United States Department of the Interior

U. S. GEOLOGICAL SURVEY

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MEMORANDUM

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

From: Michael T. Pavelko, Hydrologist and Keith J. Halford, Ground-Water Specialist, Nevada District, WRD

Subject: AQUIFER TEST—Analysis of multiple-well aquifer test RNM-2s, Frenchman Flat, Nevada

A multiple-well aquifer test was conducted in Frenchman Flat, Nevada, to estimate the hydraulic properties of the alluvial aquifer in the vicinity of well RNM-2s (Figure 1). RNM-2s was pumped for 75 days at 600 gpm between April 26, 2003 and July 10, 2003. The test was funded by the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office. Shaw Environmental, Inc. was the lead contractor responsible for providing site supervision and testing services. Stoller-Navarro Joint Venture was responsible for the primary analysis of the aquifer-test data. The U.S. Geological Survey provided quality assurance by also analyzing aquifer-test results from pumping RNM-2s. Hydraulic property estimates from the RNM-2s aquifer test will constrain calibration of local contaminant transport models (DOE/NV, 1999 and DOE/NV, 2000).

Site and Geology

The aquifer test occurred in Area 5 of the Nevada Test Site, northwest of Frenchman Lake (Figure 1). The alluvial aquifer is comprised of largely undifferentiated intervals of silt, sand, and gravel from 0 to 3,700 ft below land surface (IT Corporation, 2003).

The hydraulic base of the alluvial aquifer ranges was assumed to be 2,300 ft below land surface, but could be as deep as 3,700 ft below land surface. An interval between 2,300 and 2,800 ft below land surface has been differentiated in wells ER-5-4 and ER-5-4#2 (IT Corporation, 2001; IT Corporation, 2003). The differentiated interval

was described as silty to sandy clay in well ER-5-4 and as sand and silt deposits in well ER-5-4#2. Both lithologic descriptions suggest the differentiated interval is less permeable than the interbedded very fine to coarse sand from 760 to 2,300 ft below land surface (IT Corporation, 2001).

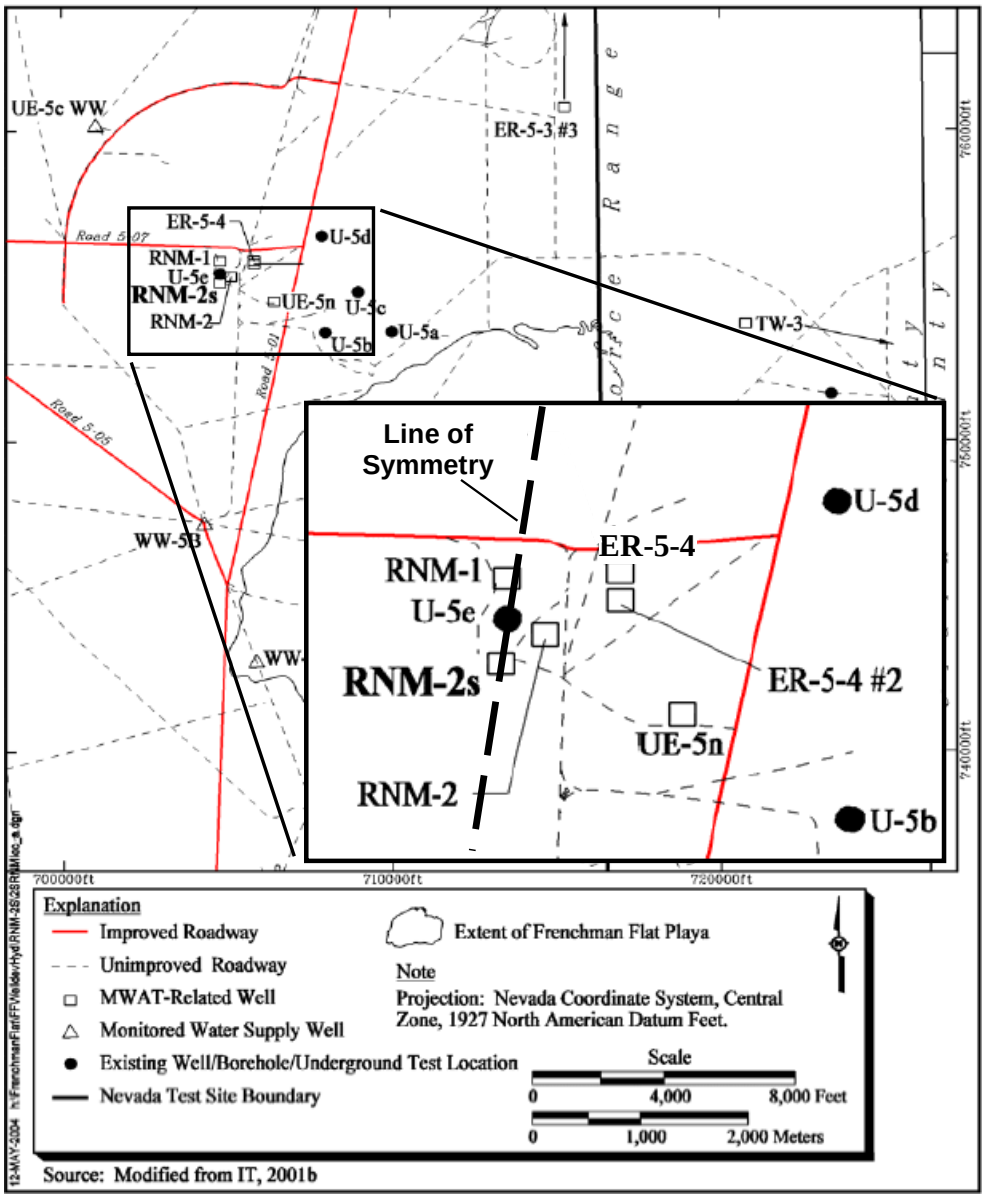

Figure 1.—Location of RNM-2s aquifer test, Frenchman Flat, Nevada.

