing zones make up 10 of the parameters. Specific storage of the same hydrogeologic units make up 10 more parameters. Vertical hydraulic conductivity was assigned uniformly as 10 percent of horizontal hydraulic conductivity. Lateral hydraulic conductivity and specific storage of the Avon Park Formation were specified in the model because sufficient information was not available in the observations to independently determine their values.

Simulated drawdowns matched measured drawdowns reasonably well during most aquifer tests with an average unweighted root-mean-squared error (RMSE) of 0.28 ft for the four tests. The fit of measured and simulated time-drawdown data is illustrated in figure 41. RMSE of individual aquifer tests ranged from 0.16 ft for the IAS-Zone 2 to 0.47 ft for the Suwannee Limestone (table 3). The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below (unpumped zones are italicized):

Hydrogeologic unit ROMP TR 4-1	T (ft^2/d)	K (ft/d)		[1]K_z/K_h	Storage		
			[2]RCS rating		S	S_s (d^{-1})	RCS rating
Surficial aquifer system	*1,200*	*45*	*fair*	*0.1*		*2.1E-6*	*fair*
IAS-Zone 1	190	3	high	0.1	7.6E-6	1.0E-7	high
IAS-Zone 2	1,200	12	high	0.1	2.5E-4	2.4E-6	fair
IAS-Zone 3	4,300	11	high	0.1	1.2E-4	3.0E-7	fair
UFA-Suwannee Limestone	7,100	34	high	0.1	8.3E-5	4.0E-7	high
UFA-Avon Park Formation	*10,000*	[1]*100*		*0.1*		[1]*1.5E-6*	

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit was determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_S) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

The resulting values of transmissivity are about the same as those derived from the analytical models, but the values of storativity are about 1 to 3 orders of magnitude lower.

Hydraulic conductivity of the pumped zones and specific storage of IAS-Zone 1 and the Suwannee Limestone were resolved with high confidence. Hydraulic conductivity of the surficial aquifer system and specific storage of the

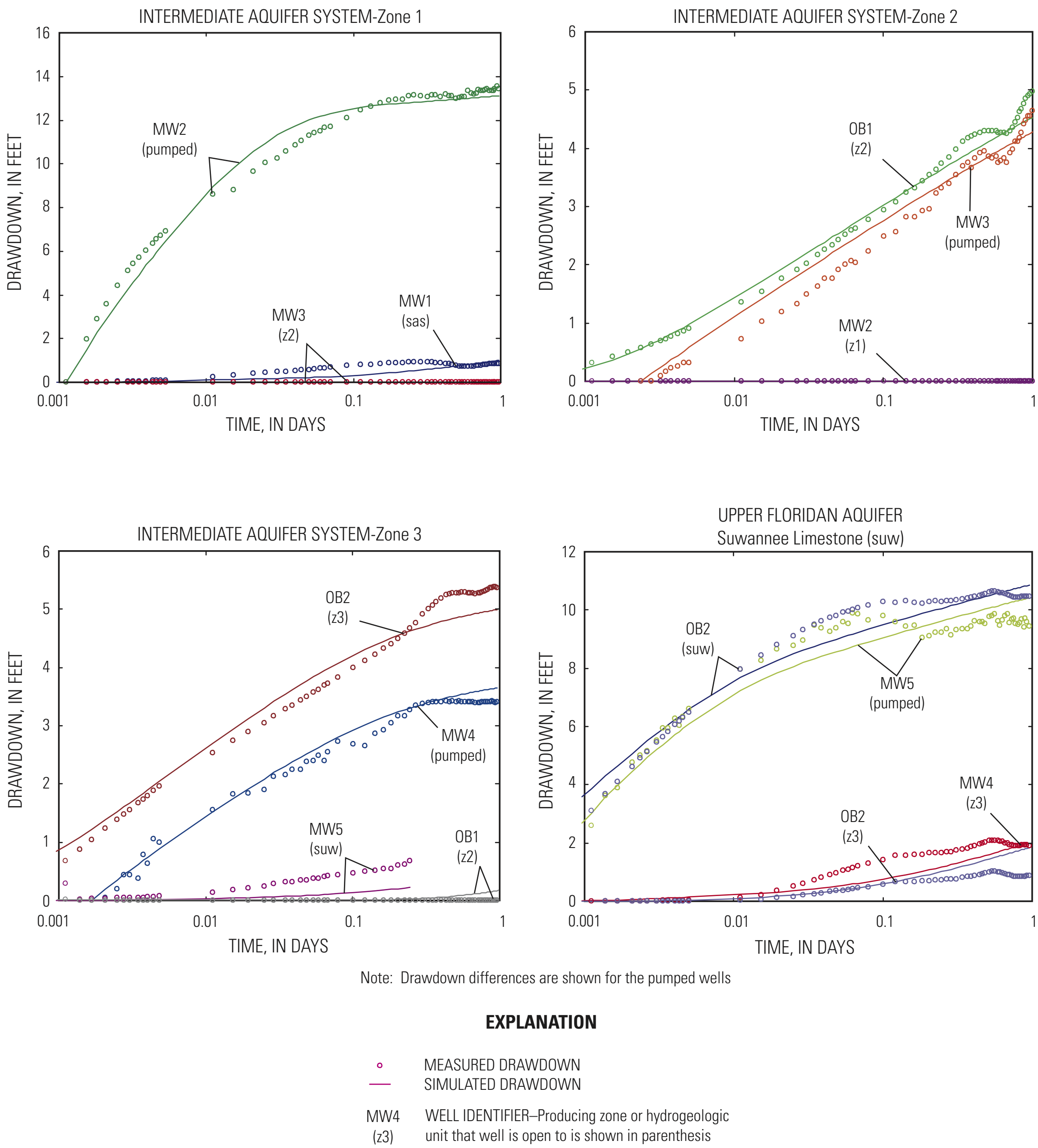


Figure 41. Simulated and measured drawdown for the four aquifer tests conducted at the ROMP TR 4-1 test site.

surficial aquifer system, IAS-Zone2, and IAS-Zone 3 were resolved with moderate confidence and are the most uncertain of the estimated aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the estimated confining units from this simulation are:

Confining unit ROMP TR 4-1	Leakance (ft/d/ft)	K_z (ft/d)		[6]K_z/K_h	Specific storage (d^{-1})	
			[5]RCS rating			RCS rating
[1]Upper	1.1E-4	1.3E-3	high	0.1	2.3E-7	fair
[2]Upper-Middle	7.1E-6	5.0E-5	low	0.1	2.5E-7	low
[3]Lower-Middle	6.5E-5	1.7E-3	low	0.1	4.6E-6	low
[4]Lower	6.3E-4	5.0E-3	fair	0.1	7.3E-7	low
Ocala Limestone	6.0E-3	1.3E+00	high	0.1	2.5E-7	low

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_z) by the appropriate thickness; K_z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 1. [2]Confining unit between IAS-Zone 1 and IAS-Zone 2. [3]Confining unit between IAS-Zone 2 and IAS-Zone 3. [4]Confining unit between IAS-Zone 3 and Suwannee Limestone. [5]Relative scaled sensitivity. [6]This parameter was assigned and not estimated with the inverse model]

Vertical hydraulic conductivity of the upper confining unit and Ocala Limestone was resolved with high confidence. Hydraulic conductivity of the lower confining unit and specific storage of the upper confining unit were resolved with moderate confidence. Hydraulic conductivity of the upper-middle and lower-middle confining units and specific storage of the upper-middle, lower-middle, and lower confining units and the Ocala Limestone were resolved with low confidence and are the most uncertain of the estimated confining unit parameters.

Relative composite sensitivity (RCS) values for the assigned and estimated parameters are shown in figure 35 and appendix 1. The model was most sensitive to hydraulic conductivity of the pumped zones and least sensitive to specific storage of the confining units. Sensitivity is highest for the hydraulic conductivity of IAS-Zone 1 and lowest for specific storage of the lower confining unit. The model was insensitive to hydraulic conductivity of the upper-middle and lower-middle confining units and specific storage of all confining units except the upper confining unit, resulting in little influence of these parameters on overall model performance.

ROMP TR 9-2 Model

ROMP TR 9-2 is located at 27°45´54˝N and 82°23´38˝W in southwest Hillsborough County near Tampa Bay (fig. 42). Land surface altitude at the well site is about 13 above NGVD 29. Five permanent and three temporary wells ranging from 2 to 12 in. in diameter were completed at ROMP TR 9-2. The deepest well, MW5, was drilled to 1,260 ft below land surface.

Two aquifer tests were conducted at the site; however, only data from the Avon Park Formation test are available for analysis. The Avon Park Formation aquifer test was conducted in February 1991. A plan view and construction records of the production and observation wells for the aquifer test site are shown in figure 42. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the test. Figure 43 shows a plot of the drawdown data used for analysis.

Well MW5, tapping the Avon Park Formation zone of the Upper Floridan aquifer, was pumped at a rate of 1,098 gal/min for 53 hours. Drawdown data measured in the pumped well MW3, Avon Park Formation wells OB2 and OB3, Suwannee Limestone wells MW3 and OB1, and Ocala Limestone well MW4 were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 70 ft in the pumped well (MW5), about 3 ft in the Avon Park Formation well OB2, and about 2 ft in Avon Park Formation well OB3. Water-level declines of about 1.5 ft in the Suwannee Limestone wells MW3 and OB1 and about 3 ft in the Ocala Limestone well MW4 were estimated.

Aquifer test data were analyzed by Basso (Southwest Florida Water Management District, written commun., 2003) using analytical techniques. Average transmissivity and storativity values reported for the aquifer test and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit ROMP TR 9-2	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
UFA-Suwannee Limestone	15,000	72	1.5E-4
UFA-Avon Park Formation	74,000	131	1.0E-4

[UFA, Upper Floridan aquifer]

Model Structure

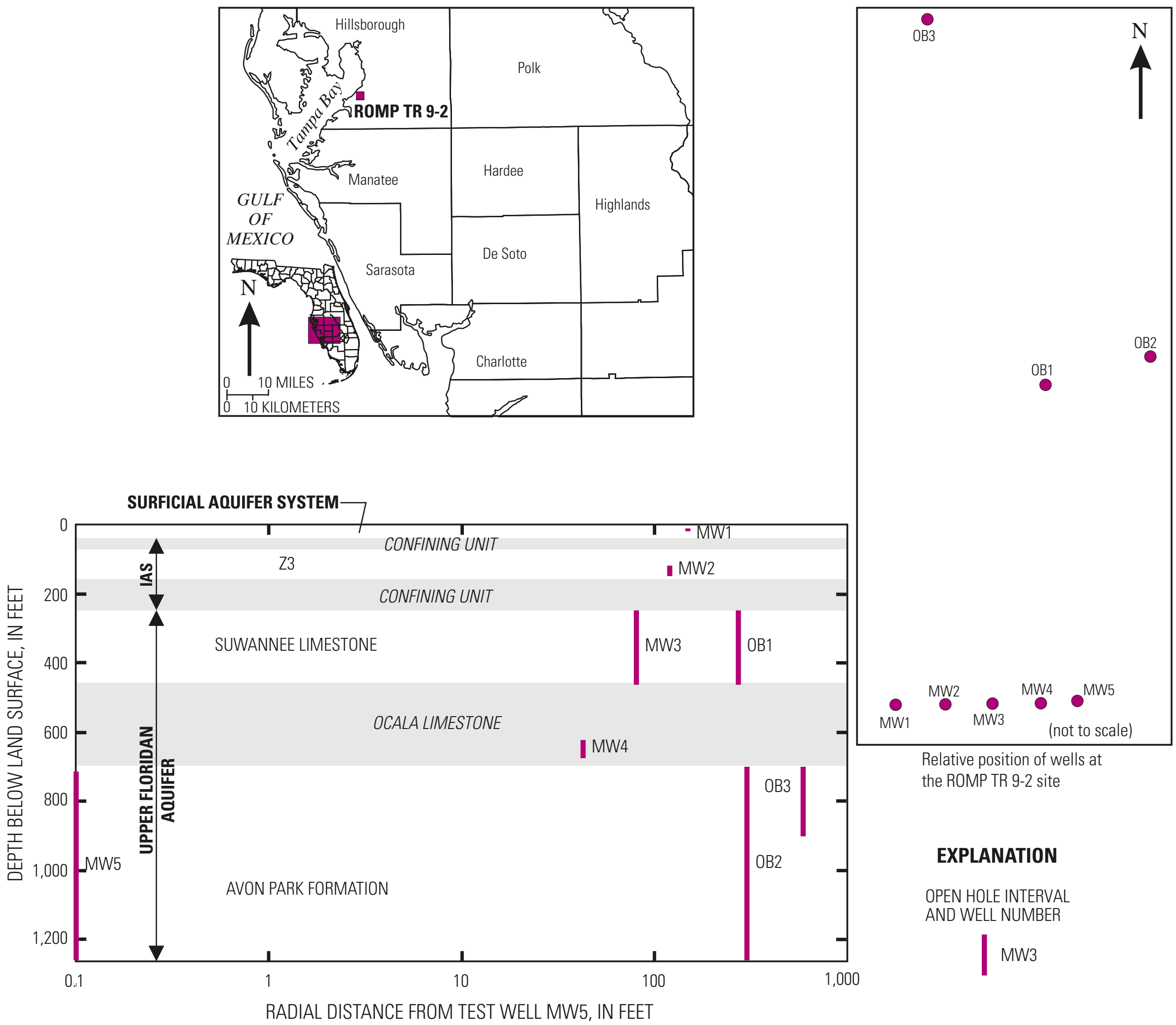
The model extended from the production well to 200,000 ft away and from the water table to 1,260 ft below land surface. The numerical model consisted of 70 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.01 to 563 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column.

