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U. S. GEOLOGICAL SURVEY

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MEMORANDUM

To: Devin Galloway, Ground-Water Specialist, RSO-Western Region

From: Joe Fenelon, Steve Reiner, Randy Laczniak, Hydrologists, Nevada WSC
Keith Halford, Groundwater Specialist, Nevada WSC

Subject: AQUIFER-TEST PACKAGE—Analysis of U-20 WW multiple-well aquifer test, Pahute Mesa, Nevada Test Site

The U.S. Geological Survey (USGS) conducted a multi-well aquifer test on Pahute Mesa at the Nevada Test Site (NTS) using pumping well U-20 WW and observation wells ER-20-6 #3, UE-20bh 1, and U-20bg (fig. 1). The test is best described as a target-of-opportunity effort which took advantage of intermittent pumping from a well in a remote area of the Nevada Test Site. Pumped water was used primarily for road and pad construction associated with the drilling of new monitoring wells in the local area. The pumping and observation wells were monitored from October 1, 2008 to August 5, 2009. Well U-20 WW produces water from moderately permeable volcanic rocks. Estimates of the transmissivity and hydraulic conductivity of these volcanic rocks are needed to constrain hydraulic parameters used to develop groundwater flow and contaminant transport models at the NTS.

AQUIFER-TEST SITE

The pumped well (U-20 WW) is located at 37°15´05´´N. 116 °25´45´´ W. on Pahute Mesa at the NTS (fig. 1). The approximate locations of the observation wells (ER-20-6 #3, UE-20bh 1, and U-20bg) are, respectively, 3,570 ft north-northeast, 6,270 ft east-southeast, and 8,020 ft southeast of well U-20 WW (fig. 1).

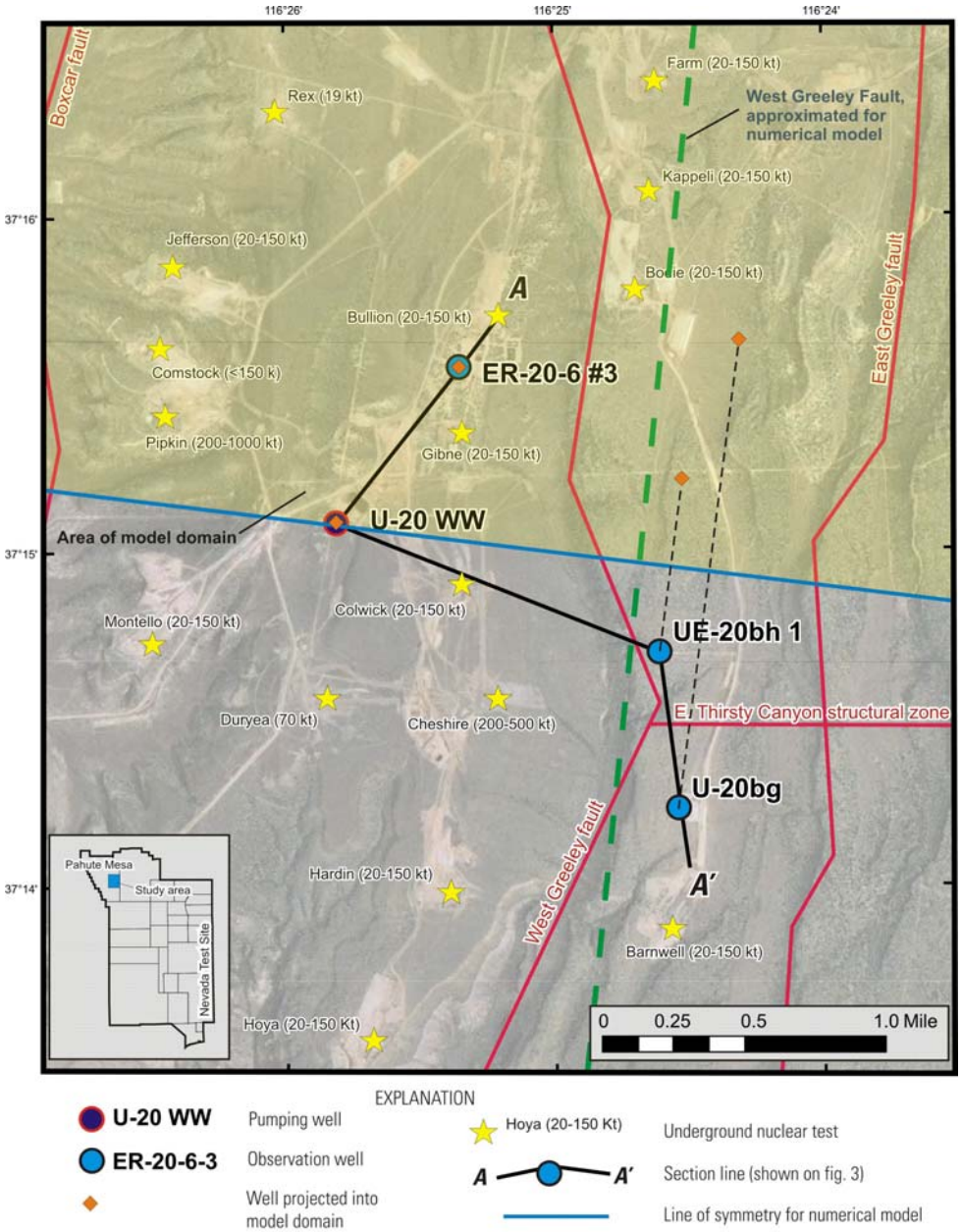

Figure 1. Location of aquifer-test wells, underground nuclear tests, geologic structures, and numerical model domain in the vicinity of well U-20 WW, Nevada Test Site.

WELL CONSTRUCTION

Well U-20 WW was drilled in 1982 on Pahute Mesa and was used intermittently as a local water supply starting in 1989 to support operation activities in the area (Laczniak and others, 1996, p. 41). Wells ER-20-6 #3 and UE-20bh 1 were drilled for gathering hydrogeologic information. Well U-20bg was drilled as an emplacement hole for potential testing of nuclear devices. Wells ER-20-6 #3, UE-20bh 1, and U-20bg were completed in 1996, 1991, and 1990, respectively. Figure 2 provides detailed information on well construction. Construction information was obtained from Boyd and others (1992), Fenix & Scisson, Inc. (written commun., 1982), Raytheon Services Nevada (written commun., 1991), and U.S. Department of Energy (1998).

