8-5-2020

Characterization of Hydraulic Properties of the Memphis Aquifer by Conducting Pumping Tests in the Memphis Area, Tennessee

Sofia Sahagun Covarrubias

CHARACTERIZATION OF HYDRAULIC PROPERTIES OF THE MEMPHIS AQUIFER BY CONDUCTING PUMPING TESTS IN THE MEMPHIS AREA, TENNESSEE

by

Sofía Sahagún-Covarrubias

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Major: Civil Engineering

The University of Memphis

August 2020

ACKNOWLEDGEMENTS

I would like to express my very great appreciation to MLGW for funding this project and for their assistance with the collection of my data. I am extremely grateful for the patience and assistance given by my main advisor, Dr. Brian Waldron, and the rest of my committee Dr. Dan Larsen and Dr. Scott Shoefernacker, as well as Rodrigo Villalpando, for their valuable suggestions during the planning and development of this project. I would like to thank the Center for Applied Earth Science and Engineering Research (CAESER), as well as the University of Memphis and the Department of Civil Engineering for the opportunity to complete my master's degree. Thank you to the CAESER crew, especially Mary for helping me in so many ways when I first arrived in Memphis. Many thanks to my friends and graduate partners for their valuable help and support during fieldwork.

Finally, my deep gratitude to my family, particularly my parents, Adriana and Ivan, for their love and encouragement. To my sister and very best friend, Andre, for her unconditional support and for looking out for our dogs while I was away: Pelu, Reba, Cane, Marcelo and Gini, for whom I also am thankful for making me so happy. To my best friends, Naye, Andres, Angie and Tere, for motivating me and being so awesome to me when things get discouraging. And to Hugo, for all the help and support, and just being there for me.

PREFACE

This chapter has been formatted in the style of the *Journal of the American Water Resources Association* (JAWRA), to which the present work will be submitted for publication.

ABSTRACT

The limitation of field measurements leads to parameter non-uniqueness of numerical models, which can be addressed by including more parameter data. Six pumping tests were conducted in five municipal well fields within Shelby County following the procedure described in the ASTM D4050-14 and considering strengthening factors to achieve greater reliability. Drawdown data of the pumping tests was analyzed using AQTESOLV, which allowed accounting for partial penetration and interference from neighboring production wells.

The values of transmissivity and storativity estimated have a combined range of 600 to 3100 m^2/day and 0.0005 to 0.002, respectively, varying within one order of magnitude on each well field. The average quality score of the tests, of 8.7, was higher than the average score of previous records of 4.1. The parameter values determined are expected to reduce non-uniqueness of numerical modeling solutions for groundwater flow, leading to improved evaluation of groundwater resources and environmental impact assessments.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Groundwater modeling provides a quantitative representation of the hydrogeologic processes occurring within an aquifer system 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, such as quantifying aquifer yield (Sun, 1999), and prediction of rates and direction of contaminant transport (McKenna *et al*., 2003). However, several authors acknowledge that the limitation of field measurements is a problem that often leads to non-uniqueness of the model solutions (Neuman, 1973; Pang *et al*., 2000; McKenna *et al*., 2003; Friedel, 2005; Yeh *et al*., 2015; Jazaei *et al*., 2019; Villalpando-Vizcaino, 2019).

Non-uniqueness refers to multiple numerical solutions obtained with different sets of parameter values leading to similarly good matches for the field measurements, which could provide an inaccurate description of the aquifer groundwater flow system (Zechman *et al*., 2006). Friedel (2005) explains that since limited hydraulic parameter field estimations used to constrain the model parameter calibration process contribute to non-uniqueness, 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 usage and evaluation of groundwater resources and environmental impact assessments (Rogiers *et al*. 2012; Criollo *et al*., 2016).

Some approaches that have been developed to determine aquifer parameters include: geoelectrical methods (Keller and Frischknecht, 1966; Koefoed, 1981) such as the resistivity method (Niwas and De Lima, 2003), laboratory methods such as grain-size analysis and permeameter tests (Wolf *et al*., 1991; Alyamani and Sen, 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 area scale than those estimated using grain-size analysis and slug test (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 many 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 the 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 that only thirteen sources from published literature of parameters estimated for the Mississippi embayment aquifer system, six of which present values of hydraulic conductivity, transmissivity and storativity 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 to 6,400 m^2/day and 0.0001 to 0.003, respectively. Unfortunately, the location for some of the tests was not specified. Thus, the available data provide only a broad range of hydraulic property values for the Memphis aquifer at a county scale.

Waldron *et al*. (2011) provided a scoring matrix to assess the reliability of the aquifer parameter values. According to this study, a reported value is considered reliable depending on the methods used, the presence of factors that could impact the aquifer test (e.g. irregular pumping rates, test duration, influence of other production wells, or production wells turning on and off), and the existence of supporting documentation. The average score of the 122 historic values collected for the Memphis aquifer, of which 93.4% where estimated within Shelby County, was 4.1, with a maximum score of 7. This analysis by Waldron *et al*. (2011) 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 non-uniqueness and aid in informed decision making on groundwater sustainability (Villalpando-Vizcaino, 2019).

SITE DESCRIPTION

The Memphis aquifer is regional in scale, underlying portions of multiple states with its greatest extent beneath Tennessee, Arkansas and Mississippi (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; Waldron *et al*., 2011).

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 (Graham and Parks, 1986). The thickness of the Memphis aquifer is of approximately 150 m in the northeastern part of the Memphis area 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 subcrops toward 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; Larsen *et al*., 2016).

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 a southwest section of Shelby County (Fig. 1).

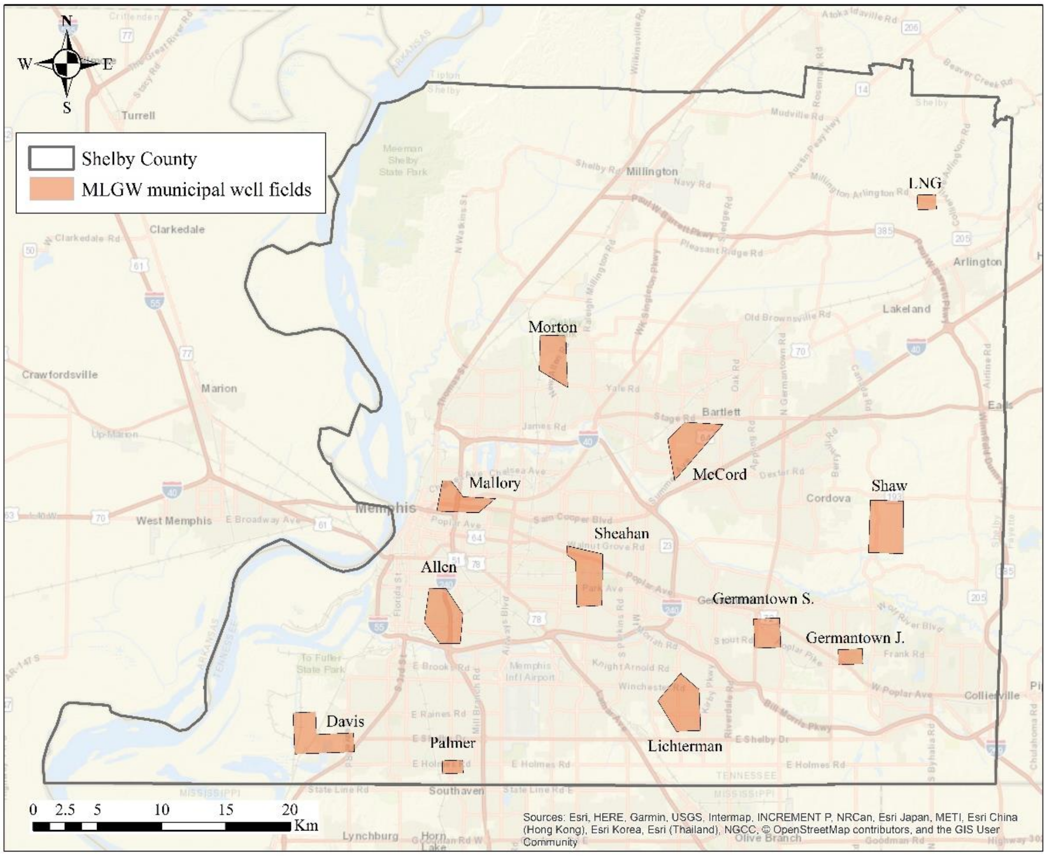

FIGURE 1. Location of Memphis Light, Gas and Water (MLGW) well fields within Shelby County.

