Effects of Unsaturated Zone on Aquifer Test Analysis in a Shallow-Aquifer System

by Keith J. Halford[a]

Abstract

A comparison between two hypothetical flow models of an unconfined aquifer, one saturated and the other variably saturated, indicates that the variably saturated model which explicitly models drainage from the unsaturated zone provides a better conceptual framework for analyzing unconfined aquifer test data and better estimates of the lateral and vertical hydraulic conductivity in fine-grained sands. Explicitly accounting for multiple aquifers, well-bore storage, and the effects of delayed drainage from the unsaturated zone increases confidence in aquifer property estimates by removing some assumptions and allowing for the inclusion of early time data and water-table observations in an aquifer test analysis. The inclusion of the unsaturated zone expands the number of parameters to be estimated, but reasonable estimates of lateral and vertical hydraulic conductivity and specific storage of the unconfined aquifer can be obtained. For the cases examined, only the van Genuchten parameter α needed to be determined by the test, because the parameters n and θ_r had a minimal effect on the estimates of hydraulic conductivities, and literature values could be used for these parameters. Estimates of lateral and vertical hydraulic conductivity using MODFLOW were not as good as the VS2DT based estimates and differed from the known values by as much as 30 percent.

The hydraulic properties of a surficial aquifer system were estimated through a series of aquifer tests conducted at Cecil Field Naval Air Station in Jacksonville, Florida. Aquifer test results were analyzed by calibrating a variably saturated, radial flow model to the measured drawdowns. Parameter estimation was performed by minimizing the difference between simulated and measured drawdowns with an optimization routine coupled to VS2DT and was constrained by assuming that the hydraulic properties of each aquifer or confining unit were homogeneous. Given the hydrogeologic conditions at the field site, estimating the hydraulic properties of the aquifers and confining units with analytically derived type curves would have been inappropriate. Estimates of the lateral hydraulic conductivity from the VS2DT solution were more consistent with the observed geology than estimates from Theis analyses, which ranged from 20 to 80 percent more than the final estimates. The unsaturated zone affected an aquifer test conducted in a leaky aquifer about 100 feet below land surface more than the other two aquifer tests because about half of the pumped water came from the overlying, unconfined aquifer.

Introduction

Previous researchers have had conflicting opinions about the importance of considering the unsaturated zone when analyzing data from unconfined aquifer tests. Neuman (1979) assumed that the gravity drainage phase of drawdown response in an unconfined aquifer is not seriously affected by unsaturated flow. A numerical investigation (Sophocleous, 1985) showed that simulated water-table rise in response to recharge events can be underestimated based on specific yield, instead of explicitly simulating the unsaturated zone. Akindunni and Gillham (1992) demonstrated with lab and field data that neglecting unsaturated flow can significantly affect estimates of specific yield. Moench (1994), however, estimated the lateral and vertical hydraulic conductivities and specific yield of three unconfined aquifers using the Neuman model and concluded that the unsaturated zone could be ignored.

The purpose of this paper is to show that the interpretation of aquifer tests in a shallow-aquifer system at Cecil Field Naval Air Station, Jacksonville, Florida, is improved by fitting drawdowns to a model that explicitly simulates flow from the unsaturated zone. This is achieved by comparing the differences between saturated and variably saturated models, estimating the known properties of a hypothetical aquifer with both a saturated and variably saturated model, and interpreting a series of aquifer tests in a shallow-aquifer system. The shallow-aquifer system is comprised of three distinct aquifers separated by two leaky confining units, and extends to about 230 feet (ft) below land surface.

Methods

Analysis of time-drawdown data from the shallow-aquifer system at Cecil Field Naval Air Station, Jacksonville, Florida, required a model that accounted for the shallowest aquifer being unconfined and for a hydraulic connection with deeper aquifers. The assumptions of the most common analytical models, the Theis (1935) solution for confined aquifers, the leaky aquifer (Hantush and Jacob, 1955), and the Neuman (1975) solution for unconfined aquifers, are not met by this shallow-aquifer system. Two of the three aquifer tests were simultaneously affected by compressible, leaky confining units, drainage from the unsaturated zone, and a shallow water table. Given the hydrogeological conditions at the field site, estimating the hydraulic properties of the aquifers and confining units with analytically derived type curves would have been inappropriate. Thus, a numerical model provided a more tractable solution.

Modeling

Two numerical models were considered, MODFLOW (McDonald and Harbaugh, 1988) and VS2DT (Healy, 1990). Both models can simulate multiple aquifers, confining units, and well-bore storage by simulating the well bore as a high conductiv-

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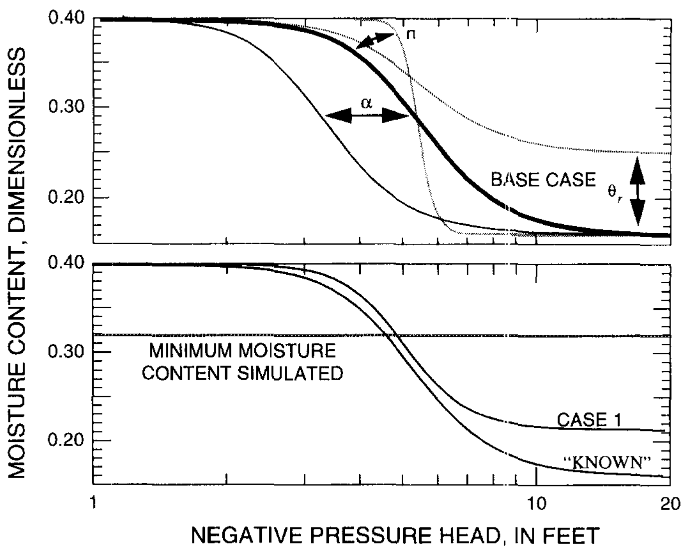

Fig. 1. The effects of varying α, n, and θ_r on the moisture content-negative pressure head relation and the known and best estimate moisture content-negative pressure head relations.

ity zone with a specific storage of one. However, they differ in their treatment of drainage at the water table. MODFLOW is a saturated-flow model and treats drainage as a function of specific yield only. VS2DT is a variably saturated model and incorporates the unsaturated zone explicitly.

A drawback of explicitly simulating the unsaturated zone is that a greater number of parameters must be estimated. Equations that define the hydraulic response of the unsaturated zone typically require three to four parameters to relate moisture content, specific moisture capacity, and relative hydraulic conductivity to pressure head. The van Genuchten (1980) equations are one set that is used in VS2DT which describe finer grained materials better than the Brooks and Corey equations (Lappala et al., 1987). Four additional parameters are needed in the van Genuchten equations to describe moisture content as a function of pressure head:

$$\theta(h) = \left[\frac{1}{1 + (-h\alpha)^n} \right]^{[1-(1/n)]} (\phi - \theta_r) + \theta_r \qquad (1)$$

where θ is the moisture content, dimensionless; h is the pressure head, ft; α is the scaling factor, ft^{-1}; n is a fitting exponent, dimensionless; ϕ is the porosity, dimensionless; and θ_r is the residual moisture content, dimensionless.

The effects of changes in these parameters can best be demonstrated by examining how they affect the moisture content-pressure head relation, equation (1). The scaling factor α primarily determines at what pressure head significant desaturation will occur (Figure 1), and increases as soils become more clayey. The fitting exponent, n, defines the pressure range over which moisture content will go from saturation to the residual moisture content, θ_r. This range is the drainable pore volume and is analogous to specific yield (Sophocleous, 1985). When n is slightly greater than 1, moisture content varies over a large pressure range. As the value of n increases, the pressure range decreases (Figure 1) and becomes a step function for $n = \infty$. Typical values of n range from about 1.5 for clays to more than 6 for clean sands (Lappala et al., 1987). In light of equation (1), the effects of the unsaturated zone will be more pronounced in aquifers with higher silt and clay content where the pressure range between water table and residual moisture content is greater than in coarse sands and gravels.