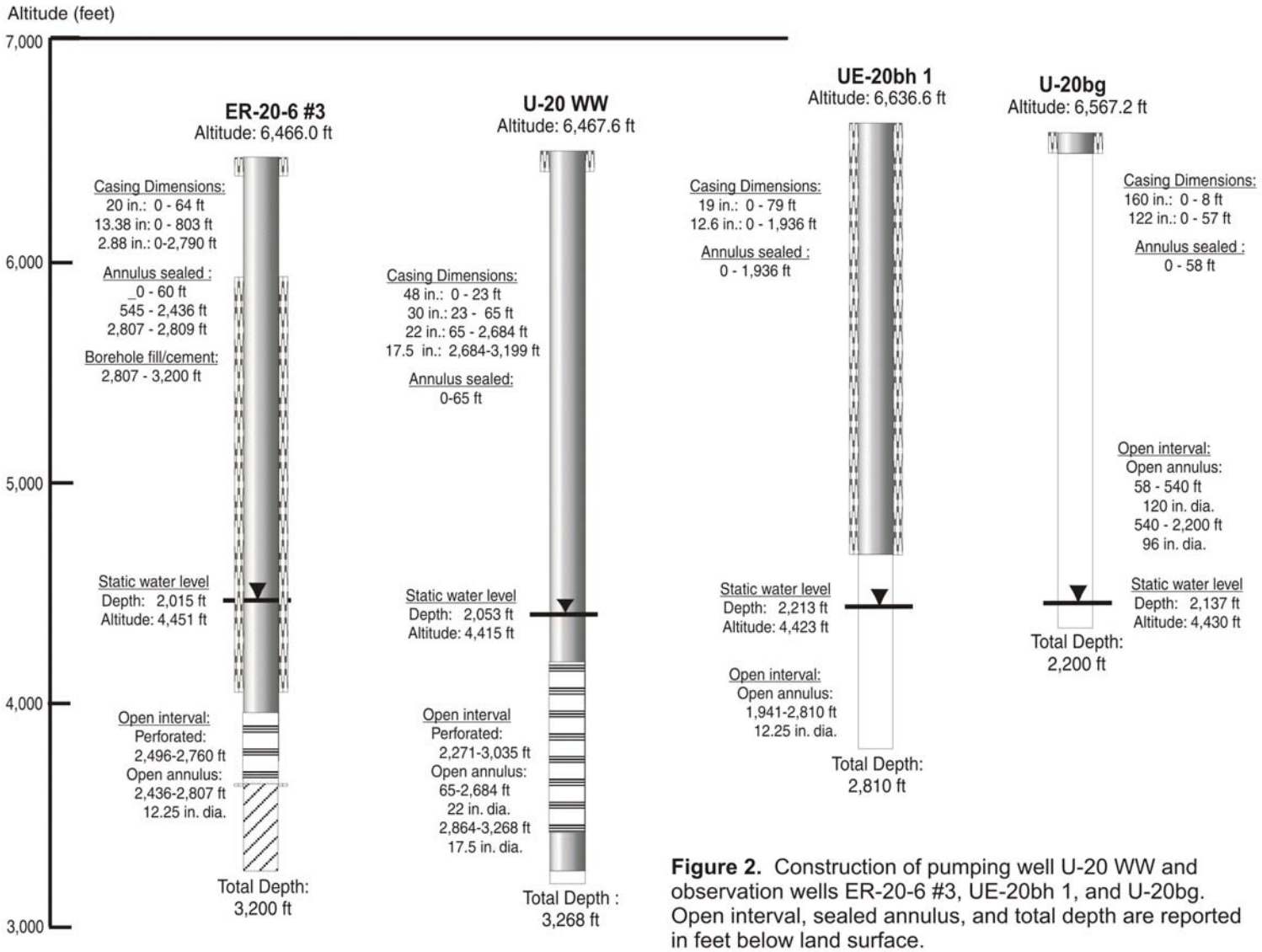

Figure 2. Construction of pumping well U-20 WW and observation wells ER-20-6 #3, UE-20bh 1, and U-20bg. Open interval, sealed annulus, and total depth are reported in feet below land surface.

HYDROGEOLOGY

Wells U-20 WW, ER-20-6 #3, UE-20bh 1, and U-20bg were completed in Tertiary volcanic rocks of the Silent Canyon caldera complex in Pahute Mesa (fig. 3). These wells penetrate about 2,000 ft of unsaturated rock consisting of the following hydrostratigraphic units identified by Bechtel Nevada (2002): Thirsty Canyon volcanic aquifer, Timber Mountain aquifer, Windy Wash aquifer, Paintbrush vitric-tuff aquifer, Upper Paintbrush confining unit, and the upper part of the Calico Hills zeolitic composite unit (CHZCM). The water table occurs in the CHZCM in this area and is the source of water to all four wells. Typical lithologies within the CHZCM are rhyolite lava flows and bedded and nonwelded tuffs that often are zeolitized (Laczniak and others, 1996, p.11).

