



University of Nevada, Reno
Statewide • Worldwide

Report on the Drilling of Monitoring Wells near Lehman Caves, Great Basin National Park, White Pine County, Nevada, May—June 2012

By David E. Prudic, Geological Sciences Department, University of Nevada, Reno

Prepared for the National Park Service

This page left intentionally blank

Contents

Summary.....	7
Introduction	8
Well Site 1—East of Sewage Lagoons	12
Drilling Method	12
Lithologic Description of Sediments and Rocks Encountered while Drilling	17
Installation of Monitoring Wells	21
Well Development.....	24
Stable Isotope Composition of Water from Middle and Deep Wells.....	28
Chloride and Sulfate Concentrations in Water from Middle and Deep Wells	28
Slug Test of Middle Monitoring Well.....	30
Slug Test of Deep Monitoring Well.....	33
Acknowledgments.....	36
References Cited	37

Figures

Figure 1. Location of Great Basin National Park, Lehman Caves, Baker Creek, Lehman Creek, Rowland Spring, Cave Springs, and Jeff Davis Peak, White Pine County, Nevada.....	10
Figure 2. Geology and location of proposed monitoring wells in the Lehman Creek drainage near Lehman Caves, Great Basin National Park, White Pine County, Nevada	11
Figure 3. Photograph of well site east of sewage lagoons at Great Basin National Park, White Pine County, Nevada showing drill rig, 20-foot length of nominal 10-inch casing attached to top driver hammer and diverter with hose to cyclone in dump truck.....	13
Figure 4. Photograph of under-reaming bit wedged in shoe at end of nominal 10-inch casing after pulling casing, drill stem, air hammer, and bit on May 11, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.....	14
Figure 5. Photograph of new nominal 10-inch shoe with new under-reaming bit extending beyond shoe prior to drilling through the neat-cement-filled hole on May 13, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.....	14
Figure 6. Photograph of nominal 8-inch casing showing perforations following a test on June 3, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.....	18
Figure 7. Summary of lithology, location of the three nested nominal 2-inch diameter wells, and a description of materials used to backfill the hole at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.....	20
Figure 8. Photograph of nominal 2-inch schedule 80 PVC well screen showing 3/16-inch holes drilled into slots to allow passage of microorganisms in deep well at wells site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.....	21
Figure 9. Photograph of the air tubes protruding from each of the three wells used for well development at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada	27
Figure 10. Photograph of water being air lifted out of each well during development at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada	28
Figure 11. Depth to water below land surface in middle well during two slug tests on June 7, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada	31
Figure 12. Results from slug test of middle well on June 7, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County.....	33
Figure 13. Results from slug test using Hvorslev method at deep well on June 9, 2012 at site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.....	35
Figure 14. Results from slug test using Cooper and others method at deep well on June 9, 2012 at site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada	36

Tables

Table 1. Temperature and specific conductance of water air lifted from the three nested wells during well development on July 7, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.....	26
Table 2. Stable isotopes of water from middle and deep wells at well site 1 east of sewage lagoons, Rowland Spring, and Baker Creek, Great Basin National Park, White Pine County, Nevada	29
Table 3. Dissolved chloride and sulfate concentrations in water from middle and deep wells at well site 1 east of sewage lagoons, Rowland Spring, and Baker Creek, Great Basin National Park, White Pine County, Nevada	30
Table 4. Water-level rise in middle well after releasing pressurized air during two slug tests on July 8, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada	32
Table 5. Water-level rise in deep well after lowering a sealed10-foot length of nominal 1-inch diameter schedule 40 polyvinyl-chloride pipe beneath the water level during a slug test on July 9, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.....	34

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
in. (in.)	25.40	millimeter (mm)
ft (ft)	0.3048	meter (m)
mi (mi)	1.609	kilometer (km)
Area		
acre	0.0040	square kilometer (km ²)
square ft (ft ²)	0.09294	square meter (m ²)
square mi (mi ²)	2.590	square kilometer (km ²)
Volume		
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m ³)
cubic ft (ft ³)	0.02832	cubic meter (m ³)
Flow rate		
gallon per minute (gal/min)	3.785	liter per minute (L/min)
cubic ft per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound avoirdupois (lb)	0.4535	kilogram (kg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8.$$

Chemical concentrations of dissolved constituents are reported in milligrams per liter (mg/L).

Concentrations of stable isotopes of deuterium (hydrogen-2 or ²H) and oxygen-18 (¹⁸O) are given in delta (δ) notation as parts per thousand (permil) where delta is the relative difference between the ratios of deuterium to protium (hydrogen-1 or ¹H) or oxygen-18 to oxygen-16 (¹⁶O) in water samples to the respective ratios in Vienna Standard Mean Ocean Water (VSMOW; Giofanti, 1978).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Summary

Two monitoring wells were proposed in the Lehman Creek drainage under the Southern Nevada Public Lands Management Act Round 8 conservation initiative programs for White Pine County (herein referred to as the SNPLMA project). The SNPLMA project, whose purpose was to evaluate the connection of aquifers to streams and springs in the southern part of the Snake Range and Snake Valley, began in August 2008. Well drilling in the park was delayed until an Environmental Assessment (EA) was completed in September 2011. Drilling commenced at site 1 east of the sewage lagoons in Great Basin National Park on May 8, 2012 and was completed June 8, 2012. Data from the well is not included in the final SNPLMA project report but data collection ceased for that report October 1, 2011. Due to difficult drilling conditions encountered at site 1, drilling was unable to be completed at site 2 northeast of Lehman Caves because all allocated drilling funds were expended during the drilling of the well at site 1.

The drill hole at site 1 encountered younger basin-fill deposits to a depth of 23 ft below land surface, older basin-fill deposits between 23 ft and 125 ft, residuum (clay formed from weathering of limestone) between 125 ft and 146 ft, fractured marble between 146 ft and 152 ft, and inter-fingered marble and granite caused by the assimilation of the Pole Canyon Limestone into magma intruding below a depth of 152 ft below land surface. Two layers of mostly sand and gravel were encountered from depths below land surface of 34 ft to 45 ft and 117 ft to 125 ft, of which the upper sand and gravel layer was not saturated above a depth of 40 ft. Water bearing sand and gravel with clay was encountered from depths from 45 ft to 86 ft and from 100 ft to 117 ft. The fractured marble also yielded some water from depths between 146 ft and 152 ft. Three nested, nominal two-in. diameter schedule 80 polyvinylchloride (PVC) wells with screens were completed within the three water bearing zones encountered during drilling. The deep well had a 5-ft long screen that was placed from 155 ft to 160 ft below land surface in the zone of fractured marble and granite. The middle well had a 10-ft long screen placed from 110 ft and 120 ft below land surface and near the top of the deepest sand and gravel unit. The shallow well had a 40-ft long screen from 31 ft to 71 ft below land surface and was designed to extend at least 1 ft above the highest anticipated water level in the well. Because the highest water level for the shallow well is unknown, the top of the well screen was placed above the top of the sand and gravel unit at a depth of 34 ft below land surface. The shallow well is designed to monitor possible contamination from the nearby sewage lagoon.

The completed wells were development for six hours by air lifting water out of each well. The deep and middle wells were clear after five hours of air lifting water but the middle well was showing a pH of 11, indicating the neat-cement grout used to seal the hole between the nested wells had not fully cured and was affecting water chemistry in the middle well. Air lifting did not work well for the shallow well because the water level in this well was 12 ft below the top of the screened interval. All three wells need additional pumping to clear the wells prior to collecting water samples for additional chemical analysis. Water samples for stable isotopes of water and for chloride and sulfate were collected only from the middle and deep wells at the end of well development. Estimated water yield and drawdown data (specific capacity data) collected during well development of the middle and deep wells were used to estimate preliminary aquifer properties of transmissivity and hydraulic conductivity. Estimates of transmissivity were about 5 ft²/d for the middle well and 1 ft²/d for the deep well. Dividing these estimates by the thickness of the sand and gravel interval screened for the middle well and the thickness of the fractured marble/granite interval screened for the deep well resulted in an estimated hydraulic

conductivity of 1 ft/d for the middle well and 0.1 ft/d for the deep well. These estimates are minimum values because of well losses during air lifting of water.

Two slug tests of the middle well were done the day after well development, and results indicate a transmissivity of about 30 ft²/d or about 6 times greater than that estimated during well development. The range in estimated hydraulic conductivity for this well is 3 to 5 ft/d. This range in hydraulic conductivity is similar to the specific capacity data from another well about ¼ mi east of the park that also was completed in buried sand and gravel layer in the older basin-fill deposits. A slug test of the deep well screened next to fracture marble and granite resulted in a transmissivity of 0.3 ft/d and a hydraulic conductivity of 0.05 ft/d, indicating the fractured marble and granite is much less permeable than the older basin-fill deposits.

The stable isotope composition of the water collected from the middle and deep wells was the same as the water in Rowland Spring and Baker Creek and is consistent with stable isotope composition of Rowland Spring and Baker Creek during peak snowmelt from May through July in 2010 and 2011. However, chloride and sulfate concentrations in the middle and deep wells were considerably higher than chloride and sulfate concentrations in Baker Creek and in Rowland Spring. Chloride and sulfate concentrations in Rowland Spring are higher than Baker Creek and indicate mixing of diffuse groundwater flow in buried sand and gravel layer and in fractured granite with more rapid flow of Baker Creek water through large conduits between Baker Creek and Rowland Spring.

Water levels in the three wells increase in elevation with increasing depth meaning the water level elevation in the deep well is much higher than that in the middle and shallow well and indicates an upward component to groundwater flow in the vicinity of the wells. The upward flow is caused by a combination of a reduced thickness of marble/limestone caused by an uneven contact with granite and a thick residuum on top of the marble/limestone and beneath sand and gravel that acts as a confining unit. All three wells had water level elevations higher than the elevation of Rowland Spring. The water level in the shallow well was about 50 ft higher than Rowland Spring whereas the deep well had a water level 65 ft higher than Rowland Spring. The estimated lateral hydraulic gradient of the groundwater surfaces between the wells and Rowland Spring ranged from 0.03 to 0.04 ft/ft.

Introduction

Supplementary water supplies are needed for a rapidly growing population in southern Nevada. Groundwater resources from basin-fill and carbonate-rock aquifers in southern Snake Valley in eastern Nevada have been identified as a potential water supply. These aquifers provide water to springs, streams, wetlands, limestone caves, and other biologically sensitive areas within Great Basin National Park located in the southern part of the Snake Range that borders Snake Valley on the west. The water provides habitat for numerous species of plants and animals within the park. The National Park Service (NPS) needs additional geologic, hydrologic, and chemical information to assess the hydraulic connection of groundwater between the mountain and valley and with springs and streams within the park that have water-dependent ecological features. Understanding these connections is important because large-scale pumping of groundwater from aquifers in Snake Valley may result in unintended capture of streamflow and/or springs that supply streams in ecologically sensitive areas in the park.

Great Basin National Park encompasses about 120 mi² of the highest elevations in the southern part of the Snake Range in eastern White Pine County, Nevada near the border with Utah (fig. 1). Lehman Caves, the main tourist attraction in the park, lie on the eastern slope of the range where an

outcrop of the middle Cambrian Pole Canyon Limestone has been tilted to the northeast by tectonic activity. The caves are in the Lehman Creek drainage but this karst limestone extends from the Baker Creek drainage across the Lehman Creek drainage (Elliott and others, 2006). Rowland Spring, located near the park entrance and about 200 ft south of Lehman Creek, is the largest discharging spring in the park. The source of water to Rowland Spring is of concern because the local drainage area size is insufficient to explain the amount of observed discharge. Streamflow losses into this karst limestone along Baker Creek were considered the principal source to Rowland Spring (Elliott and others, 2006, p. 32). Two monitoring wells were proposed in the Lehman Creek drainage as part of the SNPLMA Round 8 conservation programs for White Pine County. The SNPLMA project, whose purpose was to evaluate the connection of aquifers to streams and springs in the southern part of the Snake Range and Snake Valley, began in August 2008. Well drilling in the park was delayed until an Environmental Assessment (EA) was completed in September 2011.