Four water-bearing units were simulated—the surficial aquifer system, IAS-Zone 3, Suwannee Limestone, and Avon Park Formation; and three confining units—upper and lower confining units, and the Ocala Limestone (fig. 3E). The surficial aquifer system is about 38 ft thick underlying the ROMP TR 9-2 site (table 2). The intermediate aquifer system underlies the surficial aquifer and is about 212 ft thick, including two confining units and one producing zone. The Upper Floridan aquifer, the lowermost permeable aquifer, is about 1,010 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone.

Aquifer Test Simulation

Differences between simulated and measured drawdowns were minimized by estimating six parameters. Lateral hydraulic conductivities of the Suwannee Limestone, Avon Park Formation, and the Ocala Limestone make up three of the parameters. Specific storage of the same hydrogeologic units make up three more parameters. Vertical hydraulic conductivity was assigned uniformly as 0.1 of horizontal hydraulic conductivity in all units. Lateral conductivity and specific storages of the surficial aquifer system, the IAS-Zone 3, and the upper and lower confining units were specified in the model because sufficient information was not available in the observations to independently determine their values.

Simulated drawdowns matched measured drawdowns favorably with an unweighted root-mean-squared error (RMSE) of 0.29 ft (table 2). The fit of measured and simulated time-drawdown data is illustrated in figure 44. The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below (unpumped zones are italicized):



Well name	Stratigraphic Unit		Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet) MW5 (AvPk)
			Surficial aquifer system		
MW1	Undifferentiated surficial deposits		10/20	6	150.2
			Intermediate aquifer system (IAS)		
MW2	Arcadia Formation	(Z3)	118/148	8	119.7
			Upper Floridan aquifer		
MW3	Suwannee Limestone	(SUW)	247/462	12	80.4
OB1	Suwannee Limestone	(SUW)	247/464	2	274.1
MW4	Ocala Limestone	(OCA)	622/675	6	42.5
MW5	Avon Park Formation	(AvPk)	714/1,260	12	
OB2	Avon Park Formation	(AvPk)	700/1,260	2	301.8
OB3	Avon Park Formation	(AvPk)	700/900	2	595.7

Figure 42. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the ROMP TR 9-2 test site.

Hydrogeologic unit ROMP TR 9-2	T (ft^2/d)	K (ft/d)		[1]K_z/K_h	Storage		
			[2]RCS rating		S	S_s (d^{-1})	RCS rating
Surficial aquifer system	*380*	*[1]10*		*0.1*	*5.7E-5*	*[1]1.5E-6*	
IAS-Zone 3	*440*	*[1]5*		*0.1*	*1.3E-4*	*[1]1.5E-6*	
UFA-Suwannee Limestone	*2,600*	*12*	*high*	*0.1*	*6.3E-5*	*3.0E-7*	*high*
UFA-Avon Park Formation	56,000	99	high	0.1	1.7E-4	3.0E-7	high

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit was determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_S) by the appropriate thickness. IAS, intermediate aquifer system; UFA, Upper Floridan aquifer. [1]This value was assigned and not estimated with the inverse model. [2]Relative scaled sensitivity]

The resulting value of transmissivity for the Avon Park Formation is about 30 percent lower than that derived from the analytical models, and the resulting storativity value is about 50 percent lower.

Hydraulic conductivity and specific storage of the pumped zone and the adjacent Suwannee Limestone were resolved with high confidence.

The estimated hydraulic properties and sensitivity ratings for the confining units from this simulation are:

Confining unit ROMP TR 9-2	Leakance (ft/d/ft)	K_Z (ft/d)		[5]K_z/K_h	Specific storage (d^{-1})	
			[3]RCS rating			RCS rating
[1]Upper	[4]2.9E-6	[4]1.0E-4		0.1	[4]1.5E-6	
[2]Lower	[4]1.1E-6	[4]1.0E-4		0.1	[4]1.5E-6	
Ocala Limestone	7.6E-4	1.8E-1	high	0.1	2.5E-7	low

[Leakance was determined by dividing the simulated vertical hydraulic conductivity (K_Z) by the appropriate thickness; K_Z/K_h, vertical to horizontal anisotropy. [1]Confining unit between SAS and IAS-Zone 3. [2]Confining unit between IAS-Zone 3 and Suwannee Limestone. [3]Relative scaled sensitivity. [4]This parameter was assigned and not estimated with the inverse model]

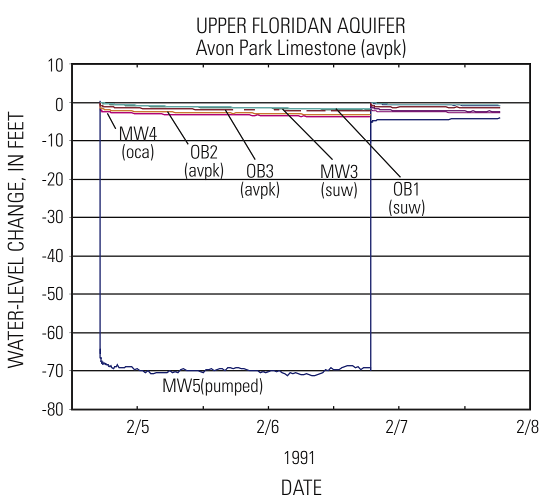


Figure 43. Water levels in selected wells during drawdown and recovery periods of the Avon Park aquifer test conducted at the ROMP TR 9-2 test site.

Vertical hydraulic conductivity of the Ocala Limestone was resolved with high confidence. Specific storage of the Ocala Limestone was resolved with low confidence and is the most uncertain of the estimated confining unit parameters.

Relative composite sensitivity (RCS) values for the assigned and estimated parameters are shown in figure 35 and appendix 1. The model was most sensitive to hydraulic conductivity and specific storage of the pumped zone (Avon Park Formation) and the Suwannee Limestone. Sensitivity also was high for the hydraulic conductivity of the Ocala Limestone. The model was insensitive to all other parameters, resulting in little influence of these parameters on overall model performance.

Lakeland Northeast Well Field Model

The City of Lakeland Northeast Well Field is located at 28°09´46˝N and 81°53´20˝W in northwestern Polk County (fig. 45). Land surface altitude at the well site is about 136 ft above NGVD 29. Thirty-seven permanent wells ranging from 1 to 16 in. in diameter were completed at the Lakeland Northeast well field. The deepest well, MW2d, was drilled to 780 ft below land surface.

One aquifer test was conducted on the Upper Floridan aquifer at the site. The production well is open to the lower Suwannee Limestone, the Ocala Limestone, and the Avon Park Formation. The aquifer test was conducted in April through May 2003. A plan view and construction records of the production and observation wells are shown in figure 45. Water levels were measured continuously in multiple wells for withdrawal and recovery periods of the tests. Figure 46 shows a plot of the drawdown data used for analysis.

The Upper Floridan aquifer was pumped at a rate of 3,000 gal/min for 287.8 hours. Drawdown data measured in the pumped well (NE1), Upper Floridan aquifer wells MW1d, MW2d, NE4d, and NE3, and intermediate confining unit wells NW, MW1i, MW2i, 4i, and 6i were used in the numerical analysis. During the drawdown phase of the aquifer test, the water level declined about 15 ft in the pumped well, about 2 to 6 ft in the Upper Floridan aquifer wells, and about 2 to 4 ft in the intermediate confining unit wells. The water-level drawdown data were corrected to account for the regional water-level trend using regression analysis with water levels in ROMP 87 and Brown Upper Floridan wells, and atmospheric pressure.

Aquifer test data were analyzed by Peterson (2004) using analytical techniques. Average transmissivity and storativity values reported for the aquifer test and hydraulic conductivity values derived for aquifer thicknesses equivalent to this report are as follows:

Hydrogeologic unit Lakeland NE Well Field	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storativity
Upper Floridan aquifer	92,000	122	1.4E-4

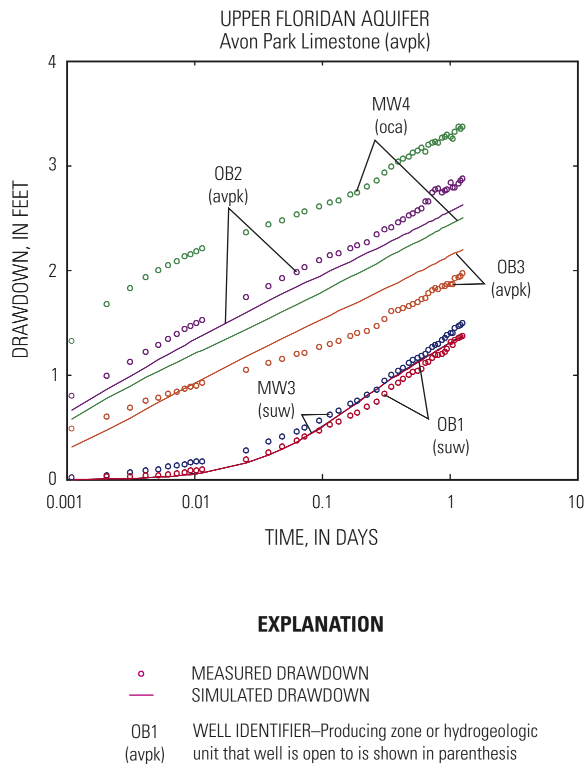


Figure 44. Simulated and measured drawdown for the Avon Park aquifer test conducted at the ROMP TR 9-2 test site.

Model Structure

The model extended from the production well to 200,000 ft away and from the water table to 800 ft below land surface. The numerical model consisted of 28 variably spaced nodes in the vertical direction and 69 variably spaced nodes in the radial direction. The vertical spacing ranged from 0.07 to 755 ft. Cell widths ranged from about 0.2 ft adjacent to the production well to about 33,000 ft in the farthest column.

Two water-bearing units were simulated—the surficial aquifer system and the Upper Floridan aquifer; and one confining unit—the intermediate confining unit (fig. 3F). The surficial aquifer system (SAS) is about 10 ft thick underlying the Lakeland Northeast Well Field site (table 2). The intermediate confining unit (ICU) underlies the surficial aquifer and is about 35 ft thick. The Upper Floridan aquifer, the lowermost permeable aquifer, is about 755 ft thick, and has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone. For this simulation, however, the Upper Floridan aquifer has been simulated as a single permeable unit.

