United States Department of the Interior

U. S. GEOLOGICAL SURVEY

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November 30, 2011

MEMORANDUM

To: Devin Galloway, Groundwater Specialist, Western Region, WRD

From: David Prudic, retired, WSC, USGS
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Subject: AQUIFER TEST—Analysis of slug test for Snake5 deep well (site ID 385524114045601), Snake Valley, Nevada, June 1, 2011

A slug test was done at an observation well completed in fractured limestone next to Snake Creek in Snake Valley, Nevada on June 1, 2011. The purpose was to evaluate the transmissivity of a confined fractured limestone that underlies alluvium beneath Snake Creek (Figure 1). Snake Creek is perennial in the reach beginning where Gruden Springs discharge water into the creek. Additional flow is contributed to Snake Creek from Spring Creek Spring after this water has passed through Nevada Department of Wildlife's Spring Creek Fish Rearing Station. Snake Creek is perennial to Garrison, Utah where it is diverted for irrigation of crops. Loss of streamflow where Spring Creek joins Snake Creek to the Nevada-Utah state line is minimal (much less than the uncertainty in the streamflow measurements; Elliot and others, 2006). Additional investigations along the creek indicate the streambed is clogged by the precipitation of calcite from the off-gassing of excess carbon dioxide in the discharge water from Gruden and Spring Creek springs (Dotson, 2010).

The Snake5 monitoring well was drilled by the U.S. Geological Survey the week of September 4-7, 2009 to a depth of 310 feet below land surface. The well is about 10 feet north of Snake Creek, about 2.5 mi east of the Great Basin National Park boundary, 1 mile east of the Nevada Department of Wildlife (NDOW) Spring Creek Fish Rearing Station, about 2.4 miles west of the Nevada-Utah Stateline, and was drilled on property owned by the Bureau of Land Management. The monitoring well and slug test was part of a larger study funded by the National Park Service through the Southern Nevada Public Lands Management Act (SNPLMA) Round 8 Conservation Initiative Project. The purpose of the study is to characterize the hydraulic connection between groundwater in the mountains with groundwater in the valleys and to evaluate the connection of groundwater with surface water along a five-mile long section of Snake Creek (Knochemus, 2008). Hydraulic property estimates of the fractured limestone will be used to compare estimates of groundwater flow from the southern Snake Range to alluvial aquifers in Snake Valley and to compare results from a regional U.S. Geological Survey groundwater flow model used to determine the hydraulic properties of the basin-fill deposits near the southern Snake Range mountain front and their connection to surface-water resources (Halford and Plume, 2011). The hydrological study was prompted by proposed groundwater pumping in Snake Valley and in nearby valleys.