Optimization

Parameter estimation was performed with an optimization routine (Halford, 1992) coupled to VS2DT. The sum-of-squares objective function is,

$$SS = \sum_{i=1}^{nobs} [(\hat{s}_i - s_i)\, w_i]^2 \qquad (2)$$

where nobs is the number of observation; $\hat{s}_i$ is the i^{th} simulated drawdown; s_i is the i^{th} measured drawdown; and w_i is the i^{th} weight. The objective function is minimized by a quasi-Newton search procedure (Gill et al., 1981) that solves for log-parameter change. The log-parameters, log(x), were estimated because the parameters, x, are usually lognormally distributed. Consequently, all sensitivities, covariances, and correlation coefficients are based on $[\partial/(\partial \log x)]\hat{s}$, not $[\partial/(\partial x)]\hat{s}$. The weights were used to increase model sensitivity to observations in wells with small drawdowns. The assignment of weights for each well was subjective, but roughly corresponded to the square root of the maximum drawdown in all the observation wells divided by the maximum drawdown in that well.

The sensitivity of the model to the estimated parameters is defined by the main diagonal of the covariance matrix,

$$C_{i,i} = \sum_{i=1}^{nobs} \left(\frac{\partial \hat{s}_k}{\partial \log x_i} w_i \right)^2.$$

The off-diagonal components, $C_{i,j}$, describe the degree of interdependence between parameters, which is evaluated by the correlation coefficients,

$$\rho_{i,j} = \frac{C_{i,j}}{[C_{i,i}\, C_{j,j}]^{1/2}}.$$

Correlation coefficients greater than 0.95 usually indicate that a pair of parameters are highly correlated and cannot be estimated independently (Hill, 1992).

Root-mean-square,

$$RMS = \left[\frac{SS}{\Sigma w_i^2} \right]^{1/2},$$

error is reported also because it is physically more meaningful than SS error and serves as a composite of the average and standard deviation of a set. RMS error is useful for comparing several models based on different sets of observations and estimated parameters.

Field Site

The aquifer test site is located along the western perimeter of Cecil Field Naval Air Station (Figure 2). The shallow-aquifer system comprises three distinct aquifers: the surficial sand, the upper rock, and the lower rock; separated by two confining units: the blue marl and the gray marl (Figure 3). The surficial sand aquifer is comprised of silty sand with interbedded clay lenses that are about one foot thick. The upper rock and lower rock aquifers are layered composites of limestone and sand. The first 10 to 20 feet of the blue marl is usually a blue-green clay which grades to a mixture of sand, shell, and clay at the top of the upper rock aquifer. The gray marl consists of a gray clay

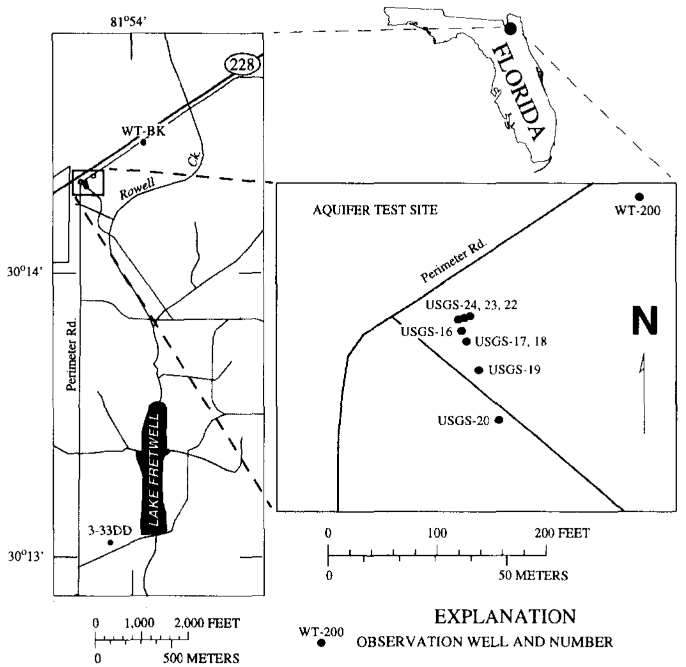

Fig. 2. Location of aquifer test site at Cecil Field Naval Air Station, background observation wells, and nearby hydrologic features.

interspersed with phosphatic sand stringers. The base of the shallow-aquifer system is the intermediate confining unit that separates the shallow-aquifer system from the Upper Floridan aquifer. The intermediate confining unit extends from about 230 to 450 ft below land surface near Cecil Field Naval Air Station and is comprised of marine clays and discontinuous limestone stringers.

The lateral flow direction at the site is south-southeast towards a small drain and Rowell Creek (Figure 2) in the surficial sand aquifer and due south toward an unnamed, more deeply incised creek in the upper rock and lower rock aquifers. The normal vertical gradients are downward throughout the shallow-aquifer system at the test site. The potentiometric surfaces of the upper rock aquifer, lower rock aquifer, and Upper Floridan aquifer are usually about 2 ft, 6 ft, and 30 ft lower than that of the water table, respectively (Figure 4). Upper Floridan water levels are not shown in Figure 4.

Three production wells and eight observation wells were used for the tests (Table 1). The configuration of the three production wells and the six wells nearest the production wells are shown in Figures 2 and 3. Two other wells monitor background-water levels for detrending water-level responses measured in the surficial sand and upper rock aquifers. These wells, WT-BK and 3-33DD, are screened across the water table 1,500 ft away and in the upper rock aquifer 8,500 ft away from the site, respectively (Figure 2).

Field Procedures

Water levels were continuously monitored with pressure transducers in wells screened in the aquifer being stressed and in adjacent aquifers during each test. The continuously monitored wells were checked by periodically making manual meausurements in all wells prior to, during, and after stressing the aquifer.