The objectives of the proposed monitoring wells near Lehman Caves were to gain a better understanding of subsurface geology, the rate and direction of groundwater flow, and to use the monitoring wells for assessing the potential for diminished water resources within Great Basin National Park caused by proposed large-scale pumping of groundwater in adjacent Snake Valley. One well was proposed east of the park's sewage lagoons and had an additional purpose of monitoring for sewage contamination from the lagoons as part of a requirement by the Nevada Department of Environmental Protection (NDEP) (fig. 2). A second well was proposed northwest of Lehman Caves along the access road to the park's water storage tank and the main water supply of Cave Springs. These two wells were meant to be drilled into the underlying limestone as part of this study. A third group of shallow wells were proposed next to Lehman Creek near the intersection of the Wheeler Peak road with the main park road (fig. 2). Since remaining SNPLMA project funds were limited, this well was not included in this phase of the work.

Difficulties during the drilling at the site east of the sewage lagoons resulted in all drilling funds being spent at this site. As a result, no attempt was made to drill at the second site along the access road to the park's water storage tank. This report describes the methods used to drill, construct and develop the well completed at site 1 east of the sewage lagoons, problems that occurred while drilling, the geologic materials encountered, results of slug tests analyses, and results of selected water-quality measurements collected during drilling and well development.

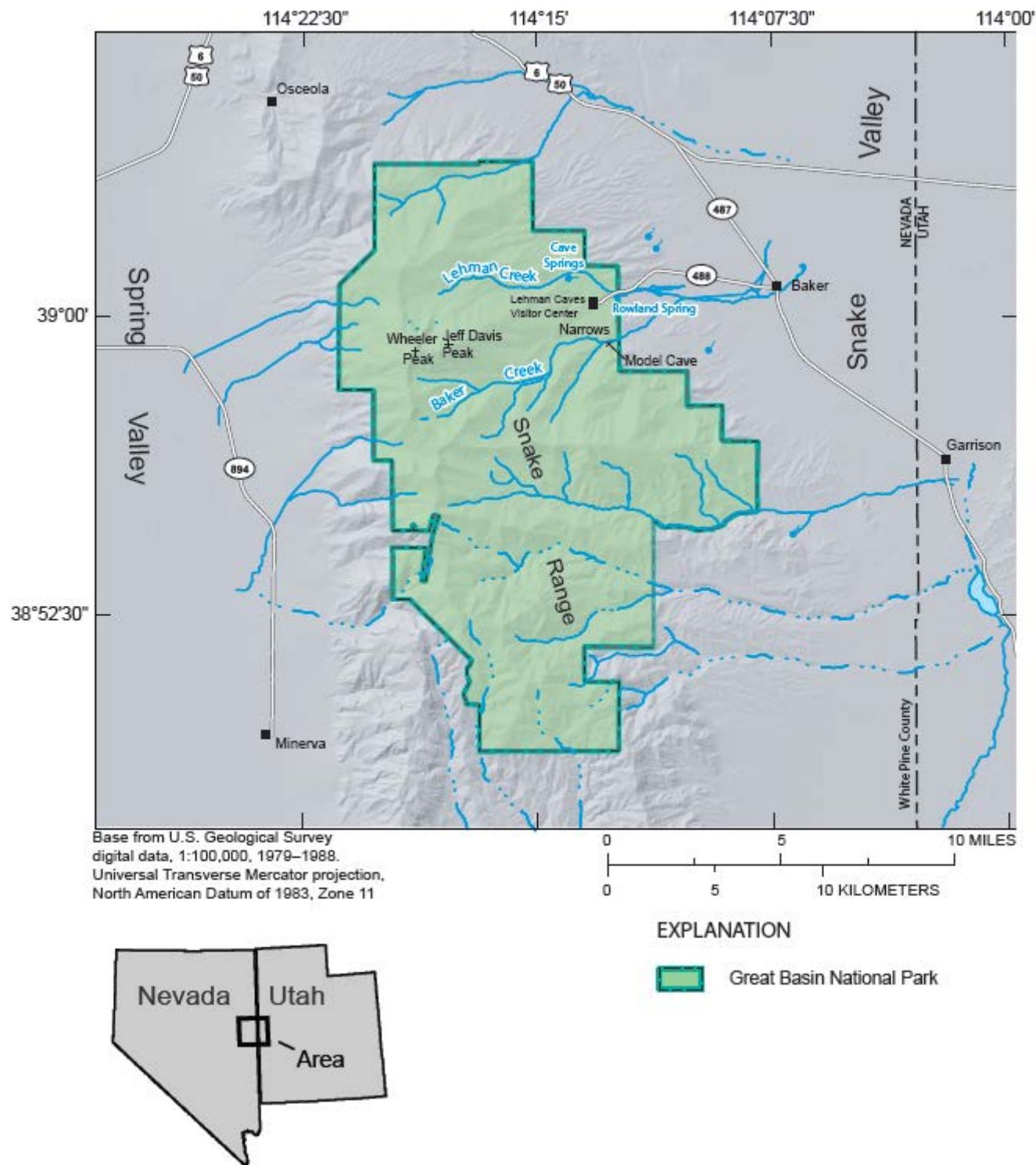


Figure 1. Location of Great Basin National Park, Lehman Caves, Baker Creek, Lehman Creek, Rowland Spring, Cave Springs, and Jeff Davis Peak, White Pine County, Nevada (modified from Prudic and Glancy, 2009, figure 1).

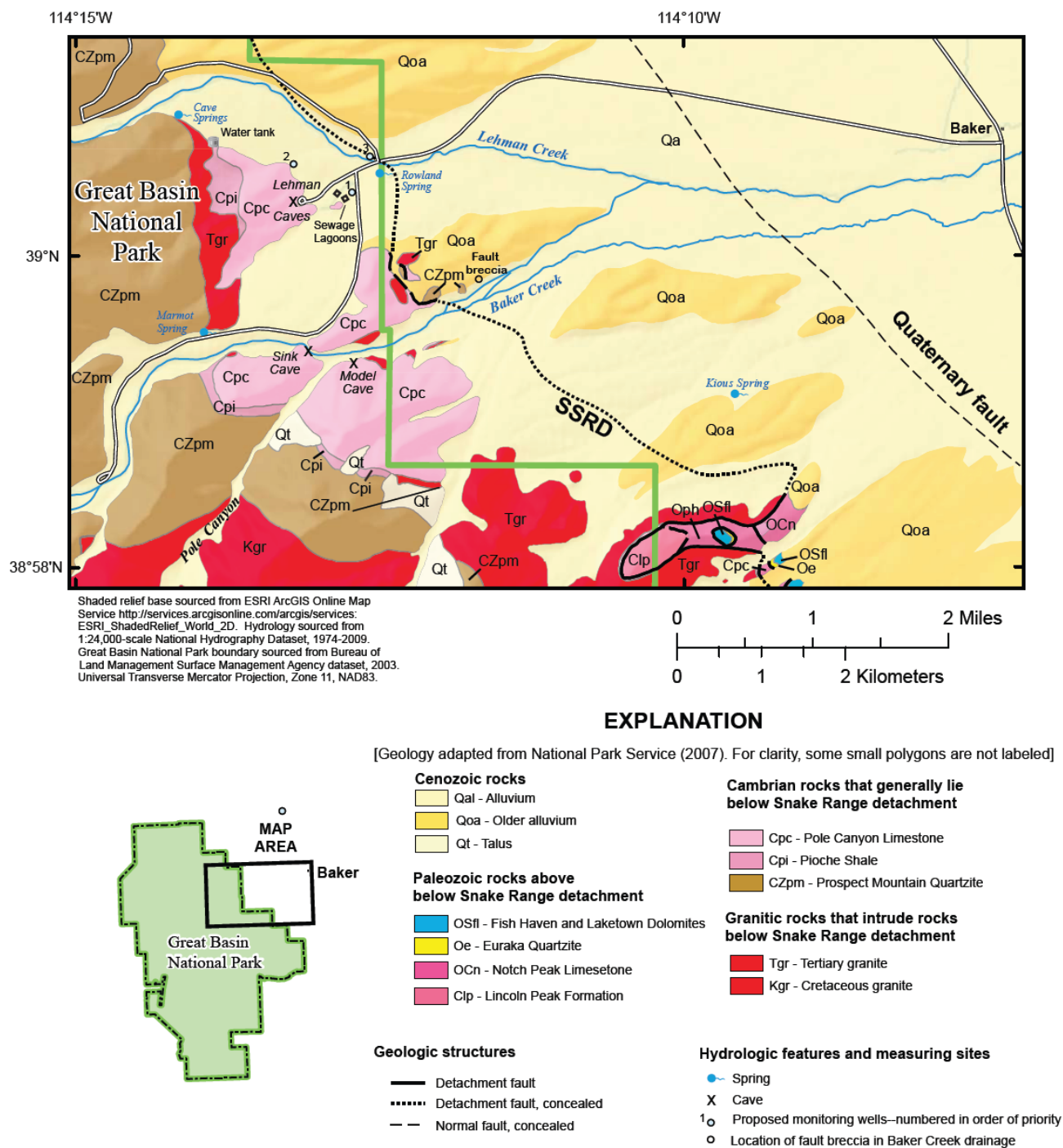


Figure 2. Geology and location of proposed monitoring wells in the Lehman Creek drainage near Lehman Caves, Great Basin National Park, White Pine County, Nevada (modified from D.S. Sweetkind, U.S. Geological Survey, Lakewood, Colo., 2011, written commun.).

Well Site 1—East of Sewage Lagoons

Drilling method

The well was drilled using the United State Geological Survey Western Research Drilling Unit rig headquartered out of Las Vegas, Nevada. The drill rig and crew arrived at the park on May 8, 2012, and the drill rig was spotted at site 1 east of the sewage lagoons. The rotary drill rig is capable of drilling holes greater than 1,000 ft deep. Compressed air was the prescribed fluid used to drill the well. A 12 ¾-in. hole was drilled starting from land surface using an eccentric under-reaming bit and nominal 10-in. casing assembly. The under-reaming bit drills a hole larger than the casing about 1 to 2 ft beyond the end of the casing. The nominal 10-in. casing had an outside diameter of 10 7/8-in. and a wall thickness of about ½ in..

The casing was driven using an air hammer attached to the top of the casing. Vegetable-based lubricating oil was used for the air hammer to minimize the potential for petroleum oil contaminating the groundwater. This compressed air drilling method was to be used when drilling through basin-fill deposits because mud drilling was not allowed in the park and because the drillers needed a method for keeping the hole from collapsing. Once into limestone, the hole was to be drilled open hole using a 9 ¾-in. bit attached to the air-percussion hammer. Given the size of the hole, an extra air compressor was brought to the site on a separate trailer. Another trailer was used to store the 10-in. casing and drill stem pipe prior to being hoisted onto the drill rig. A water truck, a crane truck used to haul the trailer with casing, and a dump truck for collecting and removing drill cuttings from the site were all needed near the drill rig (fig. 3).

Every effort was made to minimize environmental disturbance from the drilling operation. Plastic sheeting was placed beneath the drill rig, the trailer with air compressor, and the crane and dump trucks to prevent leaking vehicle oil and hydraulic fluids from absorbing into the ground. The water truck moved too frequently so absorbent pads were placed in critical places beneath it and the pipe trailer to absorb any leaking vehicle fluids.

Plastic sheeting and straw waddles were used to create an above ground ditch to convey borehole water and mud away from the dump truck and drill rig to nearby drainages and minimize surficial erosion. A plastic-lined ditch extended from the dump truck about 150 ft to a ditch near a culvert beneath the Baker Creek road. Another plastic-lined ditch from the drill rig extended north about 100 ft to a natural channel to convey well development water away from the drill rig. Cuttings from the hole were piped through a 4-in. diameter heavy duty fire hose to a cyclone separator that had been positioned into the back of the dump truck. The cyclone separator is used to slow down the entrained compressed air and rock fragments removed from the hole. Fine silt and dust escapes from a large hole in the top and larger heavier fragments fall through a smaller hole in the bottom. Cuttings that fell through the bottom hole were examined for size and mineralogy.