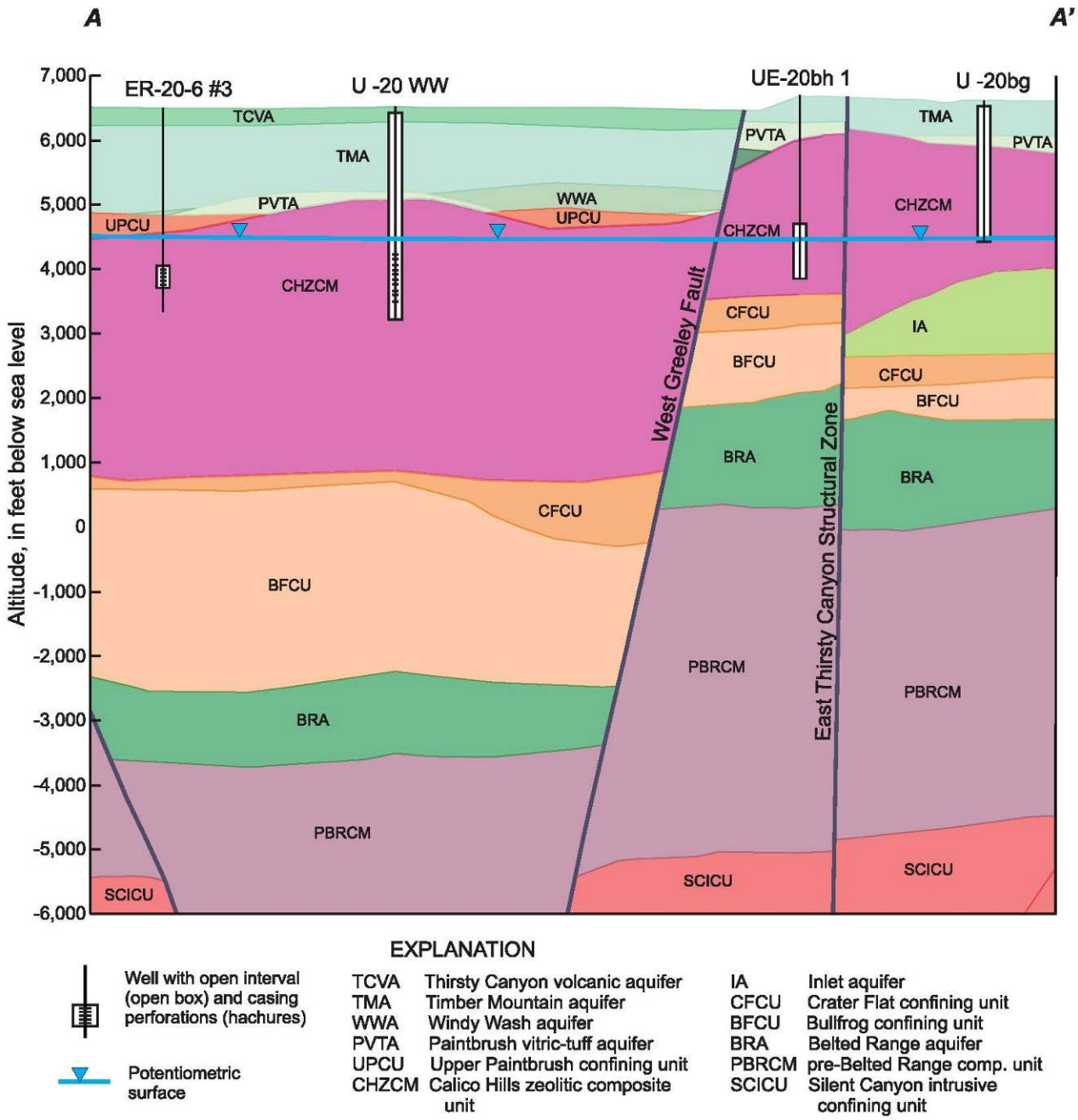

Figure 3. Simplified well construction and hydrostratigraphic units at ER-20-6 #3, U-20 WW, UE-20bh 1, and U -20bg. (Hydrostratigraphy modified from Bechtel Nevada, 2002).

The CHZCM is mapped as a composite hydrogeologic unit because it is composed of a complex distribution of aquifers and confining units that are difficult to map separately (Bechtel Nevada, 2002). Lavas within the CHZCM typically are aquifers, whereas the tuffs typically are confining units; the tuffs can have very low permeabilities if zeolitized. The lava-flow aquifers have moderate permeabilities, with primary flow through a series of interconnected fractures (Laczniak and others, 1996, p. 36). Total thickness of the CHZCM is estimated to be about 4,200 ft at U-20 WW, 3,800 ft at ER-20-6 #3, 2,300 ft at UE-20bh 1, and 2,000 ft at U-20bg (fig. 3).

Normal faults and caldera margin faults occur in the vicinity of U-20 WW. The West Greeley fault (WGF), a major fault on Pahute Mesa (McKee and others, 2001, p. 8-9), lies between wells U-20 WW and ER-20-6 #3 on the west (downthrown) side of the fault from wells UE-20bh 1 and U -20bg on the east (upthrown) side of the fault (figs. 1 and 3). The East Thirsty Canyon structural zone offsets hydrostratigraphic units between UE-20bh 1 and U-20bg (figs. 1 and 3). Faults that transect low-permeability rocks may increase flow, while faults that bring less permeable rocks into contact with more permeable rocks may decrease flow (Laczniak and other, 1996, p. 37).

PROCEDURES

The production well (U-20 WW) and three observation wells were monitored from October 1, 2008 to August 5, 2009 (table 1, fig. 1). Water levels and pumping rates were monitored continuously in the production well and water levels were measured continuously in the observation wells (fig. 4). These data provided the pumping, drawdown, and recovery information analyzed as part of the aquifer-test package documented in this memo.

Table 1.—Characteristics of wells used in U-20 WW aquifer test (see figure 1 for map locations).

				[All values in feet below land surface]			
Well	**Site ID**	**Latitude (NAD27)**	**Longitude (NAD27)**	**Static water level**	**Total depth**	**Top opening**	**Bottom opening**
U-20 WW	371505116254501	37° 15' 05.1"	116° 25' 45.4"	2,053	3,268	65	3,268
ER-20-6 #3	371533116251801	37° 15' 33.1"	116° 25' 17.5"	2,015	3,200	2,436	2,807
U-20bg	371414116242901	37° 14' 13.6"	116° 24' 28.8"	2,137	2,200	58	2,200
UE-20bh 1	371442116243301	37° 14' 41.9"	116° 24' 33.0"	2,213	2,810	1,941	2,810

Water withdrawals from U-20 WW were used to support drilling operations on Pahute Mesa. The weekly pumping schedule for well U-20 WW typically was about 8 hours per day, Monday through Thursday. Typical discharge rates during periods of pumping were between about 110 and 170 gallons per minute (gal/min). Pumping rates were limited by excessive drawdowns of about 700 ft in U-20 WW. These pumping rates resulted in drawdowns within the screened interval.

Pumping was distributed over two distinct pumping periods (fig. 4).The total withdrawal over these pumping periods was about 4.5 million gallons (Mgal). Pumping for the first period started on 10/14/2008 11:30 PST and ended on 12/10/2008 16:00 PST (fig. 4). The cumulative discharge during this period of pumping was about 3.1 Mgal. Pumping for the second period started on 06/02/2009 13:00 PST and primarily ended by 07/23/2009 11:00 PST (fig. 4). The cumulative discharge during the second period was about 1.4 Mgal.