The alluvial aquifer in the immediate vicinity of pumping well RNM-2s was altered by the Cambric Event, an underground nuclear experiment (Bryant, 1992). A 50 to 75 ft diameter cavity and chimney were created by the 0.75-Kt event. The cavity and

chimney extend above the water table, 710 ft below land surface, and below the working point, 970 ft below land surface. Hydraulic conductivity likely is increased in the rubble-filled cavity and chimney (Tompson and others, 1999). A zone of compressed rock and melt glass exists around the cavity which likely decreases hydraulic conductivity. Hydraulic conductivity around the chimney also could be affected by the Cambric event, but the effect is unknown.

Many observation wells were not designed for aquifer testing which affected drawdowns. Well RNM-1 was completed with perforated casing, instead of screen, in the Cambric cavity. RNM-2 also was completed with perforated casing, has filled with formation material, and has an obstruction at 770 ft below land surface (Stoller-Navarro, 2004). RNM-2s (Outer West Piezometer) was completed as an open tube with no screen. ER-5-4 (shallow) was not developed and communicates poorly with the aquifer because of entrained drilling fluid (Stoller-Navarro, 2004).

Table 1.—Well location and construction data for RNM-2s multiple-well aquifer test.

[Latitude and longitude are in degrees, minutes, and seconds and referenced to North American Datum of 1927; ft amsl, feet above sea level; ft bgs, feet below ground surface; wells without a bottom perforation are open-tube piezometers without screens and open at the top of perforations depth.]

Well name	Latitude	Longitude	Ground surface elevation (ft amsl)	Hole depth (ft bgs)	Perforations	
					Top (ft bgs)	Bottom (ft bgs)
RNM-2s	36°49'22"	115°58'01"	3130.22	1156	1038	1119
RNM-2s (Outer West Piezometer)	36°49'22"	115°58'01"	3130.22	1156	1038	open tube
RNM-2	36°49'23"	115°57'57"	3128.80	935	720	820
RNM-1[1]	36°49'28"	115°58'01"	3135.17	936	858	929
ER-5-4#2	36°49'27"	115°57'48"	3127.00	7000	6486	6658
ER-5-4 (deep)	36°49'27"	115°57'48"	3127.00	3732	1769	2113
ER-5-4 (shallow)	36°49'27"	115°57'48"	3127.00	3732	723	813
UE-5n	36°49'15"	115°57'41"	3113.04	1687	720	730
ER-5-3#3	36°52'23"	115°56'17"	3337.40	1800	1492	1744
TW-3	36°48'30"	115°51'26"	3484.12	1860	1356	open tube

[1] RNM-1 was drilled 21° from the vertical towards the U-5e emplacement hole.

Measurements

One production well and nine observation wells were used for the aquifer test (Table 1, Figure 1). Each well was instrumented with a pressure transducer and water-levels were measured at least once an hour. Water levels were measured between April 11, 2003 and September 12, 2003 which was two weeks before the test to two months after the test.