Wetted burlap was placed on top of the large open hole of the cyclone to control the escaping dust. Although the wetted burlap helped to momentarily suppress the dust, considerable dust also came out around the outside of the casing while drilling through the upper 30 ft of unsaturated basin-fill deposits. The dust diminished below a depth of 30 ft where basin-fill deposits had sufficient moisture.



Figure 3. Photograph of well site 1 east of sewage lagoons at Great Basin National Park, White Pine County, Nevada showing drill rig, 20-ft length of nominal 10-inch casing attached to top driver hammer and diverter with hose to cyclone in dump truck. Also shown are the crane truck, pipe trailer, water truck, and extra air compressor on trailer behind water truck. Photograph was taken May 11, 2012 looking west with Jeff Davis Peak in background.

Although the drill rig and crew arrived the morning of May 8th, drilling did not begin until the afternoon of May 10th. The first well was sited 92 ft southeast of the BLM corner section marker, and 241 ft east of the northeast corner of the fence around the south sewage lagoon. The GIS coordinate of the well was latitude North 39° 00' 23.4" and longitude West 114° 12' 44.1", NAD 83 or UTM 11S Latitude 4,321,195.19 meters North and longitude 741,395.59 East. Estimated land surface altitude was 6,690 ft NAVD88. Considerable set-up time was required to replace the drill-crew truck, which was damaged during the drive from Las Vegas to the park, and because this was the first time the casing hammer on the drill rig was used to drive 10-in. casing.

The hole was drilled to a depth of 18 ft on May 10th. Large boulders were encountered at depths from 5 ft to 6 ft, and from 10 ft to 13 ft, which slowed the drilling and caused considerable dust. Drilling became extremely slow early on May 11th at a depth of 23 ft and by a depth of 28 ft below land surface, the under-reaming bit had become stuck inside the casing shoe. Consequently, all casing, drill stem, air hammer and bit were removed from hole. The top side of the under-reaming bit had been rounded to the point it slipped back inside the casing shoe and to free the bit and air hammer the casing shoe had to be cut by torch (fig. 4). The hole collapsed at the surface with large boulders and debris. Surface width of hole increased to 3 ft and the total measureable depth of hole was 7 ft. To stabilize the borehole at the surface, nearly two cubic yards of neat cement (cement and water) was poured down the hole on the afternoon of May 12th and allowed to set overnight. The neat-cement level declined a ft overnight indicating the cement continued seeping downward and outward from the hole. Drilling recommenced at the site with a new casing shoe and under-reaming bit on May 13th (fig. 5).



Figure 4. Photograph of under-reaming bit wedged in shoe at end of nominal 10-inch casing after pulling casing, drill stem, air hammer, and bit on May 11, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine, County, Nevada.



Figure 5. Photograph of new nominal 10-inch shoe with new under-reaming bit extending beyond shoe prior to drilling through the neat-cement-filled hole on May 13, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

Drilling through to the original hole took 2 hours. Drilling between the depth of 28 and 34 ft was slowed by the same silica-cemented quartzite that was encountered between depths of 23 and 28 ft. Moisture content increased in sub-rounded gravel and sand encountered at a depth of 34 ft. Drilling went relatively quickly to a depth of 73 ft. The hole was still in basin-fill deposits even though interpretation of data collected in 1988 from a seismic-refraction line extending between the sewage lagoons and Rowland Spring had indicated a possible depth to limestone of 60 ft near the drill site (Benjamin Roberts, National Park Service, Great Basin National Park, 2012, written commun.). Additionally, limestone outcrops about 550 ft west of the drill rig and less than 100 ft from the west fence line surrounding the south sewage lagoon (fig. 2). Samples collected from the outcrop west of the south sewage lagoon were slightly marbleized. The greater than expected depth to limestone at the site was further complicated by the fact that no more 10-in. casing was available to drill deeper. Consequently, this necessitated a decision to use a different method for advancing the hole.

The top hammer was disconnected and the drill stem, air hammer, and under-reaming bit were removed from the hole. The under-reaming bit was replaced with a 9 ½-in. air-percussion bit. An attempt was made to drill 10 ft beyond the end of the casing using the 9 ½-in. bit and without advancing casing to determine if the basin-fill deposits were sufficiently consolidated to allow the hole to remain open. The total measured depth of hole was 74.9 ft below top of casing and the total casing length was 72.8 ft giving hope the hole might remain open. On May 14th, drilling using the 9 ½-in. bit advanced the hole to a depth of 85 ft and it did not remain open. Initial discussions considered the possibility of ending the drilling and completing the well with a screen from 33 ft to 73 ft depth below land surface, but further discussion eventually led to the decision of using nominal 8-in. casing and a corresponding under-reaming bit to advance the hole deeper.

More than 200 ft of nominal 8-in. unthreaded casing was at the Utah Department of Transportation yard in Garrison that was left over from drilling a well southwest of Big Springs during the fall of 2010. This casing had an outside diameter of 8-5/8 in., an inside diameter of 7-7/8 in. and a 3/8-in. wall thickness, but required welding joints together every 20 ft. The preferred option was to ship 200 ft of nominal 8-in. threaded casing with ½-in. wall thickness up from Las Vegas, except that required driving the crane truck and pipe trailer back to Las Vegas and then returning with the casing, so the 8-in. unthreaded casing was used instead. Reducing the drill-hole diameter required a reduction in the diameter of well casing from nominal 6-in. to nominal 4-in. and 2-in. casing, which necessitated the smaller diameter casing to be shipped to the site.

The water level in the casing had risen overnight (from May 14th to May 15th) to a depth of 64.02 ft below top of casing, much slower than before attempting to drill beyond the casing. The water level continued to rise slowly throughout the day on May 15th to a depth of 61.43 ft below top of casing as preparations continued that day to drill with the nominal 8-in. unthreaded casing. The water level on the morning of May 16th had risen to a depth of 56.83 ft below top of casing. The slower rate of rise was attributed to filling the bottom of the hole with less permeable materials that had collapsed into the hole when attempting to advance the hole without casing.

The morning of May 16th were spent welding joints between 20-ft lengths of nominal 8-in. casing around the drill stem pipe, air hammer, and under-reaming bit assembly and lowering it down hole. Drilling beyond a depth of 73 ft began in afternoon and the hole was advanced to a depth of 95 ft. A considerable volume of water was blown out of hole prior to drilling on the morning of May 17th. Drilling went quickly to a depth of 145 ft below land surface partly as a result of drilling through clay between depth of 125 and 145 ft. The drilling rate slowed at a depth of 146 ft when black fractured marble was encountered. Drilling slowed considerably at a depth of 152 ft when rock fragments of pink

feldspar and grey plagioclase appeared along with an unidentified green mineral, indicating that granite had been encountered. The hole was advanced only a few in. into the granite after 30 minutes, and decision was made to stop drilling and cut the remaining 7 ft of nominal 8-in. casing that was extending above the drilling table on the rig.

During the cutting of the nominal 8-in. casing, it was discovered the casing was broken at the first weld 10 ft below land surface. The first section of nominal 8-in. casing was removed prior to leaving for the night. The water level rose quickly inside casing at a rate of about 1ft every 3 minutes. The water level rose to 43.8 ft below top of 10-in. casing by the morning of May 18th. The remaining nominal 8-in. casing in the hole could not be pulled without the correct bores for the casing jacks, which were being shipped from Las Vegas. The water level rose only 1.2 ft more over a 24-period and was 42.6 ft below top of 10-in. casing on the morning of May 19th. An attempt to raise the casing with the drill stem and under-reaming bit did not work. The drill crew checked to determine if any more sections of nominal 8-in. casing were broken at welds. The drill crew was able to remove another 20-ft section out of hole but could not pull any more sections. As a result, the top of the nominal 8-in. casing after removing the second section of pipe was 30 ft below land surface.

The inability to pull the remaining nominal 8-in. casing from the hole caused considerable concern as the casing blocked three possible water bearing zones encountered during drilling between the depths of 40 and 73 ft, 115 and 125 ft, and 146 and 152 ft. The upper zone was important because one purpose of the monitoring well was to monitor possible contamination from the sewage lagoons and this could not be done without cutting off the nominal 8-in. casing near the bottom of the nominal 10-in. casing. This also meant that the remaining 80 ft of 8-in. casing at the bottom of the hole would need to be perforated in the vicinity of the lowermost water-bearing zones to allow water into the well, and to allow gravel pack and grout materials to pour out into and seal the annular space between the borehole wall and the outside of the 8-in. casing. Due to these concerns and difficulties, the design of the well was changed again and instead of a single nominal 4-in. diameter well casing, three nested 2-in. diameter well casings were to be placed across the suspected water bearing zones. This meant leaving the site, purchasing a casing cutter, picking up a casing perforation tool, and returning to the site after the upcoming Memorial Day holiday weekend.

Work recommenced May 30, 2012 after the holiday weekend. The casing was cut at a depth of 73 ft below land surface, which later turned out to be a mistake because total casing length was only 71.7 ft below the original land surface. This mistake happened because of confusion over the correct reference (depth below original land surface or from the top of the 10-in. surface casing). The gap between the bottom of the nominal 10-in. casing and the top of the nominal 8-in. casing allowed for native sand and gravel to fall into the 8-in. casing, which caused a problem when attempting to perforate the bottom part of the 8-in. casing. Prior to using the perforator tool, about 8 ft of debris was detected at the bottom of the hole and inside the 8-in. casing. A 7¾-in. air percussion bit was placed on the bottom of the air hammer, lowered into the hole and the debris was removed from the hole. The hole also was deepened to a depth of 153 ft to allow sufficient room for the perforator tool to cut holes to a depth of 151 ft. Depth to water rose quickly in the hole from 151 ft to 85 ft after only 25 minutes. Casing perforations were planned from depths of 75 ft to 85 ft, 114 ft to 135 ft and from 146 ft to 151 ft.

Attempts to perforate the casing between a depth of 146 and 151 ft failed partly because of collapsing material from the open interval between the 10-in. and 8-in. casings but also because the perforator tool did not function correctly. The perforator tool was removed from the hole, cleaned, and tested on a section of nominal 8-in. casing at the surface to determine if the perforator was punching a 1¼-in. long by ¼ in. wide hole every 2 in. vertically along the casing. A new perforating wheel was

installed but the perforator tool still failed to work properly and barely perforated the casing. Two of the drilling crew left for Las Vegas on June 1st to get replacement parts, and fix and test the perforator tool at their shop. The remaining drill-crew member remained and replaced the bores on the casing jacks so it would be able to extract the nominal 10-in. casing from the borehole.

The following day (June 2nd), the depth to water in the hole was 43 ft below land surface. Total depth of the hole was only 148.1 ft below land surface indicating another 5 ft of debris had fallen from the open interval to the bottom of the hole. A 2.7-ft section of nominal 10-in. casing was attached at the surface to the 10-in. casing in the hole. The casing was then hammered down into the hole using a large piece of ½-in. thick metal plate placed on top of the casing and a 7¾-in. air percussion bit attached to the bottom of the air hammer. The casing was successfully driven into the ground to a depth of 73.5 ft below land surface thus sealing off the open interval between the 10-in. and 8-in. casings and stopping native material from falling down the hole. A 7¼-in. tri-cone bit was attached to the air hammer and lowered into the hole to clean out the debris at the bottom of the hole. The drill-crew member slowly drilled into the 8-in. casing pushing a large stone in front of bit to the bottom of the hole where he proceeded to drill out debris at bottom of hole to a depth of 153 ft below land surface where solid rock was encountered. The total depth of the hole remained at 153 ft below land surface on the morning of June 3rd and depth to water was 42.4 ft below land surface. The hole was extended to a depth of 161.7 ft below land surface using the 7¼-in. tri cone bit to determine if the granite encountered at 152 ft depth continued with depth. If intervals of marble were encountered, then a well screened could be placed in an open hole without having to perforate the nominal 8-in. casing between a depth of 146 and 151 ft. The bit ground the rock into fine sand- and small gravel-sized pieces and the rate of drilling was slow. The other two drill-crew members returned to the drill site with the fixed perforating tool. The tool was tested on a piece of nominal 8-in. casing prior to lowering it into the hole. The tool perforated the casing as initially expected (fig. 6).