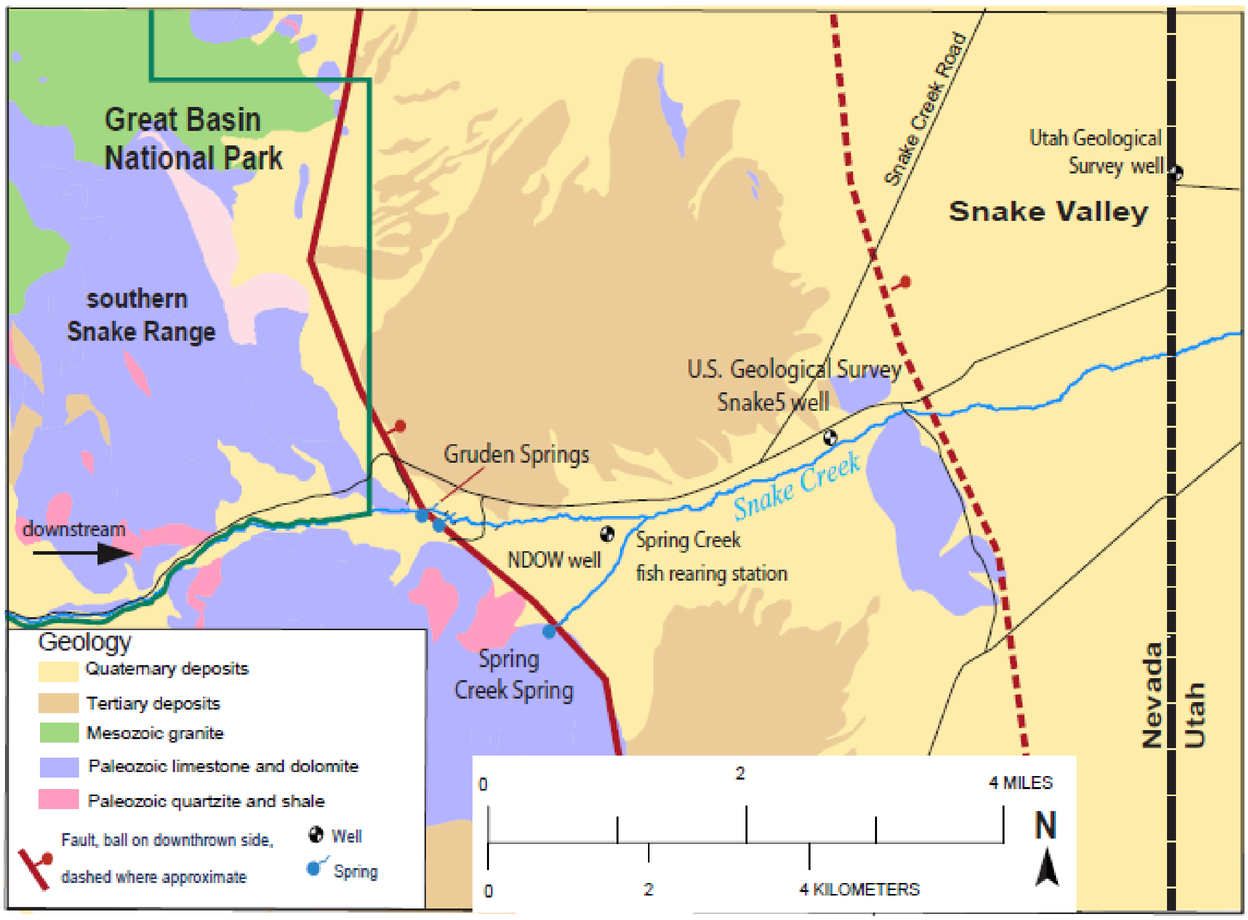

Figure 1—Location of Snake5 monitoring wells, Snake Valley, Nevada.

SITE AND GEOLOGY

The upper 40 feet of test hole drilled next to Snake Creek consisted of unconsolidated sand and gravel deposits. A moderate brown (5YR4/4) clay residuum was encountered at a depth of 40 feet. The clay residuum extended to a depth of 60 feet where it gradually changed into unweathered limestone at a depth of 75 feet. Nominal 8-inch casing was driven while drilling to a depth of 80 feet. Water was injected into the borehole to clear the clay from the casing. Below this depth the hole was deepened without casing using a 7-inch diameter bit. The hole was drilled without casing to a depth of 310 feet below land surface. Water was injected into the borehole for cutting removal to a depth of 300 feet. From 300 to 310 feet, sufficient water entered the borehole that water was not injected and drilling stopped at 310 feet because the volume of water swamped the cyclone separator used for the cuttings.

Drilling ceased and initial depth to water was 205 feet below land surface. Geophysical logs were run in the borehole including a down-hole televiewer. The televiewer clearly showed all fractures in the limestone from a depth of 80 to 290 feet were sealed with calcite veins. This is consistent with the need to inject water into the borehole to remove cuttings while drilling. Open fractures with water moving through them were evident from a depth of 295 to 310 feet, with large and open fractures between 300 and 310 feet depth. The monitoring well used for the slug test is made of nominal 2-inch schedule 80 PVC pipe. The screened opening is from 289.5 to 309.5 feet and was placed in the section of fractured limestone. The 7-inch diameter open hole around the screened interval was filled with pea-sized aquarium gravel to a depth of 279 feet below land surface. The hole from a depth of 279 feet to 80 feet was backfilled with a liquid bentonite pumped into hole through a tremie pipe (American Colloid Liquid Gold Bentonite Grout).

The hole enlarged to 9 inches at a depth of 80 feet because of the nominal 8-inch casing, which was slowly pulled out as the hole was backfilled with bentonite chips to a depth of 39 feet. Coarse sand was added to a depth of 35 feet where a second nominal 2-inch schedule 80 PVC pipe with a 5-ft screen at bottom was placed at a depth of 35 feet below land surface next to sand and gravel alluvial deposits that was identified from the gamma log. Pea-sized gravel was placed around the screened interval to a depth of 22 feet below land surface. Bentonite chips were used to fill hole to a depth of about 3 feet below land surface. The remainder of the hole was filled with a neat cement grout and a water box was placed over the two PVC pipes and set into the cement grout. The top of the water box was placed at land surface. The PVC pipes were cut about 0.4 foot below land surface inside the water box. The upper monitoring well remained dry until June 16, 2011 when the water level rose higher than depth of the screen bottom and remained higher until July 4, 2011. The water level peaked at a depth of 21.1 feet below land surface at 15:00 PDT on June 19, 2011.