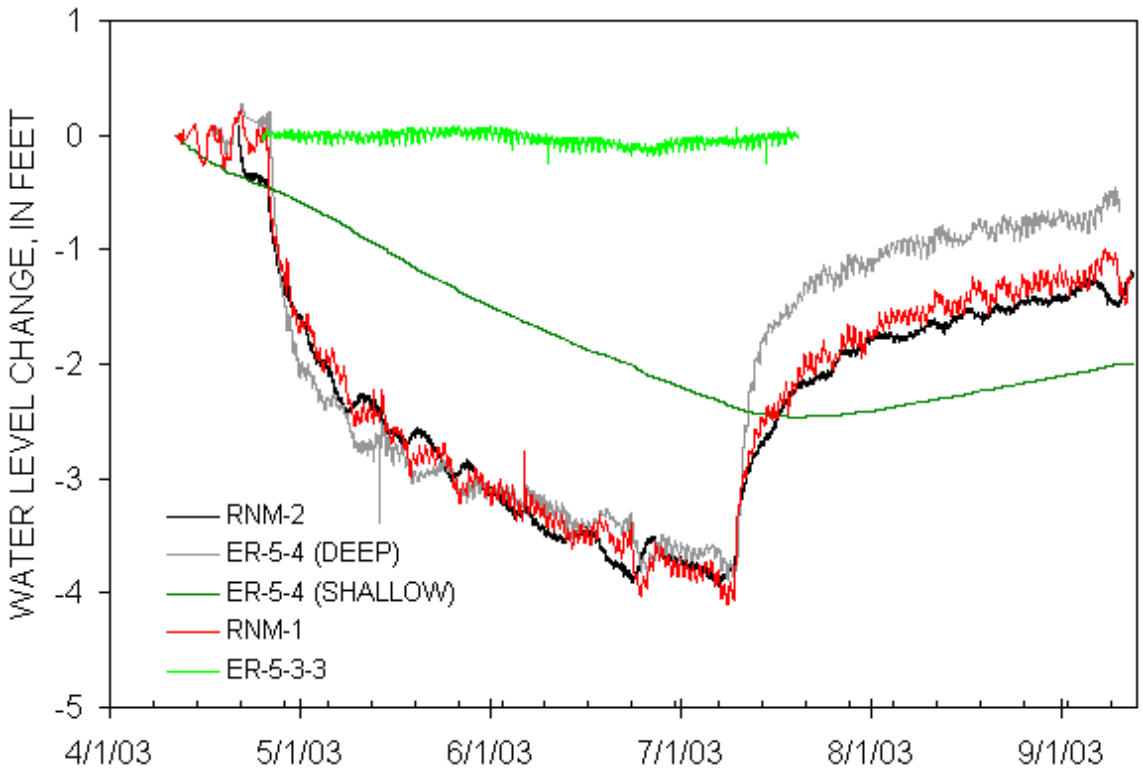

Figure 2.—Water level changes in selected observation wells.

Well RNM-2s began pumping April 26, 2003 and discharged about 600 gpm for 75 days. Production rates were measured with a 4.0-inch magnetic flowmeter system (Stoller-Navarro, 2004). Production ceased three times for periods of 3 hours or less during the 75-d test. Drawdowns were affected negligibly by these brief pauses in pumping.

Results were not affected by pumping from water supply wells near the RNM-2s aquifer test. Well WW-5B was the closest water supply well and was located 1.5 miles

south of RNM-2s (Figure 1). Monthly pumping rates averaged 50 gpm during 2003. Well WW-5C was 2.5 miles from RNM-2s and pumped less than 40 gpm during 2003.

Drawdowns were estimated by subtracting the water level prior to pumping from subsequent water levels. Barometric and earth-tide effects were removed from measured water levels before drawdowns were estimated. Drawdowns were estimated only for the pumping phase of the test. Recovery data were not analyzed because uncertainty of drawdown estimates increases while drawdowns decrease during recovery.

Drawdowns were not estimated from water levels in wells RNM-2s (Outer West Piezometer), ER-5-4#2, UE-5n, ER-5-3#3, and TW-3. Water-levels in wells ER-5-4#2 and TW-3, completed low-permeability, air-fall tuff below the alluvial aquifer, did not respond to pumping. Well ER-5-3#3 was 4 miles from RNM-2s and did not respond to pumping. Well RNM-2s (Outer West Piezometer) communicated very poorly with the aquifer so meaningful drawdowns could not be estimated (Stoller-Navarro, 2004).

Analysis

Hydraulic properties of the alluvial aquifer were estimated with analytical and numerical models. Transmissivity, specific yield, specific storage, and vertical anisotropy were estimated with all models. The analytical model was the Moench solution for unconfined aquifers (Barlow and Moench, 1999). Hydraulic properties associated with the Cambric cavity were estimated with a numerical model which was solved with MODFLOW (Harbaugh and McDonald, 1996).

All hydraulic properties were estimated by minimizing weighted sum-of-squares differences between simulated and measured drawdowns. The analytical model was calibrated with the Solver in Excel. The numerical model was calibrated with MODOPTIM (Halford, 1992). Observations from well ER-5-4(DEEP) were weighted most because the completion was good and the surrounding aquifer was unaffected by the Cambric event. Simulated and measured drawdowns from 1 day after pumping began were compared in well RNM-2s. This was done so that hydraulic properties of the aquifer affected calibration results more than the construction of the pumping well.

Analytical model: Unconfined Moench Solution

The analytical model that best approximated the alluvial aquifer was the unconfined Moench solution (Barlow and Moench, 1999). This analytical model assumes that hydraulic conductivity is homogeneous and vertically anisotropic. Effects of a partially penetrating production well and observation wells with finite screens and wellbore storage also are simulated.

Simulated drawdowns were fitted to measured drawdowns in wells ER-5-4(DEEP), ER-5-4(SHALLOW), and RNM-2s. Drawdowns in these wells were not affected by the Cambric event. Well RNM-1 penetrated the Cambric cavity. Measured drawdowns were about an order of magnitude less than any homogeneous model could explain so drawdowns in well RNM-1 were not compared. Drawdowns in well RNM-2 parallel drawdowns in well RNM-1 and likewise could not be explained. Simulated drawdowns matched measured drawdowns with a root-mean-square (RMS) error of 0.12 ft (Figure 3). The RMS error was less than 2 percent of the 7-ft range in drawdowns that were analyzed.

Hydraulic property estimates were reasonable for an alluvial aquifer (Table 2). Hydraulic conductivity is 1.1 ft/d if a 1,800-ft^2/d transmissivity is divided by a 1,600-ft aquifer thickness. Specific-storage of 2×10^{-6} ft^{-1} and specific yield of 0.19 agree with other estimates for alluvial material. A vertical-to-lateral anisotropy of 0.5 is more than expected but still plausible.

Transmissivity increased 40 percent to 2,500 ft^2/d if the alluvial aquifer was assumed to be 3,000 ft thick instead of 1,600 ft thick. Simulated drawdowns from the 1,600-ft thick and 3,000-ft thick models were very similar. Vertical-to-lateral anisotropy decreased slightly to 0.4 (Table 2). Estimates of specific-storage and specific yield were unchanged.