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 to 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).

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	---	7450	30 – 50	35	---	---
	Slug test	30 – 6400	2560	0.15 – 30	12		
2. (Criner *et al*., 1964)	Pumping test	1240 – 5100	5000	5 – 25	23	0.0015 – 0.003	0.003
3. (Moore, 1965)	Aquifer tests	620 – 5000	~3000*	3 – 23	14	0.0001 – 0.003	~0.0015*
4. (Hosman *et al*., 1968)	Aquifer tests	---	3100	---	---	---	0.001
5. (Parks and Carmichael, 1990)	Aquifer tests	620 – 5000	3100	3 – 23	15	0.0001 – 0.003	0.001
6. (Brahana and Broshears, 2001)	Aquifer tests	250 – 4000	---	1 – 19	---	0.0001 – 0.0006	---
	Model calibration	900 – 4600	---	4 – 22	---	0.0002 – 0.2	---

*Based on the intermediate value of the published interval

Villalpando-Vizcaino (2019) 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-Vizcaino (2019) and Jazaei *et al*. (2019) calibrated their models using Parameter ESTimation (PEST) that adjusts aquifer parameters on a cell-by-cell basis within user define ranges. Villalpando-Vizcaino (2019) addressed the spatial heterogeneity by using pilot points at discrete locations (Doherty, 2003), yet allowing their ranges to extend outside published values. Although values for transmissivity and storage resulting from PEST mostly fell within the ranges reported 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 non-uniqueness by restricting ranges to published values (Parks and Carmichael, 1990; Brahana and Broshears, 2001; Gentry *et al*., 2006). Both studies reference historic 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 measure of the quality of 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 from Criner *et al*. (1964), Moore (1965), Hosman *et al*. (1968), Parks and Carmichael (1990) and others, the average score of the aquifer parameters collected from 88 aquifer tests in the Memphis aquifer compiled by Waldron *et al*., (2011) from the USGS historical records was 4.1 (93.4% of the reviewed historic values fell within Shelby County) with a maximum score of 7. Using an arbitrary threshold of seven, 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 will be employed in this investigation, which is expected to increase the confidence in the parameters estimated.

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 hours +1, unknown -1, <24 hours -2, <1 hour, -3) If the pumping duration is more than 24 hours, plus 1 If the pumping duration is unknown, minus 1 If the pumping duration is less than 24 hours, minus 2 If the pumping duration is less than 1 hour, 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

Waldron et al., (2001)

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 scale 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, plus an additional City of Germantown well field, and were selected based on three criteria: (1) well-distributed across the county, (2) availability of an associated observation well completed (i.e., screened) at a similar interval, and (3) adequate distance between the production and observation wells. This last criterion was included because MLGW production wells are partially penetrating, which could cause vertical components of flow proximal to the well (Hantush, 1961; Hemker, 1999). The ideal radial distance r at which the vertical flow components could be considered negligible is given by the following relationship:

$$r > 1.5b\sqrt{k_h/k_v} \quad (1)$$

where b is the thickness of the Memphis aquifer, and was obtained from the Mississippi Embayment Regional Aquifer Study model (MERAS) developed by Clark and Hart (2009), and k_v and k_h represent its vertical and horizontal hydraulic conductivities (McWhorter and Sunada, 2010; Dawson and Istok, 1992), commonly related by a ratio of 1:10 (Freeze and Cherry, 1979; Gentry *et al*., 2006). However, this constraint 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, 2019). This time-frame 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 five MLGW municipal well fields and one municipal well field in Germantown, Tennessee (Fig. 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).

TABLE 3. Construction characteristics of wells of interest.

Well field	Well name	Type of well	Well-screen diameter centimeters	Screen top masl	Screen bottom masl	Screen length meters	Distance from pumping well meters
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*	-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*	-54	-84	30	---
	Sh:O-211	O	12	-137	-140	3	535

TABLE 3. Construction characteristics of wells of interest.

Well field	Well name	Type of well	Well-screen diameter	Screen top	Screen bottom	Screen length	Distance from pumping well
			centimeters	masl	masl	meters	meters
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

*Based on known characteristics of MLGW production wells within the same well field

P = *Pumping Well*

O = *Observation Well*

masl = Meters *above sea level*

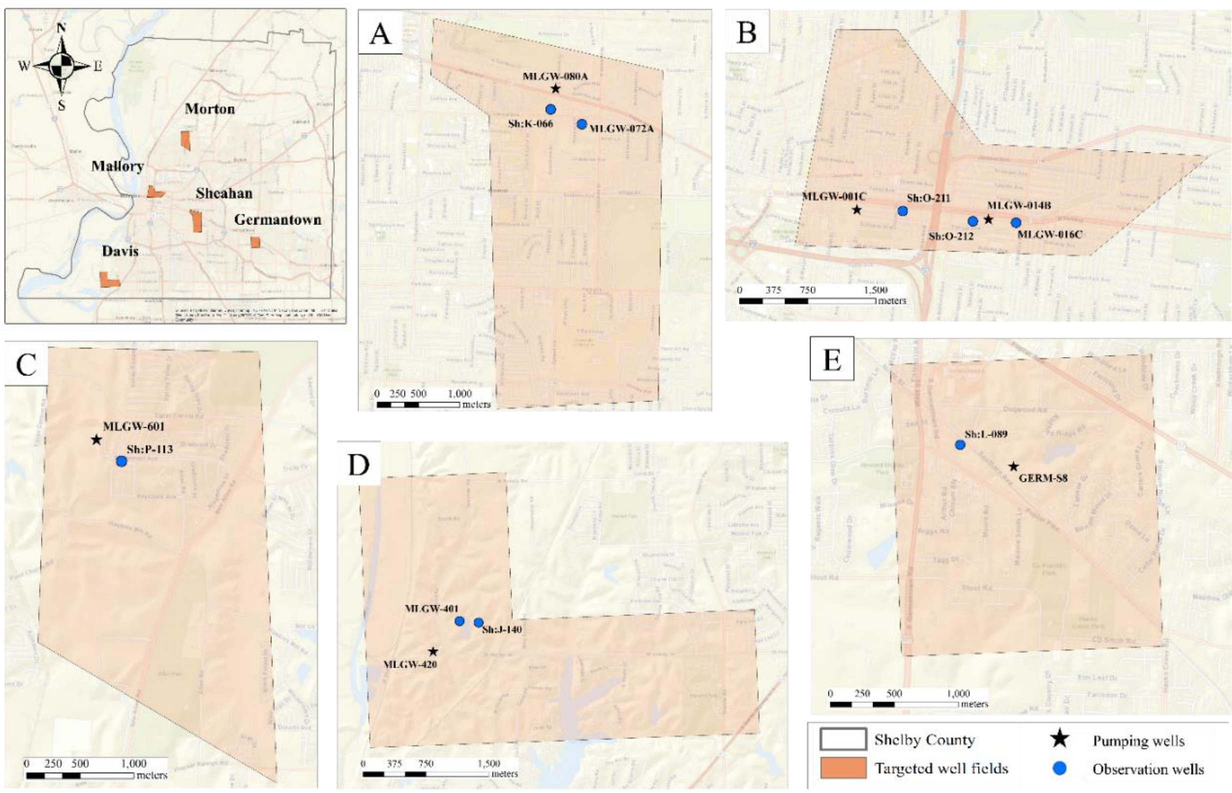

FIGURE 2. Study area showing the paired pumping and observation wells at five well fields distributed across Shelby County: (A) Sheahan, (B) Mallory, (C) Morton, (D) Davis, and (E) Germantown.

Pumping Test Procedure

Pumping tests involve measuring the water-level response produced in an observation 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) 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 ten data points through each interval. For this investigation, each interval duration was increased 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.

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*	3:00 PM	*1 min*	17 h
2-3	*Pumping well is on; nearby wells remain off*	8:00 AM	*1 s*	1 h
		9:00 AM	*10 s*	1 h
		10:00 AM	*1 min*	46 h
4	*Pumping and nearby wells are off*	8:00 AM	*1 s*	1 h
		9:00 AM	*10 s*	1 h
		10:00 AM	*1 min*	6 h

ASTM D4050-14 also suggests conducting a preliminary analysis of the pumping test data during the test and to continue until the analysis shows 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-hour minimum pump test. Waldron *et al*. (2011) assigns higher quality to conducting at least a 24-hour test. For this investigation, a 48-hour period was chosen to attain as near a stable water-level as possible (Kruseman and De Ridder, 1994) with an additional 12+ hours prior and after the test to establish a static level and for adequate aquifer recovery, respectively (Fig. 3).

