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Characterization of Hydraulic Properties of the Memphis Aquifer by Conducting Pumping Tests in Active Well Fields in Shelby County, Tennessee

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Research Impact Statement: Reliable, localized aquifer parameters were estimated using a methodology developed to account for the influence of production well interference during the pumping tests.

ABSTRACT: Limited availability of field measurements for aquifer parameters commonly leads to nonuniqueness of numerical model solutions. Six pumping tests were conducted in five municipal well fields within Shelby County following the procedure described in the ASTM D4050-14 and using an additional qualitative matrix framework to achieve greater reliability. Drawdown data of the pumping tests were analyzed using AQTESOLV, which allowed for partial penetration of well screens and interference from neighboring production wells. The values of transmissivity have a combined range of 600–3,100 m^2/day, which is 2–4 times less than published measures that used less robust data analysis and questionable or poorly documented methods. The range of storativity was 0.0005–0.002, and again, the resulting values have greater reliability than prior investigations. Robust quality assessment in the present methodology through assignment of a scoring decision matrix provides greater trust in the measurements. With a score at or above 10 considered optimal, the methodology and test environment resulted in an average score of 8.7, a vast improvement from prior investigations that together averaged 4.1. The calculated parameter values are an improvement on historical values, constraining the two critical groundwater hydraulic terms that should reduce modeling nonuniqueness of numerical modeling solutions that should lead to improved evaluation of local groundwater resources and environmental impacts.

(KEYWORDS: pump test; aquifer characterization; partial penetration; Memphis aquifer.)

INTRODUCTION

Groundwater modeling aids in the understanding of aquifer systems by providing a quantitative representation of the hydrogeologic processes based on the available field information from a site of interest (Anderson et al. 2015). During the last decades, modeling has been used to describe and predict the behavior of groundwater flow systems to address issues related to groundwater resources management (Sun 1999), such as quantifying aquifer yield, and prediction of rates and direction of contaminant transport (McKenna et al. 2003). However, the limitation of field conditions can often lead to nonuniqueness of model solutions (Neuman 1973; Pang et al. 2000; McKenna et al. 2003; Friedel 2005; Yeh et al. 2015; Jazaei et al. 2019; Villalpando-Vizcaíno et al. 2021).

Nonuniqueness refers to multiple numerical solutions obtained with different sets of parameter values

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leading to similarly good correspondence to field measurements, which could provide an inaccurate description of the aquifer groundwater flow system (Zechman et al. 2006). Friedel (2005) explains that since limited estimations for field measurements of hydraulic parameter used to constrain the model parameter calibration process contribute to nonuniqueness, the predictive uncertainty of the model can be reduced by including more parameter data. Therefore, appropriate quantification of aquifer parameters, such as hydraulic conductivity, transmissivity, and storativity will improve the accuracy of numerical model solutions and result in result in better decision making regarding evaluation and usage of groundwater resources and environmental impact assessments (Rogiers et al. 2012; Criollo et al. 2016).

Most common approaches developed to determine aquifer parameters include laboratory methods, such as grain-size analysis and permeameter tests (Wolf et al. 1991; Alyamani and Şen 1993; Boadu 2000), and traditional aquifer testing methodologies, such as slug and pumping tests (Butler 1990; Dawson and Istok 1992; Jones 1993; Mace 1999; Weight 2008). Bradbury and Muldoon (1990), Vuković and Soro (1992), and Cheong et al. (2008) identified that values of hydraulic conductivity and transmissivity estimated from pumping tests are higher than those estimated from grain-size analysis, and D'Andrea (2001) concluded that values of hydraulic conductivity estimated with the latter do not accurately represent field conditions. The selection of a determinative method depends on the purpose and extent of the investigation. For this study, pumping tests were selected because they have proven to provide reliable parameter estimates (Criollo et al. 2016) averaged over a larger scale (~4–50 m) than those estimated using grain-size analysis and slug test (~0.1 m) (Cheong et al. 2008). Pumping tests consist of stressing the aquifer of interest by withdrawing water at a constant rate, consequently producing a change in the piezometric head that can be matched to theoretical solution curves to determine the properties of the aquifer system (Theis 1935; Hantush 1961; Dawson and Istok 1992; Weight 2008).

Shelby County, Tennessee, is located within the Mississippi embayment aquifer system (Criner et al. 1964), which contains two prolific freshwater aquifers. The Memphis aquifer, along with the Fort Pillow aquifer, supply the majority of potable water to Memphis, Tennessee, and the surrounding communities. Multiple aquifer tests of the Memphis and Fort Pillow aquifers have been conducted in Shelby County to quantify the capability of these aquifers to supply a sustainable quantity of water and to predict the potential rate and direction of contaminant transport. However, a study by Waldron et al. (2011) identified only 13 reliable sources from published literature of parameters estimated for the Mississippi embayment aquifer system, six of which present values for the Memphis aquifer in Shelby County. These previous studies (Criner et al. 1964; Moore 1965; Hosman et al. 1968; Parks and Carmichael 1990; Brahana and Broshears 2001; Gentry et al. 2006) reported transmissivity and storativity values with a combined range between 30–6,400 m^2/day and 0.0001–0.003, respectively. Unfortunately, the location for some of the tests was not specified. Thus, the available data provide a broad range of hydraulic property values for the Memphis aquifer at a county scale.

Waldron et al. (2011) developed a scoring matrix to assess the reliability of the aquifer parameter values. This study determined that the majority of the aquifer tests did not adhere to traditional methods, reducing confidence in the estimated parameter values. Given the uncertainty in these values, a need exists for more aquifer tests to provide narrower ranges that better represent groundwater flow of the Memphis aquifer at local scales. Better estimates of the aquifer parameters will improve groundwater modeling efforts in Shelby County by reducing parameter nonuniqueness and aid in informed decision making on groundwater sustainability (Villalpando-Vizcaíno et al. 2021).

SITE DESCRIPTION

The Memphis aquifer is regional in scale, underlying portions of multiple states with its greatest extent beneath Arkansas, Mississippi, and Tennessee (Criner et al. 1964; Graham and Parks 1986; Schrader 2008). Although termed the Memphis aquifer in west Tennessee, it is regionally defined as the middle Claiborne aquifer and is partially correlative to the Sparta aquifer in Arkansas and Mississippi (Cushing et al. 1964).

The Memphis aquifer is comprised mostly of sand, ranging from fine to very coarse grain size (Kingsbury and Parks 1993), with lenses of clay and silt at various stratigraphic horizons (Brahana and Broshears 2001). The thickness of the Memphis aquifer is approximately 150 m in the northeastern part of Shelby County and as much as 270 m in the southwestern part (Graham and Parks 1986). It is confined above by the Jackson-upper Claiborne confining unit and below by the Flour Island Formation (Bradley 1991). The Jackson-upper Claiborne confining unit is comprised mostly of clay but includes fine sand and silt (Graham and Parks 1986). This upper aquitard to the Memphis aquifer ranges in thickness from 0 to 60 m, where zero meters thickness represents two conditions: (1) the upper aquitard pinches out in eastern Shelby County and the Memphis Sand is exposed in subcrop or (2) absence of clay within the upper Claiborne strata, creating unconfined conditions and avenues for greater exchange between the shallow aquifer above and the Memphis aquifer below (Graham and Parks 1986; Parks 1990; Kingsbury and Parks 1993; Larsen et al. 2013, 2016; Torres-Uribe et al. 2021).

The Memphis aquifer provides about 95% of the potable water to the city of Memphis, mostly for municipal and industrial use (Graham and Parks 1986; Parks and Carmichael 1990), mainly extracted in ten municipal well fields managed by Memphis Light, Gas and Water (MLGW) (Parks and Carmichael 1990; Larsen et al. 2016). Additionally, adjacent municipalities, such as the City of Germantown, also withdraw water from this aquifer through their own well fields, one of which was included in this study in order to have localized parameter values in the southeastern part of Shelby County (Figure 1).

PREVIOUS STUDIES

Previous aquifer characterization has been performed in Shelby County from 1949 to 2002 to determine the hydraulic properties of the Memphis aquifer using a variety of methodologies that include grain-size analysis and aquifer tests (Parks and Carmichael 1990; Gentry et al. 2006). As presented in Table 1, reported values of transmissivity and/or storativity range from 30 to 6,400 m^2/day and 0.0001–0.003, respectively (Criner et al. 1964; Moore 1965; Hosman et al. 1968; Parks and Carmichael 1990; Gentry et al. 2006). Most of the reported values are representative of the upper part of the Memphis aquifer. Determination of hydraulic conductivity from transmissivity values was not possible except for Gentry et al. (2006) as aquifer thickness in the other studies was not provided; hence, an estimate is made using an average thickness of 210 m (Table 1) (Waldron et al. 2011; Carmichael et al. 2018).

