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Silt and gas accumulation beneath an artificial recharge spreading basin, Southwestern Utah, U.S.A.

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ABSTRACT

Sand Hollow Reservoir in southwestern Utah, USA, is operated for both surface-water storage and artificial recharge to the underlying Navajo Sandstone. The total volume of estimated artificial recharge between 2002 and 2007 is 85 million cubic meters (69,000 acre-feet). Since 2002, artificial recharge rates have generally been declining and are inversely correlated with the increasing surface area of the reservoir. Permeability testing of core samples retrieved from beneath the reservoir indicates that this decline may not be due to silt accumulation. Artificial recharge rates also show much seasonal variability. Calculations of apparent intrinsic permeability show that these variations can only partly be explained by variation in water viscosity associated with seasonal changes in water temperature. Sporadic seasonal trends in recharge rates and intrinsic permeability during 2002-2004 could be associated with the large fluctuations in reservoir elevation and wetted area. From 2005 through 2007, the reservoir was mostly full and there has been a more consistent seasonal pattern of minimum recharge rates during the summer and maximum rates during the autumn. Total dissolved-gas pressure measurements indicate the presence of biogenic gas bubbles in the shallow sediments beneath the shallower parts of Sand Hollow Reservoir when the water is warmer. Permeability reduction associated with this gas clogging may contribute to the decrease in artificial recharge rates during the spring and summer, with a subsequently increasing recharge rates in the autumn associated with a decline in volume of gas bubbles. Other possible causes for seasonal variation in artificial recharge rates require further investigation.

Key words: artificial recharge, gas clogging, navajo sandstone, Sand Hollow, Utah

Acumulación de gas y limos bajo una balsa de recarga artificial en el suroeste de Utah, USA

RESUMEN

El embalse de Sand Hollow, en el suroeste de Utah, se utiliza tanto para almacenar agua superficial como para recargar artificialmente la formación arenisca Navajo subyacente. El volumen total recargado entre 2002 y 2007 es de 85 Mm^3. Desde 2002, las tasas de recarga han ido disminuyendo en proporción inversa con el incremento de superficie del embalse. Los ensayos de permeabilidad realizados en testigos tomados del fondo del embalse indican que ésta disminución no se debe a la acumulación de materiales arcillosos. Estas tasas de recarga muestran también una alta variabilidad estacional. Los cálculos de la permeabilidad intrínseca aparente indican que esta variación solo puede ser explicada en parte por la variación de la viscosidad del agua asociada a sus cambios de temperatura estacionales. Tendencias esporádicas estacionales tanto de las tasas de recarga como de la permeabilidad intrínseca durante el período 2002-2004 podrían asociarse con las enormes variaciones en la altura de lámina de agua en el embalse y de la superficie mojada. Desde 2005 hasta 2007, el embalse estuvo casi lleno, y se ha registrado un modelo estacional consistente, según el cual las tasas de recarga son mínimas durante el verano y máximas durante el otoño. Las medidas de la presión total de gases disueltos indican la presencia de burbujas de gas de origen biológico en los sedimentos más someros situados en las zonas menos profundas del embalse de Sand Hollow cuando el agua está más caliente. La reducción de la permeabilidad asociada con la colmatación por gas puede contribuir a la disminución de las tasas de recarga durante la primavera y el verano, con un subsecuente aumento en el otoño asociado a una menor cantidad de burbujas de gas presentes. Para determinar otras posibles causas de la disminución de las tasas de recarga, será necesario acometer nuevos trabajos de investigación.

Palabras clave: arenisca navajo, colmatación por aire, recarga artificial, San Hollow, Utah

Introduction

Sand Hollow basin is a 50-km^2 basin located in the southwestern part of Utah, USA, about 20 km northeast of St. George (fig. 1). It is part of the Virgin River drainage of the Lower Colorado River Basin and the upper Mohave Desert ecosystem. Altitudes range from 900 to 1,500 m. Sand Hollow is underlain prima-

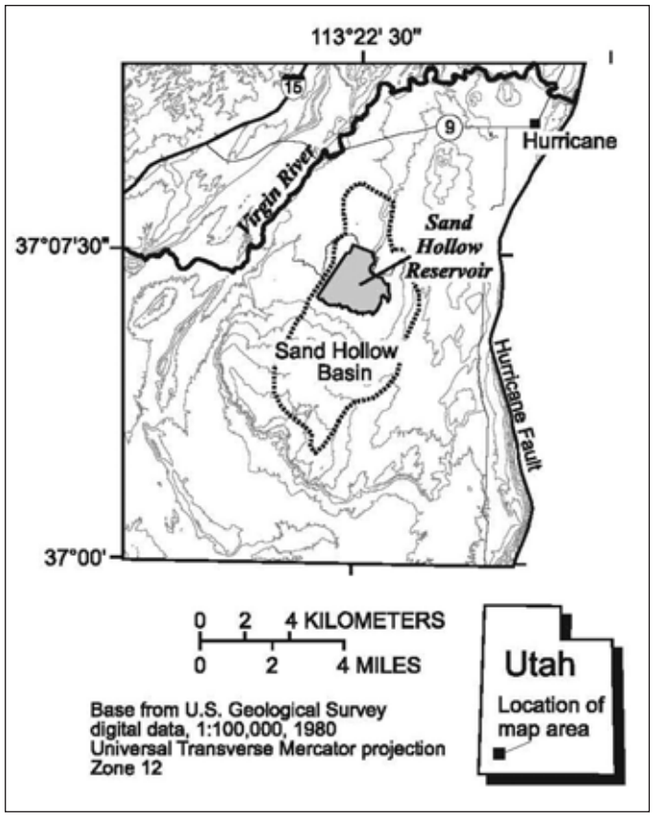

Figure 1. Location of Sand Hollow basin, southwestern, Utah, USA
Figura 1. Situación de la cuenca de Sand Hollow, suroeste de Utah, USA

rily by Navajo Sandstone that is either exposed at the surface or covered by a veneer of soil (Hurlow, 1998). The average stratigraphic thickness of the Navajo Sandstone in Sand Hollow basin is around 250 m, but ranges from about 100 to 370 m.

