ground water

# Estimating Hydraulic Properties Using a Moving-Model Approach and Multiple Aquifer Tests

by Keith J. Halford[1] and Dann Yobbi[2]


## Abstract

A new method was developed for characterizing geohydrologic columns that extended >600 m deep at sites with as many as six discrete aquifers. This method was applied at 12 sites within the Southwest Florida Water Management District. Sites typically were equipped with multiple production wells, one for each aquifer and one or more observation wells per aquifer. The average hydraulic properties of the aquifers and confining units within radii of 30 to >300 m were characterized at each site. Aquifers were pumped individually and water levels were monitored in stressed and adjacent aquifers during each pumping event. Drawdowns at a site were interpreted using a radial numerical model that extended from land surface to the base of the geohydrologic column and simulated all pumping events. Conceptually, the radial model moves between stress periods and recenters on the production well during each test. Hydraulic conductivity was assumed homogeneous and isotropic within each aquifer and confining unit. Hydraulic property estimates for all of the aquifers and confining units were consistent and reasonable because results from multiple aquifers and pumping events were analyzed simultaneously.


## Introduction

Field-scale, vertical hydraulic conductivities of confining units in layered, multiple aquifer systems are difficult to estimate. Neuman and Witherspoon (1972) were the earliest investigators to analyze multiple aquifer systems with observation wells in the confining units. Specific storage estimates for their confining units were in excess of $4 \times 10^{-4}$ m$^{-1}$, which suggests that well completion in the confining units greatly influenced drawdowns. Moench (1985) introduced an analytical solution for an aquifer that was bounded by two compressible confining units. Nevertheless, differentiating leakage from overlying and underlying confining units remains problematic even with correct analytical tools. Vertical hydraulic conductivity estimates from aquifer tests have been discarded routinely in central Florida because leakage was not differentiated correctly (Spechler and Halford 2001).

Vertical hydraulic conductivity of confining units strongly affects ground water flow in west-central Florida. The Southwest Florida Water Management District primarily has sought to improve vertical hydraulic conductivity estimates at selected Regional Observation and Monitor-Well Program (ROMP) sites. Stratigraphic columns were simplified to geohydrologic columns of aquifers and confining units (Gates 1988; Clayton 1999). Geohydrologic units were differentiated by assessing a combination of geologic, water level, and water quality changes. Assessing the hydraulic properties of these aquifers and confining units was an objective of the research described in this paper.

Multiple aquifer tests were conducted at many of the ROMP sites (Figure 1). However, carefully controlled and successful aquifer tests are conducted with difficulty in west-central Florida because aquifer systems are layered and nonuniform with respect to hydraulic conductivity (Robinson 1995). Leakage between multiple aquifers is difficult to differentiate with analytical solutions and a single aquifer test. Errors in hydraulic property estimates can

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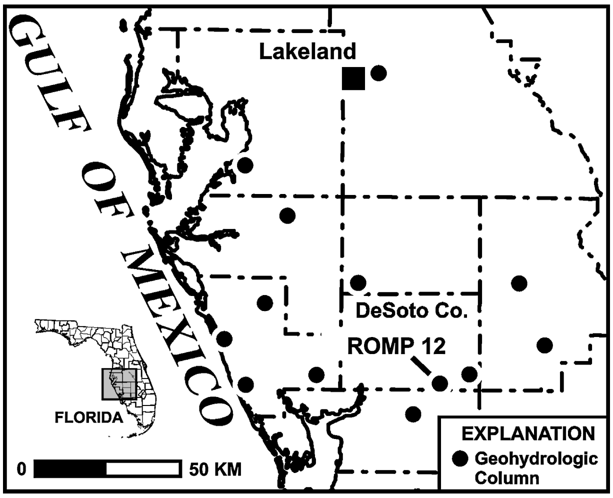


**Figure 1. Sites that were analyzed as geohydrologic columns and the ROMP 12 example site.**

be introduced because of deviations between nonideal natural systems and simplified analytical solutions (Neuman and Witherspoon 1972; Moench 1985).