Villalpando-Vizcaíno et al. (2021) and Jazaei et al. (2019) identified the broad ranges of aquifer parameters as an obstacle in appropriately representing aquifer parameters in their numerical models of Shelby County or portions thereof. Both Villalpando-Vizcaíno et al. (2021) and Jazaei et al. (2019) calibrated their models using Parameter ESTimation (PEST) that adjusts aquifer parameters on a cell-by-cell basis within user-defined ranges. Villalpando-Vizcaíno et al. (2021) addressed the spatial heterogeneity by using pilot points at discrete locations (Doherty 2003), allowing their ranges to extend outside published values. Although values for transmissivity and storage resulting from PEST mostly fell within the ranges reported

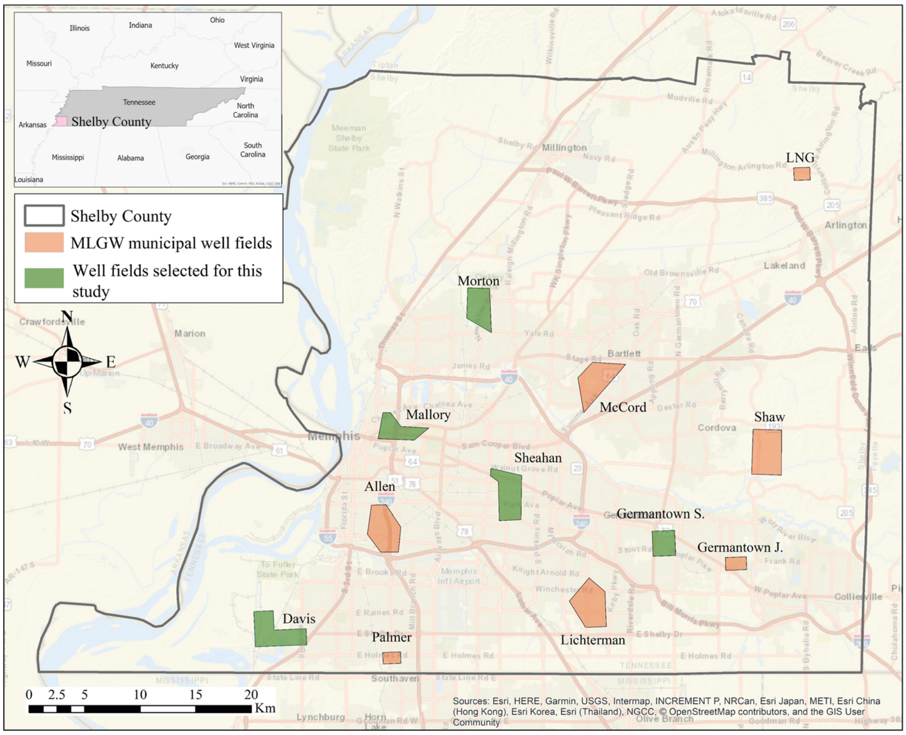

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FIGURE 1. Location of Memphis Light, Gas and Water (MLGW) and Germantown well fields within Shelby County, Tennessee.

TABLE 1. Aquifer parameter data (extracted and modified from Waldron et al. 2011).

Author(s)	Methodology	T (m^2/day)	T average (m^2/day)	K_h (m/day)	K_h average (m/day)	S	S average
1. Gentry et al. (2006)	Grain-size analysis	—	7,450	30–50	35	—	—
	Slug test	30–6,400	2,560	0.15–30	12		
2. Criner et al. (1964)	Pumping test	1,240–5,100	5,000	5–25	23	0.0015–0.003	0.003
3. Moore (1965)	Aquifer tests	620–5,000	~3,000[1]	3–23	14	0.0001–0.003	~0.0015[1]
4. Hosman et al. (1968)	Aquifer tests	—	3,100	—	—	—	0.001
5. Parks and Carmichael (1990)	Aquifer tests	620–5,000	3,100	3–23	15	0.0001–0.003	0.001
6. Brahana and Broshears (2001)	Aquifer tests	250–4,000	—	1–19	—	0.0001–0.0006	—
	Model calibration	900–4,600	—	4–22	—	0.0002–0.2	—

[1] Based on the intermediate value of the published interval.

by previous studies, it was concluded that the real distribution of parameters was not well represented; thus, resulting in model non-uniqueness and uncertainty in interpreting certain model outcomes. Similarly, Jazaei et al. (2019) attempted to minimize model nonuniqueness by restricting ranges to published values (Parks and Carmichael 1990; Brahana and Broshears 2001; Gentry et al. 2006). Both studies reference historical values, yet all are the same values questioned by Waldron et al. (2011).

RELIABILITY OF EXISTING VALUES

In the context of this study, reliability is expressed as a ranking of the quality of measured or published aquifer parameter values in regard to availability of supporting documentation or concerns in the test conditions (e.g., irregular pumping rates, test duration, influence of other production wells). To evaluate the reliability of the historically reported values of hydraulic conductivity (or transmissivity) and storativity in the region, Waldron et al. (2011), in coordination with the United States Geological Survey (USGS), developed a scoring matrix consisting of nine criteria (Table 2). Waldron et al. (2011) selected an initial value of 10, which could be increased or reduced after being evaluated. The threshold score to separate good values from bad values depends on the degree of accuracy required for the intended use. Applying this scoring matrix to published values compiled by Waldron et al. (2011) from the USGS historical records for 88 aquifer tests for the Memphis aquifer, it was estimated an average score of 4.1 with a maximum score of 7. It is worth noting that 93.4% of the reviewed historic values fell within Shelby County. Using an arbitrary threshold of 7, Waldron et al. (2011) concluded that of the 124 historic values, of which 88 correspond to values from the Memphis aquifer, only the 19% are considered to be of good quality. Conversely, the majority of the aquifer tests did not adhere to traditional methods and scored poorly. Unfortunately, precise locations for some of the good tests were not specified in the original records resulting in multiple values for the same geographic area. This broad range of values across a generalized area hinders modeling efforts attempting to represent groundwater flow at fine geographic scales (tenths of square kilometers). The factors listed in Table 2 are employed in the current investigation, increasing confidence in the estimated parameter values.

APPROACH AND METHODS

Pumping tests were selected to determine aquifer properties in the Memphis because this method has demonstrated to provide reliable parameter estimates (Criollo et al. 2016) over a larger area than those estimated using other methodologies, such as slug tests (Cheong et al. 2008). The wells used to perform the pumping test for this study correspond to existing production and observation wells that are part of MLGW well fields and a City of Germantown well field, and were selected based on two main criteria: (1) availability of an associated observation well completed (i.e., screened) at a similar interval, and (2) adequate distance between the production and observation wells. This latter criterion was included because MLGW production wells partially penetrate the aquifer, which could cause vertical components of flow proximal to the well (Hantush 1961; Hemker 1999). Vertical flow components can lead to a greater drawdown and, consequently, do not allow use of standard methods to estimate the aquifer parameters (Kruseman and Ridder 1994). Considering that vertical flow components decrease further from the production well, the ideal radial distance r at which its

TABLE 2. Scoring matrix used to qualitatively assess the reliability of the United States Geological Survey (USGS) aquifer parameter data. Retrieved from Waldron et al. (2011).

Rank criteria

1. Published or Approved (yes +1)
   Have the test results been published in a USGS report?
   If yes, plus 1
2. Multiple pumping wells (yes −2)
   Are nearby pumping wells affecting the test?
   If yes, minus 2
3. Other wells on and off (yes −5)
   Are nearby pumping wells turning on and off?
   If yes, minus 5
4. Observation wells (unknown −1, no −2)
   Were water levels monitored in observation wells for the aquifer test?
   If unknown, minus 1
   If no, minus 2
5. Test duration (>24 h +1, unknown −1, <24 h −2, <1 h, −3)
   If the pumping duration is more than 24 h, plus 1
   If the pumping duration is unknown, minus 1
   If the pumping duration is less than 24 h, minus 2
   If the pumping duration is less than 1 h, minus 3
6. Good supporting information (no −2)
   Do the records provide good supporting information for the test?
   If not, minus 2
7. Multiple Analyses (yes +1, no −2)
   Were multiple analytical methods used in the analysis?
   If yes, plus 1
   If not, minus 2
8. Multiple wells analyzed (yes +1)
   Were analysis conducted on multiple wells for the test?
   If yes, plus 1
9. Drawdown and recovery analyses (no −2)
   Were the drawdown and recovery data both analyzed?
   If not, minus 2

effect could be considered negligible is given by the following relationship:

$$r > 1.5b\sqrt{k_\mathrm{h}/k_\mathrm{v}}, \tag{1}$$

where b is the thickness of the Memphis aquifer and was obtained from the Mississippi Embayment Regional Aquifer Study model developed by Clark and Hart (2009), and $k_\mathrm{h}/k_\mathrm{v}$ represent its horizontal to vertical hydraulic conductivity anisotropy ratio (Dawson and Istok 1992; McWhorter and Sunada 2010). An anisotropy ratio of 10:1 was selected based on discussion in Freeze and Cherry (1979) indicating that vertical anisotropy is caused by the horizontal alignment of clay minerals in unconsolidated bedded sediments.