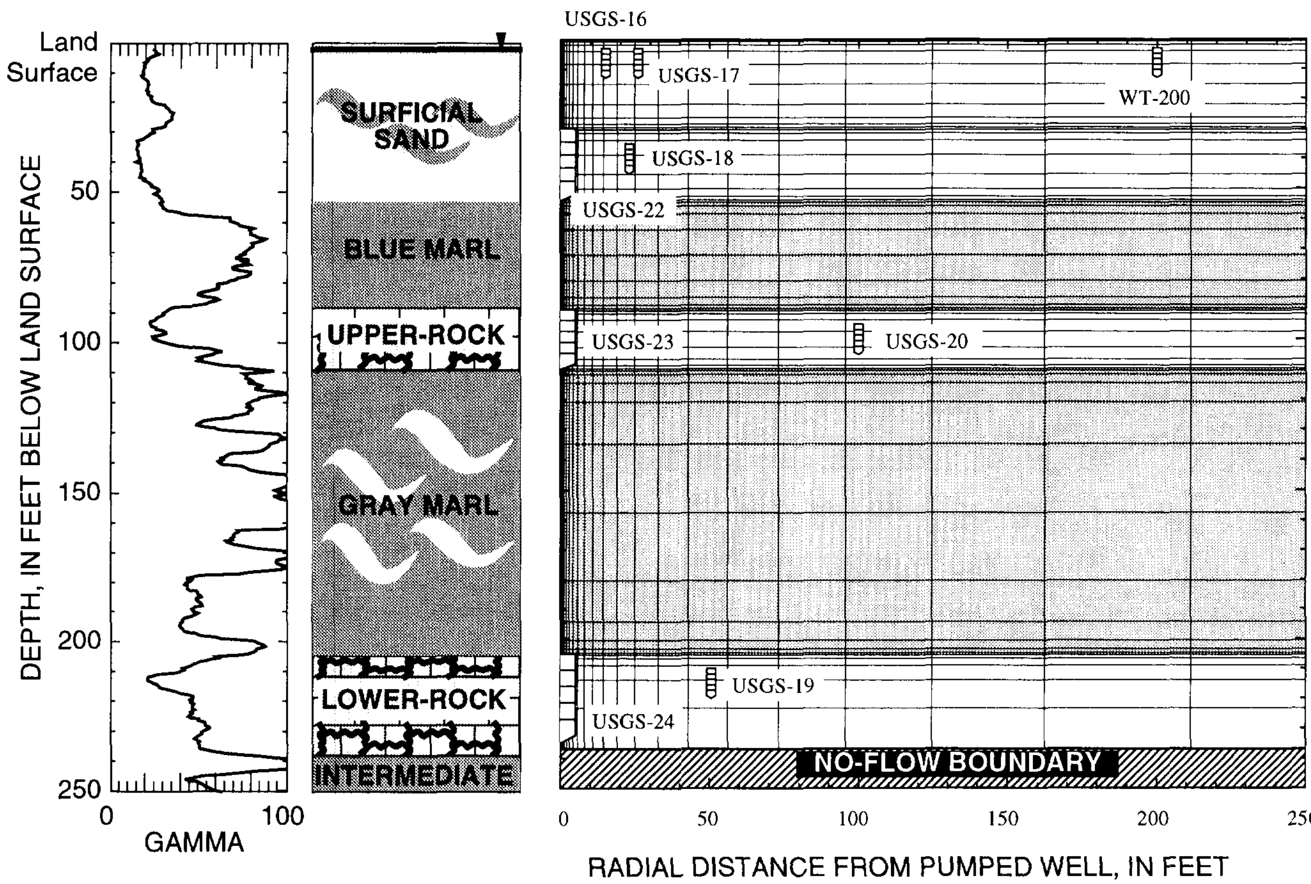

Fig. 3. Gamma log, geologist's log, and a cross section showing well placement and model grid within 250 ft of the wells pumped for the aquifer tests at Cecil Field Naval Air Station.

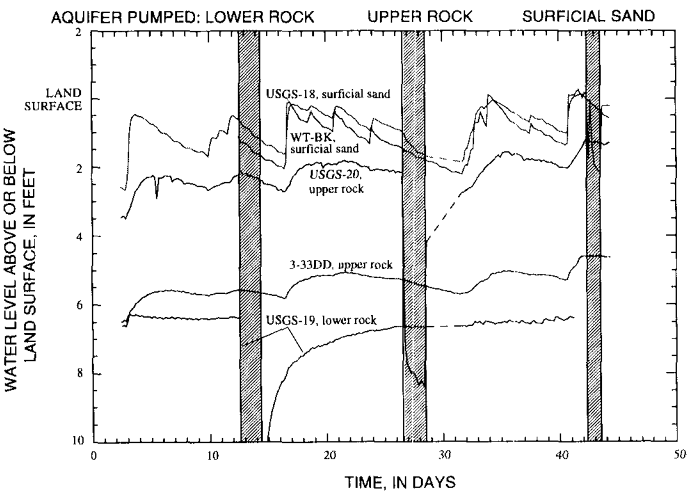

Fig. 4. Measured water-level change at selected observation wells during the aquifer tests.

Water levels were logged every 30 minutes in the two background wells, WT-BK in the surficial sand and 3-33DD in the upper rock aquifers. Drawdowns were estimated by subtracting the water-level change after pumping started in wells at the test site from the water-level change in the background well screened in the same aquifer. A background well for the lower rock aquifer did not exist and it was assumed no trend existed in that aquifer during any of the tests. This appears reasonable on the basis of water levels shown for well USGS-19 in the lower rock aquifer in Figure 4.

Flow rates were continuously monitored by measuring the pressure drop across a constriction in the discharge line, and were checked with periodic discharge measurements using a stop watch and container. All produced water was discharged to a small tributary of Rowell Creek (Figure 2), located about 400 ft south of the production wells.

Testing Effects of Unsaturated Zone with a Hypothetical Aquifer

The importance of explicitly simulating the unsaturated zone was tested by comparing two radially symmetric, hypothetical models that have identical saturated hydraulic characteristics, spatial discretization, boundary conditions, initial conditions, and stresses, but differ in how drainage from the water table is simulated. The saturated flow approach (Neuman, 1975; McDonald and Harbaugh, 1988) uses specific yield to account for all drainage from the water table. This approach assumes that the shape of the moisture-content profile remains constant (equivalent to assuming that drainage is instantaneous) and that the depth-to-water has no effect. The variably saturated approach removes these assumptions but at the cost of additional parameters that need to be estimated or assumed. The saturated flow approach was simulated with MODFLOW and the variably saturated approach was simulated with VS2DT. A few additional rows were added to the VS2DT model to simulate the unsaturated zone with values of α, n, and θ_r that might be expected in a silty sand (Lappala et al., 1987). Wellbore storage was not simulated in either hypothetical model.

Although a hypothetical aquifer was simulated, the model geometries were based on the lithology of the shallowest aquifer beneath Cecil Field Naval Air Station and the well construction used at the test site (Figure 5). The production well was screened from 30 to 50 ft below land surface and was simulated as a high conductivity zone. Each model incorporated the well bore, r_w = 0.3 ft, and the cell lengths expanded radially as multiples of 1.29 to no-flow boundary 1,000 ft away in 27 columns. Vertically, the models were discretized in 2 ft intervals from the water table at 5 ft below land surface to the leaky base of the hypothetical aquifer at 50 ft below land surface. Both models had no-flow upper boundaries. The initial heads in the variably saturated model were set at static equilibrium. An additional two rows were added on the bottom to incorporate leakage from a confining unit. The saturated hydraulic characteristics (Table 2) of both models approximated the expected conditions at the test site. The models were stressed by simulating the removal of 5 gallons per minute (gpm) from the production well for three days and simulating water-level recovery for six days.

Drawdowns simulated in hypothetical observation points Hyp-24,2 and Hyp-24,32 (Figure 5) were the basis for comparing the two models. The drawdowns from MODFLOW and VS2DT at point Hyp-24,32 were similar throughout the entire nine-day simulation period (Figure 6), but the drawdowns from the two models at point Hyp-24,2 were different. The VS2DT simulated drawdowns at Hyp-24,2 were consistently greater than the MODFLOW ones and increased to 0.26 ft of difference at the end of the pumping period (Figure 6). The early time difference arises from VS2DT accounting for delayed yield, whereas

Table 1. Wells Used for Aquifer Tests at Cecil Field Naval Air Station

Well	*Interval screened, in feet below land surface*	*Diameter, in inches*	*Distance from production well, in feet*	*Aquifer*	*Weight assigned for aquifer test*		
					Surficial sand	*Upper rock*	*Lower rock*
USGS-22[a]	30-50	4	0	Surficial sand	NA	NA	NA
USGS-23[a]	90-110	6	0	Upper rock	NA	NA	NA
USGS-24[a]	202-232	6	0	Lower rock	NA	NA	NA
USGS-16	3-13	2	16	Surficial sand	NA	NA	NA
USGS-18	35-45	2	23	Surficial sand	1	4	NA
USGS-17	3-13	2	26	Surficial sand	2	4	NA
USGS-19	210-220	2	50	Lower rock	NA	10	1
USGS-20	95-105	2	100	Upper rock	NA	1	10
WT-200	3-8	2	200	Surficial sand	4	NA	NA
WT-BK	3-8	2	1,500	Surficial sand	NA	NA	NA
3-33DD	100-110	2	8,500	Upper rock	NA	NA	NA

[a]Well was pumped.