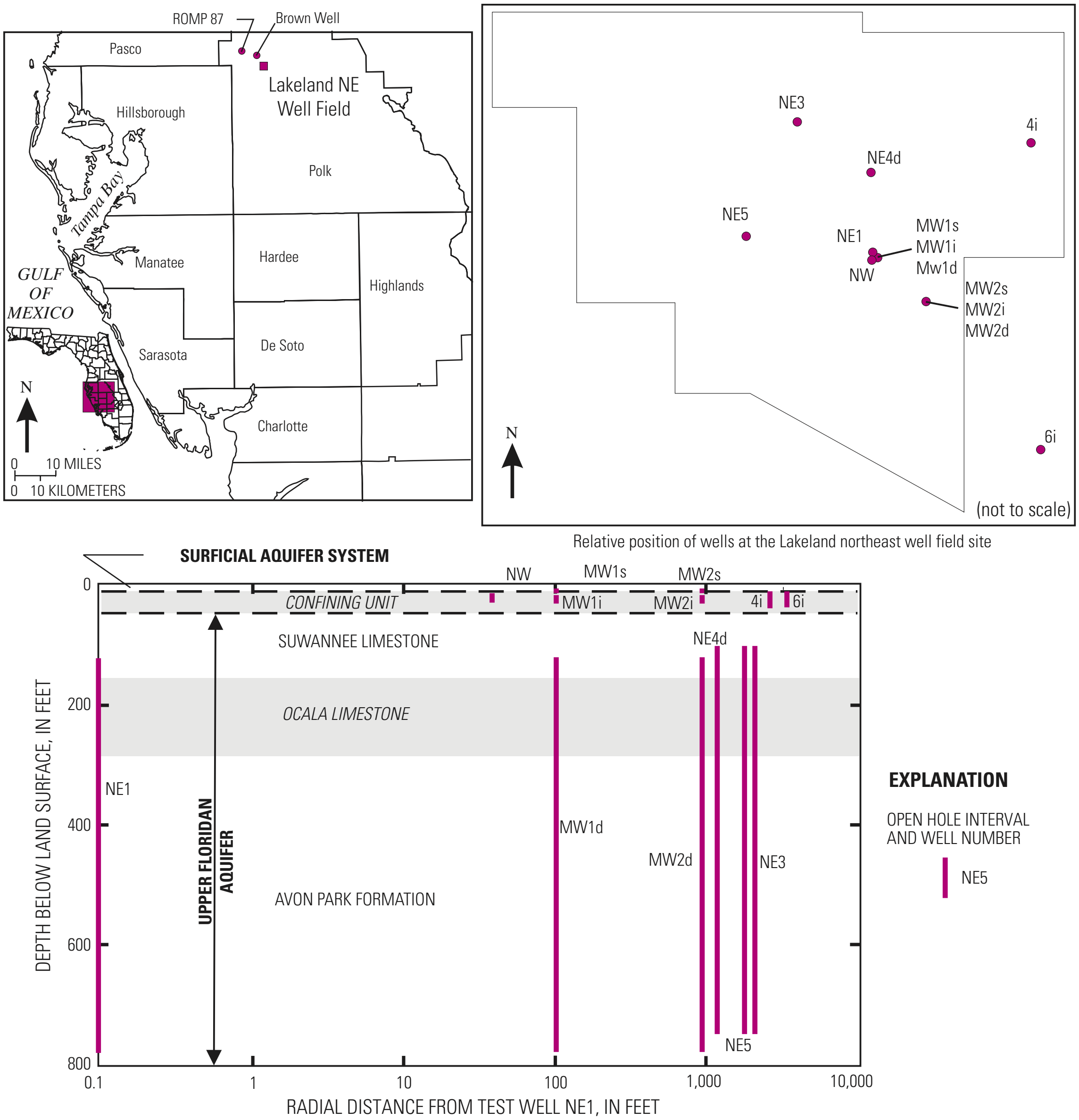
Aquifer Test Simulation

Differences between simulated and measured drawdowns were minimized by estimating seven parameters. Lateral hydraulic conductivities of the intermediate confining unit and the Upper Floridan aquifer make up two of the parameters. Specific yield of the surficial aquifer system and specific storage of the Upper Floridan aquifer make up two more parameters. Specific storage and Kz/Kh of the combined SAS-ICU represent two more parameters. These layer parameters were combined because they are highly correlated, and thus not easily separately identified. Vertical to horizontal anisotropy of the Upper Floridan aquifer is the final parameter. Hydraulic conductivity of the surficial aquifer system was assigned a value of 30 ft/d.

Simulated drawdowns matched measured drawdowns favorably with an unweighted root-mean-squared error (RMSE) of 0.33 ft (table 3). The fit of measured and simulated time-drawdown data is illustrated in figure 47. The estimated and assigned hydraulic properties and sensitivity ratings for the estimated parameters from this simulation are shown below (unpumped zone is italicized):

Hydrogeologic unit Lakeland NE Well Field	T (ft^2/d)	K (ft/d)		K_z/K_h		S_y		Storage		
			[1]RCS rating		RCS rating		RCS rating	S	S_s (d^{-1})	RCS rating
Surficial aquifer system	*300*	*30*	*fair*	*0.50*	*high*	*0.004*	*high*	*1.9E-5*	*1.9E-6*	*low*
Upper Floridan aquifer	85,000	113	high	0.004	high			4.5E-4	6.0E-7	fair

[Transmissivity (T) and storage coefficient (S) of each hydrogeologic unit were determined by multiplying the simulated hydraulic conductivity (K) and specific storage (S_s) by the appropriate thickness. K_z/K_h, vertical to horizontal anisotropy. [1]Relative scaled sensitivity]



Well name	Stratigraphic Unit	Casing depth/ Well depth (feet)	Casing diameter (inches)	Distance from production well (feet) NE1
		Surficial aquifer system		
MW1s	Undifferentiated surficial deposits	5/10	2	102.2
MW2s	Undifferentiated surficial deposits	5/10	2	937.2
		Intermediate confining unit		
MW1i	Peace River Formation	12/27	1	105
MW2i	Peace River Formation	13/28	1	950
4i	Peace River Formation	27/37	1	2,638.1
6i	Peace River Formation	25/35	1	3,420.1
NW	Peace River Formation	21/23	3	38.4
		Upper Floridan aquifer		
NE1	Suwannee/Ocala/Avon Park	123/780	16	
MW1d	Suwannee/Ocala/Avon Park	120/780	4	105
MW2d	Suwannee/Ocala/Avon Park	120/780	4	950
NE3	Suwannee/Ocala/Avon Park	100/750	16	2,092
NE4d	Suwannee/Ocala/Avon Park	100/750	16	1,188
NE5	Suwannee/Ocala/Avon Park	100/750	16	1,791

Figure 45. Generalized hydrogeologic section and location, plan view, description and configuration of wells at the Lakeland Northeast Well Field test site.

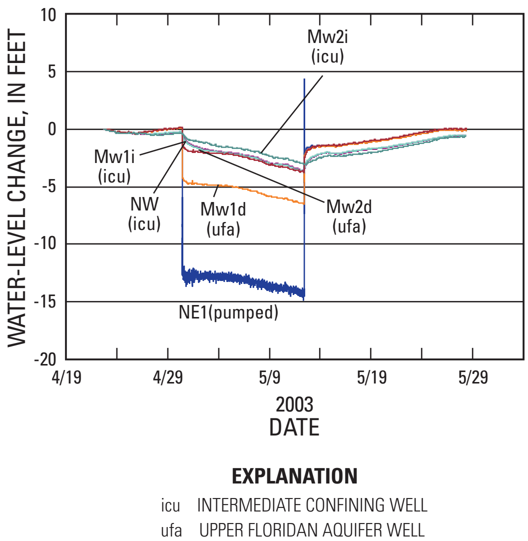


Figure 46. Water levels in selected wells during drawdown and recovery periods of the Upper Floridan aquifer test conducted at the Lakeland Northeast Well Field test site.

The resulting value of transmissivity is about the same as that derived from the analytical model, and the value of storativity is about 3 times greater than that derived from analytical models.

Hydraulic conductivity of the pumped zone (Upper Floridan aquifer), vertical anisotropy of the surficial aquifer system and the Upper Floridan aquifer, and specific yield of the surficial aquifer system were resolved with high confidence. Hydraulic conductivity of the surficial aquifer system and specific storage of the Upper Floridan aquifer were resolved with moderate confidence and are the most uncertain of the estimated aquifer parameters.

The estimated hydraulic properties and sensitivity ratings for the estimated confining unit from this simulation are shown in the table below.

Vertical hydraulic conductivity, anisotropy, and specific storage of the intermediate confining unit were resolved with moderate confidence.

Relative composite sensitivity (RCS) values for the assigned and estimated parameters are shown in figure 35 and appendix 1. The model was most sensitive to hydraulic conductivity of the pumped zone (Upper Floridan aquifer), and least sensitive to specific storage of the surficial aquifer system. Sensitivity is high for the specific yield of the surficial aquifer system, and vertical to horizontal anisotropy of the Upper Floridan aquifer and the surficial aquifer system. The model was moderately sensitive to specific storage of the surficial aquifer system and the intermediate confining unit, which had less influence on overall model performance than other parameters.

Model Limitations

Estimated values of hydraulic properties were determined with some uncertainty because of limitations imposed by the underlying assumptions and designs of the numerical models. Principal assumptions made in the application of the models are that the geologic structure and hydraulic properties are radially symmetric about the axis of the pumped well and that the model structure accurately represents the aquifer. Simplification of the conceptual model was necessary to simulate a very complex natural system; therefore, the extent to which the system is simplified represents a source of error in model results. Variations in measured and simulated drawdown curves indicate some heterogeneity of the aquifer system properties; in general, the assumption of radial symmetry in hydrogeologic properties near the pumped wells appears to be reasonable. A second assumption is that the aquifer is finite. A no-flow boundary was set at the outer boundary of the model at a radial distance of 200,000 ft, even though the aquifer systems extend beyond this distance. This boundary was determined to be far enough from the pumping nodes because it did not affect simulated drawdown at observation wells less than 1,000 ft away from pumping. The final assumption is that hydraulic properties are uniform throughout the models. This generally is not the case in a karst aquifer system; the models incorporate the best estimates of the local geology, and mean values should reasonably represent the simulated aquifer systems. The sensitivity of simulated drawdown for several of the model parameters, however, indicated that some parameters were not reliably estimated.

Simplifications also were made when discretizing the ground-water flow models in space. Resolution of the grid spacing limits the detail with which heads are computed.

Confining unit Lakeland NE Well Field	Leakance (ft/d/ft)	K_z (ft/d)		K_z/K_h		Specific storage (d^{-1})	
			[2]RCS rating		RCS rating		RCS rating
[1]Intermediate confining unit	3.4E-3	1.2E-1	fair	0.50	fair	1.9E-6	fair

[Leakance was determined by dividing the simulated vertical hydraulic conductivity by the appropriate thickness; K, vertical hydraulic conductivity; K_z/K_h, vertical to horizontal anisotropy. [1]Intermediate confining unit between surficial aquifer system and the Upper Floridan aquifer. [2]Relative scaled sensitivity]

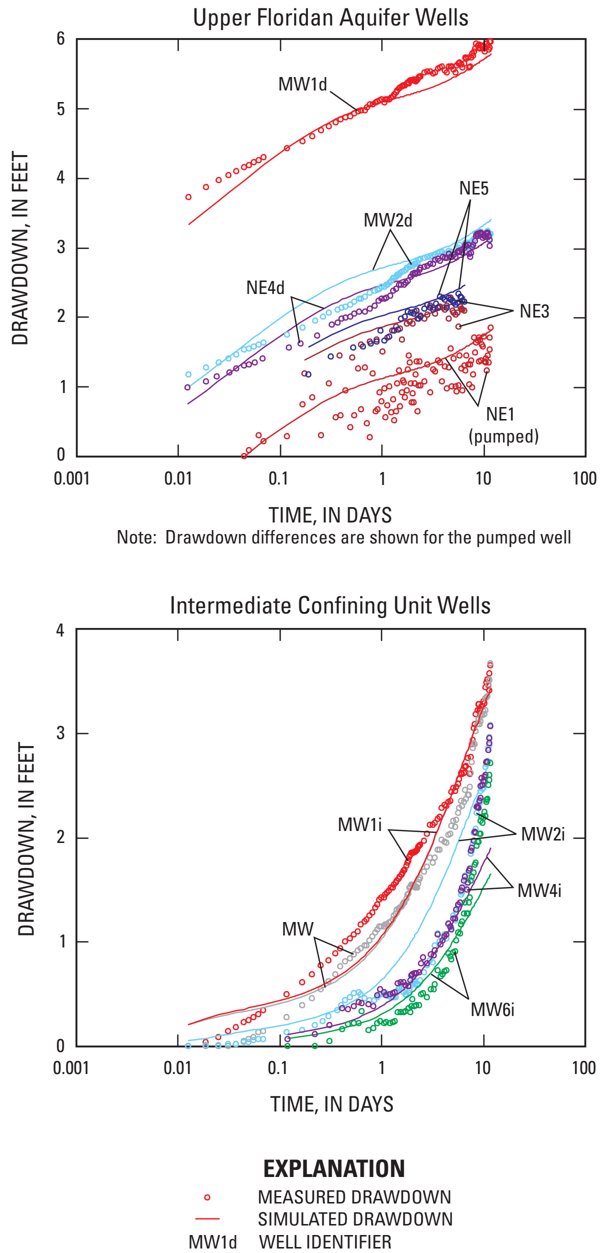


Figure 47. Simulated and measured drawdown for the Upper Floridan aquifer test conducted at the Lakeland Northeast Well Field test site.