The previous relationship would require selecting an observation well at a radial distance greater than one kilometer from a production well, which would be an impracticality in a large well field with multiple active production wells and the interference they impose during a pumping test.

To maximize the likelihood of vertical equipotential lines while reducing the influence of additional production wells, observation wells were chosen as distant as possible from a paired production well. Furthermore, the tests were performed during March through May of 2019, during a period when water demand was at an annual minimum (Villalpando-Vizcaíno et al. 2021). This timeframe allowed for other nearby production wells to be temporarily turned off without compromising supply for limited demand. To ascertain the influential nearby production wells, MLGW's wellhead maps were used to identify production wells that needed to be turned off.

Six well-pairings were selected at the five municipal well fields (Figure 2). Due to the limited number of observations wells near well fields and the variable screen depths of both production and observation wells, typically only one pair could be identified in any single well field, except for MLGW's Mallory well field where two pairings were identified and chosen (see Table 3).

Pumping Test Procedure

Pumping tests involve measuring the water-level response produced in an observation well by the withdrawal of water in a pumping well (i.e., production well). The rate at which water was withdrawn from the pumping well was measured continuously throughout the test to verify that it did not vary more than 10% from the mean discharge. In addition to the ASTM D4050-14 guidelines, factors outlined by Waldron et al. (2011) (see Table 2) were also considered to achieve greater reliability.

Water-level data were obtained using manual measurements with an electric tape (Solinst Inc. Water Level Meter® Model 101, Georgetown, Ontario, Canada) and pressure transducers adjusted for barometric pressure (Solinst Inc. Levelogger® Model 3001 and Barologger® Model 3001). Water levels were monitored in the observation wells prior to the test to establish static pre-test water-level trends. ASTM D4050-14 provides a typical measurement schedule to record water levels in the observation well at approximately logarithmic intervals of time and recommends measuring at least 10 data points through each interval. For this investigation, except for the test conducted at Germantown, each interval duration was increased — in, at least, one observation well per test — to maximize the collection of data points (Table 4), particularly at the beginning of the test, during which greater change in the piezometric head is expected.

ASTM D4050-14 also suggests conducting a preliminary analysis of the pumping test data during the test and to continue until the analysis shows

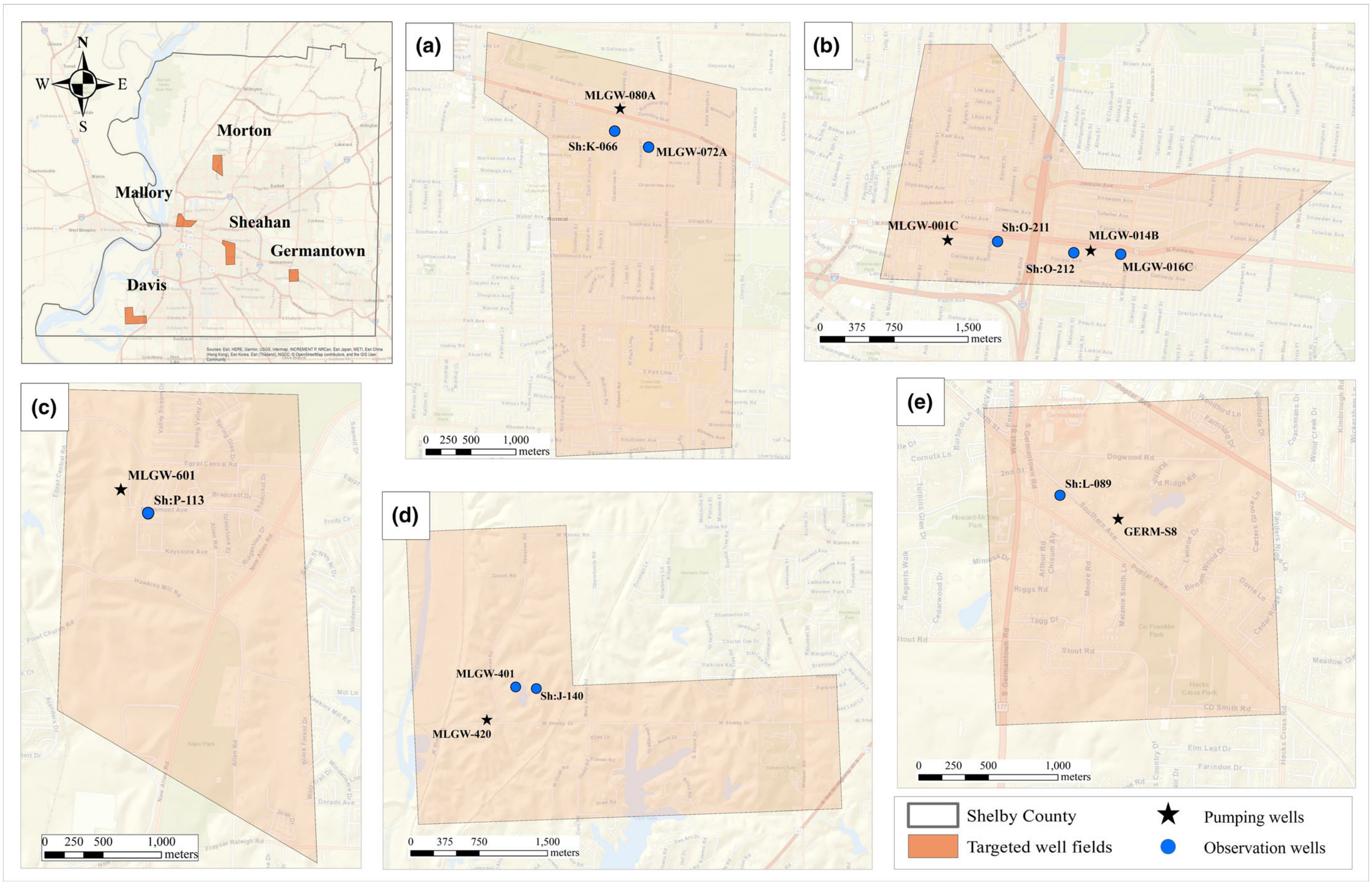

FIGURE 2. Study area showing the paired pumping and observation wells at five well fields distributed across Shelby County: (a) Sheahan, (b) Mallory, (c) Morton, (d) Davis, and (e) Germantown.

adequate test duration; hence, the duration of the pumping phase of a test can range from a few hours to several days. McWhorter and Sunada (2010) recommend a 24-h minimum pumping test. Waldron et al. (2011) assigns higher quality to conducting at least a 24-h test. For this investigation, a 48-h period was chosen to attain as near a stable water-level as possible (Kruseman and Ridder 1994) with an additional 12+ h prior and after the test to establish a static level and for adequate aquifer recovery, respectively (Figure 3).

Data Analysis

Drawdown from pumping and recovery tests were plotted vs. time using AQTESOLV (Aquifer Test Solver) developed by Duffield (1996). This software package was selected because it offers a wide range of solution techniques applicable across a range of aquifer types (i.e., confined, semiconfined, and unconfined systems), as well as allowing for analysis of drawdown data from partially penetrating wells, as is the case of pumping and observation wells used in this study. Test condition input to AQTESOLV includes: (1) saturated thickness and the vertical to horizontal hydraulic conductivity anisotropy ratio, assumed to be 1:10 (increasing the anisotropy above a ratio of 1:50 could result in significantly greater values of transmissivity not reasonable for the studied aquifer) (Freeze and Cherry 1979; Gentry et al. 2006); (2) pumping and observation well locations (Figure 2) and construction details, such as well diameter, depth, and screen interval (Table 3); and (3) pumping rates obtained from a flow meter installed at each pumping well.

The datasets collected from each pumping test were analyzed using two analytical solutions to identify the solution curve that best fits the data: (1) Theis (1935) solution for confined aquifers and (2) Hantush and Jacob (1955)/Hantush (1964) (without aquitard storage) for semiconfined aquifers. The latter condition was considered due to known breaches in the confining unit where semiconfined behavior is likely to be observed. Final determination of the aquifer parameters was based on the solution curve that minimized the residual sum of squares (RSS) while

TABLE 3. Construction characteristics of wells of interest.