The perforator tool was lowered into the hole following the test. The casing was not perforated between a depth of 146 and 151 ft as originally planned because the hole had been deepened to a depth of 161 ft below land surface, which would allow water from the deepest water-bearing zone to enter the open borehole without having to create a perforated screen section in the casing. The nominal 8-in. casing was perforated from 114 to 135 ft along 5 vertical columns to allow for the proper sealing of the borehole annulus between the deep and middle wells and for connection between the sand and gravel with the middle well. A total of 8 vertical columns were then perforated from 75 to 85 ft below land surface. The many perforations in this interval were to allow as much neat-cement grout as possible to enter the annulus between the casing and the drilled hole between the shallow well and the middle well.

Lithologic Description of Sediments and Rocks Encountered while Drilling

The interpretation of the lithology was evaluated primarily through examination of the cuttings collected during drilling and on the observed drilling rate. The finer fraction of the cuttings in the upper 30 ft of the hole was difficult to evaluate because much of it was lost through the top of the cyclone separator. The evaluation of the coarse fraction also was limited because the different bits that were used pulverized larger gravel, cobbles, and boulders as well as solid rock into pieces less than ¾-in. in diameter. Calcareous materials were assessed by placing a small quantity of 5 percent hydrochloric acid on either a rock chip or on a clump of finer grains. The interpreted lithology is summarized in figure 7 along with a summary of the borehole size, completion details of the three nested wells, and a description of the backfill materials used in the hole.



Figure 6. Photograph of nominal 8-inch casing showing perforations following a test on June 3, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

The lithology can be divided into younger Quaternary basin-fill deposits from land surface to a depth of about 23 ft below land surface, a large quartzite megablock or silica cemented fault breccia from 23 to 34 ft below land surface, older Quaternary(?) basin-fill deposits from 34 to 125 ft below land surface, weathered residuum (clay) from 125 to 146 ft below land surface, fractured marble from 146 to 152 ft below land surface, and inclusions of granite into the marble from 152 to 161.7 ft below land surface. The younger basin-fill deposits consisted of silt, sand, gravel, and large boulders that were interpreted as reworked glacial deposits. A thick interval of quartzite from 23 to 34 ft resulted in extremely difficult drilling and was either a large quartzite megablock or was silica cemented fault breccia containing large clasts of quartzite similar to the breccia found in outcrop on the north side of Baker Creek and immediately east of the park (see fig. 2 for location).

The older basin-fill deposits were moist and had two distinct and thicker clay-rich zones deposited between three relatively thin sand and gravel layers. The first clay-rich zone was interpreted from 50 to 65 ft below land surface and had a slightly different color of moderate brown (10YR3/4) than the mostly sand and gravel layers interpreted from 34 to 50 ft and from 65 to 73 ft, which were a pale brown (5YR5/2). A second clay-rich interval with sand and gravel was interpreted from 75 to 117 ft below land surface and was a moderate yellowish brown (10YR5/4). A relatively thin sand and gravel layer (about 8-ft thick) was interpreted beneath the second clay-rich zone. This sand and gravel layer

slowed the drilling rate because larger gravel pieces periodically lodged between the bit and casing which caused binding.

Dense clay was encountered at a depth of 125 ft and the drilling rate increased markedly. This clay was dark yellowish brown (10YR4/2), had streaks of grayish red (10R4/2) and dark yellowish orange (10YR6/6) and was interpreted to be residuum resulting from the weathering of limestone. The clay graded rapidly into black (N1) to grayish black (N2) marble between 145 and 146 ft below land surface.

Veins of white calcite were present in the marble along with dark rust iron staining on many of the rock fragments indicating the marble was fractured. Water was entering the borehole in the interval from 146 to 152 ft below land surface. Granite with inclusions or seams of marble occurred from 152 ft to the bottom of the hole at 161.7 ft. Rock fragments collected from this interval consisted of pink feldspar (pale red 10R6/2), plagioclase and quartz (no reaction to 5 percent HCL acid), black (N1) and white (N9) marble (reacted mildly to the 5 percent HCL acid), and an unidentified greenish mineral (greenish gray 5GY6/1 when dry and light olive 10Y6/2 when wet).

Relatively large rock fragments of fractured marble were recovered from 153.4 to 155 ft (very light gray, N8 to medium gray, N5), with iron staining (dark yellowish orange, 10YR6/6). Drilling slowed considerably from 155 to 158 ft. Rock fragments were mostly a grayish yellow green (SGY7/2, wet) with some very light gray (N8) to medium gray (N5) marble. The marble rock fragments had iron staining (dark yellowish orange, 10 YR6/6). Sand-sized particles reacted strongly to 5 percent hydrochloric acid. Short intervals (0.3 ft per minute) of rapid drilling occurred between 158 and 160 ft below land surface. In this interval was a mixture of exotic mineral (unidentified) and marble rock fragments. Drilling was again slow from 160 to 161.7 ft below land surface. Only a few exotic minerals were recovered as larger rock fragments. Sand-sized particles reacted strongly to 5 percent hydrochloric acid but none of the larger rock fragments had any reaction. Thus, the bottom interval from 152 to 161.7 ft seems to be where the most volatile parts of the magma intruded into the Pole Canyon Limestone, metamorphosed the limestone into marble, and assimilated some of the limestone into the melt prior to solidifying. The depth of the transition zone between marble and granite before only granite occurs is unknown.

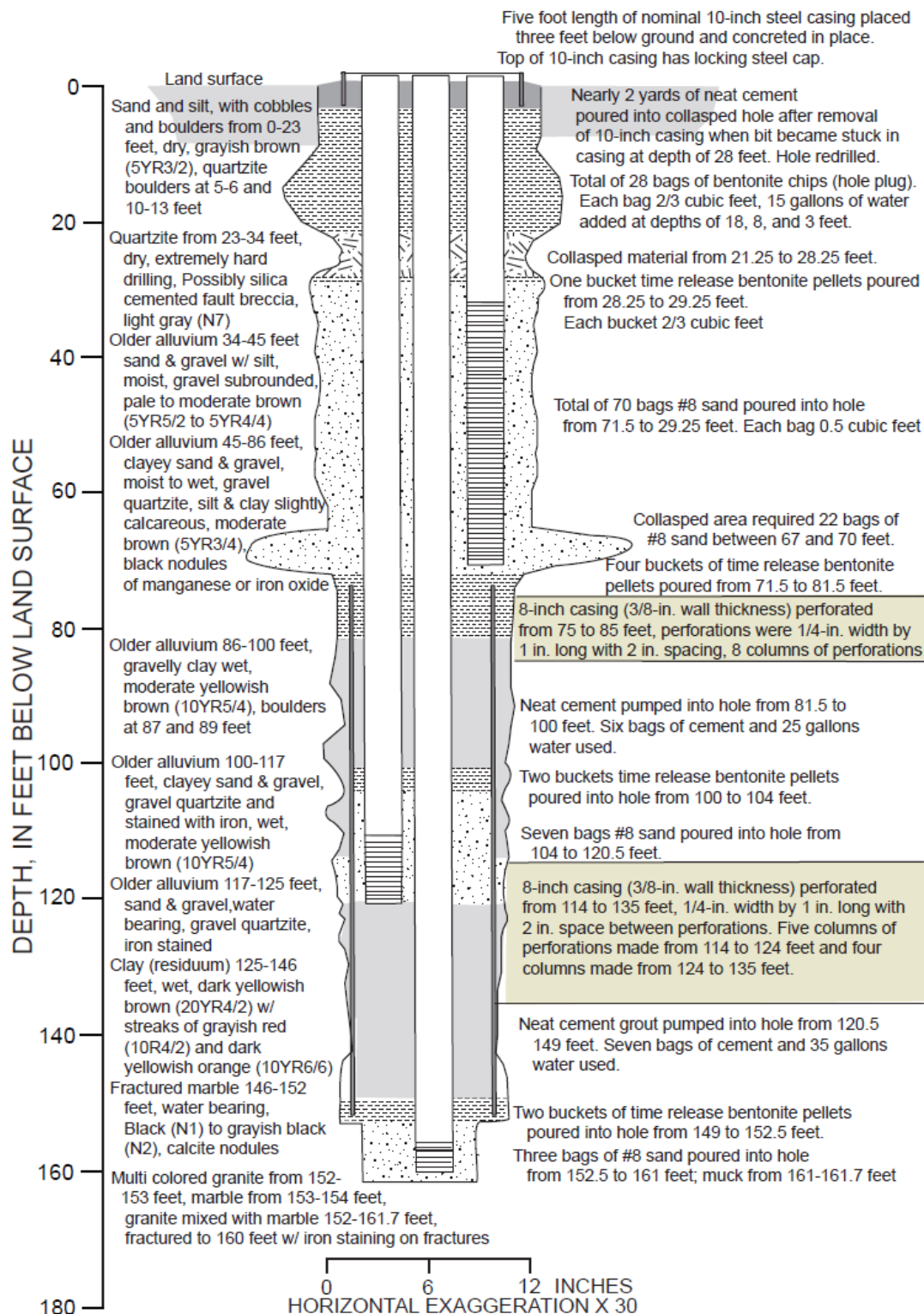


Figure 7. Summary of lithology, location of the three nested nominal 2-in. diameter wells, and a description of materials used to backfill the hole at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

Installation of Monitoring Wells

The initial plan was to drill a well at site 1 east of the sewage lagoons and install nominal 6-in. diameter schedule 80 PVC casing with a 40-ft long screen in limestone. This plan changed to installing one nominal 4-in. diameter well in limestone and one nominal 2-in. diameter well in basin-fill deposits once a saturated zone was encountered the basin-fill deposits. The plan changed again when a second sand and gravel layer was encountered from a depth of 117 to 125 ft below land surface and yielded more water than the sand and gravel from 50 to 73 ft depth and from the fractured marble at depth. The plan was revised to have three nominal 2-in. schedule 80 PVC wells installed into the hole (fig. 7).

The placement of the nominal 2-in. diameter wells and backfilling the hole began June 4, 2012. The deepest well was placed into the fractured marble in the 6 3/8-in. diameter open borehole that had been drilled 10 ft past the bottom of the nominal 8-in. casing. The 55 1/4-in. long screened interval was placed between the depth of 155 and 160 ft below land surface. The screened interval had 0.02 in. factory machined slots in the casing. Additional 3/16-in. holes were drilled manually along 39 rows of the 0.02-in. slots to allow for passage of microorganisms across the screen as part of an experiment to evaluate by personnel at the park to determine if microorganisms are transported through fractures and large pores in groundwater (fig. 8). A total of 585 holes were drilled into the screened interval. A 4-in. long end cap was placed at the bottom of the screen and the bottommost slot was 5 1/4-in. from bottom of end cap.



Figure 8. Photograph of the nominal 2-in. diameter well screen showing 3/16-in. holes drilled to enlarge the screen openings for the deep well in fractured marble and granite at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

Fine cuttings had filled the bottom 0.7 ft of hole prior to construction of the well. The borehole annulus around well screen was filled with Number 8 sand between the depths of 152.5 to 161 ft below land surface. The sand was poured through nominal 1¼-in. galvanized (tremie) pipe. The top of the screened interval was 2.5 ft below the top of the sand. A 3.5-ft layer of time-release bentonite pellets was poured on top of the sand through the tremie pipe. The bentonite was allowed to hydrate for an hour prior to pumping 7 ft³ of neat cement seal on top of the bentonite through the tremie pipe. The neat-cement grout was left to set overnight. Prior to leaving for the day, the depth to water in the deep well was measured at 30.8 ft below land surface and was much higher than any previous water-level measurement in the hole.

The depth to water in the deep well was measured at 23.6 ft below land surface on the morning of June 5, 2012, whereas the water level inside the nominal 10-in. casing was 41.8 ft below land surface. These preliminary water-level measurements indicated that the water level elevations increased with depth in the hole and that groundwater flow had an upward component at this location.

