

ANALYSIS OF COMPLEX PUMPING INTERACTIONS DURING AN AQUIFER TEST CONDUCTED AT A WELL FIELD IN THE COASTAL PLAIN NEAR AUGUSTA, GEORGIA, OCTOBER 2009

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Abstract. A 24-hour aquifer test was conducted in Well Field 2 near Augusta, Georgia, October 21–22, 2009, to characterize the hydraulic properties of the Midville aquifer system. The selected well was pumped at a rate of 684 gallons per minute. At the initiation of aquifer-test pumping, water levels in each of eight wells monitored for the test were still recovering from the well-field production. Because water levels had not stabilized, data analyses were needed to account for the ongoing recovery.

Hydraulic properties of the Midville aquifer system were estimated by an approach based on the Theis model and superposition. The Midville aquifer system was modeled as a Theis aquifer. The principle of superposition was used to sum the effects of multiple pumping and recovery events from a single pumped well and to sum the effects of all pumped wells as the estimated total drawdown at a monitored well. Simulated drawdown at each monitored well was determined by using a spreadsheet (*SUMTheis*) function of aquifer transmissivity and storativity. Simulated drawdown values were transformed into simulated water levels, accounting for long-term water-level trends. The transmissivity and storativity values that were used to calibrate the simulated water levels to measured water levels (roughly 4,000 square feet per day and 2E-04, respectively) provide estimates of the transmissivity and storativity of the Midville aquifer system in the vicinity of Well Field 2. The approach used in this study can be applied to similar well-field tests in which incomplete drawdown recovery or other known pumping is evident.

INTRODUCTION

The U.S. Geological Survey, in cooperation with the Augusta Utilities Department, is assessing groundwater flow and the hydrogeology of the Dublin and Midville aquifer systems that underlie the Augusta and Richmond County area in Georgia (Fig. 1). A 24-hour aquifer test was conducted in well 30AA06, which is in Well Field 2 and open to the Midville aquifer system, southeast of Augusta. Analysis of the aquifer-test data was complicated by incomplete recovery from the effects of well-field pumping. This created a water-level recovery curve in the monitored-well data that lasted throughout the duration of the aquifer-test and recovery period. In order to assess hydraulic properties of the Midville aquifer system, an approach was

developed to estimate drawdown of each monitored well in response to both production-well and aquifer-test pumping.

DESCRIPTION OF THE STUDY AREA

The location of the aquifer-test site is west of the Augusta Bush Field Airport and approximately 6 miles southeast of Augusta in Richmond County (Fig. 1). Well Field 2 encompasses approximately 600 acres and straddles the boundary between rolling hills to the west and the Savannah River alluvial plain to the east. Eight production wells produce about 2 million gallons per day from Well Field 2. Of these eight production wells, five were used as monitored wells for the aquifer test.

Aquifer-test well 30AA06 is in the alluvial plain of the Savannah River and has a land surface altitude of 137.5 feet (ft) above North American Vertical Datum of 1988 (NAVD 88). Land surface at the aquifer-test site wells ranges from 120 to 220 ft above NAVD 88.

The study site lies just south of the Fall Line between the Piedmont and Coastal Plain Physiographic Provinces (Fenneman, 1938). Locally, the site is underlain by sand and clay of the Dublin and Midville aquifer systems of late Cretaceous age, which gently dip to the south (Clarke and others, 1985; Williams, 2007; Fig. 2). Beneath Well Field 2, the lower Dublin aquifer is composed of relatively shallow sands, about 5–20 ft thick, interspersed with clay, and is roughly up to 130 ft in depth. The lower Dublin aquifer is underlain by the Midville confining unit, a clay layer that is roughly 20 ft thick. The Midville aquifer system is roughly 85 ft thick and is separated into the upper and lower Midville aquifers by a thin clay layer that generally is less than 5 ft thick. The Lower Dublin aquifer and Midville aquifer system are under confined conditions.

AQUIFER-TEST DESCRIPTION

Well 30AA06 was pumped at a rate of 684 gallons per minute (gal/min) from 7:14 a.m. on October 21, 2009, to 7:15 a.m. on October 22, 2009. Water levels in the pumped well and in seven observation wells within 4,400 ft of the pumped well were monitored. The pumped well and seven observation wells were open to the Midville aquifer.