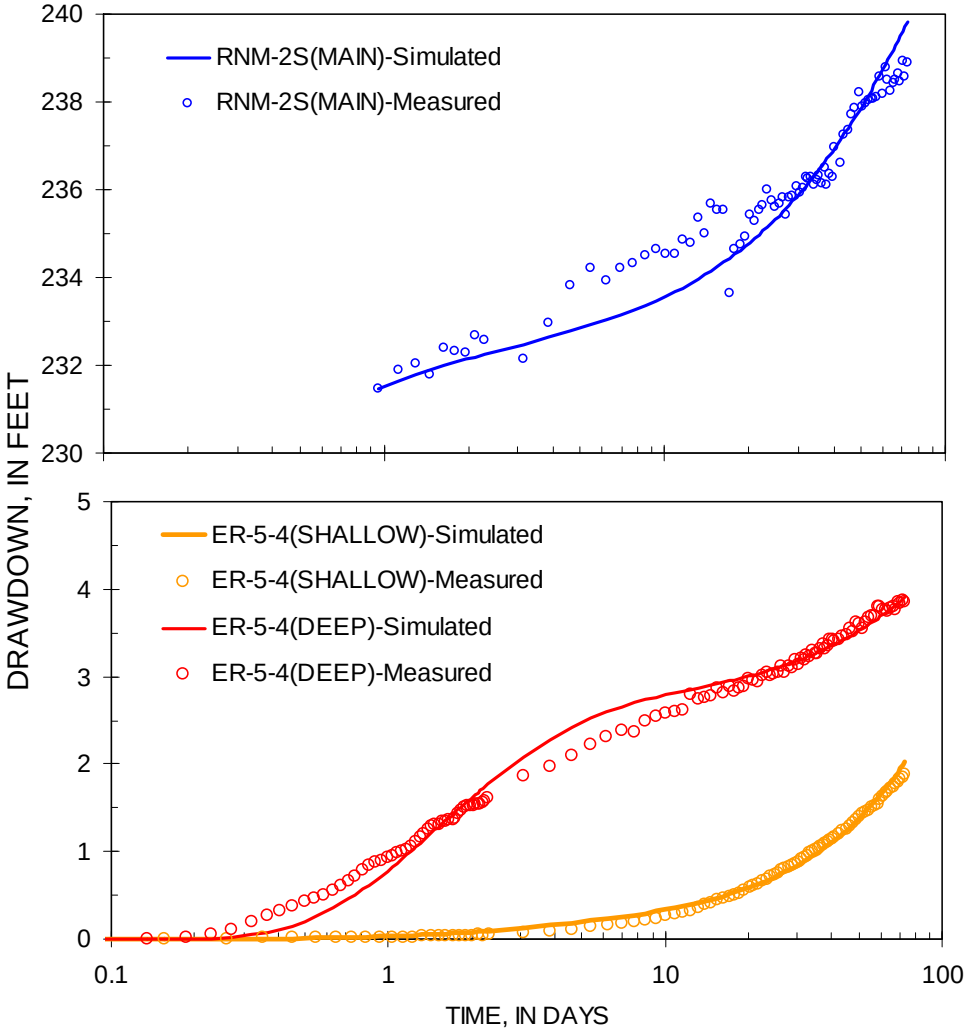

Figure 3.—Simulated drawdowns from unconfined Moench solution and measured drawdowns in wells RNM-2s, ER 5-4(Shallow), and ER 5-4(DEEP).

Table 2.—Hydraulic property estimates from analytical multiple-well, numerical multiple-well, and geometric mean of single-well solutions.

METHOD	Transmissivity, ft^2/d	Hydraulic Conductivity, ft/d [a]	Vertical-to-Horizontal Anisotropy	Specific Yield	Specific Storage, ft^{-1}
Analytical Multiple Well 1600 [1]	1,800	1.1	0.5	0.19	2.E-06
Analytical Multiple Well 3000 [1]	2,500	0.8	0.4	0.19	1.E-06
Numerical Multiple Well 1600 [1]	1,900	1.2	0.9	0.22	3.E-06
Numerical Multiple Well 3000 [1]	2,600	0.9	0.7	0.21	2.E-06
Simple Geometric Mean	8,000	5.0	0.4	0.15	1.E-05

[1] Value is the assigned thickness of the alluvial aquifer in feet.

[a] Hydraulic conductivity is the transmissivity divided by the saturated thickness of the aquifer.

Numerical model: MODFLOW

Results from the RNM-2s aquifer test also were analyzed with a numerical model to test the effect of the Cambric cavity on drawdowns in well RNM-1. A line of symmetry was assumed to bisect well RNM-2s and the cavity so only half of the area of interest was simulated (Figure 4). Heterogeneities approximated the cavity-chimney interior, cavity skin, chimney skin, and developed zone around the pumping well (Figure 5). Hydraulic conductivity was assumed to be homogeneous and vertically anisotropic in the undisturbed aquifer as in the analytical model.

The model domain was discretized into 21 layers of 80 rows and 35 columns (Figures 4 and 5). The numerical model extended laterally 100,000 ft away from well RNM-2s. The vertical extent was from 710 to 2,300 ft below land surface. Rows and columns were assigned widths of 15 ft near well RNM-2s and the cavity (Figure 4). Row and column widths were multiplied by 1.3 from near well RNM-2s to the edges of the model. Layer thicknesses ranged from 1 ft at the water table to 100 ft at the base of the aquifer (Figure 5). 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 RNM-2s aquifer test was simulated with a 99-d stress period.