Some researchers analyze individual aquifer tests with three-dimensional, numerical models where typical assumptions for analytical models are violated severely. Distinct aquifer heterogeneities (Barrash and Dougherty 1997) and surface water features (Halford 1998) do not correspond with radial symmetry. Hydraulic properties of fracture networks also are estimated by interpreting individual aquifer tests with three-dimensional models (Goode and Senior 2000; Tiedeman and Hsieh 2001). Yet, three-dimensional models are a last resort, despite their flexibility, because aquifer tests can be analyzed much more quickly with two-dimensional models. Aquifer tests have been analyzed previously with two-dimensional, radial models where aquifers and confining units were the prominent heterogeneities (Schroth and Narasimhan 1997; Halford 1997; Johnson et al. 2001).

Interpretation of multiple aquifer test data with one radially symmetric, numerical model of an entire geohydrologic column provides an alternative method of determining the hydraulic properties of multiple aquifers and confining units. Hydraulic properties are field-scale estimates that are averaged across an aquifer or confining unit over >100 m from each production well. Hydraulic properties of confining units that affect two or more aquifer tests are interpreted consistently because the geohydrologic column is simulated with a single model. Results from these numerical simulations were considered more realistic than analysis of independent tests using analytical methods. This was because more features of a complex ground water flow system can be simulated collectively and constrained simultaneously by sequential sets of drawdown observations.

All aquifer tests can be analyzed with a single, radial model because the frame of reference is translated between production wells, hereafter referred to as the moving-model approach. Radial distance between an observation well and production well differs between aquifer tests. Application of the moving-model approach assumes that aquifers and confining units are flat lying, homogeneous, and isotropic. Simulation capabilities of MODFLOW have been expanded previously by translating observations. In prior work (Halford and Campbell 2004), lateral anisotropy was estimated and simulation capabilities of MODFLOW (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996) were expanded by rotating observation positions about a production well.

## Purpose and Scope

This article presents an approach for field-scale estimation of the hydraulic properties of a geohydrologic column. Techniques for defining the geohydrology, well construction, pumping history, drawdowns, and initial estimates of hydraulic conductivity are described so that multiple aquifer tests in different aquifers can be interpreted with a single simulation. Pragmatic guides for using drawdowns from pumping wells, weighting negligible drawdowns, and initializing parameter estimates also are presented.

## Approach

Consistent hydraulic properties for a geohydrologic column are estimated from multiple aquifer tests with one simulation of a MODFLOW-based model (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996); this methodology is hereafter referred to as the geohydrologic column approach. A geohydrologic column is simulated with an axisymmetric, radial geometry in a one-layer MODFLOW model. That is, the horizontal dimension is represented by columns and the vertical dimension is represented by rows, so that the column, in effect, is laid on its side, or alternatively the one MODFLOW layer is conceptually flipped to the vertical position (Anderson and Woessner 1992, p. 175–176). The geohydrologic column approach is flexible, subject to a few assumptions. Individual aquifers and confining units are flat lying, homogeneous, and isotropic, which allows radial symmetry to shift between production wells as each test is analyzed. The number of aquifers in a geohydrologic column is limited to the number of stressed intervals. These assumptions primarily are imposed by data limitations, not MODFLOW.

Well location and construction details are needed for the moving-model approach. Wells are located in Cartesian coordinates such as Universal Transverse Mercator. Cartesian coordinates are used to compute radial distances between a production well and observation wells for each test. Multiple radial distances for each observation well are specified because a different production well is used during each test. Conceptually, the radial model moves between aquifer tests and is centered on the production well during each test.

The geohydrologic framework is characterized using qualitative and quantitative borehole data (Gates 1988). Types of data collected during the coring of test holes include water levels, water quality, geophysical logs, and specific capacities. Water levels were measured while coring and during packer testing. Specific capacities of discrete intervals were determined during packer tests. Hydraulic properties of discrete stratigraphic units were determined from falling-head permeameter tests. The identification of stratigraphic units comprising the geologic framework was based on stratigraphic picks by field geologists. The geologic and geohydrologic frameworks are linked using geophysical logs, water levels, water quality, and specific capacity data.

## Initial Hydraulic Property Estimates

Initial hydraulic property estimates of the aquifers and confining units are needed for a MODFLOW model of the geohydrologic column. Transmissivities of the aquifers are estimated initially with the Cooper-Jacob method (Cooper and Jacob 1946) because the solution is simple and can be solved graphically (Halford and Kuniansky 2002). Drawdown in the pumping well is analyzed because drawdowns are greatest and a transmissivity estimate is affected less by leakage. Aquifer storage, vertical hydraulic conductivity, and specific storage of adjacent confining units are estimated initially with a leaky aquifer solution, which also provides another estimate of transmissivity (Moench 1985). Transmissivity estimates for the leaky aquifer solution are limited to values less than the Cooper-Jacob estimates. The leaky aquifer solution is solved by optimization within a spreadsheet.