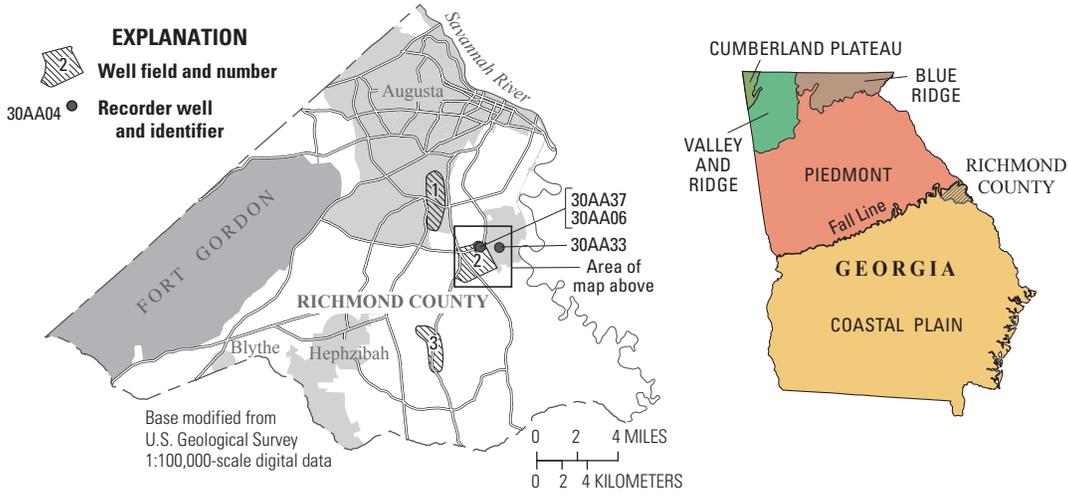
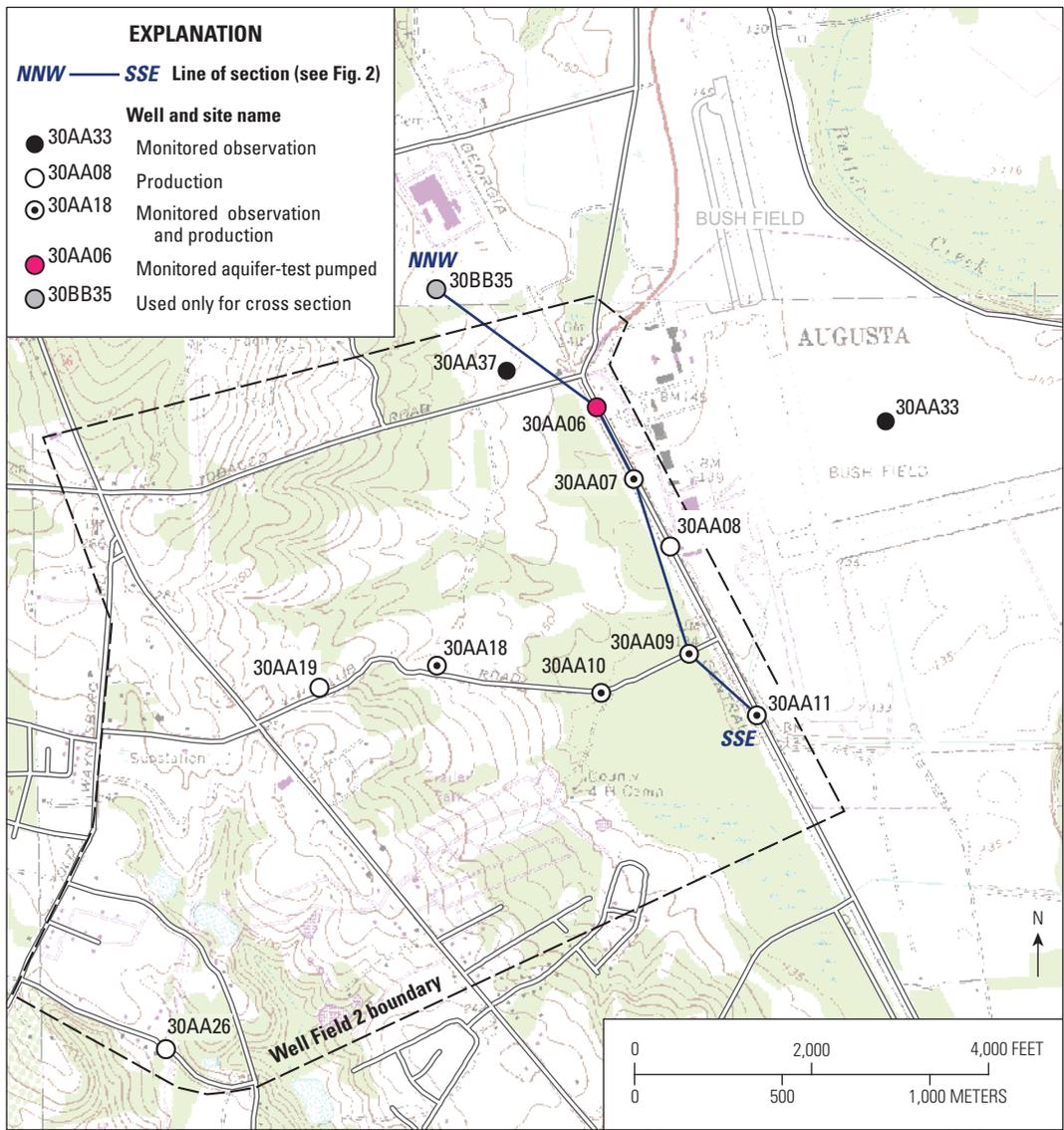


