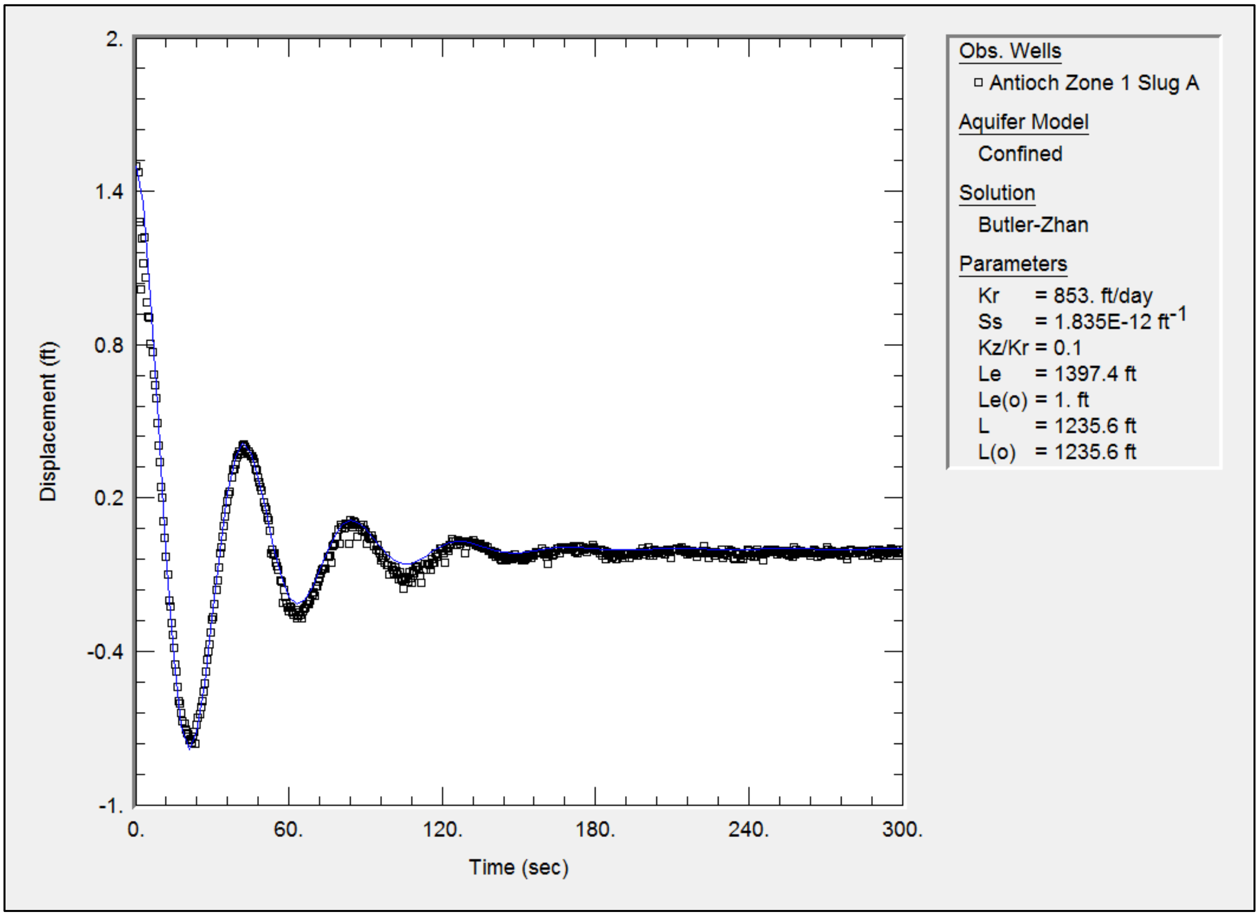
Hydraulic Conductivity Testing in the Edwards and Trinity Aquifers Using Multiport Monitor Well Systems, Hays County, Central Texas



BSEACD Report of Investigations 2016-0831

August 2016

Barton Springs/Edwards Aquifer Conservation District

1124 Regal Row

Austin, Texas

Disclaimer

All of the information provided in this report is believed to be accurate and reliable; however, the Barton Springs/Edwards Aquifer Conservation District and the report's authors assume no liability for any errors or for the use of the information provided.

Cover Page: Butler-Zhan analytical solution in AQTESOLV for water-level change in Zone 1 of the Antioch multiport well.

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ABSTRACT

Hydraulic conductivity is one of the defining characteristics of hydrostratigraphic units. Detailed and quantified permeability information from the units comprising the Edwards and Trinity Groups is lacking in central Texas. These rock groups comprise important karstic and fractured carbonate aquifers. To better manage water resources and understand fate and transport of contaminants, the hydraulic parameters of the aquifers need to be quantified.

Slug testing is one of the most commonly used field methods for obtaining hydraulic conductivity estimates. This study presents slug test results from zones within two Westbay multiport monitor wells. The multiport wells are 1,125 and 1,375 ft deep and contain 14 and 21 zones, respectively. Zones range from 20 to 197 ft thick and are hydrologically isolated from one another by inflatable packers, allowing for discrete permeability testing, head measurements, and groundwater sampling. Multiple rising- or falling-head (slug) tests were performed for each zone. Hydraulic conductivity (K) values for each zone were calculated from the data using analytical solutions in AQTESOLV software. These data were compared to available geochemistry and head data from each zone.

This study has demonstrated that the lithostratigraphic units do not necessarily correspond to hydrostratigraphic units, and that permeabilities can be very heterogeneous within an aquifer. Accordingly, qualitative hydrostratigraphic delineations may have limited value because of the need for different types of data (lithology, geochemistry, heads, and permeability) to adequately characterize hydrostratigraphy.

Results of this study reveal three groups of hydrostratigraphic units with distinct permeabilities, heads, and geochemistry, as summarized below.

Hydrogeologic Group	Thickness (ft)	Lithostratigraphy	Range of K (ft/d)	Avg. TDS (mg/L)
Edwards Aquifer	495 (Antioch); 265(Ruby)	Georgetown Fm, Edwards Group, Upper Glen Rose	0.1 to 3,382 (1,087 avg)	313
Upper Trinity Aquitard	515 (Antioch); 350 (Ruby)	Upper and Lower Glen Rose	0.01 to 2.3 (0.7 avg)	3,200
Middle Trinity	140 (Antioch); 289 (Ruby)	Lower Glen Rose, Hensel, Cow Creek	1.2 to 1,334 (348 avg)	750

INTRODUCTION

The Edwards Aquifer is an important source of water for domestic, industrial, public water supply, and agricultural use. It is the sole source of water for many people and ecological habitats in central Texas. The Barton Springs/Edwards Aquifer Conservation District (District) manages water resources in the various aquifers and regulates the amount of permissible pumping in order to ensure there is enough water to meet demand and environmental needs. Demand for groundwater has increased considerably in recent years, such that pumping during drought conditions must be restricted. The underlying Trinity Aquifers have increasingly become an alternative source of water as extraction limits have been placed on the Edwards Aquifer. Previous hydrologic studies of groundwater resources suggest a hydraulic connection between the Trinity and Edwards Aquifers in this study area (Slade et al., 1986; Mace et al., 2000). However, the extent of the hydraulic connection and the flow of water between and within the aquifers are poorly understood due to the lack of detailed data.

To better understand this critical source of water, the District carries out hydrogeologic studies and regularly monitors the conditions in the Edwards and Trinity Aquifer systems. This includes the installation of multiport wells that allow detailed data collection from discrete units within aquifer units.

This report presents hydraulic conductivity data for the hydrostratigraphic subdivisions of the Edwards, Upper Trinity, and Middle Trinity Aquifers. The data were obtained by performing rising- and falling-head (slug) tests in two multiport monitor wells (Figure 1). The goal of this study is to better characterize the permeability of the Edwards and Trinity hydrostratigraphic units. The data also allow comparisons to be made to other quantified measurements from aquifer tests and more qualitative designations such as informal hydrogeological members of the Edwards and Trinity Aquifers (Small et al., 1996; Clark 2004).

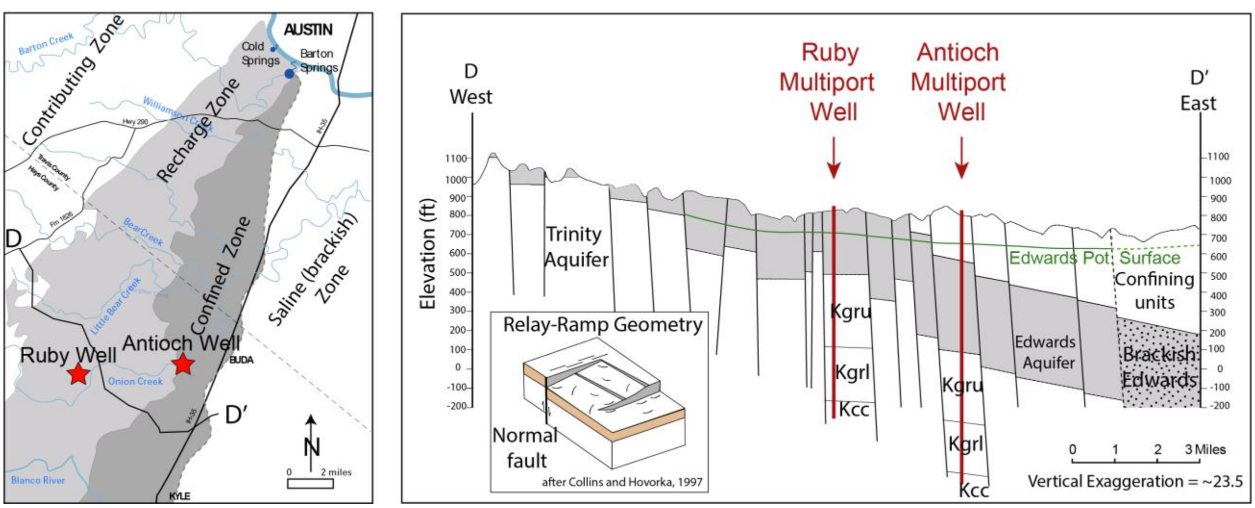

Figure 1. (left) Map of the study area showing Edwards Aquifer contributing, recharge, confined, and saline zones and the location of the Ruby Ranch and Antioch multiport monitor wells. (right) A generalized geologic cross section of the study area. Kgru = Upper Glen Rose, Kgrl = Lower Glen Rose, Kcc = Cow Creek Limestone units.

HYDROGEOLOGIC SETTING

Edwards Aquifer

The Edwards Aquifer occurs in Cretaceous karstic limestone and dolomite, historically defined as being composed of the Georgetown Formation, Edwards Group, and the Walnut Formation. (Figure 2). In the study area, the Walnut Formation is noted to be stratigraphically and lithologically equivalent to the Basal Nodular Member of the Kainer Formation of the Edwards Group (Small et al., 1996). The Edwards Group, composed of the Kainer and Person Formations, was deposited in shallow-marine, tidal, and supratidal environments (Rose, 1972). Matrix compositions vary from fossiliferous limestone, miliolid grainstone, wackestone, and mudstone (Small et al., 1996). These varying lithologies and secondary-porosity textures were the basis for informal subdivisions of the Edwards created by Rose et al. (1972) and the hydrogeological subdivisions suggested by Maclay and Small (1976) and still used in recent publications (Small et al., 1996; Clark, 2004; Figure 2). The Georgetown Limestone was deposited in an openly circulated, shallow-marine environment and consists of a fossiliferous and argillaceous limestone. The Edwards Aquifer is confined by overlying, low-permeability Upper Cretaceous clays, limestones, and marls.

The Edwards Aquifer is located in the Miocene-age Balcones Fault Zone of central Texas. In Hays County, the Balcones Fault Zone trends northeast-southwest with faults generally having a southeasterly dip. Development of the karstic Edwards Aquifer was influenced significantly by fracturing and faulting associated with Balcones Fault Zone activity and subsequent preferential dissolution through fractured limestone and dolomite by infiltrating meteoric water (Sharp, 1990; Barker et al., 1994; Hovorka et al., 1995; Hovorka et al., 1998; Small et al., 1996). In addition, development of the aquifer is also thought to have been influenced by deep dissolution processes known as hypogene speleogenesis along the freshwater/saline-water interface at the eastern margin of the aquifer (Klimchouk, 2007; Schindel et al., 2008).

Halihan et al. (1999) describe permeability in the Edwards Aquifer varying with the direction and scale of measurement, and values ranging over nine orders of magnitude. Mean hydraulic conductivities are two orders of magnitude higher in the confined zone compared to the unconfined zone (Lindgren et al., 2004). The Edwards Aquifer is often characterized as a triple permeability system consisting of conduit, fracture, and matrix permeability (White, 2016). Others have described it as having two flow regimes: a slow-flow system (diffuse or matrix flow) and a fast-flow system (fracture and conduit flow). Matrix permeability is dwarfed by fracture and conduit permeability. Fractures may control flow at the well scale, with conduits controlling flow on the regional scale (Halihan et al., 2000). Ultimately, it is likely that fractures (enlarged by solution) connect the matrix to conduits. However, a trend of relatively high matrix permeability is observed in the confined portion of the aquifer on both sides of the freshwater/saline-water interface. In contrast, the matrix permeability is relatively low for rocks in the outcrop (Hovorka et al., 1998).

Trinity Group Aquifers

Stratigraphically, the Trinity Aquifers underlie the Edwards Aquifer. However, along the Balcones Fault Zone, normal faulting has partially juxtaposed the two aquifers laterally, with Trinity units exposed west of the Edwards outcrop in the study area (Figure 1).