Sand Hollow Reservoir was constructed in 2002 to provide surface-water storage and artificial recharge to the underlying Navajo Sandstone. The reservoir is an off-channel facility that receives water from the Virgin River, diverted near the town of Virgin, Utah. From 2002 through 2007, total surface-water diversions to Sand Hollow Reservoir were about 155 hm^3 (126,000 acre-ft) (fig. 2). Above-normal precipitation during 2004 and 2005 allowed the reservoir to fill to its total storage capacity of more than 62 hm^3 (50,000 acre-ft) in 2006, with a corresponding surface area of about 5 km^2 and a maximum reservoir elevation of 933 m above sea level. During 2007, reservoir storage decreased to about 37 hm^3 (30,000 acre-ft), with a corresponding decline in reservoir elevation to about 927 m. Total evaporation during 2002-07 was estimated to be 31 hm^3 (25,000 acre-ft), based on the McGuinness and Bordne (1971) version of the Jensen-Haise method which utilizes air temperature and solar radiation data. Using a water budget method to account for inflow, evaporation, and surface-water storage, total cumulative artificial recharge to the Navajo Aquifer beneath Sand Hollow Reservoir during 2002-07 was 85 hm^3 (69,000 acre-ft) (Heilweil et al., 2005, 2009; Heilweil and Susong, 2007).

Volumetric recharge (L^3/T) was divided by the reservoir area (L^2) to evaluate temporal changes in artificial recharge rates (L/T) beneath Sand Hollow Reservoir. Estimated artificial recharge rates ranged from 0.004 to 0.13 m/d between March 2002 and December 2007 (Heilweil et al., 2009). Figure 3 shows artificial recharge rates and reservoir altitude for all but the first three months (March –May 2002). These first three months had high recharge rates of 0.10 to 0.13 m/d associated with saturation of the soils and sandstone beneath the reservoir; they were excluded from the graph to better show subsequent trends and seasonal fluctuations. While annual volumetric rates of recharge (fig. 2) during 2002-07 fluctuated between a minimum of 11 million cubic meters (9,000 acre-feet) and a maximum of 20 million cubic meters (16,000 acre-feet), artificial recharge rates (fig. 3) have generally declined and are inversely correlated with the increasing surface area of the reservoir.

Superimposed on this decline are large seasonal fluctuations in recharge rates. During 2002 through early 2005, these increases and decreases are sporadic, occurring during different times of the year and may have partly been caused by rapidly changing reservoir elevations (fig. 3). The related changes in areal extent of the reservoir resulted in accessing more or less permeable areas of the heterogeneous bottom sediments (Heilweil et al., 2007). From late 2005 through 2007, however, recharge rates generally reached a minimum during the summer, followed by rapidly rising rates during autumn. This was particularly pronounced during 2007, when rates rapidly increased from a minimum of 0.004 m/d in June to 0.024 m/d in October. Apparent intrinsic permeability (assuming a unit vertical hydraulic gradient) was calculated to remove the variability associated with the temperature-dependent dynamic viscosity of water to more closely examine causes for the seasonal variation in artificial recharge (Heilweil and Susong, 2007). Much of the monthly variation in artificial recharge rates during 2002 through 2004 is less evident in the plot of apparent intrinsic permeability. From 2005 through 2007, however, both artificial recharge rates (fig. 3) and estimated apparent intrinsic permeability