Well field	Well name	Type of well	Well-screen diameter (cm)	Screen top (masl)	Screen bottom (masl)	Screen length (m)	Distance from pumping well (m)
Sheahan	MLGW-080A	P	30.5	–31	–56	24	—
	Sh:K-066	O	12	–41	–59	19	214
	MLGW-072A	O	30.5	–36	–62	26	440
Morton	MLGW-601	P	30.5[1]	–30	–62	32	—
	Sh:P-113	O	12	1	–33	34	250
Davis	MLGW-420	P	30.5	–26	–51	26	—
	Sh:J-140	O	15	–76	–79	3	640
	MLGW-401	O	30.5	–23	–49	26	390
Germantown S.	GERM-S8	P	30.5	38	20	18	—
	Sh:L-089	O	12	18	21	3	370
Mallory E.	MLGW-001C	P	30.5[1]	–54	–84	30	—
	Sh:O-211	O	12	–137	–140	3	535
Mallory W.	MLGW-014B	P	30.5	–124	–160	35	—
	Sh:O-212	O	15	–146	–149	3	165
	MLGW-016C	O	25.4	–122	–161	38	250

Notes: masl, Meters above sea level; O, Observation Well; P, Pumping Well.
[1] Based on known characteristics of MLGW production wells within the same well field.

TABLE 4. Pressure transducer water-level measurement frequency.

Day(s)		Starting time	Frequency (one measurement every)	Elapsed time
1	Pumping and nearby wells are off	15:00	1 min	17 h
2–3	Pumping well is on; nearby wells remain off	8:00	1 s	1 h
		9:00	10 s	1 h
		10:00	1 min	46 h
4	Pumping and nearby wells are off	8:00	1 s	1 h
		9:00	10 s	1 h
		10:00	1 min	6 h

restraining the calculation of the residuals within a timeframe where interference from other production wells was either absent or considered minimal. Lastly, the reliability of the determined values was scored according to the criteria described in Table 2.

RESULTS AND DISCUSSION

Interference of Neighboring Production Wells

Information on each neighboring production well was obtained from MLGW's Supervisory Control and Data Acquisition (SCADA) network to determine their exact status during the test period. Effort was taken to identify other production wells in the well field that, due to their proximity, may influence drawdown in the pumping well during the entire test period, and request that MLGW turn those wells off. The results show, however, that in fact some nearby production wells were on for periods of time during the pumping tests. Information on the elevation and screen length of the wells was also obtained to determine those that may reside in the same proximal horizontal strata as the test pumping and observation wells, assuming that the impact may be greater (see Figure 4; Table 5). Unfortunately, the discharge rates of the interfering wells were not known.

Figures 5 through 8 show the water levels at observation wells used in the pumping test along with times when nearby production wells were active and inactive: Green lines indicate the time at which an MLGW well was turned on and red lines indicate when they were turned off (the variable length of these lines only serves labeling purposes). Turning on some production wells during the test produced an additional drop in head, whereas turning them off produced a rise in head. For example, wells 058, 074, and 097 were turned off about four hours after the test started in the Sheahan well field (see Figure 5), producing a rise in the water-level. It should be noted that more than one well can be turned on or off at the same time. Following the previous example, wells 074 and 097 did not have an individual impact (i.e., change in water-level when turned on/off) after inspecting their pumping records during the test in which these changed their status; hence, only well 058 had an influence on the test. After taking this into consideration, along with screen elevation (Table 5) and the distance from observation wells (Figure 4), wells determined to have a greater impact on the individual tests are presented in Table 6. The

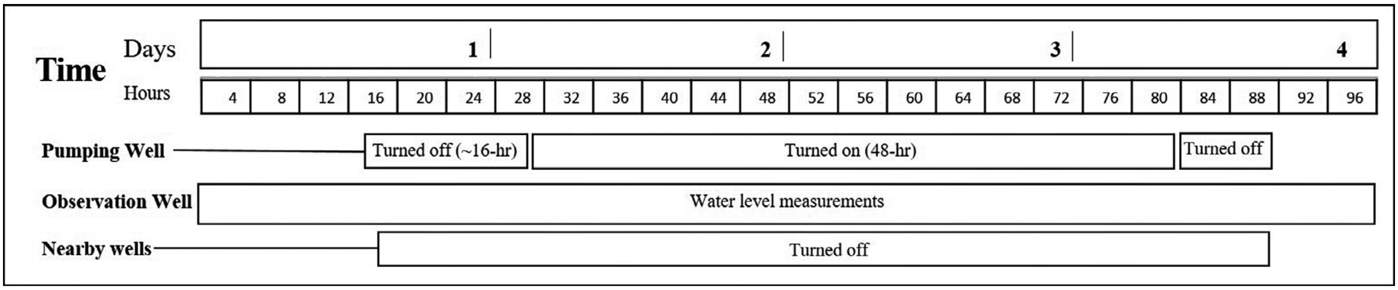

FIGURE 3. Pumping test schedule for wells involved in each test.

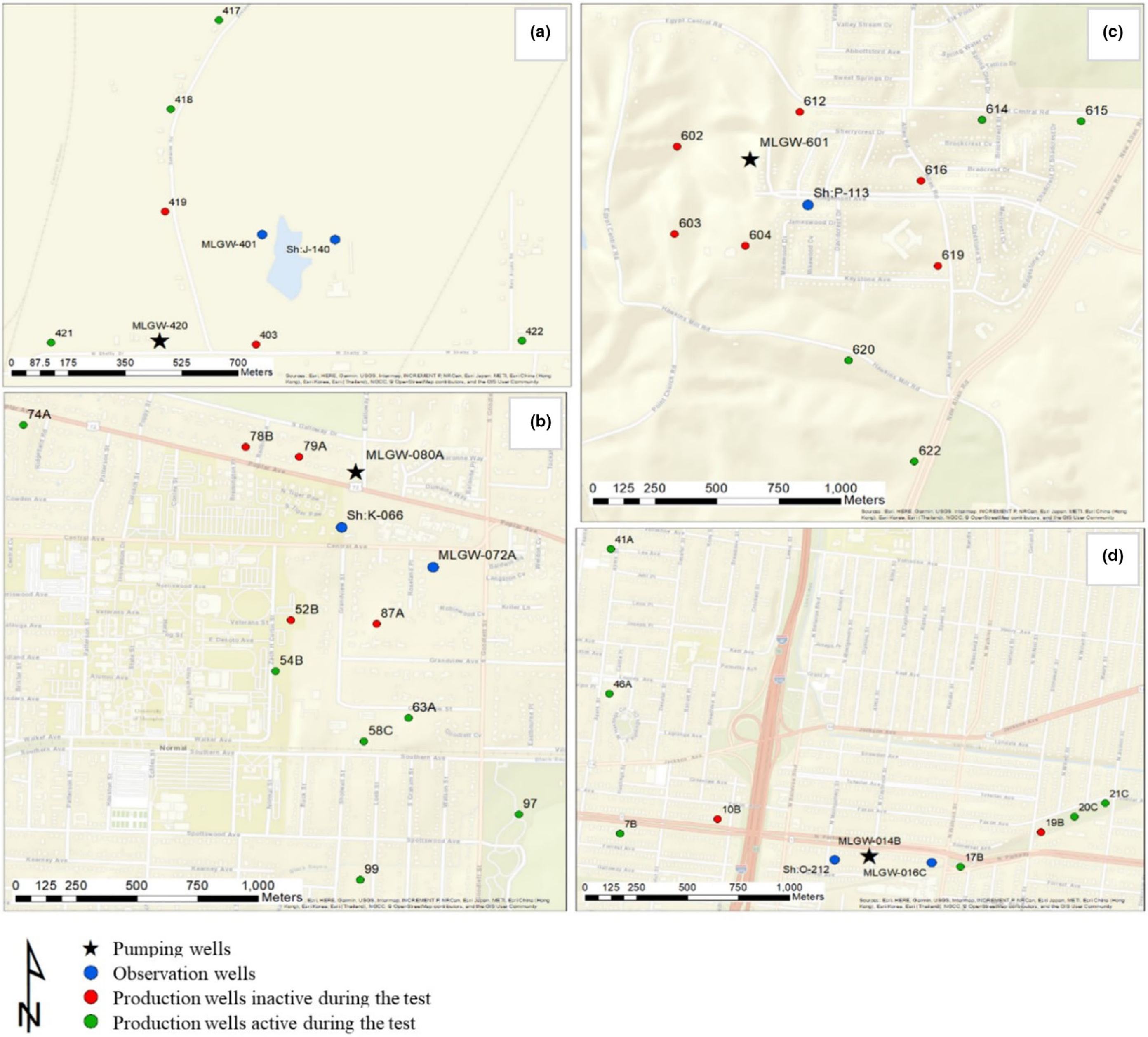

FIGURE 4. Location of pumping wells, observation wells, inactive production wells, and active production wells during the pumping tests, within each well field: (a) Davis, (b) Sheahan, (c) Morton, (d) Mallory.

TABLE 5. Screen elevation of nearby production wells that were active during the tests.