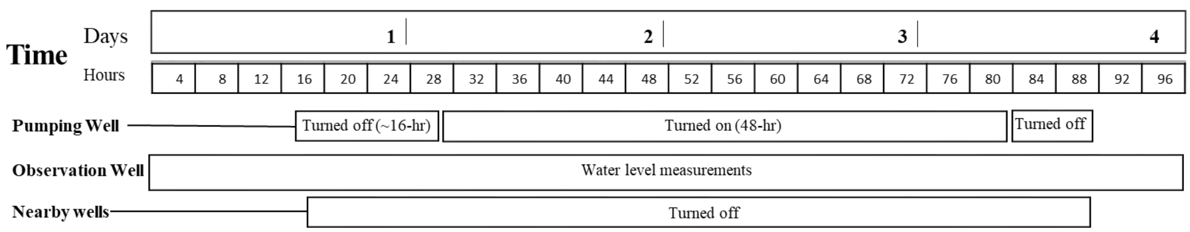

FIGURE 3. Times scheduled for wells involved in the test.

Data Analysis

Drawdown from pumping and recovery tests were plotted verses time using AQTESOLV (Aquifer Test Solver) developed by Geraghty and Miller Modelling Group (1996). This software package was selected because it offers a wide range of solution methodologies applicable across a range of aquifer types (i.e., confined, semi-confined 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. Inputs to AQTESOLV include: (1) saturated thickness and the vertical hydraulic conductivity anisotropy ratio (chosen to be 1:10) (Freeze and Cherry, 1979; Gentry *et al*., 2006); (2) pumping and observation well locations (Fig. 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-Jacob (1955)/Hantush (1964) (without aquitard storage) for semi-confined aquifers. The latter condition was considered due to known breaches in the confining unit where semi-confined 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 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 well, assuming that the impact may be greater (see Fig.4 and Table 5). Unfortunately, the discharge rates of the interfering wells were not known.

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 meters
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

masl = *Meters above sea level*

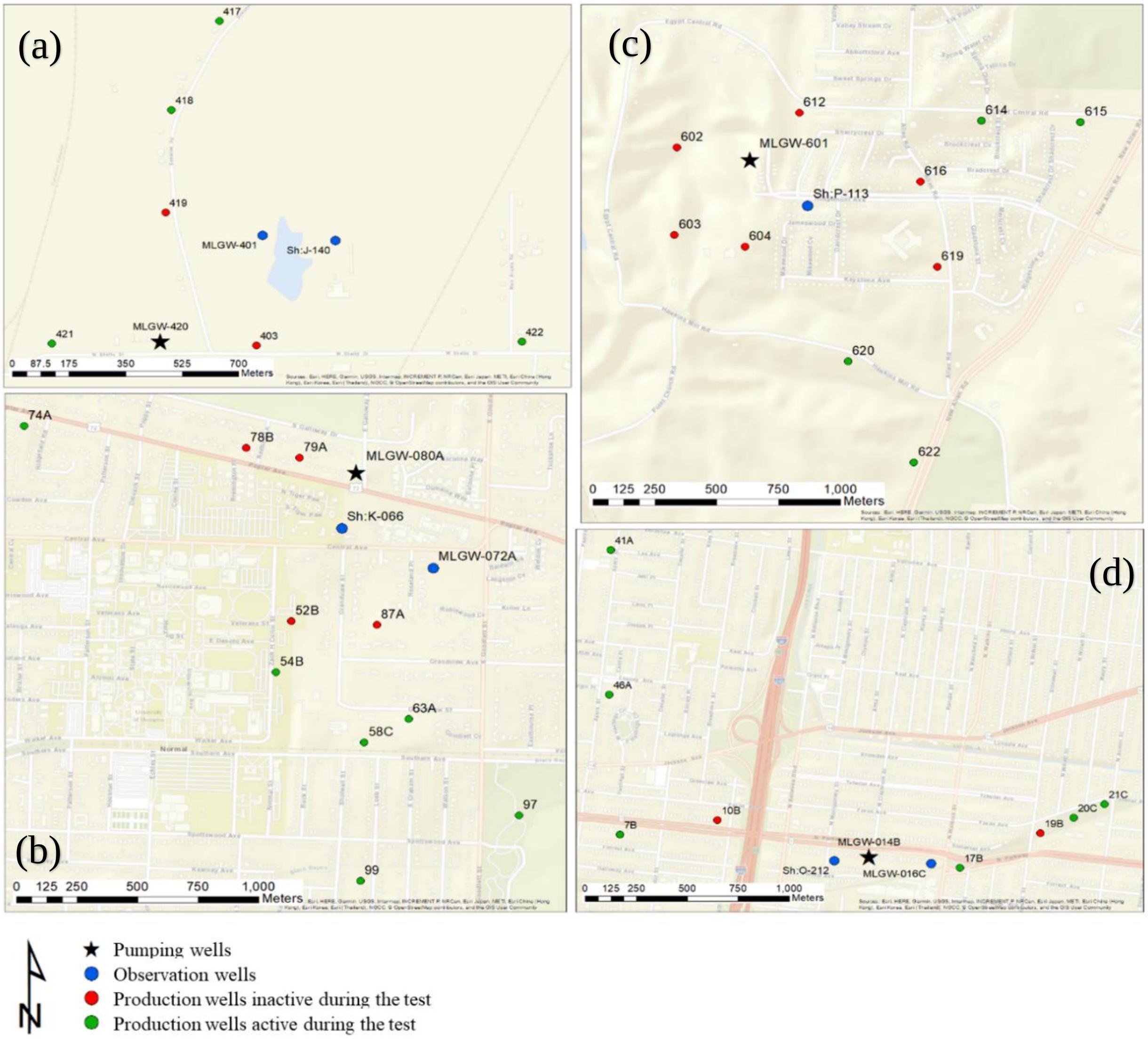

FIGURE 4. Location of pumping wells, observation wells, inactive production wells, and active production wells during the pumping tests, within each well field: (a) Davis, (b) Sheahan, (c) Morton, (d) Mallory.

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 not, where: 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 Fig. 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 were found not to have an individual impact (i.e. change in water-level when turned on/off) by looking at all the instances 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 (Fig. 4), wells determined to have a greater impact on the individual tests are presented in Table 6. The 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). In Figs. 5-8 is observed 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.

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

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

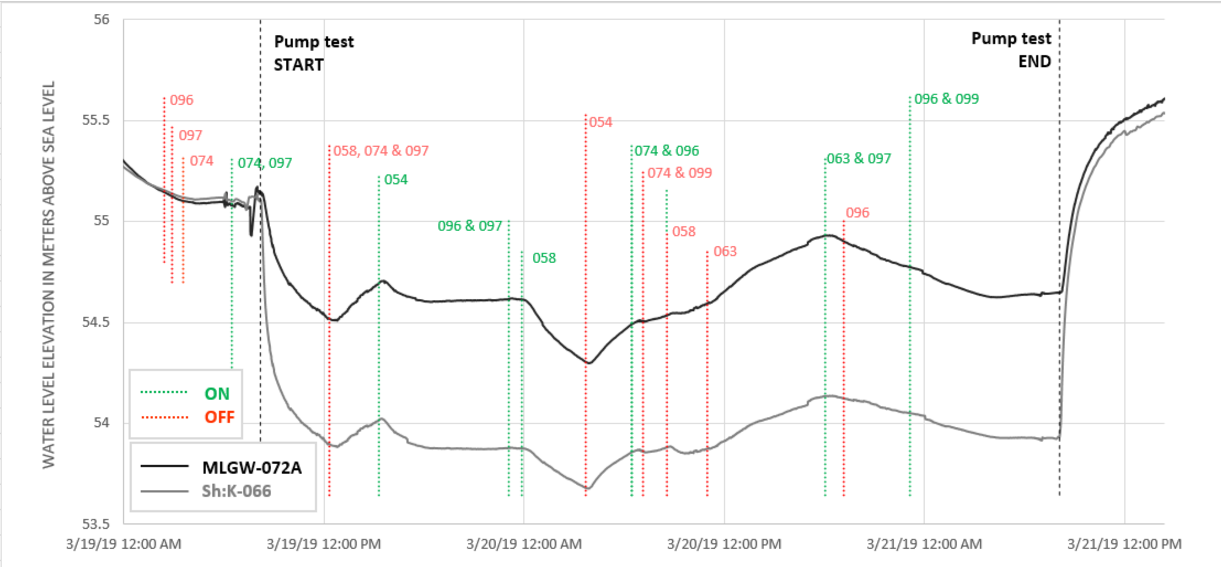

FIGURE 5. Water levels observed at wells MLGW-072A and Sh:K-066 during the pumping test at Sheahan.