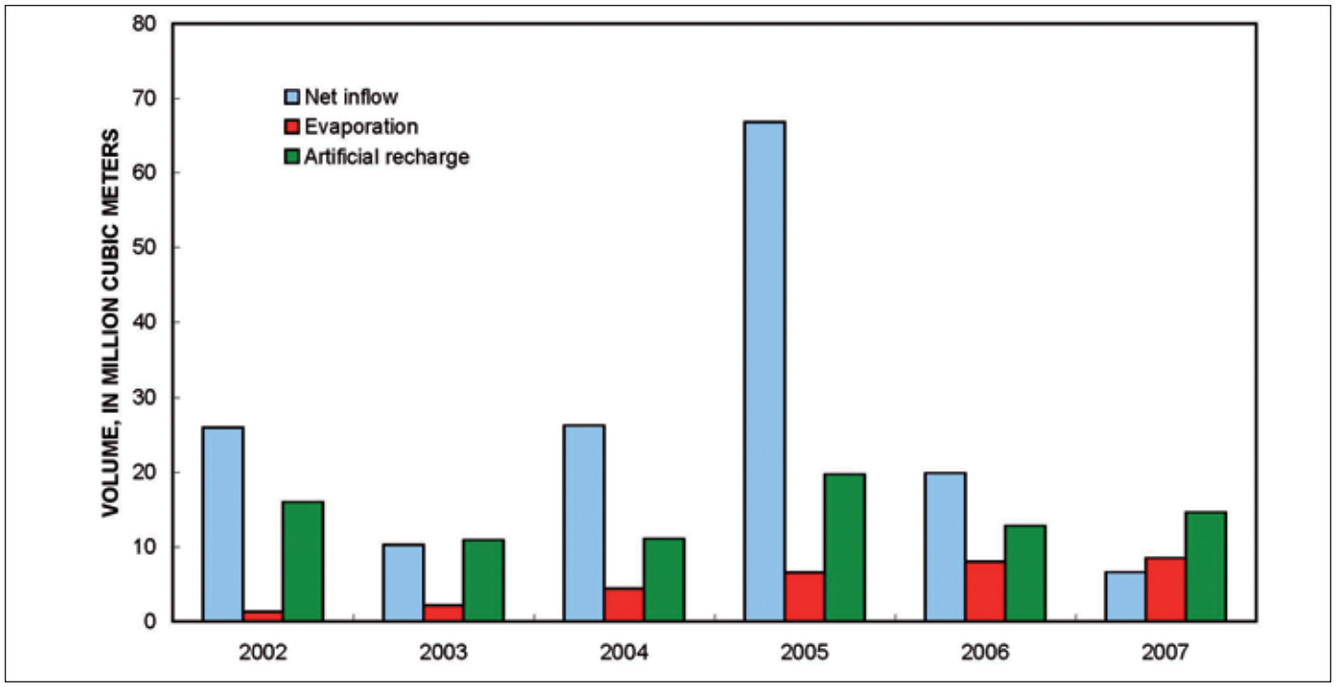

Figure 2. Annual volumes of net inflow, estimated evaporation, and artificial recharge, Sand Hollow Reservoir, southwestern Utah, 2002-07
Figura 2. Volúmenes anuales de entradas netas al embalse, evaporación estimada y recarga artificial. Embalse de Sand Hollow, suroeste de Utah, 2002-07

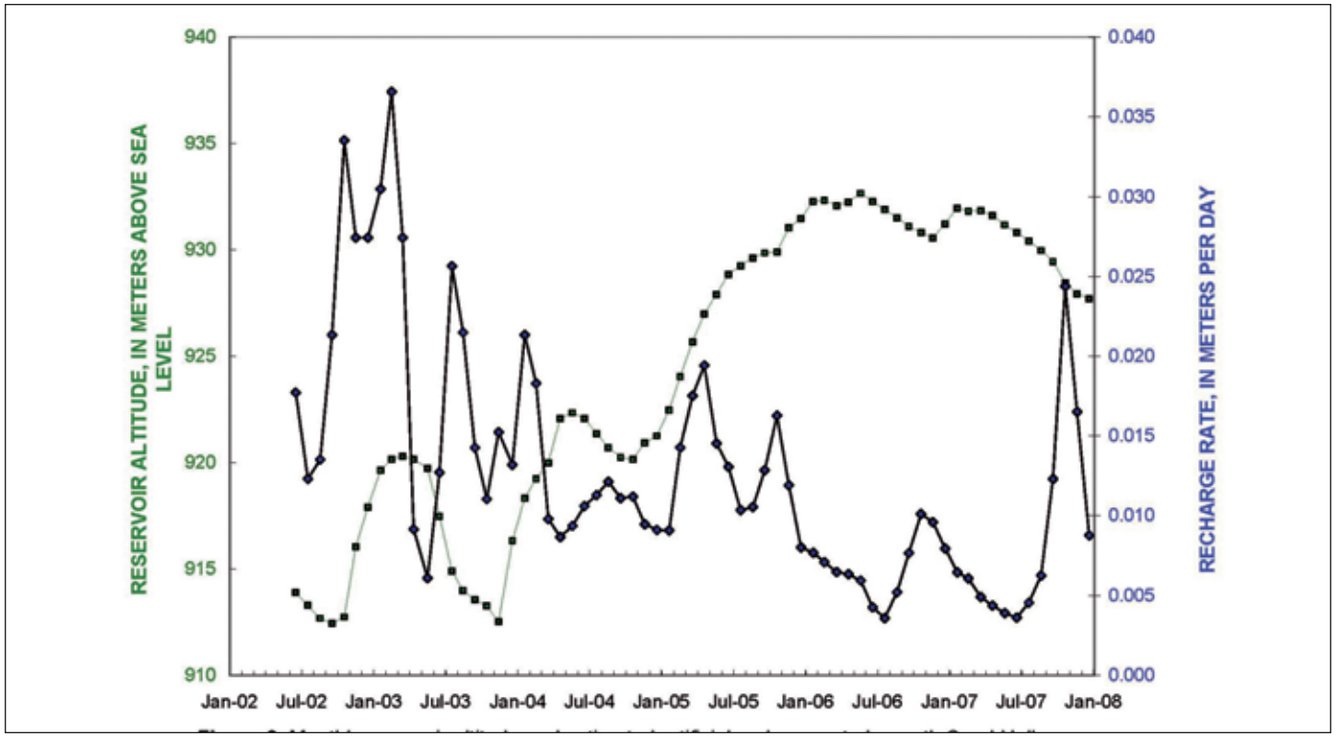

Figure 3. Monthly reservoir altitude and estimated artificial recharge rate beneath Sand Hollow Reservoir, southwestern Utah, 2002-07
Figura 3. Altitud mensual de lámina de agua y tasa de recarga artificial estimada bajo el embalse de Sand Hollow, suroeste de Utah, 2002-07

values (fig. 4) exhibit similar seasonal trends of minimum values during summer, maximum values during autumn, and declining values during winter and spring. To illustrate this similarity during recent years, artificial recharge rates and apparent intrinsic permeability both increased by about seven-fold from 0.0036 to 0.0244 m/d and from 1.74 x 10^{-12} to 1.22 x 10^{-11} cm^2, respectively, between June and October of 2007. This indicates that there are other influences affecting the temporal variability of artificial recharge besides viscosity effects.