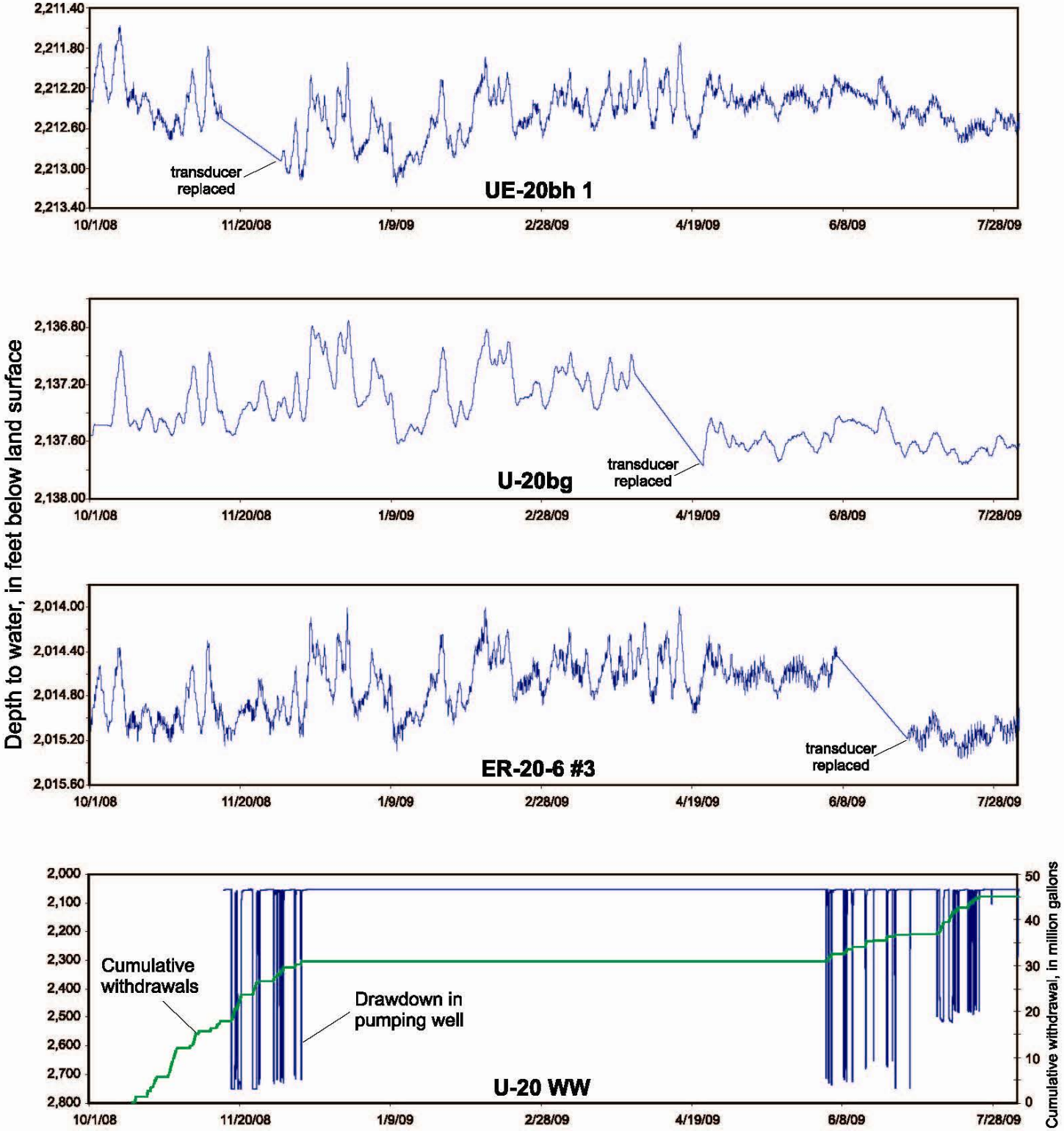

Figure 4. Water-level and withdrawal data collected from U-20 WW and three nearby observation wells, 10/1/2008 to 8/5/2009.

Water-level changes in wells ER-20-6 #3, UE-20bh 1, and U-20bg were measured from about 10/01/2008 to 8/5/2009 at 15-minute intervals with vented pressure transducers. The manufacturer-provided accuracy of these transducers was at least ±0.007 ft. Transducers in each of the three observation wells failed at some time during the measurement period and were replaced (fig. 4). Water-level change in well U-20 WW was measured from 11/14/2008 to 8/5/2009 at 2-minute intervals with an absolute pressure transducer. The manufacturer-provided accuracy of the transducer was ±1.12 ft. or better. All transducers were calibrated under laboratory and field conditions (La Camera and others, 2005, p. 10). Water temperature and barometric pressure also were measured at all well sites.

Discharge from well U-20 WW was monitored from 10/15/2008 to 8/5/2009 at 15-minute intervals with an in-line, totalizing flow meter. The accuracy of these flowmeter measurements was not verified; however, comparison of similar-type flow meters at the NTS with a portable acoustic-velocity flow meter suggests that the data are accurate to within 10 percent of actual withdrawals (Peggy Elliott, U.S. Geological Survey, written commun., 2009).

Drawdowns monitored in well U-20 WW were about 600 to 700 ft for most of the period of record, except in July and August, 2009, when they were only about 450 ft (fig. 4). Periods of greater drawdown corresponded to periods of higher short-term pumping rates.

DRAWDOWN ESTIMATION

Pumping responses in wells UE-20bh 1, ER-20-6 #3, and U-20bg were estimated by minimizing the differences between synthetic water levels and the measured water levels (Halford, 2006a). Synthetic water levels typically simulate water-level changes in a well that are caused by only non-pumping stresses. This approach was modified to simulate pumping and non-pumping stresses because pumping effects were pervasive during the 10-month period of record. Non-pumping responses were simulated with time series of barometric pressure; earth tides; a long-term linear change; and a step change between transducer installations. The predicted response at an observation well from pumping in U-20 WW was generated with a Theis (1935) approximation where multiple pumping periods were simulated with superposition. The synthetic water levels were the summation of predicted pumping response and previously specified non-pumping responses.

Water-level change resulting from the pumping of well U-20 WW was approximated using simplified cycles of pumping and recovery. The number of pumping periods was reduced based on the duration of recovery between periods of pumping. Fifty-one pumping and recovery cycles occurred in well U-20 WW between October 1, 2008 to August 5, 2009. The number of pumping and recovery cycles was reduced if recovery periods between intermittent pumping were less than a specified duration. For example, 25 pumping and recovery cycles occurred if recovery periods of less than 1 d are ignored. Ignoring recovery periods of less than 5 d reduces pumping from well U-20 WW to three pumping and recovery cycles.

Water-level changes from pumping well U-20 WW were approximated by superimposing three pumping and recovery cycles in a Theis solution, which sufficiently approximated pumping responses at up to 9,000 ft from well U-20 WW (fig. 5). The predicted Theis responses at distances that bracket distances between well U-20 WW and the three observation wells are very similar with 3 and 51 pumping and recovery cycles. Three pumping and recovery cycles were considered adequate because of similarities in predicted responses. Only the Theis response near the pumping well (radius = 0.3 ft) differed (top plot, fig. 5). However, drawdowns in the pumping well were not compared in the aquifer-test analysis.

The amplitude and phase for each of the non-pumping-stress time series and the transmissivity (T) and storativity (S) for the pumping-stress time series were estimated by minimizing the difference between the synthetic and measured water levels (Halford, 2006a). Barometric changes had the largest short-term influence on measured water levels for wells ER-20-6 #3, UE-20bh1, and U-20bg and visually masked most or all of the pumping stress in the records.

