Barton Springs
Edwards Aquifer
CONSERVATION DISTRICT

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Aquifer Parameter Estimation for the EP Well Field, Hays County, Texas

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Introduction

An application for a permit to produce 2.5 million gallons per day (MGD) of groundwater from the Middle Trinity Aquifer in central Hays County was submitted by Electro Purification LLC (EP) on July 13, 2017. In accordance with District rules, an applicant for a large-scale production permit must conduct an aquifer test and submit a hydrogeological report that provides findings and conclusions addressing the response of an aquifer to pumping over time and the potential for "unreasonable impacts" as defined by District rules.

The Aquifer Science Team reviewed the hydrogeologic data and aquifer test results and presented their findings in BSEACD Technical Memo 2017-1010. The purpose of this technical memo is to estimate aquifer parameters using a variety of tools described herein. Models are useful tools for thinking about the functioning of an aquifer system and ultimately forecasting and evaluating the potential impacts of pumping. All model results are based upon assumptions inherent in the model and hydrogeologic parameters that models produce are approximations. Thus, all model results have a degree of uncertainty (Anderson et al., 2015). A variety of mathematical models are available, and depending on the nature of the equations, they can either be empirical (experimental) or deterministic. Deterministic models predict a response due to physical laws. There are two groups of deterministic models that also depend on the type of mathematical equations—analytical and numerical.

The Theis (1935) equation is an example of an analytical model that solves one equation of groundwater flow at a point in the aquifer. Software programs such as Aqtesolv (Duffield, 2007) facilitate the use of analytical solutions. Numerical models allow for the discretization of the aquifer and the solution of groundwater flow over the entire flow field. The finite difference numerical model MODFLOW (Hughes et al., 2017) is a commonly used example. Software such as Groundwater Vistas (Rumbaugh and Rumbaugh, 2017) facilitates the use of the numerical models.

This memo documents the District's modeling evaluations of the 2016-2017 EP aquifer test data using a variety of modeling tools to learn more about the aquifer system and provide reasonable estimates of aquifer parameters. Ultimately, what is learned from the process and the best estimates of parameters will be used to estimate (forecast) the future drawdown from various pumping scenarios and evaluate the potential for unreasonable impacts.

Study Area

Figure 1 contains a map of the key wells used in this evaluation. **Table 1** is a summary of the Middle Trinity observation wells and pumping wells involved in the aquifer test that had a clear and strong response to pumping. BSEACD Technical Memo 2017-1010 contains well completion diagrams for most of these wells.

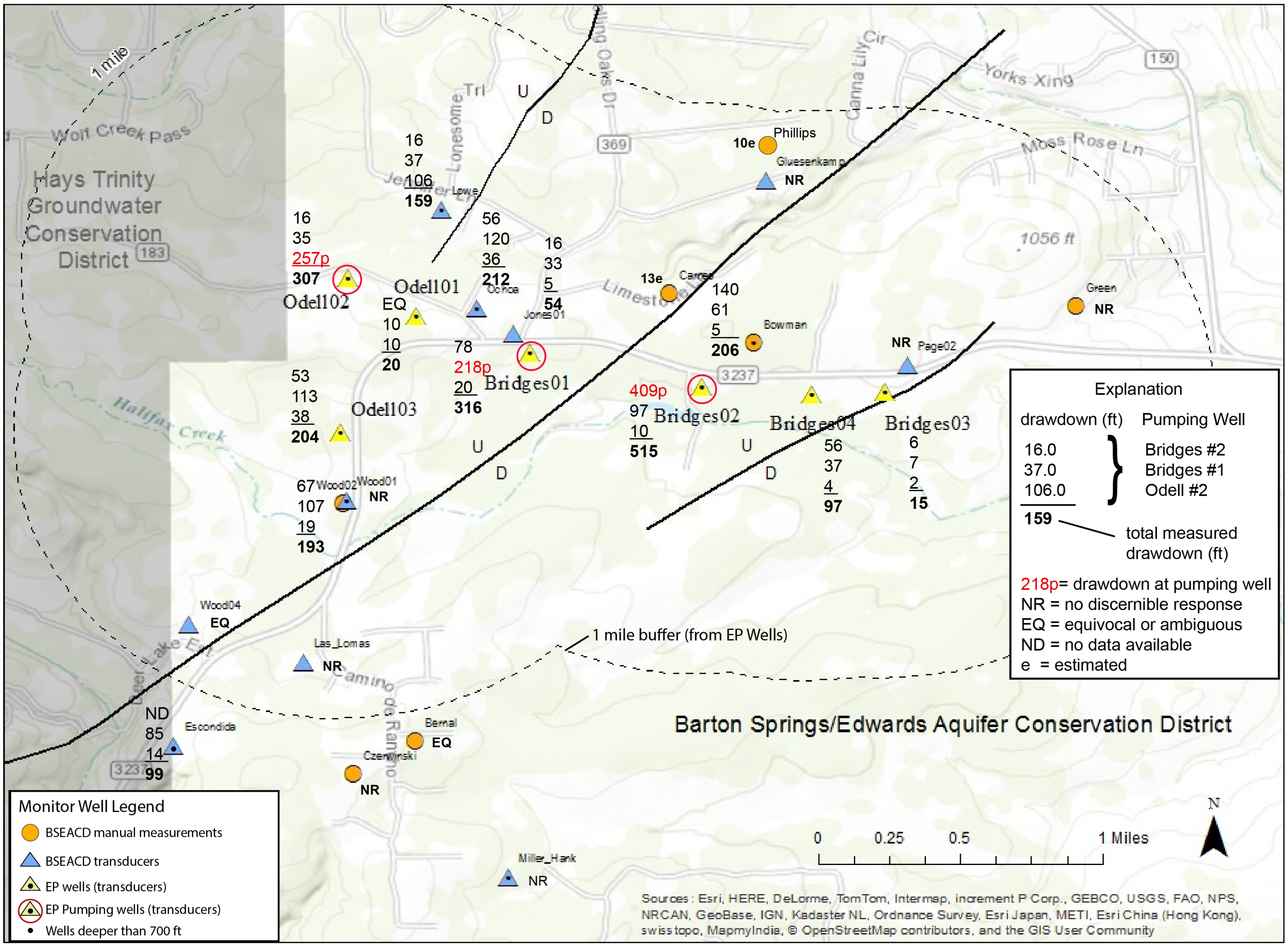


Figure 1. Study Area and Drawdown Map. *Drawdown Map from BSEACD Technical Memo 2017-1010. Map of the observed response and maximum drawdown from each of the pumping wells (red circles). The total drawdown from all three pumping wells is indicated in bold. Dark lines are mapped faults from Collins, 2002.*

Table 1. *Summary well information and drawdown results for Middle Trinity observation or pumping wells.*

Well Name	LSD (ft-msl)	Depth (ft)	Distance (ft) from B2	Drawdown (ft) Bridges #2	Distance (ft) from B1	Drawdown (ft)Bridges #1	Distance (ft) from O2	Drawdown (ft)-Odell 2	Combined drawdown (ft)	Comment
Bowman	1035	850	1140	139.6	3560	60.5	6630	4.6	204.7	
Bridges #1*	1045	930	2860	77.6	0	217.9	3330	20.2	315.7	Pumping well (lower zone)
Bridges #2*	1005	905	0	408.8	1140	96.8	6040	9.7	515.3	Pumping well (lower zone)
Bridges #3	1004	940	3020	6.4	5820	6.5	9040	1.7	14.6	
Bridges #4	990	905	1860	56	4620	37.3	7890	3.9	97.2	
Escondida 1	1104	930	10250	ND	8670	85	8450	13.5	98.5	
Lowe	1070	860	5220	16.2	3060	36.6	2070	106.4	159.2	Poor recovery
Ochoa	1073	810	3920	55.7	1230	120.1	2150	35.7	211.5	Poor recovery
Odell #2*	1097	850	6040	15.6	3330	34.5	0	257	307	Pumping well (lower zone); poor recovery overall
Odell #3	1068	845	5790	53	3290	112.8	2800	37.7	203.5	Slow recovery
Wood01	1067	790	6140	66.7	4030	106.8	4050	18.9	192.4	Woods 1 out of water 11/30/16 23:00 to 11/30/16 18:00

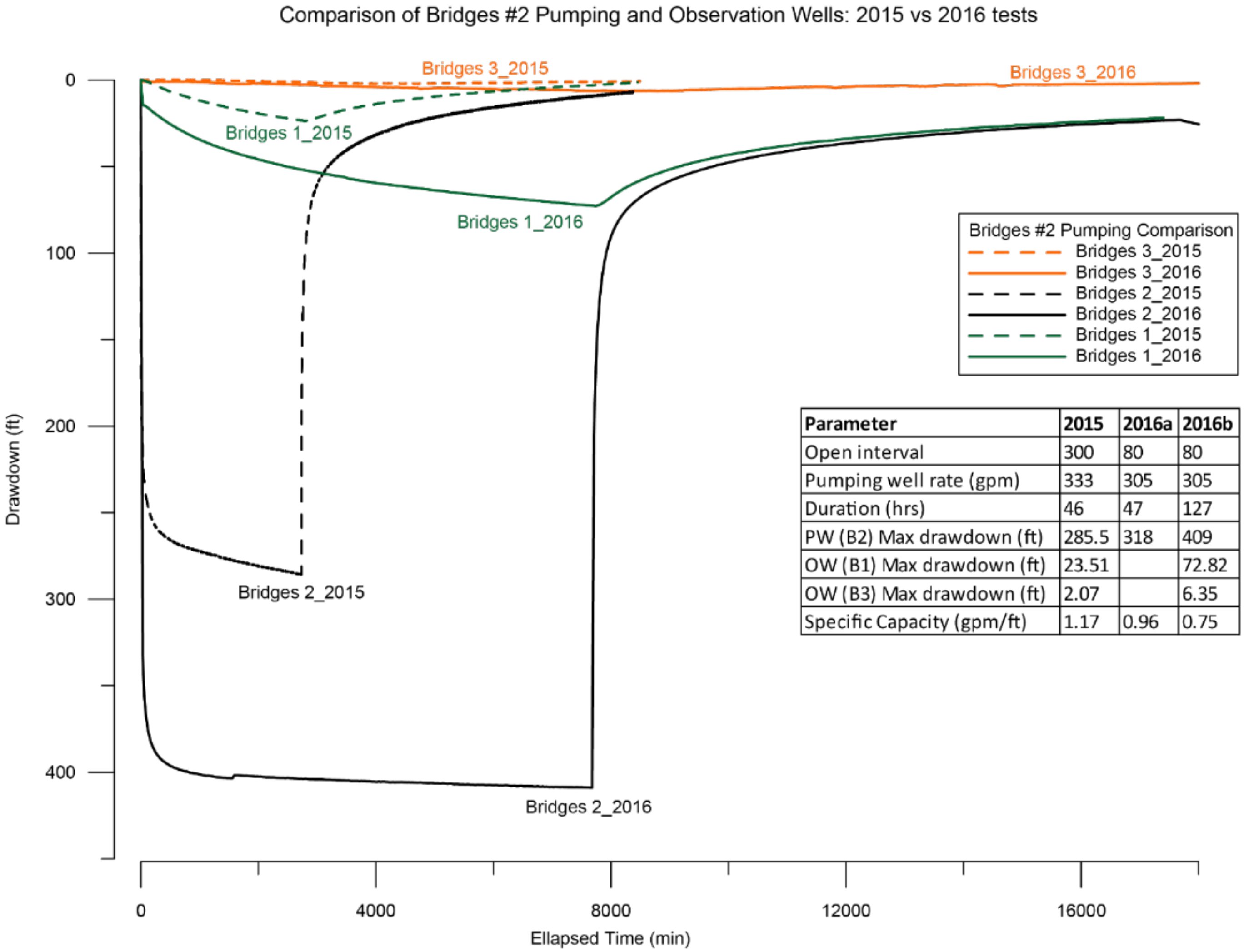
*denotes pumping well

Middle Trinity Aquifer

A short introduction to the Middle Trinity Aquifer and its hydrostratigraphy is provided here as background information. The Middle Trinity Aquifer is composed of three carbonate stratigraphic units (from lowest to highest): the Cow Creek, Hensel, and Lower Glen Rose Limestone. Aquifer-test data indicate the majority of water from the study area is derived from the Cow Creek unit of the Middle Trinity Aquifer (BSEACD, 2017). The Cow Creek is about 80 ft thick in the area, but geophysical data suggest the upper 55 ft is the likely thickness of the productive freshwater interval. Evidence for karst in the Cow Creek is seen as solutioned fractures in downhole camera surveys in the region (Hunt et al., 2016). The overlying Hensel (20 ft thick) is a semi-confining unit within the Middle Trinity Aquifer (Hunt et al., 2017). The Lower Glen Rose is also an aquifer unit of the Middle Trinity Aquifer in the study area and is locally very productive and karstic. Previous aquifer-test data indicate a localized hydraulic connection with the Cow Creek through the Hensel to the overlying Lower Glen Rose (BSEACD, 2017).