Figure 1. Locations of production and monitored wells in Well Field 2, Augusta, Georgia, 2009.

Prior to the aquifer test, eight wells were producing on an intermittent schedule whereby the pumping of all wells was turned on and off simultaneously. Production wells generally were pumped for about 2–2.5 hours, followed by inactivity for about 3–8 hours. Pumping was discontinued at Well Field 2 about 10:30 a.m. on October 19, 2009, 1.88 days (45 hours) prior to the aquifer test.

Incomplete recovery from well-field pumping was the dominant external influence on water levels during the aquifer test. Water levels recovered from well-field pumping before, during and after the 24-hour aquifer test (Fig. 3).

AQUIFER-TEST ANALYSES

Hydraulic properties of the Midville aquifer system were estimated by using an approach based on the Theis (1935) model and superposition. The Midville aquifer system is modeled as a Theis aquifer, an idealized aquifer conforming to the assumptions of Theis (1935). The principle of superposition is used to sum the effects of multiple pumping and recovery events from a single pumped well and to sum the effects of all pumped wells as the estimated total drawdown at a monitored well. Estimated drawdown at each monitored well in response to pumping was determined by using the spreadsheet function (described below) based on the transmissivity and storativity assigned to the Midville aquifer. Simulated drawdown values were transformed into simulated water levels, accounting for long-term water-level trends. The transmissivity and storativity values that were used to calibrate the simulated water levels to measured water levels were taken as the estimated transmissivity and storativity for the Midville aquifer system.

The spreadsheet function *SUMTheis* (Keith J. Halford, U.S. Geological Survey, written commun., June 1, 2010), sums up the effects of multiple pumping and recovery events from a single pumped well to determine the amount of drawdown that occurs at a monitored well in response to pumping at that well. From the perspective of determining the drawdown at a monitored well in response to pumping at a well, input includes the following:

- distance between the monitored well and the pumped well,
- the pumping schedule for the pumped well,
- current time, and
- aquifer transmissivity and storativity.

The *SUMTheis* function is based on the assumptions of Theis (1935):

- horizontal, homogeneous, isotropic aquifer of infinite extent,
- no-flow boundaries above and below the aquifer (no leakage),
- confined conditions (piezometric head is above the top of the aquifer),