The U.S. Geological Survey site identifier and local well name for the two monitoring wells at the Snake5 site are listed in table 1.

Table 1—Location and construction of the two monitoring wells.

[Latitude and longitude are in degrees, minutes, and seconds and referenced to North American Datum of 1983 (NAD 83); ft amsl, feet above North American Vertical Datum of 1988 (NAD 88)]

Site identifier	Local well name	Latitude	Longitude	Altitude, ft amsl	Screened interval, feet below ground surface		Inner diameter, inches
					Top	Bottom	
385524114045601	195 N12 E70 11DCAA1 Snake5 deep well	38º55’23.8”	114º04’55.9”	5,617	289.5	309.5	1.91
385524114045602	195 N12 E70 11DCAA2 Snake5 shallow well	38º55’23.8”	114º04’55.9”	5,617	30.	35.	1.91

An outcrop of Paleozoic limestone occurs immediately south and north of Snake Creek about 1,500 feet east (downstream) of the monitoring well (Figure 1). The Quaternary alluvium contains poorly sorted, unconsolidated boulders, gravels, sands, silts, and clays derived from glacial outwash and sediments that were transported by modern drainage systems flanking the Snake Range (Miller et al., 1995). The Tertiary deposits are composed of coarse-grained, moderately to well-cemented alluvial deposits that formed during the middle Miocene uplifting of the Snake Range. The deposits near the well dip west towards the southern Snake Range because of a fault that has displaced the deposits and placed them next to carbonate rocks on the upthrown side of the fault. This geologic unit is consolidated and typically conglomeratic. The Tertiary deposits include brecciated megablocks and typically are overlain by coarser fluvial, glacio-fluvial, alluvial, and debris-flow deposits. Some megablocks are monolithologic, whereas other megablocks have varying lithologies (Asch and Sweetkind, 2010; Jackson, 2010).

Because the alluvial deposits at Snake 5 are mostly unsaturated, the primary connection between the limestone aquifers in the southern Snake Range in Great Basin National Park and the basin-fill deposits east of the Quaternary fault (Figure 1) is through the fractured limestone aquifer encountered in the deeper monitoring well at Snake5. Thus, the hydraulic properties of this fractured limestone at Snake5 are important to understanding the connection between the fractured limestone aquifers in the mountains with the basin-fill aquifers in the valley.

MEASUREMENTS

The slug test was done by first sealing the deeper monitoring well at the surface then injecting air into the sealed monitoring well (Figure 2). The well was initially pressurized with air to a water-head equivalent of 120 inches (10 feet) measured using an air compressor and a calibrated pressure gage with 1-inch increments. This pressure was held constant for a minimum of 5 minutes and the gage monitored to see if the pressure decreased with time. The test was repeated two more times with the well pressurized to a water-head equivalent to 240 inches (20 feet). Each time, the pressure held constant during the time when the well was pressurized.

Two absolute pressure transducers were placed in the well. The lower transducer had a water-level range of about 30 feet with an accuracy of ± 0.02 foot (Schlumberger, 2008) and was placed about 21 feet below the static water level, which was measured at 114.22 feet below the top of the access port, which was 2.5 feet above land surface. A second transducer was placed at a depth of 30 feet below to top of the access port and had a range of about 10.5 feet and accuracy ± 0.01 foot. Both transducers were set to the same time and recorded pressure every 0.5 second. An electric tape with a resolution of 0.01 foot was used to determine when the water level in the well had returned to static (less than 5 minutes) once the air pressure had been released.

Because air was used to depress the water level in the well, only the recovery data was used to analyze transmissivity from the slug-test data. The time series of water levels were computed by subtracting the air pressure measured by the upper transducer from the total pressure measured by the lower transducer that was placed about 21 feet below the water level in the well (Figure 3). The more sensitive upper transducer had an average air pressure that was 0.60 ft less compared with the larger ranging lower transducer when both were measuring atmospheric air pressure. This average offset also was subtracted from the lower pressure transducer when computing head above the transducer. The rapid drop in head immediately upon the release of pressurized air is caused by smaller diameter valve used for the air-injection test (see Figure 2). The small diameter valve (nominal 1-inch) resulted in a 2 second lapse for air in the well to return to atmospheric pressure, which resulted in a lag between the water-level rise and the air pressure in the casing.