The geologic history and lithology of the Trinity units are described in detail in other publications (Ashworth, 1983; Barker et al., 1994; Wierman et al., 2010). Within the literature, the regional Trinity

Aquifers are defined as three distinct subregional aquifers, the Upper, Middle, and Lower Trinity (Bluntzer, 1992; Barker et al., 1994). Figure 2 summarizes the lithology of the various Trinity units and the hydrogeologic units of the Trinity Aquifers. The Upper Trinity Aquifer is made up of the Upper Glen Rose Member characterized as interbedded, peloid packestone, and grainstone limestone with locally fossiliferous silty marls and significant evaporitic mineral intervals. The Middle Trinity Aquifer is made up of the Lower Glen Rose Member, the Hensel Formation, and the Cow Creek Formation. It is separated from the underlying Lower Trinity Aquifer by the confining Hammett Shale. The Lower Glen Rose Member has similar composition as the Upper Glen Rose with packestone and grainstone limestones interbedded with fossiliferous marly limestone. However, the Lower Glen Rose Member has large sections of rudist reef boundstones, capable of yielding high-quality water, which are locally high-yielding units. The Hensel Formation in the study area consists predominantly of silty dolomite with some interbedded shaly intervals. The Cow Creek is a grainstone that grades into a dolomite and is the most prolific of the aquifer units in the Middle Trinity Aquifer. Karst features are common within the Middle and Upper Trinity Aquifers. The Lower Trinity Aquifer (not analyzed in this study) traditionally was not exploited in the study area because of its depth and poor water quality.

Inter- and Intra-Aquifer Flow

Previous publications in the study area conceptualize the Upper, Middle, and Lower Trinity Aquifers and the Edwards Aquifer as distinct hydrogeologic units, although having some vertical and lateral leakage (Bluntzer, 1992; Barker et al., 1994; Jones et al., 2011). However, the degree of communication is largely unknown and is likely very heterogeneous- especially within the Balcones Fault Zone. Lateral flow from the Trinity into the Edwards Aquifer has also been documented to occur outside of the study area (Johnson et al., 2010).

Recent studies (Andrews et al., 2013; Wong et al., 2014), which include much of the data in this report, indicate that the upper-most portion (~150 ft) of the Upper Glen Rose (historically defined as the Upper Trinity Aquifer) are in fact in vertical hydraulic communication with the overlying Edwards Aquifer. This is in agreement with studies to the south of the study area by Veni (1995). Wong et al. (2014) also indicate that the lower-most portion of the Upper Glen Rose (Upper Trinity) and portions of the upper-most Lower Glen Rose (Middle Trinity) have hydraulic attributes of an aquitard. Those aquitard units provide the hydraulic barrier to flow between the Edwards and Middle Trinity Aquifers (Wong et al., 2014) in the study area.

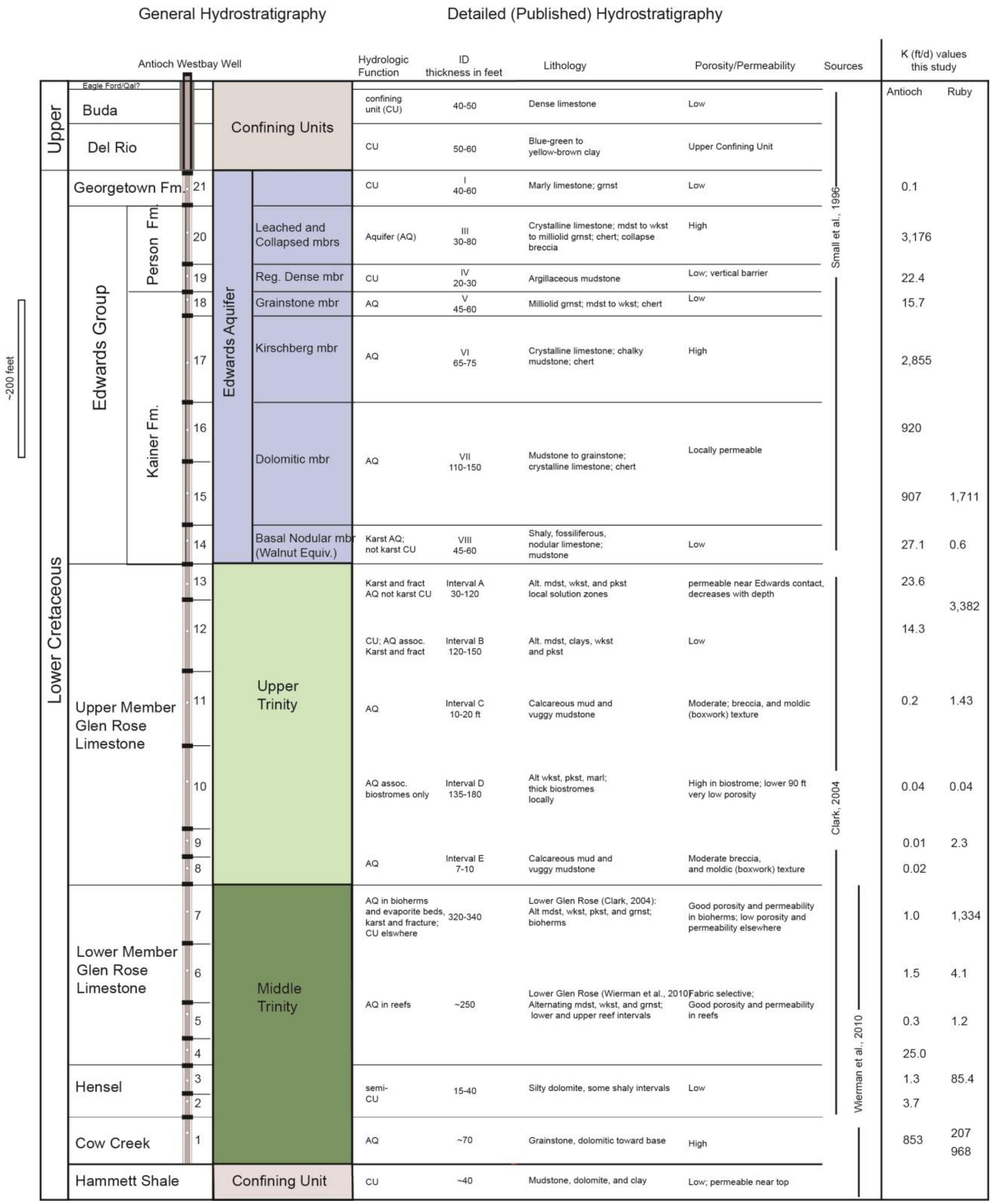

Figure 2. Stratigraphic column from the literature with informal hydrostratigraphic members (Small et al., 1996; Clark, 2004; and Wierman et al., 2010).

METHODS

The principal methods used in this study are slug tests performed in two multiport monitor wells.

Slug Testing

Slug tests are single-well tests used to estimate the hydraulic conductivity of a formation. The basic principle is that when a water-level change (slug) is induced in a well, flow either goes into or out of that part of the formation that is intersected by the screen or open interval of the well. The response rate is reflective of the hydraulic conductivity of the formation in the immediate vicinity of the borehole (Poehls and Smith, 2009). Slug testing can be done by introducing an object, water, or air into the well to quickly displace the static water level, and then measure the change over time with an electrical line or pressure transducer. The response of the water level can then be evaluated using analytical solutions (see Data Analyses).

Westbay Multiport Monitor Wells

Monitoring of discrete intervals is needed to provide data that reflect the complexity of the Edwards and Trinity stratigraphic units. Multiport wells are unique systems that allow recurrent sampling of discrete zones (Figure 3). The District has installed two multiport monitor wells, designated herein as the Ruby Ranch and Antioch wells (Figure 1).

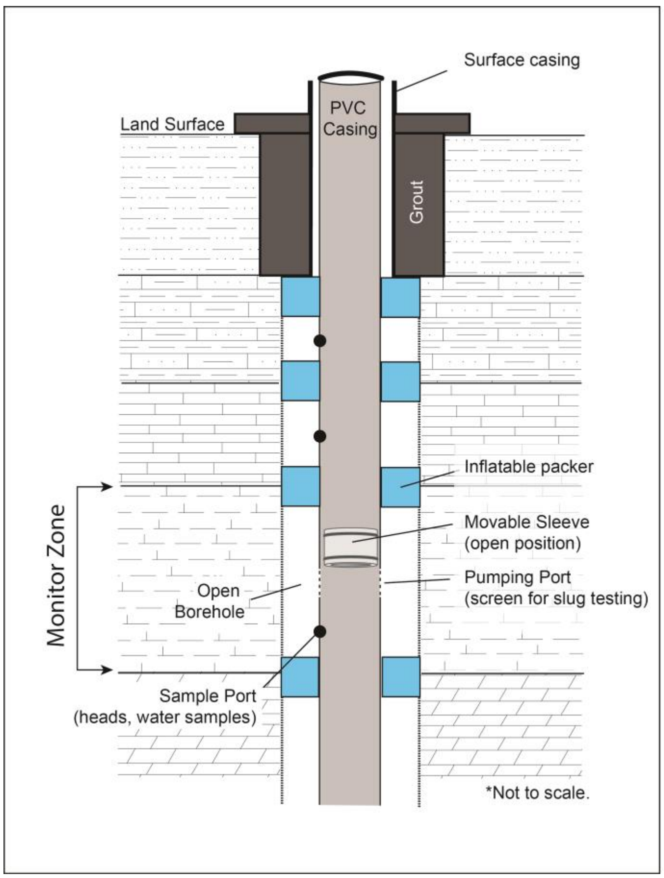

Figure 3. Schematic of the multiport well components for one zone. *The wireline tool for measuring heads is not shown.*

The multiport well systems installed by the District are manufactured by Westbay Instruments of Vancouver, Canada. The District's two multiport wells were drilled using air-rotary drilling techniques producing boreholes with nominal 5¼ inch diameters. The first well was installed in 2008 at Ruby Ranch and the second was installed in 2010 approximately 4 miles to the east near Antioch Cave (Figure 1). The Ruby Ranch well has 14 monitor zones, while the Antioch well has 21 zones. Both wells were designed to monitor groundwater in the units of the Edwards Aquifer and the Upper and Middle Trinity hydrostratigraphic units. The Antioch multiport monitor well was drilled to 1,375 ft below the land surface and penetrates into the Cow Creek Limestone--the lowest of the Middle Trinity Aquifer units. The Ruby Ranch well was drilled to a depth of 1,120 ft below the land surface, and penetrates to the Hammett Shale, the lower confining unit of the Middle Trinity Aquifer, which overlies the Lower Trinity Aquifer.

Westbay well casing consists of multiple segments of 1.9 inch outer-diameter Schedule 80 PVC, which are fitted together with PVC couplings. Monitor zones are established with permanent inflatable packers placed in the string of casing at the top and bottom of each targeted zone. A special coupling with a spring-loaded valve (sampling port) is installed between the inflatable packers. A pumping port is also installed in each zone. These are short, screened intervals through which slug tests can be conducted (Figure 3).

Multiport Monitor Well Design

The multiport monitoring well was designed after reviewing drilling, geophysical, and television logs with other information (Figure 4). A gamma log was used to determine approximate contacts of the various geologic units. A caliper log was run to measure the diameter of the borehole so that packers could be placed on relatively smooth sections where cavities were not prominent, improving the likelihood that upon inflation the packers would provide effective seals in the annular space. In the Antioch well borehole, a video log was also run to carry out lithologic and structural (fracture) inspection for packer placement. An attempt was made to isolate zones in the Edwards Aquifer that would correspond to the established informal lithologic subdivisions after Small et al. (1996). The zones in the Upper and Middle Trinity hydrostratigraphic units were placed on the basis of the expected locations of known major lithologic units (Al Broun, personal communication). Further subdivision of the Trinity lithostratigraphic units allows for a more detailed hydrogeologic understanding.

Well Completion and Data Collection

After designing the well (Figure 5), its components were assembled and inserted into the well using a guide tube (HQ casing). The guide tubing was then pulled out and the packers inflated with water (Figure 6). Inflation of the packers sealed the annular space between the PVC casing and the borehole walls, thus isolating the pumping and sampling ports into discrete zones. To measure heads in a zone or to collect a water sample, a specialized wireline tool is lowered into the casing. The tool has a built-in pressure transducer and a valve through which water samples (up to 1 L) can be collected. The instrument is controlled by an operator at the surface and pressure data are sent from the instrument to a read-out device (Figure 7).

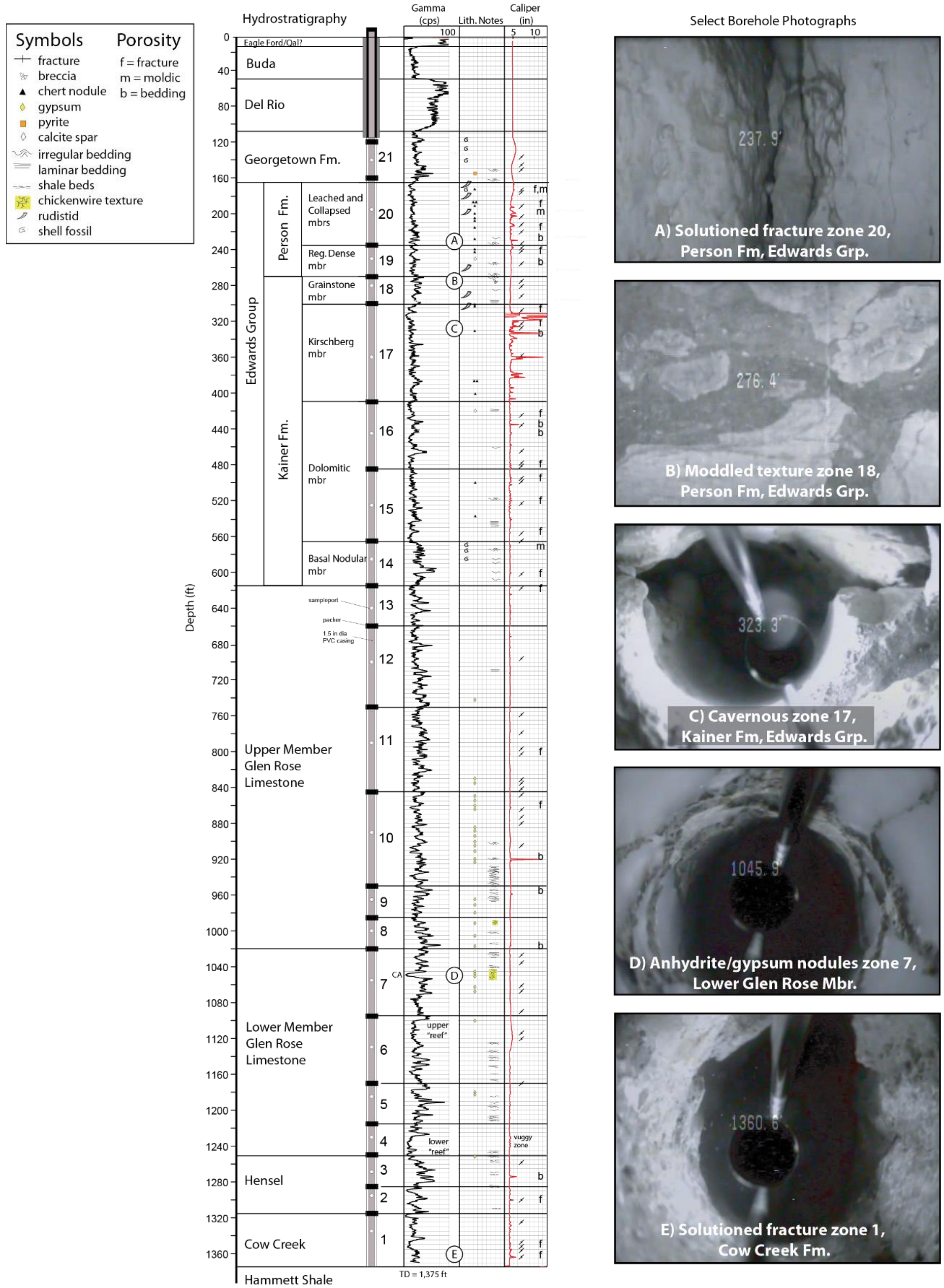

Figure 4. Antioch well schematic with geophysical logs (gamma ray and caliper) and geologic notes.