Even if we assume very limited natural hydraulic connection between these units, it is clear that well completions will influence the results of an aquifer test. Specific capacity data of the Bridges #2 pumping well in 2015 compared to 2016 provides some insight into the relative contribution of the Lower Glen Rose compared to the Cow Creek within the Middle Trinity Aquifer for wells open to both units (**Figure 2**). In 2015 the Cow Creek was not isolated during testing and thus production included the combined Cow Creek and Lower Glen Rose sources. However, in 2016 the Cow Creek was isolated during testing from the Lower Glen Rose with an inflatable packer. The specific capacity data from the Bridges #2 was lower in 2016 by 0.2 gpm/ft than the 2015 specific capacity data when normalized to the same duration (BSEACD, 2017). Thus, it is possible that 17% of the production in 2015 was derived from the Lower Glen Rose in the Bridges #2 pumping well. Similarly, many of the observation wells are open to the Cow Creek and Lower Glen Rose and the water-level measurements could be influenced by water flowing downward in the borehole from the higher heads in the Lower Glen Rose, to the lower heards in the Cow Creek (BSEACD, 2017). This effect masks drawdown effects and increases recovery.

While most of the water pumped from the EP test wells was derived from the Cow Creek, there is evidence for some hydraulic communication from the Lower Glen Rose to the Cow Creek likely due to: 1) well construction with long open-borehole intervals, and 2) natural leakage through the Hensel induced by pumping. However, quantified parameters reflecting that hydraulic connection between the Cow Creek and Lower Glen Rose are unknown. One of the goals of this evaluation is to provide reasonable constraints on those parameters.



Parameter	2015	2016a	2016b
Open interval	300	80	80
Pumping well rate (gpm)	333	305	305
Duration (hrs)	46	47	127
PW (B2) Max drawdown (ft)	285.5	318	409
OW (B1) Max drawdown (ft)	23.51		72.82
OW (B3) Max drawdown (ft)	2.07		6.35
Specific Capacity (gpm/ft)	1.17	0.96	0.75

Figure 2. *Comparison hydrograph of drawdown over time during pumping of the Bridges #2 well in 2015 and 2016. Also shown are the observation wells (Bridges 1 and Bridges 3) during the test. The 2016a data in the table was normalized to a similar duration of testing as 2015.*

Modeling Results: Spreadsheet

The District's Aquifer Science Team developed a spreadsheet containing empirical and simple analytical models described in Mace (2001). The input data are from specific capacity (single well) tests. The purpose of this evaluation is to provide an initial evaluation of aquifer parameters prior to analyzing more complicated observation-well data with more sophisticated software. **Figure 3** illustrates the drawdown over time for the three pumping wells used in this evaluation. Input data and results of the various empirical and analytical solutions are provided in **Table 2.** Results indicate a spatial difference in transmissivity (average from 350 to 750 ft^2/d), with values increasing from east to west.

Table 2. *Input parameters and summary of evaluations using spreadsheet modeling tool. These are single-well test evaluations.*

Well	**Bridges 2**	**Bridges 1**	**Odell 2**
Date	11/2/2016 7:59 to 11/7/2016 15:01	11/25/2016 13:11 to 11/30/2016 13:17	12/29/2016 13:34 to 1/3/2017 14:48
Duration (hrs)	127	120	121
Borehole Diameter (in)	9.875	9.875	9.875
Avg Discharge (gpm)	305	655	565
Drawdown (ft)	409	218	157
Specific capacity (gpm/ft	0.75	3.00	3.60
Transmissivity (ft^2/d)			
Empirical (Mace, 2001)	106	416	497
Analytical (Theis, 1963)	215	930	1,126
Analytical (Driscoll, 1986)	199	802	962
Analytical (Cooper and Jacob, 1946)	896	462	406
Average (ft^2/d)	354	652	748

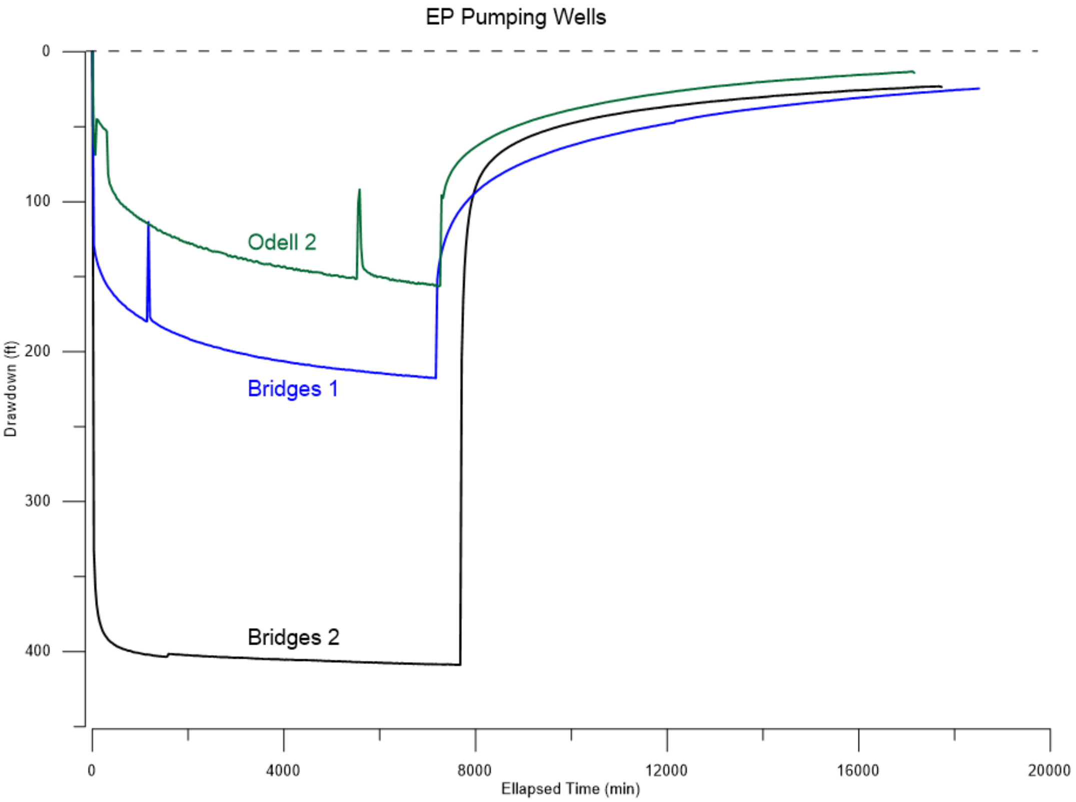


Figure 3. *Drawdown over time within the pumping wells of the EP 2016-2017 aquifer test. Only the full 5-day drawdown data for each pumping well was used in this evaluation.*

Modeling Results: Aqtesolv

Aqtesolv (Duffield, 2007) is a commercial software package developed for the design and analysis of aquifer-test data. The software provides a model of the theoretical response to pumping for the given input parameters. Aqtesolv is an important tool used by the District to analyze aquifer-test data. The software provides a comprehensive suite of solutions for confined, leaky, and fractured aquifers.

Aqtesolv Input Data

Aqtesolv allows for assigning multiple wells to an X and Y coordinate system, and certain well construction information (**Table 3**). **Table 4** summarizes the wells and pumping duration and rates for each well. Detailed pumping times and rates were directly imported into the software. Aquifer-test data was formatted into elapsed time (minutes) and drawdown (ft). Some estimates of the water level at the time of pumping were made, particularly for sites with manual measurements. The thickness (b) of the Cow Creek unit was input at 55 ft, with vertical to horizontal permeability (Kv/Kh) of 0.1. Estimates of the parameters are generally insensitive to changes in these parameters.

Aqtesolv Analysis

District staff followed the same guidelines while evaluating the data and considering other factors. Some of those include: 1) analyzing late data for a given test; 2) the more distant observation wells generally provide a better estimate of storativity; 3) drawdown data from pumping wells generally have high levels of head loss and should be used carefully in any evaluation; and 4) deviations of the observation data from theoretical (model) type curves can illuminate processes within the aquifer such as boundary conditions. Identification of boundary conditions is critical to the evaluation of the aquifer test (Duffield and Butler, 2015).

The data indicate a lack of a full recovery for most observation wells due to pumping the wells to fill injection (frac) tanks for the acid injection and brief pumping periods due to mechanical failures. Initial heads at the start of the aquifer test (time zero) need to be adjusted for truly static conditions, otherwise the lack of recovery from previous pumping would result in apparent smaller magnitude drawdown and a resulting higher transmissivity value. Due to the lack of recovery from the various development activities and pumping tests it was recommended by Glenn Duffield (creator of Aqtesolv; email communication 2/17/17) that the data from all three pumping wells be evaluated as one continuous test that captures the full aggregated pumping history. Aqtesolv allows for the analysis of variable pumping rates and variable pumping wells. For this evaluation, each of the three pumping wells was initially evaluated independently (Evaluations A-C, **Table 4**). In addition, the full duration of the pumping was analyzed in aggregate to account for the lack of recovery from preceding testing (Evaluation D; **Table 4**).

Boundary Conditions

The underlying Hammett Shale is assumed to be a no-flow boundary, while the overlying Hensel is thought to be a leaky confining layer (BSEACD, 2017). The deviation of observed water levels relative to modeled water levels can highlight factors influencing the data, such as recharge or no-flow boundaries. Since most of the water is derived from the Cow Creek, and is the completion target for production wells, lateral boundary conditions influencing the Cow Creek were the focus of this evaluation.

