United States Department of the Interior

U. S. GEOLOGICAL SURVEY

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August 29, 2013

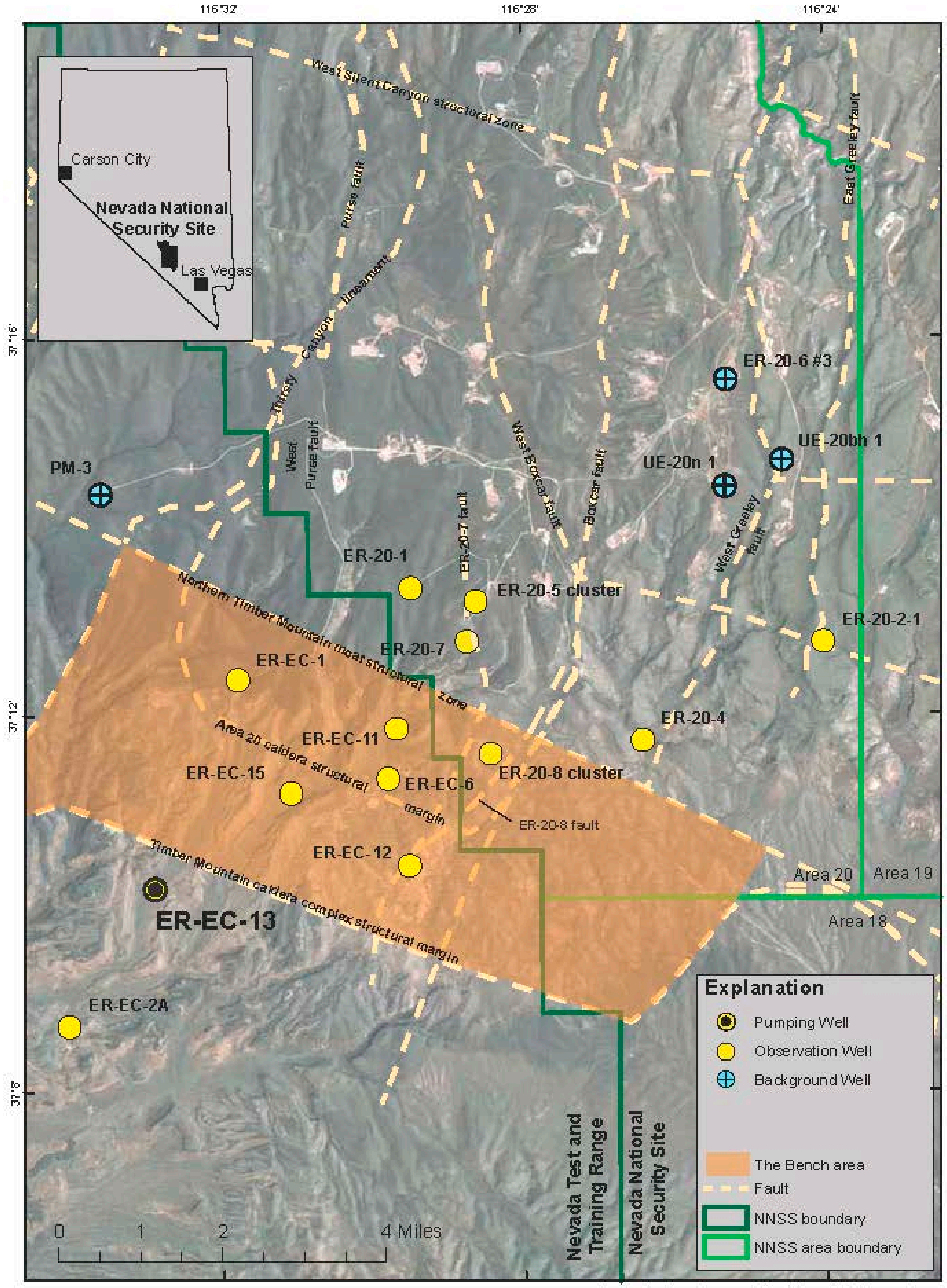
MEMORANDUM

To: Devin Galloway, WSFT-West Groundwater Specialist, Sacramento, CA

From: Keith J. Halford and Steve Reiner, Hydrologists, Nevada WSC, USGS

Subject: AQUIFER TEST—Analysis of *ER-EC-13 main upper zone* and *ER-EC-13 main lower zone*, multiple-well aquifer test of volcanic rocks, Pahute Mesa, Nevada National Security Site

A pair of aquifer tests were conducted by Navarro-Intera, LLC (N-I) in wells *ER-EC-13 main upper zone* and *ER-EC-13 main lower zone* at Pahute Mesa on the Nevada National Security Site (NNSS) in southern Nevada (Figure 1). Hydraulic conductivities of tuff confining units and lava-flow aquifers within the Fortymile Canyon composite unit and total transmissivity were estimated. Drawdowns in all three observation wells at the ER-EC-13 well cluster site (Table 1, deep, intermediate and shallow) during both aquifer tests were interpreted simultaneously so that estimated hydraulic properties were consistent. Well *ER-EC-13 main upper zone* was pumped intermittently between June 22, 2012 and August 2, 2012. Well *ER-EC-13 main lower zone* was pumped for development and a constant-rate test between March 7, 2013 and March 29, 2013. Hydraulic properties estimated from the aquifer tests in wells ER-*EC-13 main upper zone* and *ER-EC-13 main lower zone* can be used to constrain estimates of radionuclide transport through volcanic rocks beneath Pahute Mesa, NNSS.



Base from U.S. Geological Survey Digital data, 1:100,000, 1978-88
Universal Transverse Mercator projection, Zone 11, NAD83
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Geologic structures modified from U.S. Department of Energy (2009) and Sigmund L. Drellack, National Security Technologies, LLC, written commun. (2011)

Figure 1.—Well construction, lithology, and location of ER-EC-13 well cluster, Pahute Mesa, Nevada National Security Site and vicinity. (Observation and background wells were monitored, but not used in this interpretation.)

Table 1.—Well location and construction data for analyzed wells in ER-EC-13 cluster, Pahute Mesa, Nevada National Security Site.

[Latitude and longitude are in degrees, minutes, and seconds and referenced to North American Datum of 1927 (NAD27); ft amsl, feet above National Geodetic Vertical Datum of 1929 (NGVD29); ft bgs, feet below ground surface.]