Figure 5. Photograph showing layout and design of Westbay PVC casing system prior to installation. *Blue sections are packers that separate zones.*

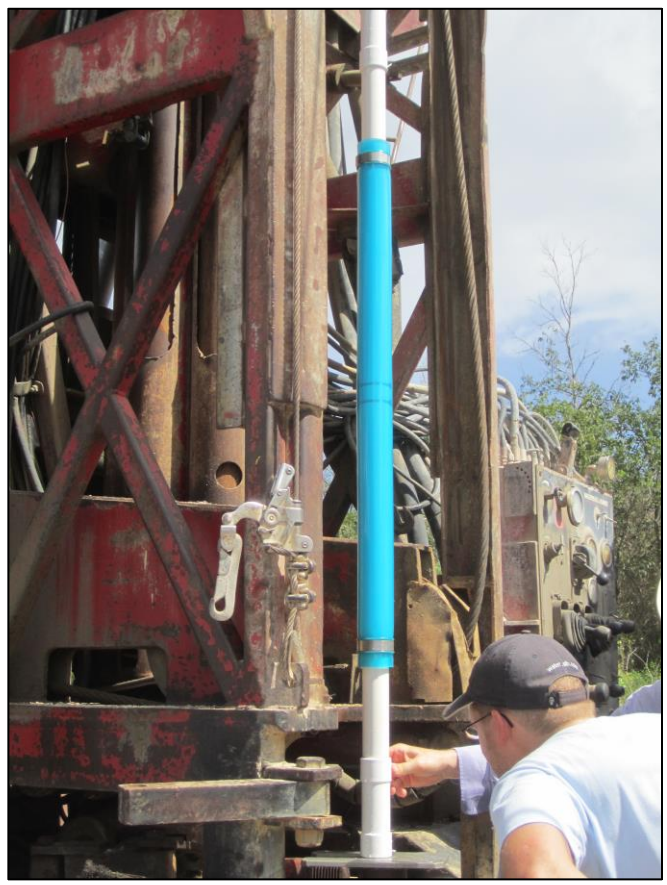

Figure 6. Photograph showing installation of Westbay PVC casing, couplings, and packer. *The PVC casing is lowered within a guide tube set to the bottom of the well. Once the entire casing system is installed and the guide tube pulled out, the packers are then inflated with water to isolate zones.*

Figure 7. Photograph showing data collection from the multiport well. *The wireline tool is lowered by the winch in the trailer. Control of the sampling tool and display of data are done electronically.*

Multiport Monitor Well Slug Testing

Traditional slug testing using a solid slug can be performed on zones within the multiport monitor well. Slug testing involves opening the screen (pumping port) within a given zone and then conducting the test. In addition, the opening of a given zone offers an opportunity to measure the response of the water level inside the casing. For example, if a zone has a lower head than the water level inside the casing, the water will flow out of the casing and into the formation—equivalent to a falling-head test. Conversely, if a zone has a higher head than the water level in the casing, water will flow from the formation into the casing—equivalent to a rising-head test.

A profile of heads in each zone of the multiport well was made before slug testing commenced so as to measure the head differentials between zones (anticipated H_0*). For this study, up to three slug or rising- or falling-head tests were conducted on each zone. To distinguish between methods, Table 1 defines the terminology for the purposes of this study.

Table 1. Slug testing terminology, methods, and description for this study.

Slug Test Name	Description	Displacement H_0
Rising or falling	Differential head between the zone and inside the casing. These data were collected for every zone when the pumping port for a given zone was initially opened.	Up to ~50 ft
Slug in or slug out	Solid-slug* testing was done when the zone had equilibrated after opening the pumping port and the rising or falling head test was completed.	About 1.5 ft

36 in long, 1.05 in OD (nominal 3/4 inch diameter PVC) filled with sand and tied to a nylon rope. Expected slug response (H_0) within the PVC casing is 1.5 ft.

Data Collection and Procedures

Depth to water was measured manually with an e-line. Water-level changes were measured by placing a pressure transducer (In-Situ Level TROLL, 100 psi) below the water level inside the PVC before a zone's pumping port was opened and allowing sufficient submergence for the anticipated change in head. The probe was inserted above a special wireline "open/close" tool that is employed to open and close pumping ports for rising- or falling-head tests (Figures 9 and 10).

After the rising or falling heads became static for the given zone, the slug tests were initiated using the same pressure transducers. In most instances, both the slug-in and slug-out data were recorded, but in some low-permeability zones the rising and falling head data were deemed sufficient as they did not reach static levels due to time constraints.

Figure 9. Picture of the pumping port and tool implemented for opening and closing. *Sleeve is in open position with the open-close tool in a position to close the sleeve.*

Figure 10. Picture showing opening of a pumping port. *The arms on the open/close tool are deployed such that the flat edges are facing upward so they catch the pumping port sleeve. A handle is attached to the cable and the tool is manually pulled until a sudden release of tension confirms the pumping port has slid open. The black cable going into the well is for the pressure transducer, which is submerged below the water table and measures the amount of change (rise or fall) that is induced by opening the port to a particular zone.*

Data Processing

All the data collected were plotted and reviewed before analyzing with AQTESOLV software. The program calculates hydraulic conductivity values by fitting solutions to graphical representations of deviation of head (ft) from static level with respect to time (elapsed time in seconds).

For the rising- and falling-head tests, processing must be done to the raw data. The important aspect is to determine the expected H_0 and add or subtract from the raw data (Table 2; Figure 11). H_0 can be estimated from the difference in head between tested zones, or simply use the measured total displacement if it reaches equilibrium. Some H_0 values were estimated when the preceding zones did not reach static or equilibrium conditions.

Raw data collected from the slug-in and slug-out testing were adjusted to clean up early-time noise, change of sign, and correct the elapsed time to account for when the displacement occurred (Table 3; Figure 12).

Table 2. Example data from Antioch Zone 4 falling-head test. *The measured difference in head between Zone 4 (zone being tested) and the static level in the PVC pipe (from the preceding zone) was 26.8 ft and this was added to each raw water-level change.*

Raw ET (sec)	Raw WL change (ft)	Corrected ET (sec)*	Corrected WL Change from static (H_0, in ft)*
130	0	0	26.79
130.5	-0.933	0.5	25.85
131	-0.445	1	26.342
131.5	-0.981	1.5	25.81
132	-2.034	2	24.75

*used in evaluation

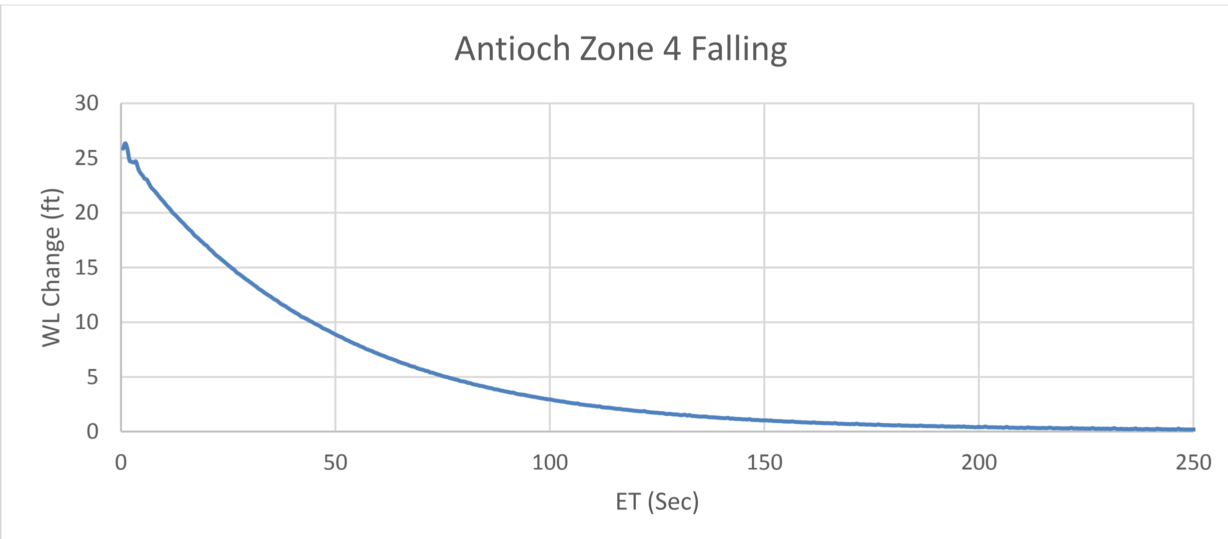

Figure 11. Example hydrograph of corrected falling-head test used in evaluations.

Table 3. Example data and corrections from Antioch Zone 4 slug-in test.

Raw ET (sec)	Raw WL	Corrected ET (sec)*	Change from static H_0, in ft)*
41.5	-2.12	0.5	2.12
42	-1.78	1	1.78
42.5	-1.97	1.5	1.97
43	-2.25	2	2.25

*used in evaluation

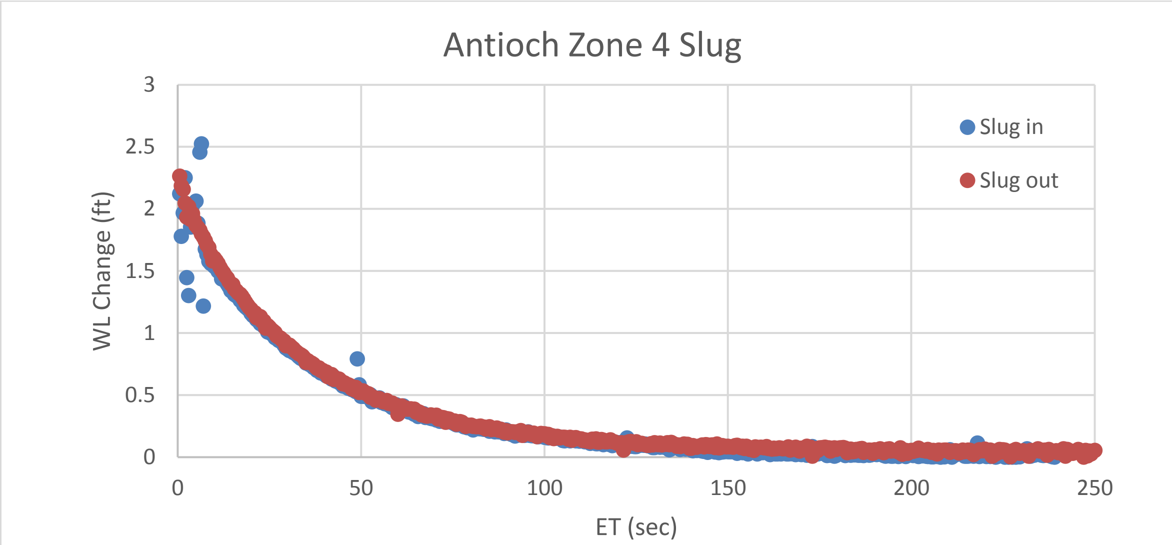

Figure 12. Example hydrograph of corrected slug-in and slug-out data used in evaluations.

Well and Aquifer Parameters

Despite the advanced level of karst conduit formation in some units and the large amount of faulting in the study area, it was assumed each hydrogeologic unit was relatively homogeneous and isotropic within the vicinity of the well. However, the hydraulic conductivity's anisotropy ratio (Kv/Kh) was assumed 0.1 for all zones, as typical of most sedimentary rocks. Tested zones were in either confined settings or in unconfined conditions with the screened intervals below the water table.

Analytical methods required the same parameters: initial displacement (total change of head), static water-column height, casing and well radius, depth to the top of well screen, and saturated thickness above the screened portion. Table 4 and Figure 13 define those input parameters for this study.