Well field	Well ID	Screen top (masl)	Screen bottom (masl)	Screen length (m)
Sheahan	054	−24	−51	26
	058	−26	−58	32
	063	−2	−34	32
	074	−59	−78	20
	096	−126	−156	30
	097	−53	−84	31
	099	−22	−54	32
Morton	614	−42	−52	10
	615	−45	−56	10
	620	−17	−26	9
	622	−15	−27	12
Davis	409	−68	−77	9
	417	−11	−19	8
	418	−11	−14	3
	421	−11	−18	7
	422	−10	−18	7
	424	−8	−16	7
	429	−6	−16	10
	430	−12	−24	12
	432	−6	−17	11
Mallory E.	003	−15	−22	7
	007	−16	−23	8
	017	−16	−25	8
	020	−39	−49	10
	021	−25	−35	10
	034	−12	−20	7
	041	−34	−44	10
	046	−22	−32	10

predicted drawdowns for each interfering well were included in the pumping test analysis (discussed next section) using superposition theory to assess the effects of multiple wells (Dawson and Istok 1992). Figures 5–8 show that other production wells were active prior to the test. The recovery produced by these wells going off during the test was accounted for in AQTESOLV by assuming they were injecting water at a rate equal to that of which they were extracting water before the test began.

Time-Window Constrains

Analysis of the drawdown curves was constrained to specific time windows when the interference from other production wells was minimized, increasing the likelihood of this segment of data to better fit a theoretical curve. Datasets for every test were constrained between the beginning and 155–650 min into the test, where interference from additional production wells was considered negligible. Though drawdown curves were time-constrained, the RSS was estimated for the entirety of the curve to assess the impact of including interfering wells in the sum of residuals. The Germantown test proved more difficult to determine additional wells that may have influenced the test so a time-windows of one hour was used.

Analysis of Pumping Test Data for Semiconfined Aquifers

The graphical solution developed by Hantush and Jacob (1955) was selected to analyze the drawdown data collected from the pumping tests influenced by leakage from the aquitard overlying the Memphis aquifer. The logarithmic plot of the time-drawdown field data was superposed on the family of semiconfined type curves in AQTESOLV (Hantush and Jacob 1955; Walton 1962). Hantush and Jacob (1955) family-type curves are function of *r*/*B*, which defines the proportion of flow to the pumping well that comes from leakage. The ratio *r*/*B* is explained by the relationship between the distance from the pumping well

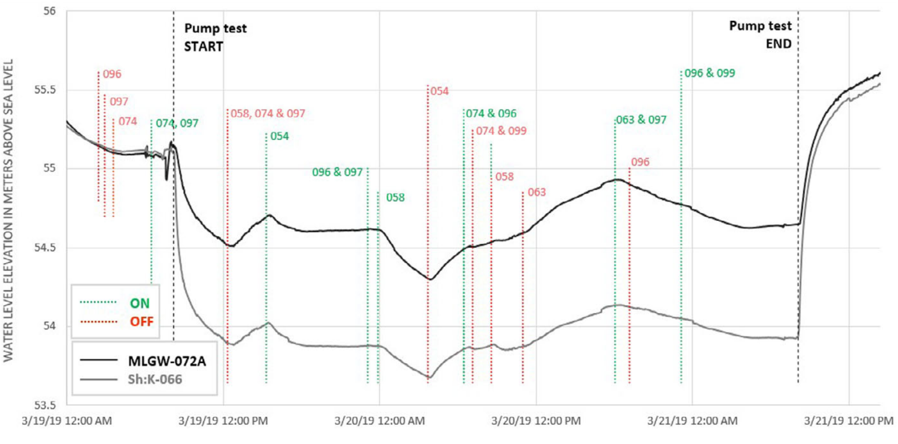

FIGURE 5. Water levels observed at wells MLGW-072A and Sh:K-066 during the pumping test at Sheahan.

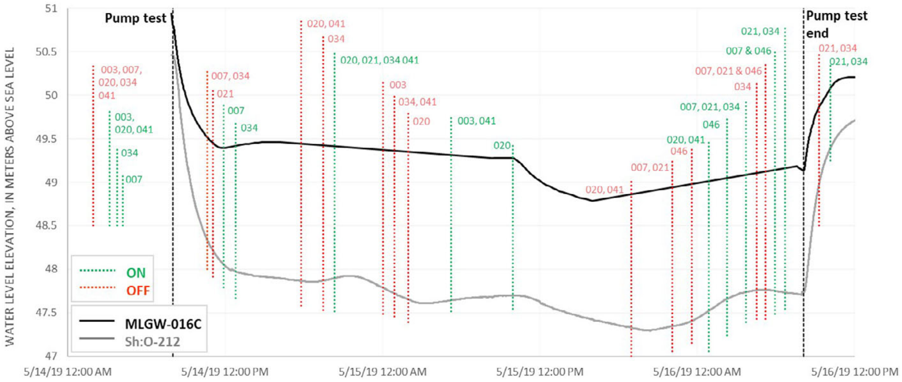

FIGURE 6. Water levels observed at wells MLGW-016C and Sh:O-212 during the pumping test at Mallory.

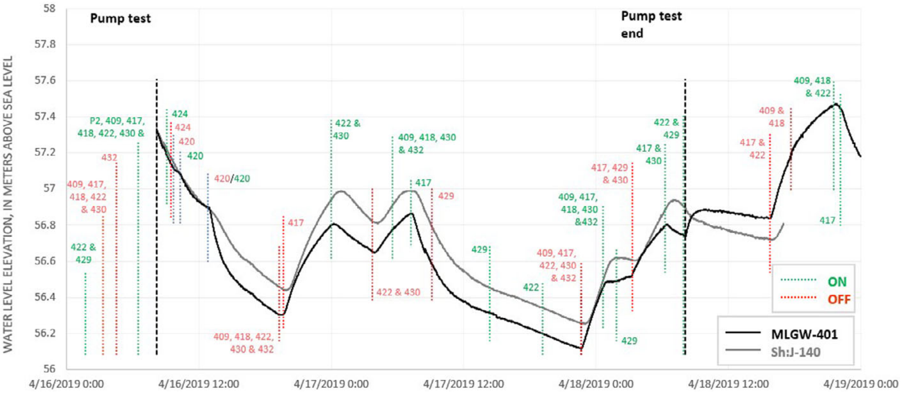

FIGURE 7. Water levels observed at wells MLGW-401 and Sh:J-140 during the pumping test at Davis.

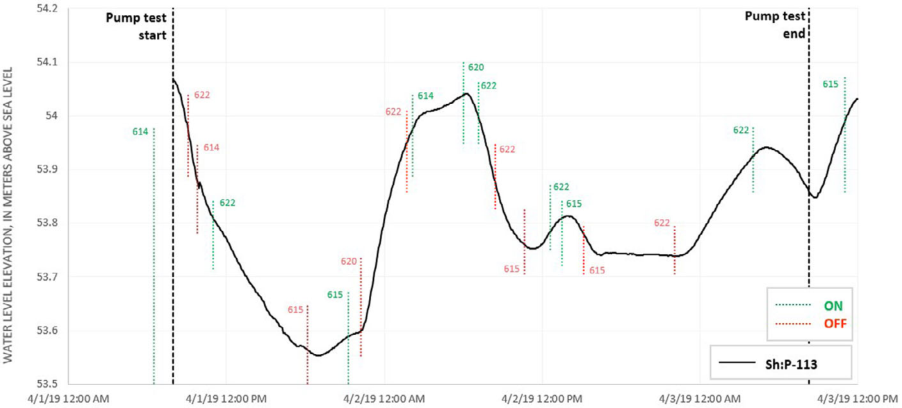

FIGURE 8. Water levels observed at well Sh:P-113 during the pumping test at Morton.

to the observation wells r and the leakage factor B, which is expressed as:

$$B = \sqrt{Tb'/K'}, \tag{2}$$

where T = transmissivity of the Memphis aquifer, in square meters per day; K' = vertical hydraulic conductivity of the aquitard, in meters per day; b' = thickness of the aquitard, in meters.

For this study, ranges of r/B were estimated for each well field to confirm that the values determined from the pumping tests are within reasonable estimates of the aquitard's leakage to the Memphis aquifer. These values considered the characteristics of the aquifer system determined by previous studies

(Criner et al. 1964; Moore 1965; Hosman et al. 1968; Parks 1990; Parks and Carmichael 1990; Gentry et al. 2006; Villalpando-Vizcaíno et al. 2021). Transmissivity values are shown in Table 1. A range between 6×10^{-6} and 8×10^{-4} m/day was used for the vertical hydraulic conductivity of the aquitard (Gentry et al. 2006; Villalpando-Vizcaíno et al. 2021), and between 1×10^{-4} and 3×10^{-3} m/day for the vertical hydraulic conductivity of a breach (Villalpando-Vizcaíno et al. 2021). The thickness of the aqtard was assigned according to the thickness of the confining layer derived by Villalpando-Vizcaíno et al. (2021). Ranges of r/B estimated for each well field are presented in Table 7.