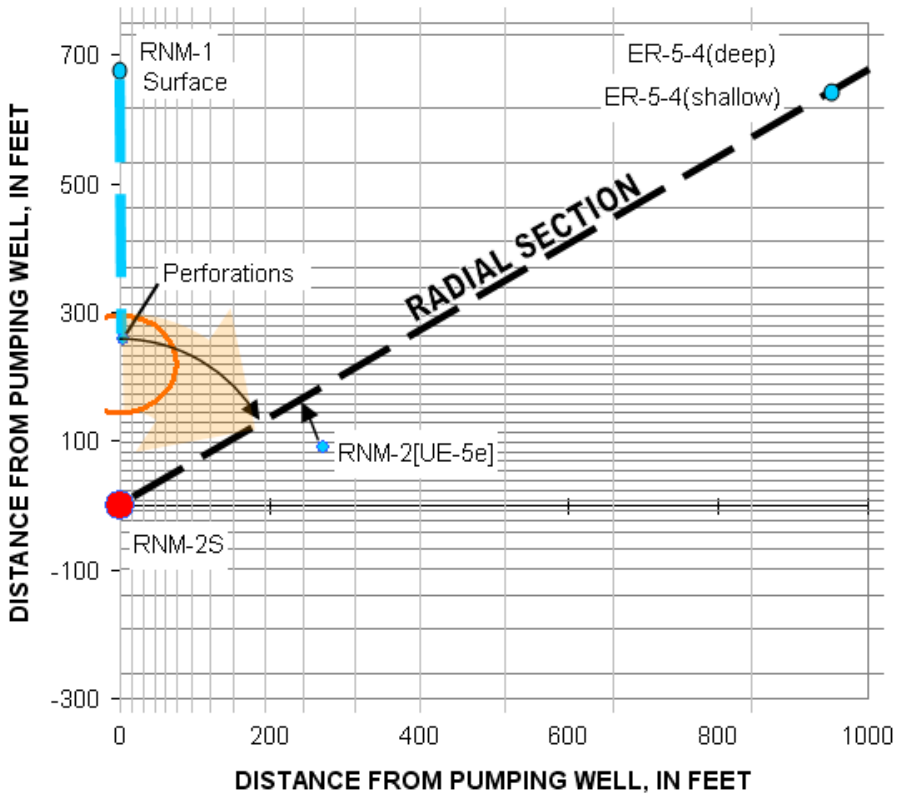

Figure 4.-- Numerical model grid and observation wells near RNM-2s oriented about the line of symmetry through well RNM-2s and the cavity.

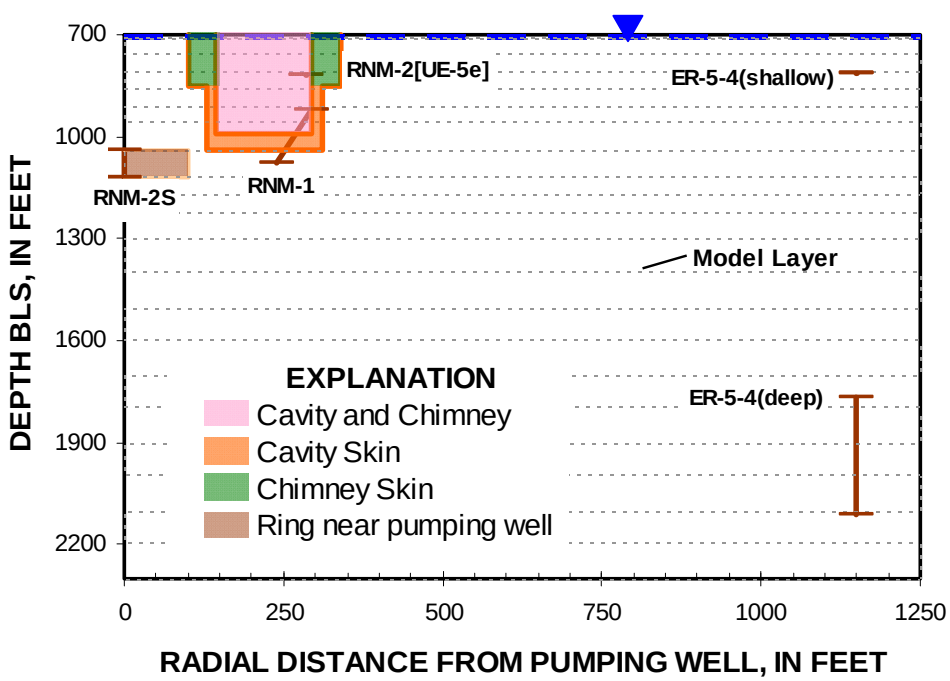

Figure 5.-- Radial cross section with hydrologic features and observation wells.

Measured drawdowns in well RNM-1 were compared with simulated drawdowns from the numerical model. Hydraulic conductivity estimates for the cavity-chimney, cavity skin, and chimney skin were constrained by observations from well RNM-1. Simulated drawdowns also were fitted to measured drawdowns in wells ER-5-4(DEEP), ER-5-4(SHALLOW), and RNM-2s as was done with the analytical models. Simulated drawdowns matched measured drawdowns with a root-mean-square (RMS) error of 0.08 ft (Figure 6). The RMS error was about 1 percent of the 7-ft range in drawdowns that were analyzed.

Measured drawdowns in well RNM-2 could not be explained with any reasonable model (Figure 7). Measured drawdowns in wells RNM-1 and RNM-2 paralleled one another which suggested that both wells were completed in the cavity. The reported position of the RNM-2 completion is more than 200 ft from the likely edge of the Cambric cavity. Simulated drawdowns were more than 3 times greater than measured drawdowns in well RNM-2 after 50 d of pumping (Figure 7).