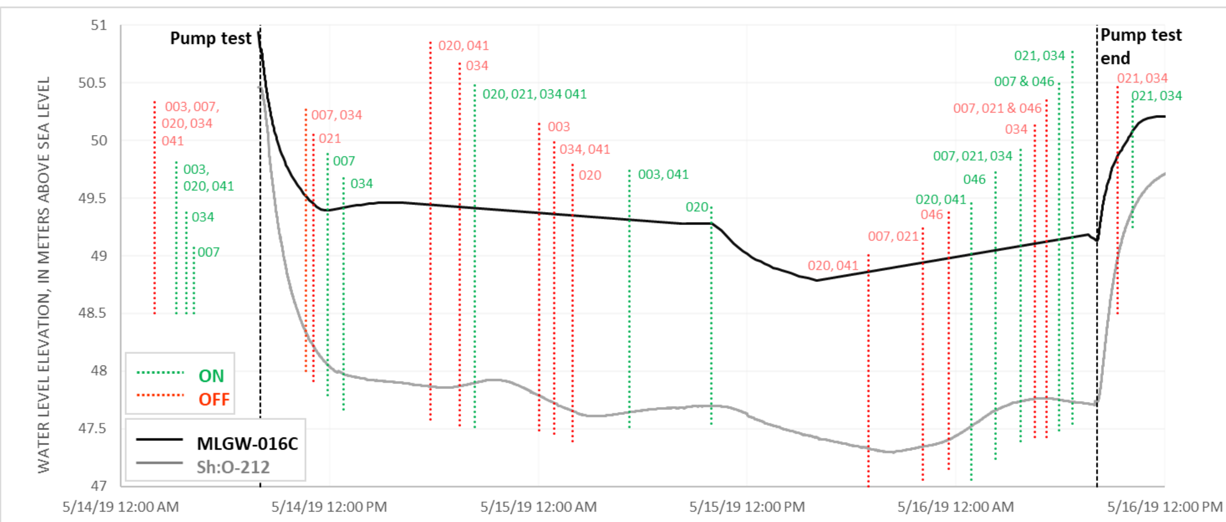

FIGURE 6. Water levels observed at wells MLGW-016C and Sh:O-212 during the pumping test at Mallory.

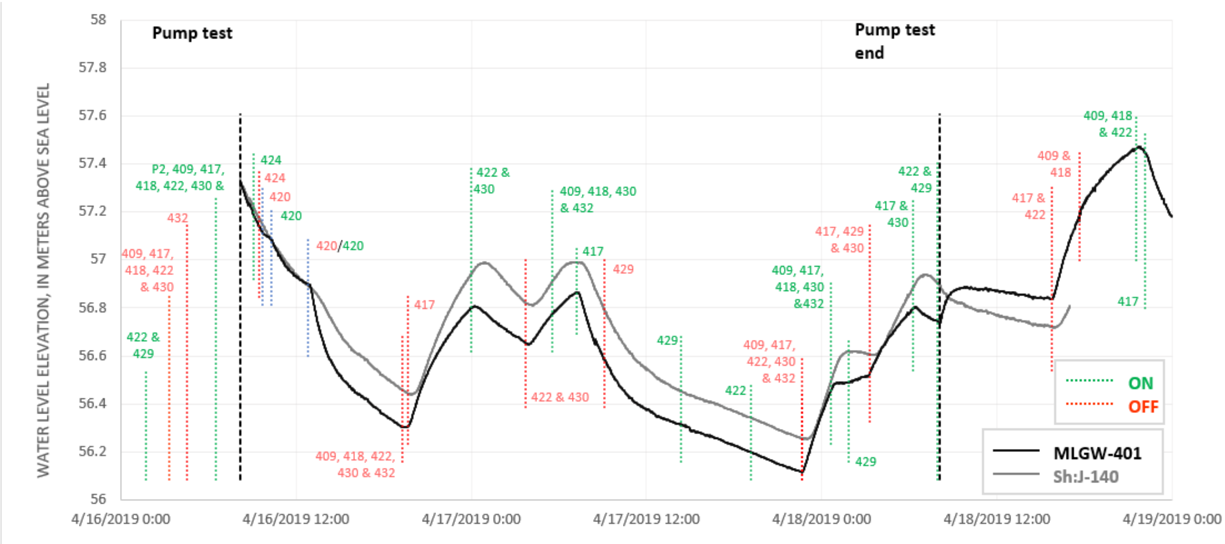

FIGURE 7. Water levels observed at wells MLGW-401 and Sh:J-140 during the pumping test at Davis.

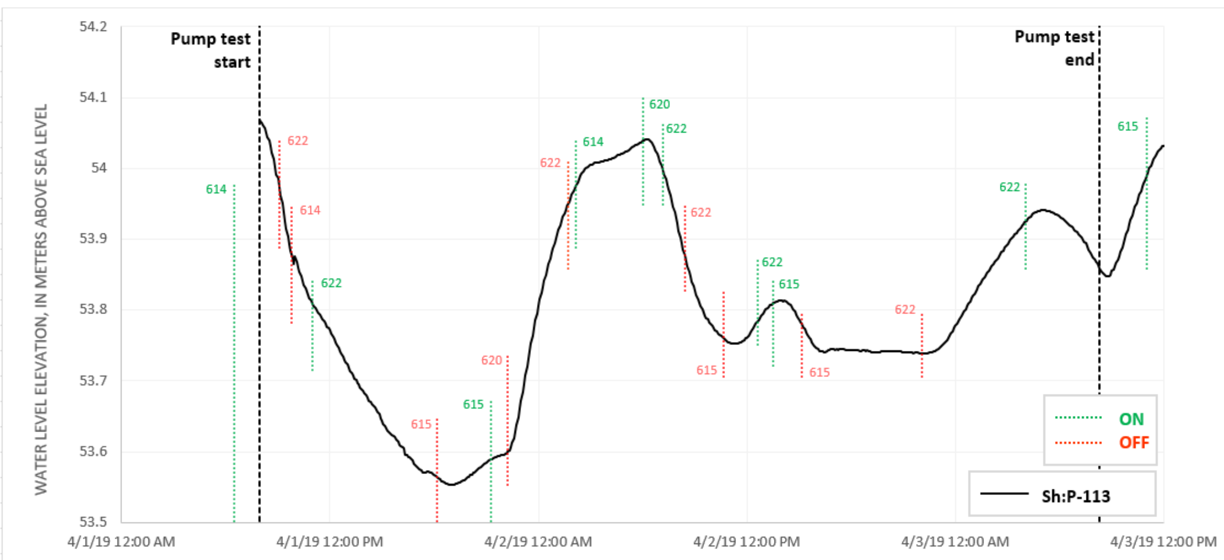

FIGURE 8. Water levels observed at well Sh:P-113 during the pumping test at Morton.

Time-Window Constrains

Analysis of the drawdown curves were 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 to 650 minutes 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 which additional wells may have influenced the test so a time-windows of 1 hour was used.

Analysis of Pumping Test Data for Leaky 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 leaky type curves in AQTESOLV (Hantush and Jacob, 1955; Walton, 1962). Hantush-Jacob (1955) family-type curves are function of r/B, which defines the proportion of flow to the pumping well that comes from leakage (Hantush, 1954). The ratio r/B is explained by the relationship between the distance from the pumping well 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 and Carmichael, 1990; Parks, 1990; Gentry *et al*., 2006; Villalpando-Vizcaino, 2019). Transmissivity values are shown in Table 1. A range between 6×10^{-6} to 8×10^{-4} m/day was used for the vertical hydraulic conductivity of the aquitard (Gentry *et al*., 2006; Villalpando-Vizcaino, 2019), and between 1×10^{-4} to 3×10^{-3} m/day for the vertical hydraulic conductivity of a breach (Villalpando-Vizcaino, 2019). The thickness of the aquitard was assigned according to the thickness of the confining derived by Villalpando-Vizcaino (2019). Ranges of r/B estimated for each well field are presented in Table 7.