The overall goal of this study is to assess potential causes for both long-term and seasonal variations in artificial recharge rates beneath Sand Hollow Reservoir. One particular objective of this study was to test the hypothesis that accumulated silt deposits are causing a long-term decline in artificial recharge rates. Other studies of artificial recharge beneath spreading basins utilizing surface water with suspended sediments generally show a large reduction in infiltration rates with time, associated with the formation of a low-permeability clay/silt or biofilm layer (Bouwer, 1996; Mousavi and Rezai, 1999; Rinck-Pfeiffer et al., 2000; Schuh, 1990). Three potential sources of silt accumulation beneath Sand Hollow Reservoir have been identified: (1) suspended sediments in the inflowing surface water, (2) eolian dust transport, and (3) reworking of sandstone-derived sediments by wave action along the bottom of the reservoir. To evaluate whether the gradual decline in artificial recharge rates beneath Sand Hollow between 2002 and 2007 was caused by low permeability silt deposits, core samples of the sediments beneath the reservoir were collected for laboratory analysis of vertical hydraulic conductivity.

A second objective was to investigate the seasonal formation of biogenically derived gas bubbles. One hypothesis is that gas bubbles beneath the reservoir cause a decrease in effective permeability. Invoking Henry's Law pressure/gas-solubility relations, theoretical calculations indicate there would be a donut-shaped area beneath the shallow part of the reservoir where low hydrostatic pressure allows the formation and entrapment of gas bubbles in the shallow sediments during warmer months. A subsequent decrease in bubble size (following from the ideal gas

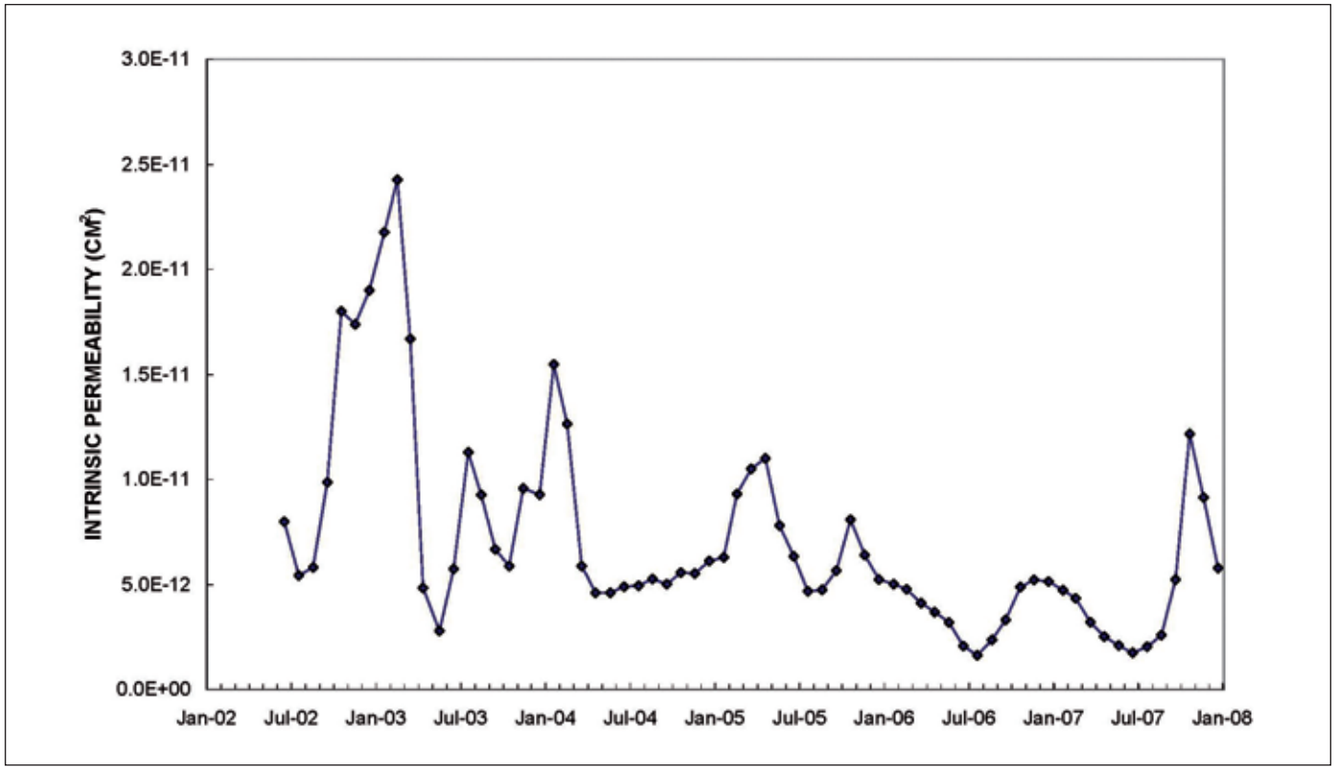

Figure 4. Apparent intrinsic permeability of sediments beneath Sand Hollow Reservoir, southwestern Utah, 2002-07
Figura 4. Permeabilidad intrínseca aparente de los sedimentos de fondo en el embalse de Sand Hollow, suroeste de Utah, 2002-07

law) or dissolution associated with cooler water temperatures (governed by reverse solubility) during autumn would cause an increase in monthly artificial recharge rates. Because of the approximately 25° C seasonal variation in reservoir water temperature (Heilweil and Susong, 2007), extensive vegetation and algal mats cover the bottom of the shallower parts of the reservoir during the warm summer months and dissipate during the cool winter months. Gas bubbles, assumed to be of biogenic origin from plant respiration and decay, can often be observed during sediment disturbance in these shallow areas of the reservoir. It is likely, therefore, that these entrapped gas bubbles cause a seasonal reduction in permeability, similar to the gas clogging previously documented at a nearby infiltration test site in Sand Hollow basin (Heilweil et al., 2004).