Even though less neat cement was poured into the hole than was calculated to be needed, the depth to the top of the neat cement on the morning of June 5, 2012 was 120.5 ft below land surface, indicating that about half of the lowermost perforated interval of the nominal 8-in. casing next to the deepest sand and gravel layer had been overfilled with the neat-cement grout. The reason for the overfilling of the neat-cement grout in this portion of the casing is because the tremie tube had been flushed with about 15 gal of water after the grout had been injected which increased the volume of neat cement by 2 ft³. Apparently little of the neat-cement grout escaped through the perforations in the nominal 8-in. casing adjacent to the interval of the residuum (clay) probably because the clay had deformed around the outside of the casing and formed an effective seal. Otherwise, the water level in the deep well likely would have been more similar to the water level measured inside the nominal 10-in. casing earlier that morning.

Even though the remaining open perforated interval of the nominal 8-in. casing was only 6.5 ft long (between 114 and 120.5 ft below land surface), a ten-ft screened interval was used for the well (fig. 7). The actual length of the 0.02 in. slotted interval of the screen was 9-1/3 ft. The bottom of the screen interval was positioned at a depth of 120 ft while the top of the screened interval was at a depth of 110.67 ft below land surface. The annulus between the 8-in. casing and the two nominal 2-in. well casings were filled with Number 8 sand. The sand was poured through the tremie pipe and filled the hole from 120.5 to 104 ft below land surface. A 4-ft thick layer of time-release bentonite pellets was poured through the tremie pipe and on top of the sand. The bentonite pellets were allowed to hydrate for an hour prior to pouring a neat-cement grout seal on top of the bentonite.

A 25-ft length of the nominal 8-in. casing was to be filled with neat-cement grout. The volume for filling this section less the volume of the two nominal 2-in. wells inside the 8-in. casing was calculated to be 7 ft³. However, only 6 ft³ of neat-cement grout was used for fear of grout setting up inside the larger nominal 10-in. casing. This would have made pulling the 10-in. casing considerably more difficult and could have damaged the two wells already installed in the hole. The neat-cement grout in the hole was allowed to set overnight.

The depth to water in the middle well was measured at 41.6 ft below land surface on the morning of June 6, 2012. Depth to water in the well had decreased about 1.6 ft overnight and was similar to the water level measured in the nominal 10-in. casing the morning before (41.8 ft below land surface). Depth to the top of the neat-cement grout was 81.5 ft below land surface and the grout was 3.5 ft above the bottom of the uppermost section of perforations in the nominal 8-in. casing. The estimated

volume of grout that flowed through these perforations was between 0.7 and 1 ft³. Assuming an annulus outside of the nominal 8-in. casing was 2-in. larger than the casing and that the some clay, silt, sand, and gravel deformed to fill this annulus to a porosity of 50 percent, the estimated length of seal would be between 7 and 10 ft. If no sand and gravel filled the annulus outside the casing, then the length of seal would be between 3.5 and 5 ft.

The remaining nominal 8-in. casing, along with the lower 1.5-ft of the nominal 10-in. casing, was filled from a depth of 81.5 to 73 ft below land surface with time-release bentonite pellets using the tremie pipe. The nominal 10-in. casing was pulled out 1.5 to 2 ft and the tremie pipe was removed from the hole. The shallow well was constructed with about 40 ft of 0.02-in. slot openings (two 20-ft lengths of screen) and a 6-in. long pointed end cap. The bottom of the end cap was placed at a depth of 71.5 ft with the bottom of screened interval at 71 ft below land surface. The hole was filled with Number 8 sand from a depth of 71.5 to 29.25 ft below land surface. The nominal 10-in. casing was pulled out in 2- to 8-ft increments once sand filled the bottom 3 to 5 ft of the casing. A large cavity was encountered from a depth of 69.5 to 67 ft below land surface that required 11 ft³ of sand (22 50 lb. bags) to fill this cavity. The radius of the hole in this area was estimated to be about 2.4 ft in diameter or about twice the size of the drilled hole.

A 1-ft thick layer of time-release bentonite pellets was poured on top of the sand and hydrated with water. The casing was pulled 12 ft which resulted in about 7 ft of collapsed material falling on top of the time-release bentonite pellets and across the upper part of the silica cemented quartzite (21.25 to 28.25 ft below land surface). The collapsed material was unexpected because this portion of the borehole was in the unstable interval of the original hole that had been drilled and filled with neat-cement grout to stabilize this portion of the hole prior to drilling the same hole the second time. This effectively left the 1-ft bentonite seal to limit infiltration across the 11-ft thick quartzite interval encountered from 23 to 34 ft below land surface. The remaining hole to a depth of 3 ft below land surface was filled by pouring 3 to 9 bags of 3/8-in. bentonite chips down the hole, pulling casing 3 to 5 ft, adding 3 to 5 gal of water, and then repeating the process. The backfilling of the hole was complete except for the placement of the 5-ft long, nominal 10-in. diameter protective metal surface casing around the three nominal 2-in. schedule 80 PVC wells.

Installation of the protective surface casing was not done until after developing the wells on June 7, 2012 and after the drill rig had been driven away from the hole. The protective surface casing was set 3 ft into the ground. Concrete was used to fill the remaining hole inside and outside the surface casing to land surface. The top of the surface casing was set 2 ft above land surface. The top of the nominal 2-in. PVC casing of the deep well (well 1) is 0.2 ft below the top of the surface casing or 1.8 ft above land surface. Top of the nominal 2-in. PVC casing of the middle well (well 2) is 0.25 ft below the top of the surface casing or 1.75 ft above land surface. The top of the nominal 2-in. PCV casing of the shallow well (well 3) is 0.3 ft below the surface casing or 1.7 ft above land surface.

Depth to water below land surface following well completion on June 6, 2012 for the three wells was: 23.5 ft for the deep well, 41.7 ft for the middle well, and 43.1 ft for the shallow well. The water level in the three wells was measured again prior to well development on June 7, 2012. Depth to water below land surface was: 23.4 ft for the deep well, 41.7 ft for the middle well, and 44.3 ft for the shallow well. Only the shallow well showed much change and it declined a foot overnight.

Depth to water below land surface on June 8, 2012 for the three wells following well development was: 29.92 ft for the deep well, 41.86 ft for the middle well, and 43.79 ft for the shallow well. Total depth of each well below land surface was: 160.43 ft for the deep well, 120.39 ft for the

middle well, and 71.3 ft for the shallow well. All of the wells had a total depth of casing near the targeted depth of casing at the time they were installed. The decline in the water level at the deep well following well development indicates the well is relatively slow to recover following pumping and suggests that the fracture marble/granite between a depth of 152.5 and 161.7 ft is not very permeable.

The increase in water level depths from the fractured marble (i.e. deep well) upward to the water table in the older basin-fill deposits (i.e. shallow well) suggests a rapid thinning of the fractured limestone/marble caused by the uneven contact between the Pole Canyon Limestone and the granite intrusion even though a rapid connection is known to exist between Baker Creek and Rowland Spring through large fractures or karst features in the limestone (Tom Aley, Ozark Underground Laboratory, Inc., Protem, Missouri, 2011, written commun.). The well site east of the sewage lagoons is in a natural depression between outcrops of Pole Canyon limestone to the west (across from the south sewage lagoon, see fig. 2). The depression may mark the historical channel of Baker Creek prior to it being pirated into the Pole Canyon drainage through fractures in the limestone (Lange, 1958). The relatively thick sequence of residuum (clay) and clay-rich intervals in the older basin-fill deposits probably limit the quantity of upward flow between more permeable water bearing zones and enhance the gradient between the wells. Although the original intent of the monitoring well was to intersect the zone of rapid connection, the zone is probably east of the monitoring well as much of the flow lost in Baker Creek is near Sink Caves in the Narrows and a straight line projection between Sink Cave and Rowland Spring is of the monitoring well (see fig. 2).

The water levels in the three wells were higher than the elevation of Rowland Spring (elevation of 6,595 ft above mean sea level) and ranged from 50 ft for the shallow well to 65 ft for the deep well. The lateral distance between the wells and spring is about 1,500 ft and results in a lateral gradient between the shallow well and spring of 0.03 ft/ft and between the deep well and spring of 0.04 ft/ft.

Well Development

Nominal ¾-in. galvanized pipe was lowered to a depth of 120 ft below land surface in the deep well, 88 ft below land surface in the middle well, and 57 ft below land surface in the shallow well. The air tubes were attached to flexible tubing at the well head (fig. 9) and the other end of the flexible tubing was attached to a manifold that allowed for simultaneous develop of the three wells and for control of the quantity of air injected down each well. A larger flexible tube delivered air from the air compressor on the drill rig to the manifold where the air was distributed to each well.

Tens of gallons of water were flushed from each well when air was initially injected into each well. The rate of flow decreased substantially as the water level in all wells declined to the bottom of each air tube. Less air was applied to the shallow well because of the potential for damaging the well screen next to the air tube. Additionally, less water was removed from the shallow well because about 13 ft of screen was above the initial water level and some air and water was lost through the screen above the saturated sand pack. The rate of water removal was estimated for each well using 5-gal buckets for the shallow and middle wells and a 1-gal bucket for the deep well (fig. 10).

The wells were surged 3 times during the first 20 min then air flow remained nearly constant for the next 160 min. At that time, air to the wells was turned off and the water levels in the wells were allowed to recover for 10 min. Afterwards, each well was surged again. Following the surge, air flow to each well remained nearly constant until 16:00 PDT when the air was turned off. No further development occurred because although water in the middle and deep wells were nearly clear, water

temperature nearly constant, and specific conductance about 200 $\mu\text{S}/\text{cm}$ at 25°C, the middle well had a pH of 11 indicating the neat-cement grout had not fully cured and was affecting the water chemistry of the well. Additionally, the shallow well could not be adequately developed using air because the well screen extended above the initial water level in the well.

The reason for having the shallow-well screen extend above the water level in the shallow well was to fulfill a Nevada Department of Environmental Protection requirement that a monitoring well down gradient of the sewage lagoons have a screened interval at least 1-ft above the highest water level in the well. Knowing where the highest water level will be in a new well is difficult to assess until after the well has been monitored through a series of wet and dry periods. Consequently, the well screen was extended to 3 ft above the depth of where moisture was first encountered in the drill cuttings. Due to the problem of not being able to properly develop the shallow well and the problem with incomplete curing of the grout seal in the middle well, only water samples of the middle and deep wells were collected for analysis of stable isotopes of hydrogen and oxygen, and for the anions chloride and sulfate. Pumping of the shallow well is needed to adequately develop it, whereas periodic pumping of the middle and deep wells are needed to determine if water chemistry effects from the neat-cement grout will be persistent.

The rate of water flow after 35 minutes of development was 0.25 gal/min for the deep well, 1.25 gal/min for the middle well, and about 0.6 gal/min for the shallow well. These rates remained nearly consistent throughout well development. The specific conductance was initially low in the deep well (151 $\mu\text{S}/\text{cm}$ at 25°C) after 45 minutes of development, whereas the middle well had a specific conductance of 1,100 $\mu\text{S}/\text{cm}$ at 25°C, and the shallow well had a specific conductance of 228 $\mu\text{S}/\text{cm}$ at 25°C (table 1). The specific conductance gradually increased in the shallow well, decreased in the middle well, and gradually increased then decreased in the deep well. The specific conductance increased in the middle and deep wells after air injection stopped at 12:50 PDT and the wells surged 10 minutes later. As development continued, the specific conductance again slowly decreased in the middle and deep wells and increased slightly in the shallow well until the end of development.