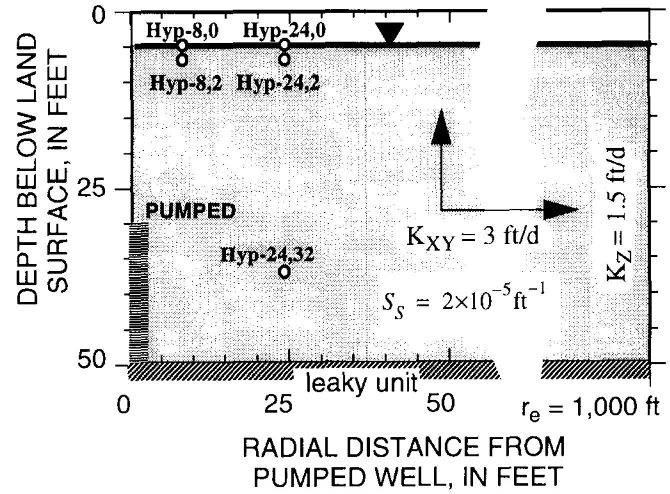

Fig. 5. Obvservation point locations and hydraulic properties of a hypothetical unconfined aquifer, but with wells and boundary conditions similar to that at the test site. The first number in the observation point name is the radial distance from the pumped well and the second number is the depth below the water table.

MODFLOW does not. At later times, part of this difference is due to the boundary effects of the capillary fringe not being fully developed because the water table is near land surface. The drawdown in Hyp-24,2 from another VS2DT simulation with 25 ft of unsaturated zone instead of 5 ft and the same initial saturated thickness comes close to converging with the MODFLOW solution after three days of pumping.

Drawdowns simulated by MODFLOW at the water table, the uppermost model layer, at Hyp-24,0 were not comparable in either shape or magnitude to either the MODFLOW or VS2DT drawdowns at Hyp-24,2 (Figure 6). The stress could be detected in minutes at Hyp-24,2 by both models whereas the results from MODFLOW at Hyp-24,0 would not indicate detection until after an hour. The large difference between points Hyp-24,0 and Hyp-24,2 suggest coarse discretization schemes should be avoided near the water table and measured, early time drawdowns should not be compared to MODFLOW simulated drawdowns in the uppermost layer.

The large early time drawdowns in water-table wells suggest that a variably saturated model would provide a better conceptual framework for analyzing the unconfined aquifer test data, based on the differences between the MODFLOW and VS2DT approximations of the water table during the first days of pumping. Moench (1994) suggests avoiding these problems by not using water-table wells; however, these wells are the easiest and most economical to install. In addition, that approach does not address boundary effects if the water table is close to land surface (Narasimhan and Zhu, 1993).

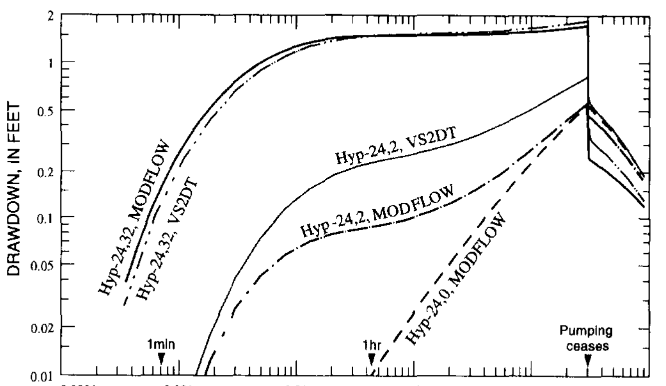

Fig. 6. Differences between drawdowns simulated by MODFLOW and VS2DT at observation points Hyp-24,0, Hyp-24,2, and Hyp-24,32 located 24 feet from the pumped well.

Parameter Estimation Applied to a Hypothetical Aquifer

Unconfined aquifers are usually described by four parameters: lateral and vertical hydraulic conductivity (K_{XY} and K_Z), specific storage (S_S), and specific yield (S_Y). The inclusion of the unsaturated zone expands the number of parameters to be estimated from four to six, assuming porosity is a known, where the three terms α, n, and the residual moisture content replaces specific yield. Porosity was not considered as a parameter to estimate because it can be measured directly.

The feasibility of estimating the six parameters, K_{XY}, K_Z, S_S, α, n, and θ_r, was tested by using the simulated drawdowns at points Hyp-8,2, Hyp-24,2, and Hyp-24,32 that were generated by VS2DT using the values labeled as "KNOWN" in Table 2 as measured values. A total of 99 observations were used, 33 from each observation point with 21 from the pumping period and 12 from the recovery period. Four sets of initial parameter estimates were made for VS2DT because some of the final parameter estimates are dependent on the initial estimates (Table 2).

The drawdowns produced by VS2DT with estimated parameters for cases 1, 2, 3, and 4 fit the "KNOWN" responses reasonably well (Figure 7, case 4) and the RMS error was reduced from greater than 0.3 ft to about 0.01 ft for all four cases (Table 2). The parameter estimates for K_{XY}, K_Z, and S_S were reasonable and could be reliably estimated (Table 2). The unsaturated flow parameters α, n, and θ_r were not as sensitive to the observed data and could not be reliably estimated. All of the unsaturated flow parameters (α, n, and θ_r) were highly correlated. Estimates of lateral and vertical hydraulic conductivity and specific storage were relatively independent of initial estimates, but the unsaturated flow parameters were affected by initial estimates (Table 2).

The lack of sensitivity to estimates of n and θ_r was expected. These parameters influence the moisture content/negative pressure head relation more as the moisture content decreases (Figure 1). Only a small portion of the moisture content/negative pressure head distributions (Figure 1) for either the "KNOWN" model or the test cases were used because the minimum simulated moisture content was 0.32. Estimation of these parameters could be improved by stressing the system longer and including moisture content data in the objective function (Gavalas et al., 1976; Watson et al., 1980).

By corollary, reasonable estimates of lateral and vertical hydraulic conductivity values can be made with only poor estimates of n and θ_r from literature values, as was done in hypothetical case 4 (Figure 7 and Table 2). Case 4 was further constrained by using only drawdowns from the pumping period. Estimates of 2.97 ft/d and 1.50 ft/d for the lateral and vertical hydraulic conductivity values do not differ greatly from the "KNOWN" values of 3.00 ft/d and 1.50 ft/d. If K_{XY} and K_Z are the parameters of interest, tests of shorter durations may be used to obtain estimates without frequent collection of cores to measure saturation changes.

Table 2. Known and Estimated Parameters that Define the Hydraulic Characteristics for a Hypothetical Unconfined Aquifer

	CASE		K_{xy}, ft/d	K_z, ft/d	S_s, 10^{-5} ft^{-1}	α, ft^{-1}	n	θ_r	S_y, $\phi - \theta_r$, $\phi = 0.4$	SS, ft^2	RMS[a], ft
VS2DT	1	INITIAL	1.50	3.00	0.50	0.25	7.0	0.20	0.20	15.0	0.39
		FINAL	3.03	1.48	1.99	0.21	6.5	0.21	0.19	0.005	0.007
	2	INITIAL	1.50	0.03	10.0	0.67	3.0	0.26	0.14	404.	2.01
		FINAL	2.97	1.50	2.05	0.30	3.7	0.22	0.18	0.015	0.012
	3	INITIAL	10.0	0.20	5.00	0.50	3.00	0.10	0.30	12.5	0.35
		FINAL	3.00	1.49	2.05	0.87	1.85	0.23	0.17	0.015	0.012
	4[b]	INITIAL	10.0	0.10	0.50	0.40	3.0[c]	0.10[c]	0.30	6.02	0.31
		FINAL	2.97	1.50	2.03	0.28	3.0[c]	0.10[c]	0.30	0.015	0.015
MODFLOW	5[d]	INITIAL	3.00	1.50	2.00	NA	NA	NA	0.24	2.85	0.17
		FINAL	4.87	0.76	1.92	NA	NA	NA	0.024	0.99	0.10
	6[e]	INITIAL	3.00	1.50	2.00	NA	NA	NA	0.24	1.97	0.14
		FINAL	2.91	1.30	2.06	NA	NA	NA	0.13	0.49	0.07
	7[b,d]	INITIAL	3.00	1.50	2.00	NA	NA	NA	0.24	2.40	0.19
		FINAL	5.81	0.62	1.82	NA	NA	NA	0.008	0.54	0.09
	8[b,e]	INITIAL	3.00	1.50	2.00	NA	NA	NA	0.24	1.44	0.15
		FINAL	2.29	1.59	1.93	NA	NA	NA	0.18	0.28	0.07
	9[b,e]	INITIAL	1.50	3.00	0.50	3.0[f]	NA	NA	0.20	5.23	0.29
		FINAL	3.17	1.27	2.14	0.40[f]	NA	NA	0.10	0.009	0.012
	10[b,e]	INITIAL	10.0	0.10	0.50	0.10[f]	NA	NA	0.30	6.38	0.32
		FINAL	3.87	1.04	2.13	0.26[f]	NA	NA	0.05	0.01	0.013
KNOWN			3.00	1.50	2.00	0.20	5.0	0.16	0.24		