Table 4. Well parameters used in analytical solutions (AQTESOLV)

Parameter	Inches	Feet	Comment
Casing radius (rc)	0.75	0.06	
Equipment radius (req)	0.125	0.01	In-Situ Communication cable
Well borehole radius (rw)	2.6	0.22	Average value, varies 4.8-5.9
Length screen (L)	1.2	0.1	All zones are considered "partially penetrating"
Zone thickness (b)		19 to 197	Zone dependent
Depth to top well screen (de)		0.5 to 100	Zone dependent
Static water-column height (H)		76 to 896	Zone dependent

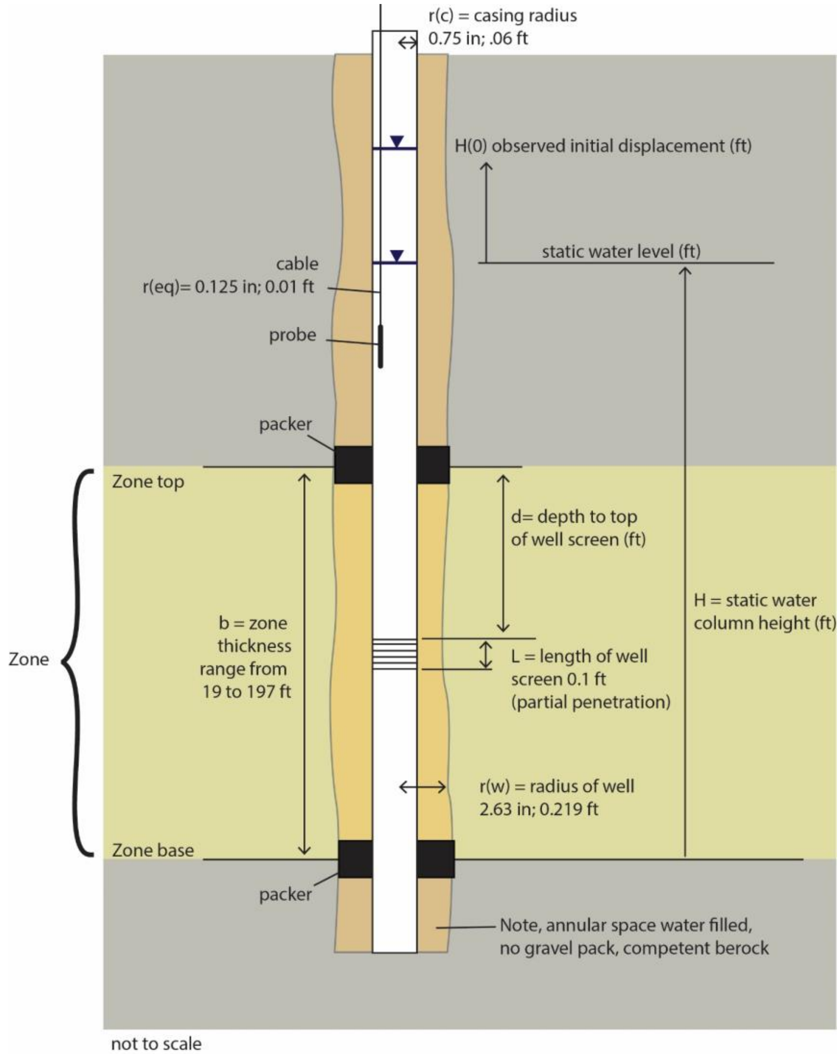

Figure 13. Multiport monitor well zone schematic and analytical solution input parameters.

Data Analyses

Data were analyzed using solutions in AQTESOLV Professional for Windows version 4.5 (Table 5). Data from slug tests can be classified as either overdamped or underdamped (Duffield, 2014). Overdamped slug tests occur in low to moderate hydraulic conductivity aquifers and exhibit the type of response shown in Figures 11 and 12. Underdamped slug tests occur in high conductivity aquifers and exhibit oscillatory behavior shown in Figures 14 and 15.

Analytical solutions for the overdamped responses fit both types of test methods (slug in-out and falling/rising). However, underdamped responses are only appropriate using data from the slug in-out method in most cases (Table 5). Rising and falling tests on the high permeability zones have large amounts of linear (i.e., non-Darcian) head loss due to the small well screen length (0.1 ft), and large displacement H_0. Thus, analytical solutions greatly underestimate permeability by at least one order of magnitude. The exception is the Antioch Zone 17 rising-head test that had a small initial displacement (H_0) of about 5 ft, which was similar in magnitude and results to the slug test.

Analytical models selected for the analyses are listed in Table 5 for the given response of the aquifer and data category (e.g. overdamped or underdamped). All methods can be used for confined or unconfined conditions and fully- or partially-penetrating wells.

For overdamped data, we selected the commonly-used Bouwer and Rice (1976) straight-line method. AQTESOLV provides suggested head ranges for the straight-line match (Butler, 1988). Results using other straight-line methods (e.g. Hvorslev, 1951) produced similar results. For overdamped data, we also selected the Hyder et al. (1994) type-curve method in AQTESOLV (also known as the Kansas Geological Survey or KGS model). For underdamped (oscillatory) data, we selected the Butler-Zhan (2004) type-curve method.

Assumptions for these solutions include:

- Aquifer has infinite areal extent;
- Aquifer is homogeneous and of uniform thickness;
- Aquifer potentiometric surface is initially horizontal;
- Change in water level is injected or discharged instantaneously; and
- Flow is steady.

Table 5. Data categories, slug methods, and analytical models

Data Category	**Slug Method**	**Analytical Models**	**Comment**
Overdamped (Figures 6 and 7)	Slug in and out; rising/falling	Bouwer-Rice (1976); Bouwer, 1989	Straight-line method. Similar results to Hvorslev model.
Overdamped	Slug in and out; rising/falling	KGS (Hyder et al., 1994)	Solution handles partial penetration (instead of Cooper-Bredehoeft-Papadopulos (1967) solution)
Underdamped (Figure 9)	Slug in and out only*	Butler-Zhan (2004)	Highly permeability zones (oscillatory), partially penetrating.

*The exception is Antioch Zone 17 which had a small H_0

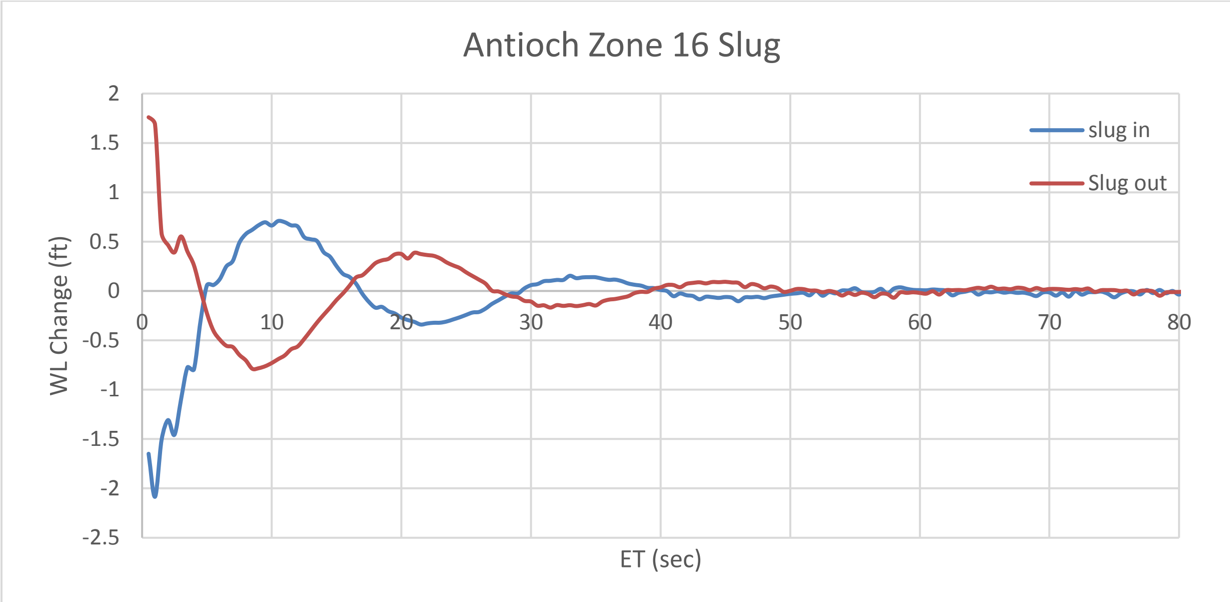

Figure 14. Example of underdamped (inertial) water-level response from a slug test in a highly permeable zone. The Butler-Zhan solution is best used to calculate hydraulic conductivity with small displacement data (H_0=1.5 ft) and inertial effects.

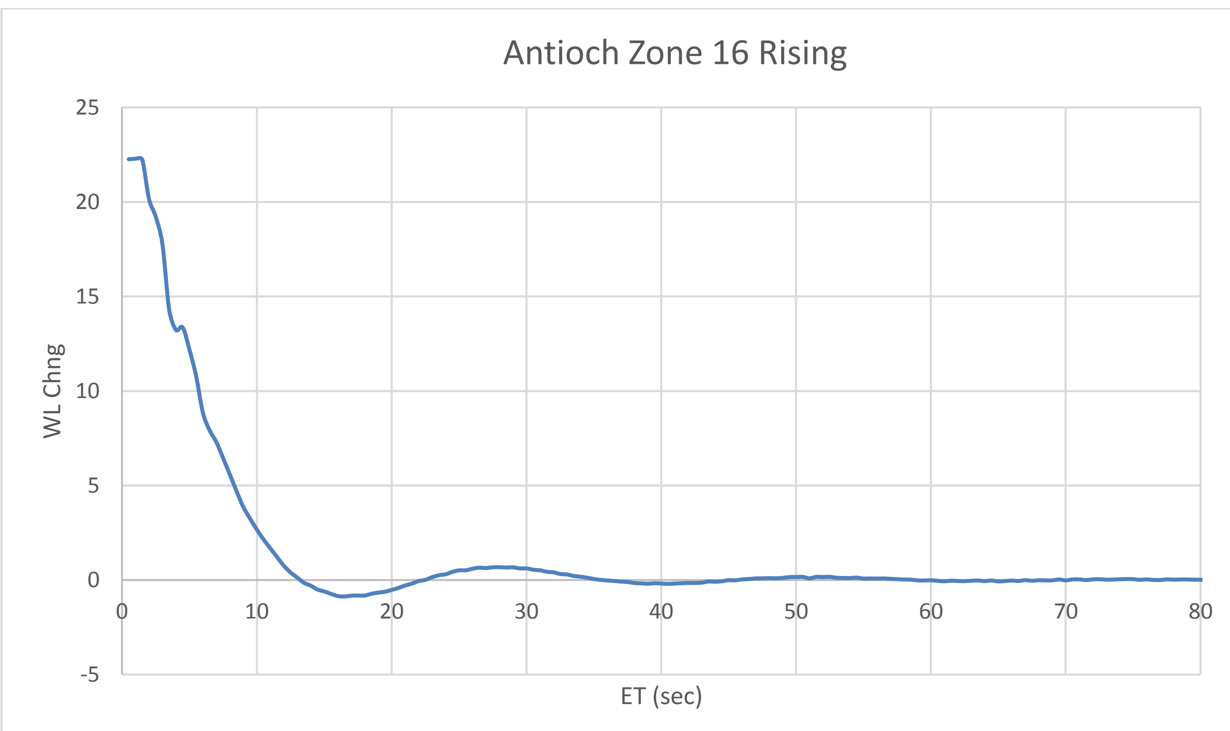

Figure 15. Example of underdamped (inertial) water-level response from the rising head test in a highly permeable zone. The large displacement (H_0=22 ft) with partial penetration (small screen length, L) creates large linear head loss and produces results that significantly underestimate K.

Errors Corrected from Previous Analyses

Initial analyses of these test data were published by Andrews et al. (2013) and Wierman et al. (2010). Although the relative permeability values from one zone to the next are generally consistent with this report, the absolute values were in error. The largest magnitude errors occurred in zones that are highly permeable. Previous analyses underestimated those zones by up to three orders of magnitude. A list of sources for all errors in those initial analyses include:

- Input well parameters (L, R_c) were too large and resulted in much lower permeability results for underdamped zones;
- Analytical solutions originally selected did not account for partial penetration;
- Inclusion of results calculated from falling/rising head tests for underdamped zones. In general, these data should not be used for permeability estimates for underdamped zones;
- Data corrections forced data to recover to zero (incorrect H_0) in both rising and falling tests. Recovery was, in fact, incomplete and thus resulted in an overestimate of permeability. This occurred only with very low permeability zones, but to only modest effect.

RESULTS

Results of hydraulic conductivity testing are presented in Tables 6 and Figure 16 for the Ruby Ranch well, and Table 7 and Figure 17 for the Antioch well. Figures 18 and 19 present the average hydraulic conductivity values in the context of the lithostratigraphy, heads, and geochemistry. Figure 20 is a whisker plot of the hydraulic conductivities by lithostratigraphic unit. Figure 21 is a comparison of these overall values with published ranges of values. Table 8 is a summary table of the results.

Table 6. Data collected from the Ruby Ranch multiport well.