The purpose of this report is to document data collection and present interpretations related to silt and bubble formation in these sediments beneath Sand Hollow Reservoir to better understand potential causes for both seasonal and long-term variation in artificial recharge rates. This study is a cooperative effort by the Washington County Water Conservancy District (WCWCD), the U.S. Geological Survey (USGS), the Spanish Geological and Mining Institute

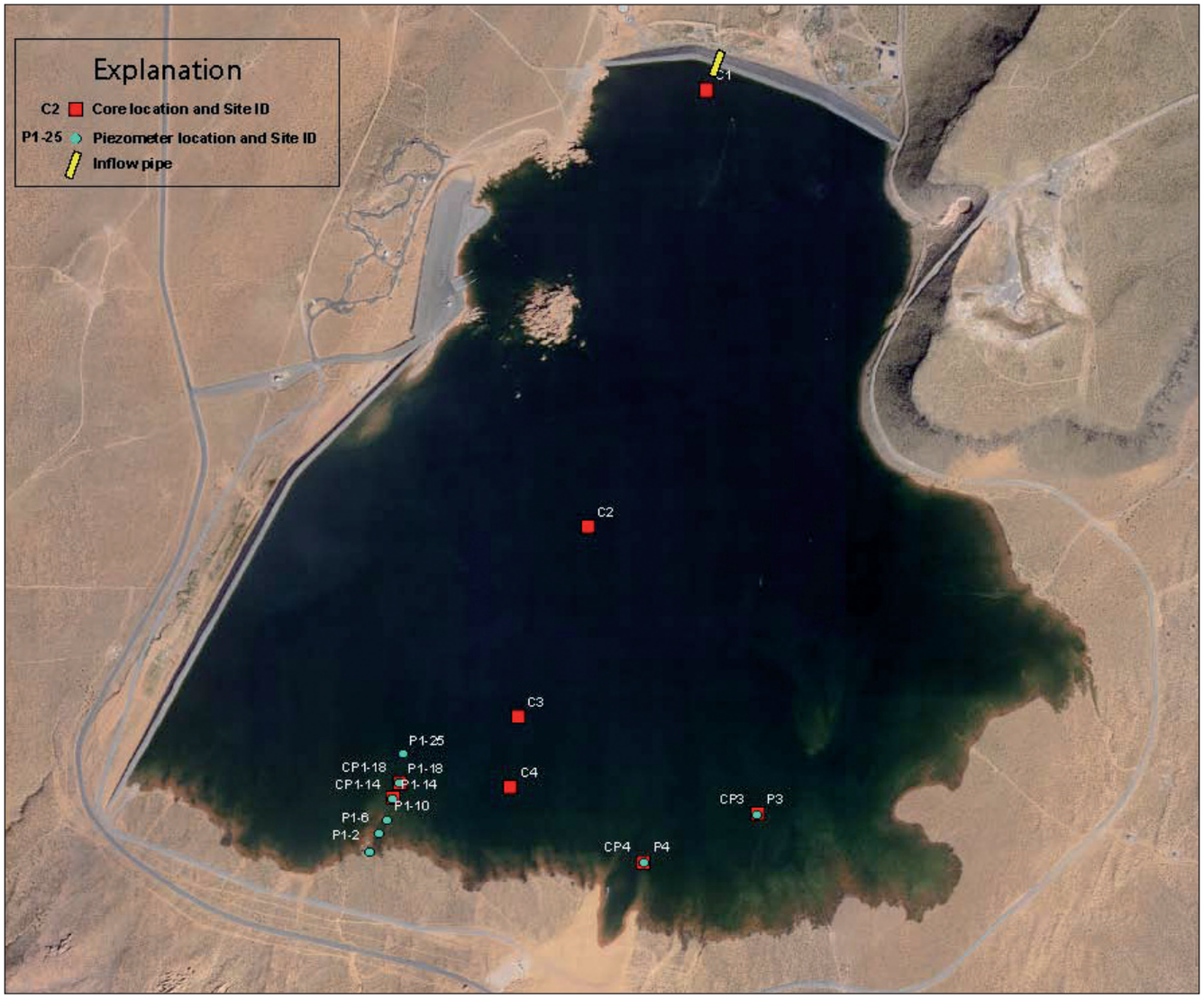

Figure 5. Location of core sample collection and temporary piezometer sites, Sand Hollow Reservoir, southwestern Utah
Figure 5. Situación de las muestras y piezómetros temporales. Embalse de Sand Hollow, suroeste de Utah