The drawdown data suggests that the Cow Creek aquifer is at least partially compartmentalized (BSEACD, 2017). Lateral no-flow boundary conditions appear to influence the aquifer-test data and could to be related to faulting. The study area contains several normal faults in the area. **Figure 4** presents the study-area map showing grid and positions of wells and faults within the defined grid. The named faults are mapped by Collins (2002). The red fault in **Figure 4** is meant to represent a fault to the west of the pumping wells, analogous to the Tom Creek Fault Zone (TCFZ). **Table 5** provides a description of the fault and end point coordinates used in Aqtesolv for no-flow boundaries. **Figure 5** illustrates analysis of the observation results using Theis with and without a no-flow boundary (faults in **Figure 4**). In some cases, the use of no-flow boundaries with the models improved the fit of the model to the pumping and recovery data. In general, use of the no-flow boundaries resulted in higher transmissivity estimates when compared to models without modeled faults.

Observation wells that were open to both the Glen Rose and the Cow Creek may have had muted drawdown, and allowed for rapid recovery. Both responses deviate from theoretical curves. Such response could be interpreted as a recharge boundary. We consider this an artifact of well construction and not a natural (regional) recharge boundary.

Table 3. *Summary well input for Aqtesolv*

Name	Type	X coordinate	Y coordinate	Fully Penetrating	Radius - casing (ft)	Radius-equip (ft)	Radius-borehole (ft)	Comment
Bridges 1-PW	PW	-60	30	y	0.448	0.27	0.41	
Bridges 1-upper	OW	-60	30	n	0.448	0.27	0.41	
Bridges 1	OW	-60	30	y	0.448	0	0.41	
Bridges 2-PW	PW	2730	-620	y	0.448	0.27	0.41	
Bridges 2-upper	OW	2730	-620	n	0.448	0.27	0.41	
Bridges 2	OW	2730	-620	n	0.448	0	0.41	
Bridges 3	OW	5760	-720	y	0.448	0	0.41	
Bridges 4	PW	4620	-730	y	0.448	0	0.41	
Odell 1	PW	-1840	630	n	0.448	0	0.41	no measureable response to Bridges #2 pumping
Odell 2-PW	PW	-3030	1330	y	0.448	0.27	0.41	
Odell 2-upper	OW	-3030	1330	n	0.448	0.27	0.41	
Odell 2	OW	-3030	1330	y	0.448	0	0.41	
Odell 3	PW	-3000	-1520	y	0.448	0	0.41	
Bowman	OW	3570	140	y	0.21	0.08	0.33	
Ochoa	OW	-920	770	y	0.21	0.08	0.33	
Wood#1	OW	-3020	-2810	y	0.21	0.08	0.33	
Lowe	OW	-1390	2600	y	0.21	0.08	0.33	
Carnes	OW	2250	1040	n	0.21	0.08	0.33	
Escondida 1	OW	-5410	-6800	y	0.25	0.08	0.33	Recovery for B1
Jones01	OW	-200	220	n	0.25	0	0.33	
Phillips	OW	3950	3450	n	0.25	0.08	0.33	

Table 4. *Summary times and pumping rates of aquifer test and recovery*

	Aquifer Test					***Aqtesolv***	***Aqtesolv***
	Date Start	***Stop***	***Duration (hrs)***	***Average GPM***	***Max GPM***		
Bridges 2-A	10/24/2016 12:23	10/24/2016 15:27	3.1	507	750	Not analyzed	Evaluation D "Aggregate" All Wells
Bridges 2-recovery	10/24/2016 15:27	10/31/2016 9:44	162.3				
Bridges 2-B	10/31/2016 9:44	11/1/2016 3:23	17.6	395	600	Evaluation A Bridges #2 Pumping	
Bridges 2-B recovery	11/1/2016 3:23	11/2/2016 7:59	28.6				
Bridges 2-C	11/2/2016 7:59	11/7/2016 15:01	127	305	620		
Bridges 2 recovery	11/7/2016 15:01	11/22/2016 8:00	177				
Bridges 1-A	11/22/2016 9:02	11/24/2016 13:19	52.3	738	810	Evaluation B Bridges #1 Pumping	
Bridges 1-A recovery	11/24/2016 13:19	11/25/2016 13:11	23.9				
Bridges 1-B	11/25/2016 13:11	11/30/2016 13:17	120.1	655	710		
Bridges 1 recovery	11/30/2016 13:17	12/8/2016 10:06	188.8				
Odell 2	12/29/2016 13:34	1/3/2017 14:48	121.2	565	620	Evaluation C Odell #2 Pumping	
Odell 2 recovery	1/3/2017 14:48	1/10/2017 11:18	164.5				

Table 5. *Fault segment end-point coordinates in Aqtesolv.*

Name	**NE Endpoint (X/Y)**	**SW Endpoint (X/Y)**
East Fault	*7375/643*	*1762/-3260*
Wimberley Fault	*7427/5842*	*-9810/-8000*
Rolling Oaks Fault	*2286/9731*	*-1665/1753*
Modeled Fault Tom Creek Fault Zone (TCFZ)	*0/10,000*	*-10,000/-6400*

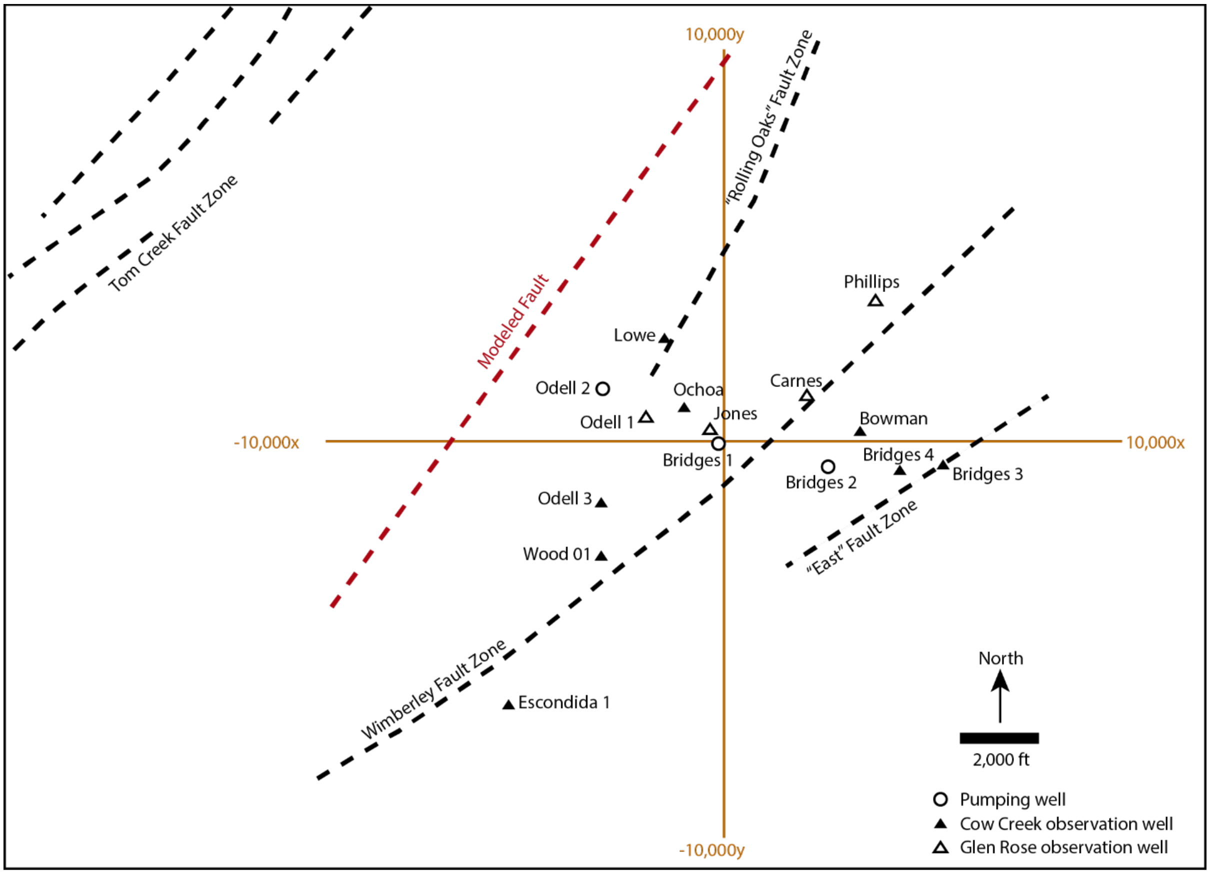


Figure 4. *Map showing coordinate grid and positions of wells and boundary within the defined grid. The named faults were mapped by Collins (2002). The red fault is meant to represent a fault to the west of the wells, analogous to the Tom Creek Fault Zone shown west of the study area.*

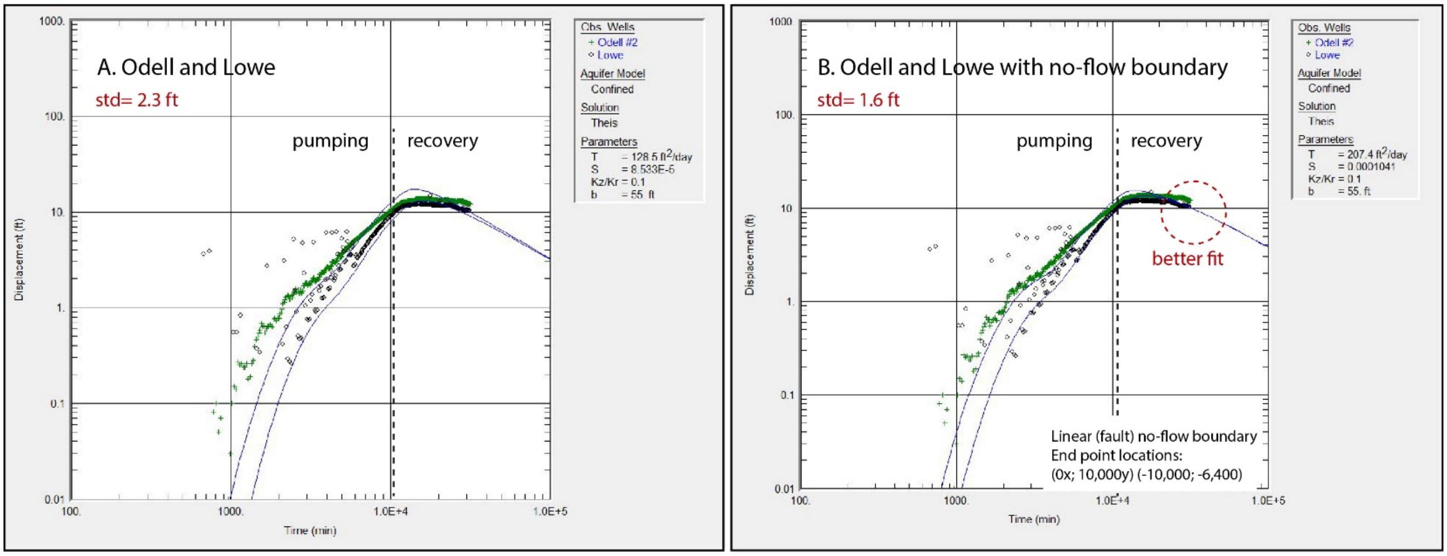


Figure 5. *Analysis of observation-well data from the Lowe and Odell #2 from the Bridges #2 pumping test. The lack of recovery from these two wells could be explained by no-flow boundaries. A) Best fit of the data to the Theis solution shows a standard deviation from the model of 2.3 ft. B) Best fit of the data to the Theis solution for the observation well-data and a no-flow boundary has a better fit with a standard deviation of 1.6 ft.*

Aquifer Parameter Estimates

Final analyses of the aquifer-test data and aquifer parameter estimates are provided in **Table 6**. The Theis solution (Theis, 1935; Hantush, 1961a and 1961b) within Aqtesolv provided the best fit to the observed data and all parameters in **Table 6** reflect that solution. Other models and solutions were evaluated, including leaky confined aquifer models, but those did not provide a good match to the observation data. Although other methods provided similar fit to the data, other solutions such as straight-line (Cooper and Jacob, 1946) and recovery methods (Theis recovery) are limited to analyses from only one pumping well, or to only portions of the data. Therefore, those methods only partially analyze the observation data and often provided larger magnitude aquifer parameter estimates than Theis.