Zone				Falling/Rising Tests		Slug In-Out Tests			Statistics		
Zone	**Geologic Unit**	**Pumping Port Depth (ft)**	**b, zone thickness (ft)**	**Bouwer-Rice K (ft/d)**	**KGS (ft/d)**	**Bouwer-Rice K (ft/d)**	**KGS (ft/d)**	**Butler-Zhan K (ft/d)**	**Min. (ft/d)**	**Max. (ft/d)**	**Avg. or select (ft/d)**
14	Edwards	n/a	136.00	*nd*	*nd*	*nd*	*nd*		nd	nd	nd
13	Edwards	189.27	72.00	*NA*	*NA*	*NA*	*NA*	1,711	NA	NA	1,711
12	Edwards-Basal Nodular	224.36	34.00	0.4	0.9	0.4	0.7		0.4	0.9	0.6
11	Upper Glen Rose A	336.38	159.00	*NA*	*NA*	*NA*	*NA*	3,382	NA	NA	3,382
10	Upper Glen Rose B	513.41	197.00	0.9	2.1	1.1	1.5		0.9	1.5	1.4
9	Upper Glen Rose C	648.02	97.00	0.02	0.06	*NA*	*NA*		0.02	0.06	0.04
8	Lower Glen Rose A	738.18	56.00	2.5	4.7	1.3	0.7		0.7	4.7	2.3
7	Lower Glen Rose B	796.89	68.00	*NA*	*NA*	*NA*	*NA*	1,334	NA	NA	1,334
6	Lower Glen Rose C	867.64	72.00	1.5	2.1	5.2	7.4		1.5	7.4	4.1
5	Lower Glen Rose D	937.76	77.00	*nd*	*nd*	0.7	1.7		0.7	1.7	1.2
4	Hensel	1002.77	26.00	37.9	85.2	82.7	135.7		37.9	135.7	85.4
3	Cow Creek	1032.43	27.00	NA		NA		207	NA	NA	207
2	Cow Creek	1057.53	19.00	NA		NA		968	NA	NA	968
1	Hammett Shale	1084.34	41.00	*nd*	*nd*	*nd*	*nd*	*nd*	nd	nd	nd

NA- data not applicable for given analytical solution; nd= no data available

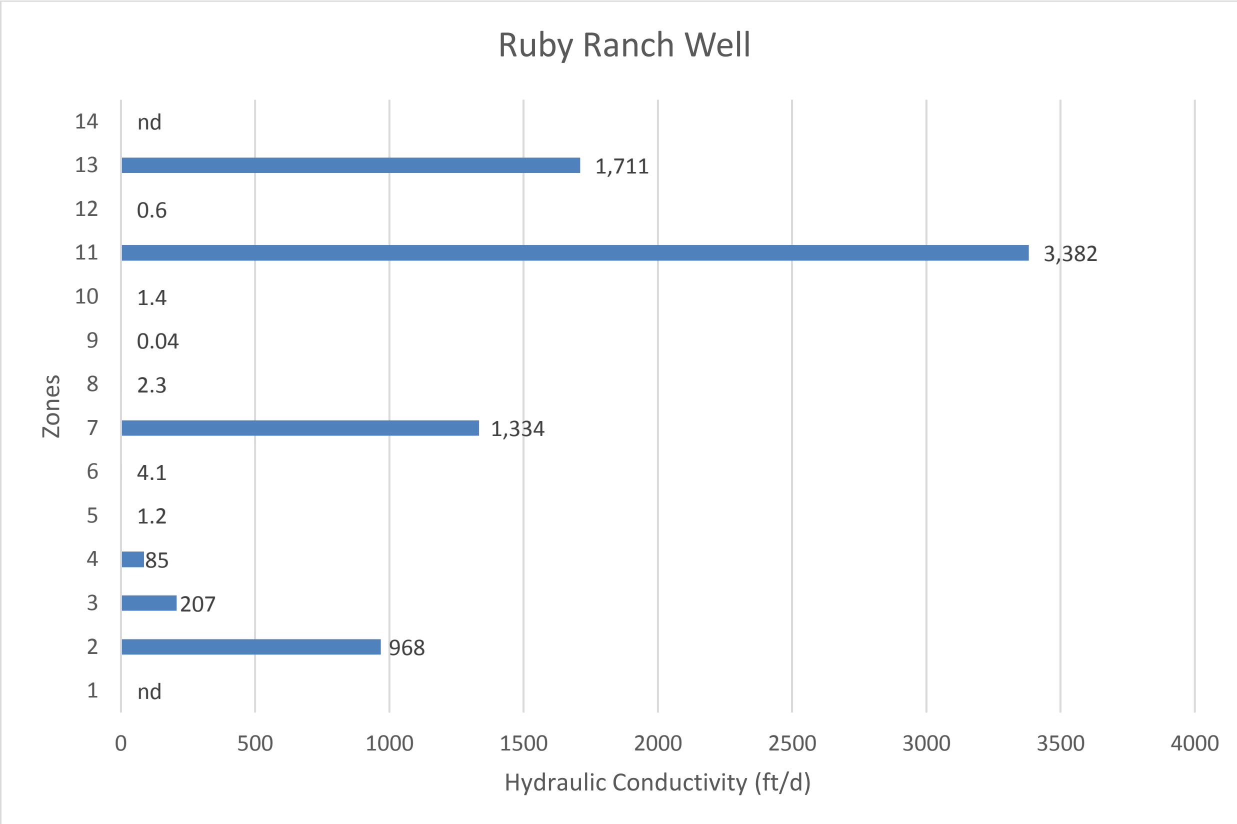

Figure 16. Hydraulic conductivity data for each zone from the Ruby Ranch multiport tests.

Table 7. Hydraulic conductivity values of the different zones in the Antioch multiport well.

Zone				Falling/Rising Tests			Slug In-Out Tests			Statistics		
Zone	Geologic Unit	Pumping Port Depth (ft)	b, zone thickness (ft)	Bouwer-Rice K (ft/d)	KGS (ft/d)	Butler-Zhan (ft/d)	Bouwer-Rice K (ft/d)	KGS (ft/d)	Butler-Zhan (ft/d)	Min. (ft/d)	Max. (ft/d)	Avg. or select (ft/d)
21	Georgetown Formation	170.5	35	0.1	0.2	NA	nd	nd	nd	0.1	0.2	0.1
20	Person Formation A	245.5	70	NA	NA	NA	NA	NA	3317 and 3035	3,035	3,317	3,176
19	Person Formation B	280.5	30	12.5	21.2	NA	19.4	36.4	NA	12.5	40.3	22.4
18	Kainer Formation A	310.5	25	1.8	5.8	NA	8.5	46.7	NA	1.8	46.7	15.7
17	Kainer Formation B	420.5	105	NA	NA	3,177	NA	NA	2533	2,533	3,177	2,855
16	Kainer Formation C	495.5	70	NA	NA	NA	NA	NA	813.7 and 1025	814	1,025	920
15	Kainer Formation D	575.5	75	NA	NA	NA	NA	NA	907	--	--	907
14	Basal Nodular/Walnut Fm	625.5	45	15.5	35.1	NA	12.1	45.7	NA	12.1	45.7	27.1
13	Upper Glen Rose A	670.5	40	14.0	35.1	NA	13.2	31.9	NA	13.2	35.1	23.6
12	Upper Glen Rose B	760.5	85	7.8	20.7	NA	nd	nd	nd	7.8	20.7	14.3
11	Upper Glen Rose C	855.5	90	0.1	0.3	NA	nd	nd	nd	0.10	0.3	0.2
10	Upper Glen Rose D	960.5	100	0.02	0.06	NA	nd	nd	nd	0.02	0.06	0.04
9	Upper Glen Rose E	995.5	30	0.001	0.005	NA	0.03	0.005	NA	0.001	0.02	0.01
8	Upper Glen Rose F	1030.5	30	0.04	0.007	NA	nd	nd	nd	0.01	0.04	0.02
7	Lower Glen Rose A	1105.5	70	0.9	1.1	NA	nd	nd	nd	0.9	1.1	1.0
6	Lower Glen Rose B	1180.5	70	0.1	0.2	NA	3.0	2.8	NA	0.1	3.0	1.5
5	Lower Glen Rose C	1225.5	40	0.2	0.5	NA	0.2	0.4	NA	0.2	0.5	0.3
4	Lower Glen Rose D	1260.5	30	15.5	28	NA	19	37.5	NA	15.5	37.5	25.0
3	Hensel A	1295.5	30	0.1	0.1	NA	2.3	2.7	NA	0.1	2.7	1.3
2	Hensel B	1325.5	25	2.3	6.2	NA	1.8	4.5	NA	1.8	6.2	3.7
1	Cow Creek	1385	54.5	NA	NA	NA	na		853	--	--	853

NA- data not applicable for given analytical solution; nd= no data available

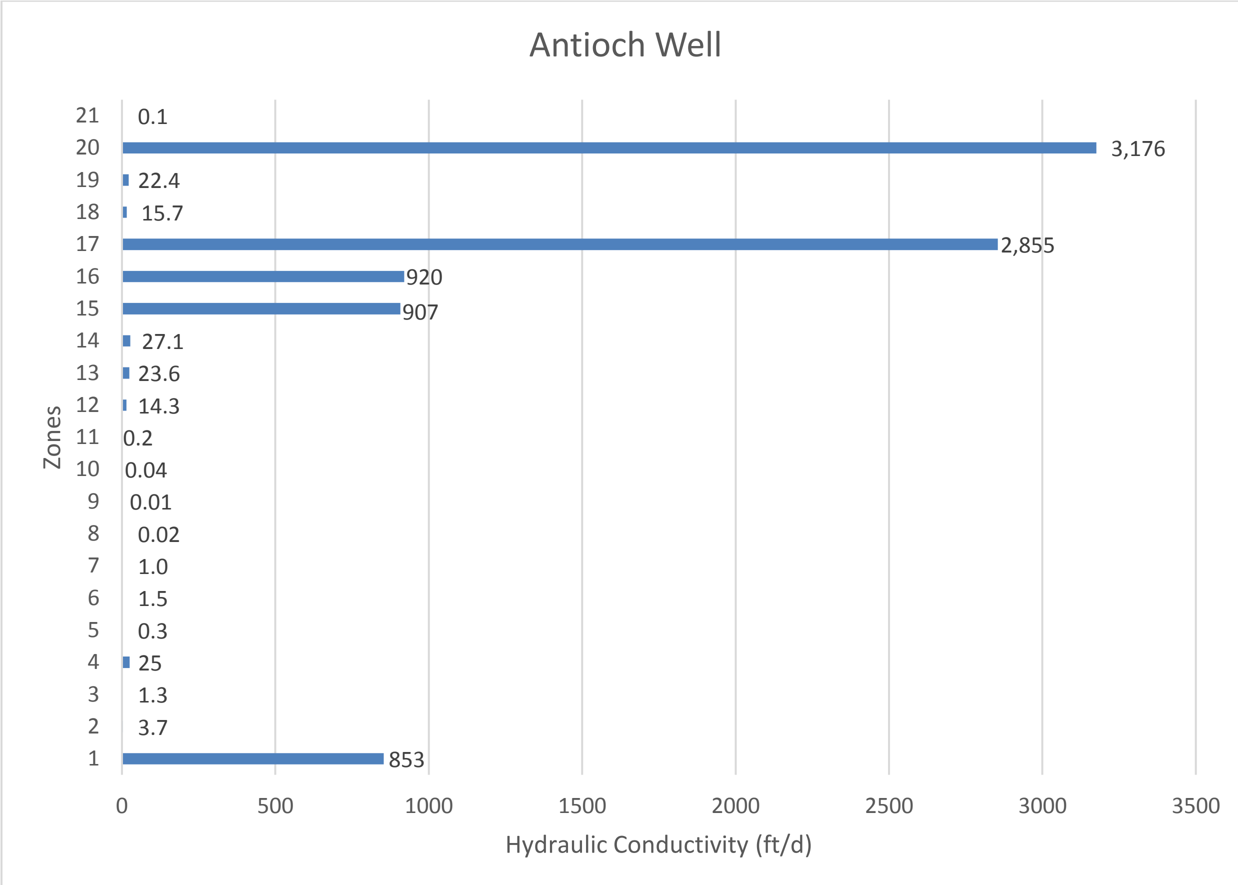

Figure 17. Hydraulic conductivity data for each zone from the Antioch multiport tests.

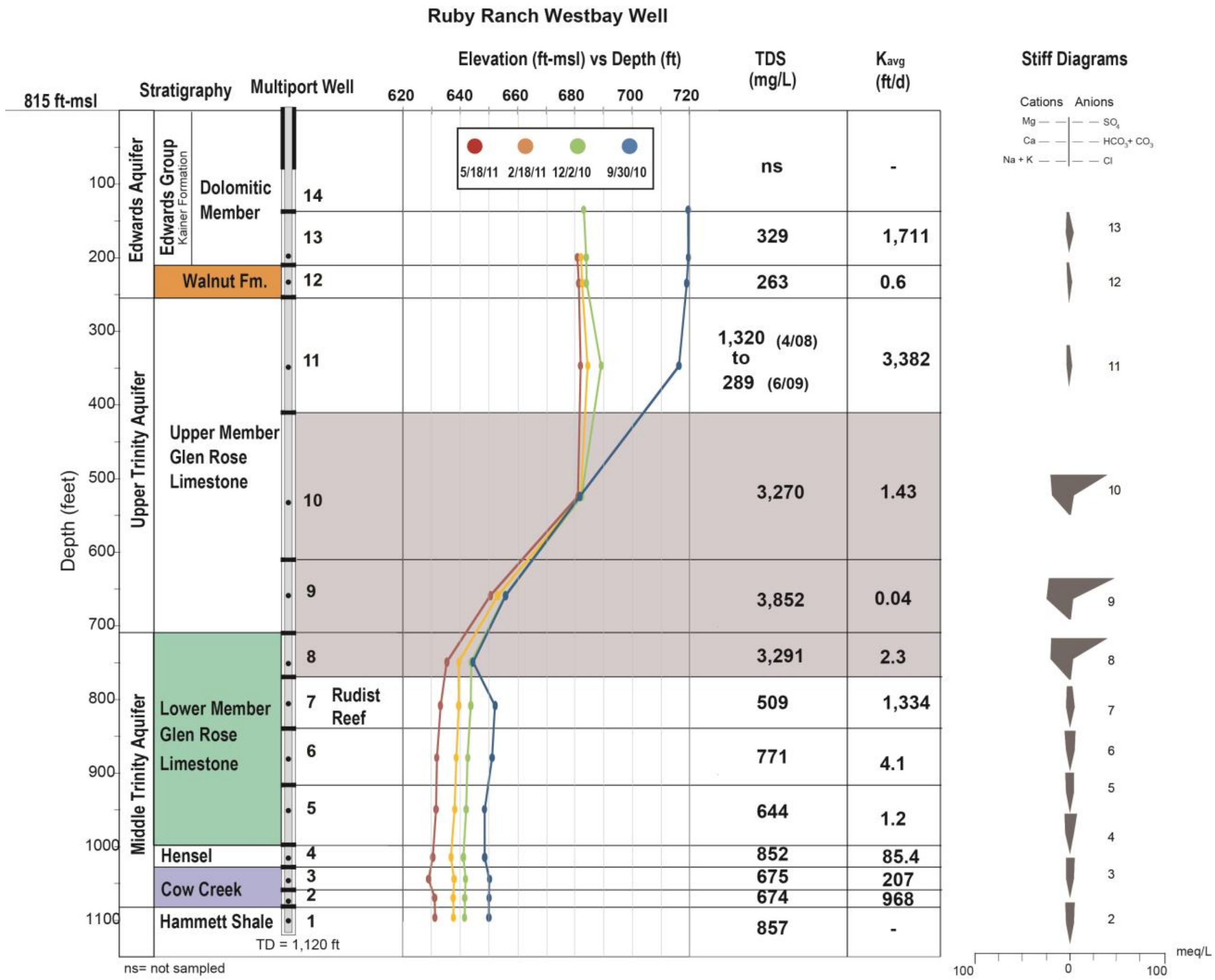

Figure 18. Summary diagram and data from the Ruby Ranch multiport well.