Initial hydraulic conductivity estimates of the aquifers and confining units in the MODFLOW model were estimated with geometric means from different analytical solutions. Although this approach is scientifically unsound because it lumps inconsistent assumptions about the flow system into the same population, empirically it has worked well for more than a dozen sites (Halford and Yobbi 2003). Geometric means of the transmissivity values obtained from the Cooper-Jacob and leaky solutions were divided by aquifer thicknesses to yield initial hydraulic conductivity estimates. Geometric means of hydraulic conductivities using the leaky solution above and below a confining unit defined initial estimates in the MODFLOW model. Specific storage was specified initially as $3 \times 10^{-6}$ m$^{-1}$ in all units because storage estimates from field data and analytical solutions were unreliable.

Parameter estimation worked better where initial hydraulic conductivity estimates were within 1 to 2 orders of magnitude of the best estimates because the general shape of the measured drawdowns was simulated initially. For example, the flattening of a drawdown curve is controlled by the hydraulic conductivity and specific storage of a confining unit (Figure 2). 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.

## Numerical Model

The aquifer system and pumping wells are simulated with an axisymmetric, radial geometry in a one-layer

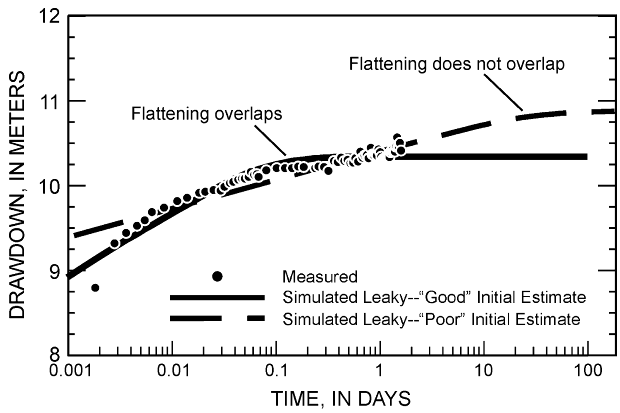


**Figure 2. Effect of poor initial parameter estimates on model fit and final estimates.**

MODFLOW model. Radial distance increases with increasing column indexes, and depth increases with increasing row indexes. Hydraulic conductivities and storage coefficients 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. Axisymmetric, radial flow previously was solved with MODFLOW by using many layers and a single row (Reily and Harbaugh 1993; Clemo 2002). A single MODFLOW layer is more convenient because input is defined easily, all conductances are computed within the BCF package, and output is checked quickly.

Vertical discretization typically is coarse for aquifers and fine for confining units. Aquifers with fully penetrating production wells are defined with a primary row that simulates most of the thickness and two 0.003-m-thick rows above and below the primary row. Thin rows restrict the volume of an aquifer system where hydraulic conductivity is defined by aquifer and confining unit properties, which simplifies interpretation of hydraulic property estimates. Confining units are defined with uniform hydraulic properties but are discretized variably into 20 rows or more to simulate drawdown adequately. Rows range in thickness from 1% to 10% of the total thickness of a confining unit, with the thinnest rows being adjacent to contacts between aquifer and confining unit.

Vertical gradients are simulated by uniformly dividing the unconfined aquifer into at least 20 rows. Vertical flow exists at the top of the geohydrologic column because the production well penetrates partially and the water table drains. The production well is simulated as a high-conductivity zone in column 1 that spans multiple rows (Halford 1997). Water is removed from the uppermost node in a well, and MODFLOW distributes flow to the other cells that represent the well.

Multiple aquifer tests are simulated within a single model by using multiple stress periods. For example, drawdowns during three aquifer tests within a geohydrologic column would be simulated by using three stress periods. Elapsed time and off-site stresses between aquifer tests are not simulated. Effects of off-site stresses are assumed to be eliminated when drawdowns are estimated, so heads are initialized to zero at the beginning of each stress period.

## Parameter Estimation and Observations

Parameter estimation is performed by MODOPTIM (Halford 1992), which is an optimization routine coupled to MODFLOW. MODOPTIM minimizes weighted sum-of-squares differences between simulated and measured drawdowns. MODOPTIM differs from other parameter estimation programs such as UCODE (Poeter and Hill 1998), MODFLOW-2000 (Harbaugh et al. 2000), or PEST (Doherty 2004) by automatically excluding insensitive parameters.