Map Identifier	Site Identifier	Latitude	Longitude	Ground surface elevation, ft amsl	Depth to Static Water Level, ft bgs	Diameter Screen, in inches	Top Screen, ft bgs	Bottom Screen, ft bgs
ER-EC-13 main upper zone	371010116325401	N37°10'10"	W116°32'54"	5,175	N/A	6 5/8	1,888	2,097
ER-EC-13 main lower zone	371010116325401	N37°10'10"	W116°32'54"	5,175	N/A	6 5/8	2,286	2,601
ER-EC-13 deep	371010116325402	N37°10'10"	W116°32'54"	5,175	1,011	2 7/8	2,292	2,611
ER-EC-13 intermediate	371010116325403	N37°10'10"	W116°32'54"	5,175	1,010	2 7/8	1,900	2,100
ER-EC-13 shallow	371010116325404	N37°10'10"	W116°32'54"	5,175	1,011	2 7/8	1,014	1,094

Site and Geology

The aquifer tests occurred beneath Pahute Mesa in the northwest corner of NNSS where transport of radionuclides is a concern (Laczniak and others, 1996). The three wells that were monitored during aquifer testing at Pahute Mesa are completed in Tertiary volcanic rocks. The volcanic rocks of Pahute Mesa are dominated by lavas and tuffs of rhyolitic composition (Laczniak and others, 1996). Geologic structures at Pahute Mesa include normal faults with surface exposure and buried structural zones and caldera margins. The ER-EC-13 well cluster is located south of the Bench area (Figure 1). Well *ER-EC-13 main* penetrates about 1,000 ft of unsaturated rock, and 2,000 ft of saturated rock where it produces water from lava-flow aquifers within the Fortymile Canyon composite unit, FCCM (Figure 2).

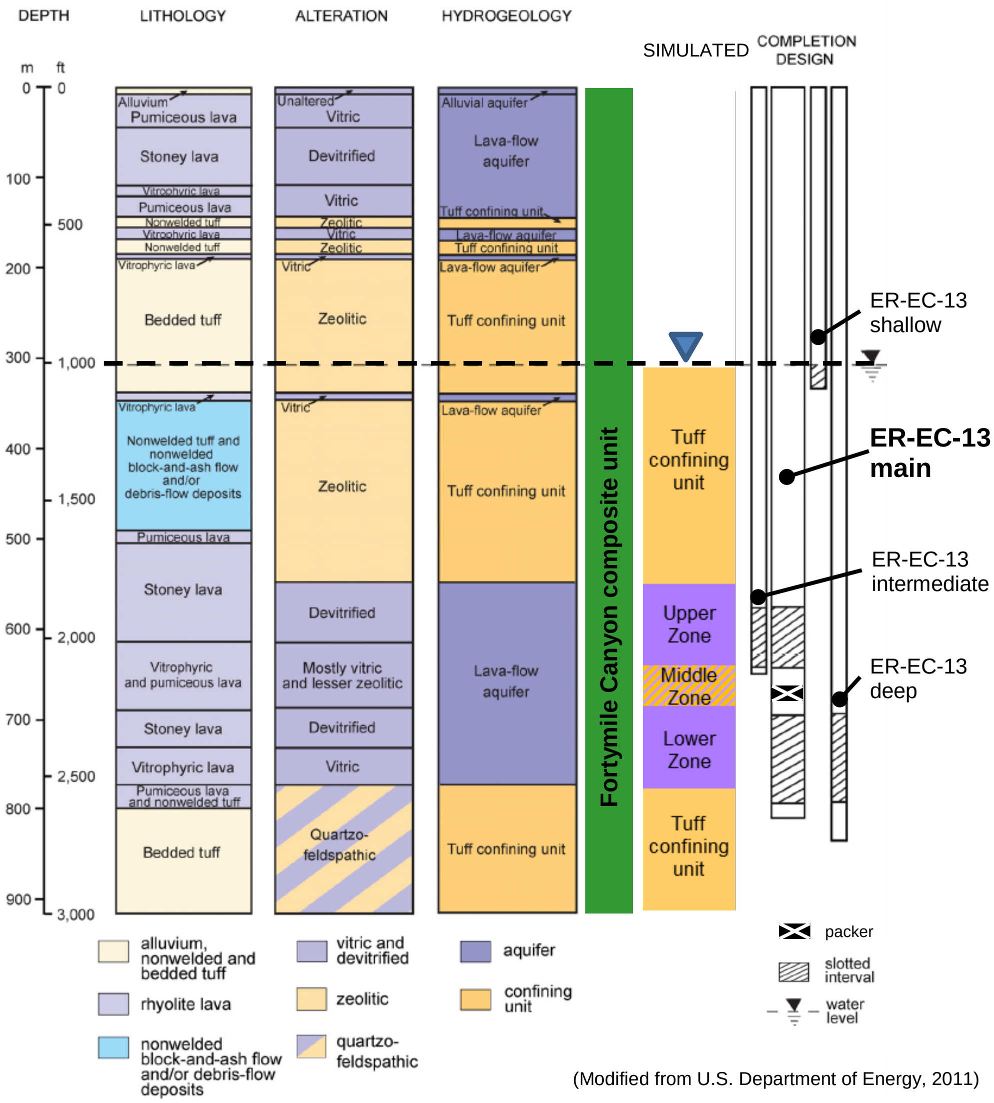

Figure 2.—Lithology, alteration, hydrogeology, and well completion at ER-EC-13 well cluster Pahute Mesa, Nevada National Security Site.

The lithologies of major water-producing hydrostratigraphic units in the aquifer-test area are stoney, vitrophyric, and pumiceous lavas (U.S. Department of Energy, 2011). An undifferentiated, lava-flow aquifer was identified as the contributing unit for both screens of the well *ER-EC-13 main* (Figure 2). The Lava-flow aquifer was differentiated into three zones so that heterogeneous hydraulic conductivities could be estimated (Figure 2). Ash-flow tuffs adjacent to the lava-flow aquifers are nonwelded and zeolitized. Similar units at the NNSS typically are characterized as confining units (Laczniak and others, 1996, p.11; U.S. Department of Energy, 1997).

Pumping and Water-Level Changes

Well *ER-EC-13 main* has upper and lower screened intervals that were isolated with a packer (Figure 2). The upper screen of well *ER-EC-13 main* is coincident with the open interval of well ER-EC-13 intermediate, and the lower screen of well *ER-EC-13 main* is coincident with the open interval of well ER-EC-13 deep. Upper and lower screens of well *ER-EC-13 main* produce water from the FCCM.