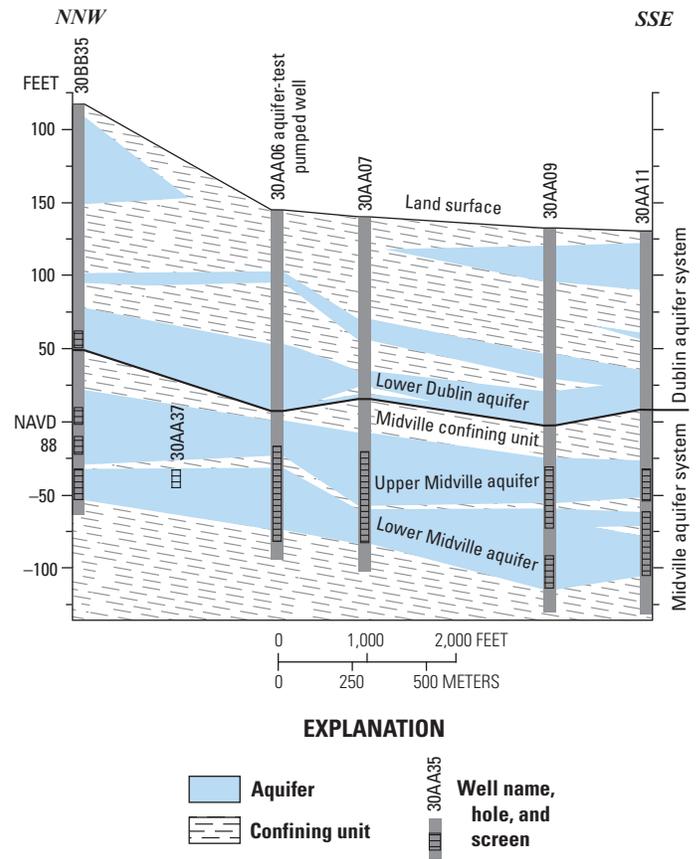


Figure 2. Hydrogeologic cross section of Well Field 2 based on drillers' logs and interpretation at well 30AA11 from Williams (2007), Augusta, Georgia. (Line of section shown in Fig. 1)

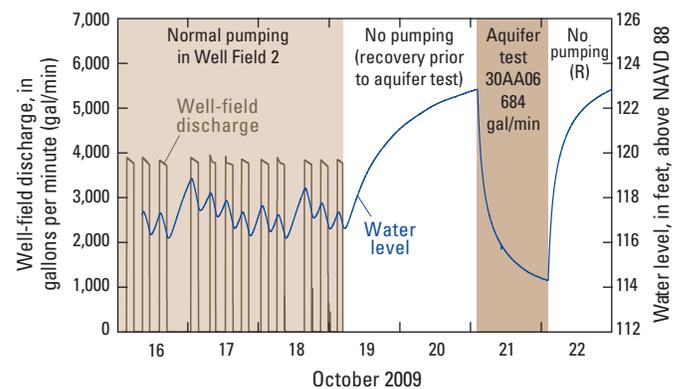


Figure 3. Water-level response in well 30AA37 to different phases of pumping activity before, during, and after an aquifer test, Well Field 2, Augusta, Georgia, October 16–22, 2009. No-pumping phase (R) when water level was recovering from both the normal well-field and aquifer-test pumping.

- horizontal piezometric surface prior to pumping,
- instantaneous change in discharge rate, and
- horizontal flow (well opening fully penetrates the aquifer)

Drawdown from the *SUMTheis* function can be expressed as

$$DD_{(w,p,t)} = \frac{1}{4\pi T} \sum_{i=1}^n \left\{ \Delta Q_i W \left(\frac{r_{(w,p)}^2 S}{4T[t - \tau_i]} \right) \right\}, \quad (1)$$

where

- $DD_{(w,p,t)}$ is the drawdown, from the *SUMTheis* function, at monitored well w in response to pumping p at well at time t , in feet;
- T is the aquifer transmissivity, in square feet per day;
- S is the aquifer storativity or the “storage coefficient,” dimensionless;
- n is the number of discharge-rate changes;
- ΔQ_i is the increase in discharge rate from one step to the next, in cubic feet per day;
- $r_{(w,p)}$ is the distance between the monitored well w and the pumped well p , in feet;
- τ_i is the time of discharge-rate step change i ; and
- $[t - \tau_i]$ is the time after the start of discharge-rate step change i at time t , in days.

The value of $\Delta Q_i W \left(\frac{r_{(w,p)}^2 S}{4T[t - \tau_i]} \right)$ is zero when $t \leq \tau_i$. Note that

ΔQ_i is negative when the discharge decreases from one step to the next.

Drawdown in a monitored well in response to nearby pumping is the sum of the drawdown in the monitored well in response to each pumping source. In this study, there are nine pumping sources—eight production wells and the aquifer-test well 30AA06.

The total drawdown in a monitored well is then transformed into simulated water levels by adding a slope and constant, characteristic of the measured water levels:

$$WL_{(w,t)} = C_{(w)} + m(t - t_0) - \sum_{p=1}^9 DD_{(w,p,t)}, \quad (2)$$

where

- $WL_{(w,t)}$ is the simulated water level of well w at time t to be compared to measured water level in well w , in feet above NAVD 88;
- m is the slope of the long-term water-level trend, with respect to time, in feet per day;
- t_0 is the arbitrary reference or pivot time, which was 7:14 a.m. on October 21, 2009;

$(t - t_0)$ is time with respect to the reference time, in days;

$C_{(w)}$ is a constant value, representing the water level in well w , at time t_0 with no draw-down, in feet above NAVD 88; and