Weighted differences are in the objective function 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 about equally significant in nearby and distant wells. In the examples presented herein, 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. Entire time series from a well during an aquifer test were weighted uniformly.

Drawdowns also were weighted implicitly by subsampling of the original time series. As many as 2000 observations from an aquifer test were reduced to ~80 observations. The data were reduced primarily so that time series could be analyzed quickly. Three periods, 0–0.02 d, 0.02–0.3 d, and 0.3 d to pump-off, were sampled uniformly 7, 35, and 35 times, respectively. Fewer observations were sampled during the first 30 min to reduce the influence of wellbore storage effects in observation wells.

Simulated and measured drawdown differences in pumping wells only are compared after entry head losses stabilize, which usually occurs between 15 and 30 min after pumping commences (Figure 3). Drawdown differences are matched because late-time changes are controlled by the hydraulic characteristics of the aquifer system, not well construction or partial-penetration effects. Fitting a drawdown difference is equivalent to estimating the slope of drawdown as is done with a Cooper-Jacob analysis. Explicit simulation of head losses to production wells is unnecessary, and skins for production wells do not need to be estimated.

Analyzing multiple aquifer tests with a single model requires good bookkeeping of drawdowns and observation positions. Many drawdown time series are estimated for each aquifer test because water level changes are observed in the pumped and adjacent aquifers. Multiple drawdown time series can exist for a well because water levels respond to multiple aquifer tests. These drawdowns are best tracked as independent sites because radial distances between a pumping well and observation wells differ between aquifer tests. Each drawdown time series can be written to a separate file that is named after the pumped aquifer and well. For example, a file named OBSERVE_ROMP12-AvonPark_MW9.txt would contain drawdowns in well MW9 from pumping in the Avon Park Aquifer at the ROMP 12 site.

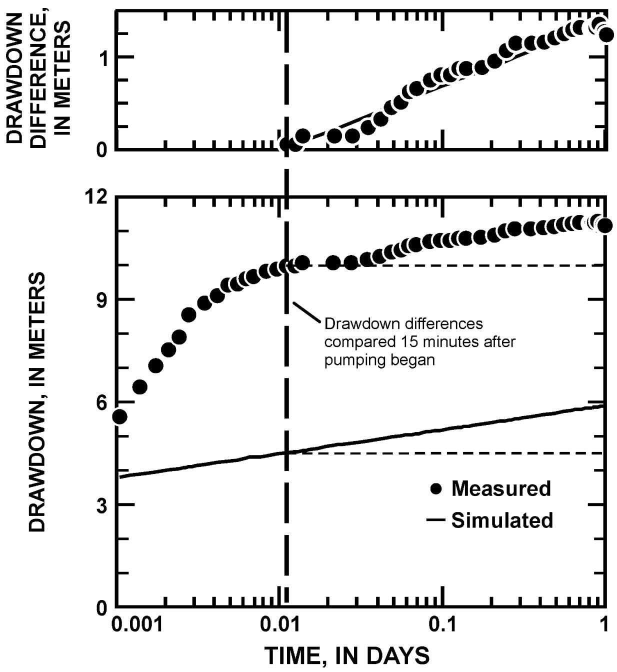


**Figure 3. Entry losses in production wells cause measured drawdowns to be greater than simulated drawdowns, which can be negated by comparing drawdown differences.**

## Application to ROMP 12

Fourteen wells were completed at the ROMP 12 site (Figure 1) and ranged from 0.05 to 0.3 m in diameter (Figure 4). The deepest well, MW10_AvPk, was drilled to 430 m below land surface. Six aquifer tests were conducted at ROMP 12 between July 1997 and September 1998 (Table 1). Pumping rates were least from the surficial aquifer at 120 $m^3$/d and were greatest from the lower part of the Upper Floridan Aquifer (UFA) (Avon Park Formation) at 28,000 $m^3$/d. About 160,000 $m^3$ were discharged cumulatively from all six aquifer tests.