Figure 2.—Photograph of air injection apparatus attached to the deeper well at Snake5 during slug test on June 1, 2011.

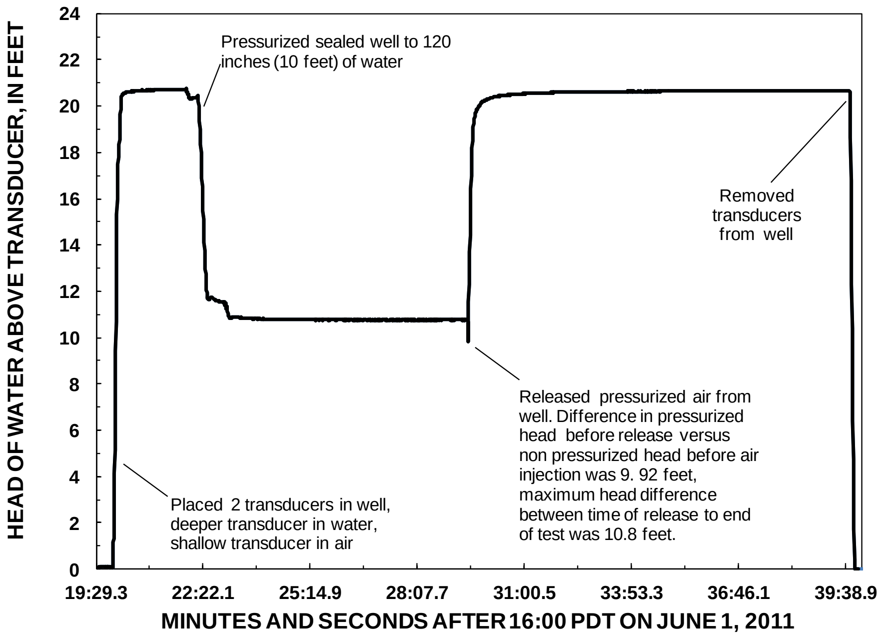

Figure 3.—Water-level changes in the deeper well at Snake5 during an air injection slug test on June 1, 2011. The data are for a 10-foot displacement caused by injecting air into the sealed well then releasing the air after several minutes.

The displacement caused by the injection of air to an equivalent pressure of 120 inches of water resulted in an initial decrease in water level in the well of 9.92 feet compared with the initial water level in the well but maximum water-level change was computed at 10.8 feet from the initial release of the pressurized air to the end of the test (Figure 3).

Displacement from the release of air in the well was computed two ways. The first computed the displacement by subtracting the air pressure measured by the upper transducer from the total pressure measured by the lower transducer and this head was subtracted from the final water-level measured at the end of the test and is referred to as “corrected” in Figure 4. The second method (referred to as “uncorrected”) simply subtracted the total pressure measured in the deeper transducer at each 0.5 second interval from the total pressure average over the last minute prior to releasing the pressurized air (Figure 4). Except for the first 1.5 seconds and at the very end of the test, results computed by the two methods are nearly identical. The initial difference is caused by the non instantaneous release of air caused by the nominal 1-inch diameter valve (see Figure 2), and the difference in the later data is caused by slight variations in atmospheric pressure.

Increasing the displacement to 20 feet for the subsequent 2 additional tests caused the air transducer in the well to become over pressurized but upon release of pressurized air, the transducer responded and was used to correct the difference in pressure between the transducer in water with the transducer in air. Results of the two additional tests were nearly the same as the initial test (Figure 5).