								Particle-size distribution			
Site name	Site ID	Latitude	Longitude	Reservoir Water Depth (m)	Core Length (m)	[1]Thickness of silt layer (cm)	Vertical hydraulic conductivity (m/d)	Percent coarser than 0.15 mm (top 5 cm)	Description	Percent coarser than 0.15 mm (bottom 5 cm)	Description
Core at Piezometer 1-14	CP1-14	370623.2	1132303.5	4.3	0.30	14	2.1	80	silty sand	87	sand with silt
Core at Piezometer 1-18	CP1-18	370624.8	1132302.7	5.5	0.73	11	9.8	75	sand with silt	75	sand with silt
Core at Piezometer 3	CP3	370622.3	1132218.0	4.8	0.22	11	2.2	55	silty sand	55	silty sand
Core at Piezometer 4	CP4	370617.2	1132232.0	5.8	0.41	13	22.1	80	sand with silt	85	sand with silt
Core 1	C1	370735.4	1132226.2	17.7	0.61	23	1.0	43	sandy silt	30	silty sand
Core 2	C2	370651.0	1132239.8	17.9	0.61	15	4.2	50	silty sand	45	sand with silt
Core 3	C3	370631.7	1132248.1	12.2	0.25	8	16.6	86	sand with silt	88	sand with silt
Core 4	C4	370624.5	1132248.8	8.7	0.25	8	26.7	78	sand with silt	70	sand with silt

[1] Thickness of recently deposited silt based on measured thickness of black organic sediment in core barrel

Table 1. Vertical hydraulic conductivity and particle-size distribution of sediments collected beneath Sand Hollow Reservoir, southwestern Utah

Table 1. Distribución de la conductividad hidráulica vertical y del tamaño de grano de los sedimentos recogidos en el fondo del embalse de Sand Hollow, suroeste de Utah

(IGME), and the University of Utah Department of Geology and Geophysics.

Approach and methods

In order to evaluate potential permeability reduction caused by recently accumulated silt deposits beneath Sand Hollow Reservoir, core samples of sediments were collected for laboratory permeability testing and particle-size distribution at eight sites with water depths ranging from 4.3 to 17.9 m (fig. 5). Cores were retrieved in clear 7.0-cm diameter by 61- or 122-cm long polycarbonate core barrels (tubes) using a slide hammer percussion coring device. This equipment was deployed beneath a 10-m long motorboat and guided by a team of scuba divers on the floor of the reservoir to keep the core barrel aligned vertically and assist driving the core into the soft sediments. Core recovery lengths varied from 0.2 to 0.7 m (Table 1). The remaining section of each core barrel was filled with water and sealed underwater with plastic plugs and end caps to maintain hydraulic pressure. Core samples were kept in an upright vertical position during retrieval and transportation to the laboratory in order to minimize disturbance of the sediments. Vertical hydraulic conductivity was measured for each core sample using a modified version of the

[**TDG pressure**: Total dissolved gas pressure; **ΔTDG pressure**: TDG pressure minus atmospheric pressure; **Excess TDG pressure**: positive values indicate the presence of gas phase]

Site name	Site ID	Date	Reservoir water depth (m)	Latitude	Longitude	Diameter of casing, in cm	Depth to water below top of casing, in m	Specific conductance	pH	Water temperature, in °C	Atmospheric pressure, in mm Hg	TDG pressure, in mm Hg	Source of TDG measurement	ΔTDG pressure, in mm Hg	ΔTDG pressure, in m H_2O	Total height of water above screen (m)	Excess TDG pressure, in m H_2O
Piezometer 1-2	P 1-2	6/3/2008	0.6	370617.8	1132306.2	2.5	0.6	775	6.4	20.0	673	735	lab	62	0.8	1.1	-0.27
Piezometer 1-6	P 1-6	6/2/2008	1.8	370619.7	1132305.2	2.5	0.5	910	6.8	19.5	679	844	lab	165	2.2	2.3	-0.08
Piezometer 1-10	P 1-10	6/2/2008	3.0	370620.0	1132304.9	2.5	1.2	899	7.2	19.0	679	958	lab	279	3.8	3.5	0.25
Piezometer 1-14	P 1-14	4/29/2008	4.0	370623.2	1132303.6	2.5	0.9	1,026	7.7	13.0	680	827	lab	147	2.0	4.5	-2.50
Piezometer 1-14	P 1-14	6/2/2008	4.2			2.5	0.8	943	7.5	19.0	679	1,123	lab	444	6.0	4.7	1.30
Piezometer 1-14	P 1-14	10/21/2008	1.2			5.0	0.9	821	8.7	18.1	687	683	in-situ	-4	-0.1	1.7	-1.77
Piezometer 1-18	P 1-18	6/2/2008	5.5	370624.8	1132302.7	2.5	0.5	828	7.3	19.0	679	945	lab	266	3.6	6.0	-2.37
Piezometer 1-18	P 1-18	10/23/2008	2.4			5.0	0.9	818	8.6	18.1	687	686	in-situ	-1	0.0	2.9	-2.95
Piezometer 1-25	P 1-25	10/21/2008	4.6	370627.7	1132302.4	5.0	0.9	819	8.7	18.0	687	690	in-situ	3	0.0	5.1	-5.03
Piezometer 3	P 3	5/1/2008	5.3	370622.3	1132218.0	2.5	0.9	857	7.8	13.0	680	1,016	lab	336	4.6	5.8	-1.26
Piezometer 4	P 4	5/1/2008	4.6	370617.2	1132232.0	2.5	0.9	901	7.5	13.0	680	794	lab	114	1.6	5.1	-3.52

Table 2. Field parameters and total dissolved gas pressure of ground water from temporary piezometers installed beneath Sand Hollow Reservoir, southwestern Utah