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

Well field	**Thickness of the aquitard, b' (m)**		**Observation well**	**r/B**
	min	**max**		
Sheahan	1.5[a]	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

[a] Parks (1990)

Aquifer Parameter Results

Drawdown was plotted against time on a logarithmic scale and was superposed with a solution curve. AQTESOLV (1996) 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 constrains applied on each dataset are indicated with a red discontinuous line It was verified that the rate at which water was withdrawn from the pumping well did not vary more than 10% from the mean discharge at most tests, except on Davis, where pumping well MLGW-420 was turned off twice for 40-minute periods, early on the test. This was accounted for in the solution. 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 1000 – 1500 GPM (personal correspondence MLGW). Along with transmissivity and storativity, values of r/B were also estimated for the leaky-type curves.

Logarithmic plots of the data sets from the pumping tests at Sheahan, Davis, and Mallory (Figs. 9-12) showed a decrease in the drawdown rate over time, typical of semi-confined aquifer systems (Dawson and Istok, 1992). This is mostly attributed to downward leakage from the confining unit as these well fields are located near suspected breach locations. 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 to 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, 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 .

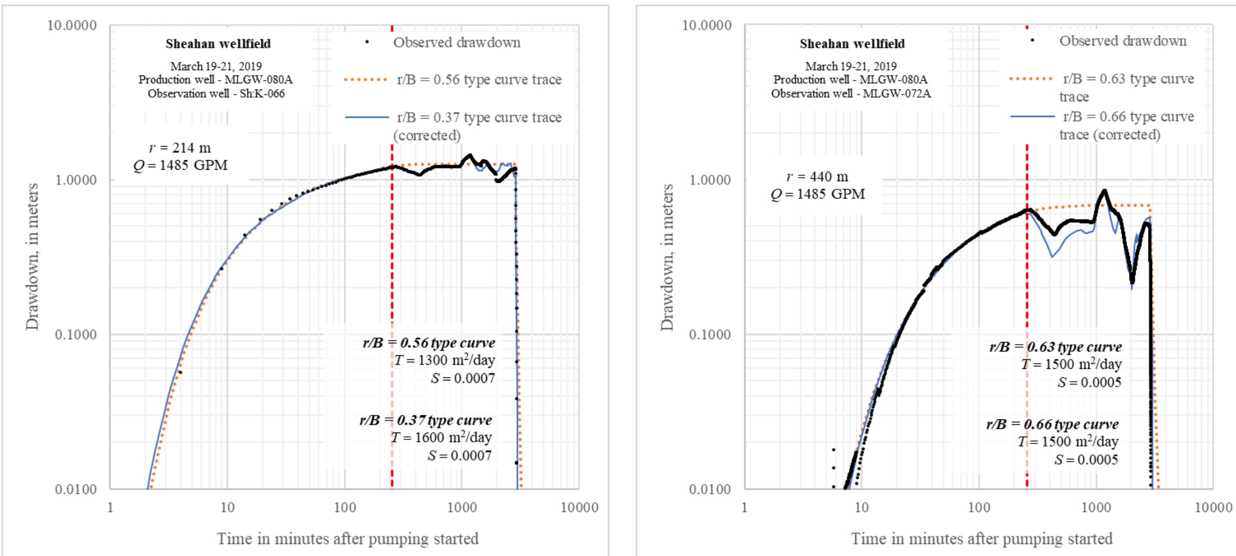

FIGURE 9. Hantush-Jacob solution curves for the test performed at Sheahan.

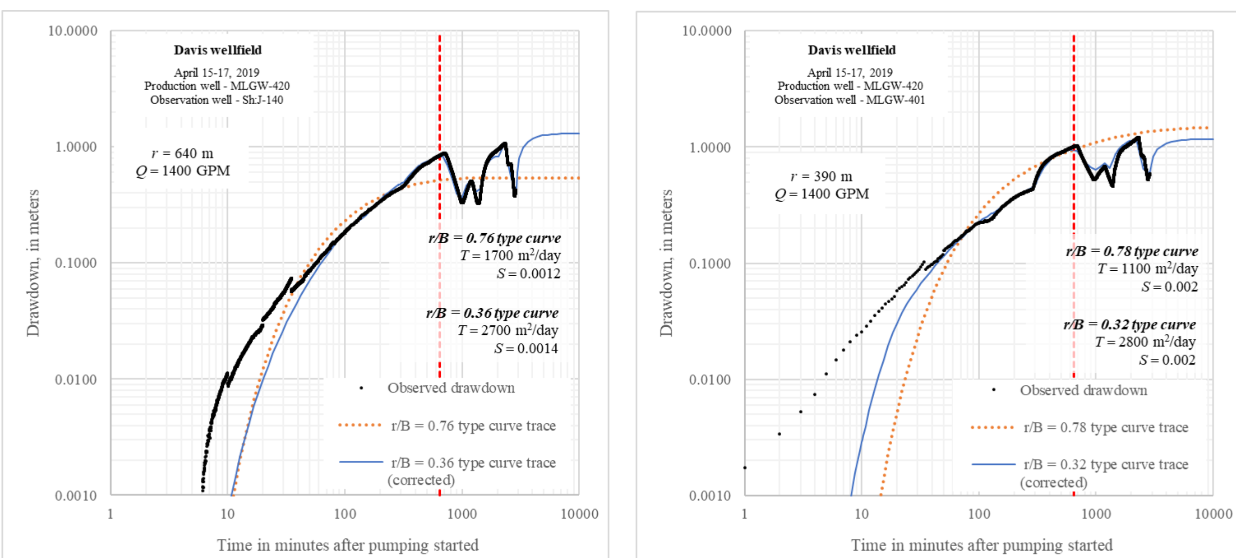

FIGURE 10. Hantush-Jacob solution curves for the test performed at Davis.

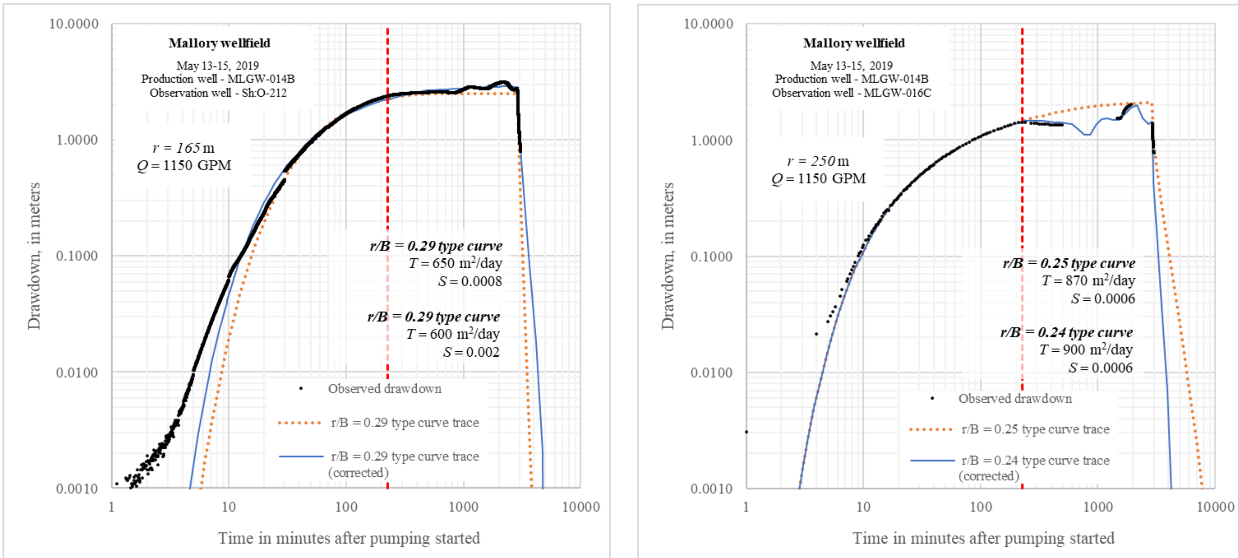

FIGURE 11. Hantush-Jacob solution curves for the test performed at Mallory E.