For this evaluation we analyzed the pumping and observation wells as independent tests (Evaluations A-C), and then in aggregate (Evaluation D). Some observations of the evaluations include:

- Higher average transmissivities moving from east (Bridges #2) to west (Odell #2).
- Multiple observation-well data can be fit simultaneously to modeled values for some tests. This is particularly true of the Bridges #2 pumping (up to six wells; **Figure 6**) and decreases in occurrence with Bridges #1 and Odell #2 (only two observation wells can simultaneously be fit). This may reflect an increased heterogeneity and anisotropy associated with the two (westerly) pumping wells.
- Slow recovery in observation wells was not as pronounced in response to Odell #2 pumping compared to the Bridges #2 and #1 pumping.
- Modeling faults (no-flow boundaries) improved the fit of the data in the Bridges #2 and Bridges #1 tests, yet was not as beneficial in the Odell #2 and aggregate (Evaluation D) analyses.
- **Figure 7** illustrates how the Theis model fits data from the three pumping/observation wells for the full testing period (Evaluation D). Generally, there is a qualitatively good fit of the data set using the Theis model.
- The Theis solution does not provide a good match or reasonable parameter estimates for the measured data in the Bridges #1 pumping well. This is likely due to local effects of the Wimberley fault and fractures that result in a locally very high transmissive zone immediately around Bridges #1. However, observation well data surrounding Bridges #1 fit the Theis solution relatively well.
- Deviations from the Theis solution (quick recovery and muted drawdown) in some observation wells reflect influence of the Glen Rose from open-hole completions (**Figure 8**).

A qualitative assessment of the measured and modeled drawdown using average parameters from **Table 6** are provided in **Figures 9-11.** These figures show theoretical curves of distance and drawdown after 5 days of pumping versus actual measured drawdown for the same duration. The solid line is the modeled distance-drawdown curve after 5 days using average parameters calculated during the individual well testing phase (bottom of **Table 6;** Evaluations A-C). The dashed line is the modeled distance drawdown after 5 days using average parameters from the combined aggregate pumping (**Table 6**, Evaluation D).

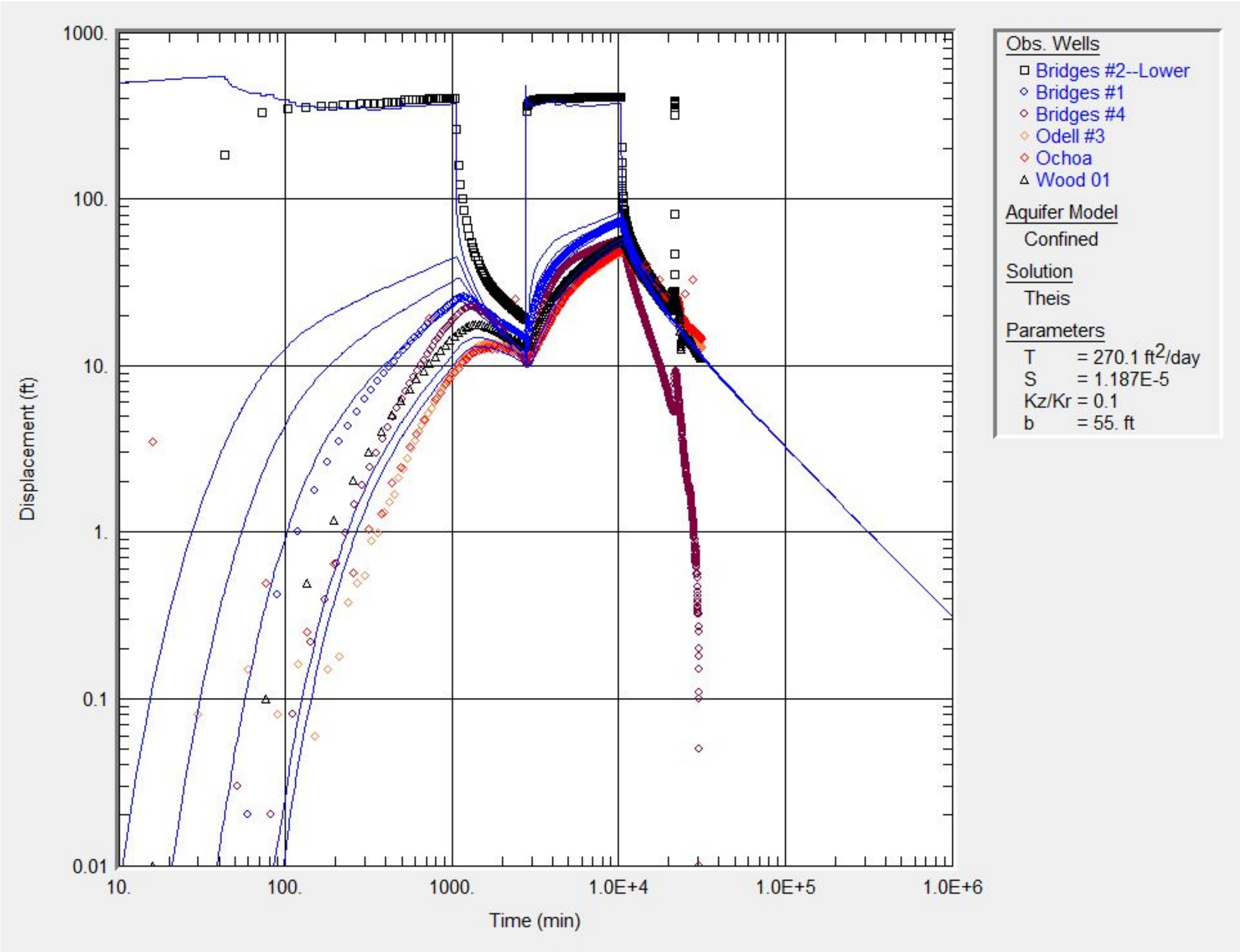


Figure 6. *Results of analysis of six predominantly Cow Creek wells during Bridges #2 pumping (Evaluation A). The symbols represent measured data within a well and the solid lines represent the theoretical Theis model.*

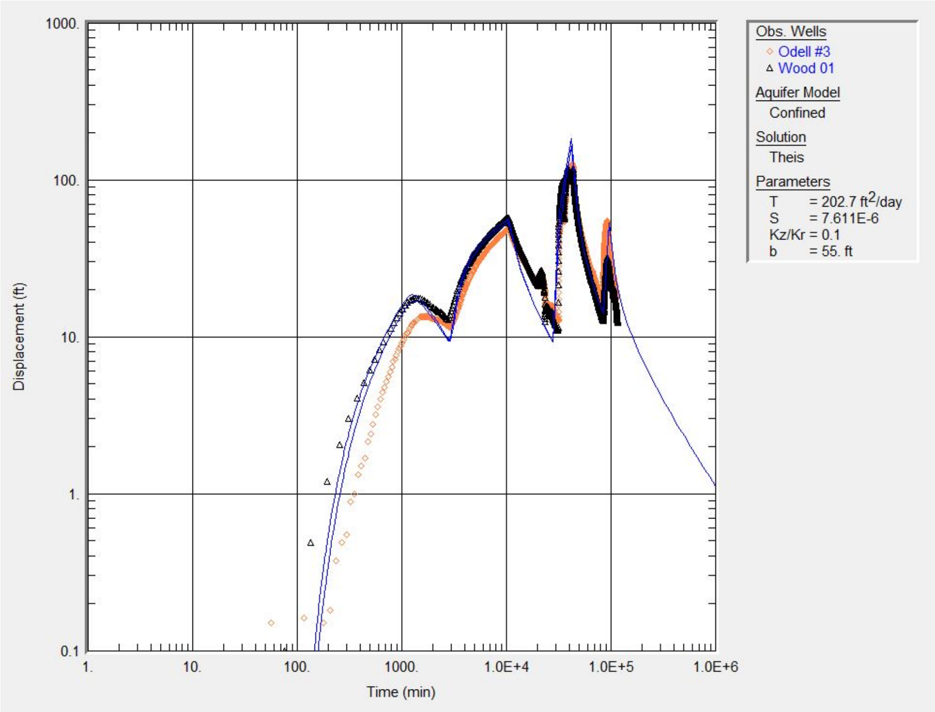


Figure 7. *Graph of the fit of the observation data from the Odell #2 and the Wood 01 over the full aggregate pumping history (Evaluation D). Generally there is a good fit of the observation data to the Theis model.*

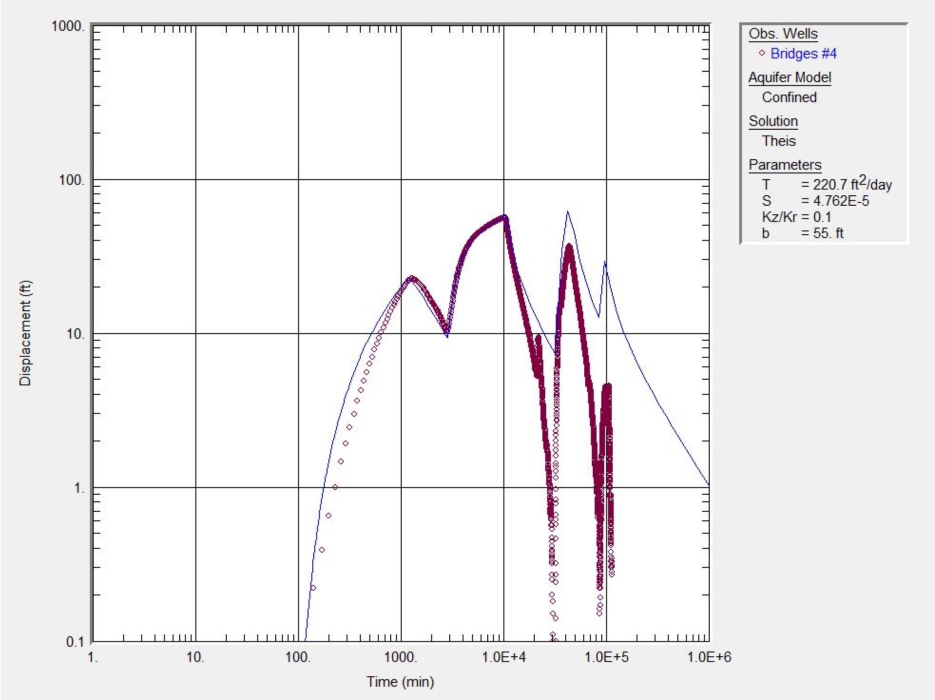


Figure 8. *Graph of the fit of the observation data from the Bridges #4 well over the full pumping history (Evaluation D). Water levels deviate from the Theis model (quick recovery and muted drawdown) likely owing to leakage from the Glen Rose due to the open completion of this well.*