[a]Based on 63 observations from the pumping period and 36 observations from the recovery period, if the recovery data were used. All observations were equally weighted.
[b]Only observations from the pumping period were used.
[c]Parameters were not estimated.
[d]The hypothetical observed water-table drawdowns were compared to MODFLOW simulated drawdowns at the water table.
[e]The hypothetical observed water-table drawdowns were compared to MODFLOW simulated drawdowns from layer 2 which is 2 feet below the water table.
[f]Number reported is the vertical hydraulic conductivity, ft/d, between layers 1 and 2 and served as a fitting parameter.

The unconfined aquifer parameters, K_{XY}, K_Z, S_S, and S_Y, were also estimated using MODFLOW to test if reasonable estimates of K_{XY} and K_Z could be obtained despite the limitations of a saturated flow model. The effects of three factors on parameter estimation were investigated: the inclusion of recovery data (cases 5 and 6) in addition to pumping data (cases 7 and 8); the comparison of measured drawdowns to simulated drawdowns in layer 1 (cases 5 and 7) or in layer 2 (cases 6 and 8); and the addition of an extra parameter to account for the effects of delayed yield (cases 9 and 10).

Better parameter estimates were obtained with cases that used both pumping and recovery data as shown by cases 5 and 6 compared to cases 7 and 8, respectively (Table 2). The inclusion of recovery data did not affect parameter estimates as much when "KNOWN" drawdowns were compared to simulated drawdowns that approximated the shape of the "KNOWN" drawdowns (Figure 7, case 8). The estimates of K_{XY} and K_Z from case 6 were 2.9 and 1.3 ft/d and did not differ greatly from the estimates for case 8, 2.3 and 1.6 ft/d. Although the inclusion of recovery data improved estimates of K_{XY} and K_Z in case 5 relative to case 7, both cases produced poor parameter estimates (Table 2) and did not fit the "KNOWN" drawdowns well (Figure

7, case 7), because simulated drawdowns from layer 1 were compared to the "KNOWN" responses. Both estimates of K_{XY} were more than 1.6 times greater than the "KNOWN" value of 3.0 ft/d, and both estimates of K_Z were about 0.5 times the "KNOWN" value of 1.5 ft/d.

In order to test if a fitting parameter could adequately account for the effects of delayed yield, the vertical hydraulic conductivity between layers 1 and 2 was used and estimated independently of K_Z in cases 9 and 10. Both cases matched the "KNOWN" drawdowns very well with RMS errors of about 0.01 ft and the difference between "KNOWN" and estimated drawdowns were similar to those shown for case 4 (Figure 7), which is a VS2DT simulation. Unfortunately, the estimates of K_{XY} and K_Z were not as good as those based on VS2DT and were affected by initial parameter estimates (Table 2). The estimates of K_{XY} ranged from about 1.06 to 1.29 times the "KNOWN" value of 3.0 ft/d, and K_Z values were underestimated by 0.69 to 0.85 times the "KNOWN" value of 1.5 ft/d.

For analyzing the unconfined aquifer test data at Cecil Field Naval Air Station, parameter estimation applied to a hypothetical aquifer suggests VS2DT can provide better estimates of K_{XY} and K_Z than MODFLOW. If MODFLOW were used instead of VS2DT, the estimates of K_{XY} and K_Z might differ by as much as 30 percent.

Analysis of Aquifer Tests at Field Site

One variably saturated model that spanned the entire shallow-aquifer system from land surface to the base of the lower rock aquifer was used to analyze all three tests. The entire vertical section was simulated for all test analyses to avoid prescribing boundary conditions within the section. This required a few iterations to update the parameters of adjacent aquifers not estimated during a given test.

The field-site model was vertically discretized into 54 rows extending from 0 to 237 ft below land surface (Figure 3). The thinnest rows were at the surface (0.25 ft) and the ends of the well bores (0.5 ft), where the greatest head changes were expected. The upper and lower boundaries of the model were no flow. These boundaries were considered reasonable because the top is at land surface and the bottom is the lower rock aquifer, which abuts a thick clay in the intermediate confining unit. Laterally, the model covered 10 miles from the production wells to a no-flow boundary along the outer circumference. The model included 42 columns, beginning with a 0.25 ft wide ring with each successive ring being 1.33 times wider than the previous one. The initial heads for a given test were at static equilibrium in the unsaturated zone based on the water-table elevation at the beginning of the test.

The well-bore storage, $S_{S\text{-}WELL}$, associated with each production well was simulated and estimated for each test, because these effects can alter other parameter estimates (Narasimhan and Zhu, 1993; Jiao and Rushton, 1995). The effects of well-bore storage are clearly evident during the first few minutes of pumping the lower rock aquifer (Figure 8). Appropriate analysis of these data requires either simulating well-bore storage or discarding the early time data.

Ideally, the well-bore storage should equal one, but estimated values can be lower due to displacement by the pump string, mismatches between simulated and actual well geometries, and by not explicitly considering well-bore damage. All production wells were simulated as porous media with high

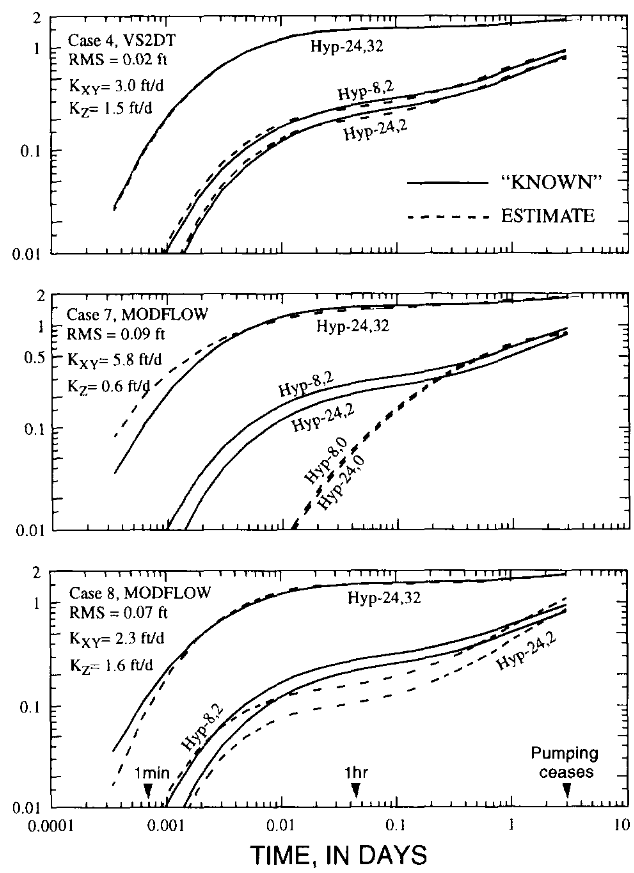

Fig. 7. Lateral and vertical hydraulic conductivity estimates and drawdowns at observation points Hyp-8,0, Hyp-8,2, Hyp-24,0, Hyp-24,2, and Hyp-24,32 calculated with the known parameters and the parameter estimates from cases 4, 7, and 8.

conductivity values of $K_{XY} = 1{,}000$ ft/d and $K_Z = 10^7$ ft/d. Water was removed from the lowermost node in a well while the simulator was apportioned inflow across the well face.