This simplification inevitably results in model error, and the introduced error may translate into model bias in computed parameters and in heads computed using these parameters. One of the more important factors contributing to model error is the vertical discretization of the complex, three-dimensional hydrogeologic framework into a few layers. Whereas multiple layers are an improvement over analytical models, the actual hydrogeologic system may be anisotropic, heterogeneous, and possess secondary porosity owed to dissolution and fracturing.

Finally, the numerical models are a mathematical description of a hydrogeologic system. The mathematical solution is an approximate solution to the differential equations that define the hydrogeologic framework. The validity of the analysis depends on the extent to which the mathematical description reflects the properties of the hydrogeologic system and accurately quantifies the aquifer characteristics, boundaries, and hydrologic stresses.

Evaluation of Hydraulic Properties

The productivity of individual water-producing zones within the aquifer systems in west-central Florida is highly variable from site to site. Areal variations in the geology in west-central Florida result in a wide range in hydraulic properties of the ground-water flow system (tables 2 and 4). A statistical analysis of the aquifer test results for each hydrogeologic unit is shown in tables 5 and 6. Geometric means, ranges, and coefficients of variation of hydraulic conductivity, transmissivity, leakance, and storativity were calculated for each producing zone and confining unit. The hydraulic conductivity and storativity of producing zones and confining units span more than 4 orders of magnitude and vary over short distances. Heterogeneity, solution development, discontinuous confining beds, and varying degrees of aquifer stratification are common reasons for the substantial variation in hydraulic properties.

Table 4. Summary of estimated or assigned parameter values for confining units.

[sas, surficial aquifer system; ias, intermediate aquifer system; Z1, ias Zone 1; Z2, ias Zone 2; Z3, ias Zone 3; suw, Suwannee Limestone; avp, Avon Park Limestone; icu, intermediate confining unit; UCU, confining unit between sas and ias; U-MCU, upper-middle confining unit between Z1 and Z2; L-MCU, lower-middle confining unit between Z2 and Z3; MCU, confining unit between Z1/2 and Z3; LCU, confining unit between ias and suw; ft/d, foot per day; ft/d/ft, foot per day per foot; --, not applicable]

Site	Vertical hydraulic conductivity, ft/d						[2]Leakance, ft/d/ft					
	UCU (sas:ias)	U-MCU (Z1:pz2)	L-MCU (Z2:Z3)	MCU (Z1/2:Z3)	LCU (ias:suw)	Ocala (suw:avp)	UCU (sas:ias)	U-MCU (Z1:Z2)	L-MCU (Z2:Z3)	MCU (Z1/2:Z3)	LCU (ias:suw)	Ocala (suw:avp)
5	1.1E-03	--	--	3.5E-03	5.0E-01	1.4E-01	2.4E-05	--	--	1.6E-05	4.2E-03	1.5E-03
9	1.7E-03	8.0E-04	6.0E-04	--	3.9E-02	4.5E+00	1.4E-04	1.7E-05	2.0E-05	--	1.7E-04	1.6E-02
12	7.9E-04	4.9E-02	6.5E-02	--	1.2E-01	2.2E+00	4.6E-05	2.9E-04	1.1E-03	--	6.0E-03	9.7E-03
13	5.7E-04	--	--	1.1E-04	1.2E-03	5.5E-01	2.2E-06	--	--	1.3E-06	9.8E-06	2.0E-03
14	6.1E-05	--	--	--	5.5E-05	2.3E+00	5.8E-07	--	--	--	4.3E-07	7.8E-03
20	2.7E-04	--	--	5.4E-04	8.8E-03	3.4E-01	1.3E-05	--	--	4.4E-06	8.9E-05	1.0E-03
22	[1]1.0E-03	--	--	2.5E-03	8.5E-03	5.2E+00	1.5E-05	--	--	3.2E-05	8.5E-04	1.7E-02
25	[1]5.0E-04	--	--	--	1.3E-03	2.9E-01	1.1E-05	--	--	--	8.1E-06	9.6E-04
28	1.1E-01	--	--	--	1.1E-03	9.5E-01	7.9E-04	--	--	--	2.2E-05	3.7E-03
39	[1]1.0E-03	--	--	1.0E-03	1.4E-04	1.9E-02	1.0E-05	--	--	2.4E-05	7.8E-07	7.7E-05
4-1	1.3E-03	5.0E-05	1.7E-03	--	5.0E-03	1.3E+00	1.1E-04	7.1E-06	6.5E-05	--	6.3E-04	6.0E-03
9-2	[1]1.0E-04	--	--	--	[1]1.0E-04	1.8E-01	2.9E-06	--	--	--	1.1E-06	7.6E-04
[1]WF	1.2E-01						3.4E-03					

Site	Thickness of unit, ft						Specific storage, 10-6/ft					
	UCU (sas:ias)	U-MCU (Z1:Z2)	L-MCU (Z2:Z3)	MCU (Z1/2:Z3)	LCU (ias:suw)	Ocala (suw:avp)	UCU (sas:ias)	U-MCU (Z1:Z2)	L-MCU (Z2:Z3)	MCU (Z1/2:Z3)	LCU (ias:suw)	Ocala (suw:avp)
5	46	--	--	220	120	91	0.2	--	--	0.2	0.2	0.3
9	12	48	30	--	225	284	0.8	0.8	1.0	--	3.1	1.6
12	17	169	59	--	20	226	3.0	3.0	1.9	--	1.7	1.1
13	255	--	--	85	123	277	1.5	--	--	2.3	0.2	4.7
14	106	--	--	--	127	295	3.1	--	--	--	3.1	210.0
20	21	--	--	122	99	324	0.3	--	--	0.5	0.2	11.7
22	68	--	--	79	10	302	[1]1.5	--	--	0.9	0.5	0.6
25	47	--	--	--	160	301	[1]1.5	--	--	--	0.4	0.1
28	140	--	--	--	49	260	10.9	--	--	--	0.6	0.1
39	96	--	--	41	180	246	[1]1.5	--	--	1.5	0.1	4.1
4-1	12	7	26	--	8	215	0.2	0.5	4.6	--	0.7	0.2
9-2	35	--	--	--	87	239	[1]1.5	--	--	--	[1]1.5	0.1
[3]WF	35						1.9					

[1]This value was specified and not estimated with the inverse model.
[2]Equals vertical hydraulic conductivity times thickness of unit.
[3]Lakeland Northeast Well Field.

Table 5. Statistical analysis of aquifer test results for confining units.

[N, number of observations; ft/d/ft, feet per day per foot; GM, geometric mean; CV, coefficient of variation]

Confining unit	N	Leakance, ft/d/ft			Specific storage, d^{-1}		
		Range	GM	CV	Range	GM	CV
Upper	12	5.8E-7 to 7.9E-4	1.8E-5	230	2.0E-7 to 1.1E-5	1.2E-6	134
Middle	11	1.3E-6 to 1.1E-3	2.8E-5	224	5.0E-7 to 4.6E-6	1.1E-6	84
Lower	12	4.3E-7 to 6.0E-3	4.8E-5	197	1.0E-7 to 3.1E-6	5.8E-7	107
Ocala Limestone	12	7.7E-5 to 1.7E-2	3.0E-3	96	[1]1.0E-7 to 1.2E-5	[1]6.8E-7	[1]158

[1]Does not include ROMP 14.

Table 6. Statistical analysis of aquifer test results for pumped zones.

[N, number of observations where respective hydrogeologic unit was pumped; ft/d, feet per day; ft^2/d, feet squared per day; GM, geometric mean; CV, coefficient of variation; SUW, Suwannee Limestone; OCA, Ocala Limestone; AVP, Avon Park Limestone; --, not applicable]

Hydrogeologic unit	N	Hydraulic conductivity, ft/d			Transmissivity, ft^2/d		
		Range	GM	CV	Range	GM	CV
Surficial aquifer system	5	13 to 790	58	182	520 to 22,000	5,444	92
Intermediate aquifer system							
Zone 1	3	1 to 100	7	163	31 to 4,900	307	162
Zone 2	8	1 to 95	7	177	30 to 5,200	519	141
Zone 3	7	2 to 184	20	140	200 to 43,000	3,061	160
Upper Floridan aquifer							
SUW	11	1 to 41	16	58	170 to 16,000	3,360	82
AVP	6	46 to 1,518	204	141	37,400 to 1,500,000	154,226	154
SUW/OCA/AVP	1	--	113	--	--	85,000	--

Hydrogeologic unit	N	Specific storage, d^{-1}			Storage coefficient		
		Range	GM	CV	Range	GM	CV
[1]Surficial aquifer system	4	3.0E-7 to 1.9E-6	1.4E-6	53	4.2E-5 to 1.4E-4	9.2E-5	46
Intermediate aquifer system							
Zone 1	3	1.0E-7 to 1.5E-5	6.7E-7	168	7.6E-6 to 4.3E-4	3.0E-5	164
Zone 2	8	3.0E-7 to 1.1E-5	1.6E-6	88	1.8E-5 to 6.6E-4	1.3E-4	103
[2]Zone 3	6	1.0E-7 to 6.0E-7	2.4E-7	61	2.6E-5 to 1.2E-4	4.3E-5	70
Upper Floridan aquifer							
[3]SUW	10	1.0E-7 to 3.1E-6	5.2E-7	109	3.3E-5 to 3.8E-4	1.2E-4	74
AVP	6	2.0E-7 to 4.5E-6	7.2E-7	126	1.4E-4 to 2.2E-3	5.5E-4	93
SUW/OCA/AVP	1	--	5.9E-7	--	--	4.5E-4	--

[1]Does not include ROMP 28.
[2]Does not include ROMP 9.
[3]Does not include ROMP 14.

Confining Units

In the study area, confining units separate water-producing zones or aquifers and generally consist of clay and low permeability carbonates. Although the confining units have low permeability, impeding the movement of water between the various producing zones, they are leaky and allow water to move from one aquifer to another depending on hydraulic head differences and the average hydraulic conductivity of the confining unit. The lateral transition from aquifer to confining unit in the intermediate aquifer system occurs where clay is abundant in the lithology. Where clay is the dominant lithology, the hydrogeologic unit is considered a confining unit. This transition for the intermediate aquifer system appears to occur northward from a line extending from northern Manatee County to southern Polk County and eastward from a line extending from Polk through eastern De Soto Counties.

The vertical hydraulic conductivity of the confining units shows large variations, spans more than 4 orders of magnitude (table 5), and varies with lithology and unit thickness. On average, permeability is high for the Ocala Limestone, somewhat lower for the lower and middle confining units, and lowest for the upper confining unit. Of the confining units, the Ocala Limestone has the highest leakance, and the upper confining unit that separates the surficial aquifer system from the uppermost permeable zone in the intermediate aquifer system has the lowest leakance.

The upper confining unit is the top of the intermediate aquifer system and generally consists of sandy clay, clay, and marl. Excluding Lakeland Northeast Well Field, thickness of the upper confining unit ranges from 12 to 255 ft and averages about 65 ft at 12 of the 13 test sites (table 4). Simulated leakance of the upper confining unit spans about 3 orders of magnitude, ranging from 5.8E-7 to 7.9E-4 ft/d/ft, with a geometric mean of 1.8E-5 ft/d/ft. Leakance of the upper confining unit is greatest in southern Sarasota and northern Highlands Counties (fig. 48). Specific storage of the upper confining unit also varies about 2 orders of magnitude, ranging from 2.0E-7 to 1.1E-5 day^{-1}, with a geometric mean of about 1.2E-6 day^{-1}.