Table 6. *Summary of aquifer parameter results.*

	Bridges #2 (Evaluation A)			***Bridges #1 (Evaluation B)***			***Odell #2 (Evaluation C)***			***Combined Pumping (Evaluation D)***		
Parameter	*Transmissivity (ft2/d)*	*Storativity*	*Comment*	*Transmissivity (ft2/d)*	*Storativity*	*Comment*	*Transmissivity (ft2/d)*	*Storativity*	*Comment*	*Transmissivity (ft2/d)*	*Storativity*	*Comment*
Bridges #1	222.7	1.80E-05	Better fit with TCFZ fault (improved std by 0.8 ft)	332	nd	Problems fitting data; unreasonable storativity; cannot fit with other wells	755.4	2.26E-04	Slightly better qualitative fit with TCFZ	277.2	1.70E-05	Poor match of itself during pumping
Bridges #2	227.9	1.06E-04	Better fit with RO fault (improved std by 3 ft)	263.3	4.59E-05	Better fit without faults	511	1.70E-04	No fault needed	218.5	7.32E-05	Fit better without fault; lack of full recovery each test
Bridges #3	nd	nd	Fast recovery, Kgrl leakage; no fault; T= 894; S=5.2E-4	nd	nd	Poor match; T=1063; S=5.2E-4; Kgrl leakage?	nd	nd	Poor match; Kgrl leakage?	nd	nd	Poor fit; Kgrl leakage; T = 1120 ft2/d; S=5.786e-4
Bridges #4	203.3	5.13E-05	Fast recovery, Kgrl leakage; no fault	414.3	7.98E-05	Fast recovery at end of test; leakage from Kgrl; better match without fault	nd	nd	Poor match; leaky Kgrl? T=655.3, S=2.564e-4	189.7	5.51E-05	Poor fit to B1 and O2; leakage from Kgrl
Odell #2	198	9.48E-05	Better fit with TCFZ (poor fit to RO fault), improves std 0.3 ft	302.7	2.78E-04	Slow recovery, qualitatively better recovery fit with TCFZ	331.1	nd	Storativity unreasonable; faults do not affect fit; Cooper-Jacob produces T = 567.7	96.75	6.67E-05	Faults do not improve significantly
Odell #3	251.1	1.62E-05	Better fit with TCFZ improves std 0.5 ft (RO fault and no fault same)	513.4	1.65E-05	Fast recovery; leakage from Kgrl; TCFZ better fit (improves std 0.2 ft), without fault T=268.8	432	9.52E-05	Fault does not improve fit	226.2	2.64E-05	Fit B1 and O2 best; faults do not improve significantly
Bowman	131.7	2.03E-05	Better fit without faults	287.5	6.69E-05	Quick recovery at end of test=	nd	nd	Insufficient data	120.3	5.62E-05	Poor data and perhaps fit for O2

	Bridges #2 (Evaluation A)			***Bridges #1 (Evaluation B)***			***Odell #2 (Evaluation C)***			***Combined Pumping (Evaluation D)***		
Parameter	*Transmissivity (ft2/d)*	*Storativity*	*Comment*	*Transmissivity (ft2/d)*	*Storativity*	*Comment*	*Transmissivity (ft2/d)*	*Storativity*	*Comment*	*Transmissivity (ft2/d)*	*Storativity*	*Comment*
						leakage from Kgrl						
Lowe	134.4	1.06E-04	Better fit with no fault (by std 0.6 ft)	283.9	2.94E-04	Slow recovery, qualitatively better fit of recovery with fault boundary	330.8	1.87E-05	Fault does not improve fit	173.5	1.00E-04	Poor fit to B1
Ochoa	200.5	3.02E-05	Better fit with TCFZ (improve 1.1 ft std)	451.7	1.00E-04	Better fit with RO fault; quick recovery= Kgrl leakage	784.4	1.00E-05	Slightly better recovery fit with TCFZ (std 0.3 ft); T=461 without fault	197.4	2.87E-05	Poor fit to B1
Wood 01	263.2	1.02E-05	Better fit with TCFZ, improves std 0.5 ft	519.9	8.54E-06	Quick recovery at end of test= leakage from Kgrl;TCFZ gives slightly better std (0.1 ft); T=267.2 without	494	1.00E-04	Fault does not improve fit	180.8	1.01E-05	Poor fit to O2
Escondida	nd	nd	No data	263.1	5.42E-06	Quick recovery at end of test= leakage from Kgrl; no fault needed	665	7.14E-05	Fault does not improve fit	nd	nd	T= 427.5 ft2/d; S=2.31E-5, leakage affects drawdown and recovery; no data from B2
Average	204	5.03E-05		363	9.95E-05		538	9.88E-05		187	4.82E-05	
Median	203	3.02E-05		317	6.69E-05		503	9.52E-05		190	5.51E-05	
Min	132	1.02E-05		263	5.42E-06		331	1.00E-05		97	1.01E-05	
Max	263	1.06E-04		520	2.94E-04		784	2.26E-04		277	1.00E-04	
Std	43	3.84E-05		97	1.04E-04		167	7.20E-05		51	2.80E-05	

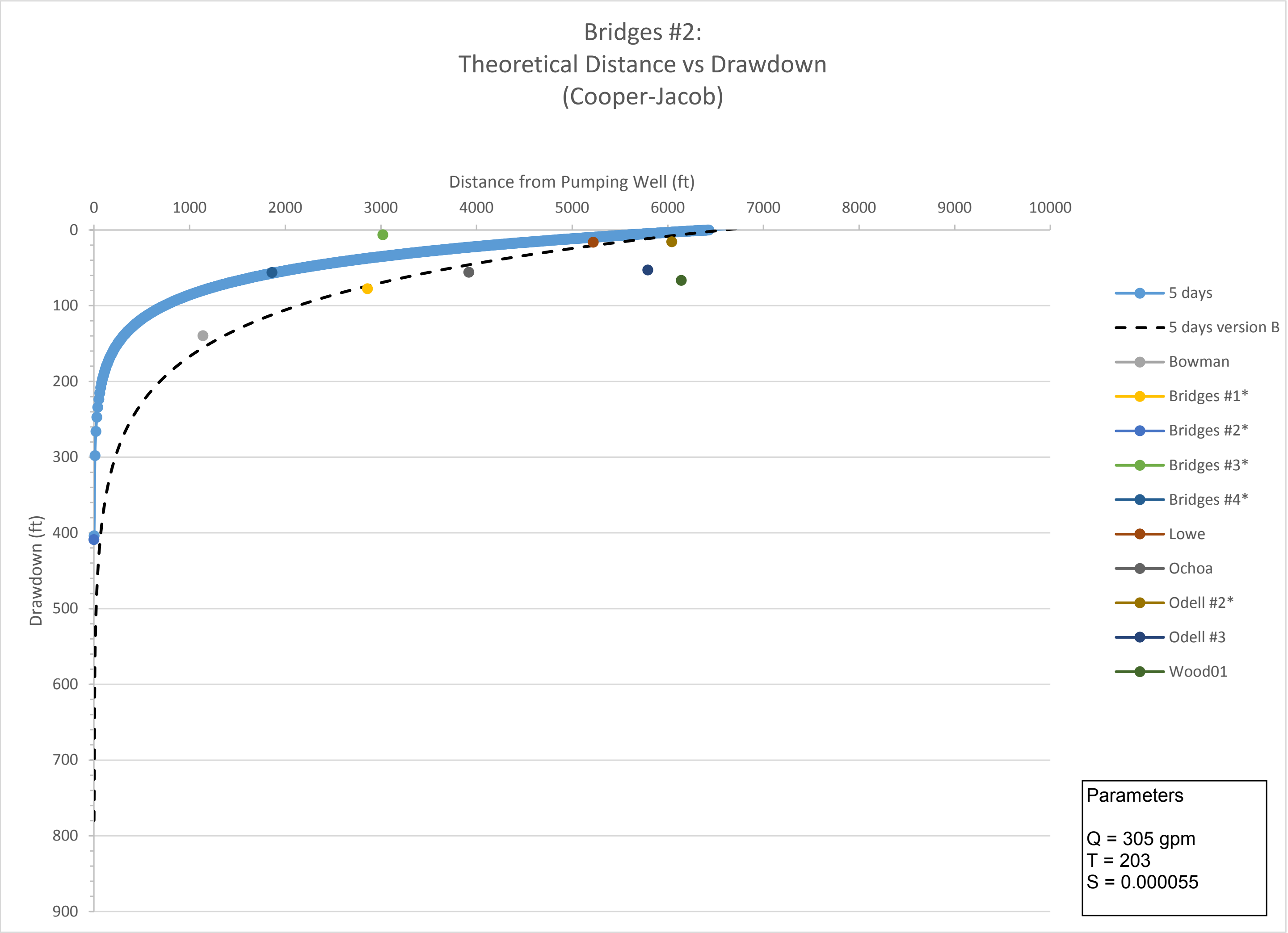


Figure 9. *Graph showing theoretical curves of distance and drawdown after 5 days of pumping versus actual measured drawdown after 5 days. The solid line is the modeled distance drawdown after 5 days using average parameters calculated during the Bridges #2 testing phase (Evaluation A). The dashed line is the modeled distance drawdown after 5 days using average parameters from the combined aggregate pumping (Evaluation D).*