Approximately 3 million gallons were withdrawn from *ER-EC-13 main upper zone* for well development prior to the constant-rate test. The constant-rate test lasted about 123 hours from 7/3/2012 to 7/8/2012. Discharge during the constant-rate test averaged 303 gal/min with a total groundwater withdrawal of about 2.2 million gallons. Total withdrawal during the period of well development and testing (through July 21) was about 5.2 million gallons (Figure 3).

An additional 2.8 million gallons were pumped from the upper and lower screened intervals of well *ER-EC-13 main* between 7/21/2012 and 8/2/2012 (Figure 3). The pump and packer were reset prior to 7/21/2012 so that *ER-EC-13 main lower zone* could be developed and tested. Pumping ceased after realizing that significant flow inadvertently came from the upper zone because the packer was leaking. The additional pumpage does not affect this analysis, but is significant to responses in distant observation wells.

Water-levels were measured in wells *ER-EC-13 shallow*, *ER-EC-13 intermediate*, and *ER-EC-13 deep* during development and testing of *ER-EC-13 main* upper zone. Water levels measured in wells *ER-EC-13 intermediate* and *ER-EC-13 deep* were affected minimally by thermal expansion because transducers were submerged 1,057 and 1,608 ft, respectively, prior to pumping. Heating affected water columns at depths of less than 1,900 ft below land surface which affected water levels measured in well *ER-EC-13 shallow* where the transducer was submerged less than 50 ft.

Drawdowns in wells *ER-EC-13 intermediate* and *ER-EC-13 deep* were estimated by subtracting water levels prior to pumping from measured water levels. Environmental fluctuations were ignored in these wells because barometric and tidal changes were less than the measurement resolution of the transducers (0.1 ft). Maximum drawdown in well *ER-EC-13 intermediate*, adjacent to the pumping well, during the constant-rate test was about 60 ft (Figure 3).

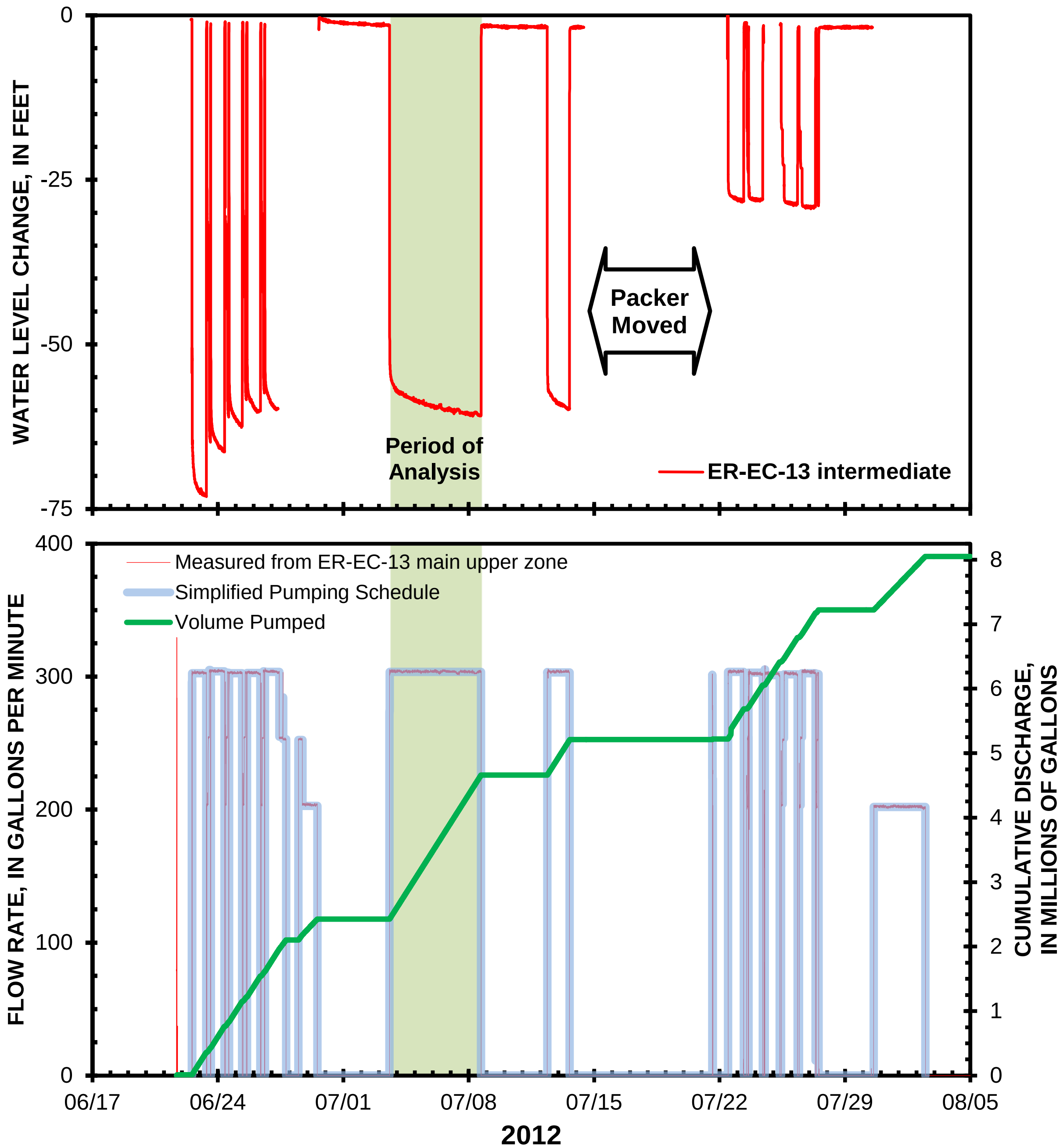

Figure 3.—Pumping from *ER-EC-13 main upper zone* during well development and aquifer testing, June-July, 2012 and pumping from *ER-EC-13 main lower zone* after July 21, 2012 where packer leaked.

Drawdowns in well *ER-EC-13 shallow* were indeterminate because of thermal expansion of about 900 ft of water column. Water-levels changed about 0.2 ft during development and testing of well *ER-EC-13 main* upper zone. These changes could be resolved to within 0.01 ft because the transducer had a smaller measurement range than the deep transducers in wells *ER-EC-13 intermediate* and *ER-EC-13 deep*. Transducer submergence was less than 50 ft in well *ER-EC-13 shallow*, which allowed thermal expansion to effect water-level measurements. Most all of the observed change could be explained by thermal expansion. Maximum drawdown in well *ER-EC-13 shallow* was assumed to be less than 0.1 ft.