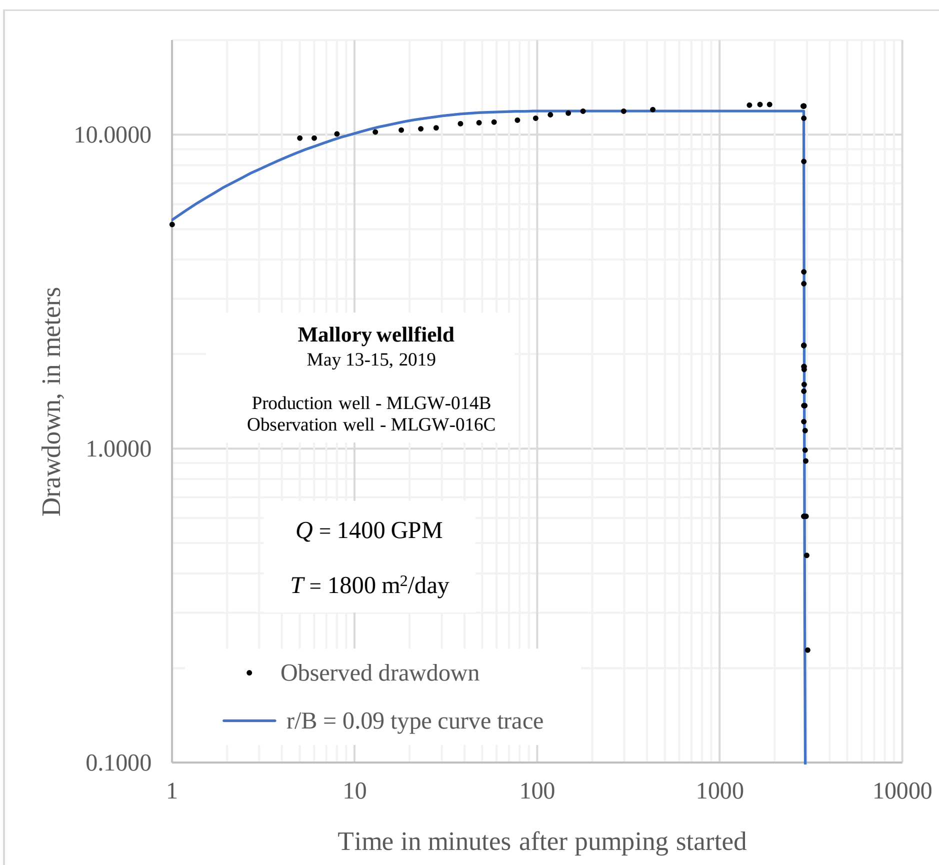

FIGURE 12. Hantush-Jacob solution curves for the test performed at Mallory W.

Morton's drawdown curve was observed to resemble a typical non-equilibrium type curve for confined aquifers despite the influence of interfering pumping wells (Fig. 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 was 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 is important to note that early drawdown data is more susceptible to the immediate well environment, reducing the reliability in the parameters estimated in Germantown.

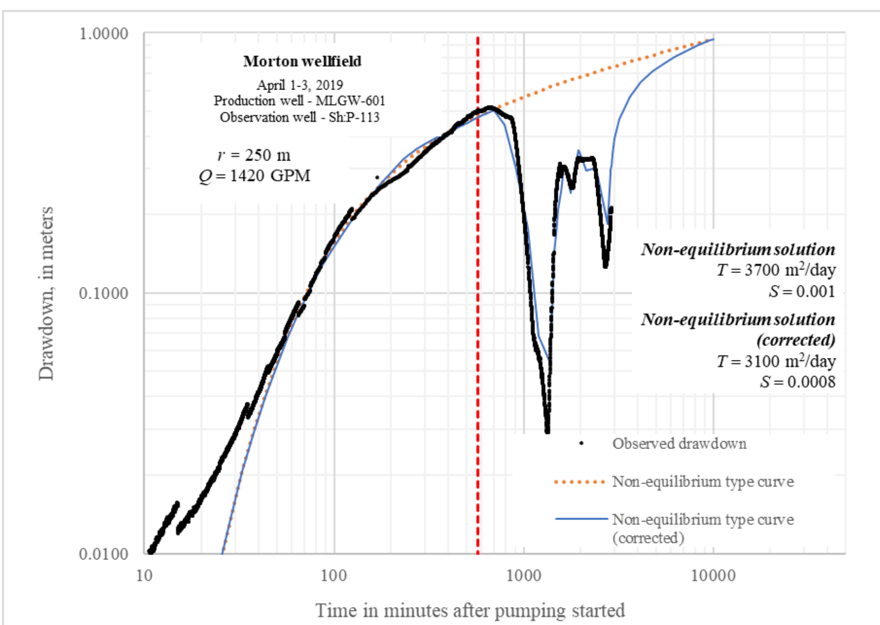

FIGURE 13. Theis solution curves for the test performed at Morton.

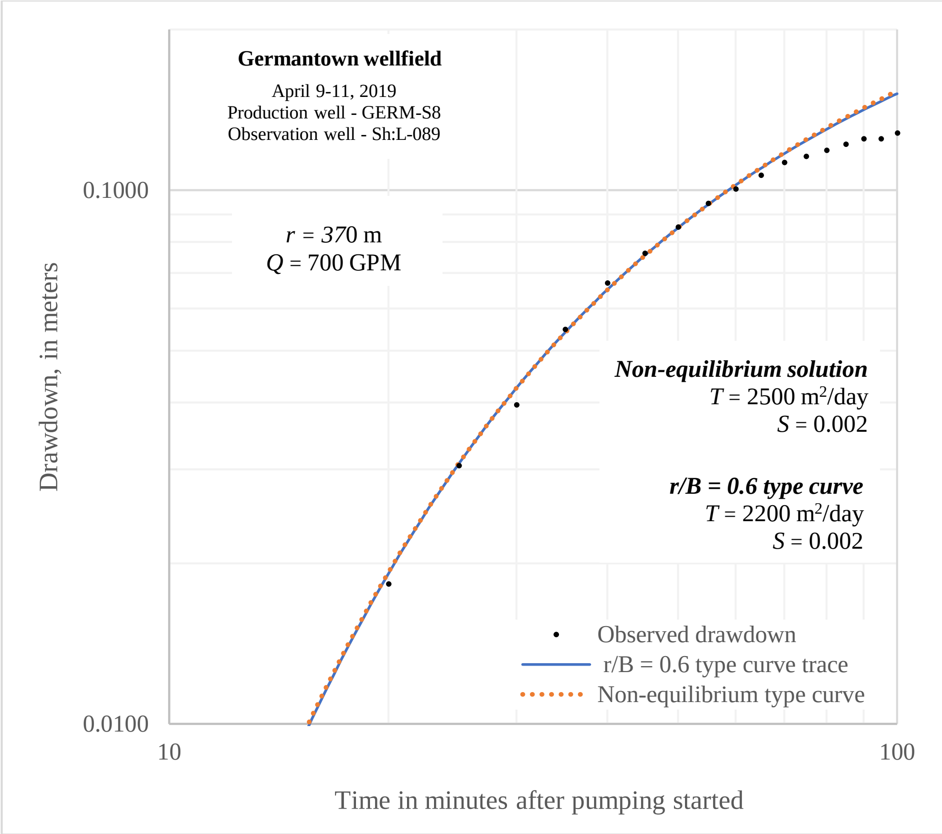

FIGURE 14. Theis and Hantush-Jacob solution curves for the test performed at Germantown.

A difference between the transmissivities estimated with the solutions before and after accounting for interference of other production wells can be observed in Figs. 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 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 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, 2000 m^2/day, falls below the average reported by previous studies (Table 1) of about 4000 m^2/day; whereas the average storativity of 0.002 estimated in this study is in accordance to the average of previous studies.

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

Wellfield	Average discharge (GPM)	Well	Pumping test			Recovery test	
			Transmissivity (m^2/day)	Storativity	r/B	Transmissivity (m^2/day)	Storativity
Sheahan	1485	Sh:K-066	1600	0.0007	0.37	1300	0.0005
		MLGW-72A	1500	0.0005	0.66	1500	0.0002
Morton	1420	Sh:P-113	3100	0.009	---	---	---
Germantown	700	Sh:L-089	2500	0.002	---	---	---
Davis	1400	Sh:J-140	2700	0.001	0.36	---	---
		MLGW-401	2800	0.002	0.32	---	---
Mallory W.	1400	MLGW-001C	1800	---	0.09	1700	N/A
Mallory E.	1150	Sh:O-212	600	0.002	0.29	640	0.002
		MLGW-016C	900	0.0006	0.24	900	0.001

N/A – Not applicable

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 10). 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 9).