Aquifer Parameter Results

Drawdown was plotted against time on a logarithmic scale and was superposed with a solution curve. AQTESOLV allows use of on-screen visual matching of solution curves to drawdown data, which was later complemented with a nonlinear least-square approach to estimate the aquifer parameters with the smallest sum of residuals. The time-window constraints applied to each dataset are indicated with a red discontinuous line. The rate at which water was withdrawn from the pumping well was verified to have not varied more than 10% from the mean discharge at most tests, except for Davis, where pumping well MLGW-420 was turned off twice for 40-min periods, early during the test. The pumping rate for interfering MLGW wells is not known; therefore, accounting for the interference of other production wells on the test required an assumption that their discharge ranged between 1,000 and 1,500 gallons per minute (GPM) (personal correspondence MLGW). Along with transmissivity and storativity, values of r/B were also estimated for the semiconfined-type curves.

TABLE 6. MLGW production wells determined to have an influence on the pumping test at each well field.

Well field	Wells interfering with the test
Sheahan	054, 058, 063
Morton	616, 620, 622
Davis	417, 418, 421, 422
Mallory E.	007, 017, 020, 021

TABLE 7. Ranges of r/B estimated for each well field.

Well field	Thickness of the aquitard, b' (m) Min	Max	Observation well	r/B
Sheahan	1.5[1]	29	Sh:K-066	0.006–0.6
			MLGW-72A	0.01–1.25
Morton	26	39	Sh:P-113	0.001–0.1
Germantown	5	16	Sh:L-089	0.003–0.6
Davis	12	29	Sh:J-140	0.02–0.6
			MLGW-401	0.01–0.4
Mallory	7	24	Sh:O-212	0.005–0.2
			MLGW-016C	0.007–0.3

[1] Parks (1990).

Logarithmic plots of the datasets from the pumping tests at Sheahan (Figure 9) and Mallory (Figures 11 and 12) showed a decrease in the drawdown rate over time, typical of semiconfined aquifer systems (Dawson and Istok 1992). This is mostly attributed to downward leakage from the confining unit, especially in Sheahan, as it is located near a suspected breach location. The same behavior was expected at the Davis well field, which is located near a suspected breach; however, interference from other pumping wells active during the test made it harder to identify. Figures 9–12 show the logarithmic plot of the time-drawdown data superposed with the type-curve of the Hantush family that better adjusted before and after accounting for the influence of other production wells (i.e., corrected curves). Figure 12 shows the solution curve that was considered to better fit the field data for the first test conducted in Mallory. Interference of wells near the observation well, Sh:O-211, in Mallory W. hindered any attempt to match a solution curve to the data. Hence, the estimation of parameters for Mallory W. relied on airline measurements taken at the pumping well, MLGW-001C. An analysis in AQTESOLV indicated that the influence from other production wells in the test at this well field is negligible.

Morton's drawdown curve was observed to resemble a typical nonequilibrium type curve for confined aquifers despite the influence of interfering pumping wells (Figure 13), most likely attributed to this area being under confined condition. Additional to the solution curve that best represents the hydraulic properties of the aquifer at this well field (i.e., corrected curve), Figure 13 also indicates the solution curve calculated without accounting for external stresses from other pumping wells, marked as a discontinuous line. Lastly, due to the interference of pumping wells occurring at an early stage, around one hour into the test, and the lack of information to account for it, the solution curves for Germantown were calculated using both a non-equilibrium type curve (i.e., Theis solution for confined aquifers) and an $r/B = 0.2$ type curve, which is the greatest value of r/B estimated for this well field (see Table 7). However, due to the solution curves being adjusted to only early drawdown data, both solutions overlap. It

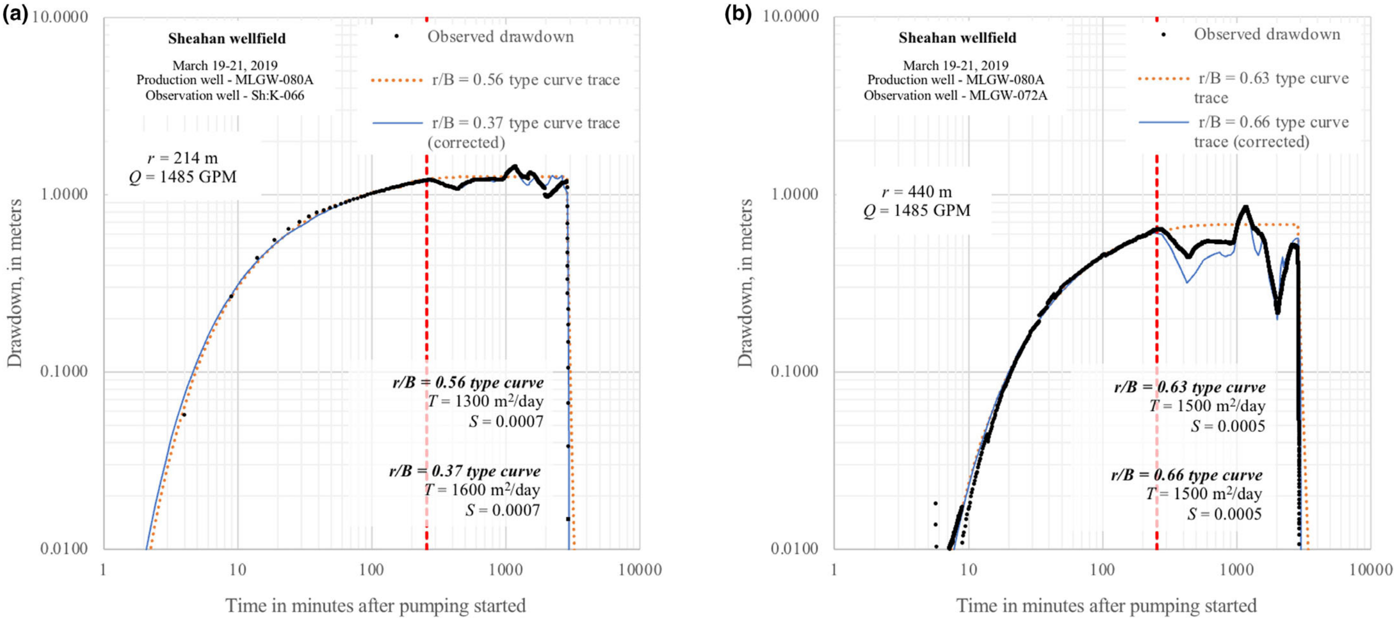

FIGURE 9. Hantush–Jacob solution curves for the data collected on the Sheahan well field at observation wells (a) Sh:K-066, and (b) MLGW-072A.

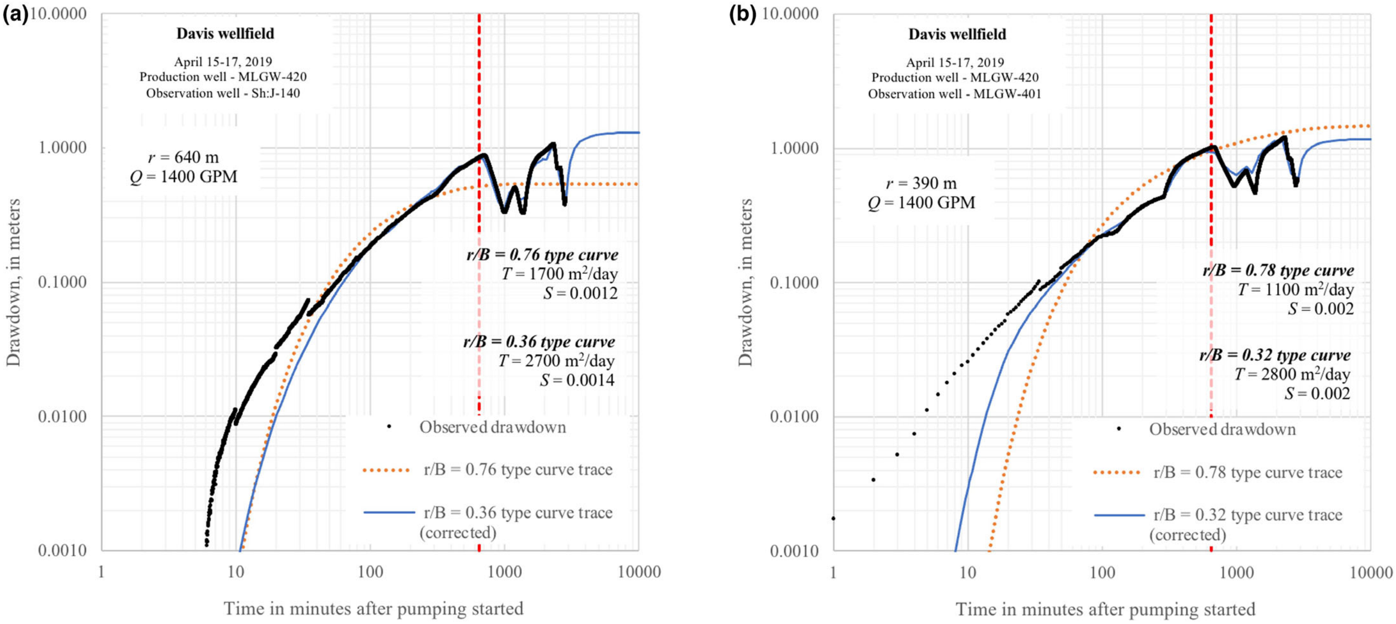

FIGURE 10. Hantush–Jacob solution curves for the data collected on the Davis well field at observation wells (a) Sh:J-140, and (b) MLGW-401.

is important to note that early drawdown data are more susceptible to the immediate well environment, reducing the reliability in the parameters estimated in Germantown (Figure 14).