Estimated transmissivity of the middle and deep wells from water yield and drawdown observations during air injection were determined using a method described by Theis and others (1963). Because transmissivity is defined on both sides of their equation an iterative method was used to solve for transmissivity assuming a range in the storage coefficient (Prudic, 1991). Drawdown was the difference between the initial water level prior to well development and the bottom of the air injection tube. The length of the test was estimated at 6 hours (10:00 to 16:00 PDT), and the pumping rates were 1.25 gal/min for the middle well and 0.25 gal/min for the deep well. The storage coefficient for the middle well ranged from 1×10^{-4} to 1×10^{-5} . The storage coefficient for the deep well was estimated at 1×10^{-6} to 1×10^{-8} assuming a range in fractured porosity of 1 to 10 percent for the fractured marble and granite over a distance of 9 ft using the equation of storage coefficient originally described by Jacob (1940) and summarized by Prudic (2012). The well diameter for the middle well was 9 in. (outside diameter of the nominal 8-in. casing) and the well diameter for the deep well was 6.4 in. (diameter of the tricone bit used to drill the hole). The estimated range in transmissivity was about 5 ft^2/d for the middle well and 1 ft^2/d for the deep well. Dividing the estimated transmissivity for the middle well by the perforated interval of the nominal 8-in. casing not cemented (about 6 ft) for the middle well yields an estimate of hydraulic conductivity of 1 ft/d , and dividing the estimated transmissivity for the deep well by the thickness of the gravel pack for the deep well yields an estimate for hydraulic conductivity of 0.1 ft/d . These estimates are minimum values because of well losses during air lifting and because drawdown was assumed to be to the bottom of the air tube in both wells. No estimate was made for the shallow well because the screened interval extended above the water level in the well.

Table 1. Temperature and specific conductance of water air lifted from the three nested wells during well development on July 7, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

<i>Pacific Daylight Time (PDT)</i>	<i>Temperature (degrees Celsius)</i>			<i>Specific conductance (microsiemens per centimeter at 25 degrees Celsius)¹</i>		
	<i>Shallow</i>	<i>Middle</i>	<i>Deep</i>	<i>Shallow</i>	<i>Middle</i>	<i>Deep</i>
10:20	15.4	12.8	14.7	230(T)	1,100(T)	150(T)
11:15	17.1	12.7	15.1	600(T)	600(T)	210(T)
11:40	17.1	12.6	15.0	530(T)	360(T)	490(T)
12:25	16.6	12.6	14.6	490(T)	290(T)	340(C)
12:45	16.7	12.2	14.9	490(T)	260(T)	280(C)
12:50	Air off wells recovering					
13:10	Wells surged					
13:15	--	--	--	490(T)	440(T)	350(T)
13:40	16.2	12.4	15.4	550(T)	290(T)	310(C)
14:10	18.1	12.4	15.6	600(T)	240(C)	290(C)
14:30	--	12.7	15.7	--(T)	240(C)	270(C)
15:00 ²	--	12.6	15.5	--(T)	220(C)	250(C)

¹ Rounded to two significant digits. Letters in parentheses are abbreviations—T means turbid and C means nearly clear to clear.

² Measurements of field parameters for sample collection from middle and deep wells began. No sample for shallow well, still too turbid. Stopped sample collection after measuring pH of 11.1 in middle well and 9.1 in deep well. Middle well chemistry affected by incomplete curing of neat-cement grout. Need to let middle well sit until grout fully cured. Also need to pump shallow well as air lifting not effective in removing water. Samples were collected from middle and deep wells for stable isotopes of water and for chloride and sulfate.



Figure 9. Photograph of the air tubes protruding from each of the three wells used for well development at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.



Figure 10. Photograph of water being air lifted out of each well during development at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

Stable Isotope Composition of Water from Middle and Deep Wells

Water samples collected from the middle and deep wells at the end of well development were analyzed for the stable isotopes of water by Simon Paulson at the Stable Isotope Laboratory in the Geological Sciences Department, University of Nevada, Reno. The stable isotope composition of water from the two wells is listed in table 2 along with isotope composition of water collected from Rowland Spring and Baker Creek within 24 hours of those collected at the wells. The isotopic composition of the two wells is nearly identical to those of Rowland Spring and Baker Creek and is similar to the composition of water from Rowland Spring and Baker Creek collected June 2-3, 2011 (table 2). The stable isotope composition of Rowland Spring and Baker Creek are nearly the same but show a seasonal variation with lightest isotopic composition (more oxygen-16 compared with oxygen-18 and hydrogen-1 compared with hydrogen-2 or deuterium) during the snowmelt runoff (late May to early August) and heavier isotopic composition during the winter. This pattern is opposite the pattern in precipitation with lighter isotopic composition during winter and heavier composition during summer (Acheampong, 1992 and Friedman and others, 2002). However, the mean isotopic composition of water from Rowland Spring and Baker Creek approximate the mean composition of precipitation indicating little change in the isotopic composition from evaporation or from chemical reactions (Prudic and Glancy, 2009).

Table 2. Stable isotopes of water from middle and deep wells at well site 1 east of sewage lagoons, Rowland Spring, and Baker Creek, Great Basin National Park, White Pine County, Nevada.

Sample collection ¹	Delta Oxygen-18 values ²				Delta Deuterium values ²			
	Middle	Deep	Rowland Spring	Baker Creek	Middle	Deep	Rowland Spring	Baker Creek
06/07/2012	-15.1	-14.9	-15.2	-15.2	-111	-110	-111	-110
08/18/2011	--	--	-15.5	-15.4	--	--	-115	-114
06/02/2011	--	--	-15.2	-15.5	--	--	-113	-113
04/19/2011	--	--	-15.0	-15.2	--	--	-112	-114
01/25/2011 ²	--	--	-14.9	-14.8	--	--	-109	-108
12/07/2010 ²	--	--	-14.9	-14.8	--	--	-109	-107
10/28/2010 ²	--	--	-14.9	-14.7	--	--	-109	-106
09/27/2010 ²	--	--	-15.0	-14.8	--	--	-110	-108
08/26/2010 ²	--	--	-15.0	-14.9	--	--	-110	-108
07/21/2010 ²	--	--	-15.9	-15.8	--	--	-114	-113

¹Samples collected within a 24-hour period for all dates. Samples from April 2011 to June 2012 analyzed at the Stable Isotope Laboratory, Geological Sciences Department, University of Nevada, Reno, Nevada. Samples prior to April 2011 analyzed at the U.S. Geological Survey Stable Isotope Laboratory in Reston, Virginia.

² Rounded to three significant digits. Ratios reported in delta notation as parts per thousand (permil). Delta is the relative difference between the ratios of hydrogen-2 or deuterium to hydrogen-1 ($^2\text{H}/^1\text{H}$) or oxygen-18 to oxygen-16 ($^{18}\text{O}/^{16}\text{O}$) in water samples to the respective ratios in Vienna Standard Mean Ocean Water (VSMOW; Giofanti, 1978). A negative value represents water with less deuterium relative to hydrogen-1 or oxygen-18 relative to oxygen-16 than VSMOW. Standard error at 95-percent confidence level is 2 permil for delta deuterium and 0.2 permil for delta oxygen-18.

Chloride and Sulfate Concentrations in Water from Middle and Deep Wells

Water samples collected from the middle and deep wells at the end of well development also were analyzed for dissolved constituents of chloride and sulfate as well as samples collected from Rowland Spring and Baker Creek. The analyses were done by Alpha Analytical, Inc., Sparks, Nevada. A complete analysis of dissolved constituents was not done for the wells because of the high pH measured during well development that was caused by curing of the neat-cement grout. Additional well development is recommended prior to collection of any samples for a complete analysis of dissolved constituents. Chloride and sulfate were chosen for analysis after initial well development because they are unaffected by the curing of the neat-cement grout or from bentonite used as a seal between the grout and the coarse sand pack around the screens in each well. The chloride and sulfate concentrations in the middle and deep wells were greater than the concentrations from Rowland Spring and Baker Creek (table 3). Chloride and sulfate concentrations in water from Rowland Spring and Baker Creek show a seasonal variation with highest concentrations during winter and early spring and lowest concentrations in June and July following peak snowmelt runoff.

Table 3. Dissolved chloride and sulfate concentrations in water from middle and deep wells at well site 1 east of sewage lagoons, Rowland Spring, and Baker Creek, Great Basin National Park, White Pine County, Nevada.

Sample collection ¹	Dissolved Constituent in milligrams per liter ²							
	Chloride				Sulfate			
	Middle	Deep	Rowland Spring	Baker Creek	Middle	Deep	Rowland Spring	Baker Creek
06/07/2012	4.2	5.3	3.1	0.6	10	22	3.2	1.9
08/18/2011	--	--	3.1	0.8	--	--	3.0	1.6
06/02/2011	--	--	3.9	1.6	--	--	4.2	2.4
04/19/2011	--	--	5.6	2.4	--	--	6.2	3.3
01/25/2011 ²	--	--	4.3	1.7	--	--	4.7	3.2
12/07/2010 ²	--	--	3.1	1.2	--	--	3.4	2.6
10/28/2010 ²	--	--	3.5	1.1	--	--	3.5	2.6
09/27/2010 ²	--	--	3.6	0.9	--	--	3.6	2.4
08/26/2010 ²	--	--	2.6	0.7	--	--	2.9	2.0
07/21/2010 ²	--	--	2.1	0.5	--	--	2.6	1.6

¹Samples collected within a 24-hour period for all dates. Samples from July 21, 2010 and December 7, 2010 analyzed at the U.S. Geological Survey National Water Quality Laboratory, Lakewood, Colorado. Remaining samples collected from August 2010 to August 2011 analyzed through David Stonestrom at the U.S Geological Survey, Research Laboratory, Menlo, Park, California, and samples collected June 7, 2012 analyzed by Alpha Analytical, Inc., Sparks, Nevada.

² Rounded to 0.1 mg/L, detection limit 0.5 milligrams per liter.

Higher concentrations of chloride and sulfate in the well water was expected because of the overall higher concentrations at Rowland Spring compared with Baker Creek that indicates a component of discharge at Rowland Spring from higher chloride groundwater not part of the rapid flow between Baker Creek and Rowland Spring (Tom Aley, Ozark Underground Laboratory, Inc., Protom, Missouri, 2011, written commun.). The dissolved chloride concentrations in the wells are nearly the same as Cave Springs (5.3 mg/L in a water sample collected September 2007) and Marmot Spring (4.97 mg/L also collected September 2007) that discharges in the drainage between Baker Creek and Lehman Creek (Prudic and Glancy, 2009, p. 12, see fig. 2 for location of springs). However, the sulfate concentrations in the monitoring wells had much higher concentrations than those from the springs and thus, those concentrations may be affected by curing of the neat-cement grout.

Slug Test of Middle Monitoring Well

Two slug tests were done on the middle well using the same apparatus as that used for the Snake 5 deep well (Prudic, 2012), except the 1-in. ball valve used to release the pressurized air was replaced with a 2-in. ball valve to allow for a more rapid escape of the air. Two absolute pressure transducers were placed into the well, one about 12.6 ft below the water level in the well (depth of 54.6 ft below land surface) and another near the top of the well casing. Both transducers had a water-level range of about 30 ft with an accuracy of + 0.02 ft (Shlumberger Water Services, <http://www.swstechnology.com/groundwater-monitoring/groundwater-dataloggers/mini-diver>, accessed

August 27, 2012). The apparatus was sealed and the well pressurized using a bicycle pump to a displacement of about 10 ft according to an outside gage. The actual displacement was 9.7 ft. The well was allowed to equilibrate to the added pressure for several minutes prior to opening the ball valve. The water level in the well was allowed to recover for 10 min before the ball valve was closed again and the test repeated (fig. 11). Displacement for the second test was 8.2 ft.