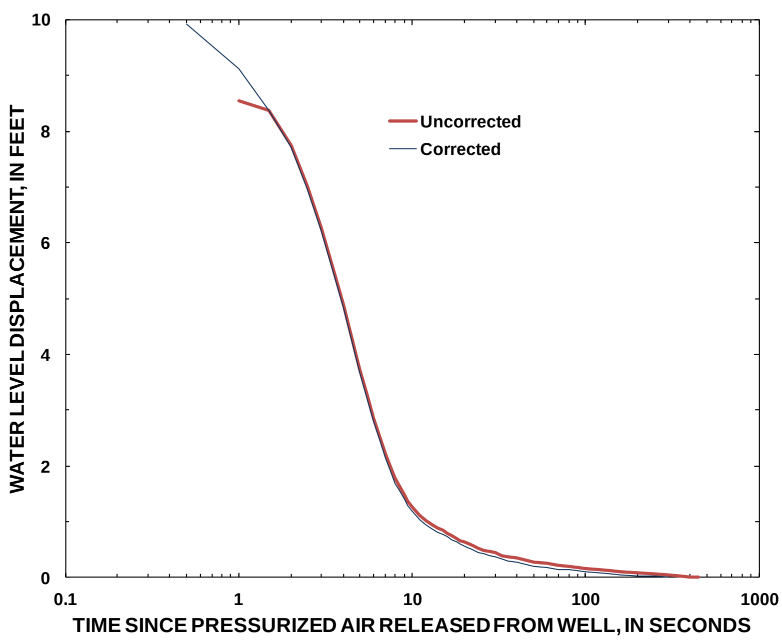

Figure 4.—Water-level displacement in the deeper well at Snake5 during an air injection slug test on June 1, 2011. The data are for a 10-foot displacement caused by injecting air into the sealed well then releasing the air after several minutes.

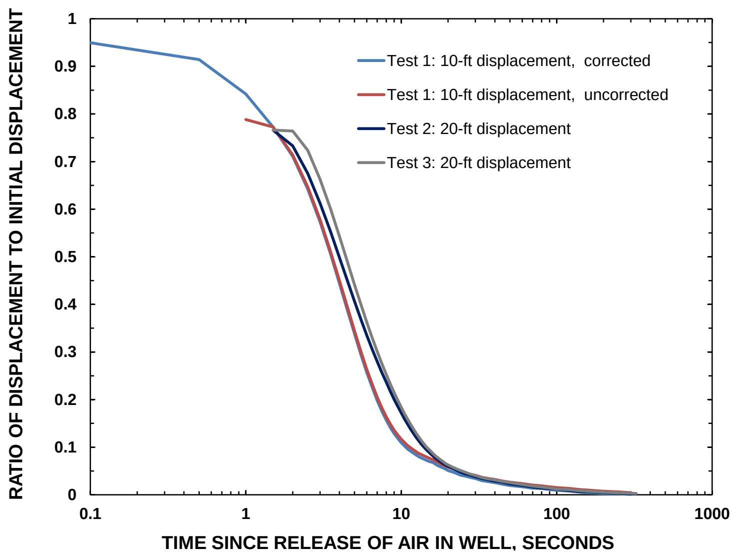

Figure 5.—Ratios of water-level displacement to initial displacement following release of air in well for all three slug tests in the deeper well at Snake5 on June 1, 2011.

ANALYSIS

Transmissivity of the fractured carbonate-rock aquifer was analyzed using the EXCEL spreadsheet developed by Halford and Kuniansky (2002). The analysis assumes a confined aquifer with storage and is based on the method by Cooper and others (1967) and modified by Greene and Shapiro (1995). The method is insensitive to storage, particularly when the storage coefficient was less than 0.0001 as the type curves for storage values less than 0.0001 are similar. Consequently a range in a storage coefficient was estimated on the basis of the original equation derived by Jacob (1940; 1941) but neglecting compressibility of included and adjacent clay beds and gases either dissolved in the water or occupying part of the void space:

$$S = \rho g \theta \mathrm{m} \left[\frac{1}{E_w} + \frac{b}{\theta E_s}\right], \qquad 1$$

where;

S is the storage coefficient, volume of water released per volume of aquifer per unit change in head;

ρ is the density of water, in mass per volume;

g is the gravitational acceleration, 32.2 feet per second squared;

θ is the total porosity expressed as a fraction of the aquifer volume;

m is the thickness of the aquifer, in feet;

E_w is the modulus of elasticity of water, about 3.2 x 10^5 pounds per square inch or 4.6 x 10^7 pounds per square foot at standard temperature [dissolved gases in water affects the elasticity; Jacob (1941) added a fourth term in his original storage equation to account for the gas fraction of the total porosity and the pressure in the aquifer];

b is a constant defined by Jacob (1940) to range from 1 for unconsolidated granular material (sand, etc.) to the porosity for limestone with tubular openings; and

E_s is Young's modulus of elasticity of the aquifer skeleton, limestone has a range from 1.3×10^6 to 1.2×10^7 pounds per square inch or 1.9×10^8 to 1.7×10^9 pounds per square foot (9 to 80 gigapascals: Bell, 2007; Cobb, 2009).