Hydraulic property estimates for the alluvial aquifer from the analytical and numerical models differed little (Table 2). Hydraulic conductivity is 1.2 ft/d if a 1,900-ft^2/d transmissivity is divided by a 1,600-ft aquifer thickness. The vertical-to-lateral anisotropy of 0.9 was double the estimate from the analytical model. This was the only hydraulic property estimate for the alluvial aquifer that differed significantly between analytical and numerical models. Specific-storage of 3×10^{-6} ft^{-1} and specific yield of 0.22 agree with estimates from the analytical model.

The Cambric cavity is connected poorly to the surrounding alluvial aquifer. Hydraulic conductivity estimates of the cavity and chimney skins were 0.001 and 0.003 ft/d, respectively (Table 3). Conductance estimates of the cavity and chimney skins were equal because the thicknesses of the cavity and chimney skins were 15 and 45 ft, respectively. Hydraulic conductivity of the cavity-chimney fill is 2 ft/d which is similar to the hydraulic conductivity of the undisturbed aquifer.

Drawdown surfaces were predominantly spherical shells between the pumping well and the most distant observation well ER-5-4(DEEP) (Figure 8). Spherical

drawdown resulted from an 80-ft pumping interval which was 5 percent of the aquifer thickness. The Cambric cavity affected drawdown locally. Water flowed around the Cambric cavity which was hydraulically similar to an impermeable cylinder (Wheatcraft and Winterberg, 1985).

Transmissivity increased 40 percent to 2,600 ft^2/d if a 3,000-ft thickness was simulated instead of a 1,600-ft thickness. Simulated drawdowns from the 1,600-ft thick and 3,000-ft thick numerical models differed little. Vertical-to-lateral anisotropy decreased slightly to 0.7 (Table 3). Estimates of specific-storage and specific yield were unchanged. Hydraulic conductivity estimates for the cavity-chimney, cavity skin, and chimney skin were not affected by simulating a 3,000-ft thick aquifer.

Table 3.—Hydraulic properties estimated with the numerical model.

Hydraulic Property	Numerical 1600 [1]	Numerical 3000 [1]	Units
Transmissivity	1,900.	2,600.	ft^2/d
Vertical-to-Horizontal Anisotropy	0.9	0.7	d'less
Specific Yield	0.22	0.20	d'less
Specific Storage	0.000003	0.000002	ft^{-1}
Hydraulic Conductivity of Cavity-Chimney	1.9	2.0	ft/d
Hydraulic Conductivity of Cavity Skin	0.0014	0.0011	ft/d
Hydraulic Conductivity of Chimney Skin	0.003	0.003	ft/d
Specific Yield of Chimney [2]	0.50	0.50	d'less
Hydraulic Conductivity of developed zone around pumping well [2]	15.	15.	ft/d

[1] Value is the assigned thickness of the alluvial aquifer in feet.

[2] Value was assigned and was not estimated.

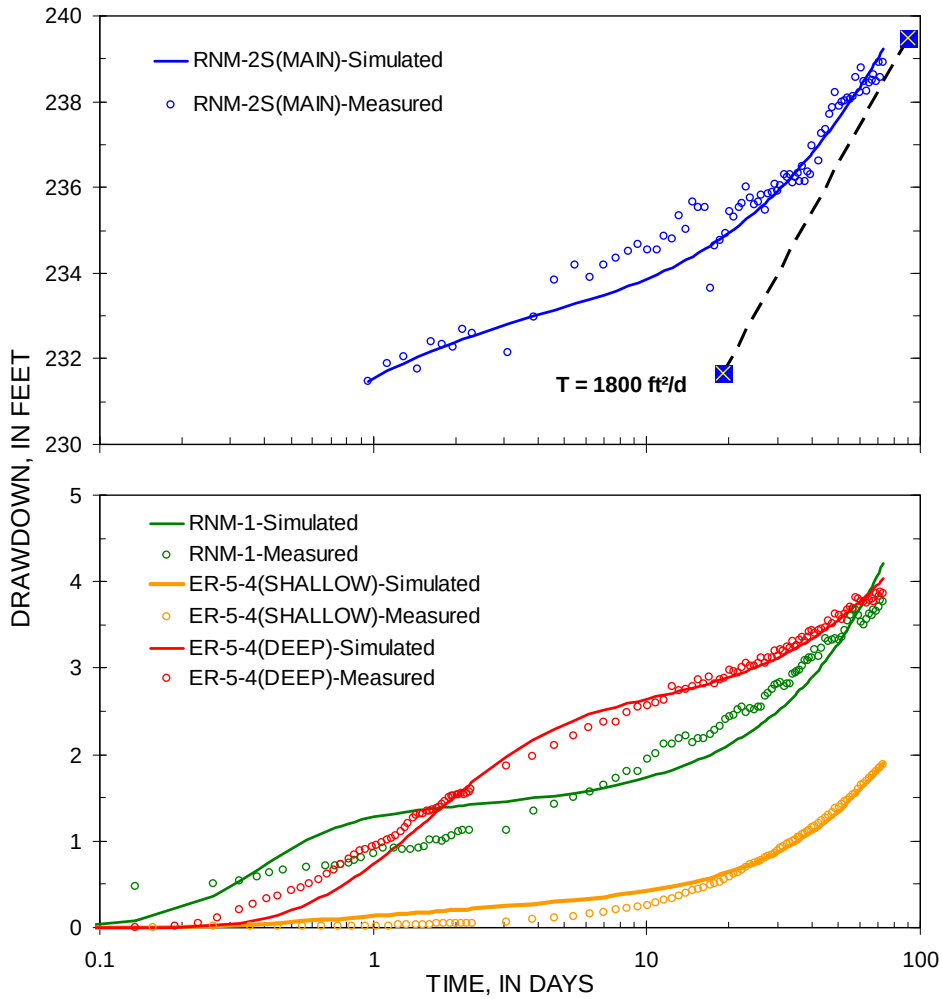

Figure 6.-- Simulated drawdowns from numerical model and measured drawdowns in wells RNM-2s, RNM-1, ER 5-4(Shallow), and ER 5-4(DEEP).