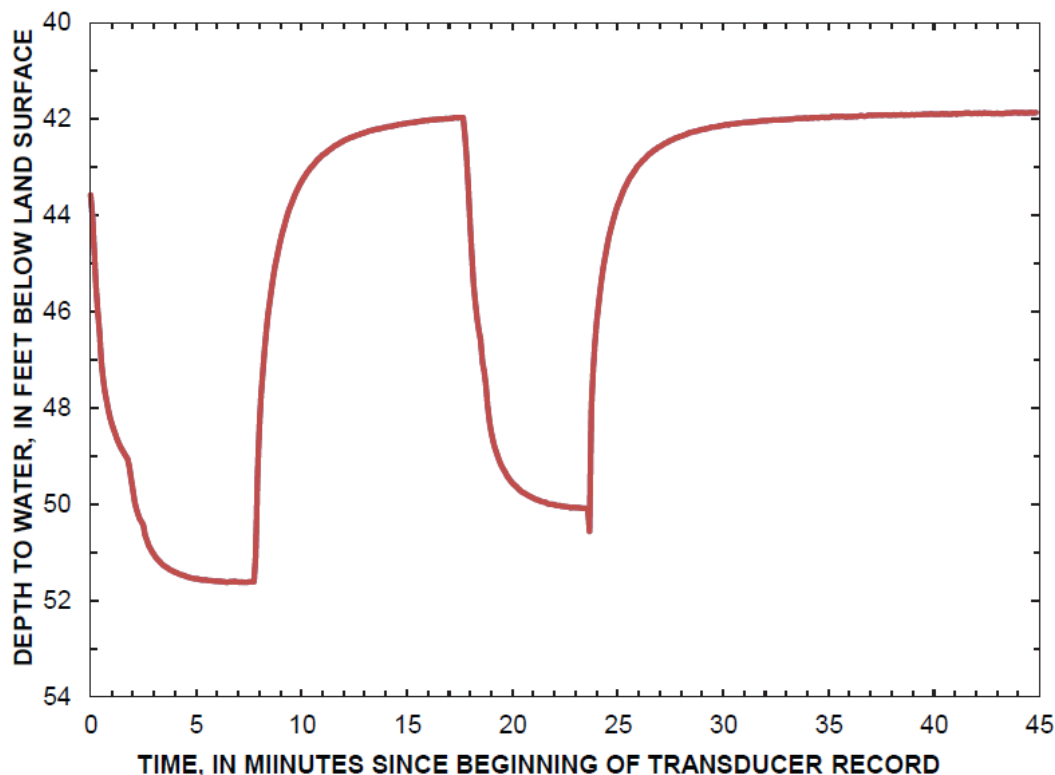


Figure 11. Depth to water during slug test of middle well on June 8, 2012 at site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada. The pressure transducers began recording at 9:40 PDT when the well was being pressurized with air for the first test.

Since air was used to depress the water level in the well, only the recovery data after the ball valve was opened was used to analyze transmissivity. The time series of water-level recovery following the release of pressurized air from the well were computed by subtracting the air pressure measured by the upper transducer from the total pressure measured by the lower transducer. Water-level recovery for each test is listed in table 4.

Transmissivity of the sand and gravel adjacent to the middle well 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 is less than 0.0001 as the type curves for storage values less than 0.0001 are similar. Although the sand and gravel unit was only 8 ft thick (fig. 7) and the nominal 8-in. casing was perforated across the interval, the bottom half of the perforated interval was filled with a neat-cement grout and only a 6-ft of perforated interval remained with half of that in a clay-rich sand and gravel. The storage coefficient of the sand and gravel across the perforated interval was estimated to range from 0.6 to 3×10^{-5} assuming a

specific storage between 1 and 2×10^{-6} per ft and an effective thickness between 6 and 11 ft. However, the slope of the recovery curve was best matched when the storage coefficient was 1×10^{-4} and the estimated transmissivity was 30 ft²/d or about 5 times greater than that estimated during well development (fig. 12). Both tests yielded the same result. The estimated hydraulic conductivity is between 3 and 5 ft/d assuming a thickness between 10 and 6 ft. The estimated hydraulic conductivity is similar to that estimated for a well in similar deposits about ¼ mi east of Rowland Spring on the north side of Lehman Creek (see fig. 2 for location). The hydraulic conductivity of this well was estimated from the specific capacity data from the Nevada well driller's log of the well (log number 70663) using the same method described earlier for estimating transmissivity and hydraulic conductivity during well development.

Table 4. Water-level rise in middle well after releasing pressurized air during two slug tests on July 8, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

<i>Time in seconds since air releases</i>	<i>Water-level rise in feet</i>		<i>Time in seconds since air releases</i>	<i>Water-level rise in feet</i>	
	<i>Test 1</i>	<i>Test 2</i>		<i>Test 1</i>	<i>Test 2</i>
0	0	0	130	8.30	7.03
2	0.87	0.70	140	8.43	7.13
4	1.89	1.66	160	8.63	7.28
6	2.39	2.10	180	8.79	7.41
8	2.77	2.44	200	8.91	7.52
10	3.11	2.73	220	9.03	7.60
12	3.41	2.98	240	9.12	7.68
16	3.92	3.41	260	9.19	7.74
20	4.34	3.77	280	9.25	7.79
24	4.71	4.08	310	9.33	7.85
28	5.03	4.34	350	9.41	7.93
32	5.32	4.59	390	9.46	7.97
36	5.59	4.81	430	9.52	8.01
40	5.82	5.01	470	9.56	8.04
46	6.14	5.27	510	9.60	8.06
52	6.41	5.50	550	9.62	8.08
58	6.66	5.71	590	9.64	8.11
64	6.88	5.88	640	--	8.13
70	7.07	6.04	700	--	8.14
80	7.36	6.28	800	--	8.18
90	7.61	6.47	900	--	8.18
100	7.82	6.64	1020	--	8.19
110	8.00	6.78	1140	--	8.21
120	8.17	6.92	1260	--	8.22

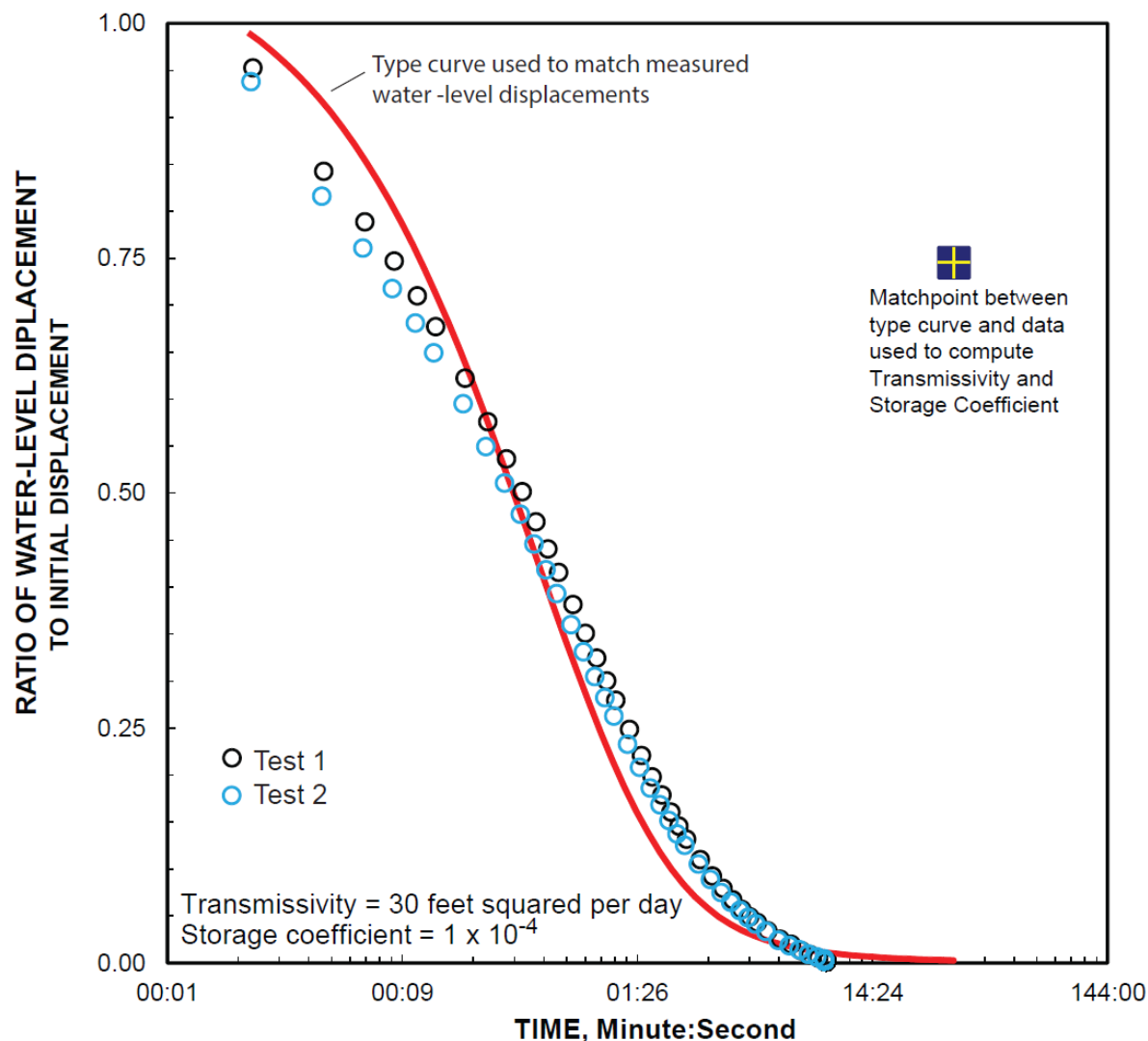


Figure 12. Slug test results of middle well on June 8, 2012 at site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

Slug Test of Deep Monitoring Well

The deep well was not tested on the same day as the middle well because the water level on the morning of June 8, 2012 was still 4 ft lower than the water level prior to development the day before. The well was tested from 18:00 to 20:12 Pacific Daylight Time on June 9, 2012 by Scott Tyler (University of Nevada, Reno) as part of a field exercise for geology field camp students. This test was done by lowering a vented pressure transducer (Insitu Co., Level Troll 700) 15 ft below the water level in the well. The water level prior to lowering the transducer was 28 ft below land surface, about 5 ft below the water level prior to well development. The slug used for this test was a sealed 10-ft piece of nominal 1-in. diameter schedule 40 PVC pipe. The pipe was attached to a cable and lowered quickly

into the water until it was below the measured water level. The theoretical volume displacement was estimated at 0.094 ft^3 and should have resulted in a water-level rise (or upward displacement) of 4.7 ft inside the nominal 2-in. casing. The measured rise was 6 ft because the transducer was pushed downward in the well as the pipe was lowered into the well. This extra displacement was removed from the data by subtracting the 1.3 ft offset created by increasing the depth of the pressure transducer. Analysis of this data was done using two different methods. The first method assumes isotropic spherical incompressible flow (Hvorslev, 1951), whereas the second method assumes horizontal compressible flow through a confined aquifer (Cooper and others, 1967) and was the same method used to estimate the transmissivity of the middle well. The Hvorslev method produces lower estimates of hydraulic conductivity than the method of Cooper and others using the same data (Prudic, 1982). The corrected water-level rise during the test is listed in table 5.

Table 5. Water-level rise in deep well after lowering a sealed 10-ft length of nominal 1-in. diameter schedule 40 polyvinyl-chloride pipe beneath the water level during a slug test on July 9, 2012 at well site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada. Slug-test data are from Scott Tyler, University of Nevada, Reno, July 2012, written commun.)

<i>Time in minutes since pipe lowered below initial water level in well</i>	<i>Water-level rise in feet</i>
0	4.68
0.02	4.26
0.08	4.01
0.17	3.92
0.33	3.85
0.67	3.80
1	3.76
2	3.69
4	3.58
8	3.43
16	3.15
32	2.72
48	2.33
64	2.00
80	1.72
96	1.49
112	1.29
128	1.14
130	1.12

The estimated hydraulic conductivity from the Hvorslev method was 0.03 ft/d. Data collected during the first minute after the pipe was lowered had a more rapid decrease in the displacement than data afterwards (fig. 13). The initial rapid response is probably related to the sand pack surrounding the well screen. Once that effect dissipated, the gradual decrease in water levels followed a slope that could be used to estimate the hydraulic conductivity. The equation used to estimate hydraulic conductivity is shown on the graph along with the time when displacement is 0.37 the initial displacement (t_{37}). The equation is valid when the effective length (L_e) is greater than the radius of the well and sand pack (R) or 7 ft versus 0.27 ft. Radius of the standpipe or casing above the screen (r) is 0.08 ft.