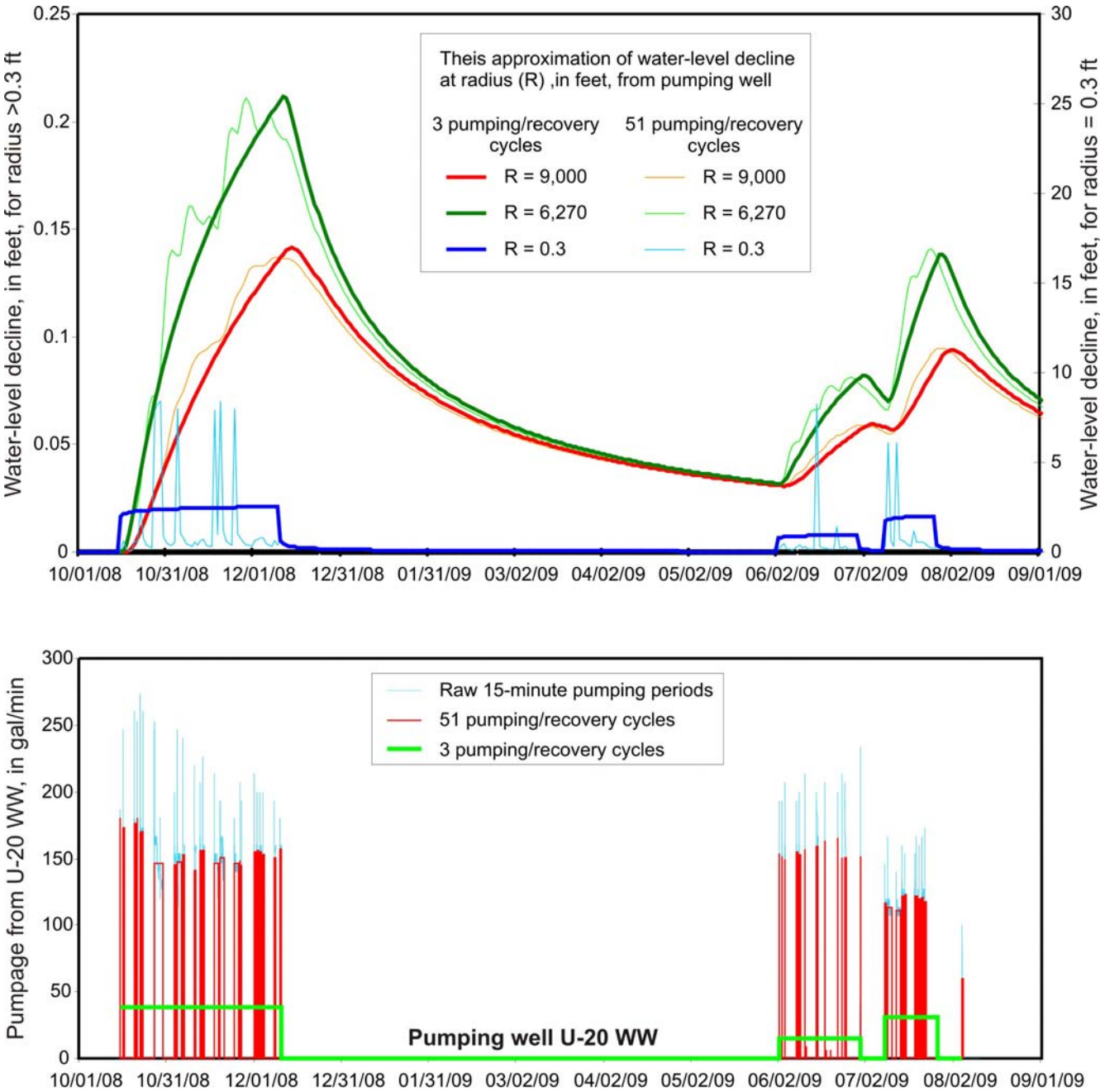

Figure 5. Pumpage from U-20 WW binned three different ways (bottom plot) and the effect of binning on the estimate of the pumping response at three distances from the pumping well (top plot).

AQUIFER-TEST ANALYSIS

Hydraulic properties of lithologic units within the CHZCM were estimated with analytical and numerical models. Bulk transmissivity and storativity were estimated with an analytical Theis (1935) approximation. The transmissivity of lava and bedded tuff units, specific yield, and specific storage were estimated with the numerical model, which was solved with MODFLOW (McDonald and Harbaugh 1988; Harbaugh and McDonald, 1996).

THEIS APPROXIMATION

Well UE-20bh 1 had the largest and most clearly defined drawdown response of the three observation wells from pumping in U-20 WW (fig. 6). Measured water levels from 10/8/2008 to 8/4/2009 were simultaneously fitted to time series of barometric pressure, earth tides, a linear trend, a step change, and an estimated Theis response from pumping. The synthetic time series generated from this fit was subtracted from the measured water level. The residuals resulting from this subtraction (fig. 6) show that most of the water-level changes in UE-20bh 1 have been explained. The Theis approximation resulting from the fitting process shows a maximum drawdown of about 0.4 ft in well UE-20bh 1 (fig. 6). Apparent drawdowns in wells U-20bg and ER-20-6 #3 were small (less than 0.1 ft) or nonexistent and difficult to distinguish from the background noise that could not be removed from the water-level record by the fitting procedure.

A best fit for well UE-20bh 1 resulted in estimates for T and S of 3,700 ft^2/d and 0.0013, respectively (table 2; fig. 6). The RMS error was 0.03 ft relative to the measured drawdown of about 0.4 ft.

Smaller drawdowns in the remaining two observation wells resulted in poorly constrained approximations of drawdown and corresponding T and S, using the above method. Interestingly, little or no drawdown was observed in ER-20-6 #3, which is the nearest observation well to the pumping well and is open to a relatively transmissive lava, previously estimated to be about 2,000-4,000 ft^2/d (IT Corporation, 1998). The close proximity of a lava unit showing little or no pumping response suggests that the CHZCM is not a homogeneous, isotropic medium. This is not surprising, given that the CHZCM is classified as a composite unit consisting of aquifers and confining units.

Table 2.—Hydraulic properties for the Calico Hills zeolitic composite unit estimated with a Theis approximation at well UE-20bh 1.

Hydrostratigraphic unit	Transmissivity (ft^2/d)	Storativity (dimensionless)
Calico Hills zeolitic composite unit	3,700	0.0013