For the purpose of parameter estimation, the hydraulic properties of each aquifer or confining unit were assumed to be homogeneous and could be described by a single value. Not all parameters were estimated during any individual test. The initial values of lateral hydraulic conductivity and specific storage came

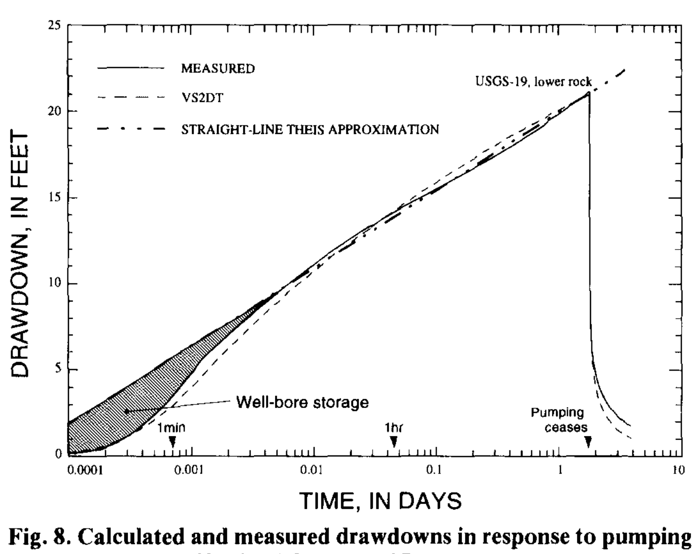

Fig. 8. Calculated and measured drawdowns in response to pumping the lower rock aquifer for 1.8 days at 85 gpm.

from Theis analyses of the drawdown data by a least-squares fit (Table 3). Initial estimates of vertical hydraulic conductivity came from a regional flow model. The results of other aquifer tests were used to update unestimated parameters. Parameters were re-estimated until the properties used in all three models were internally consistent.

Lower Rock Aquifer Test

Well USGS-24 in the lower rock aquifer was pumped at 85 gpm for 43 hours, and drawdowns were estimated from water-level measurements in wells USGS-19 in the lower rock and USGS-20 in the upper rock aquifers. No background water-level trend was assumed to exist in well USGS-19 during the test (Figure 4). Small drawdowns in USGS-20 are difficult to quantify due to noise induced by nearby pumpage. The upper rock aquifer is the shallowest available unit for irrigation wells at homes located about a mile west of the site. A difference in water-level responses exists between wells USGS-20 and 3-33DD after recharge events (Figure 4), so part of the change observed in the upper rock aquifer is not due to the test. Two days after pumping ceased, drawdown in USGS-20 was between 0.05 ft and 0.2 ft. The smaller values were used because they were more consistent with observations made during the upper rock test. The drawdowns from USGS-20 were weighted 10 times more than those from USGS-19. The greater weight was given to account for the smaller drawdowns and sensitivities associated with these measurements.

Four parameters were estimated: K_{XY}, S_S, and $S_{S\text{-}WELL}$ of the lower rock aquifer, and K_Z of the gray marl. Initial estimates of K_{XY} and S_S in the lower rock aquifer from a Theis analysis were 19 ft/d and 1.6×10^{-6} ft^{-1}, respectively. The specific storage of the gray marl was not estimated because it was too highly correlated with the hydraulic conductivity of the lower rock aquifer. A preliminary estimate of the specific storage of the blue marl, 5×10^{-6} ft^{-1} (Table 3), was applied to the gray marl.

The final parameter estimates of K_{XY} and S_S in the lower rock aquifer are 16 ft/d and 1.5×10^{-6} ft^{-1}, respectively. A Theis analysis would have been adequate for estimating the hydraulic conductivity and specific storage of the lower rock aquifer but would not have ascertained any information about the gray marl (Table 3). The most highly correlated parameters were the hydraulic conductivities of the lower rock aquifer and gray marl with a correlation coefficient of 0.63. The simulated and measured drawdowns mirrored one another throughout the test and the maximum difference was about a foot (Figure 8).

Upper Rock Aquifer Test

On average, the upper rock aquifer was pumped at 54 gpm for 46 hours. Production from the upper rock aquifer was more problematic than from the lower rock aquifer (Figure 9). Initially, well USGS-23 in the upper rock aquifer was pumped at an erratic rate that averaged 51 gpm for 8 minutes. The pump was shut off, reset from 85 to 100 ft below land surface, and restarted 29 minutes later. The discharge during the second pumping period was erratic for the first 10 minutes, but was stabilized at 55 gpm by constricting the discharge line. This rate was maintained for the first day and declined to 53 gpm by the end of the test. Average flow rates of 51 and 54 gpm in the first

Table 3. Initial and Final Aquifer and Confining Unit Properties Determined by Aquifer Tests

	AQUIFER or CONFINING UNIT	K_{XY}, ft/d	K_Z, ft/d	S_S, 10^{-6} ft^{-1}	b, ft	S_{S-WELL}	ϕ	α^c, ft^{-1}
INITIAL	Surficial sand	9	0.9	20	54	0.30	0.42	0.3
	Blue marl	0.05[a]	0.05	5	36	NA	0.4	NA
	Upper rock	58	6[a]	1.1	20	1.00	0.3	0.3
	Gray marl	0.01[a]	0.01	5[a]	95	NA	0.4	NA
	Lower rock	19	2[a]	1.6	32	1.00	0.2	NA
FINAL	Surficial sand	5	0.4[b]	40	54	0.10	0.42	2.0
	Blue marl	0.01[a]	0.01	9	36	NA	0.4	NA
	Upper rock	36	4[a]	1.5	20	0.63	0.3	0.4
	Gray marl	0.002[a]	0.002	5[a]	95	NA	0.4	NA
	Lower rock	16	2[a]	1.6	32	0.63	0.2	NA

[Values of K_{XY}, and S_S were estimated from aquifer test unless otherwise noted; All thicknesses and aquifer porosities were measured; Values of 0.14 and 5 were obtained for the van Genuchten (1980) parameters θ_r and n from literature values (Lappala et al., 1987).]

[a]Assumed $K_{XY}/K_Z = 10$ for aquifers and $K_{XY}/K_Z = 1$ for confining units. Estimated $S_S = 5 \times 10^{-6}$ 1/ft by extrapolation from shallower intervals.

[b]The vertical hydraulic conductivity, K_Z, estimated from the upper rock test was 0.39 ft/d and the estimate from the surficial sand test was 0.40 ft/d.

[c]Two different estimates of α were obtained from the surficial sand and upper rock aquifer tests. The value of 0.4 ft^{-1} is the most reasonable.

and second pumping periods, respectively, were used in the analysis.

Water-level responses were clearly detected in the surficial sand aquifer (Figure 9) and upper rock aquifers. A maximum response of 0.02 to 0.05 ft can be seen in the lower rock aquifer (Figure 4). Drawdowns were estimated from water-level measurements in wells USGS-17, 18, 19, and 20 for parameter estimation. The water-level changes shown in Figure 9 illustrate why a linear decline was not assumed for estimating drawdowns and the water-level change in a background well was used instead. Surficial sand drawdowns, wells USGS-17 and USGS-18, were weighted five times more than drawdowns from USGS-20 in the upper rock aquifer. The greater weight was given to account for the smaller drawdowns and sensitivities associated with these measurements. Drawdowns from well USGS-19 in the lower rock aquifer were not weighted because these estimates were of a more speculative nature.