The geologic framework that forms the aquifer systems at ROMP 12 consists of undifferentiated surficial deposits and heterogeneous clastic and marine deposits comprising the Hawthorn Group, and laterally extensive carbonates comprising the Suwannee Limestone, Ocala Limestone, and Avon Park Formation (Clayton 1999). Stratigraphic and hydraulic units forming the geohydrologic framework were delineated using lithologic and geophysical logs, water levels, and water quality data, and hydraulic characteristics from the ROMP 12 test site.

The intermediate aquifer system and the Upper Floridan Aquifer are the principal geohydrologic units that underlie ROMP 12 (Figure 4). The intermediate aquifer system is a 200-m-thick sequence of clastic sediments interbedded with calcareous materials (Tables 2 and 3). Interbedded clay and finer-grained clastics form the confining units that separate the carbonate rock aquifers (Clayton 1999). The intermediate aquifer system is divided into three transmissive zones, the upper (PZ1),

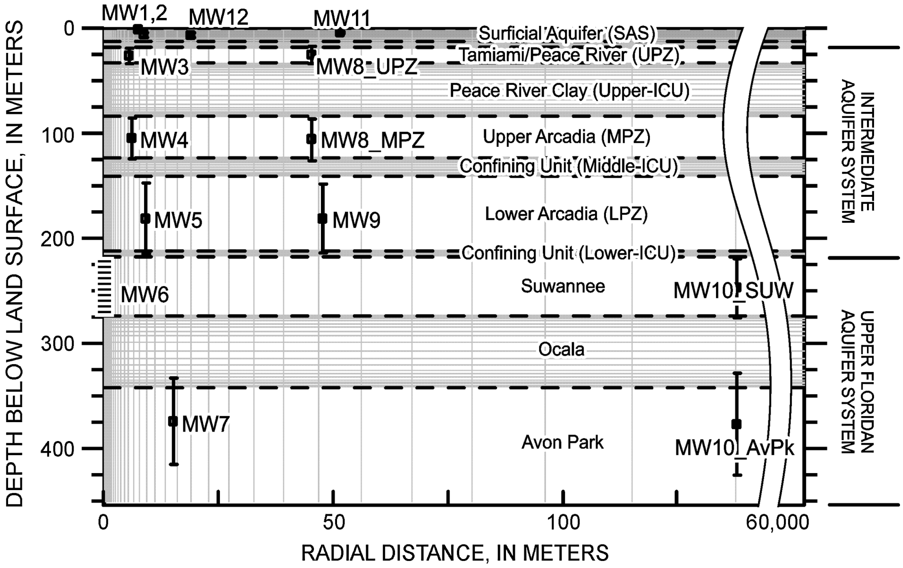


**Figure 4. Geohydrologic column at the ROMP 12 site, MODFLOW grid near the production wells, and radial distances between observation wells and production well MW6 that were used during stress period 5, the Suwannee Aquifer test.**

middle (PZ2), and lower (PZ3). The primary producing interval within the intermediate aquifer system is in the Lower Arcadia Formation (PZ3).

The Upper Floridan Aquifer is the lowermost aquifer underlying the ROMP 12 site and consists of a 420-m-thick, stratified sequence of limestone and dolomite. The Upper Floridan Aquifer is divided into two transmissive zones, the shallow and deep. The producing interval within the shallow Upper Floridan Aquifer is in the Suwannee Limestone, whereas the producing interval within the deep Upper Floridan Aquifer is in the Avon Park Formation. The Ocala Limestone is less permeable than the adjacent Suwannee Limestone and Avon Park Formation and is a confining unit in the Upper Floridan Aquifer. Chloride concentrations exceed 300 mg/L in the Suwannee Limestone and range from 450 to 18,000 mg/L in the Avon Park Formation.

Thirty drawdown time series from the six aquifer tests at ROMP 12 were compared (Table 1). Drawdowns at the end of each aquifer test ranged from ~5 to 15 m in the pumping wells and ranged from <0.06 to 1.5 m in the observation wells. Drawdowns were attenuated greatly by confining units. For example, pumping 4000 $m^3$/d from MW6 caused 0.9 m of drawdown 120 m away in the Suwannee Aquifer and 0.15 m of drawdown <15 m away in adjacent aquifers (Figure 5).

Drawdowns were estimated by subtracting measured water levels from concurrent water levels in other aquifers that were not directly adjacent to the pumped aquifer. Water levels in other aquifers were assumed equivalent to unpumped water levels during a test. This approach was deficient because background water level fluctuations exceeded drawdowns that were observed outside of the pumped aquifer (Figure 5). Undefined regional trends caused apparent drawdown decreases between 0.5 and 2 d, which is inconsistent with any conceptual model. Drawdown was not estimated with better methods because antecedent information generally was unavailable.