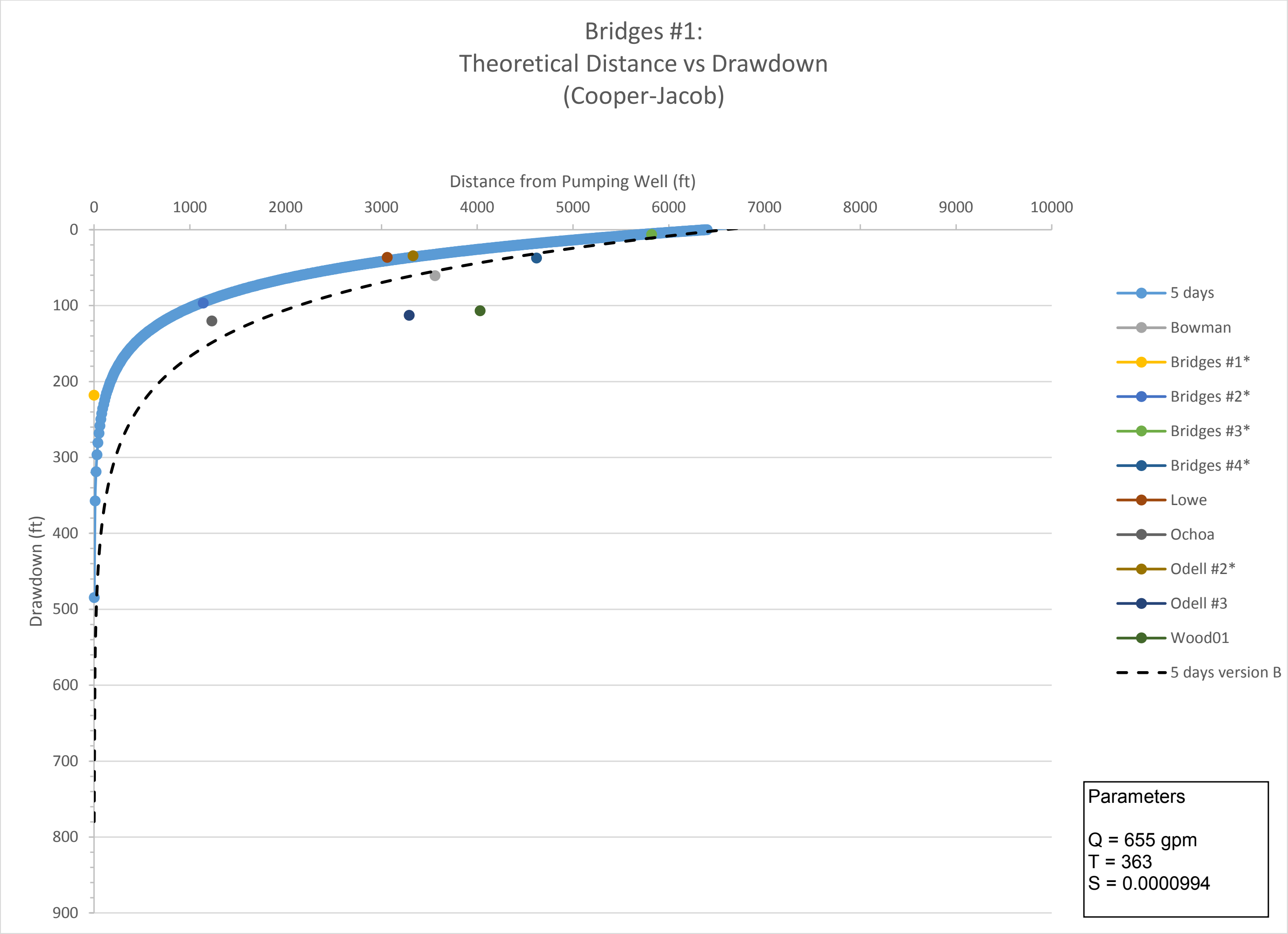


Figure 10. *Graph showing theoretical curves of distance and drawdown after 5 days versus actual measured drawdown after 5 days. The solid line is the modeled distance drawdown after 5 days using average parameters calculated during the Bridges #1 testing phase (Evaluation B). The dashed line is the modeled distance drawdown after 5 days using average parameters from the combined aggregate pumping (Evaluation D).*

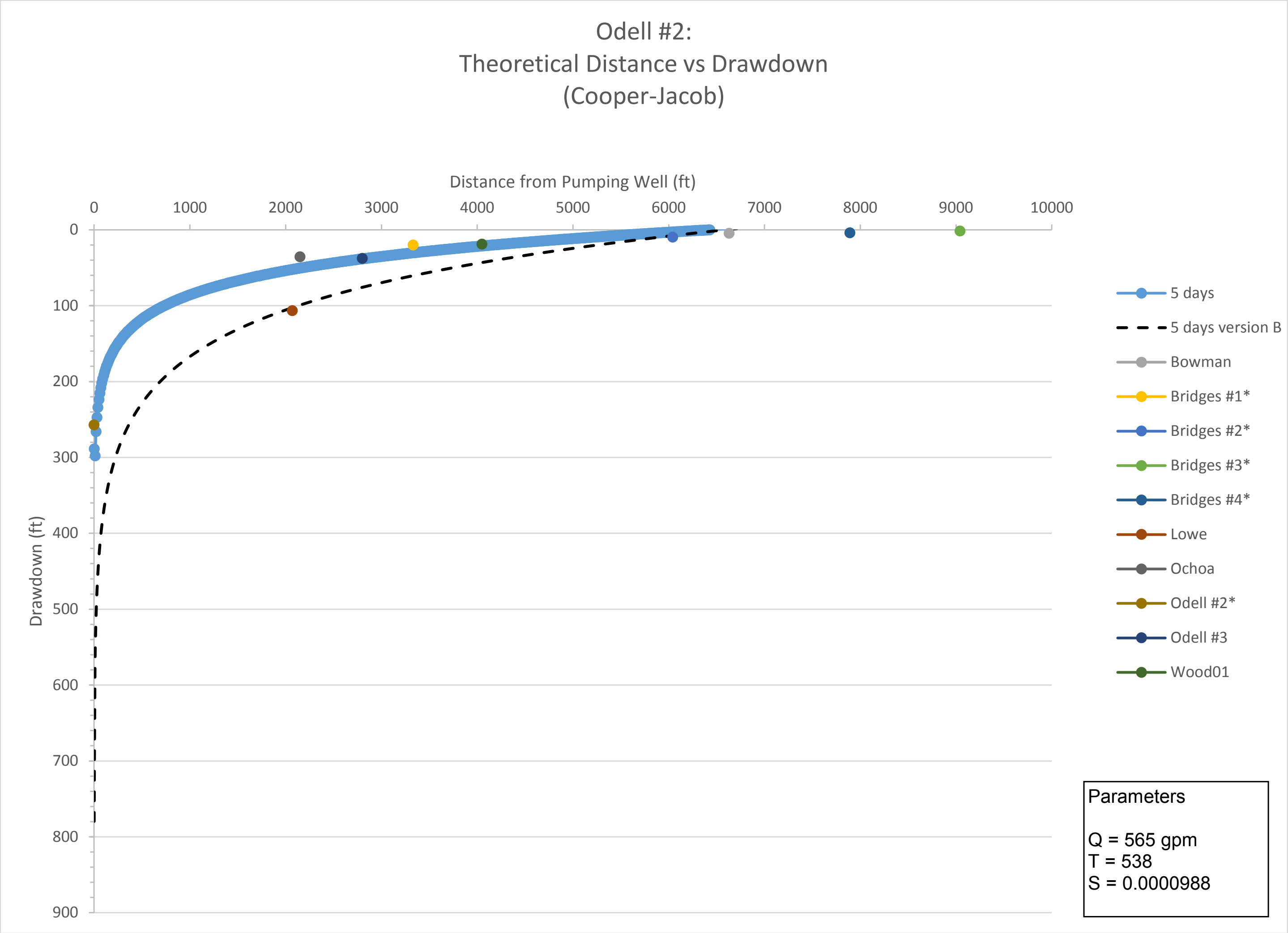


Figure 11. *Graph showing theoretical curves of distance and drawdown after 5 days versus actual measured drawdown after 5 days. The solid line is the modeled distance drawdown after 5 days using average parameters calculated during the Odell #2 testing phase (Evaluation C). The dashed line is the modeled distance drawdown after 5 days using average parameters from the combined aggregate pumping (Evaluation D).*

Modeling Results: MLU software

MLU (Multi-Layer Unsteady state) software provides an analytical solution to estimate aquifer parameters, but in layered aquifer systems. The same simplifying assumptions for other analytical models (e.g. Theis) exist for the MLU. However, MLU allows estimation of aquifer parameters in a layered stratigraphic environment with aquifers and aquitards (up to 40 layers) that can be used to test conceptual models and to evaluate and estimate the horizontal and vertical hydraulic conductivty and storativity. The sofware can be found at: http://www.microfem.com/products/mlu.html. A review of the software and its abilities are summarized in Carlson and Randall (2012).

The focus of the MLU modeling is to confirm the results of Cow Creek parameters obtained using Aqtesolv, test a layered stratigraphic conceptual model, and provide some estimates of the vertical hydraulic conductivity (Kv) of the Hensel. This will help future evaluations of the potential effects of drawdown in the Cow Creek and aquifer units above the Hensel.

Initial evaluations assumed a simple one-layer model that provided a good match to the Bridges #2 pumping and the Bridges #1 observations for the Cow Creek aquifer (**Figure 12**). The resulting aquifer parameters were similar to those derived using the Theis equation in Aqtesolv. These parameters were then held constant for a three-layer model that includes Cow Creek (aquifer 2), the Hensel formation (aquitard), and the undifferentiated Glen Rose (aquifer 1) (**Figure 12**). In the three-layer model an additional observation well response was added from the Bridges #2 upper zone (above the packer) from the Bridges #2 pumping phase. To optimize the fit of the data, the storativity values were held constant and the transmissivity of the Glen Rose and the vertical hydraulic conductivity (Kv) of the Hensel were iteratively changed to get a qualitatively good fit. Results of this evaluaton suggest the Kv of the Hensel is about 1.0E-5 ft/d.

Using a similar three-layer configuration we modeled the pumping from the Bridges #1 and the response to the observation wells of Bridges #1, Bridges #2, and the Odell #1 (**Figure 13**). The Odell #1 well is completed in the Lower Glen Rose. The fit of the data (estimates of transmissivity) was optimized for Bridges #2. For the purposes of modeling, the observation data from Bridges #1 were moved laterally from the pumping well, but did not affect transmissivity estimates because the targets for calibration were Bridges #2 and Odell #1. Transmissivity and storativity values were held consistent once a reasonable match was made for data from the Cow Creek wells. In an interative process, the transmissivity and storativity values for the Lower Glen Rose were changed to fit the magnitude of drawdown observed in Odell #1. The Kv of the Hensel was initially estimated at 1.0E-5, but was gradually decreased. While the magnitude of modeled and measured drawdown in Odell #2 was obtained, the delayed timing of the measured drawdown response in Odell was not matched. Results of the modeling are shown in **Figures 13 and 14**. In this model run, the storativity of the aquitards was considered zero and the upper and lower confining units were defined as impermeable (aquicludes). Results of this later evaluaton suggest the Kv of the Hensel is about 1.0E-6 ft/d.

Transmissivity and storativity results obtained using MLU for the Cow Creek generally reproduced the values obtained using Aqtesolv and the Theis equation. This was one of the goals of using MLU. In addition, the final conceptualized two-aquifer system provided reasonable results for the overlying Glen Rose and also the Kv for the Hensel. While these results are non-unique, they help to constrain future parameter estimation evalutions and modeling results.