Approximately 1.8 million gallons were withdrawn from *ER-EC-13 main lower* zone for well development prior to the constant-rate test. The constant-rate test lasted about 219 hours and was conducted from 3/20/2013 to 3/29/2013. The analyzable period ended on 3/25/2013 after 6 days of pumping because packer leakage increased and water levels rose (Figure 4). Discharge during the constant-rate test averaged 303 gal/min with a total groundwater withdrawal of about 4.0 million gallons. Total withdrawal during the period of well development and testing was about 5.8 million gallons (Figure 4).

Water-levels were measured in wells *ER-EC-13 shallow*, *ER-EC-13 intermediate*, and *ER-EC-13 deep* during development and testing of *ER-EC-13 main* lower zone. Water-level changes measured in wells *ER-EC-13 intermediate* and *ER-EC-13 deep* were affected minimally by thermal expansion because transducers were submerged 1,061 and 1,607 ft, respectively, prior to pumping. This was because most of the thermal expansion occurred above the transducers so measured pressures were affected minimally. Heating did affect water levels measured in well *ER-EC-13 shallow* where the transducer was submerged less than 50 ft.

Drawdowns in wells *ER-EC-13 intermediate* and *ER-EC-13 deep* were estimated by subtracting water levels prior to pumping from measured water levels. Environmental fluctuations were ignored in these wells because barometric and tidal changes were less than the measurement resolution of the transducers. Maximum drawdown in well *ER-EC-13 intermediate*, adjacent to the pumping well, during the constant-rate test was about 290 ft (Figure 4).

Drawdowns in well *ER-EC-13 shallow* were indeterminate because of thermal expansion. Maximum drawdown in well *ER-EC-13 shallow* was assumed to be less than 0.1 ft.

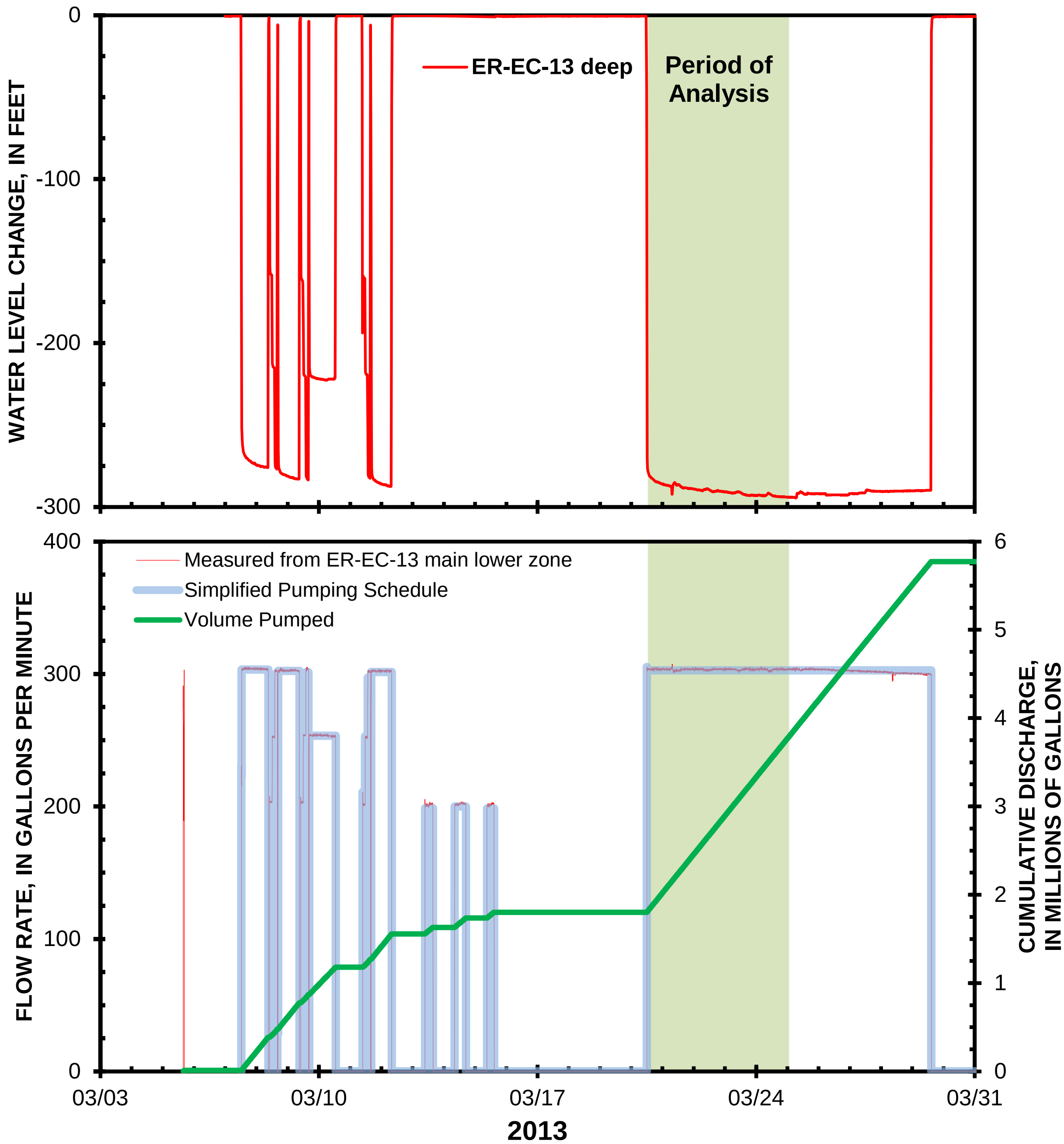

Figure 4.—Pumping from *ER-EC-13 main lower zone* during well development and aquifer testing, March, 2013.

Analysis

Hydraulic conductivities of Upper, Middle, and Lower zones of the lava-flow aquifer and adjacent tuff confining units (Figure 2) were estimated at the ER-EC-13 well cluster by simultaneously minimizing differences between simulated and measured drawdowns during both aquifer tests. Drawdowns were simulated with two-dimensional, radial MODFLOW models (Harbaugh and others, 2000). The models were identical except that well construction differed between upper-zone and lower-zone aquifer tests. Parameter estimation was performed by minimizing a weighted sum-of-squares objective function with PEST (Doherty, 2008).