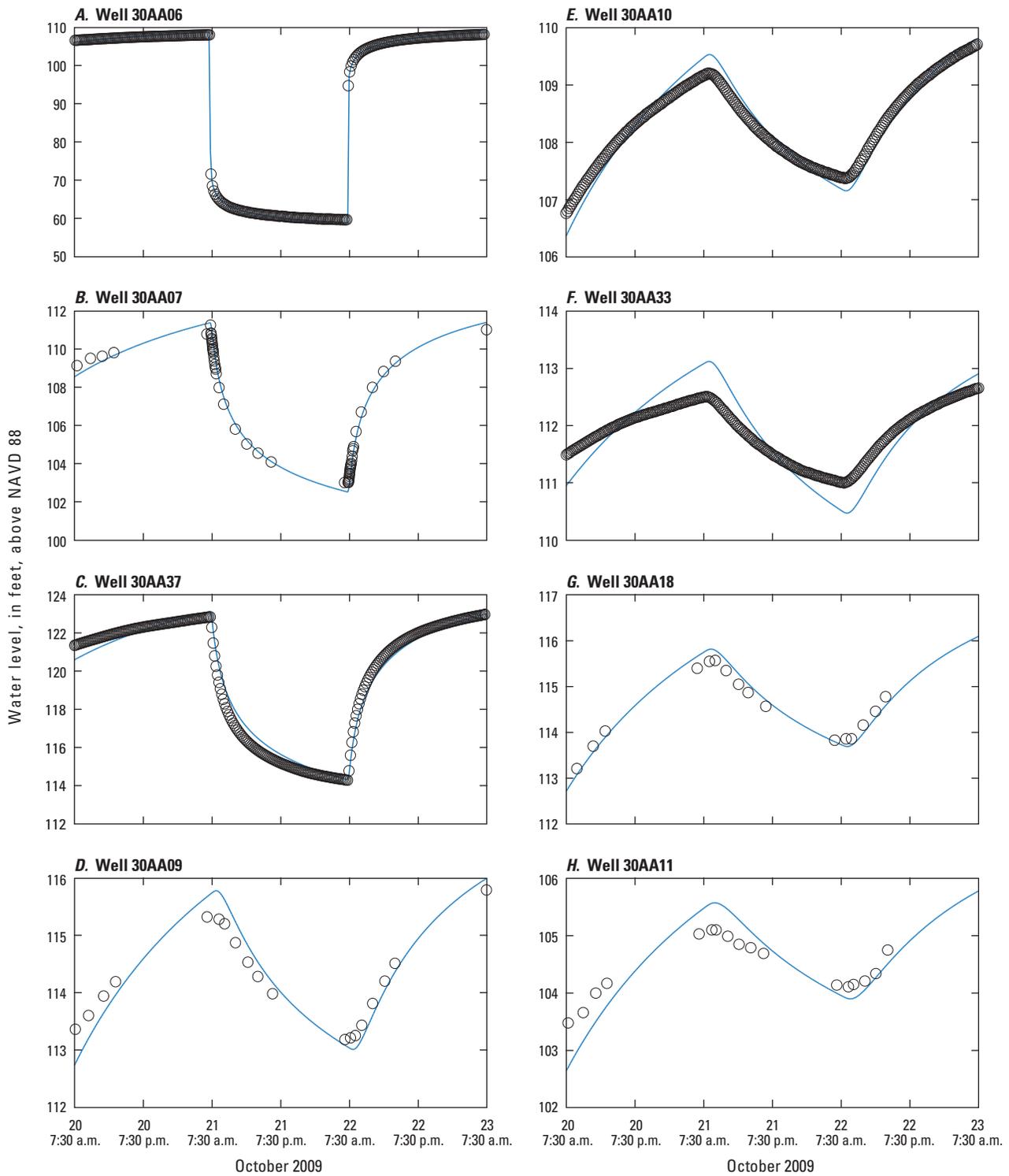
$\sum_{p=1}^9 DD_{(w,p,t)}$ is total drawdown ($DD_{(w,p,t)}$, from eq. 1), at monitored well w , in response to pumping at eight production wells and the aquifer-test well 30AA06 at time t , in feet.

Simulated water levels were fit to measured water levels by adjusting a single value of transmissivity, storativity, and long-term trend for all monitored wells and by adjusting the reference water level $C_{(w)}$ for each monitored well. Therefore, the values of T , S , m , and $C_{(w)}$ are determined in the process of fitting simulated water levels to measured water levels. Values of $C_{(w)}$ were not the same for all wells and ranged from 118.8 to 136.21 ft (Table 1), which indicates that the initial head in the Midville aquifer system was not perfectly horizontal and deviated from a Theis assumption of initial horizontal piezometric surface.