## Numerical Model of ROMP 12

Hydraulic conductivity and specific storage were estimated for six aquifers and five confining units in the geohydrologic column of ROMP 12 (Figure 4) by fitting simulated drawdowns to measured drawdowns from the six aquifer tests. Drawdowns were simulated with a

**Table 1**
**Date, Stress Period, Duration, Pumping Rate, Number of Observation Wells, and RMS Error of the Six Aquifer Tests That Defined the Geohydrologic Column at ROMP 12**

| Aquifer | Abbreviation | Start of Test | Stress Period | Duration (h) | Discharge ($m^3$/d) | Observation Wells | RMS (m) |
|---|---|---|---|---|---|---|---|
| Surficial | SAS | July 22, 1997 | 1 | 31 | 120 | 3 | 0.01 |
| IAS-PZ1 | UPZ | August 31, 1998 | 2 | 50 | 1400 | 4 | 0.02 |
| IAS-PZ2 | MPZ | July, 13 1998 | 3 | 75 | 260 | 4 | 0.04 |
| IAS-PZ3 | LPZ | June 8, 1998 | 4 | 121 | 4900 | 7 | 0.01 |
| UFA-Suwannee | SUW | May 12, 1998 | 5 | 145 | 4000 | 7 | 0.02 |
| UFA-Avon Park | AvP | November 2, 1997 | 6 | 91 | 28,000 | 5 | 0.02 |

**Table 2**
**Lateral Hydraulic Conductivity and Specific Storage Estimates**

| | | | Hydraulic Conductivity (m/d) | | | Specific Storage ($m^{-1}$) | |
|---|---|---|---|---|---|---|---|
| Aquifer | Abbreviation | Thickness (m) | Cooper-Jacob | Leaky | MODOPTIM | Leaky | MODOPTIM |
| Surficial | SAS | 12 | 3.0 | —[1] | 3.9 | —[1] | $6 \times 10^{-6}$ |
| IAS-PZ1 | UPZ | 15 | 38 | 10 | 30 | $5 \times 10^{-5}$ | $6 \times 10^{-7}$ |
| IAS-PZ2 | MPZ | 40 | 2.8 | 0.4 | 1.6 | $2 \times 10^{-5}$ | $2 \times 10^{-5}$ |
| IAS-PZ3 | LPZ | 71 | 63 | 8.4 | 56 | $7 \times 10^{-8}$ | $5 \times 10^{-7}$ |
| UFA-Suwannee | SUW | 57 | 25 | 5.9 | 8.2 | $3 \times 10^{-8}$ | $3 \times 10^{-6}$ |
| UFA-Avon Park | AvP | 290 | 380 | 290 | 460 | $3 \times 10^{-6}$ | $3 \times 10^{-6}$ |

Note: Specific storage estimates in excess of $2 \times 10^{-5}$ $m^{-1}$ are not reasonable.
[1]not determined.

two-dimensional, radial MODFLOW model (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996). Aquifers and confining units were discretized with rows. Parameter estimation was performed by minimizing a weighted sum-of-squares objective function with MODOPTIM (Halford 1992).

The model extended from the production wells to 60,000 m away and from the water table to 640 m below land surface. The model domain was discretized into a layer of 135 rows of 69 columns (Figure 4). Cell widths ranged from 0.06 m adjacent to the production well to 10,000 m in the farthest column. Vertical discretization also was variable and finer across the confining units. All external boundaries were specified as no-flow. The base of the model coincides with the base of the Avon Park, which is assumed impermeable. Changes in the wetted thickness of the aquifer were not simulated because the maximum drawdown of 0.3 m near the water table was small relative to the 12-m thickness of the surficial aquifer.

Each of the six aquifer tests (Table 1) was simulated with a 10-d stress period in a single radial model. Heads throughout the model were set to zero and pumping well locations moved at the start of each stress period. Stress periods of 10 d were specified for convenience, so drawdown observation time would be equivalent to elapsed time during each successive test plus a multiple of 10 d. Two stress periods would be needed for each aquifer test if recovery data were also analyzed. Heads would be set to zero after the second stress period, which simulated recovery. Results would be analyzed more easily if the combined time of the drawdown and recovery stress periods were a uniform multiple for all aquifer tests analyzed.