Seven parameters were estimated: K_{XY}, S_S, $S_{S\text{-WELL}}$ of the lower rock aquifer, K_Z and S_S of the blue marl, and K_Z and α of the surficial sand aquifer. Initial estimates of K_{XY} and S_S in the upper rock aquifer were 58 ft/d and 1.1×10^{-6} ft^{-1}. The only van Genuchten parameter that could be estimated from these tests, α, primarily determines the negative pressure head when substantial desaturation occurs.

The final parameter estimates of K_{XY} and S_S in the upper rock aquifer are 36 ft/d and 1.7×10^{-6} ft^{-1}, respectively (Table 3). The most highly correlated parameters were the hydraulic conductivity of the blue marl and α with a correlation coefficient of 0.77. The estimated value of α (0.4 ft^{-1}) is consistent with literature values for this type of soil (Lappala et al., 1987). This estimate is fairly reliable because α is second in sensitivity only to the lateral hydraulic conductivity of the upper rock aquifer.

The high degree of sensitivity to estimates of α was not expected but is understandable upon closer examination of the contribution of water from the surficial sand aquifer to the blue marl. Both the pore velocity and unit flow rate from the surficial sand aquifer (Figure 10) show that the upper rock aquifer test influenced the surficial sand aquifer at distances exceeding 1,000 ft from the production well throughout most of the test. Half of the production, 27 gpm, came from the surficial sand aquifer 24 hours after the test began (Figure 10). By the end of the test, this fraction increased to 63 percent (34 gpm).

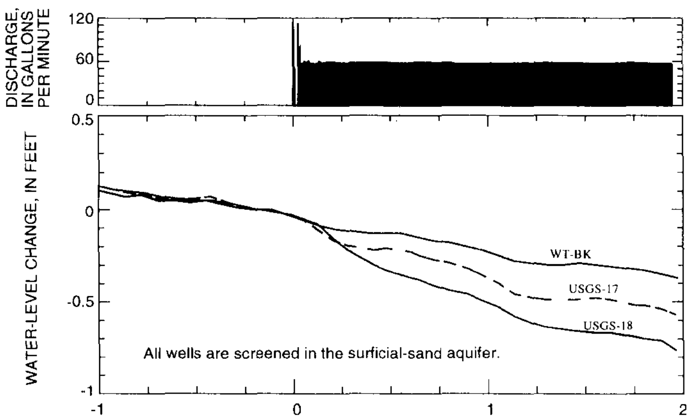

Fig. 9. Measured flow rate from the upper rock aquifer and water-level changes in the surficial sand aquifer prior to and during the upper rock aquifer test.

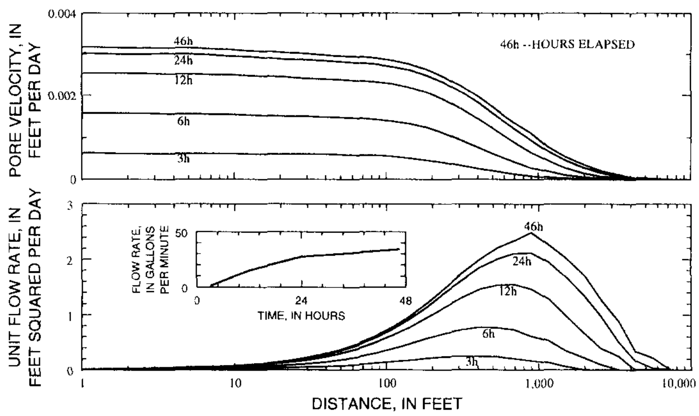

Fig. 10. Velocity distribution, unit flow rate distribution, and flow rate from the surficial sand aquifer to the blue marl at selected times during the upper rock aquifer test.

Appropriate analysis of the upper rock aquifer test required using the variably saturated flow model as the conceptual framework. The simulated and measured drawdowns mirrored one another throughout the test (Figure 11) showing that the effects of a compressible, leaky confining unit and an unconfined aquifer were taken into account. Simulated drawdowns at the end of the test showed that all aquifers and confining units were affected by the upper rock aquifer test.

Surficial Sand Aquifer Test

Well USGS-22 in the surficial sand aquifer was pumped at 4.8 gpm for 4 hours, allowed to recover 7 hours, and pumped

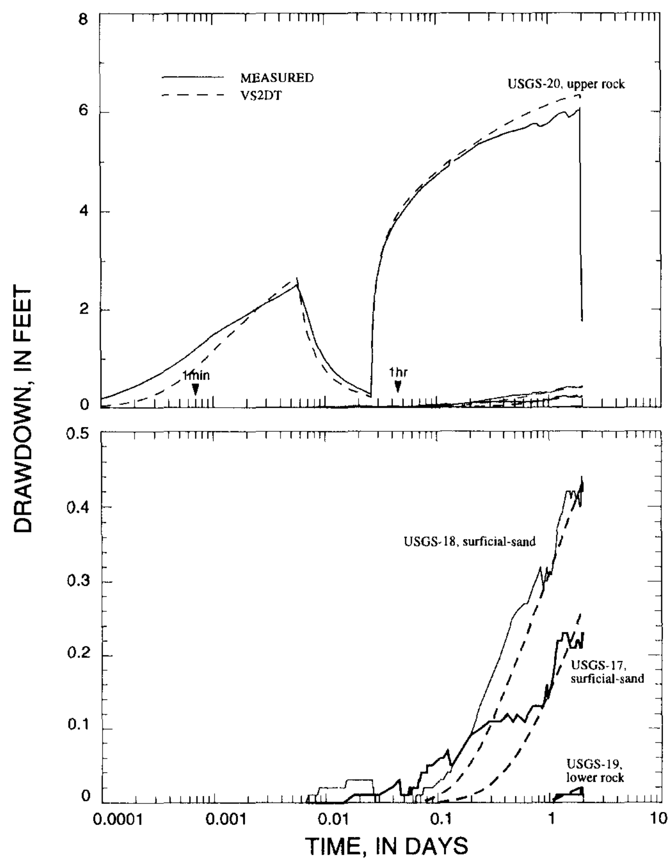

Fig. 11. Calculated and measured drawdowns in response to pumping the upper rock aquifer for 1.9 days at 54 gpm.

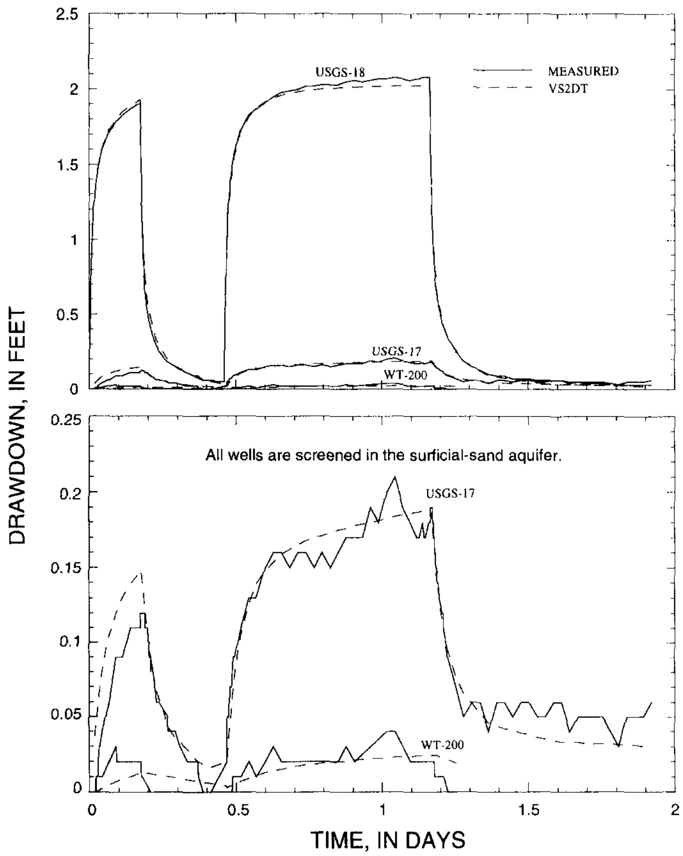

Fig. 12. Calculated and measured drawdowns in response to pumping the surficial sand aquifer for 1.0 day at 5 gpm.

again at 4.85 gpm for 17 hours. Production during this test was very uniform and consistent throughout the entire test. Several discharge measurements were made during the test in addition to initial measurements.