The pumping schedule for each of the production wells was set at zero until October 10, 2009. Within the pumping schedule, a constant discharge rate of 180 gal/min for each production well, which represented long-term, average pumping, was input for the period of October 10–16, 2009. The start of pumping earlier than October 10 led to very large simulated drawdown and recovery that did not fit the measured water levels. This result indicates that, unlike the Theis assumption of no leakage, some leakage between aquifers probably occurs and serves to sustain water levels in the Midville aquifer system. During October 16–19, 12 pumping events (Fig. 3) were used to develop the production-well pumping schedule (475 gal/min for each production well during pumping events). The production-well pumping schedule in Figure 3 includes the roughly 4-day inactive period of October 19–23, during which a second pumping schedule represents the 24-hour aquifer test at well 30AA06.

The goodness of fit is quantified with the root-mean-square (RMS) of the difference between simulated and measured water levels divided by the range in measured water levels during the comparison period, from about 7:30 a.m. on October 20 to 7:30 a.m. on October 23, 2009 (Table 1).

The best fit of simulated to measured water levels for all wells was derived by using transmissivity, storativity, and long-term water-level rise values of 3,800 feet squared per day, 2.125E-04, and 0.76 foot per day, respectively. Visual fits (Fig. 4) were best for wells with the smallest ratios of RMS over the range of measured water levels. Well 30AA06 visually fit particularly well (Fig. 4A), whereas the worst visual fit was for well 30AA33 (Fig. 4F) where the simulated water levels had larger fluctuations than measured water levels in response to the aquifer test. The ratio of RMS over the range of measured water levels was lowest (most favorable fit) for aquifer-test well 30AA06, 0.01 (Fig. 4A) and highest (least favorable fit) for wells 30AA33 (Fig. 4F) and 30AA11 (Fig. 4H), 0.20 and 0.22, respectively.



EXPLANATION

Water levels

— Simulated ○ Measured

Figure 4. Simulated and measured water levels in (A) aquifer-test pumped well 30AA06, and in wells (B) 30AA07, (C) 30AA37, (D) 30AA09, (E) 30AA10, (F) 30AA33, (G) 30AA18, and (H) 30AA11 completed in the Midville aquifer system in response to the 24-hour aquifer test at Well Field 2, Augusta, Georgia, October 20–23, 2009.

Table 1. Root-mean-square (RMS) of the difference between simulated and measured water levels in monitored wells completed in the Midville aquifer during a 24-hour aquifer test at well 30AA06, Augusta, Georgia.

[Spreadsheet function *SUMTheis* was used to estimate drawdown. $C_{(w)}$, added constant used for each well to fit simulated water levels to measured water levels. Comparison period is from 7:30 a.m. on October 20 to 7:30 a.m. on October 23, 2009; ft, foot; NAVD 88, North American Vertical Datum of 1988]

Midville aquifer well name	Range of measured water levels (ft)	RMS (ft)	RMS/range	Number of data points	$C_{(w)}$ (ft above NAVD 88)
30AA06	48.61	0.38	0.01	288	122.03
30AA07	8.24	0.44	0.05	58	124.72
30AA37	8.68	0.42	0.05	452	136.21
30AA09	2.61	0.31	0.12	19	128.84
30AA10	3.01	0.18	0.06	290	123.06
30AA33	1.65	0.34	0.20	289	125.67
30AA18	3.40	0.18	0.05	18	129.29
30AA11	1.80	0.40	0.22	18	118.8

CONCLUSIONS

The Theis-superposition model was able to determine transmissivity and storativity results by estimating the drawdown resulting from both production-well and aquifer-test pumping. The transmissivity and storativity of the Midville aquifer system were determined to be 4,000 feet squared per day and 2E-04, respectively. The transmissivity translates to a horizontal hydraulic conductivity of 45 feet per day, which is within a range of values reported by Clarke and others (1985). The storativity translates to a specific storage of about 2.5E-06 ft⁻¹, which is slightly lower than the low end of sand aquifers published by Jumikis (1969). Two other methods, not described in this paper, were used to estimate transmissivity and storativity, and results agreed with those of the Theis-superposition model. The approach used in this study can be applied to similar well-field tests in which incomplete drawdown recovery or known pumping is evident.

ACKNOWLEDGMENTS

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