The middle confining units that separate the intervening permeable zones within the intermediate aquifer system (Zone 1, Zone 2, and Zone 3) generally consist of clay and clayey sand. Thickness of the middle confining unit ranges from 7 to 220 ft and averages about 80 ft at the 12 test sites (table 4). Simulated leakance of the middle confining units spans about 3 orders of magnitude and ranging from 1.3E-6 to 1.1E-3 ft/d/ft, with a geometric mean of 2.8E-5 ft/d/ft (table 5). No apparent pattern is observed in the spatial distribution of leakance for the middle confining units (fig. 48). Specific storage of the middle confining unit varies about 1 order of magnitude, ranging from 5.0E-7 to 4.6E-6 day^{-1}, with a geometric mean of about 1.1E-6 day^{-1}.

The lower confining unit is the bottom of the intermediate aquifer system and generally consists of sandy clay and clayey sand. The lower confining unit separates the lowermost intermediate aquifer system permeable zone (Zone 2 or Zone 3) from the Upper Floridan aquifer at the 12 test sites. Generally, leakance is greater for the lower confining unit than for the middle or upper confining units. Thickness of the lower confining unit ranges from 8 to 225 ft and averages about 93 ft thick for the 12 test sites (table 4). Simulated leakance of the lower confining unit spans about 3 orders of magnitude and ranges from 4.3E-7 to 6.0E-3 ft/d/ft, with a geometric mean of 4.8E-5 ft/d/ft (table 5). Leakance of the lower confining unit is greatest in central and southern Sarasota County and in Charlotte County (fig. 48). Specific storage of the lower confining unit varies about 1 order of magnitude ranging from 1.0E-7 to 3.1E-6 day^{-1}, with a geometric mean of about 5.8E-7 day^{-1} (table 5).

The Ocala Limestone is the lowermost confining unit and is composed mostly of soft, fine-grained, foraminiferous limestone. The Ocala Limestone separates the two major flow zones in the Upper Floridan aquifer and is regionally extensive. Leakance is greater for the Ocala Limestone than for either the upper, middle, or lower confining units. Thickness of the Ocala Limestone ranges from 91 to 324 ft and averages about 238 ft thick at the 12 test sites (table 4). Simulated leakance of the Ocala Limestone spans about 3 orders of magnitude and ranges from 7.7E-5 to 1.7E-2 ft/d/ft, with a geometric mean value of 3.0E-3 ft/d/ft (table 5). Leakance of the lower confining unit is greatest in northern and southern Sarasota County (fig. 48). Excluding one outlier (ROMP 14), specific storage of the Ocala Limestone is fairly uniform. Specific storage of the Ocala Limestone varies about 2 orders of magnitude, ranging from 1.0E-7 to 1.2E-5 day^{-1}, with a geometric mean of about 6.8E-6 day^{-1}.

Calculations were made to check the reasonableness of the simulated leakance values. Leakance of individual confining layers can be multiplied by the head difference across the units to compute areal leakage from/into adjoining aquifers, based on the direction of the gradient. Using a form of Darcy´s Law, annual leakage for unstressed conditions in October 2001 was formulated as:

$$Q = (L*h)\ 365, \tag{3}$$

where

Q is the annual leakage rate across the confining unit, in foot per year;

L is the leakance of the confining unit, in foot per day per foot; and

h is the head difference across the confining unit, in feet.

During October 2001, downward flow existed at ROMP 13, 14, 22, 25, 28, and 39; upward flow existed at ROMP 12 and TR 4-1; and both upward and downward flows existed at ROMP 5, 20, and TR 9-2.

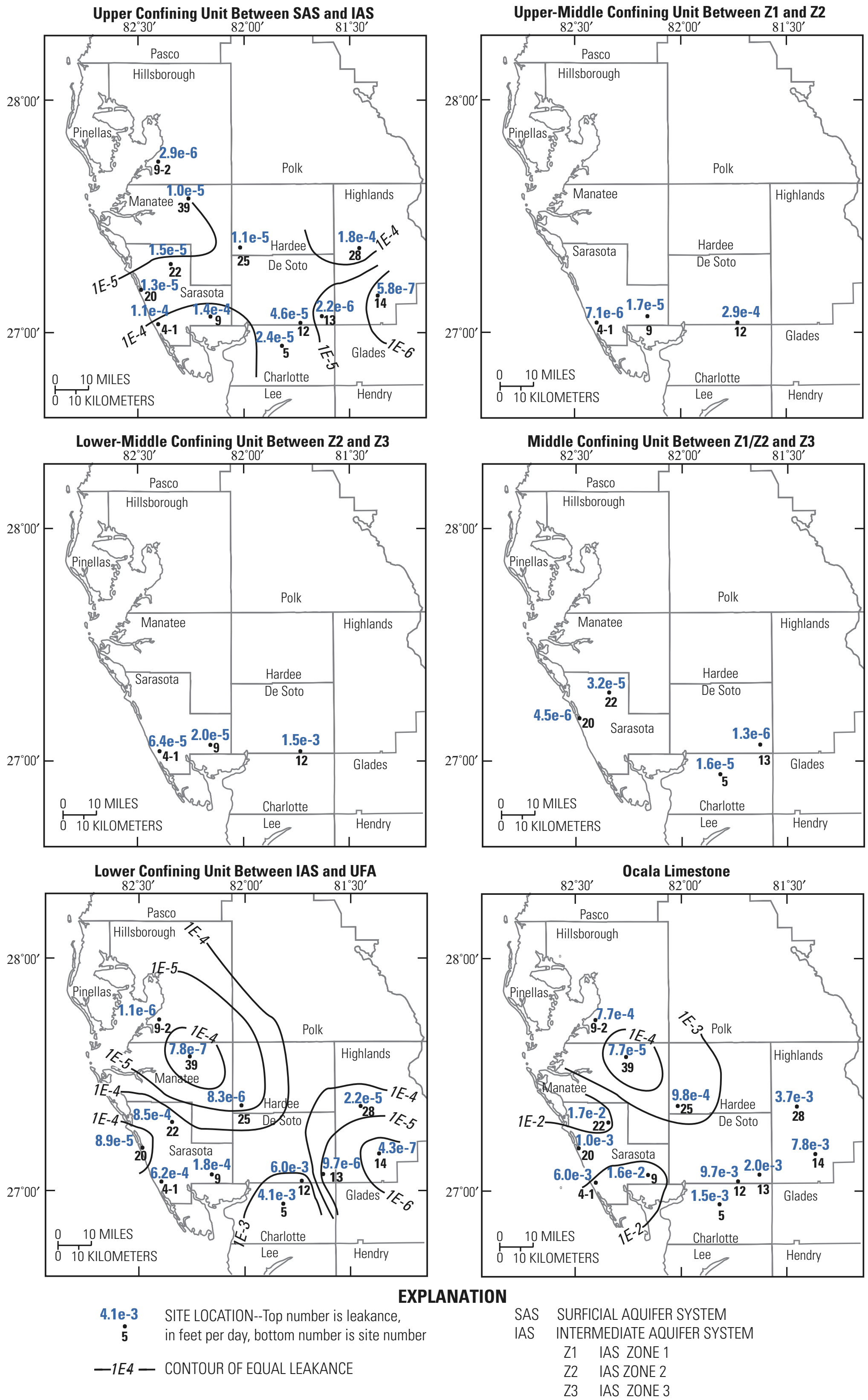


Figure 48. Distribution of leakance values estimated from numerical analyses of aquifer-test data collected at test sites.

The empirical relations between annual leakage rate (in units of inches per year (in/yr)), leakance values, and head differences observed in October 2001 were compared (fig. 49). The graphs in figure 49 show leakage rates generally less than 5 in/yr. Leakage across the upper confining unit averaged about 0.8 in/yr and ranged from 0.01 to 1.8 in/yr, except at ROMP 28, where leakage across the upper confining unit exceeded 20 in/yr. Leakage rates across the middle confining unit averaged about 1.5 in/yr and ranged from less than 0.1 to about 9 in/yr. Leakage rates across the lower confining unit averaged about 1.5 in/yr and ranged from less than 0.1 to about 5 in/yr. Leakage across the Ocala Limestone is about 5 times greater than across the other confining units, averaging about 5 in/yr, and ranging from to less than 0.1 to about 20 in/yr (fig. 49). One exception is at ROMP 22, where the hydraulic gradient across the Ocala Limestone is moderate, leakance is relatively high, and the leakage rate exceeded 100 in/yr.

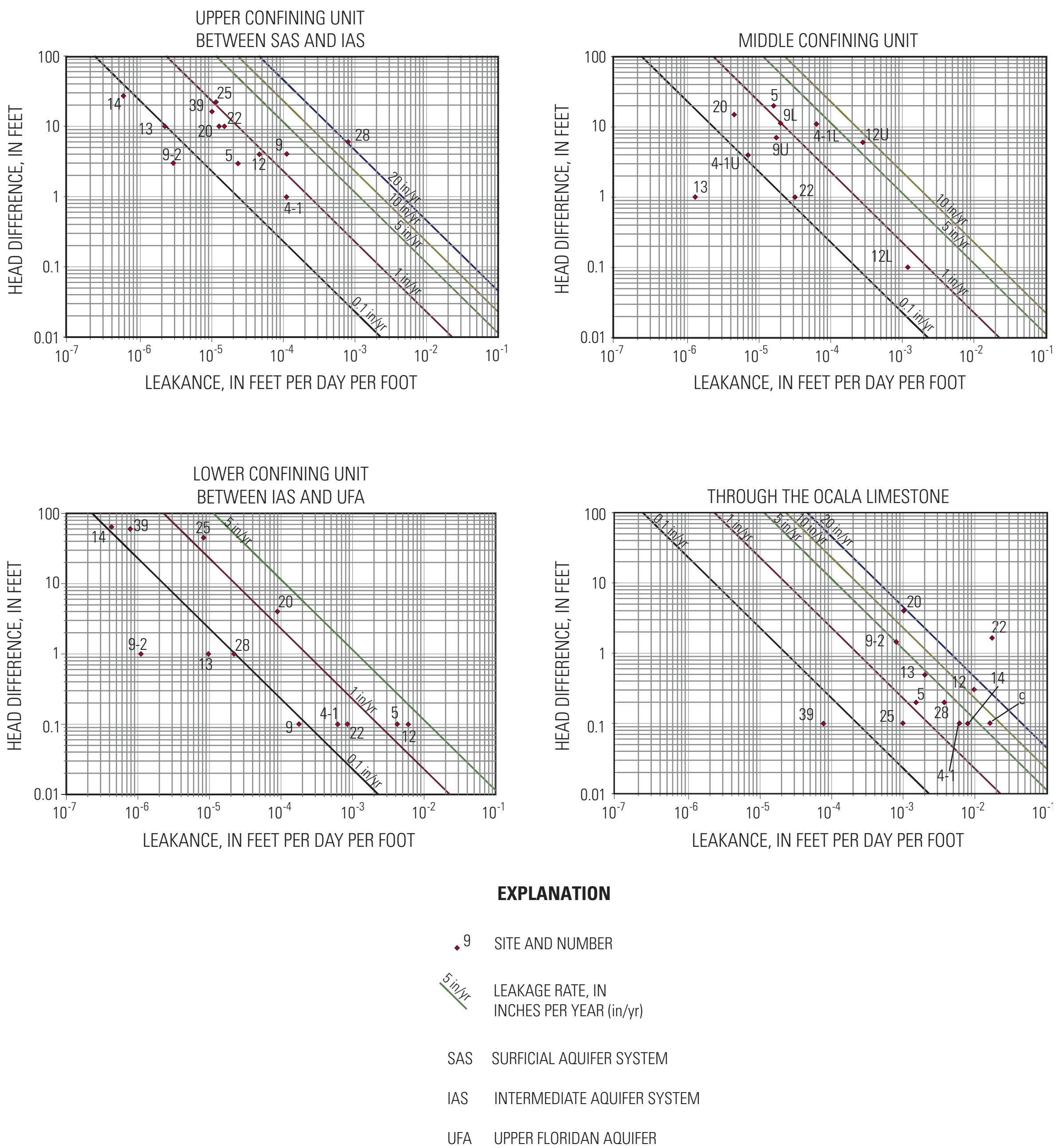


Figure 49. Comparison between simulated leakance values, head differences, and leakage rates across confining units at selected sites.