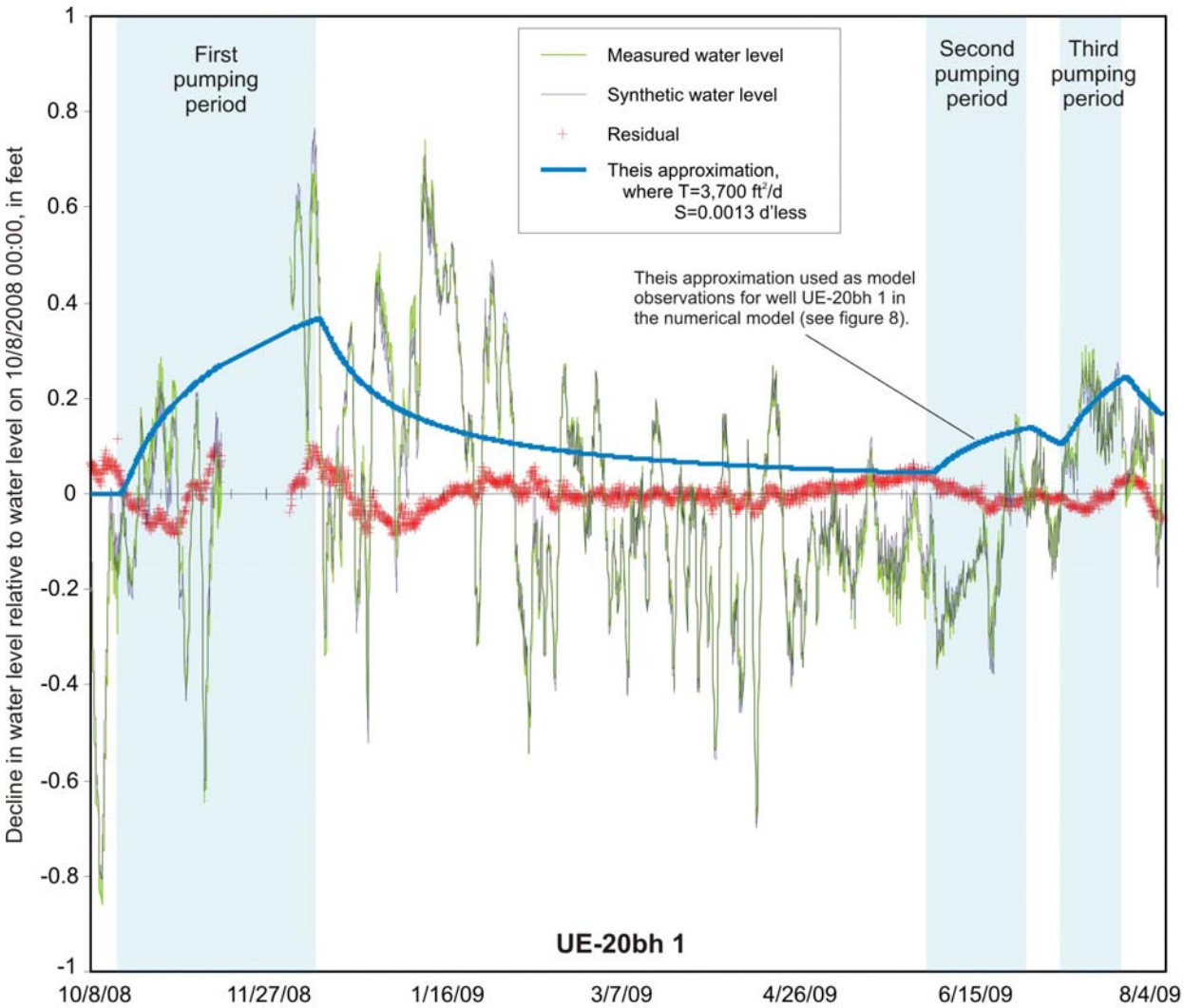

Figure 6. Measured, synthetic, and residual water levels and a Theis approximation of the pumping response in well UE-20bh 1 between 10/8/2008 and 8/4/2009. Residual data represent response of measured water level that was not accounted for by barometer, earth tides, long-term linear trend, step change from transducer replacement, or pumping effects that were approximated with a Theis equation.

Numerical Model

A three-dimensional MODFLOW model was developed to (1) explain the small or nonexistent pumping response observed at well ER-20-6 #3; (2) refine the framework of the volcanic units within the CHZCM; and (3) to estimate their hydraulic properties. A line of symmetry perpendicular to the West Greeley fault (WGF) was assumed to bisect well U-20 WW so that only half of the area of interest was simulated (fig. 1). Wells south of this line of symmetry (UE-20bh 1 and U-20bg) were projected into the model area.

The lithologic units in the CHZCM were conceptualized from lithologic logs of the pumping and observation wells. The volcanic rock below the water table in the model was divided into the five units (fig. 7):

(1) a 250-ft upper layer of lava that supplies water to U-20 WW and truncates at the WGF,
(2) a 750-ft lobe of lava that surrounds ER-20-6 #3, but is not hydraulically connected with U-20 WW and does not extend east to the WGF,
(3) a 700-ft layer of lava east of the WGF that supplies water to UE-20bh 1,
(4) a 950-ft bedded tuff west of the WGF, and
(5) a 200-ft upper layer of bedded tuff east of the WGF that supplies water to U-20bg.

Hydraulic properties were estimated by minimizing differences between simulated and measured drawdowns in the observation wells. Parameter estimation was performed by minimizing a weighted sum-of-squares objective function with MODOPTIM (Halford, 2006b).