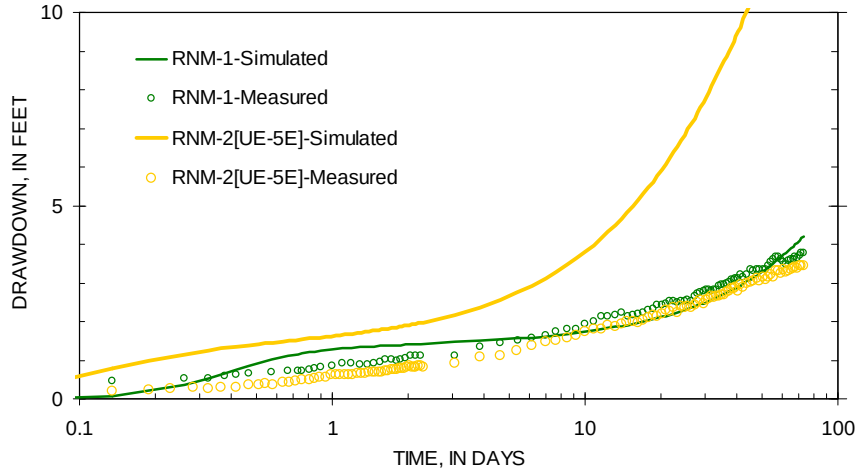

Figure 7.-- Simulated drawdowns from numerical model and measured drawdowns in wells RNM-1 and RNM-2[UE-5E].

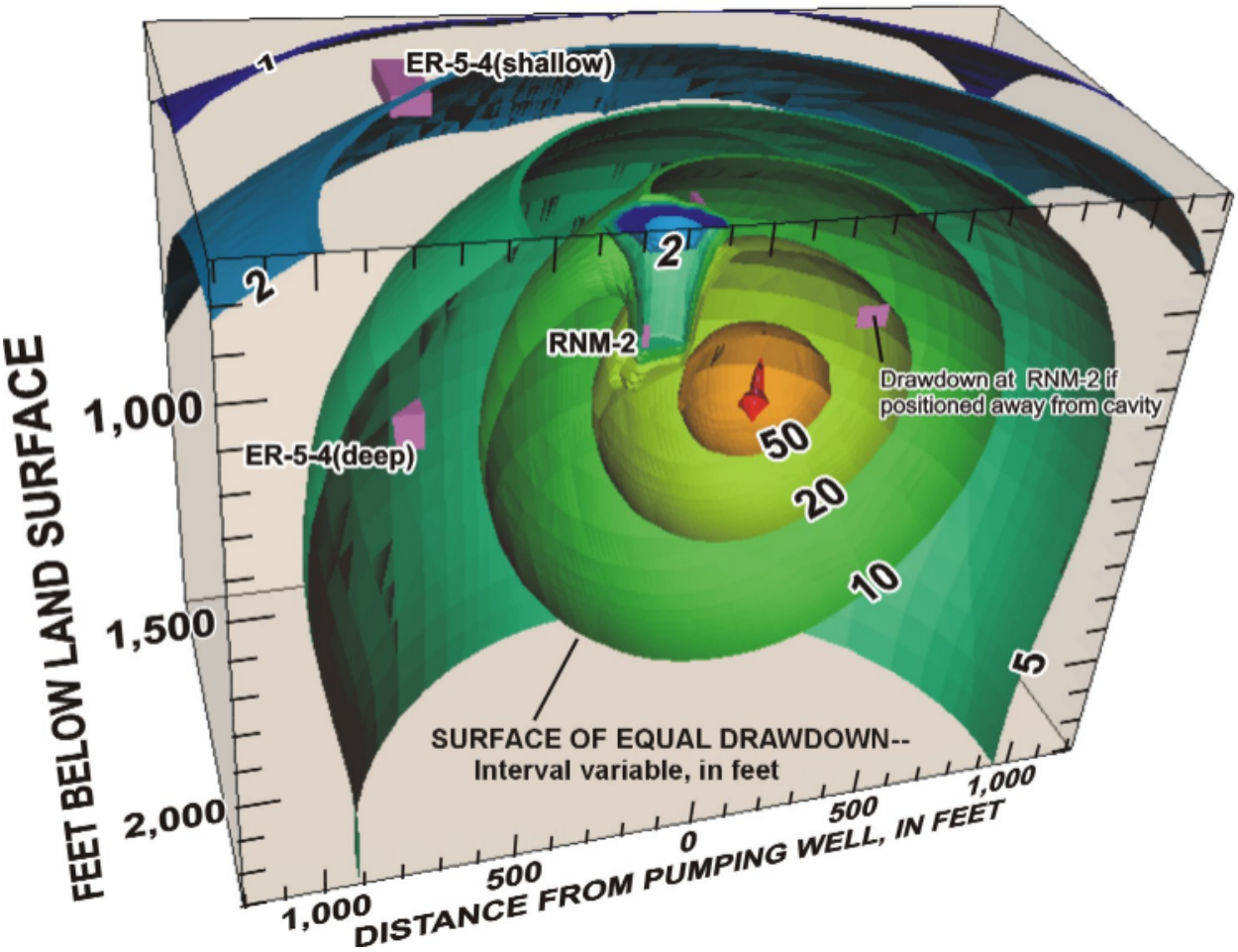

Figure 8.-- Simulated drawdown surfaces from numerical model after 50 d of pumpage at 600 gpm.