Because b equals θ for a confined fractured limestone aquifer the equation can be simplified to:

$$S = \gamma\theta \mathrm{m}\left[\frac{1}{E_w} + \frac{1}{E_s}\right], \qquad 2$$

where $\gamma = \rho g$ and is called the specific weight of water.

Assuming a reasonable range in porosity (θ) of the fractured limestone from 0.01 to 10 percent (Harrill and Prudic, 1998, p. A15), a value of 62.4 pounds per cubic foot for the specific weight of water (γ), a range in thickness (m) from 10 to 20 ft on the basis of the geologic log, a range in the elasticity of water from 2.9 to 4.6×10^7 pounds per square foot (to account for dissolved gases in the water) and a range in elasticity of the limestone from 1.9×10^8 to 1.7×10^9 pounds per square foot, yields a range in storage coefficient from 2×10^{-9} to 2×10^{-6} (dimensionless). Matching the slug test data to this range in storage coefficient yields a range in transmissivity from 300 and 500 ft^2/d (Figures 6 and 7) using the Test 1 data (corrected 10-ft displacements), although the data did not match as well to the higher storage coefficient suggesting a porosity of less than 10 percent and a thickness less than 20 feet. The uncorrected data produced similar results.

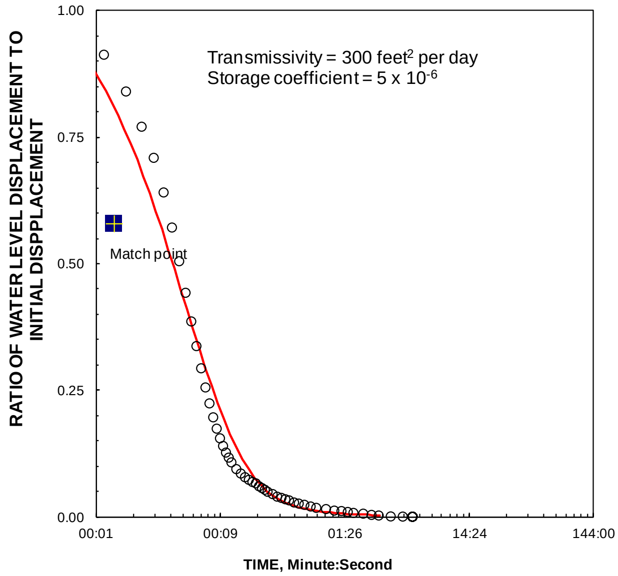

Figure 6—Results of analytical match from Greene and Shapiro (1995) to water-level displacement in the deeper well at Snake5 during an air injection slug test with a 10-ft displacement on June 1, 2011 and a storage coefficient of 5 x 10^{-6}.

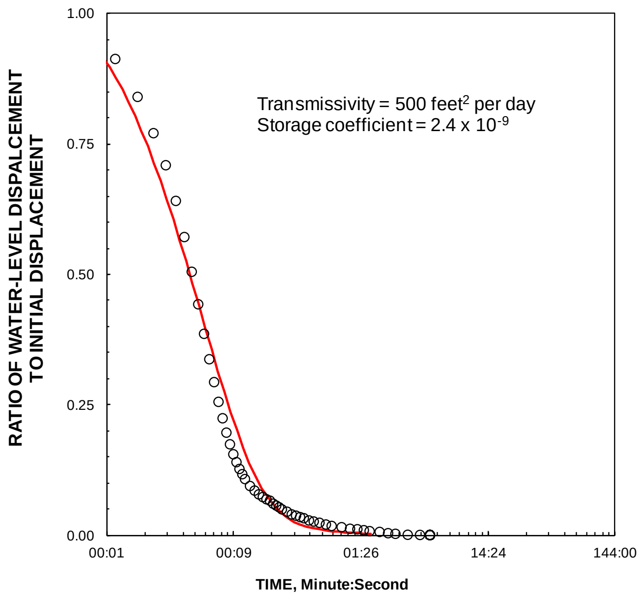

Figure 7—Results of analytical match from Greene and Shapiro (1995) to water-level displacement in the deeper well at Snake5 during an air injection slug test with a 10-ft displacement on June 1, 2011 and a storage coefficient of 2 x 10^{-9}.