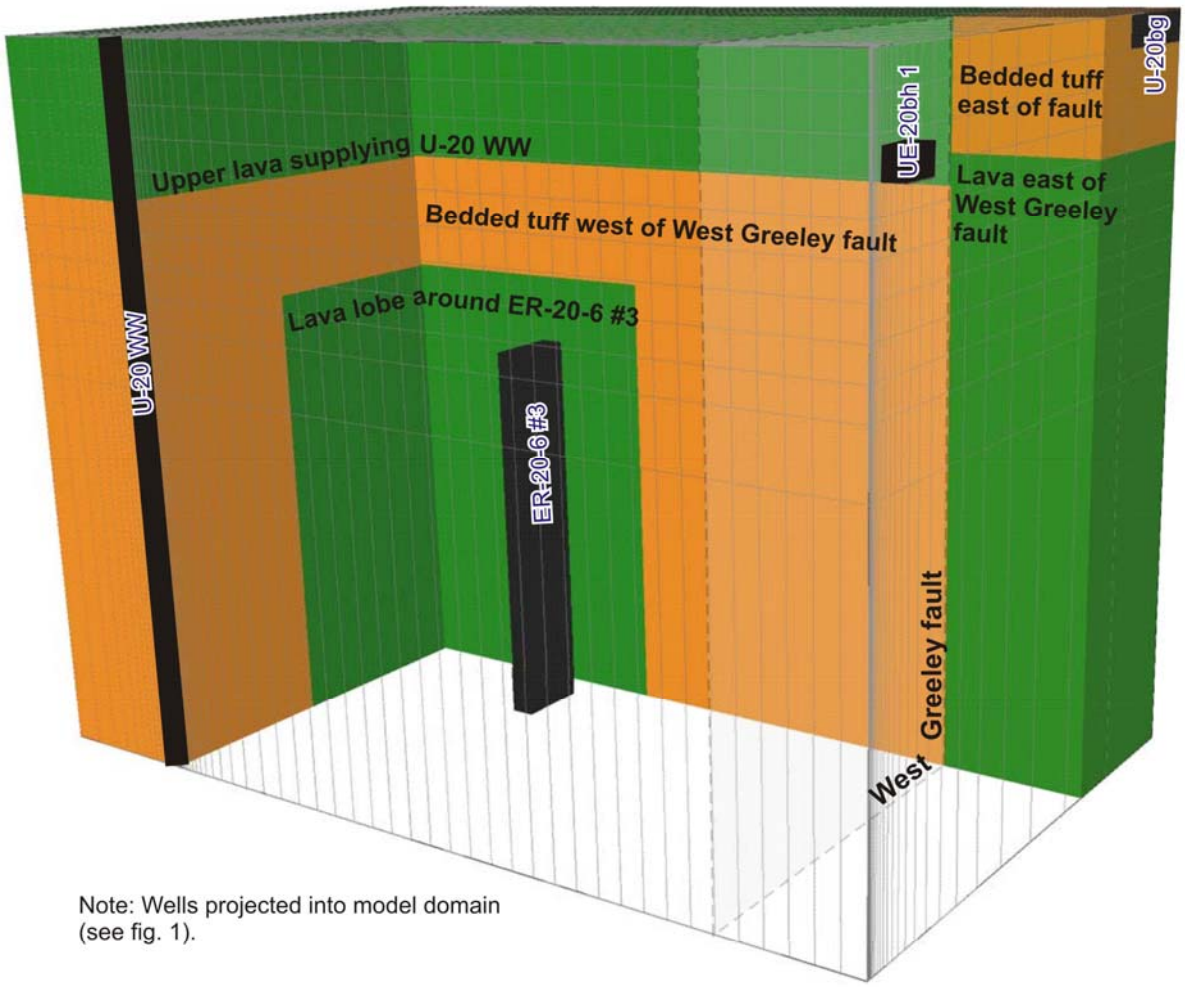

Figure 7. Model layering and lithologic unit intervals in numerical flow model used to simulate pumping response in U-20 WW.

The pumping responses used as model observations at the three observation wells simulated in the numerical flow model were the Theis approximations generated during drawdown estimation (blue line on figure 6 for well UE-20bh 1). The Theis approximation calculated at each of the observation wells was considered an acceptable estimate of drawdown. Model observations, based on Theis approximations, for the three observation wells are shown in figure 8. The smaller drawdown responses approximated at U-20bg and ER-20-6 #3 are attributed to attenuation of the pumping signal by low-permeability tuff. Large drawdowns in the pumping well were not simulated because they are more indicative of well completion effects rather than gross aquifer properties.

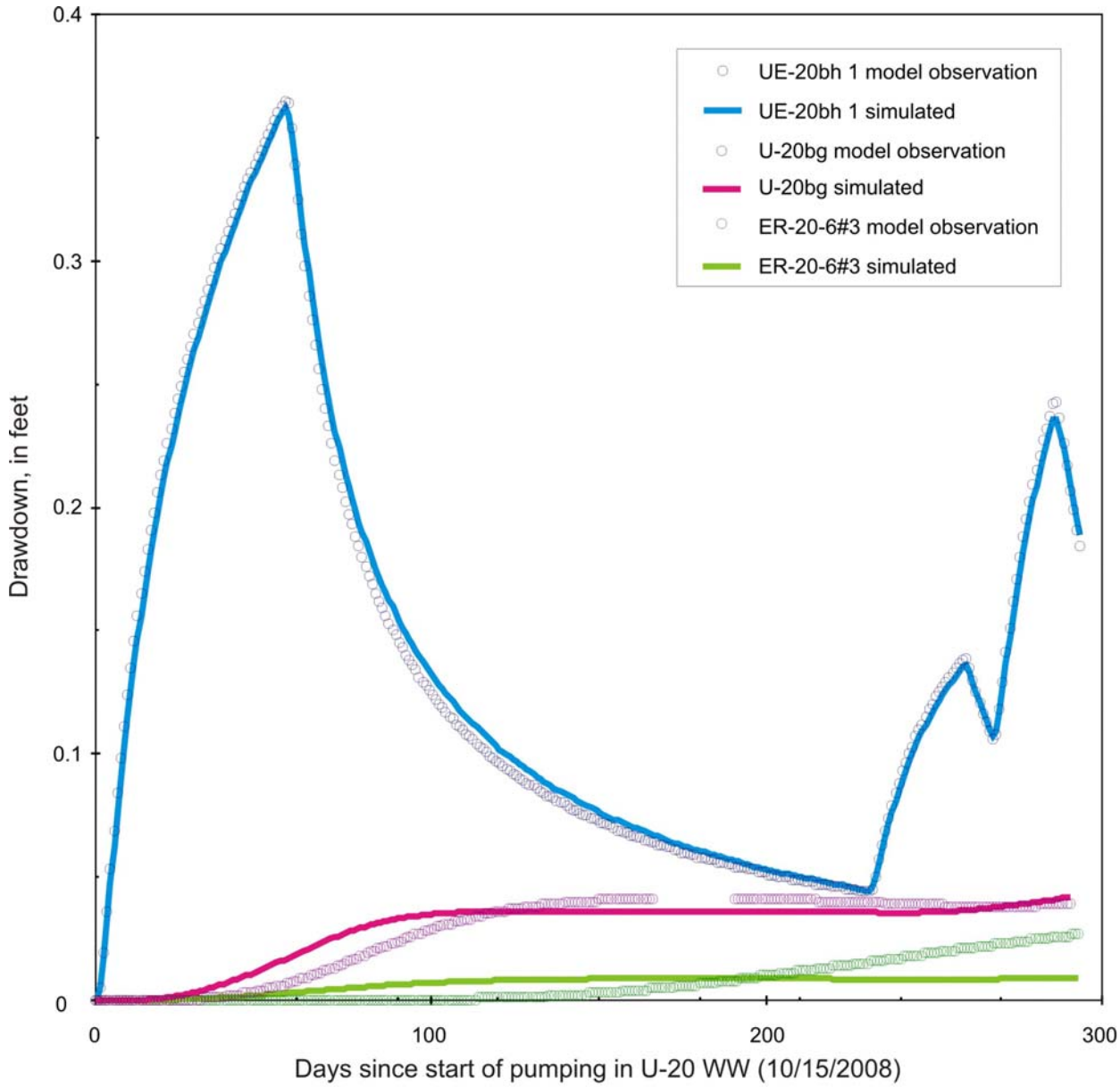

Figure 8. Comparison of model observations to simulated data for three observation wells used in numerical flow model. Model observations are the Theis approximations of the pumping response generated during the fitting process of the raw transducer data to nonpumping and pumping stresses (see "Drawdown Estimation" section of report).