Tabla 2. Parámetros de campo y presión total de gases disueltos en el agua subterránea en los piezómetros temporales instalado en el fondo del embalse de Sand Hollow, suroeste de Utah

falling-head permeameter method (Bowles, 1992). For each sample, the plastic plugs and end caps were removed and the core tube was placed on a #100 mesh (100 openings per inch) sieve. The sieve kept the sampled sediments in the tube while allowing the water to freely drain. Permeability measurements were conducted in the original sample collection tubes, rather than re-compacting the sediments into a permeability mold, in an attempt to obtain more accurate *in situ* values. The initial head was then measured and a timer started. As water passed through the sample and water level declined, the volume of water was measured and used to calculate permeability. After completion of the hydraulic conductivity measurements, two sediment samples from each core barrel (the top and bottom 5 cm, respectively) were removed and dried for grain-size analysis using ASTM method D 422-63 (ASTM International, 2006). Sieve analysis was used for the fraction coarser than the #200 sieve size and hydrometer analysis was used for the finer fraction.

Figure 6. Photo of a core sample collected at the P4 site beneath Sand Hollow Reservoir, southwestern Utah
Figura 6. Fotografía de una muestra recogida en el punto P-4 en el fondo del embalse de Sand Hollow, suroeste de Utah

Potential permeability reduction by trapped gas bubbles beneath Sand Hollow Reservoir was investigated using temporary drive-point piezometers. These piezometers were installed to a 0.6-m depth in the sediments at eight sites (fig. 5) having water depths ranging from 0.6 to 5.5 m. The presence of trapped gas bubbles was evaluated by measuring total dissolved-gas (TDG) pressure in the sediments beneath the reservoir and comparing the TDG pressure (TDG pressure minus barometric pressure) to hydrostatic pressure to determine if gas exsolution (bubble formation) occurred. Two types of piezometers were used: (1) a 1.9-cm diameter by 30-cm long stainless steel drive point with a 15-cm-long screen interval attached to 2.5-cm diameter galvanized steel pipe; and (2) a 5-cm diameter by 61-cm long galvanized steel drive point with 15-cm long screen interval attached to 5-cm diameter schedule 80 polyvinylchloride pipe (Table 2). Both types of piezometers were driven manually approximately 0.6 m into the sediments beneath the reservoir with either a fence-post driver or a 2-kilogram sledge hammer, resulting in a median screen interval depth of about 0.5 m beneath the top of the sediments. The top of the casing for each piezometer was between 0.5 and 1.2 m above the surface of the reservoir to prevent surface water entry by wave action. Prior to ground-water sampling, a minimum of three casing volumes was purged from these piezometers using either a peristaltic pump (for the 2.5-cm diameter piezometers) or a 1.6-cm diameter check-valve hand pump (for the 5-cm diameter piezometers). Field and laboratory TDG pressure measurements of water samples from these piezometers were used to identify the presence of gas bubbles in the shallow sediments. For ground water from the 5.0-cm diameter piezometers (n = 3), total dissolved-gas pressure was measured using an in-situ multi-parameter probe equipped with gas-permeable tubing and a 30 psi pressure transducer. Other measured field parameters included barometric pressure, water temperature, pH, dissolved oxygen, and specific conductance. Because the diameter of the multi-parameter probe was too large to enter the 2.5-cm diameter piezometers, gas samples (n = 8) were instead collected with in-situ diffusion samplers (Sheldon, 2002) and total dissolved-gas pressure was quantified at the University of Utah's Dissolved Gas Service Center by measuring vacuum line inlet pres-

sure on a quadrapole mass spectrometer. This laboratory method for measuring TDG pressure also provided an analysis of major dissolved-gas chemistry. These gases included nitrogen, oxygen, argon, carbon dioxide, and methane.

Results

Based on visual observations through the clear polycarbonate core barrels, the sediment columns within the eight retrieved core samples were relatively undisturbed (fig. 6). The core samples contained 8 to 23 cm of recently deposited organic black silt (Table 1). Laboratory vertical hydraulic conductivity measurements of the eight core samples range from 1.0 to 26.7 m/d, similar to previously reported ranges for silt and sand (Bouwer, 2002; Freeze and Cherry, 1979). The spatial distribution of these values is consistent with their physical settings within the reservoir. The lowest value of 1.0 m/d was measured from the C1 sample, nearest the reservoir inflow pipe. This core also had the thickest layer (23 cm) of recently deposited silts, substantially more than the 8 to 15 cm of silt observed in the other core samples, consistent with settling out of suspended sediments from the inflowing surface water. The highest vertical hydraulic conductivity measurements of 16.6, 22.1, and 26.7 m/d were from the C3, CP4, and C4 sites, respectively, located nearest the sand dune deposits at the south end of the reservoir. Earlier work shows that these dune deposits are the coarsest soils found within Sand Hollow basin (Heilweil et al., 2007).

Particle-size analysis of sediments from the top 5 cm of the core samples (within the recent silt accumulation) had a range of 43 to 86 percent coarser than 0.15 mm diameter, indicating either silty sand or sand with silt (Table 1). This is similar to the range of 30 to 88 percent measured from the bottom 5 cm of the core samples, assumed to represent natural soil deposits prior to the inception of the reservoir. These particle size distributions are consistent with the previously reported range of soil coarseness values (18 and 86 percent coarser than 0.15 mm) for Sand Hollow basin (Heilweil et al., 2007). Except for the finer sediments found at the C1 site, the difference in coarseness between the recent silt (top 5 cm) and the pre-existing sediment (bottom 5 cm) of the core samples is ≤ 10 percent. This indicates that much of the recently accumulated silt deposits may be derived from or mixed with the reworking of the natural (pre-existing) soils by wave action or locally derived eolian transport and deposition.