Generally, the leakage imbalance between producing zones is not too severe, indicating reasonable confining unit leakance values. Several exceptions are noted. At ROMP 12 and ROMP 20, a leakage imbalance of about 10 and 16 in/yr, respectively, exists in the Suwannee Limestone. At these sites, substantially more water is moving from the Avon Park Limestone into the Suwannee Limestone than is leaving the Suwannee Limestone. Obviously, not all water is going into storage in the Suwannee Limestone, so either the identified leakance is too large or the head difference across the Ocala Limestone is localized at the site. At ROMP 9, 13, 28, and TR 9-2, leakage imbalances of about 3 to 7 in/yr exist across the Ocala Limestone. Once again, either the identified leakance is too large or the head difference across the Ocala Limestone is localized at the site. At ROMP 22, a leakage imbalance of about 120 in/yr exists across the Ocala Limestone and substantially less water is moving out of the Suwannee Limestone than is moving into the Avon Park Formation. Again, not all of this water is going into storage in the Avon Park Formation, so either the identified leakance is too large or the head difference across the Ocala Limestone is localized at the site. At ROMP 12, a leakage imbalance of about 8 in/yr exists across the upper-middle confining unit and substantially less water is moving out of IAS–Zone 1 than is moving from IAS-Zone 2 into IAS-Zone 1. The identified leakance is either too large or the head difference across the upper-middle confining unit is localized at the site.

Water-Producing Zones

The surficial aquifer system is moderately productive, and hydraulic properties are highly variable and limited by the saturated thickness and lithology. Thickness of the surficial aquifer system ranges from 28 to 353 ft and averages about 80 ft for the five surficial aquifer test sites (table 2). The lithofacies in the study area range from sand with substantial clay content (low water yield), to clean sand (moderate water yield), to beds with substantial limestone and shell content (high water yield). Simulated ranges for transmissivity and horizontal hydraulic conductivity of the surficial aquifer system for the five tests were 520 to 22,000 ft^2/d and 13 to 790 ft/d, respectively, with geometric means of 5,440 ft^2/d and 58 ft/d, respectively (table 6). Spatially, permeability of the surficial aquifer system is greatest in Highlands and Sarasota Counties in areas where the aquifer system is thick and where substantial shell beds exist (fig. 50). With the exception of one outlier (ROMP 28), storativity and specific storage of the surficial aquifer system varies about 1 order of magnitude. Storativity of the surficial aquifer system ranged from 4.2E-5 to 1.4E-4; with a geometric mean of about 9.2E-5; whereas specific storage ranged from 3.0E-7 to 1.9E-6, day^{-1}, with a geometric mean of about 1.4E-6 day^{-1}. Specific yield ranged from 0.04 to 0.24.

For the most part, the water-producing capacity of the intermediate aquifer system is low, with hydraulic conductivity values 5 to 50 times less than the underlying Upper Floridan aquifer. The intermediate aquifer system consists of discrete flow zones designated Zone 1, Zone 2, and Zone 3. Hydraulic properties of the intermediate aquifer system are highly variable and span more than 3 orders of magnitude, varying with lithology, texture, and postdepositional processes such as dolomitization, recrystallization, fracturing, and dissolution (Torres and others, 2001). Generally, permeability is moderate in Zone 3 and substantially lower in Zone 1 and Zone 2.

Zone 1 is thin and discontinuous within the study area. Zone 1 is composed of discontinuous limestone, dolostone, sand, gravel, and shell beds in the unconsolidated sediments of the Peace River Formation and uppermost Arcadia Formation (L.A. Knochenmus, U.S. Geological Survey, written commun., 2005). Zone 1 exists in all of Sarasota, Charlotte, and Lee Counties, and in parts of Manatee and De Soto Counties, and is generally found above the Venice Clay (L.A. Knochenmus, U.S. Geological Survey, written commun., 2005). The thickness of Zone 1 ranges from 24 to 76 ft and averages about 50 ft at the three test sites (table 3). Zone 1 is poorly productive and permeability is more variable than underlying zones. Simulated transmissivity and horizontal hydraulic conductivity of Zone 1 span about 2 orders of magnitude, ranging from 31 to 4,900 ft^2/d and 1 to 100 ft/d, respectively; with geometric means of about 307 ft^2/d and 7 ft/d, respectively, for the three tests. No significant pattern is observed in the spatial distribution of transmissivity (fig. 50). Storativity of Zone 1 varies over 1 order of magnitude, ranging from 7.6E-6 to 4.3E-4, with a geometric mean value of about 3.0E-5. Specific storage of Zone 1 varies about 2 orders of magnitude, ranging from 1.0E-7 to 1.5E-5 day^{-1}, with a geometric mean of about 6.7E-7 day^{-1}.

Zone 2 is regionally extensive and found throughout most of the study area. This water bearing zone is composed of dolomite and limestone units within the undifferentiated Arcadia Formation (L.A. Knochenmus, U.S. Geological Survey, written commun., 2005), and is generally found above the Tampa Member. The thickness of Zone 2 ranges from 53 to 145 ft and averages about 77 ft at the 8 test sites (table 3). Zone 2 is the least productive zone of the intermediate aquifer system and its properties are less variable than overlying or underlying zones. Hydraulic properties vary more according to lithology and solution development than thickness (Wolansky, 1983). Simulated ranges for transmissivity and horizontal hydraulic conductivity of Zone 2 are 30 to 5,200 ft^2/d, respectively, and 1 to 95 ft/d, respectively, with geometric means of about 519 ft^2/d and 7 ft/d for the eight tests. Transmissivity of Zone 2 decreases from south to north (fig. 50). Storativity of Zone 2 varies about 1 order of magnitude, ranging from 1.8E-5 to 6.6E-4, with a geometric mean of about 1.3E-4. Specific storage of Zone 2 varies about 2 orders of magnitude, ranging from 3.0E-7 to 1.1E-5 day^{-1}, with a geometric mean of about 1.6E-6 day^{-1}.

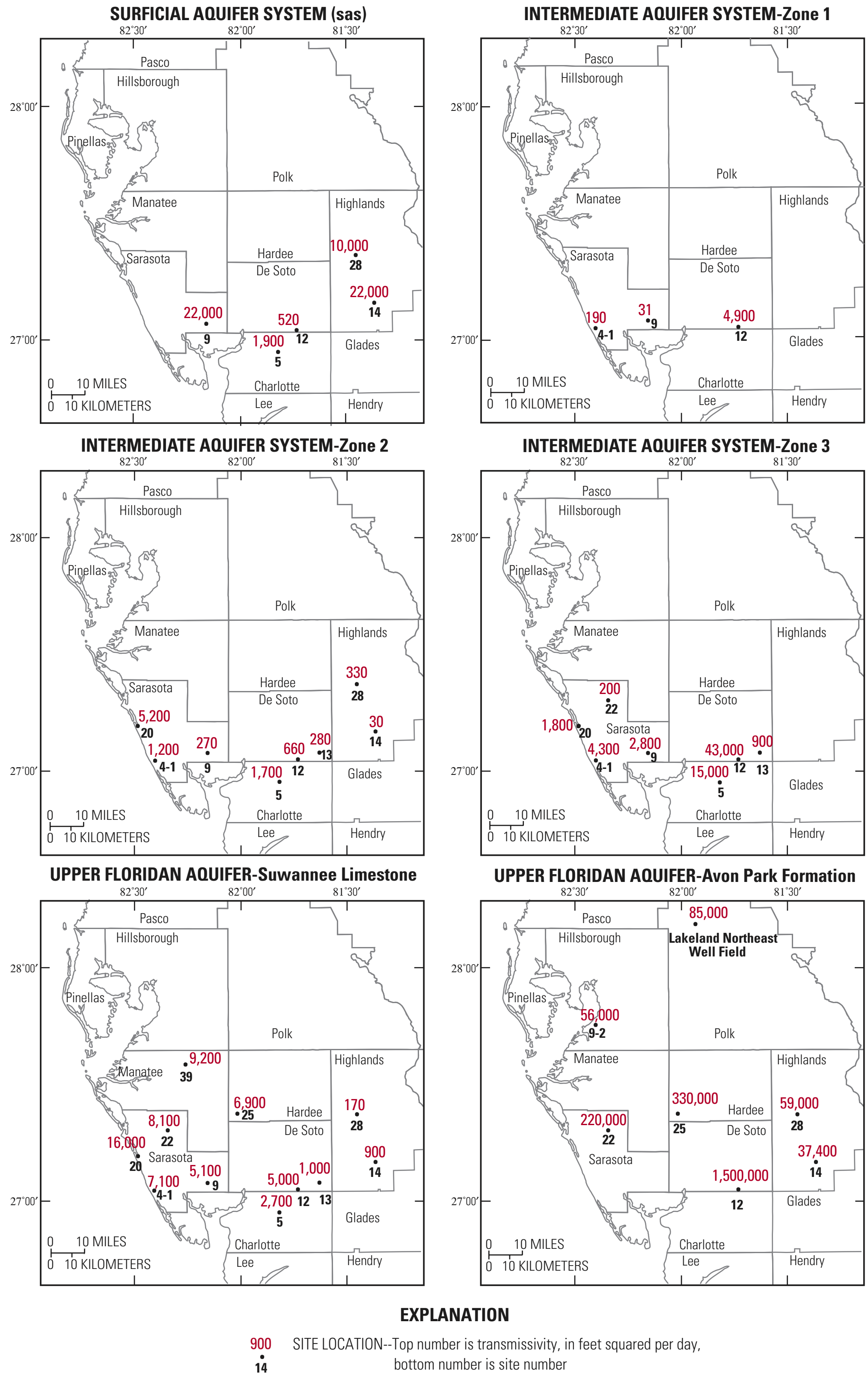


Figure 50. Transmissivity of the pumped zones based on aquifer thickness and simulated horizontal hydraulic conductivity from numerical models.

Zone 3 is regionally extensive and found in most of the study area; it is the thickest of the intermediate aquifer system water-producing zones. In the northwestern and southeastern parts of the study area, however, Zone 3 is in direct hydraulic connection with the Upper Floridan aquifer. The water-bearing zone is composed of limestone and dolostone within the Tampa Member of the Arcadia Formation and the undifferentiated Arcadia Formation found near the base of the Hawthorn Formation (L.A. Knochenmus, U.S. Geological Survey, written commun., 2005). The thickness of Zone 3 ranges from 76 to 390 ft and averages about 168 ft at the seven test sites (table 2). Generally, Zone 3 is the most productive zone of the intermediate aquifer system. The hydraulic properties of Zone 3 are more variable than overlying zones, which probably is related to the degree of solution development within the limestone and dolomite beds. Simulated ranges and averages for transmissivity and horizontal hydraulic conductivity of Zone 3 are 200 to 43,000 ft^2/d and 2 to 184 ft/d, respectively; with geometric means of about 3,100 ft^2/d and 20 ft/d, respectively, for the seven tests. Transmissivity of Zone 3 decreases from south to north and from east to west (fig. 50). Excluding one outlier (ROMP 9), storativity and specific storage of Zone 3 is fairly uniform. Storativity of Zone 3 varies less than 1 order of magnitude, ranging from 2.6E-5 to 1.2E-4, with a geometric mean of about 4.3E-5. Specific storage of Zone 3 ranged from 1.0E-7 to 6.0E-7 day^{-1}, with a geometric mean of about 2.4E-7 day^{-1}.

As with transmissivity of the intermediate aquifer system, transmissivity of the Upper Floridan aquifer is highly variable. Areal variation in transmissivity and hydraulic conductivity in the Upper Floridan aquifer is primarily controlled by the presence of fractures and secondary porosity. Locations of fractures and conduits create contrasts in transmissivity arising from the difference between wells penetrating zones of well-connected fractures and wells penetrating zones of sparse, tight, poorly connected fractures (Knochenmus and Bowman, 1998). The wide range of transmissivity values for the Upper Floridan aquifer tests is most likely caused by one or both of these factors: (1) some tests do not penetrate the highly permeable dolomite stratum commonly located at the top of the Avon Park Formation, or (2) the wells may or may not penetrate a permeable stratum that is only present locally (Wolansky and Corral, 1985).