No solution to the measured slug-test data could be found that exactly matched the data. The reason for the inability to match the measured data may be the result of a low percentage of high-permeability fractures within a limestone that is largely impermeable. Although the large and open fractures were viewed from a depth of 300 to 310 feet below land surface with a televiewer camera at the time the well was drilled, the lateral extent of these fractures away from the well are unknown. However, water chemistry data from the well is nearly identical to water issuing from Spring Creek Spring and from Gruden Springs along the Tertiary fault shown in Figure 1 (Dotson, 2010). This fault placed limestone rocks next to west dipping Tertiary conglomerates. Increasing the injected air pressure to 240 inches (20 feet) produced similar results (Figures 8 and 9).

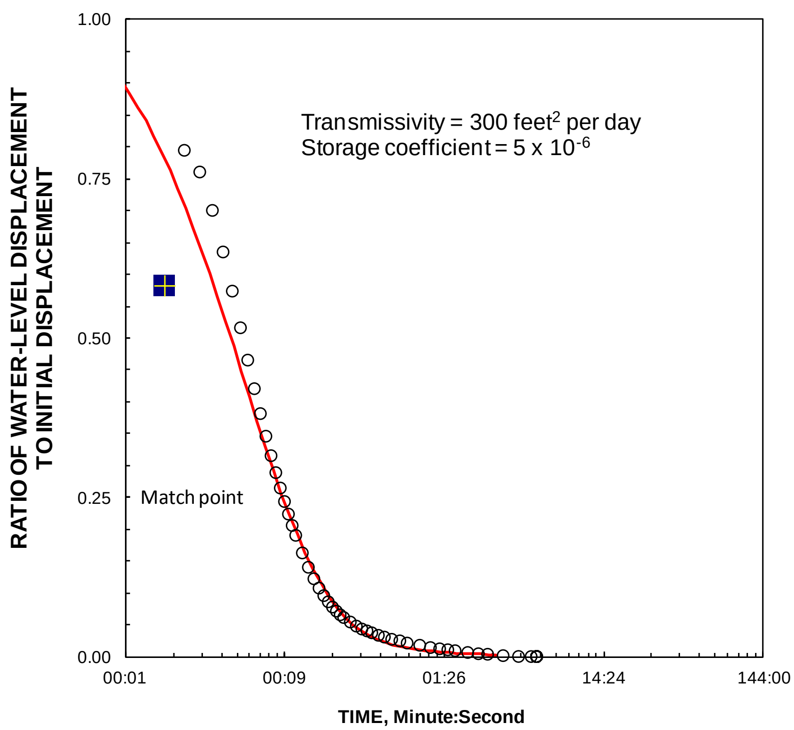

Figure 8—Results of analytical match from Greene and Shapiro (1995) to water-level displacement in the deeper well at Snake5 during an air injection slug test (test 2) with a 20-ft displacement on June 1, 2011 and a storage coefficient of 5 x 10^{-6}.

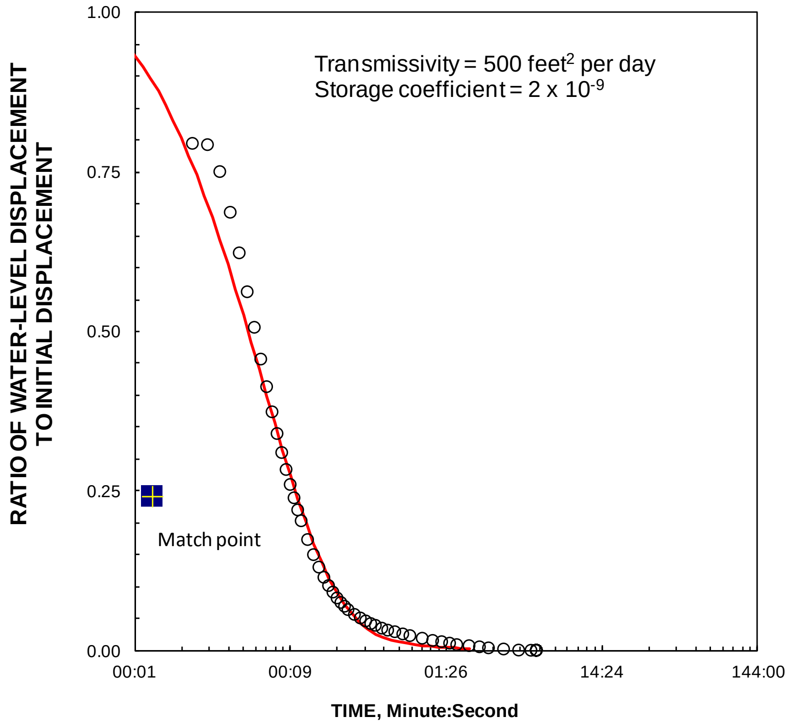

Figure 9—Results of analytical match from Greene and Shapiro (1995) to water-level displacement in the deeper well at Snake5 during an air injection slug test (test 3) with a 20-ft displacement on June 1, 2011 and a storage coefficient of 2 x 10^{-9}.