The model domain was discretized into 13 layers of 57 rows and 153 columns (fig. 7). The model grid extended laterally about 200,000 ft away from well U-20 WW, and vertically from the water table to 1,200 ft below the water table. Rows and columns were assigned widths of 0.2 ft near well U-20 WW. Row and column widths were multiplied by 1.25 from near well U-20 WW to the edges of the model; the exception to this was columns 89 to 129 (columns from about 800 to 9,000 ft east of U-20 WW), which were

assigned widths of 200 ft. Layer thicknesses ranged from 1 ft at the water table to 650 ft at the base of the model; most layers were 50 ft thick (fig. 7). All external boundaries were no-flow. Changes in the wetted thickness of the aquifer were not simulated because the maximum drawdown near the water table was small relative to the total thickness. The U-20 WW aquifer test was simulated with six stress periods, which included three pumping periods (fig. 5) each followed by a period of no pumping.

HYDRAULIC-PROPERTY ESTIMATES

The hydraulic properties of the volcanic-rock units making up the CHZCM were defined in the numerical flow model using six parameters:

(1) horizontal hydraulic conductivity of lava (all lava units were assumed equal);
(2) horizontal hydraulic conductivity of bedded tuff east of WGF;
(3) horizontal hydraulic conductivity of bedded tuff west of WGF;
(4) specific yield of bedded tuff east of WGF;
(5) specific storage of all units; and
(6) vertical–to-horizontal anisotropy, which was assigned a value of 0.1 from the water table to the base of the model.

The three hydraulic conductivity, specific yield, and specific storage values were estimated during model calibration. Vertical–to-horizontal anisotropy was assigned and not estimated. A specific yield was not assigned west of the WGF because the upper lava supplying well U-20 WW was assumed to be confined.

Simulated pumping responses closely matched the model observations (fig. 8). Results from the numerical flow model indicate that the drawdown and recovery measured at each of the observation wells open to the CHZCM can be simulated with multiple lithologic layers of different hydraulic conductivity. The drawdown simulated by the flow model at the end of the third pumping period is shown in figure 9. The figure shows a large drawdown cone in the more permeable lava unit at the top of the water table west of the WGF. The drawdown extends across the WGF and spreads through the deeper lava that supplies water to well UE-20bh 1. Drawdown is constrained vertically on the west side of the WGF by less permeable bedded tuff that isolates the lava supplying well ER-20-6 #3. Drawdown also is constrained by less permeable bedded tuff at the water table east of the WGF, where well U-20bg is located.

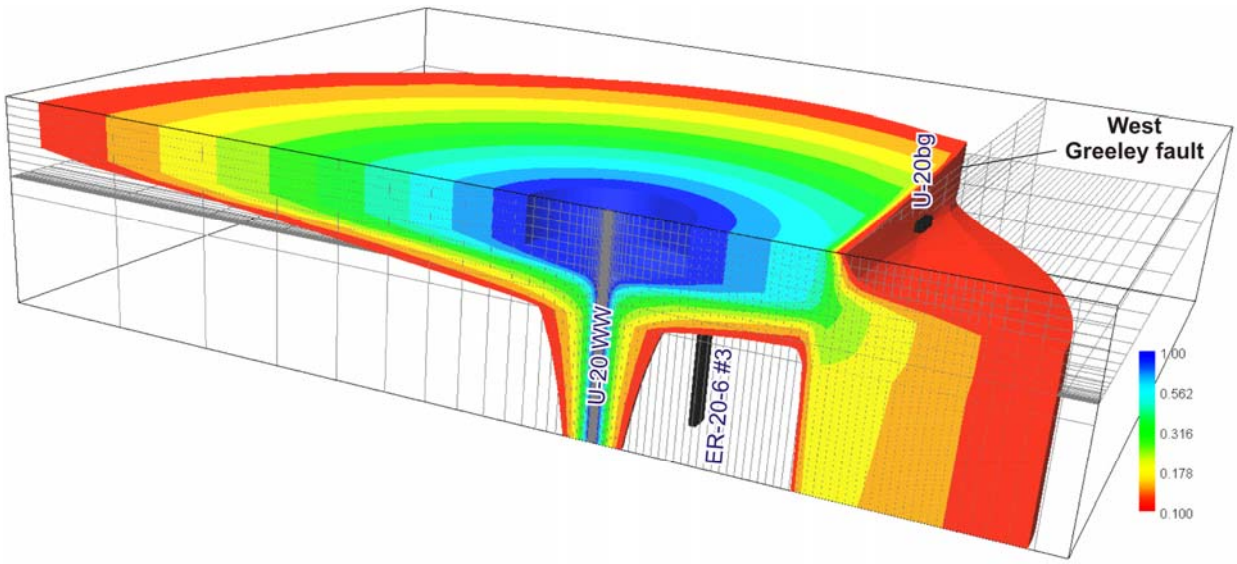

Figure 9. Drawdown cone at end of third pumping period (day 285) in numerical flow model. Cone is truncated at 0.1 ft of drawdown.

The transmissivity of the lava supplying water to U-20 WW, as estimated from the numerical flow model is about 1,600 ft^2/d (table 3). The transmissivity of the lava east of the WGF that is hydraulically connected to the lava supplying U-20 WW was estimated to be about 4,600 ft^2/d (table 3). These numbers compare well to the bulk transmissivity of 3,700 ft^2/d that was estimated with the Theis approximation of drawdown at well UE-20bh 1 (table 2). Transmissivity estimates for lava around well ER-20-6 #3 and in the bedded tuffs are highly uncertain because of poorly constrained estimates of drawdown in wells ER-20-6 #3 and U-20bg. However, the transmissivity estimates for the bedded tuffs can be considered upper bounds because the drawdown estimates that were used as observations in the numerical model for the aforementioned wells were considered maximums.

Model-based estimates of specific yield and specific storage also are given in table 3. The somewhat low specific yield value of 0.002 estimated by the model for the bedded tuff unit east of the WGF may reflect the inability of this confining unit to drain substantial amounts of water. Vertical–to-horizontal anisotropy was not estimated but assigned a value because often it is correlated with specific yield and any model-derived estimate would be highly unconstrained. The assigned vertical–to-horizontal anisotropy and specific storage values are considered reasonable for the volcanic units of interest (table 3).

Table 3.—Estimated and assigned hydraulic properties for the lithologic units simulated in the U-20 WW numerical flow model. Hydraulic properties in red were assigned.

Lithologic unit	Horizontal hydraulic conductivity (ft/d)	Unit thickness (ft)	Transmissivity (ft^2/d)	Storage	Vertical-to-horizontal anisotropy (d'less)
Upper lava supplying U-20 WW	6.5	250	1,600	[a] 2.2×10^{-6} 1/ft	0.1
Lava east of WGF	6.5	700	4,600	[a] 2.2×10^{-6} 1/ft	0.1
Lava lobe around ER-20-6 #3	6.5	750	4,900	[a] 2.2×10^{-6} 1/ft	0.1
Bedded tuff east of WGF	<0.006	200	<1	[b] 0.002 d'less	0.1
Bedded tuff west of WGR	<0.003	950	<2	[a] 2.2×10^{-6} 1/ft	0.1

[a]Specific storage
[b]Specific yield

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