The permeability of the Suwannee Limestone is substantially lower and less variable than the underlying Avon Park Formation. Horizontal hydraulic conductivity is fairly uniform because most of the permeability is intergranular. Transmissivity of the Suwannee Limestone increases from east to west (fig. 50). Simulated ranges for transmissivity and horizontal hydraulic conductivity of this unit are 170 to 16,000 ft^2/d and 1 to 41 ft/d, respectively; with geometric means of 3,360 ft^2/d and 16 ft/d, respectively, for the 11 tests. Excluding one outlier (ROMP 14), storativity and specific storage of the Suwannee Limestone are fairly uniform. Storativity varies by about 1 order of magnitude, ranging from 3.3E-5 to 3.8E-4 with a geometric mean of about 1.8E-4. Specific storage of the Suwannee Limestone also varies about 1 order of magnitude, ranging from 1.0E-7 to 3.1E-6 day^{-1}, with a geometric mean of about 5.2E-7 day^{-1}.

The Avon Park Formation is the most productive zone in the Upper Floridan aquifer, and permeability of the Avon Park Formation primarily results from fracturing and secondary porosity. The extremely high hydraulic conductivity of the Avon Park Formation is more variable than the Suwannee Limestone owing to the variability in fractures and enhanced permeability features. Transmissivity of the Avon Park Formation increases from north to south (fig. 50). Simulated ranges for transmissivity and horizontal hydraulic conductivity of this unit are 37,400 to 1,500,000 ft^2/d and 46 to 1,518 ft/d, respectively; with geometric means of about 154,000 ft^2/d and 200 ft/d, respectively, for the six tests. Storativity of the Avon Park Formation differs by about 1 order of magnitude, ranging from 1.4E-4 to 2.1E-3 with a geometric mean of about 5.5E-4. Specific storage of the Avon Park Formation also varies about 1 order of magnitude, ranging from 2.0E-7 to 4.5 E-6 day^{-1}, with a geometric mean of 7.2E-7 day^{-1}.

The relations between specific capacity and transmissivity were compared for each of the producing zones. Typically, high specific capacities indicate an aquifer of high transmissivity, and low specific capacities indicate an aquifer of low transmissivity. Although the graphs in figure 51 can be used to obtain rough estimates of transmissivity, the high coefficients of variation indicate that there is a large degree of uncertainty in using specific capacity data for transmissivity estimates in the study area. The variability is influenced by a variety of factors including (1) uneven distribution of fractures, (2) solution-enhanced conduits, (3) well efficiency, (4) storage coefficient of the aquifer, (5) effective radius of the well, and (6) the pumping rate. There is a good correlation between transmissivity and specific capacity for the Suwannee Limestone, presumably because permeability is primarily intergranular.

Summary

This report presents the analysis of 41 aquifer tests that were conducted from 1980 through 2004 at 13 sites in west-central Florida. This report expands upon the previous analyses of the Southwest Florida Water Management District by using radial axisymmetric numerical modeling and a method of automatic parameter estimation for aquifer test analysis.

The ground-water flow system in west-central Florida consists of a sequence of aquifers and confining units, each containing discrete zones of varying permeability. The principal hydrogeologic units are the surficial aquifer system, the intermediate aquifer system, and the Upper Floridan aquifer. Aquifer heterogeneity results in vertical and areal variability in hydraulic properties.

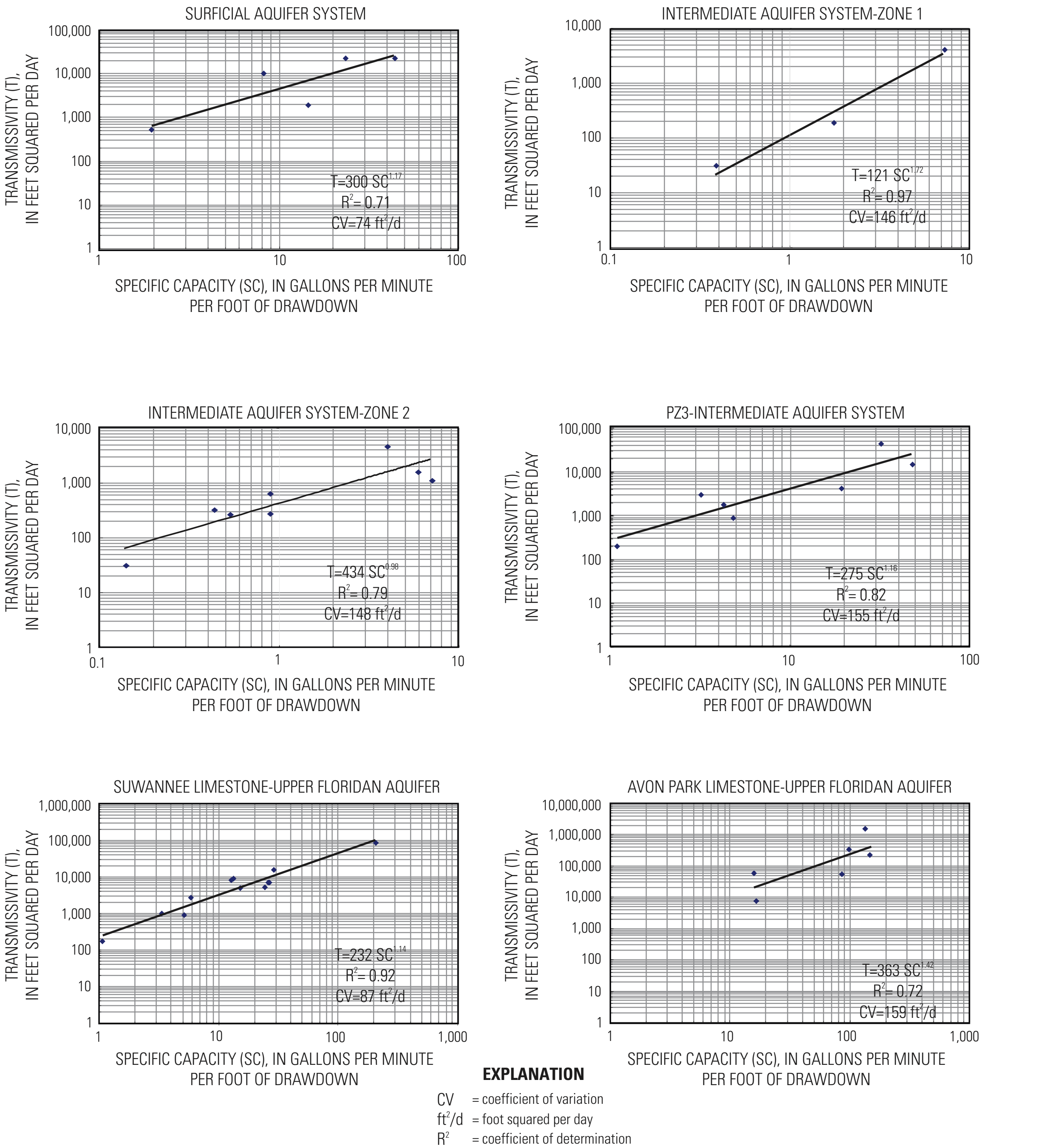


Figure 51. Relation of transmissivity to specific capacity.

The surficial aquifer system is an unconfined system and is composed of clastic deposits that may be as much as 350 ft thick. The surficial aquifer system is moderately productive and hydraulic properties are highly variable and related to lithology and saturated thickness. Thickness of the surficial aquifer system averages about 80 ft at the test sites. The estimated range in values for transmissivity and horizontal hydraulic conductivity are 520 to 22,000 ft^2/d and 13 to 790 ft/d, respectively, for the five tests conducted on this unit. Storativity of the surficial aquifer system varies about 1 order of magnitude, ranging from 4.2E-5 to 1.4E-4, while specific storage ranges from 3.0E-7 to 1.9E-6 day^{-1}. Specific yield ranges from 0.04 to 0.24.

The intermediate aquifer system is a confined system, having as many as three producing units designated as Zone 1, Zone 2, and Zone 3. The system is composed of clastic sediments interbedded with carbonate rocks. Interbedded clay and fine grained clastics separate the producing zones. Hydraulic properties of these zones vary depending on texture of the sediments and postdepositional processes such as dolomitization, recrystallization, fracturing, and dissolution. The water-producing capacity of the intermediate aquifer system is low, with hydraulic conductivity values from 5 to 50 times less than the underlying Upper Floridan aquifer.

Zone 1 is not extensive in the area underlying parts of western Manatee, southern and western Sarasota, and western Charlotte Counties. Zone 1 is generally the uppermost water-bearing zone and the thinnest producing zone of the intermediate aquifer system, averaging about 50 ft thick at the test sites. Zone 1 is poorly productive and hydraulic properties are highly variable. The estimated range in values of transmissivity and horizontal hydraulic conductivity of Zone 1 span about 2 orders of magnitude and ranged from 31 to 4,900 ft^2/d, and 1 to 100 ft/d, respectively, for the three tests conducted on this unit. Storativity of Zone 1 spans over 2 orders of magnitude, ranging from 7.6E-6 to 4.3E-4, whereas specific storage ranges from 1.0E-7 to 1.5E-5 day^{-1}.

Zone 2 is regionally extensive, underlying most of the study area. Zone 2 is typically the least productive zone of the intermediate aquifer system and hydraulic properties are less variable than overlying or underlying zones. Thickness of Zone 2 averages about 77 ft at the test sites. Hydraulic properties vary with lithology and solution development, more so than with variation in thickness. The estimated range in values for transmissivity and horizontal hydraulic conductivity of Zone 2 are 30 to 5,200 ft^2/d, and 1 to 95 ft/d, respectively, for the eight tests conducted on this unit. Storativity of Zone 2 spans over 1 order of magnitude, ranging from 1.8E-5 to 6.6E-4, whereas specific storage ranges from 3.0E-7 to 1.1E-5 day^{-1}.

Zone 3 also is regionally extensive, underlying most of the study area. In the northwestern and southeastern parts of the study area, Zone 3 is in direct hydraulic connection with the Upper Floridan aquifer. Zone 3 is generally the thickest producing zone of the intermediate aquifer system, averaging about 168 ft at the test sites. Zone 3 is the most productive zone of the intermediate aquifer system and hydraulic properties are more variable than overlying zones, which is probably related to the degree of solution development within the limestone and dolomite beds. The estimated range in values for transmissivity and horizontal hydraulic conductivity of Zone 3 are 200 to 43,000 ft^2/d, and 2 to 184 ft/d, respectively, for the seven tests conducted on this unit. Storativity of Zone 3 varies less than 1 order of magnitude, ranging from 2.6E-5 to 1.2E-4, whereas specific storage ranges from 1.0E-7 to 6.0E-7 day^{-1}.

The Upper Floridan aquifer underlies all of west-central Florida and is the principal source of water in the area. The Upper Floridan aquifer has two major water-bearing zones—the Suwannee Limestone and Avon Park Formation, which are separated by the less permeable Ocala Limestone at the study sites. Permeability of the Upper Floridan aquifer is very high in parts of the Avon Park Formation, somewhat lower in the Suwannee Limestone, and lowest in the Ocala Limestone. Thickness of the aquifer ranges from about 1,200 to 1,400 ft in the study area. The estimated range in values for transmissivity and horizontal hydraulic conductivity of the Suwannee Limestone are 170 to 16,000 ft^2/d and 1 to 41 ft/d, respectively, for the 11 tests conducted on this unit. Storativity of the Suwannee Limestone spans about 1 order of magnitude, ranging from 3.3E-5 to 3.8E-4, whereas specific storage ranges from 1.0E-7 to 3.1E-6 day^{-1}.

The Avon Park Formation is the most productive zone in the Upper Floridan aquifer and permeability is primarily from fracturing and secondary porosity. The extremely high, hydraulic conductivity of the Avon Park Formation is more variable than the Suwannee Limestone owing to fractures and enhanced permeability features. The estimated range in values for transmissivity and horizontal hydraulic conductivity of the Avon Park Formation are 37,400 to 1,500,000 ft^2/d and 46 to 1,518 ft/d, respectively, for the six tests conducted on this unit. Storativity of the Avon Park Formation spans about 1 order of magnitude, ranging from 1.4E-4 to 2.2E-3, whereas specific storage ranges from 2.0E-7 to 4.5E-6 day^{-1}.