The modest transmissivity and estimated low storage coefficient result in high hydraulic diffusivity of the fractured limestone adjacent to the screened interval of the test well (transmissivity divided by storage coefficient). The hydraulic diffusivity is on the order of 10^8 to 10^{11} feet squared per day. This high hydraulic diffusivity explains the rapid and accentuated water-level response in the confined fractured limestone to snowmelt in the mountains during the late spring and early summer even though the fractured carbonate well is not connected to Snake Creek at the well (Figure 10).

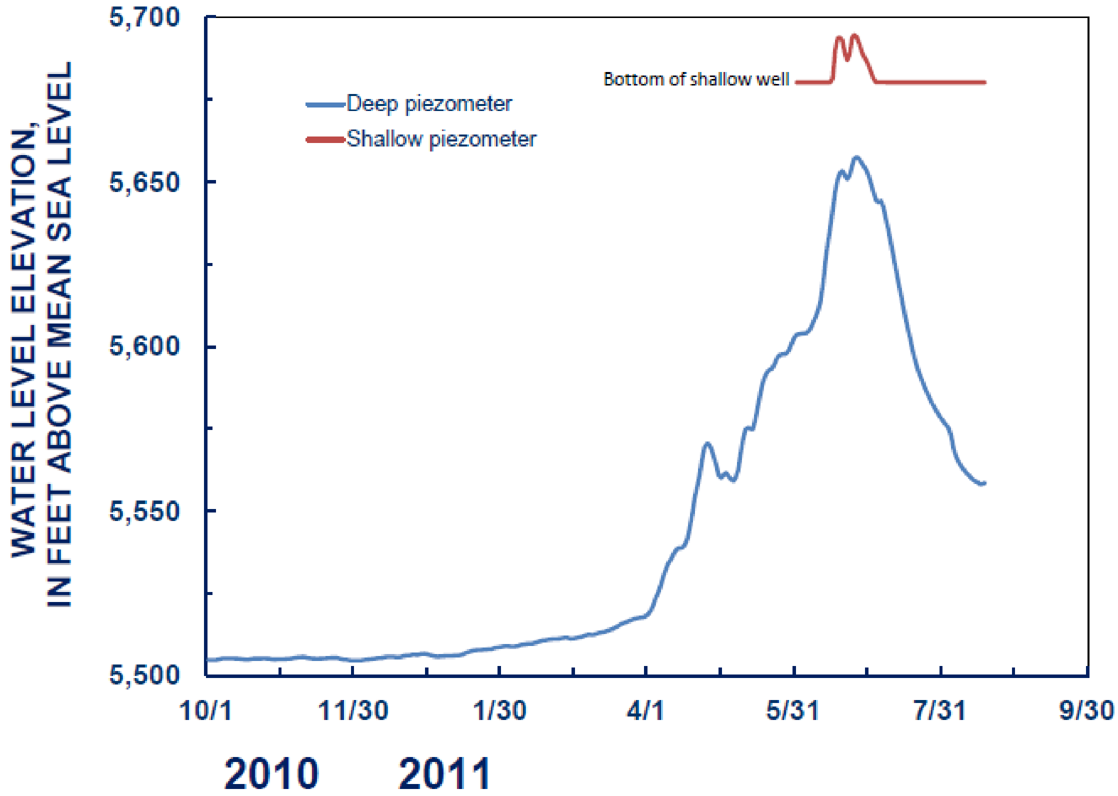

Figure 10—Daily mean water levels in the deep and shallow monitoring wells at Snake5 from October 1, 2010 to August 18, 2011. The shallow well screened in alluvial deposits that overlie a clay residuum and calcite-filled fractured limestone had no water in it until June 2011. Depth to water in the deeper well at peak water-level elevation was still more than 50 feet below Snake Creek and depth to water in the shallow well at peak water-level elevation was more than 18 feet below Snake Creek.

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