A difference between the transmissivities estimated with the solutions before and after accounting for interference of other production wells can be observed in Figures 9–11, especially in Davis, where pumping interference was considered to have a great effect in the test. Values of r/B estimated for Sheahan, Davis and Mallory with curve matching in AQTESOLV fell within the range determined for each well field prior to the analysis of drawdown data (Table 7), and transmissivities within each well field

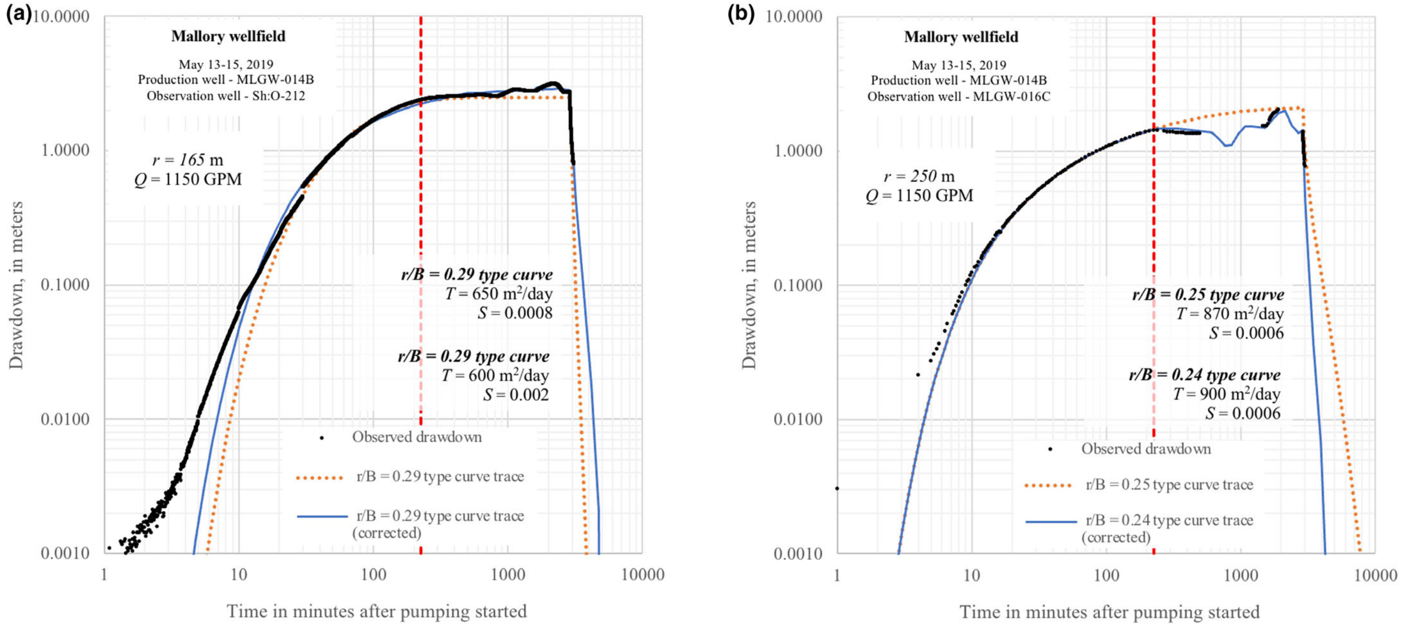

FIGURE 11. Hantush–Jacob solution curves for the data collected on the Mallory well field at observation wells (a) Sh:O-212, and (b) MLGW-016C.

were of the same order of magnitude. The latter observation, along with matching curves that resemble the field data, provides confidence in the parameters estimated for these well fields. Values of *r*/*B* are dependent on both the degree of leakage from the confining unit and the total discharge of nearby production wells; thus, the unknown pumping rate for interfering wells is a source of error in the estimated *r*/*B* values. Given that the solution curves for the field data collected in Germantown could only be matched to the first hour of the test, a transmissivity of 2,500 m^2/day and a storativity of 0.002 was estimated with both solutions.

A summary of the aquifer properties determined from this study is presented in Table 8. All values fall within the ranges reported by previous studies presented in Table 1. However, values provided in this study (Table 8) varied in less than one order of magnitude within each well field, providing narrower, more localized values across Shelby County. Values of transmissivity estimated for Sheahan and Mallory are below the values reported by Moore (1965) for these same well fields, with transmissivities of 3,300 and 2,400 m^2/day, respectively. The same study estimated a transmissivity of 2,200 m^2/day for Germantown, which is close to the value determined in this study.

Most estimates of storativity are in agreement with the ranges reported by Moore (1965) and Parks and Carmichael (1990), except for Morton, where higher values were observed. Storativity could not be estimated for Mallory W. since the test was performed only on the pumping well (Leven and Dietrich 2006). The average value of transmissivity determined for the Memphis aquifer within Shelby County, 2,000 m^2/day, falls below the average reported by previous studies (Table 1) of about 4,000 m^2/day; whereas the average storativity of 0.002 estimated in this study is in accordance with the average of previous studies.

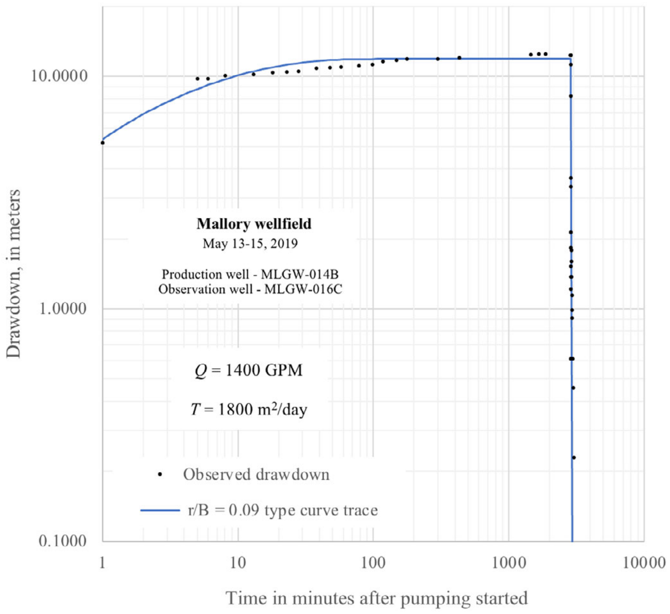

FIGURE 12. Hantush–Jacob solution curve for the test performed at Mallory W.

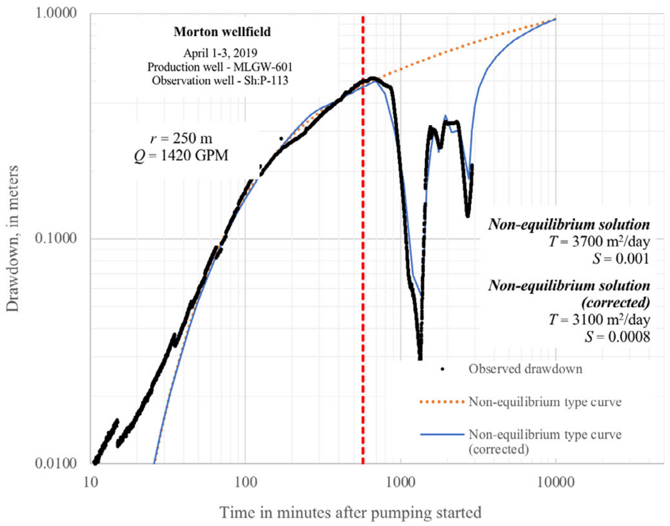

FIGURE 13. Theis solution curves for the test performed at Morton.