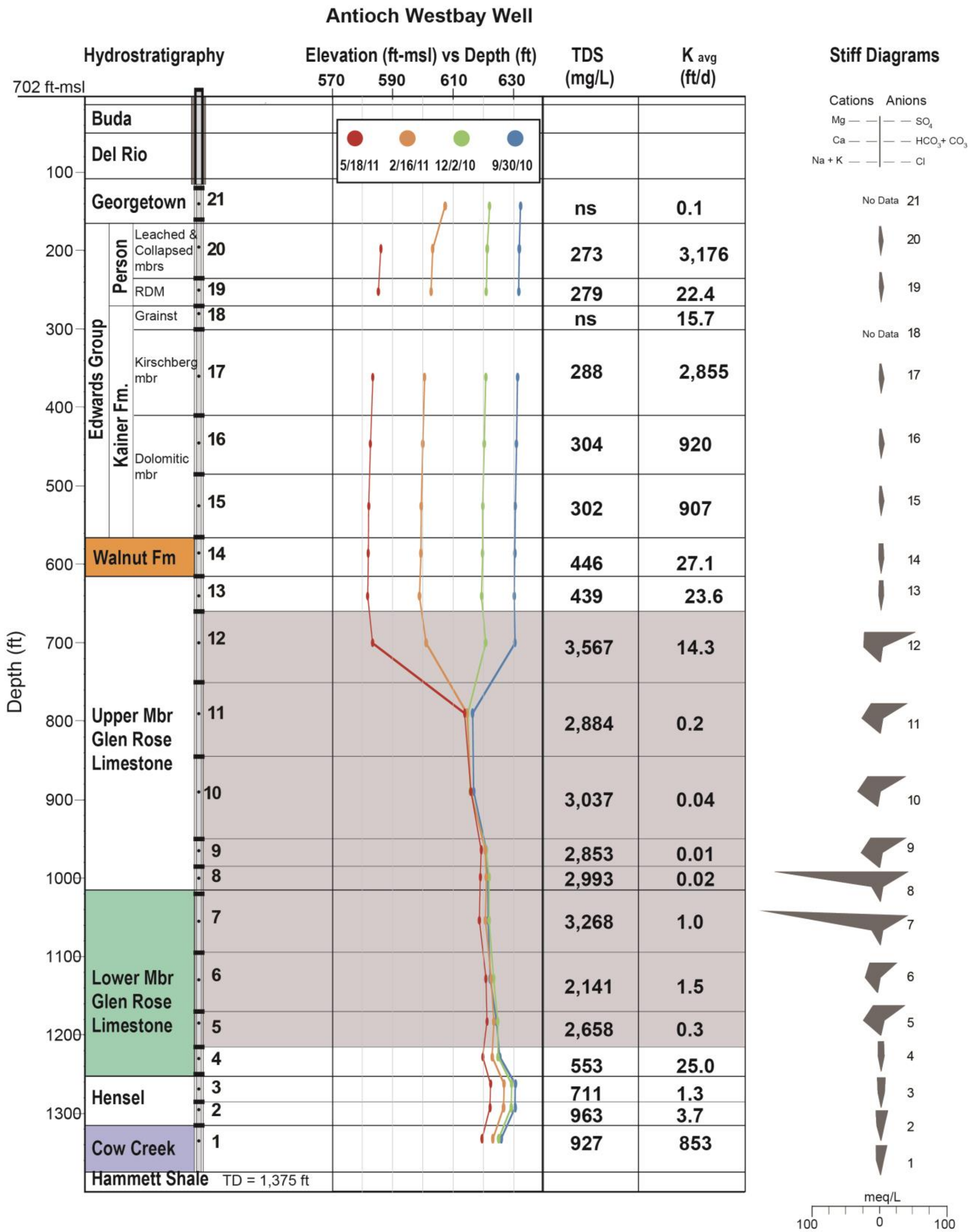

Figure 19. Summary diagram and data from the Antioch multiport well.

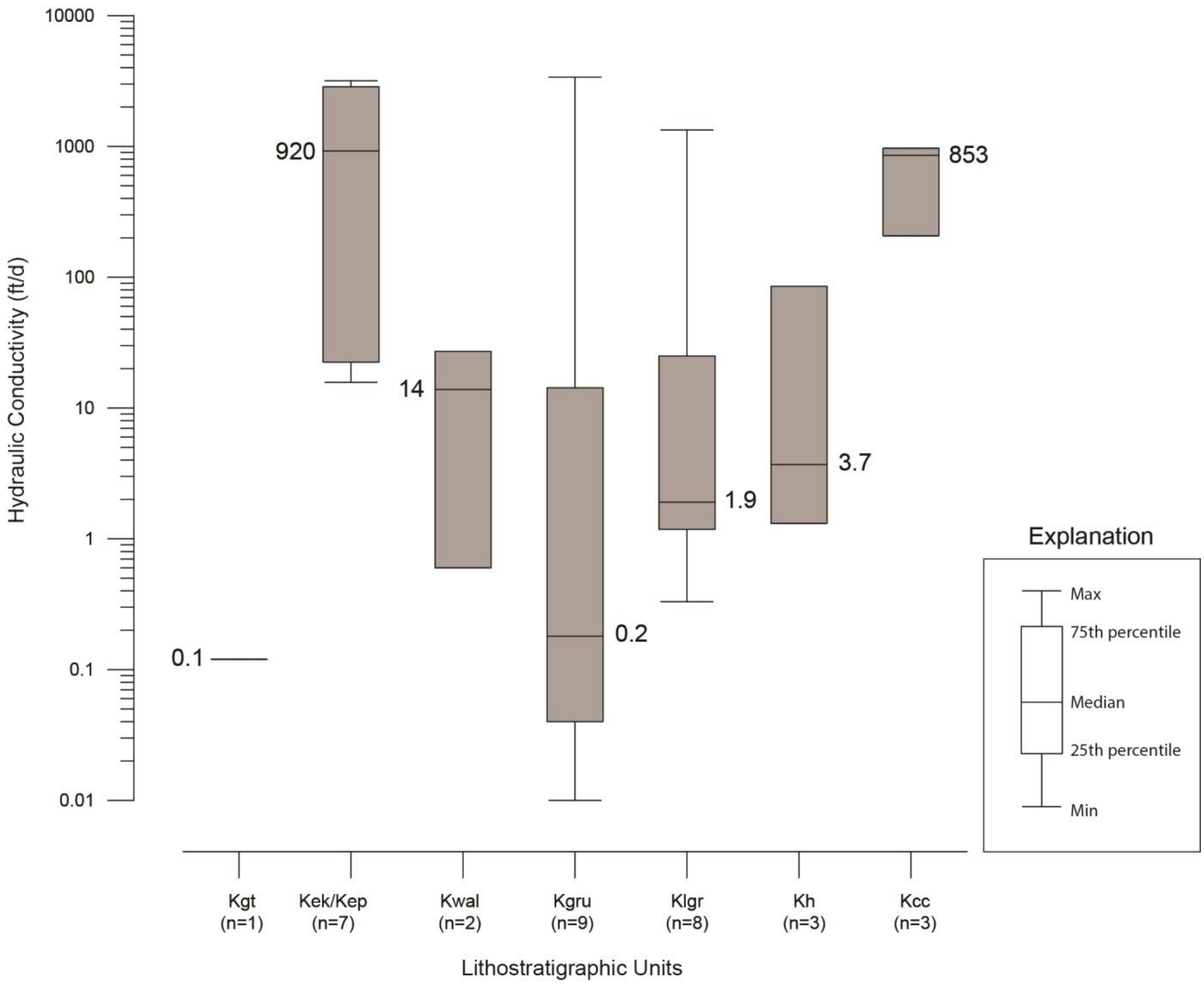

Figure 20. Whisker plot of hydraulic conductivity from all zones by lithostratigraphic unit. Median value indicated for each zone. *Kgt= Georgetown Fm., Kek/Kep= Person and Kainer Formations of the Edwards Group, Kwal= Walnut Fm., Kgru= Upper Glen Rose Fm., Kgrl= Lower Glen Rose Fm., Kh= Hensel Mbr, Kcc= Cow Creek Mbr.*

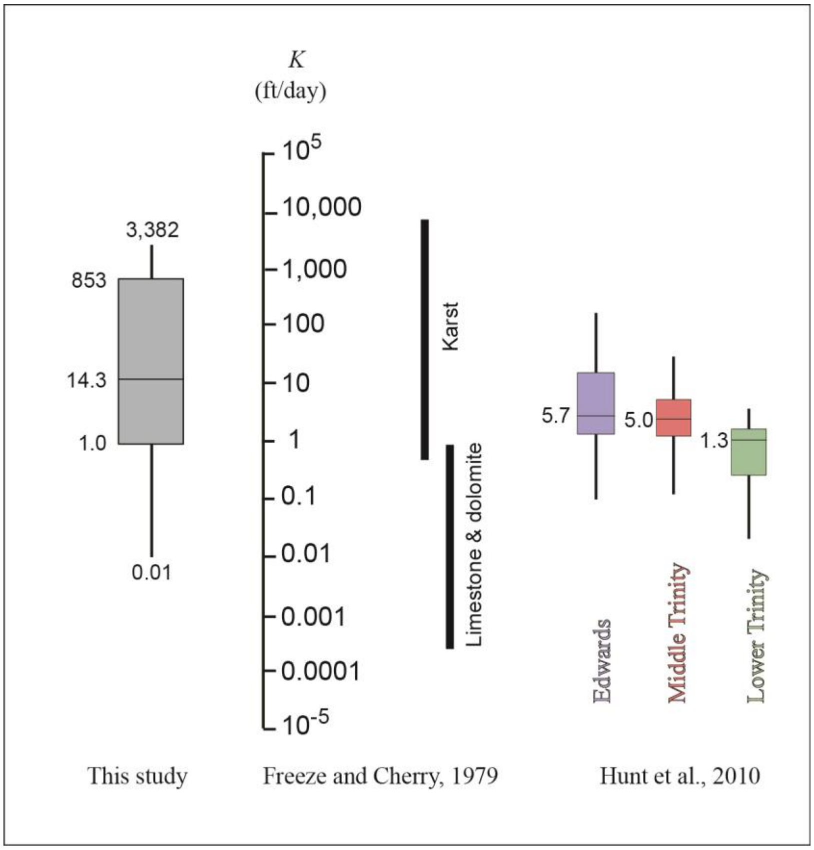

Figure 21. Comparison of hydraulic conductivity ranges from this study (all zones) to other published sources. *Note the median slug test value for this study is greater than the compilation of aquifer tests in Hunt et al. (2010).*

Table 8. Summary of results from zones and hydrostratigraphy.

Hydrogeologic Group	Thickness (ft)	Lithostratigraphy	Multiport Zones	Range of K (ft/d)	Avg. TDS (mg/L)
Edwards Aquifer	495 (Antioch) 265 (Ruby)	Georgetown Fm, Edwards Group, Upper Glen Rose	Antioch Zones 21-13 Ruby Zones 12-14	0.2 to 3,382 (1,087 avg)	313
Upper Trinity Aquitard	515 (Antioch) 350 (Ruby)	Upper and Lower Glen Rose	Antioch Zones 12-5 Ruby Zones 8-10	0.02 to 2.3* (0.7 avg)	3,200
Middle Trinity	140 (Antioch) 289 (Ruby)	Lower Glen Rose, Hensel, Cow Creek	Antioch Zones 4-1 Ruby Zones 2-7	1.2 to 1,334 (348 avg)	750

**Omits upper value from Zone 12 because it is likely transitional.*

DISCUSSION

This is one of the first detailed studies of hydraulic conductivity of various units within the Edwards and Trinity Aquifers in central Texas. Hydraulic conductivity data presented in this study allow the comparison of permeability, lithologic, chemical, and head data for a better characterization of the hydrostratigraphy of the aquifer units (Figures 18 and 19; Table 8).

These results are order-of-magnitude estimates and may not be directly comparable to other studies derived from aquifer tests. However, the range of results of this study (Figure 21) appear comparable to other published studies (Hunt et al., 2010) with the median values of the slug tests slightly higher than those in Figure 21. This is in contrast to studies that have demonstrated hydraulic conductivity measured through slug testing is generally smaller than values obtained through aquifer tests. Aquifer tests involve testing a larger formation volume, while slug tests involve testing a much smaller volume of formation material. Butler and Healey (1998) attribute differences between aquifer and slug tests to involve incomplete well development, aquifer thickness, and vertical anisotropy.

However, the relative values for each of the zones in this study are directly comparable and therefore offer some valuable insight into the relative permeabilities of these stacked aquifer units. Below is a discussion of the results from each well by major hydrogeologic unit.

Antioch Well: Edwards Aquifer

The Antioch well has the full section of the Edwards Aquifer, and some of the confining units of the aquifer present (Figure 19). The top-most zone in the Antioch well is completed within the Georgetown Formation. The conductivity value of 0.1 ft/d is over 5 orders of magnitude smaller than the directly-underlying zone of the Edwards Group and is similar to the results of Land et al. (1988). This appears to validate the classification of this formation as a confining unit by authors such as Small et al. (1996). However, it should be noted that this unit is only locally confining, as many karst features are developed through the Georgetown, especially when fractured, and extending into the Edwards formations. Antioch Cave in Onion Creek (0.3 mi west of the multiport well) is an exceptional example of a fracture-controlled shaft cave in the Georgetown Formation and is the single largest recharge feature in the study area. The relatively low matrix permeability may influence the vertical nature, versus horizontal development, of the cavernous porosity.