The production well and aquifer system were simulated with an axisymmetric, radial geometry in a single MODFLOW layer in each model (Langevin, 2008). Radial distance increased with increasing column indices and depth increased with increasing row indices. Hydraulic conductivities and storages of the i^{th} column were multiplied by $2\pi r_i$ to simulate radial flow where r_i was the distance from the outer edge of the first column to the center of the i^{th} column.

Models extended from a production well to more than 200,000 ft away and from the water table to 3,000 ft below land surface. The model domain was discretized into a layer of 41 rows of 53 columns. Cell widths ranged from 0.05 ft adjacent to the production well to 40,000 ft in the farthest column. Vertical discretization (row height) was a uniform 50 ft, except for a 1-ft thick layer at the water table so specific yield values could be specified directly. All external boundaries were at sufficient radial distance to be specified as 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. Discharges during the constant-rate tests were simulated with a single stress period. Initial heads were specified as 0.

The production well was simulated as a high conductivity zone with vertical conductances multiplied by 10^9. Water was removed from the uppermost node in a well and MODFLOW was allowed to apportion inflow to the well. Wellbore storage associated with the production well was simulated, but early-time data (where wellbore storage is active) was not compared in the objective function.

Potential leakage around packers also was simulated with two cells in the well between the upper and lower zones that could be estimated independently during each aquifer test. Packer leakage seemed likely because most of the drawdown in the unpumped interval occurred during the first hour of each aquifer test followed by very little additional drawdown over the remaining test period. For example, a drawdown of 1.5 ft was observed in well *ER-EC-13 deep* an hour after pumping began from well *ER-EC-13 main upper zone* (Figure 5). Less than 0.2 ft of additional drawdown occurred during the next 5 days of pumping well *ER-EC-13 main upper zone*.

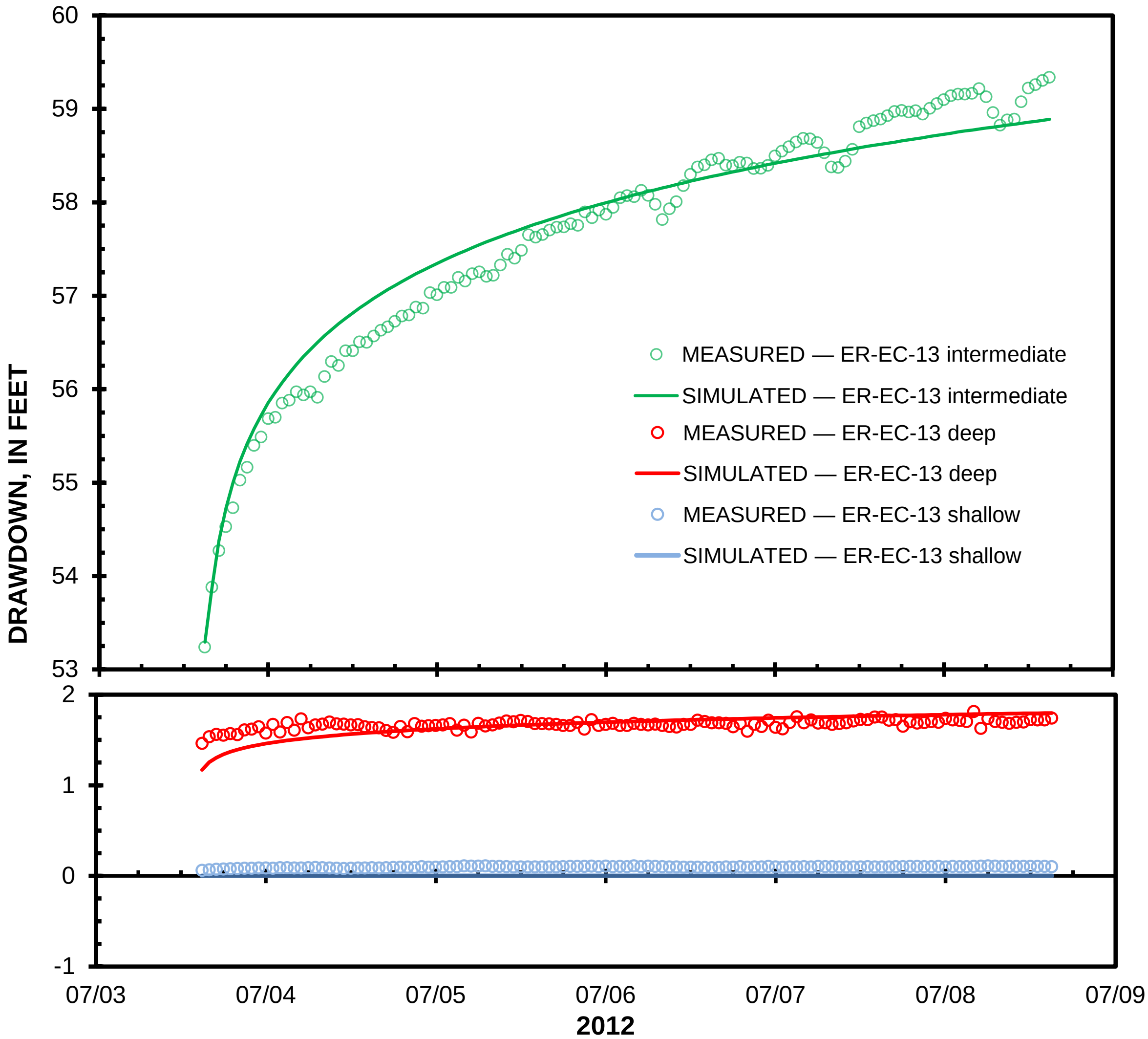

Figure 5.—Measured and simulated drawdowns during the constant-rate aquifer test of well *ER-EC-13 main upper zone* in wells *ER-EC-13 shallow*, *ER-EC-13 intermediate*, and *ER-EC-13 deep*.

Hydraulic Property Estimates

Hydraulic properties of the geohydrologic column and wells were estimated at the ER-EC-13 well cluster. Horizontal hydraulic conductivities of Upper, Middle, and Lower zones of the lava-flow aquifer were estimated independently. A single hydraulic conductivity was assigned and estimated for the tuff confining units that overlie and underlie the lava-flow aquifer (Figure 2). Two uniform hydraulic conductivities were assigned to the well screens of the upper and lower zones and were estimated independently. Different hydraulic conductivities were assigned and estimated for the packer during each aquifer test. A uniform vertical–to-horizontal anisotropy of 1 was assigned from the water table to the base of the aquifer. Uniform specific storage and specific yield of 2.0E-6 1/ft and 0.02 dimensionless, respectively, were assigned throughout the geohydrologic column and were not estimated (Halford and others, 2010).