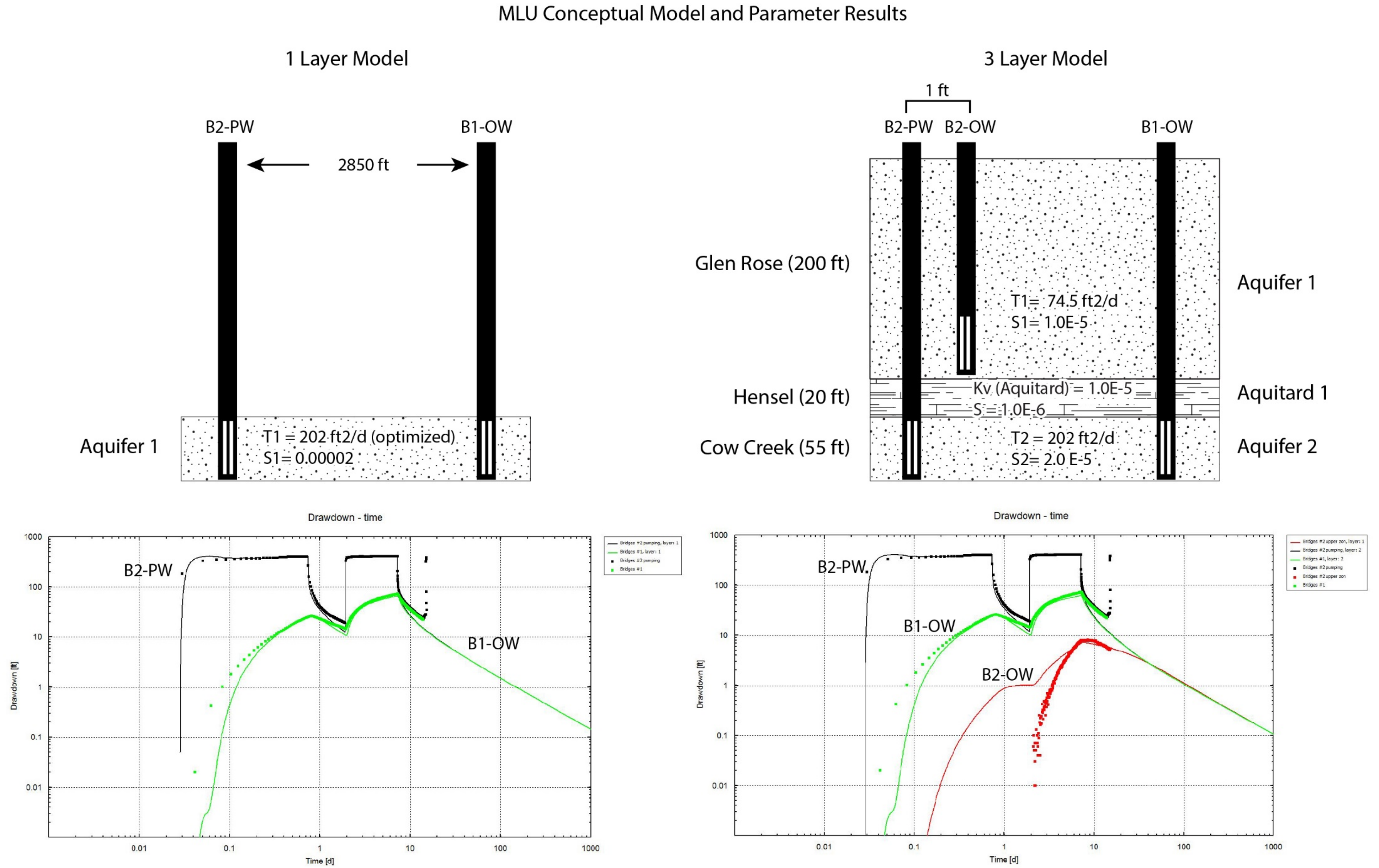
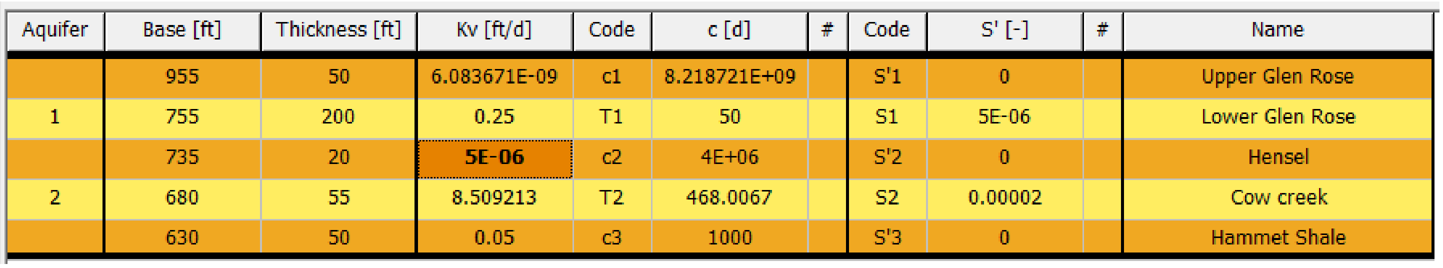


Figure 12. *Conceptualized 1 and 3 layer models and results from MLU.*



Aquifer	Base [ft]	Thickness [ft]	Kv [ft/d]	Code	c [d]	#	Code	S' [-]	#	Name
	955	50	6.083671E-09	c1	8.218721E+09		S'1	0		Upper Glen Rose
1	755	200	0.25	T1	50		S1	5E-06		Lower Glen Rose
	735	20	5E-06	c2	4E+06		S'2	0		Hensel
2	680	55	8.509213	T2	468.0067		S2	0.00002		Cow creek
	630	50	0.05	c3	1000		S'3	0		Hammet Shale

Figure 13. *Two layer aquifer model of Bridges #1 pumping with Bridges #2 and Odell #1 observation data. The model configuration is similar to that shown in Figure 12, except with an aquitard at the top representing the Upper Glen Rose evaporite zone. Odell 1 is completed in the Lower Glen Rose*

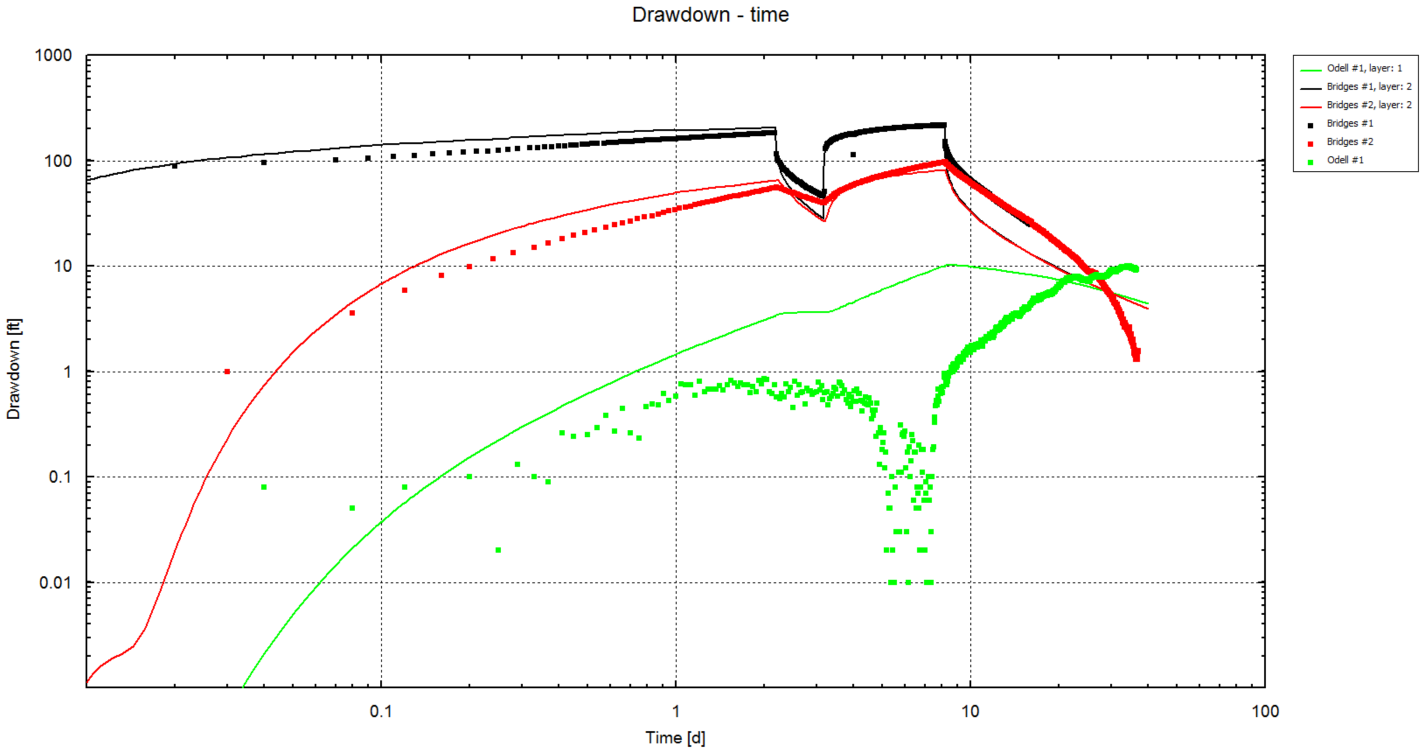


Figure 14. *Drawdown over time graphs of the observed data and modeled drawdown based on parameters in Figure 13. Bridges #1 (Cow Creek, black) and Bridges #2 (Cow Creek, red) and Odell #1 (Lower Glen Rose, green).*

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Other Aquifer Parameter Evaluations

Evaluations of aquifer parameters for the region around EP have been conducted by various parties. The most recent results are reviewed and evaluated below.

GMA-10 Explanatory Report

A model was developed for the EP area as part of the development of the Groundwater Management Area 10 Explanatory Report. The model was developed by Intera (2016) to evaluate the potential impacts of proposed pumping from the EP well field on the Desired Future Condition (DFC) of the Trinity Aquifers in GMA 10. The modeling code used was TTIM andwas calibrated to data provided in WRGS (2015). Details of the model and its results are described in a technical memorandum (Intera, 2016). **Table 7** is a summary of the relevant aquifer parameters from the model. One of the important parameters that the model attempted to constrain is the drawdown of the units overlying the Cow Creek production zone, which is controlled by the vertical hydraulic conductivity of the Hensel. Very few data were available when this report was written to constrain those values. Simulations were run with the Hensel vertical hydraulic conductivity (Kv) on the order of 10^{-4} to 10^{-6} ft/d.

Table 7. *Summary of aquifer parameters using TTIM from Intera (2016).*

Well	***Aquifer thickness (ft)****	***Transmissivity (Ft^2/d)***	***Horizontal Hydraulic conductivity (ft/d)***	***Specific storage***	***Storativity***
Upper Glen Rose	470	*0.8178*	*0.00174*	*7.94E-07*	3.73E-04
Lower Glen Rose	195	45.44	0.233	3.29E-07	6.42E-05
Hensel	45	0.0045	0.0001	1.52E-04	6.84E-03
Cow Creek	75	454.5	6.06	1.00E-07	7.50E-06

Bond Geological Services

A water availability study was prepared for the Escondida Ranch Subdivision by Bond Geological Services (BGS, 2016). The subdivision will have 19 lots, each with their own domestic supply well completed primarily into the Middle Trinity Aquifer. An observation and pumping well completed in the Middle Trinity Aquifer were used for a 24-hour aquifer test on October 31-November 2, 2016. Estimated transmissivity for the pumping well is reported to be 393 gpd/ft (52 ft^2/d).

Wetrock (WRGS)

WRGS has produced several hydrogeologic reports in support of their application for a pumping permit. Each report has some estimates of aquifer parameters, which are summarized below.

WRGS (2015) reported the results of well testing of all seven test wells within the EP well field (**Table 8a**). This report was produced by WRGS for Electro Purification LLC to document and justify a production rate of 2.5 MGD. This aquifer test had two other observation wells for the calculation of parameters for each pumping well. Production zones were not isolated for this testing and represent parameters from the combined Cow Creek and Lower Glen Rose. Results were summarized as:

> *"Transmissivity values were highest at Bridges Test Well No. 1, Odell Test Well No. 2 and Bridges Test Well No. 2 with transmissivities ranging from 58.7 ft^2/day to 1,000 ft^2/day. Average transmissivity for the seven tests was 366 ft^2/day. Storativity values from the tests ranged from 7.00 x 10-5 to 7.58 x 10^{-4} with an average storativity of 3.61 x 10^{-4}."*

An aquifer test was conducted and a hydrogeologic report was prepared by WRGS (2017a) according to BSEACD guidelines and submitted in support of the proposed pumping request of 2.5 MGD. Three of the seven existing test wells were selected for acidization. Following the acidization procedures, aquifer tests were conducted utilizing a packer to isolate the target production zone (Cow Creek). The three wells were selected to be representative of the existing transect of seven wells. Many more observation wells (greater than 20) were used during the 2016 aquifer testing than in 2015. This testing included wells completed in the Upper and Middle Trinity Aquifers. Accordingly, many more parameter estimates between the pumping well and each observation well were presented in WRGS (2017a). The report presents tables of results from three different analytical methods to estimate parameters, which include: Cooper-Jacob, Theis, and Theis Recovery. Average values using the Theis method are reported from WRGS (2017a) and summarized in **Table 8b**.