Hydraulic conductivities measured in zones of the Edwards Group, Zones 20 to 14 of the Antioch well, are relatively high compared to other zones, and range in value from 16 to 3,176 ft/d. The total dissolved solids (TDS) values of these zones are low and range between 273 to 446 mg/L, indicating fresh water, good circulation, and short residence time in the aquifer. Antioch Zone 20, the Leached and Collapsed Member of the Person Formation of the Edwards Group, exhibits the highest conductivity (3,176 ft/d) and the lowest TDS value (273 mg/L) of all the zones in the Edwards. This zone is likely the most hydraulically connected to Antioch Cave (see Appendix--Antioch Cave Injection Test). Fracturing in this zone contributes to its high conductivity (Figure 4). The Regional Dense Member (Zone 19) of the Person Formation and the Grainstone Member (Zone 18) of the Kainer Formation exhibit the lowest hydraulic conductivities of the members that make up the Edwards Aquifer with values of 16 ft/d and 22 ft/d, respectively. Similarly, the Walnut Formation (Zone 14; also called the Basal Nodular Member of the Kainer Formation) has relatively low hydraulic conductivity at 27 ft/d. Heads and geochemistry suggest that neither of these relatively low hydraulic conductivity zones or units behaves as an aquitard in the vicinity of the well. In addition, response to recharge in Antioch

Cave within all the Edwards units may suggest that the Edwards units are hydrologically linked at a scale larger than that evaluated by slug testing (see Appendix--Antioch Cave Injection Test**)**.

Stiff diagrams of the Edwards sections in the Antioch well exhibit calcium bicarbonate water chemistry and suggest dissolution of limestone and dolomite (Figure 19). Zones with water chemistries of this type extend from Zones 20 to 13. The Stiff plot for Zone 13 (Upper Glen Rose) is similar to those of the overlying Edwards zones. In addition, high hydraulic conductivity of 24 ft/d and a TDS value of 439 mg/L are more similar to the Edwards rather than the underlying Upper Glen Rose zones. These data, along with head data, suggest that the upper-most portion of the Upper Glen Rose (Zone 13) is in hydrologic communication with the Edwards in the vicinity of the well.

Antioch Well: Glen Rose Aquitard

Zones 12 through 8, completed in the Upper Glen Rose, exhibit a decrease in hydraulic conductivity, an increase in TDS, and a different shape of the Stiff diagram from those in the overlying Edwards Aquifer. Heads and relatively high permeability (14.3 ft/d) in Zone 12 suggest partial communication with the overlying zones, but geochemically it is more similar to the underlying zones.

Hydraulic conductivity values in Zones 11 through 8 range from 0.2 to 0.01 ft/d and are smaller by up to five orders of magnitude from the overlying Edwards. TDS values obtained from these zones range between 2,853 mg/L (Zone 9) to 3,567 mg/L (Zone 12). The high TDS values correlate with the low hydraulic conductivities and suggest that water flows more slowly in these zones than in the overlying Edwards Aquifer. Stiff plots show that Mg++, Ca++, and SO_4= are the major ions in Zones 12 to 9, indicating gypsum dissolution (Figure 19). Zone 8 and the underlying Zone 7, completed in the Lower Glen Rose, exhibit Stiff diagrams with a spike in Mg++ relative to the other ions. These may correlate with the "chicken wire" texture of anhydrite or gypsum nodules visible in downhole camera imagery (Figure 4). Zones 7 through 5 are completed in the Lower Glen Rose and exhibit properties similar to the overlying Upper Trinity units, with low hydraulic conductivities (0.3 to 1.5 ft/d) and high TDS (3,268 to 2,141 mg/L). The Stiff diagrams for Zones 6 and 5 resemble those for Zones 12 through 9 where Ca++ and SO4= are dominant and Mg++ makes an important contribution.

Zones 11 through 5, and especially Zones 10 through 8, have low permeability and high TDS. Those data and heads suggest these zones are an aquitard between the overlying Edwards Aquifer and the underlying Middle Trinity Aquifer in the vicinity of the well.

Antioch Well: Middle Trinity Aquifer

Zones 4 through 1 have higher permeability and lower TDS compared to the overlying Trinity zones. TDS values in these zones range from 553 mg/L (Zone 4) up to 963 mg/L (Zone 2). Zone 4 has a hydraulic conductivity of 25 ft/d, more than two orders of magnitude higher than the overlying Zones 5 through 12. Zone 4 is completed in the lowermost units of the Lower Member of the Glen Rose Limestone, and the geophysical log and hydrologic parameters suggest that the zone is comprised of a permeable reef interval seen in other studies (Wierman et al., 2010). Zones 3 and 2 (Hensel) exhibit modest hydraulic conductivities of 1.3 to 4.7 ft/d. Zone 1 is completed in the Cow Creek Limestone and has the highest hydraulic conductivity of any of the zones in the Middle Trinity Aquifer at 853 ft/d. The Cow Creek zone contains fresh water (927 mg/L) and a similar Stiff diagram to the overlying zones with contributions from Mg++, Ca++, HCO3-, and SO4=.

Ruby Ranch: Edwards Aquifer

The Edwards Aquifer is relatively thin in the Ruby Ranch well, with only the lower 250 ft of Edwards units present (Figure 18). Zones 13 and 12 are completed in the Dolomitic Member of the Kainer Formation and the Walnut Formation (Basal Nodular equivalent) of the Edwards Group, and exhibit low TDS of 329 mg/L and 263 mg/L, respectively. Zone 13 has a permeability of 1,711 ft/d while the Walnut Formation has a relatively low permeability of 0.6 ft/d. The Stiff plots for these two zones indicate limestone and dolomite dissolution, with the major ions being Ca++ and HCO_3-.

Fewer zones were designed for testing in the Upper Trinity section of the Ruby Ranch well than in the Antioch Well, thus they are thicker zones. But, despite the lower resolution, the results obtained are similar to the Antioch Well. The top-most units of the Upper Glen Rose (Zone 11) contain similar chemical signatures and heads as in the overlying Edwards Group (Figure 18). Zone 11 has a very high hydraulic conductivity of 3,382 ft/d suggesting cavernous permeability and porosity similar to the Edwards zones. TDS values range between 289 mg/L and 1,320 mg/L. The two TDS values for this zone were taken at different times and indicate that zone 11 is likely partly in communication with the underlying zones, similar to Zone 12 in the Antioch well containing elevated TDS, depending on recharge (head) conditions.

Ruby Ranch: Glen Rose Aquitard

Zones 10 through 8 are completed in the Upper Glen Rose (Figure 18). These zones have hydraulic conductivities of 0.04 ft/d to 2.3 ft/d, four orders of magnitude lower than zone 11 above. The water quality in these zones is poor, ranging from 3,270 mg/L (Zone 10) to 3,852 mg/L (Zone 9). The Stiff diagrams for these zones exhibit characteristic gypsum and dolomite dissolution showing spikes in SO4= and a large contributions from Ca++ and Mg++.

Zones 10 through 8 have low permeability and high TDS. These data and the heads suggest these zones are an aquitard between the overlying Edwards Aquifer and the underlying Middle Trinity Aquifer in the vicinity of the well. The zones comprising the aquitard are thinner than in the Antioch well.

Ruby Ranch: Middle Trinity Aquifer

The freshwater zones comprising the Middle Trinity Aquifer are thicker in the Ruby Ranch well compared to the Antioch well. Heads and geochemistry suggest the aquifer is composed of Zones 1 through 7 (Figure 18).

The uppermost units of the Lower Glen Rose (Ruby Zone 7) have a value of hydraulic conductivity of 1,334 ft/d. This zone corresponds to a distinct reef unit in the Lower Glen Rose. The TDS values in the Middle Trinity Aquifer in the Ruby Ranch well are also lower than those in the Upper Trinity, ranging from 509 mg/L in Zone 7 to 852 mg/L in Zone 4. Lower Glen Rose Zones 6 and 5 have hydraulic conductivities of 4.1 ft/d and 1.2 ft/d, respectively. Hydraulic conductivities in the Hensel in the Ruby Ranch well are an order of magnitude larger than in the Antioch well. The Cow Creek Limestone, corresponding to Zones 3 and 2, exhibits very high hydraulic conductivities between 207 ft/d and 968 ft/d. Stiff diagrams here show Mg++, Ca++, and HCO_3- as the major (Figure 11).

Qualitative vs Quantitative Hydrostratigraphy

The data in this study indicate that the qualitative values for hydraulic conductivity assigned to the informal hydrostratigraphic subdivisions by the USGS (Small et al., 1996; Clark, 2004; Figure 2) generally correlate with the values directly measured in this study, in some zones. However, zones in the Edwards and Upper Glen Rose in the Ruby Ranch well do not appear to correlate to the equivalent hydrostratigraphic subdivisions described in the literature. This suggests that there is a high degree of heterogeneity within these aquifers and that quantitative or qualitative permeability data alone do not adequately characterize these units. Therefore, qualitative hydrostratigraphic delineations relating to lithostratigraphy (Small et al., 1996; Clark, 2004) may be of limited value. This report demonstrates the need for multiple types of data, such as lithology, geochemistry, heads, and permeability, to adequately characterize hydrostratigraphy and groundwater resources.

CONCLUSIONS

This study resulted in a detailed characterization of hydraulic conductivity of various units within and between the Edwards and Trinity Aquifers in this part of central Texas. This study, combined with other data, demonstrates that the lithostratigraphic units do not necessarily correspond to hydrostratigraphic units and that permeabilities can be very heterogeneous within aquifer units.

Three groups of hydrostratigraphic units with distinct permeabilities, heads, and geochemistry are summarized in Table 8. Two well-defined aquifers, the Edwards Aquifer and the Middle Trinity Aquifer, are separated by the aquitard units of the Upper Glen Rose Formation (and portions of the Lower Glen Rose in the Antioch well). The Upper Trinity Aquifer (Upper Glen Rose Formation) is best characterized as having two distinct hydrogeologic and hydrostratigraphic characteristics within the Balcones Fault Zone. The upper-most portion of the Upper Trinity Aquifer (up to about 150 ft) is in hydrologic communication with the Edwards Aquifer, and should be considered part of the Edwards Aquifer in the study area. The lower portion is best characterized as an aquitard. The aquitard has up to three orders of magnitude smaller hydraulic conductivity and 5 to 10 times higher TDS than the overlying and underlying aquifers. The Upper Trinity aquitard prevents any significant vertical interaction between the Edwards and Middle Trinity Aquifers in the study area.

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Appendix: Antioch Cave Valve Test and Response at Antioch Multiport Well

To test the hydrologic connection between Antioch Cave and the Edwards zones in the Antioch multiport well, District staff conducted an injection test on May 18, 2012 (Figure A-1). Materials for the multiport monitor well were provided by Westbay Instruments of Vancouver, Canada. This was a preliminary investigation and only the top six zones were monitored for a short period of time (5.4 hrs).

Streamflow changes in Onion Creek due to the closing and opening of the valve at Antioch were measured at the LCRA's gage at FM 967. The gage height corresponds to changes in flow and therefore provides an estimate of recharge (or injection) into the aquifer (Figure A-2). Levels were measured in six zones of the Edwards before the valve, that allows recharge into Antioch Cave, was closed. Water levels were measured again after the valve was closed for 5.4 hrs (Figure A-3). Tabular results from select multiport zones are provided in Table A-1.

The data collected for this test were used to estimate the hydraulic conductivity of the formation between the vault (injection or recharge point) and zones within the Edwards Aquifer. Figure A-3 hydrograph shows that there was indeed a response in the Edwards zones from the closure of the Antioch Cave valve resulting in recharge decreasing from 46 cfs to zero. Throughout the test, Zone 20 in the Edwards had the highest head values. The response to the valve testing generated a similar response in all six zones, with about 1.1 to 1.6 ft of decline.

For this analysis, the reduction of recharge of 46 cfs at Antioch and the response of water levels in the multiport well are interpreted to be similar to an aquifer test. We used AQTESOLV to estimate the hydraulic conductivity of the zones in the Edwards (Figure A-4). Average hydraulic conductivity from the best fit of all the zones is about 2,200 ft/d.

These data and results are a preliminary evaluation using limited data, so it should not be considered a conclusive result. But it does reasonably agree with estimates based on slug tests of the relevant zones within the multiport well. This test confirms the hydraulic connection from Antioch Cave to the multiport well. Future studies will need to collect data more frequently and for longer periods of time.

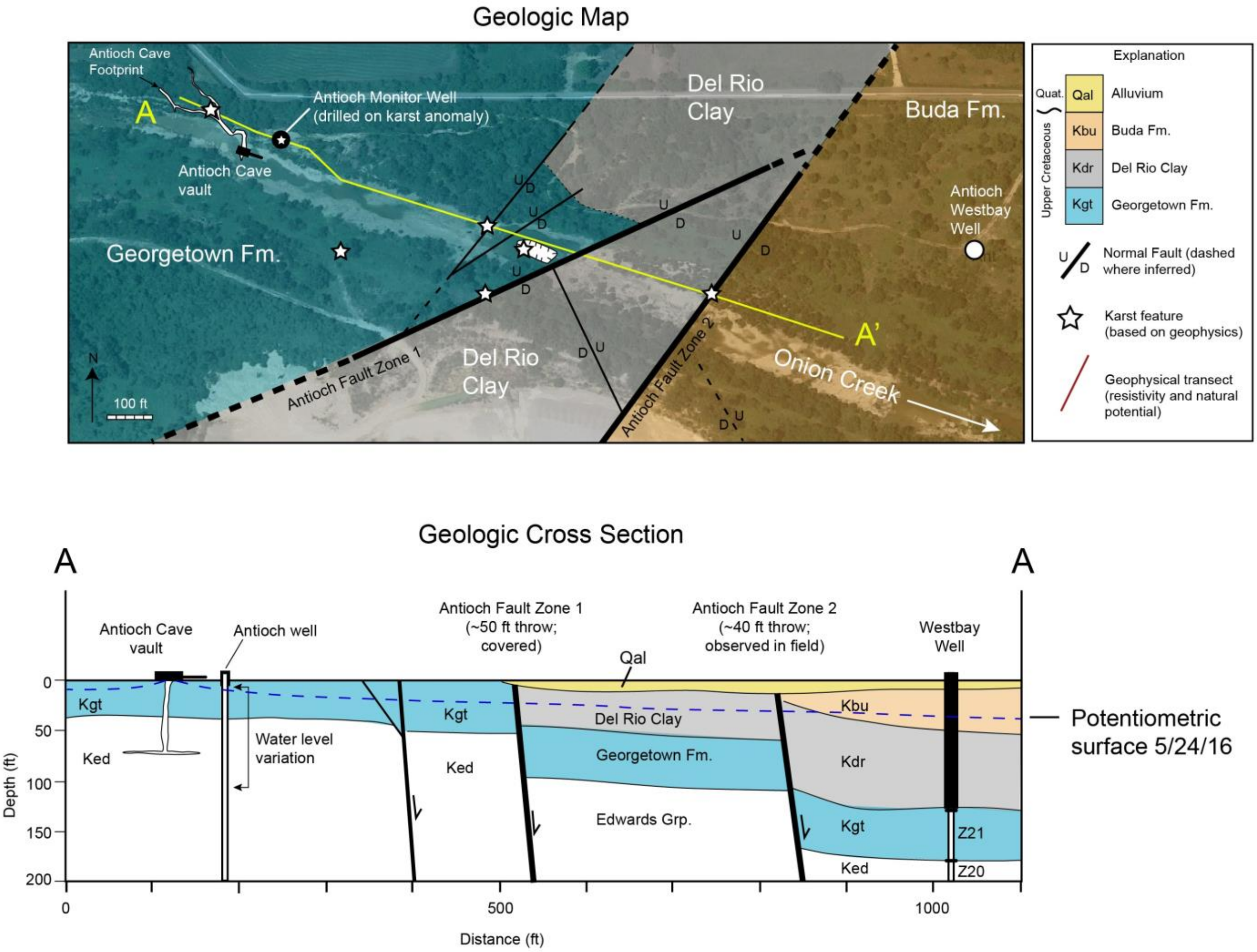


Figure A-1. Location map of Antioch Cave and Antioch multiport well.