Simulated and measured drawdowns matched within the error of the measurements (Figures 5 & 6). RMS errors of 0.3, 0.1, and 0.1 ft in wells *ER-EC-13 intermediate*, *ER-EC-13 deep*, and *ER-EC-13 shallow*, respectively, during the constant-rate aquifer test of well *ER-EC-13 main upper zone* were similar to the noise in the respective measurements (Figure 5). RMS errors of 0.9, 0.06, and 0.03 ft in wells *ER-EC-13 deep*, *ER-EC-13 intermediate*, and *ER-EC-13 shallow*, respectively, during the constant-rate aquifer test of well *ER-EC-13 main upper zone* were similar to the noise in the respective measurements (Figure 6).

Transmissivity of the Fortymile Canyon composite unit totaled 5,000 ft^2/d. Transmissivity estimates for the Upper and Lower zones were 3,600 and 1,400 ft^2/d, respectively (Table 2). Vertical leakances of the tuff confining units were indeterminate because drawdowns were not detected in well *ER-EC-13 shallow* during either aquifer test. Drawdowns ceased to be simulated in well *ER-EC-13 shallow* where hydraulic conductivities of the tuff confining units were less than 0.0001 ft/d or vertical leakances were less than 1.0E-7 1/day (Table 2). The middle zone of the lava-flow aquifer is a low permeability interval with a vertical leakance of less than 3.0E-7 1/day. Transmissivities and vertical leakances are reported because these values will change little if the geohydrologic units are reinterpreted and thicknesses change.

Table 2.--Hydraulic property estimates at ER-EC-13 well cluster.

Simulated Unit	Top of Unit, feet BLS	Hydraulic Conductivity, feet/day	Transmissivity, feet²/day	Vertical leakance, 1/day
Tuff confining unit	1,010	< 0.0001	0	< 1.E-07
Lava-Flow aquifer, upper zone	1,800	12	3,600	—
Middle Zone	2,100	< 0.0001	0	< 3.E-07
Lava-Flow aquifer, lower zone	2,250	5	1,400	—
Tuff confining unit	2,550	< 0.0001	0	< 3.E-07
Base of model	3,000	—	—	—

Drawdowns in unpumped intervals of the lava-flow aquifer resulted from packer leakage rather than flow across the middle zone. Alternative models were created and calibrated where hydraulic conductivities of 0.0001, 0.001, 0.01, and 0.1 were assigned to the middle zone. Simulated drawdowns in well *ER-EC-13 intermediate* during the constant-rate aquifer test of well *ER-EC-13 main lower zone* ceased to match measured drawdowns where hydraulic conductivities of the middle zone exceeded 0.001 ft/d (Figure 7). The shape of the drawdowns also diverged as simulated drawdowns increased gradually during the 5-day test while measured drawdowns increased rapidly during the first hour and little during the remainder of the pumping period. Simulated drawdowns in well *ER-EC-13 deep* during the constant-rate aquifer test of *ER-EC-13 main upper zone* (Figure 8) were similar to simulated drawdowns in well *ER-EC-13 intermediate* from the *ER-EC-13 main lower zone* test (Figure 7) because packer leakage controlled drawdowns in the unpumped zone.