Differences between simulated and measured drawdowns were minimized by estimating 23 parameters. Lateral hydraulic conductivities of the five confining units and six aquifers comprised 11 of the parameters. Specific storage of the same geohydrologic units comprised 10 additional parameters. Specific storage of the two shallowest confining units was defined with a single parameter because their lithologies were similar and highly correlated. Vertical anisotropy and specific yield of the surficial aquifer comprised the last two parameters. Vertical hydraulic conductivity of all units other than the surficial aquifer was assigned uniformly as 0.1 of horizontal hydraulic conductivity. An assumed vertical anisotropy of 0.1, as opposed to 1, was assigned because bedding existed in all units.

Simulated drawdowns matched measured drawdowns reasonably well during most aquifer tests with a root-mean-square (RMS) error of 0.02 m. RMS errors of individual aquifer tests ranged from 0.01 m for the surficial and lower permeable zone (LPZ) to 0.04 m for the middle permeable zone (MPZ) aquifer test (Table 1).

The fit between simulated and measured drawdowns from the UFA-Suwannee Aquifer test was typical of results from the other five tests (Figure 5). An RMS error of 0.02 m for the UFA-Suwannee Aquifer test was similar to the noise in the measured drawdowns. Apparent

**Table 3**
**Vertical Hydraulic Conductivity and Specific Storage Estimates**

| | | | Hydraulic Conductivity (m/d) | | Specific Storage ($m^{-1}$) | |
|---|---|---|---|---|---|---|
| Confining Unit | Abbrev. | Thickness (m) | Leaky | MODOPTIM | Leaky | MODOPTIM |
| UpperUpper-ICU | UUI | 5 | 0.1 | 0.0002 | $1 \times 10^{-6}$ | $1 \times 10^{-5}$ |
| Upper-ICU | UIC | 52 | 0.2 | 0.01 | $2 \times 10^{-6}$ | $1 \times 10^{-5}$ |
| Middle-ICU | MIC | 18 | 0.2 | 0.02 | $1 \times 10^{-2}$ | $6 \times 10^{-6}$ |
| Lower-ICU | LIC | 6 | 0.1 | 0.04 | $8 \times 10^{-4}$ | $6 \times 10^{-6}$ |
| Ocala-UFA | Oca | 69 | 6 | 0.7 | $8 \times 10^{-1}$ | $4 \times 10^{-6}$ |

Note: Specific storage estimates in excess of $2 \times 10^{-5}$ $m^{-1}$ are not reasonable.

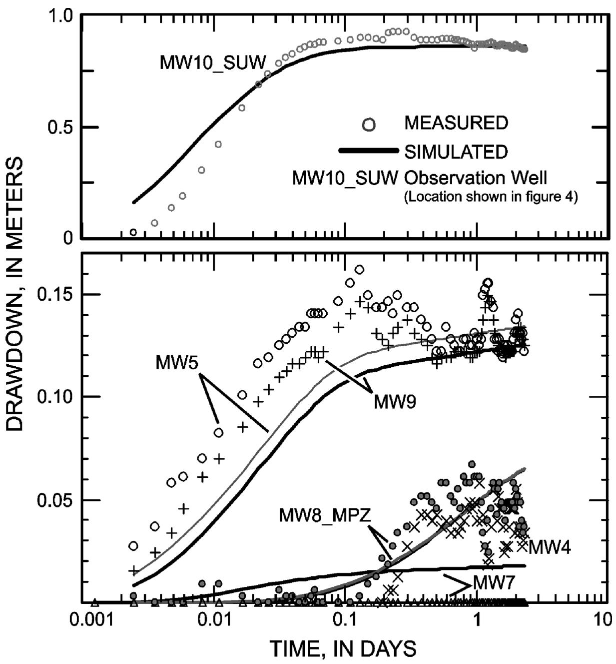


**Figure 5. Simulated and measured drawdowns for the Suwannee Aquifer test, May 12–14, 1998. Test was simulated in stress period 5 of the six stress periods. Elapsed simulation time was 40 d at the start of the Suwannee Aquifer test.**