TABLE 9. Residual sum of squares (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	---	1350	---
	Sh:O-212	98	1420	93%
	MLGW-016C	0.2	92	99%

TABLE 10. 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	1510	159	89%
Morton	Sh:P-113	7880	177	98%
Davis	Sh:J-140	1640	103	94%
	MLGW-401	1300	338	74%
Mallory	Sh:O-212	701	476	32%
	MLGW-016C	59	22	63%

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 of 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-hour 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 to 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 presented in this study; the average score for the tests in this study is 8.7. If accurate pump schedule data would have 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.

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

CONCLUSIONS

Estimation of aquifer properties provide valuable information to address issues related to groundwater storage and movement, which is important in the planning and decision making to assure the sustainability of the quantity and quality of groundwater resources. This study provided narrower and more reliable ranges of transmissivity and storativity of the Memphis aquifer that fell within the hydraulic properties reported by other authors, following a method for pumping tests that met the criteria established in Table 2 to increase the quality of the data collected and ultimately reduce groundwater numerical model non-uniqueness. These values represent the heterogeneity of 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 of 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. 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, except for 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.

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. Complicating factors that would lend to a lower score, such as the interference from other production wells, were considered non-impactful since they were recognize and addressed in the analysis. Overall, tests were conducted following the recommendations by Waldron *et al*. (2011) and addressing the sources of error 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.

LITERATURE CITED

Alyamani, M.S. and Z. Şen, 1993. Determination of Hydraulic Conductivity from Complete Grain-Size Distribution Curves. *Groundwater* 31(4):551–555. https://doi.org/10.1111/j.1745-6584.1993.tb00587.x.

Anderson, M.P., W.W. Woessner, and R.J. Hunt, 2015. *Applied Groundwater Modeling-Simulation of Flow and Advective Transport* (2^{nd}). San Diego, Academic Press, 630 pp.

HydroSOLVE., 1996., Aquifer Test Solver (AQTESOLV) Version: 4.50.002, HydroSolve, VA, USA. https://www.aqtesolv.com/.

ASTM Standard D4050 - 20., 1991, "Standard Test Method for (Field Procedure) for Withdrawal and Injection Well Testing for Determining Hydraulic Properties of Aquifer Systems", ASTM International, West Conshohocken, PA, 2003. doi: https://doi.org/10.1520/D4050-20. www.astm.org.

Boadu, F.K., 2000. Hydraulic Conductivity of Soils from Grain-Size Distribution: New Models. *Journal of Geotechnical and Geoenvironmental Engineering* 126(8):739–746. https://doi.org/ 10.1061/(ASCE)1090-0241(2000)126:8(739).

Bradbury, K. and M. Muldoon, 2009. Hydraulic Conductivity Determinations in Unlithified Glacial and Fluvial Materials. D. Nielsen and Johnson A. (Editors). Ground Water and Vadose Zone Monitoring. ASTM International, West Conshohocken, pp. 138–14. https://doi.org/10.1520/stp23404s.

Bradley, M.W., 1991. Ground-Water Hydrology and the Effects of Vertical Leakage and Leachate Migration on Ground-Water Quality Near the Shelby County Landfill, Memphis, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 90-4075, 42 pp. https://pubs.er.usgs.gov/publication/wri904075.

Brahana, J.V. and R.E. Broshears, 2001. Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 89-4131, 56 pp. https://pubs.er.usgs.gov/publication/wri894131.

Butler, J.J., 1990. The Role of Pumping Tests in Site Characterization: Some Theoretical Considerations. *Groundwater* 28(3):394–402. https://doi.org/10.1111/j.1745-6584.1990.tb02269.x.

Carmichael, J.K., J.A. Kingsbury, D. Larsen, and S. Schoefernacker, 2018. Preliminary Evaluation of the Hydrogeology and Groundwater Quality of the Mississippi River Valley

Alluvial Aquifer and Memphis Aquifer at the Tennessee Valley Authority Allen Power Plants, Memphis, Shelby County, Tennessee. U.S. Geological Survey Open-File Report 2018–1097, 66 pp. https://pubs.er.usgs.gov/publication/ofr20181097.

Cheong, J.Y., S.Y. Hamm, H.S. Kim, E.J. Ko, K. Yang, and J.H. Lee, 2008. Estimating Hydraulic Conductivity Using Grain-Size Analyses, Aquifer Tests, and Numerical Modeling in a Riverside Alluvial System in South Korea. *Hydrogeology Journal* 16(6):1129–1143. https://doi.org/ 10.1007/s10040-008-0303-4.

Clark, B.R. and R.M. Hart, 2009. The Mississippi Embayment Regional Aquifer Study (MERAS): Documentation of a Groundwater-Flow Model Constructed to Assess Water Availability in the Mississippi Embayment. U.S. Geological Survey Scientific Investigations Report 2009-5172, 62 pp. https://pubs.er.usgs.gov/publication/sir20095172.

Criner, J.H., P.-C.P. Sun, and D.J. Nyman, 1964. Hydrology of Aquifer Systems in the Memphis Area, Tennessee. U.S. Geological Survey Water Supply Paper 1779-O, 31 pp. https://pubs.er.usgs.gov/publication/wsp1779O.

Criollo, R., V. Velasco, E. Vázquez-Suñé, A. Serrano-Juan, M. Alcaraz, and A. García-Gil, 2016. An Integrated GIS-Based Tool for Aquifer Test Analysis. *Environmental Earth Sciences* 75(5):1–11. https://doi.org/10.1007/s12665-016-5292-3.

Cushing, E.M., E.H. Boswell, R.L. Hosman, and W.T. Pecora, 1964. General Geology of the Mississippi Embayment. U.S. Geological Survey Professional Paper 448-B, 28 pp. https://pubs.er.usgs.gov/publication/pp448B.

D'Andrea, R., 2001. Hydraulic Conductivity of Soils from Grain-Size Distribution: New Models. *Journal of Geotechnical and Geoenvironmental Engineering* 127(10):899–900. https://doi.org/10.1061/(ASCE)1090-0241(2001)127%3A10(899).

Dawson, K.J. and J.D. Istok, 1992. Aquifer Testing - Design and Analysis of Pumping and Slug Tests. Boca Raton, CRC Press, 368 pp.

Doherty, J., 2003. Ground Water Model Calibration Using Pilot Points and Regularization. *Groundwater* 41(2):170–177. https://doi.org/10.1111/j.1745-6584.2003.tb02580.x.

Freeze, R.A. and J.A. Cherry, 1979. *Groundwater*. Englewood Cliffs. New Jersey, Prentice Hall, 604 pp.

Friedel, M.J., 2005. Coupled Inverse Modeling of Vadose Zone Water, Heat, and Solute Transport: Calibration Constraints, Parameter Nonuniqueness, and Predictive Uncertainty. *Journal of Hydrology* 312(1-4):148–175. https://doi.org/10.1016/j.jhydrol.2005.02.013.

Gentry, R., L. McKay, N. Thonnard, J.L. Anderson, D. Larsen, J.K. Carmichael, and D.K. Solomon, 2006. Novel Techniques for Investigating Recharge to the Memphis Aquifer. American Water Works Association Report 91137, 97 pp.

Graham, D.D. and W.S. Parks, 1986. Potential for Leakage Among Principal Aquifers in the

Memphis Area, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 85-4295, 46 pp. https://pubs.er.usgs.gov/publication/wri854295.

Hantush, M.S., 1961. Aquifer Tests on Partially Penetrating Wells. *Journal of the Hydraulics Division* 87(5):171–195.

Hantush, M.S., 1964. Hydraulics of Wells. V.T. Chow (Editor). Advances in Hydroscience. Academic Press, New York, pp. 281–442.

Hantush, M.S. and C.E. Jacob, 1954. Plane Potential Flow of Ground Water with Linear Leakage. *Transactions, American Geophysical Union* 35(6):917–936. https://doi.org/10.1029/TR035i006p00917.

Hantush, M.S. and C.E. Jacob, 1955. Non-Steady Radial Flow in an Infinite Leaky Aquifer. *Eos, Transactions American Geophysical Union* 36(1):95–100. https://doi.org/ 10.1029/TR036i001p00095.

Hemker, C.J., 1999. Transient Well Flow in Vertically Heterogeneous Aquifers. *Journal of Hydrology* 225(1-2):1–18. https://doi.org/10.1016/S0022-1694(99)00137-7.

Hosman, R.L., A.T. Long, T.W. Lambert, H.G. Jeffery, 1968. Tertiary Aquifers in the Mississippi Embayment. U.S. Geological Survey Professional Paper 448-D, 27 pp. https://pubs.er.usgs.gov/publication/pp448D.