Simple Approach

Multiple-well aquifer tests have been interpreted by independently analyzing drawdowns in each well. Drawdowns that resulted from a single pumping event are interpreted and multiple transmissivity estimates are reported (Goode and Senior, 1998). Best estimates of transmissivity and other hydraulic properties are averages of individual estimates (Geldon and others, 2002). This method will be referred to as the "Simple Approach" in this memo.

Hydraulic property estimates from the RNM-2s aquifer test are non-unique if interpreted with the Simple Approach. For example, transmissivity could be estimated to be 3,000 or 14,000 ft^2/d by fitting an unconfined Moench solution to drawdowns in well ER-5-4(DEEP) (Figure 9). Fit between simulated and measured drawdowns is the

same for both models, but the aquifer system is interpreted quite differently. The aquifer with a transmissivity of 14,000 ft^2/d would be interpreted incorrectly as confined because the response is Theis like and a specific yield of 0.0001 is too small for unconfined aquifers. The aquifer with a transmissivity of 3,000 ft^2/d would be interpreted correctly as unconfined.

The RNM-2s aquifer test should not be interpreted with the Simple Approach despite good fits between simulated and measured drawdowns (CompareALL+IndependentTests_RNM-2s.xls). Transmissivities estimated from the RNM-2s test with the Simple Approach range from 1.5 to 10 times the multiple-well estimate of 2,000 ft^2/d (Table 4). The geometric mean of Simple-Approach estimates is 8,000 ft^2/d (Table 2). Transmissivity estimates departed most from the multiple-well estimate where the analyzed well had a poor completion or was in the cavity. Estimates of specific-storage, specific yield, and vertical-to-lateral anisotropy each range over an order of magnitude. Treating the five sets of parameter estimates from the Simple Approach as equivalent, independent results suggests a greater uncertainty than exists.

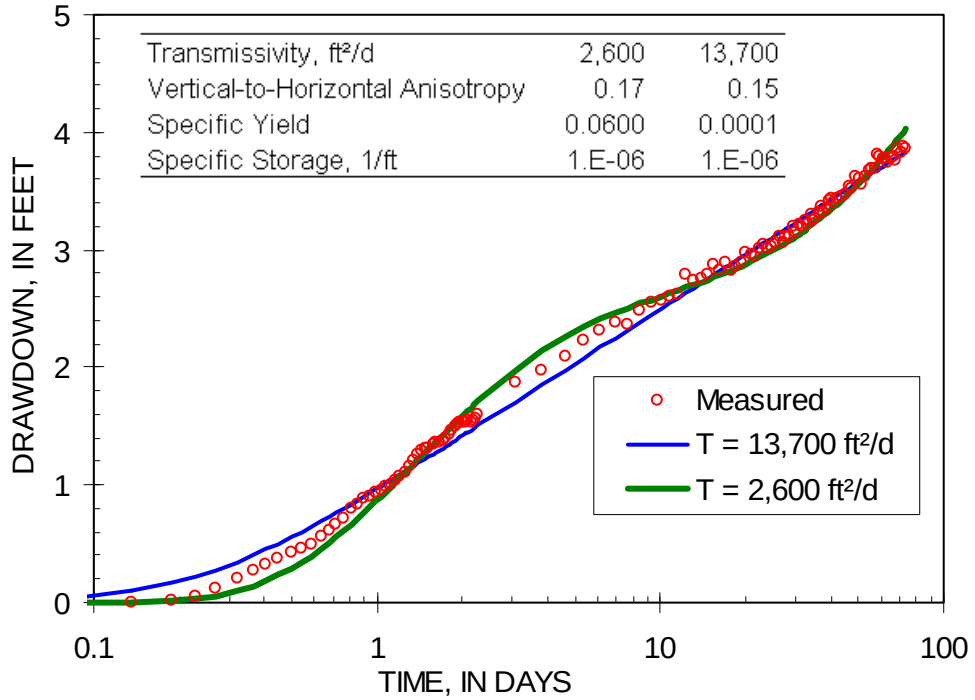

Figure 9.—Simulated drawdowns from alternative, unconfined Moench solutions and measured drawdowns in well ER 5-4(DEEP).

Table 4.—Hydraulic property estimates from five alternative Moench models that were matched to wells individually.

Observation Well	Transmissivity, ft²/d	Hydraulic Conductivity, ft/d	Vertical-to-Horizontal Anisotropy	Specific Yield	Specific Storage, ft^{-1}
ER-5-4(shallow)	9,000	5.7	0.59	0.18	8.E-06
ER-5-4(deep)	2,600	1.6	0.17	0.06	1.E-06
RNM-1	13,000	8.2	2.43	0.51	3.E-05
RNM-2[UE-5e]	22,000	14.0	0.07	0.09	4.E-05
RNM-2S	5,000	3.2	0.65	0.17	8.E-06

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