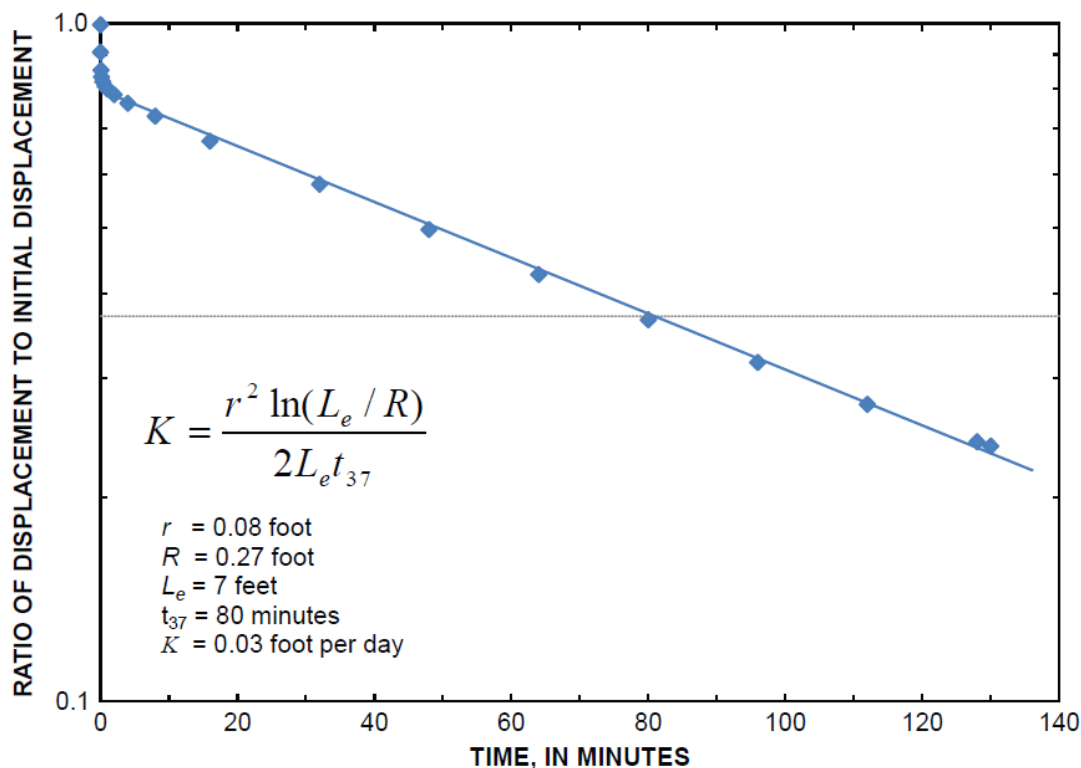


Figure 13. Slug test results using Hvorslev method of test at deep well on June 9, 2012 at site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

The estimated transmissivity and hydraulic conductivity from the Cooper and others method (1967) was $0.34 \text{ ft}^2/\text{d}$ and 0.05 ft/d , respectively. Since data collected during the first minute after the pipe was lowered had a more rapid decrease in the displacement than data afterwards, only data after one minute were used to estimate the transmissivity. Additionally, the initial displacement was adjusted to 4 ft to account for the water-level response from within the sand pack. Analysis of the data including the equations is shown in figure 14. The data are matched to series of type curves (m) that have the same vertical axis but a different horizontal axis related to a function (η). A time is selected after the data have been matched to a type curve and a value of η chosen as 1. The time for the deep well slug test was 29 minutes (fig. 14). Terminology differs slightly from the Hvorslev method in that r_c is the inside radius of the well casing above the screen and r_s is the radius of the well screen and sand pack. Other curves could have been chosen to compute transmissivity and storage from the type curves. The method can produce a large range in storage (2 to 3 orders of magnitude) but the transmissivity is generally within 20 percent over several type curves (Cooper and others, 1967). The storage coefficient of 9×10^{-7} is reasonable when 10 percent fracture porosity is assumed for the marble/granite.

The estimate of transmissivity and hydraulic conductivity from the slug test is about half that estimated from well yield and drawdown during well development. The difference is probably related to the inability to accurately measure the volumetric rate of water air lifted during development. Still the results are quite similar indicating that the hydraulic conductivity and transmissivity of fractured marble

and granite next to the screened interval in the deep well is much less than that of the older basin-fill next to the screened interval of the middle well.

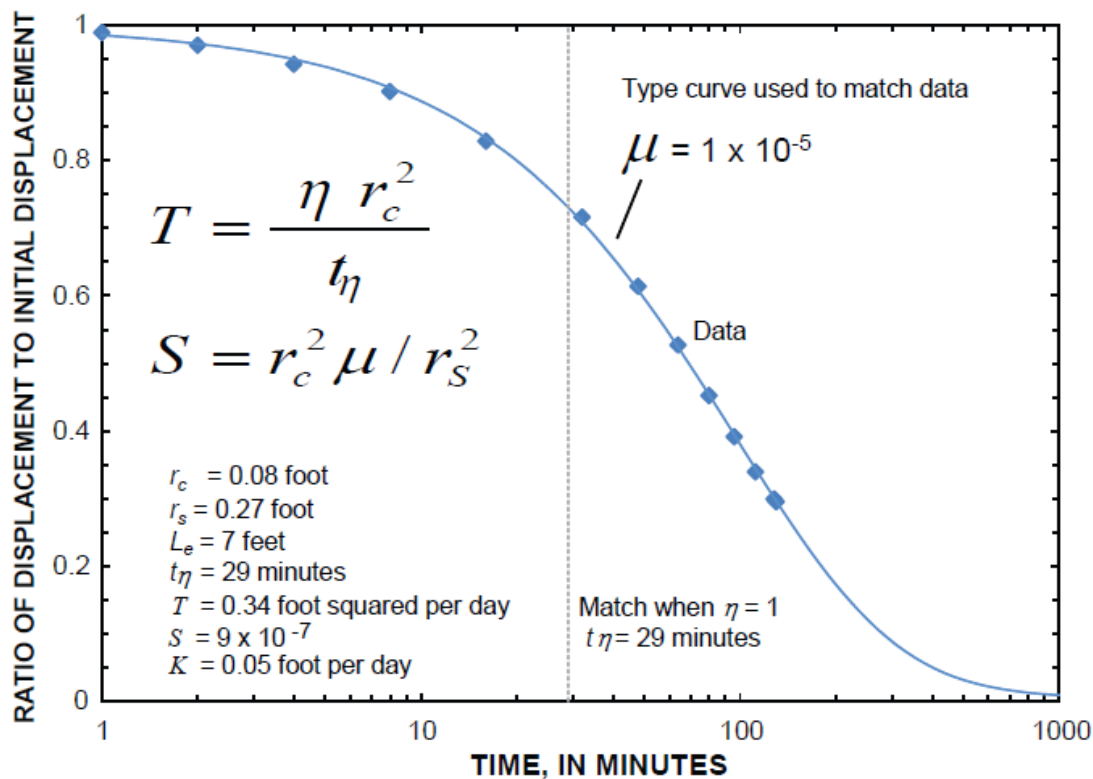


Figure 14. Slug test results from Cooper and others method (1967) of deep well on June 9, 2012 at site 1 east of sewage lagoons, Great Basin National Park, White Pine County, Nevada.

Acknowledgments

The University of Nevada, Reno (UNR) appointed David Prudic and Scott Tyler as the principal investigators for this study. The investigators were funded under Task Agreement Number P12AC10876 through the Great Basin Cooperative Ecosystem Studies Unit. The Southern Nevada Public Lands Management Act Round 8 conservation initiative project funded the drilling of the monitoring well as part of a larger project to evaluate the connection between aquifers, springs, and streams in Great Basin National Park and aquifers in Snake Valley. The monitoring well east of the sewage lagoon was drilled by the U.S. Geological Survey Research Drilling Program. Lead oversight from the National Park Service was shared by Gordon Bell (Great Basin National Park), Gary Karst (Regional Hydrologist based at Lake Mead National Recreation Area) and William P. Van Liew (Hydrologist with the NPS Water Rights Branch). Mark Pepper and John Reynolds (Great Basin National Park) provided assistance in the final cleanup of the site and helped install straw waddles and plastic underneath the drill equipment and used to form canals to carry water away from the drill site. Personnel at Great Basin National Park also cleared the drill site of all trees prior to drilling.

References Cited

- Acheampong, S.Y., 1992, Isotope hydrology of Lehman and Baker Creek drainages, Great Basin National Park, Nevada: Las Vegas, University of Nevada, Department of Geoscience, Unpublished M.S. Thesis, 105 p.
- Cooper, H.H., Jr., Bredehoeft, J.D., and Papadopoulos, I.S., 1967, Response of a finite-diameter well to an instantaneous charge of water: *Water Resources Research*, vol. 3, no. 1, p. 263-269.
- Elliott, P.E., Beck, D.A., and Prudic, D.E., 2006, Characterization of surface-water resources in the Great Basin National Park and their susceptibility to ground-water withdrawals in adjacent valleys, White Pine County, Nevada: U.S. Geological Survey Scientific Investigations Report 2006-5099, 156 p.
- Friedman, Irving, Smith, G.I., Johnson, C.A., Moscati, R.J., 2002, Stable isotope compositions of waters in the Great Basin, United States 2. Modern precipitation: *J. of Geophysical Research*, v. 107, no. 4401, 22 pp.
- Giofanti, R., 1978, Standards for stable isotope measurements in natural compounds: *Nature*, v. 271, p. 534-536.
- Greene, E.A. and Shapiro, A.M., 1995, Methods of conducting air-pressurized slug tests and computation of type curves for estimating transmissivity and storage: U.S. Geological Survey Open-File Report 95-424, 43 p.
- Halford, K.J., and Kuniansky, E.L., 2002, Spreadsheets for the analysis of aquifer-test and slug-test data, version 1.1: U.S. Geological Survey Open-File Report 02-197, 51 p., <http://water.usgs.gov/pubs/of/ofr02197/>
- Hvorslev, M.J., 1951, Time land and soil permeability in ground-water observations: Vicksburg, Miss., U.S. Army Corps of Engineers Experimental Station, Bulletin, 36 50 p.
- Jacob, C.E., 1940, On the flow of water in an elastic artesian aquifer: *Transactions of the American Geophysical Union*, part 2, p. 574-586.
- Lange, A.L., 1958, Stream piracy and cave development along Baker Creek, Nevada: Santa Barbara, Calif., Western Speleological Institute Bulletin 1, p. 1-24.
- National Park Service, 2007, Digital geologic map of Great Basin National Park and vicinity, Nevada: online digital geologic database, accessed October 27, 2009, at <http://science.nature.nps.gov/nrdata/datastore.cfm?ID=44849>
- Prudic, D.E., 1982, Hydraulic conductivity of a fine-grained till, Cattaraugus County, New York: *Groundwater*, v. 20, no. 2, p. 194-204.
- Prudic, D.E., 1991, Estimates of hydraulic conductivity from aquifer-test analyses and specific-capacity data, Gulf Coast regional aquifer systems, south-central United States: U.S. Geological Survey Water Resources Investigations Report 90-4121, 38 p.
- Prudic, D.E., 2012, AQUIFER TEST—Analysis of slug test for Snake5 deep well (site ID 385524114045601), Snake Valley, Nevada, June 1, 2011, available online at

http://nevada.usgs.gov/water/AquiferTests/snake_valley_Snake5deep_cfm?studyname=snake_valley_Snake5deep

Prudic, D.E. and Glancy, P.A., 2009, Geochemical investigation of the source water to Cave Springs, Great Basin National Park, White Pine County, Nevada: U.S. Geological Survey Scientific Investigations Report 2009-5073, 28 p.

Theis, C.V., Brown, R.H., and Meyer, R.R., 1963, Estimating the transmissibility of aquifers from the specific capacity of wells, in Bentall, Ray, Methods of determining permeability, transmissibility and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 331-341.