Jazaei, F., B. Waldron, S. Schoefernacker, and D. Larsen, 2019. Application of Numerical Tools to Investigate a Leaky Aquitard beneath Urban Well Fields. *Water* 11(1):5. https://doi.org/10.3390/w11010005.

Jones, L., 1993. A Comparison of Pumping and Slug Tests for Estimating the Hydraulic Conductivity of Unweathered Wisconsian Age Till in Iowa. *Groundwater* 31(6):896–904. https://doi.org/10.1111/j.1745-6584.1993.tb00862.x.

Keller, G.V. and F.C. Frischknecht, 1966. Electrical Methods in Geophysical Prospecting. Oxford, Elsevier Science Limited, 519 pp.

Kingsbury, J.A. and W.S. Parks, 1993. Hydrogeology of the Principal Aquifers and Relation of Faults to Interaquifer Leakage in the Memphis Area, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 93-4075, 18 pp. https://pubs.er.usgs.gov/publication/wri934075.

Koban, J., D. Larsen, and S. Ivey, 2011. Resolving the Source and Mixing Proportions of Modern Leakage to the Memphis Aquifer in a Municipal Well Field Using Geochemical and 3H/ 3He Data, Memphis, Tennessee, USA. *Environmental Earth Sciences* 66:295–310. https://doi.org/ 10.1007/s12665-011-1239-x.

Koefoed, O., 1981. Geosounding Principles 1. Resistivity Sounding Measurements (Methods in Geochemistry and Geophysics 14A). *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 18(2), 40 pp. https://doi.org/ 10.1016/0148-

9062(81)90963-3.

Kruseman, G.P. and N.A. de Ridder, 1994. Analysis and Evaluation of Pumping Test Data. Wageningen, International Institute for Land Reclamation and Improvement, 377 pp.

Larsen, D., J. Morat, B. Waldron, S. Ivey, and J. Anderson, 2013. Stream Loss Contributions to a Municipal Water Supply Aquifer in Memphis, Tennessee. *Environmental and Engineering Geoscience* 19:265–287. https://doi.org/10.2113/gseegeosci.19.3.265.

Larsen, D., B. Waldron, S. Schoefernacker, H. Gallo, J. Koban, and E. Bradshaw, 2016. Application of Environmental Tracers in the Memphis Aquifer and Implication for Sustainability of Groundwater Resources in the Memphis Metropolitan Area, Tennessee. *Journal of Contemporary Water Research & Education* 159(1):78–104. https://doi.org/10.1111/j.1936-704x.2016.03231.x.

Leven, C. and P. Dietrich, 2006. What Information Can We Get from Pumping Tests? Comparing Pumping Test Configurations Using Sensitivity Coefficients. *Journal of Hydrology* 319(1-4):199–215. https://doi.org/10.1016/j.jhydrol.2005.06.030.

Mace, R.E., 1999. Estimation of Hydraulic Conductivity in Large-Diameter, Hand-Dug Wells Using Slug-Test Methods. *Journal of Hydrology* 219(1-2):34–45. https://doi.org/10.1016/S0022-1694(99)00039-6.

McKenna, S.A., J. Doherty, and D.B. Hart, 2003. Non-Uniqueness of Inverse Transmissivity Field Calibration and Predictive Transport Modeling. *Journal of Hydrology* 281(4):265–280. https://doi.org/10.1016/S0022-1694(03)00194-X.

McWhorter, D.B. and D.K. Sunada, 2010. Ground-Water Hydrology and Hydraulics. Highlands Ranch, Water Resources Publications, 290 pp.

Moore, G.K., 1965. Geology and Hydrology of the Claiborne Group in Western Tennessee. U.S. Geological Survey Water-Supply Paper 1809-F, 44 pp.

Neuman, S.P., 1973. Calibration of Distributed Parameter Groundwater Flow Models Viewed as a Multiple-Obiective Decision Process under Uncertainty. *Water Resources Research* 9(4):1006–1021. https://doi.org/10.1029/WR009i004p01006.

Niwas, S. and O.A.. De Lima, 2003. Aquifer Parameter Estimation from Surface Resistivity Data. *Groundwater* 41(1):94–99. https://doi.org/10.1111/j.1745-6584.2003.tb02572.x.

Pang, L., M.E. Close, J.P.C. Watt, and K.W. Vincent, 2000. Simulation of Picloram, Atrazine, and Simazine Leaching through Two New Zealand Soils and into Groundwater Using HYDRUS-2D. *Journal of Contaminant Hydrology* 44(1):19–46. https://doi.org/10.1016/S0169-7722(00)00091-7.

Parks, W.S., 1990. Hydrogeology and Preliminary Assessment of the Potential for Contamination of the Memphis Aquifer in the Memphis Area, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 90-4092, 39 pp.

https://pubs.er.usgs.gov/publication/wri904092.

Parks, W.S. and J.K. Carmichael, 1990. Geology and Ground-Water Resources of the Memphis Sand in Western Tennessee. U. S. Geological Survey Water-Resources Investigations Report 88-4182, 30 pp. https://pubs.er.usgs.gov/publication/wri884182.

Parks, W.S., J.E. Mirecki, and J.A. Kingsbury, 1995. Hydrogeology, Ground-Water Quality, and Source of Ground Water Causing Water-Quality Changes in the Davis Well Field at Memphis, Tennessee. U. S. Geological Survey Water-Resources Investigations Report 94-4212, 58 pp. http://pubs.er.usgs.gov/publication/wri944212.

Rogiers, B., D. Mallants, O. Batelaan, M. Gedeon, M. Huysmans, and A. Dassargues, 2012. Estimation of Hydraulic Conductivity and Its Uncertainty from Grain-Size Data Using GLUE and Artificial Neural Networks. Mathematical *Geosciences* 44(6):739–763. https://doi.org/10.1007/s11004-012-9409-2.

Schrader, T., 2008. Potentiometric Surface in the Sparta-Memphis Aquifer of the Mississippi Embayment, U.S. Geological Survey Scientific Investigations Map 3014. https://pubs.er.usgs.gov/publication/sim3014.

Sun, N.-Z., 1999. Inverse Problems in Groundwater Modeling 2013 Springer Science & Business Media (Editor). Springer-Science+Business Media B.V. https://doi.org/doi:10.1007/978-94-017-1970-4.

Theis, C. V., 1935. The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage. *American Geophysical Union* 16(2):519–524. https://doi.org/10.1029/TR016i002p00519.

Villalpando-Vizcaíno, R., 2019. Development of a Numerical Multi-Layered GroundwaterModel to Simulate Inter-Aquifer Water Exchange in Shelby County, Tennessee. Master's Thesis, The University of Memphis Memphis, Tennessee.

Vuković, M. and A. Soro, 1992. Determination of Hydraulic Conductivity of Porous Media from Grain-Size Composition. Littleton, Water Resources Publications, 83 pp.

Waldron, B., D. Larsen, R. Hannigan, R. Csontos, J. Anderson, C. Dowling, and J. Bouldin, 2011. Mississippi Embayment Regional Ground Water Study. U.S. Environmental Protection Agency, 192 pp. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=230439

Walton, W.C., 1962. Selected Analytical Methods for Well and Aquifer Evaluation. Department of Registration and Education, 81 pp. https://www.isws.illinois.edu/pubdoc/B/ISWSB-49.pdf.

Weight, W.D., 2008. Hydrogeology Field Manual. Butte, McGraw Hill Professional,751 pp.

Wolf, S.H., M.A. Celia, and K.M. Hess, 1991. Evaluation of Hydraulic Conductivities Calculated from Multiport-Permeameter Measurements. *Groundwater* 29(4):516–525.

https://doi.org/10.1111/j.1745-6584.1991.tb00543.x.

Yeh, T. chyi J., D. qiang Mao, Y. yuan Zha, J. chau Wen, L. Wan, K. chin Hsu, and C. haw Lee, 2015. Uniqueness, Scale, and Resolution Issues in Groundwater Model Parameter Identification. *Water Science and Engineering* 8(3):175–194. https://doi.org/10.1016/j.wse.2015.08.002.

Zechman, E.M., S.R. Ranjithan, and L. Liu, 2006. Niched Co-Evolution Strategies to Address Non-Uniqueness in Engineering Design. 8th Annual Conference on Genetic and Evolutionary Computation, GECCO’06. ACM Press, Raleigh, 8 pp.