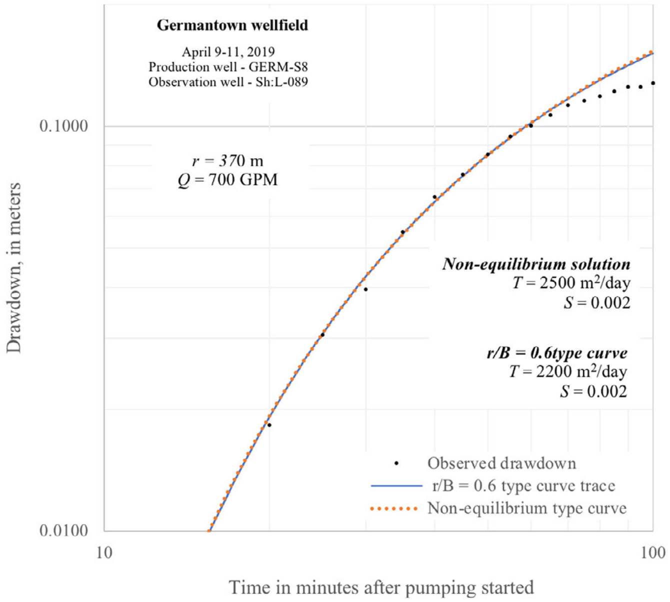

FIGURE 14. Theis and Hantush–Jacob solution curves for the test performed at Germantown.

Estimation of Error in Curve Matching

The type-curve matching methodology is based on finding the theoretical curve that better fits the time-drawdown field data. For this, AQTESOLV calculates the sum of square residuals (RSS), which consists of an estimated difference between the observed and simulated drawdowns. When interfering wells were accounted for in the drawdown analysis, the RSS was reduced by 32%–98% (Table 9). Smaller reductions in RSS were observed in Mallory, which is likely due to the fact that the disturbance produced by interfering pumping wells was already minimal. By constraining the analysis to an appropriate time window, the RSS was reduced to more than 98% for most cases (Table 10).

Pumping Test Scoring Results

The scoring matrix developed by Waldron et al. (2011) was used to evaluate the reliability of the values estimated with this study, according to the criteria in Table 2. Score breakdown for each test is presented in Table 11. Availability of more than one observation well accounts for an added increase in one point in the score for half of the tests. The score of all tests, except for Germantown, increased one point more for extending through a 24-h test period. Unfortunately, due to multiple wells pumping throughout most of the tests, two points were subtracted from the total score. Nonetheless, the five points associated with these wells being turned on and off were preserved as their effect was accounted for in the solution. It should be noted that a test with a low score does not necessarily invalidate the estimated parameters.

A specific threshold score was not specified to discern "good tests" from the "bad tests"; however, the historical record assessment presented in Waldron et al. (2011) estimated an average score of 4.1 for the Memphis aquifer, where 93.4% of the reviewed historic values fell within Shelby County. Used as a starting threshold, this average score was surpassed by five out of six of the tests in the present study; the average score for the tests in this study is 8.7. If accurate pump schedule data had been available to account for the influence of nearby production wells in the test at Germantown, five points would have been added to the total score of this well field, increasing the average score to 9.5.

CONCLUSIONS

Estimation of aquifer properties helps to achieve a better understanding of groundwater systems and provides valuable information to address issues related to groundwater storage and movement, which are important in planning and decision making to preserve the sustainability of the quantity and quality of groundwater resources. This study provided an approach to perform pumping tests on an operational well field, allowing for the estimation of localized and more reliable values of transmissivity and storativity of the Memphis aquifer. The resulting values determined were within the range of hydraulic properties

TABLE 8. Transmissivity and storativity values estimated from the pumping and recovery tests performed at five well fields.

			Pumping test			Recovery test	
Well field	**Average discharge (GPM)**	**Well**	**Transmissivity (m^2/day)**	**Storativity**	***r/B***	**Transmissivity (m^2/day)**	**Storativity**
Sheahan	1,485	Sh:K-066	1,600	0.0007	0.37	1,300	0.0005
		MLGW-72A	1,500	0.0005	0.66	1,500	0.0002
Morton	1,420	Sh:P-113	3,100	0.009	—	—	—
Germantown	700	Sh:L-089	2,500	0.002	—	—	—
Davis	1,400	Sh:J-140	2,700	0.001	0.36	—	—
		MLGW-401	2,800	0.002	0.32	—	—
Mallory W.	1,400	MLGW-001C	1,800	—	0.09	1,700	N/A
Mallory E.	1,150	Sh:O-212	600	0.002	0.29	640	0.002
		MLGW-016C	900	0.0006	0.24	900	0.001

Note: N/A, not applicable.

reported by other authors but following a well-documented and consistent method improved the quality of the data collected and provided more precise local data. The application of these results to numerical groundwater flow should reduce uncertainty due to non-uniqueness. These values represent the heterogeneity and localized confining unit leakage to the Memphis aquifer in different locations distributed across Shelby County, which is expected to be useful for future modeling efforts by achieving a better representation of the system.

Decrease in the drawdown rate over time in Sheahan, Davis and Mallory supports the findings of several authors (Graham and Parks 1986; Parks 1990; Kingsbury and Parks 1993; Parks et al. 1995; Koban et al. 2011; Larsen et al. 2016) regarding the presence of zones where the protective clay layer is thin or absent. The improved fit of leakage-based well solutions to the Mallory well field suggests that more detailed studies are warranted, such as the tracer studies at the Davis and Sheahan well fields (Koban et al. 2011; Larsen et al. 2003, 2013). Interference from other pumping wells within the well fields was identified as the greatest source of uncertainty in this study, but it still was possible to account for the majority of outside stresses resulting from the pumping of nearby production wells if accurate pump schedule data exist, which was the case for most well fields. An exception to this was observed in Germantown, where accurate pumping schedule data did not exist and, therefore, the effects of interfering wells pumping could not be addressed. In the event of performing future aquifer characterization, better planning that avoids the influence of pumping from other production wells during the aquifer tests should lead to better parameter estimates. Additionally, it is recommended to perform aquifer testing in the northern part of Shelby County to better evaluate the hydraulic characteristics of the Memphis aquifer at the county scale.

TABLE 9. Residual sum of squares (RSS) calculated before and after accounting for the influence of other production wells.

Well field	**Well**	**RSS (before accounting for influence)**	**RSS (after accounting for influence)**	**RSS difference (%)**
Sheahan	Sh:K-066	318	94	70
	MLGW-72A	1,510	159	89
Morton	Sh:P-113	7,880	177	98
Davis	Sh:J-140	1,640	103	94
	MLGW-401	1,300	338	74
Mallory	Sh:O-212	701	476	32
	MLGW-016C	59	22	63

TABLE 10. RSS calculated for the solution curve when constrained to a time window, the total curve, and their difference.

Well field	**Well**	**RSS (time const.)**	**RSS (total)**	**RSS difference (%)**
Sheahan	Sh:K-066	0.5	94	99
	MLGW-72A	0.4	159	99
Morton	Sh:P-113	2.8	177	98
Germantown	Sh:L-089	5E-04	606	99
Davis	Sh:J-140	25	103	76
	MLGW-401	4	338	99
Mallory	MLGW-001C	—	1,350	—
	Sh:O-212	98	1,420	93
	MLGW-016C	0.2	92	99

The scores to evaluate the quality of the data collected from the pumping tests were higher than the average score of previous records by 4.7 points, showing improvement upon historical records that may not have adhered to adequate procedures. The interference from multiple production wells is a complicating factor that leads to lower quality scores; however, since it was recognized and addressed in the analysis, impacts were

TABLE 11. Scores achieved by the pumping tests performed at each well field.

Well field	Published or Approved	Multiple pumping wells	Other wells on and off	Observation wells	Test duration	Good supporting information	Multiple analyses	Multiple wells analyzed	Drawdown and recovery analyses	Total
Davis	0	−2	0	0	1	0	1	0	−2	8
Germantown S.	1	−2	−5	0	−2	0	1	0	−2	1
Mallory W.	1	0	0	−2	1	0	1	1	0	12
Mallory E.	1	−2	0	0	1	0	1	1	0	12
Morton	0	−2	0	0	1	0	1	0	−2	8
Sheahan	1	−2	0	0	1	0	1	0	0	11

minimized. Overall, tests adhered to the recommendations made by Waldron et al. (2011) and sources of error were addressed to achieve the better values possible. Additionally, these tests are considered to have more precise data than previous studies due to the usage of automatic recording devices, such as pressure transducer and a more rigorous analysis allowed by computational tools such as AQTESOLV, producing aquifer parameters that are expected to lead to a better understanding of the Memphis aquifer system.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in Supporting Information of this article.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Spreadsheets with the original datasets used to determine the aquifer parameters reported in the manuscript.

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AUTHOR CONTRIBUTIONS

Sofía Sahagún-Covarrubias: Conceptualization; Formal analysis; Investigation; Methodology; Writing — original draft; Writing — review & editing. **Brian Waldron:** Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Validation; Writing — review & editing. **Daniel Larsen:** Formal analysis; Investigation; Methodology; Supervision; Validation; Writing — review & editing. **Scott Schoefernacker:** Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation; Writing — review & editing.

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