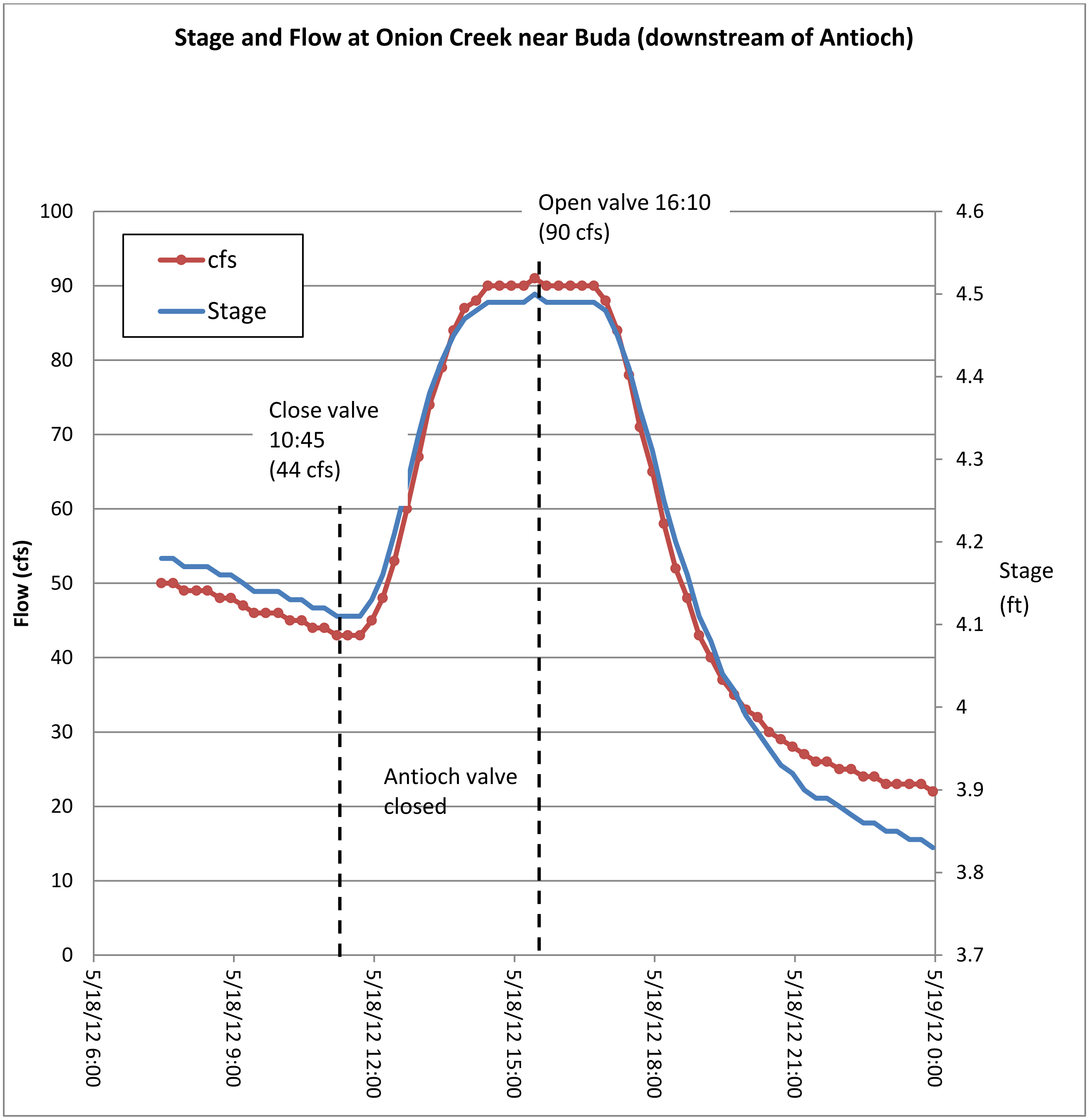


Figure A-2. Hydrograph of Onion Creek showing variations in flow resulting from closing the valve at Antioch Cave for about six hours and then opening the valve again. *This effectively restricted recharge into the cave while the valve was closed.*

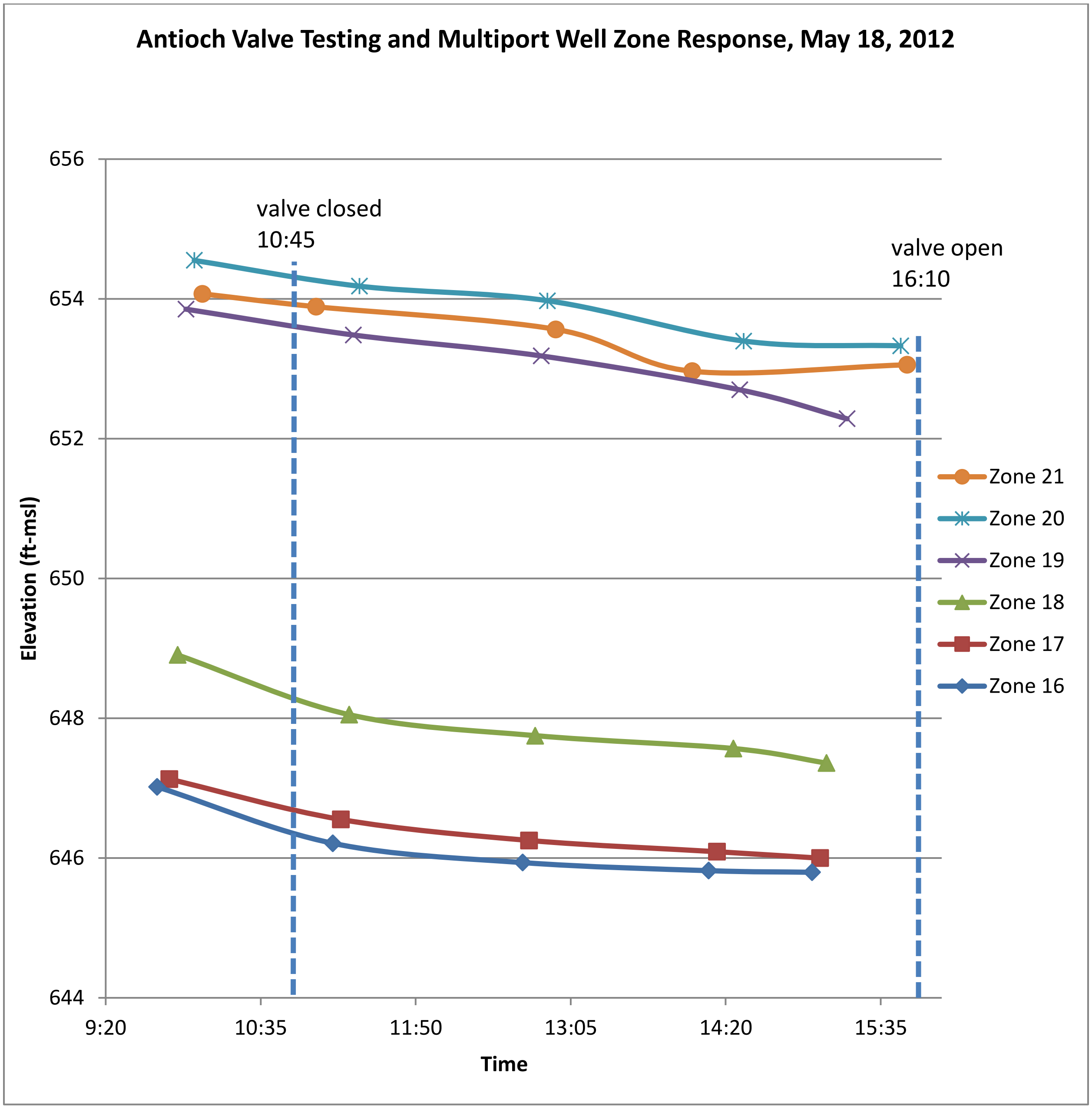


Figure A-3. Hydrograph of water-level elevations from the Antioch multiport Well. *The drawdowns are noted on the graph. Data provided in Table A-1.*

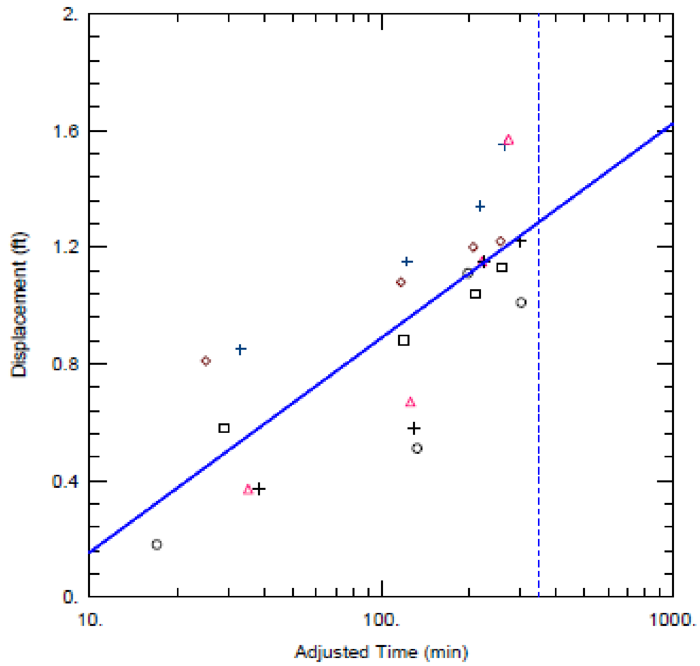
Table A-1. Results of water-level change in the Antioch multiport well resulting from opening and closing Antioch Cave valve.

Z16 Elev (ft-msl)	Z16 Time	z16 ET (min)	Z16 Drawdown (ft)	Z17 Elev (ft-msl)	z17 Time	z17 ET (min)	Z17 Drawdown (ft)	Z18 Elev (ft-msl)	z18 Time	z18 ET (min)	Z18 Drawdown (ft)
647.02	9:45	-60.00		647.13	9:51	-54.00		648.90	9:55	-50.00	
646.21	11:10	25.00	0.81	646.55	11:14	29.00	0.58	648.05	11:18	33.00	0.85
645.93	12:42	117.00	1.08	646.25	12:45	120.00	0.88	647.75	12:48	123.00	1.15
645.82	14:12	207.00	1.20	646.09	14:16	211.00	1.04	647.57	14:24	219.00	1.34
645.80	15:02	257.00	1.22	646.00	15:06	261.00	1.13	647.36	15:09	264.00	1.55

Z19 Elev (ft-msl)	z19 Time	z19 ET (min)	Z19 Drawdown (ft)	Z20 Elev (ft-msl)	z20 Time	z20 ET (min)	Z20 Drawdown (ft)	Z21 Elev (ft-msl)	z21 Time	21 ET (min)	Z21 Drawdown (ft)
653.85	9:59	-46.00		654.55	10:03	-42.00		654.07	10:07	-38.00	
653.48	11:20	35.00	0.37	654.18	11:23	38.00	0.37	653.89	11:02	17.00	0.18
653.18	12:51	126.00	0.67	653.97	12:54	129.00	0.58	653.56	12:58	133.00	0.51
652.70	14:27	222.00	1.15	653.40	14:29	224.00	1.15	652.96	14:04	199.00	1.11
652.28	15:19	274.00	1.57	653.33	15:45	300.00	1.22	653.06	15:48	303.00	1.01

Table A-1. Valve testing at Antioch

Parameter	Value	unit
Valve closed duration	325	min
Flow rate	46	cfs
Flow rate	20,608	gpm
Antioch to multiport well distance	1,660	ft



WELL TEST ANALYSIS

Data Set: C:\Users\bhunt\Desktop\Antioch Valve Test\Antioch Valve Test all zones.aqt
Date: 03/07/16 Time: 09:14:28

PROJECT INFORMATION

Location: Antioch Cave
Test Well: Antioch Valve
Test Date: 5/18/2012

AQUIFER DATA

Saturated Thickness: 450. ft Anisotropy Ratio (Kz/Kr): 0.1

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Antioch Cave	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
◇ Zone16	1660	0
□ Zone 17	1660	0
+ Zone18	1660	0
△ Zone19	1660	0
+ Zone 20	1660	0
○ Zone21_Kgt	1660	0

SOLUTION

Aquifer Model: Confined Solution Method: Cooper-Jacob

T = 9.92E+5 ft^2/day S = 0.003468

Figure A-4. Estimates of hydraulic conductivity from valve testing using AQTESOLV.