Water-level responses were clearly detected in well WT-200 near the water table 200 ft from the production well. Although a response of 0.05 ft can be seen in well USGS-20 in the upper rock aquifer (Figure 4), it is not clear enough to use in the analysis. Drawdowns were estimated from water-level measurements in wells USGS-17, USGS-18, and WT-200 for parameter estimation. No drawdowns were estimated in well USGS-16, because the water-level responses are almost identical to those in USGS-17. Drawdowns in wells USGS-17 and WT-200 were weighted two and four times more than drawdowns from USGS-18, respectively. The greater weights were given to account for the smaller drawdowns and sensitivities associated with these measurements.

The natural rate of water-level decline was greater in the background well, WT-BK, than in the wells near the production well during the surficial sand test. The slope of the WT-BK response was reduced to 0.56 of its measured value for detrending purposes. Detrending by using the coefficient 0.56 caused the WT-BK and WT-200 curves to match after pumping effects had dissipated.

Five parameters were estimated: K_{XY}, K_Z, S_S, and $S_{S\text{-WELL}}$ of the surficial sand aquifer. Initial estimates of K_{XY} and S_S in the surficial sand aquifer were 9 ft/d and 20×10^{-6} ft^{-1} respectively, assuming aquifer thickness is equal to the length of the screen (24 ft). This estimate came from a Theis analysis of the first two hours of data.

The estimate of α (2.0 ft^{-1}) from this test is unreasonably high and reflects extreme conditions prior to the test when about 6 inches of rain fell the day before (Figure 4). The water levels in wells USGS-17 and USGS-18 were above land surface prior to the test, and other areas had standing water. Within a 300 ft radius of the production well, the water table was within 0.5 ft of land surface on average. The high estimate of α shows the upper boundary of the aquifer could have been approximated as a specified head boundary, and a variably saturated flow model was not needed.

The simulated and measured drawdowns mirrored one another throughout the test, and the maximum difference was less than 0.1 ft (Figure 12). The final parameter estimates of K_{XY} and S_S in the surficial sand aquifer are 5 ft/d and 40×10^{-6} ft^{-1}, respectively. The specific storage estimate of 40×10^{-6} ft^{-1} for the surficial sand aquifer seems high, but is possible because the surficial sand aquifer is a silty sand and contains several clay stringers. In part, the estimate could also be an artifact of errors in estimated drawdowns. A lower specific storage estimate for the surficial sand aquifer would not significantly affect the hydraulic conductivity estimates.

The most highly correlated parameters were the lateral and vertical hydraulic conductivities of the surficial sand aquifer having a correlation coefficient of 0.95. The high degree of correlation between these two parameters shows that a unique solution does not exist given the data collected in this test. Any pair of lateral and vertical hydraulic conductivities taken from the interchangeable parameter section of the curve in Figure 13 adequately characterizes the surficial sand aquifer. The range of interchangeable hydraulic conductivity pairs is constrained somewhat by estimates of the vertical hydraulic conductivity of the surficial sand aquifer from the upper rock aquifer test.

Conclusions

A comparison between two flow models of a hypothetical, unconfined aquifer, one saturated and the other variably saturated, indicates that the variably saturated model provides a better conceptual framework for analyzing unconfined aquifer

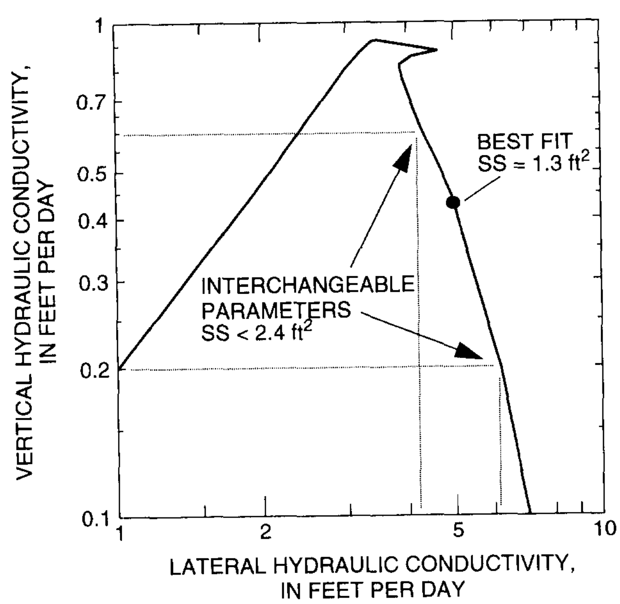

Fig. 13. Map of search path for best fit in the lateral and vertical hydraulic conductivity plane.

test data and better estimates of the lateral and vertical hydraulic conductivity in fine-grained sands. Explicitly accounting for multiple aquifers, well-bore storage, and the effects of the unsaturated zone increases confidence in estimates of aquifer parameters by removing some assumptions. This allows for the inclusion of early time data and water-table observations in an aquifer test analysis that are not incorporated into analytical solutions (Theis, 1935; Hantush and Jacob, 1955; Neuman, 1975). The need for a variably saturated model is greater when analyzing tests from aquifers with higher silt and clay contents. Capillary rise is greater in these aquifers than in coarse sands and gravels, and drawdown in these aquifers is more likely to be influenced by land surface.

The inclusion of the unsaturated zone expands the number of parameters to be estimated, but reasonable estimates of lateral and vertical hydraulic conductivity and specific storage of the unconfined aquifer can be obtained despite the uncertainties associated with the unsaturated flow parameters. For the cases examined, only the van Genuchten parameter α needed to be estimated. The van Genuchten parameters n and θ_r had a minimal effect on the estimates of the other parameters. This allowed estimation of lateral and vertical hydraulic conductivity, specific storage, and α with only coarse values of n and θ_r taken from the literature.

Estimates of lateral and vertical hydraulic conductivity using MODFLOW were not as good as the VS2DT based estimates, and differed from the known values by as much as 30 percent. If measured drawdowns at the water table are compared to simulated drawdowns in the uppermost model layer, estimates of K_{XY} and K_Z averaged about 1.8 and 0.5 times the known values, respectively. Using K_Z between layers 1 and 2 as a fitting parameter improved the match between known and simulated drawdowns, but the estimates of K_{XY} and K_Z were not as good as those based on VS2DT and were affected by initial parameter estimates.

Analysis of time-drawdown data from the shallow-aquifer system at Cecil Field Naval Air Station, Jacksonville, Florida, required a model that accounted for a complex hydrogeologic environment. Two of the three aquifers tested were simultaneously affected by compressible, leaky confining units, drainage from the unsaturated zone, and a shallow water table. Given the hydrogeologic conditions at the field site, estimating the hydraulic properties of the aquifers and confining units with analytically derived type curves would have been inappropriate. Estimates of the lateral hydraulic conductivity from the VS2DT solution were more consistent with the observed geology than estimates from Theis analyses, which ranged from 20 to 80 percent more than the final estimates.

The unsaturated zone affected the upper rock aquifer test more than the unconfined aquifer test as shown by the high degree of sensitivity to the van Genuchten parameter α. The unexpected sensitivity to α was due to the leakiness of the overlying confining unit which allowed the unconfined, surficial sand aquifer to supply 63 percent (34 gpm) of the pumped water by the end of the test. This test yielded an estimate of α (0.4 ft^{-1}) that was consistent with literature values for a silty sand.

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