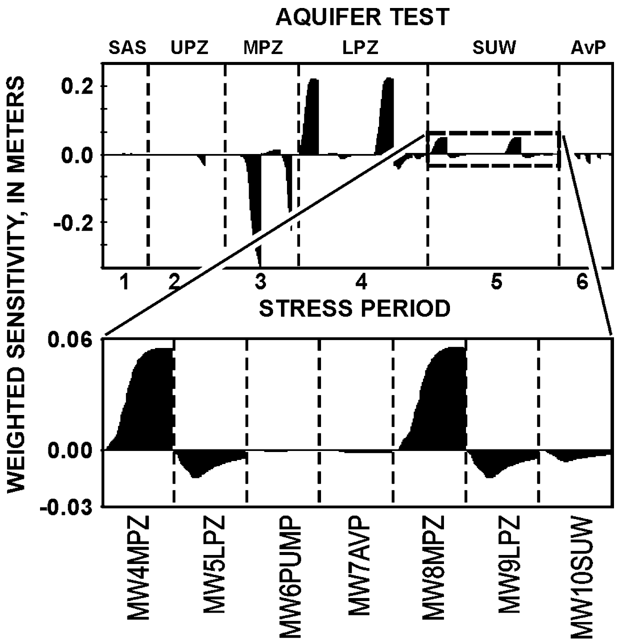


**Figure 6. Weighted sensitivities of each drawdown for hydraulic conductivity of the middle-ICU.**

declines in drawdown during the last day of the test resulted from regional water level increases, not changes in the pumping rate of well MW6. Antecedent water level data were insufficient to filter regional trends from the measured drawdowns. Slight biases can appear between simulated and measured drawdowns from any one aquifer test because not all comparisons are depicted. Only 6 of the 30 time series in the objective function for ROMP 12 appear in the Suwannee Aquifer test (Figure 5).

Results from more than one aquifer test affected all hydraulic property estimates. Estimates of confining unit hydraulic properties were influenced most by results from tests in adjacent aquifers but not exclusively. For example, hydraulic conductivity of the middle Intermediate Confining Unit (middle-ICU) was affected most by tests in the MPZ and LPZ aquifers (Figure 6). Observations in wells MW4 and MW8 during the Suwannee Aquifer test also affected estimates of hydraulic conductivity of the middle-ICU (Figure 6). Lateral hydraulic conductivity, vertical anisotropy, specific storage, and specific yield of the surficial aquifer were determined almost exclusively with results from the surficial aquifer test.

## Hydraulic Property Estimates

Lateral hydraulic conductivities of the aquifers that were estimated with Cooper-Jacob, leaky aquifer, or MODOPTIM differed by <1 order of magnitude (Table 2). MODOPTIM estimates typically were between estimates from Cooper-Jacob and leaky aquifer solutions. Hydraulic conductivity of Avon Park that was estimated with MODOPTIM exceeded the analytical estimates. The MODOPTIM estimate likely is better than the analytical estimates because information from the LPZ and UFA-Suwannee tests also affected hydraulic conductivity and specific storage of the UFA-Avon Park in the geohydrologic column.

Vertical hydraulic conductivities of confining units were estimated consistently less with MODOPTIM than with the leaky aquifer solution (Table 3). MODOPTIM estimates ranged from 3 to 10 times less than the leaky aquifer solution estimates of vertical hydraulic conductivities. The MODOPTIM estimates appeared more reasonable because related specific storage estimates deviated less from expected values of $0.3 \times 10^{-6}$ to $1 \times 10^{-5}$ m$^{-1}$.

## Conclusions

A new approach has been presented for consistently estimating the hydraulic properties of a geohydrologic column using a moving MODFLOW model and data from multiple aquifer tests. The many hydraulic properties that define a geohydrologic column are estimated with MODOPTIM, which minimizes a weighted sum-of-squares objective function. Hydraulic conductivity and specific storage estimates for all aquifers and confining units were consistent and reasonable because results from multiple aquifer tests were analyzed simultaneously. Vertical hydraulic conductivity estimates are directly comparable to properties in a regional ground water flow model, which makes the results more applicable than individual analyses from multiple analytical solutions.

Furthermore, layered sequences within an aquifer also can be analyzed with the geohydrologic column approach. Hydraulic conductivity changes with depth can be differentiated with multiple aquifer tests where pumping intervals are from different depths, which may overlap. All aquifer tests can be interpreted with a single, moving model if the layered sequences are flat lying, homogeneous, and isotropic. Simulating multiple aquifer tests with a single model facilitates better parameter estimation because a single, self-consistent set of hydraulic properties is estimated.


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