Confining units separating producing zones and aquifer systems consist of clays and low permeability carbonates. Variations in hydraulic properties of the confining units vary according to lithology and thickness. Typically, the Ocala Limestone has the highest leakance, and the upper confining unit that separates the surficial aquifer system from the uppermost permeable zone in the intermediate aquifer system has the lowest leakance.

The upper confining unit is the least permeable of the confining units and consists of sandy clay, clay, and marl. The upper confining unit is generally the thinnest confining unit of the intermediate aquifer system. Thickness of the upper confining unit ranges from 12 to 255 ft and averages about 71 ft at the test sites. Estimated values of leakance for the upper confining unit span about 3 orders of magnitude and range from 5.8E-7 to 7.9E-4 ft/d/ft. Leakage across the upper confining unit is variable, ranging from less than 0.1 to about 1.8 in/yr. Specific storage of the upper confining unit ranges from 2.0E-7 to 1.1E-5 day^{-1}.

The middle confining units that separate the intervening permeable zones within the intermediate aquifer system (Zone 1, Zone 2, and Zone 3) generally consist of clay and clayey sand. Thickness of the middle confining units ranges from 7 to 220 ft and averages about 80 ft at the test sites (table 4). Estimated values of leakance of the middle confining units span about 3 orders of magnitude and ranges from 1.3E-6 to 1.1E-3 ft/d/ft. Leakage across the middle confining units averages about 2 in/yr. Specific storage of the middle confining units span about 1 order of magnitude and ranges from 2.0E-7 to 4.6E-6 day^{-1}.

The lower confining unit is the bottom of the intermediate aquifer system and generally consists of sandy clay and clayey sand. The lower confining unit is generally the thickest confining unit of the intermediate aquifer system. Thickness of the unit ranges from 8 to 225 ft and averages about 93 ft at the test sites. Typically, leakance is greater for the lower confining unit than either the middle or upper confining units. Leakance of the lower confining unit spans about 3 orders of magnitude and ranges from 4.3E-7 to 6.0E-3 ft/d/ft. Leakage across the lower confining unit averages about 2 in/yr. Specific storage of the lower confining unit spans about 1 order of magnitude, ranging from 1.0E-7 to 3.1E-6 day^{-1}.

The Ocala Limestone separates the two major flow zones in the Upper Floridan aquifer and is composed mostly of fine-grained limestone. Leakance is greater for the Ocala Limestone than either the upper, middle, or lower confining units. Thickness of the Ocala Limestone averages about 238 ft at the 13 test sites. Leakance of the Ocala Limestone spans about 3 orders of magnitude, ranging from 7.7E-5 to 1.7E-2 ft/d/ft. Leakage across the Ocala Limestone averages about 5 in/yr. Specific storage of the lower confining unit spans about 2 orders of magnitude, ranging from 1.0E-7 to 2.1E-4 day^{-1}.

Conclusions

The method of analysis used in this report provides for better aquifer test analysis of layered aquifer systems than separate interpretation of aquifer tests using analytical methods because the hydrogeologic data collected during drilling and logging could be used in an optimal way and more features of a complex ground-water flow system could be collectively simulated and constrained by observations. Compared to traditional methods where time-drawdown or distance-drawdown curves are separately interpreted, the inverse numerical model has the advantage that the entire drawdown observed during multiple aquifer tests can be interpreted at the same time. Numerical modeling of aquifer tests provides five major advantages: (1) the numerical model allows the user to take advantage of the hydrogeologic knowledge developed for the system, tailor a more appropriate conceptual model of the ground-water system, and selectively choose which properties to calibrate and what assumptions to make; (2) the numerical model represents leakage between multiple aquifers better because results from multiple tests are analyzed as a whole; (3) hydraulic properties of confining units that affect two or more aquifer tests are interpreted consistently because the hydrogeologic system is simulated with a single model; (4) all observations contribute to determining one set of values of hydraulic parameters together with their accuracies; and (5) combined with parameter estimation, the approach provides quantitative insights into parameter uniqueness and uncertainty. In contrast, hydraulic parameters estimated by fitting separate time-drawdown curves to type curves can result in very different values for the parameters if the actual flow regime is different from the analytical model corresponding to the type curve.

It was possible to infer the vertical hydraulic conductivity of confining units with accuracies comparable to those of the horizontal hydraulic conductivity of pumped permeable layers; however, specific storage of the confining units were determined with significantly less reliability. Overall, it was possible to determine with decreasing reliability the vertical hydraulic conductivity of the Ocala Limestone, the lower confining unit, the middle confining units, and the upper confining unit. The most reliable estimates were obtained when drawdown was measured in adjacent permeable layers. If the pumping rate was too low, or if permeability of the confining unit was too small to induce observable drawdown in the indirectly pumped aquifers, the inverse model lost valuable input data and reliability was reduced.

Horizontal hydraulic conductivity and specific storage were determined reliably for the producing zones. The best estimates were obtained when a large number of observations were included in the inverse process and when drawdown was measured in adjacent permeable and confining units.

Although alternate combinations of model parameters may provide similar results to those outlined in this report, the models in this report incorporate the best estimates of the unknown parameters and local geology, and are reasonable for this type of aquifer system.

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Appendix 1: Relative composite sensitivity for estimated and assigned parameter values.

Appendix 1. Relative composite sensitivity for estimated and assigned parameter values.

[RCS, relative composite sensitivity; K, hydraulic conductivity; S, Specific storage; Sy, specific yield; sas, surficial aquifer system; ias, intermediate aquifer system; Z1, ias Zone 1; Z2, ias Zone 2; Z3, ias Zone 3; suw, Suwannee Limestone; oca, Ocala Limestone; avp, Avon Park Limestone; ufa, Upper Floridan aquifer; ucu, confining unit between sas and ias; umcu, confining unit between Z1 and Z2; lmcu, confining unit between Z2 and Z3; mcu, confining unit between Z1/2 and Z3; lcu, confining unit between ias and suw; V, vertical anisotropy; shaded cells highlight parameters with RCS values less than 0.2]

ROMP 5

Parameter	[1]RCS
K-Z2	1.000
K-sas	0.523
K-suw	0.323
V-sas	0.188
S-Z2	0.148
K-Z3	0.122
S-suw	0.069
K-lcu	0.064
K-oca	0.063
Sy	0.027
K-ucu	0.011
K-avp	0.011
K-mcu	0.009
S-Z3	0.008
S-lcu	0.008
S-mcu	0.005
S-sas	0.005
S-oca	0.004
S-avp	0.000
S-ucu	0.000

ROMP 9

Parameter	RCS
K-Z2	1.000
K-suw	0.822
K-Z3	0.312
K-Z1	0.299
S-suw	0.159
S-Z2	0.155
S-Z1	0.136
K-oca	0.072
S-Z3	0.060
K-lmcu	0.033
K-umcu	0.033
K-sas	0.026
S-ucu	0.025
K-ucu	0.022
S-lmcu	0.020
K-lcu	0.019
S-lcu	0.014
K-avp	0.011
Sy	0.010
V-sas	0.009
[2]S-oca	0.002
[2]S-avp	0.001
[2]S-sas	0.000

ROMP 12

Parameter	RCS
K-Z1	1.000
K-sas	0.897
K-Z2	0.869
K-Z3	0.654
K-suw	0.474
V-sas	0.328
K-oca	0.261
S-Z2	0.241
K-lmcu	0.205
K-lcu	0.171
K-avp	0.159
Sy	0.147
K-umcu	0.130
S-suw	0.096
S-ucu	0.082
S-sas	0.029
S-Z1	0.023
S-avp	0.023
K-ucu	0.018
S-oca	0.017
S-lmcu	0.015
S-Z3	0.011
S-lcu	0.008

ROMP 13

Parameter	RCS
K-Z3	1.000
K-oca	0.204
K-Z2	0.194
S-Z3	0.147
K-suw	0.125
K-lcu	0.112
S-Z2	0.036
S-oca	0.033
S-mcu	0.029
K-mcu	0.028
S-suw	0.023
S-lcu	0.010
K-avp	0.005
S-ucu	0.005
K-ucu	0.001
S-avp	0.000
[2]K-sas	0.000
[2]S-sas	0.000

ROMP 14

Parameter	RCS
K-suw	1.000
K-Z2	0.665
K-sas	0.338
K-avk	0.324
S-Z2	0.240
K-oca	0.174
S-suw	0.166
Sy	0.054
S-avk	0.051
V-avp	0.046
S-oca	0.039
K-ucu	0.034
S-ucu	0.030
K-lcu	0.024
S-lcu	0.018
[2]K-avp2	0.001
V-sas	0.000
S-sas	0.000
[2]S-avp2	0.000

ROMP 20

Parameter	RCS
K-Z3	1.000
K-suw	0.581
K-Z2	0.542
S-Z3	0.143
K-lcu	0.129
S-oca	0.083
S-Z2	0.073
S-suw	0.068
K-oca	0.065
K-mcu	0.016
S-mcu	0.016
S-lcu	0.016
K-ucu	0.013
S-ucu	0.003
K-avp	0.003
S-avp	0.000
[2]K-sas	0.000
[2]S-sas	0.000

ROMP 22

Parameter	RCS
K-Z3	1.000
K-suw	0.761
K-avp	0.577
S-Z3	0.258
K-lcu	0.158
K-oca	0.151
K-mcu	0.085
S-mcu	0.074
S-avp	0.074
S-suw	0.067
S-oca	0.009
K-Z2	0.007
S-lcu	0.007
S-Z2	0.007
[2]K-ucu	0.000
[2]S-ucu	0.000
[2]S-sas	0.000
[2]K-sas	0.000

ROMP 25

Parameter	RCS
K-suw	1.000
K-avp	0.280
K-oca	0.165
S-suw	0.126
S-avp	0.026
K-lcu	0.005
S-lcu	0.005
S-oca	0.004
S-Z2	0.001
K-Z2	0.001
[2]K-ucu	0.000
[2]S-ucu	0.000
[2]S-sas	0.000
[2]K-sas	0.000

ROMP 28

Parameter	RCS
K-suw	1.000
K-avk	0.768
K-oca	0.473
K-sas	0.424
K-Z2	0.340
S-suw	0.184
S-sas	0.119
K-ucu	0.091
S-Z2	0.073
S-avp	0.058
K-lcu	0.038
S-oca	0.025
S-ucu	0.024
Sy	0.019
S-lcu	0.010

ROMP 39

Parameter	RCS
K-suw	1.000
K-oca	0.073
S-oca	0.070
S-suw	0.061
[2]K-avp	0.001
K-lcu	0.001
S-lcu	0.001
[2]S-avp	0.000
[2]S-mcu	0.000
[2]K-Z2L	0.000
[2]S-Z2L	0.000
[2]K-ucu	0.000
[2]S-Z2U	0.000
[2]S-ucu	0.000
[2]K-Z2U	0.000
[2]K-sas	0.000
[2]S-sas	0.000

ROMP TR 4-1		ROMP TR 9-2		Lakeland NE WF	
Parameter	RCS	Parameter	RCS	Parameter	RCS
K-Z1	1.000	K-avp	1.000	K-ufa	1.000
K-suw	0.920	S-avp	0.156	Sy	0.252
K-Z3	0.390	K-oca	0.138	V-ufa	0.218
K-Z2	0.344	K-suw	0.107	S-ufa	0.066
K-ucu	0.261	S-suw	0.080	[2]K-sas	0.051
S-Z1	0.242	[2]K-lcu	0.006	V-sas	0.038
K-oca	0.185	[2]S-lcu	0.006	K-icu	0.038
S-suw	0.168	S-oca	0.005	S-sas	0.007
K-lcu	0.093	[2]S-ias	0.000		
[2]K-avp	0.072	[2]S-sas	0.000		
S-Z3	0.060	[2]S-ucu	0.000		
S-Z2	0.051	[2]K-ias	0.000		
S-ucu	0.047	[2]K-ucu	0.000		
[2]S-avp	0.030	[2]K-sas	0.000		
S-sas	0.026				
K-sas	0.021				
K-lmcu	0.018				
S-oca	0.015				
K-umcu	0.014				
S-lmcu	0.014				
S-umcu	0.012				
S-lcu	0.005				

[1]The larger the value of RCS, the more sensitive the model is to that parameter, as a whole. The model is highly insensitive to parameters with RCS values less than 0.02 (shaded cells), resulting in little influence of these parameters on overall model performance.

[2]This parameter was specified and not estimated with the inverse model.