In response to a request for additional information, WRGS drafted a letter and provided additional information and summaries of aquifer parameters with a proposed pumping distribution (WRGS, 2017b). Aquifer parameters are presented in tables for each pumping well with a list of parameters for each well presenting results of analytical methods using Theis, Theis Recovery, Cooper-Jacob, and an average of the three methods. Those averaged values were used to simulate drawdown under various time and pumping scenarios. **Table 9** is a compilation of the average aquifer parameter values from WRGS (2017b) compared to the analyses done by the BSEACD in this memo.

Review of **Table 9** reveals similar results between WRGS and BSEACD for the three wells tested in 2017 (Bridges #1, #2, and Odell #2). Where the BSEACD results have higher transmissivity values, it is generally the result of the inclusion of no-flow boundaries within the evaluation. For example, the evaluation of the Ochoa data during the Odell #2 pumping resulted in a transmissivity of 784 ft/d compared to WRGS's 445 ft/d. However, without including a modeled fault the BSEACD result would be more similar to the WRGS result at 461 ft/d (**Table 6**).

Estimates of transmissivity from WRGS generally decreased from the 2015 to the 2017 reports. This is primarily due to the isolation of the Cow Creek in those test wells with packers in 2017. The aquifer-test data and evaluations in 2015 were likely influenced by contributions from the Lower Glen Rose. Because of the open-hole completions and other hydrogeologic variables, the results of aquifer estimates for some wells, and in particular Bridges #3, Bridges #4, and Odell #1, appear to be anomalous or in error (**Table 9**). Prime examples of this are the anomalously high transmissivity values, or unreasonable storativity values. For example, transmissivity values estimated by WRGS from the Bridges #3 for all pumping wells in 2017 are greater than 1,000 ft^2/d--yet the yields for the wells are low. These apparent high transmissivity values likely result from the open-hole completion of this well.

Table 8a. *Summary of aquifer parameters for the test wells from WRGS (2015).*

Well	Aquifer thickness (ft)	Transmissivity (Ft2/d)	Hydraulic conductivity (ft/d)	Storativity	Pumping Duration (hrs)	Discharge (gpm)	Date	Static WL (ft-bgs)	Drawdown (ft)	Specific Capacity (gpd/ft)
Odell 1	318	134	0.421	7.58E-04	62	95	2/11/2015	349	265	0.36
Odell 2	311	668	2.1		77	300	2/4/2015	333	260.5	1.15
Odell 3	318	234	0.734	1.03E-04	42	175	1/22/2015	324	250.2	0.7
Bridges 1	302	1,000	3.31	7.00E-05	47	435	1/15/2014	321	187.4	2.3
Bridges 2	313	358	1.14	1.34E-04	46	333	1/24/2014	290	285.5	1.17
*Bridges 3**	298	107	0.358	7.40E-04	44	48	12/30/2013	349	446	0.11
Bridges 4	316	58.7	0.185		49	66	2/16/2015	300	265.3	0.25
Average	310	417	1.34	3.61E-04						

*recommended plugging

Table 8b. *Summary of aquifer parameters using Theis for the test wells from WRGS (2017a).*

Well	Aquifer thickness (ft)*	Transmissivity (Ft2/d)	Hydraulic conductivity (ft/d)	Storativity	Pumping Duration (hrs)	Discharge (gpm)	Date	Static WL (ft-bgs)	Drawdown (ft)	Specific Capacity (gpd/ft)
Odell 2	91	404	4.99	1.23E-04	120	560	12/29/16		157.5	3.55
Bridges 1	88	908	11.10	1.79E-04	120	645	11/25/16		217.3	2.97
Bridges 2	85	323	4.09	1.45E-04	128	300	11/2/16		401.65	0.75
Average	88	545	6.73	1.49E-4						

*isolated with packer

Table 9. Average aquifer parameters compiled from WRGS (2017b) shown in black, compared to BSEACD analyses shown in grey. Highlighted values are anomalous and likely in error.

Pumping Well	*Bridges #2 (2017)*				*Bridges #1 (2017)*				*Odell #2 (2017)*				*Bridges #3*		*Bridges #4*		*Odell #1*		*Odell #3*	
Well	**WRGS T (ft^2/d)**	BSEACD T (ft^2/d)	**WRGS Storativity**	BSEACD Storativity	**WRGS T (ft^2/d)**	BSEACD T (ft^2/d)	**WRGS Storativity**	BSEACD Storativity	**WRGS T (ft^2/d)**	BSEACD T (ft^2/d)	**WRGS Storativity**	BSEACD Storativity	**WRGS T (ft^2/d)**	**WRGS Storativity**	**WRGS T ft^2/d)**	**WRGS Storativity**	**WRGS T (ft^2/d)**	**WRGS Storativity**	**WRGS T (ft^2/d)**	**WRGS Storativity**
Bridges 1	244	223	1.79E-05	1.80E-05	365	332	1.10E+01	Nd	552	755	2.01E-04	2.26E-04					894.05	1.54E-04	354.5	1.30E-05
Bridges 2	656	228	1.00E-06	1.60E-04	299	263	3.95E-05	4.59E-05	746	511	1.38E-04	1.70E-04	2209	9.11E-04	312.3	1.87E-04				
Bridges 3	1367	Nd	4.09E-04	Nd	2092	Nd	4.46E-04	Nd	1681	Nd		Nd	191.35	9.16E-04						
Bridges 4	325	203	4.34E-05	5.13E-05	362	414	8.81E-05	7.98E-05	1681	Nd	3.35E-04	Nd			112.8	8.24E-05				
*Odell 1**	6743	Nd	3.34E-04	Nd	10780	Nd	6.36E-03	Nd	6670	Nd	3.31E-02	Nd					468.6	1.97E-12	592.2	7.50E-05
Odell 2	574	198	6.86E-05	9.48E-05	287	303	2.32E-04	2.78E-04	391	331	1.74E+01	Nd								
Odell 3	257	251	1.31E-05	1.62E-05	327	513	1.29E-05	1.65E-05	554	432	7.52E-05	9.52E-05					794.25	5.50E-05	432.6	7.28E-12
Wood 01	242	263	8.30E-06	1.02E-05	305	520	6.98E-06	8.54E-06	587	494	1.31E-04	1.00E-04								
Lowe	419	134	9.36E-05	1.06E-04	261	284	2.59E-04	2.94E-04	324	331	2.00E-05	1.87E-05								
Bowman	208	132	1.84E-04	2.03E-05	239	288	8.49E-05	6.69E-05	4561	Nd	2.38E-04	Nd								
Escondida1		Nd		Nd	168	263		5.42E-06	653	665	6.29E-05	7.14E-05								
Ochoa	254		2.80E-05		312	452	8.30E-05	1.00E-04	445	784	1.08E-04	1.00E-05								
Average (all)	1026	204	1.09E-04	5.96E-05	1316	363	1.00	9.95E-05	1570	538	1.5	9.88E-05								
Average (without anomalies)	366				456		7.61E-04		532		1.45E-04									

*Assumes Cow Creek completion

Nd= no data, BSEACD analyses

Discussion

There are a variety of analytical solutions available for the analysis of aquifer-test data. This evaluation demonstrated that the in the EP area the Theis solution is the preferred analytical method because it can be matched for both pumping and recovery data and can also fit the entire aggregated pumping history (**Figure 7**). The Theis solution fits the observation data better than most other analytical solutions such as straight-line or recovery methods. The use of those straight-line and recovery solutions generally results in elevated aquifer parameters when compared to Theis (**Table 9**). In addition, we determined that the Theis solution fits the data better than other solutions that consider leaky or fractured aquifers.

Evaluation of the aquifer parameters reveals an aquifer that is somewhat heterogeneous and anisotropic, findings that are consistent with the drawdown shown in **Figure 1** and **Table 1**. However, despite the heterogeneity and anisotropy, analytical methods used to evaluate the test provide a good fit to the measured data with average and median statistics nearly identical, and with a relatively low standard deviation among all the representative Middle Trinity wells (**Table 6**). We believe the results indicate that aquifer parameters determined for a particular pumping-observation well pair are the most accurate. However, the average values provided in **Table 6** (Evaluations A-C) provide satisfactory estimates of aquifer parameters (**Figures 9-11**). Furthermore, inclusion of full aggregate pumping history and observation data (Evaluation D) result in an accurate evaluation and estimation of parameters. Such an approach allows the analyses to include the effects from the lack of recovery from the preceding tests and activities. Evaluation D results in lower average aquifer transmissivity when compared to the individual well evaluations (Average results A-C; **Table 6**).

Faults and fractures have an influence on the aquifer test with elongate drawdown along the fault, and aquifer parameters generally higher west of the Wimberley Fault zone. The faults appear to at least locally behave as no-flow barriers. Within Aqtesolv, modeled faults quantitatively improved the fit of the observed data to the model in some wells (**Figure 5**). This is particularly true for many of the data analyses involving Bridges #1 and Bridges #2 pumping wells. Using a fault in the evaluation effectively increased the estimates of transmissivity by a factor of two, and often provided a better match to the aquifer-test data.

Well completions strongly influence parameter estimation and may have also contributed to the reported high transmissivity and yields reported in WRGS (2015). The quick recovery and reduced drawdown, which deviates from the Theis solution, reflects apparent "recharge" derived from the overlying Glen Rose due to the open-hole completion on many of the wells (**Figure 8**). Such apparent "recharge" would result in an apparently highly transmissive well, as reflected in some of the analyses of WRGS, but are in contrast to the actual yield of those wells. This may explain some of the anomalous aquifer parameter values identified in **Table 9**. When comparing the results of aquifer parameter estimates between WRGS and this evaluation, they appear divergent. However, when anomolous values are removed from **Table 9**, the average values of both evaluations are very similar and comparable.

An additional analytical tool used in a qualitative manner was MLU. Transmissivity and storativity results obtained using MLU for the Cow Creek generally reproduced the values obatined using Aqtesolv and the Theis equation. In addition, a conceptualized two-aquifer system (Cow Creek and Lower Glen Rose) separated by a leaky Hensel aquitard provided a reasonable match to observation data, supporting the likelihood of hydrologic communication between the Cow Creek and the Lower Glen Rose as described in BSEACD (2017). In our evaluation, Hensel vertical hydraulic conductivity (Kv) ranges from 1.0E-6 to 1.0E-5 in the vicinity of the Bridges #2 and Bridges #1 pumping wells. These values are similar to the range of values presented by Intera (2016). Estimates of drawdown in the overlying Lower Glen Rose should use these ranges of values for Kv in the Hensel.

Conclusions

The Theis analytial solution provides a very good fit to the aquifer-test data. Aquifer parameters of the Cow Creek provided in **Table 6** are the most comprehensive and representative of the area considering the entire aggregated pumping history, well completions, and flow barriers.

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