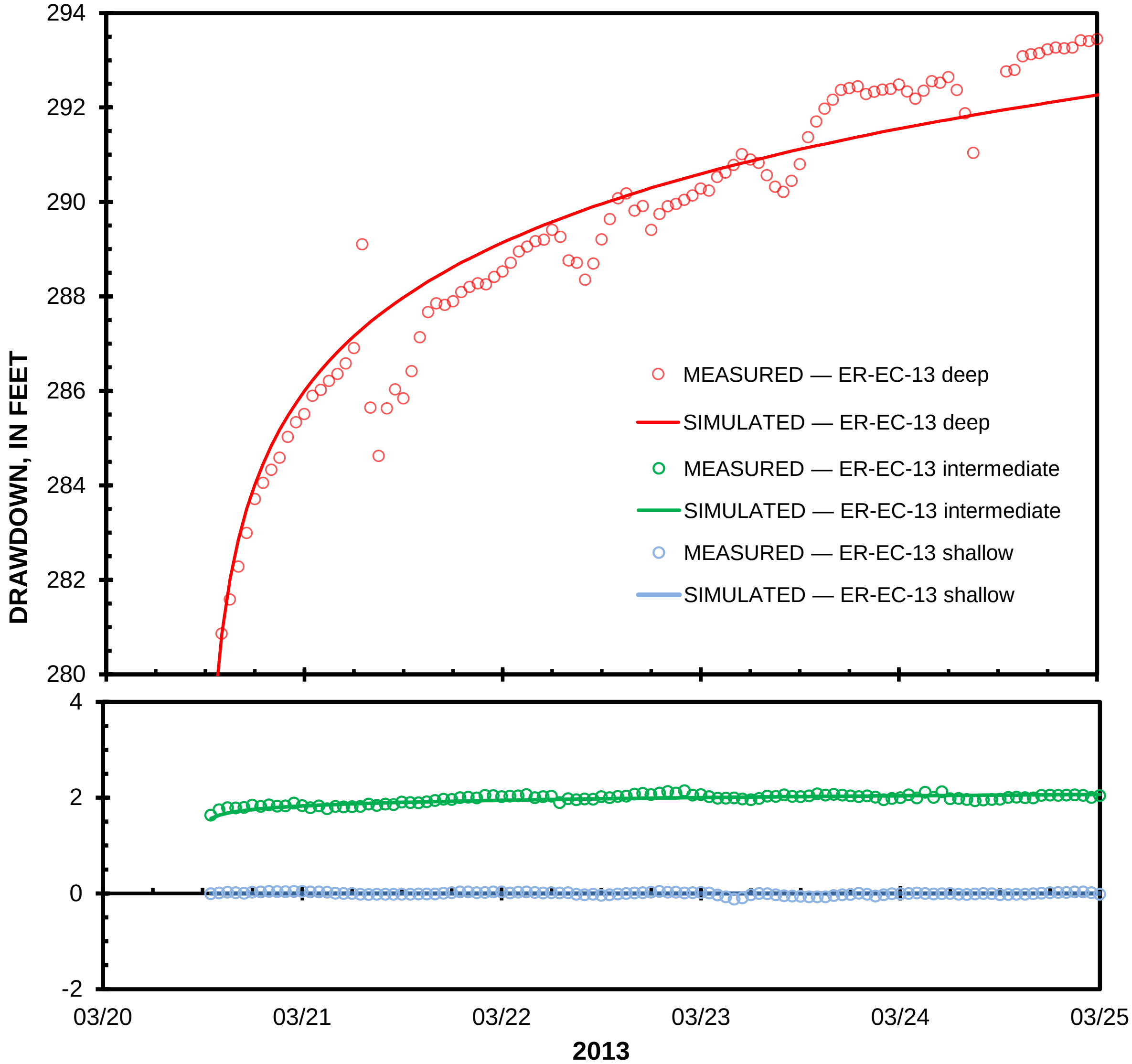

Figure 6.—Measured and simulated drawdowns during the constant-rate aquifer test of well *ER-EC-13 main lower zone* in wells *ER-EC-13 shallow*, *ER-EC-13 intermediate*, and *ER-EC-13 deep*.

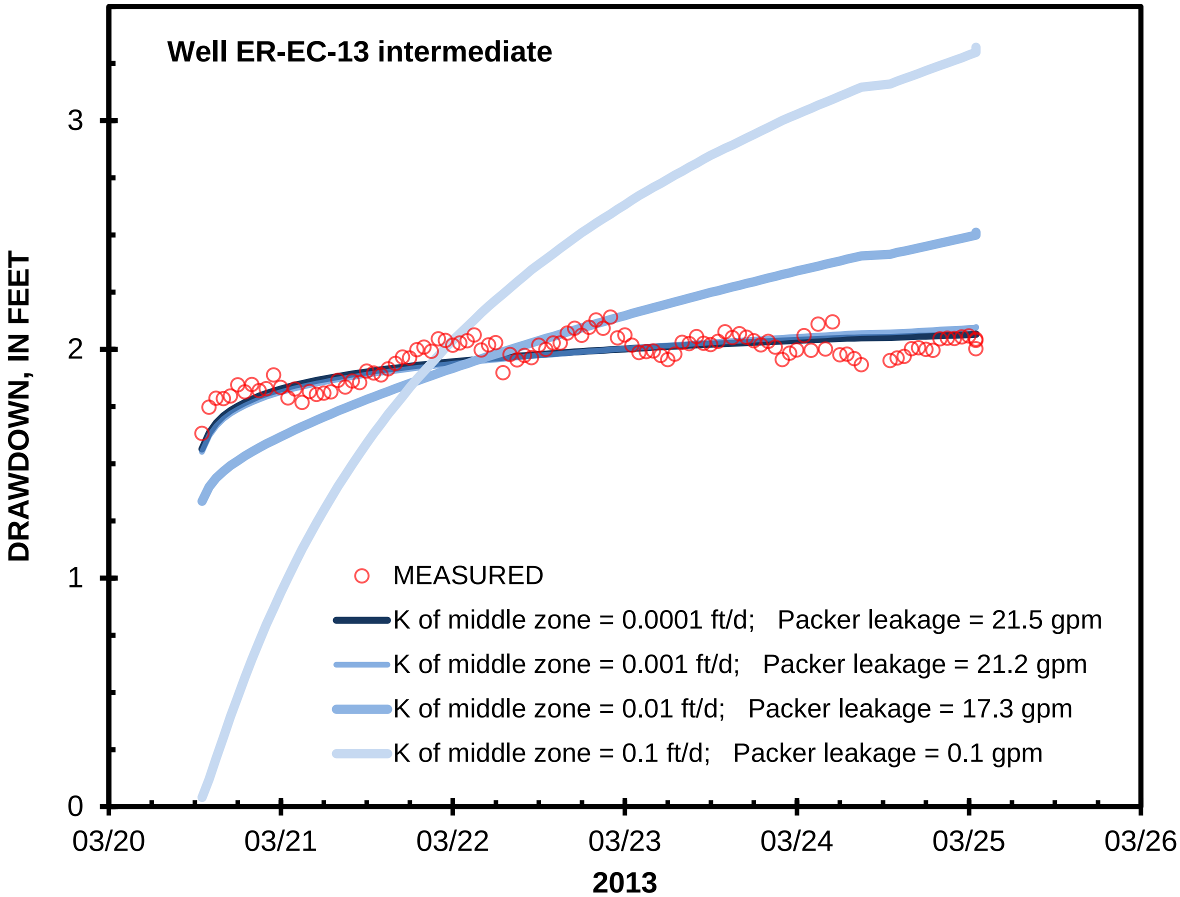

Figure 7.—Measured and simulated drawdowns in well *ER-EC-13 intermediate* during the constant-rate aquifer test of well *ER-EC-13 main lower zone*. Drawdowns were simulated with alternative models where different hydraulic conductivities of the middle zone were specified.

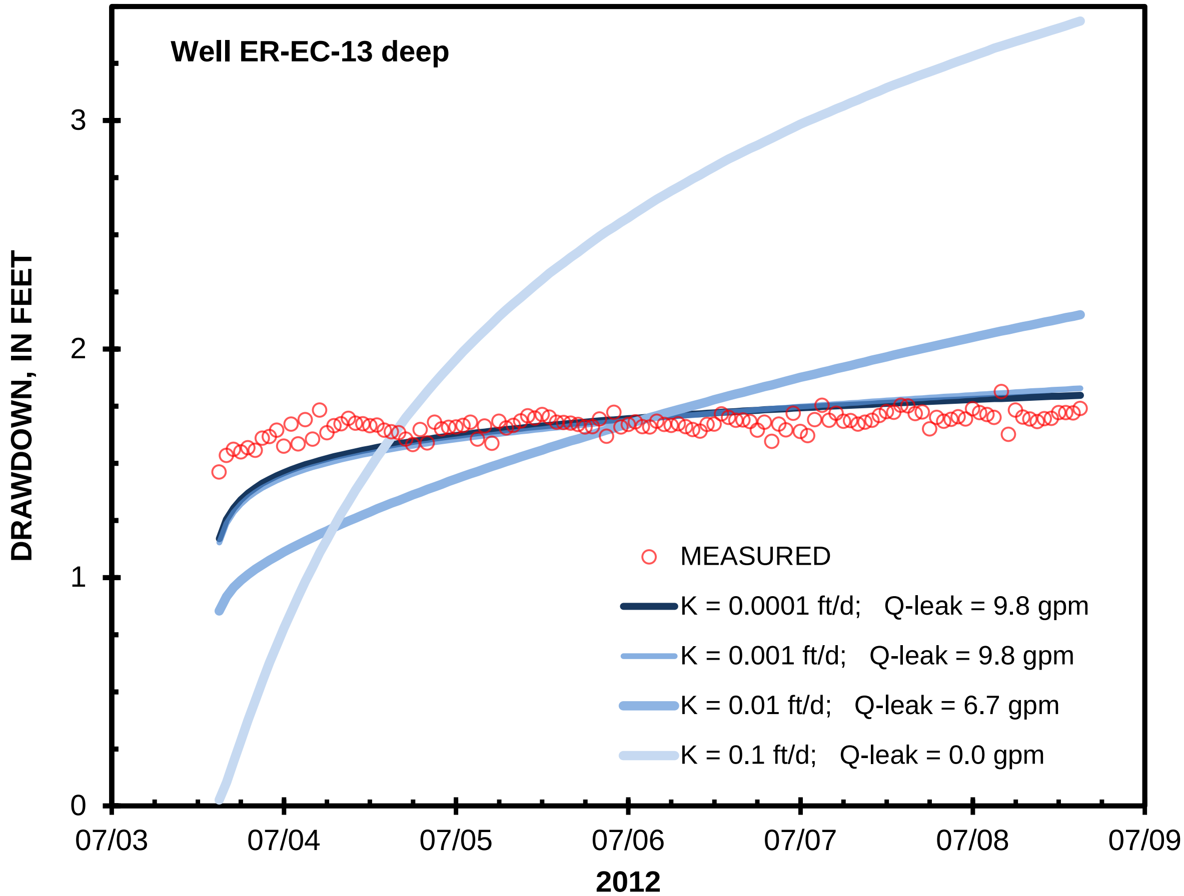

Figure 8.—Measured and simulated drawdowns in well *ER-EC-13 deep* during the constant-rate aquifer test of well *ER-EC-13 main upper zone*. Drawdowns were simulated with alternative models where different hydraulic conductivities of the middle zone were specified.

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Appendix A. Construction diagram well cluster ER-EC-13

As-built diagram of the well completion for well cluster ER-EC-13 which includes the wells *ER-EC-13 main, ER-EC-13 deep, ER-EC-13 intermediate,* and *ER-EC-13 shallow* (U.S. Department of Energy, 2011).

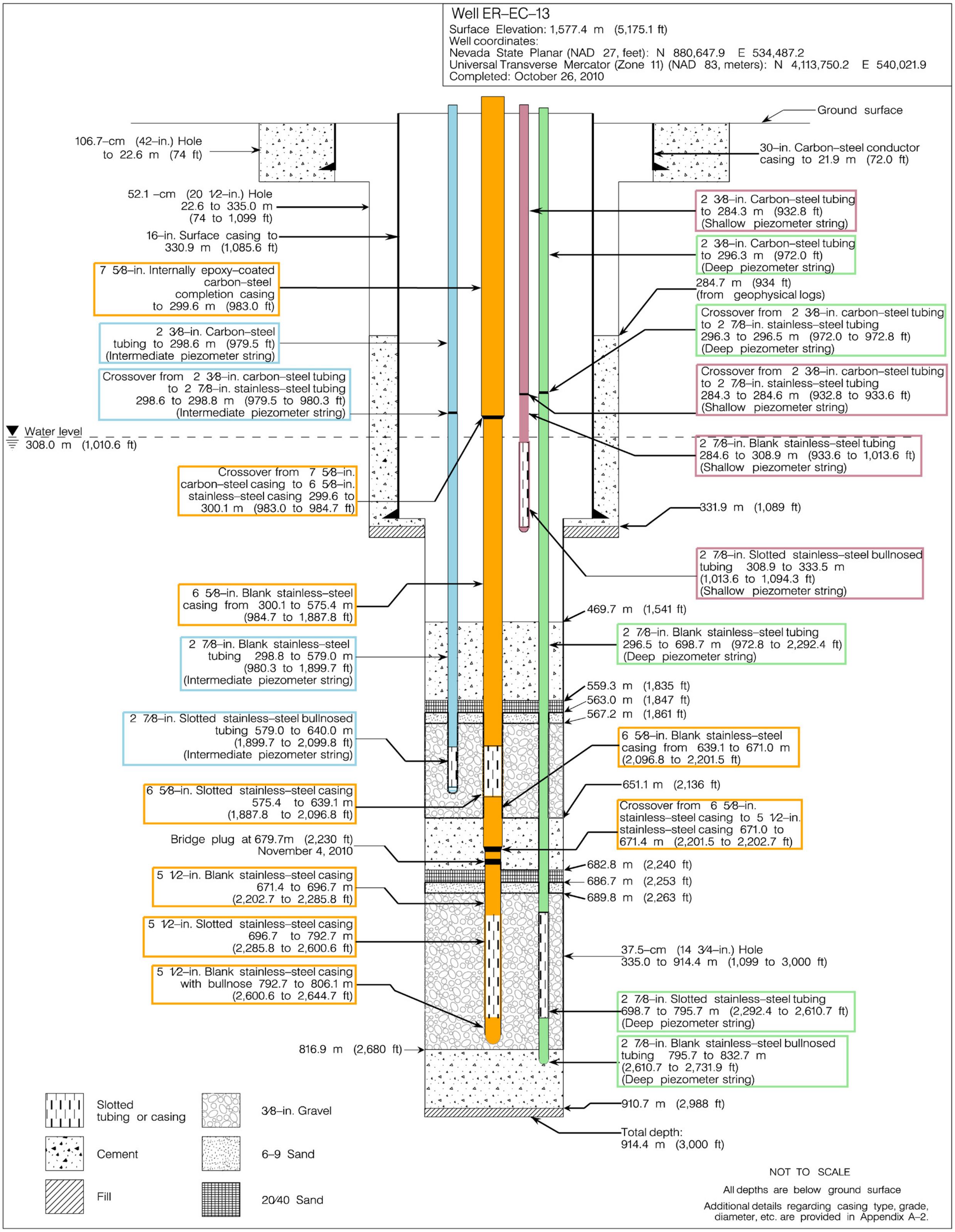

Figure 7-1
As-Built Completion Schematic for Well ER-EC-13