Eight dissolved-gas analyses of nitrogen, oxygen, argon, carbon dioxide, and methane from seven of the piezometers (including one replicate) are given in Table 3. The following ranges of concentrations are given in cubic centimeters per gram at standard temperature and pressure (cm^3 STP/g): nitrogen, 0.75 to 1.1 cm^3 STP/g (68 to 97%); oxygen, 0.00 to 0.36 cm^3 STP/g (0 to 22%); argon: 7.1 x 10^{-3} to 3.5 x 10^{-2} cm^3 STP/g (1 to 3%); carbon dioxide: 9.3 x 10^{-4} to 6.5 x 10^{-2} cm^3 STP/g (0 to 6%); methane: 3.2 x 10^{-3} to 0.4 cm^3 STP/g (0 to 31%). These dissolved-gas concentrations, as defined by Henry's Law, are dependent upon water temperature, atmospheric pressure (approximately 680 mm Hg), and salinity. While some of the samples have gas fractions similar to air (also given in table 3), most samples are depleted in oxygen and enriched in carbon dioxide and methane. This indicates biogenic respiration and decay, assumed to be associated with benthic algae and aquatic plants observed along the bottom of the reservoir at these locations during summer months. The most elevated concentrations of biogenic gases are from sample P1-14 on 6/1/05 (6% carbon dioxide), and sample P3 on 5/1/08 (31% methane).

TDG pressure measurements of ground water in the temporary piezometers installed in the shallow sediments beneath the reservoir ranged from 683 to 1,123 mm Hg (Table 2). Atmospheric pressure measurements at these same sites varied from 673 to 687 mm Hg. The difference in total dissolved-gas pressure (ΔTDG) was then calculated by subtracting atmospheric pressure from the measured TDG pressure at each site. ΔTDG pressures ranged from -4 mm Hg at site P1-14 on 10/21/2008 to 444 mm Hg at site P1-14 on 6/2/2008. Excess TDG pressure was then calculated by subtracting the total height of water above the screen interval from ΔTDG pressure (converted to m H_2O). Four of the eleven measurements had either positive or near zero (greater than -1 m of water) calculated excess TDG pressures, indicating gas bubble formation in the shallow sediments beneath the reservoir.

Discussion

The vertical hydraulic conductivity of the silt and sand recovered in the eight core samples were all similar to or higher than previous measurements of soil (0.004 to 0.06 m/d), weathered Navajo Sandstone (0.10 to 0.23 m/d), and non-weathered Navajo Sandstone samples (0.01 to 0.42 m/d) from Sand Hollow basin (Heilweil et al., 2004). This indicates that the recently deposited silts generally are not acting as a rate-limiting permeability layer for artificial

Site Name	Date sampled	Water temperature	N_{28}		O_{32}		Ar_{40}		CO_2		CH_4	
		(°C)	(cm^3STP/g)	Percent	(cm^3STP/g)	Percent	(cm^3STP/g)	Percent	(cm^3STP/g)	Percent	(cm^3STP/g)	Percent
Piezometer 1-2	6/5/2008	20.0	8.1E-01	91%	4.7E-02	5.3%	9.1E-03	1.0%	1.9E-02	2.2%	3.2E-03	0.36%
Piezometer 1-6	6/5/2008	19.5	1.0E+00	97%	0.0E+00	0.00%	1.3E-02	1.2%	5.4E-03	0.53%	8.8E-03	0.85%
Piezometer 1-10	6/5/2008	19.0	9.0E-01	76%	2.5E-01	21%	3.5E-02	3.0%	9.3E-04	0.08%	9.2E-03	0.78%
Piezometer 1-14	5/1/2008	13.0	7.5E-01	73%	1.9E-01	19%	7.1E-03	0.68%	6.5E-02	6.3%	1.4E-02	1.3%
Piezometer 1-14	6/5/2008	19.4	1.1E+00	83%	1.8E-01	13%	1.3E-02	1.0%	6.6E-03	0.48%	4.2E-02	3.1%
Piezometer 1-18	6/5/2008	19.0	8.7E-01	75%	2.6E-01	22%	9.1E-03	0.79%	7.9E-03	0.68%	9.5E-03	0.83%
Piezometer 3	5/1/2008	13.0	8.6E-01	68%	1.4E-03	0.11%	8.1E-03	0.63%	7.9E-03	0.62%	4.0E-01	31%
Piezometer 4	5/1/2008	13.0	8.5E-01	86%	9.7E-02	9.8%	9.0E-03	0.90%	2.1E-02	2.1%	9.7E-03	0.97%
Air	---	--	--	78.1%	--	20.9%	--	0.93%	--	0.039%	--	0.001%

Table 3. Major dissolved-gas chemistry of ground water from temporary piezometers installed beneath Sand Hollow Reservoir, southwestern Utah

Tabla 3. Química de gases disueltos en el agua subterránea de los piezómetros temporales instalado bajo el embalse de Sand Hollow, suroeste de Utah

recharge and likely are not causing the observed gradual decline in artificial recharge rates beneath Sand Hollow Reservoir between 2002 and 2007. This conclusion is also supported by the similarity in soil coarseness of these recently deposited sediments to the underlying soils. Possible explanations for this similarity are the re-working/mixing of recent and pre-existing sediments by wave action along the edges of the reservoir and/or the eolian transport and deposition of nearby silts and sands. This similarity between recent and pre-existing soil coarseness is even found at the C1 and C2 sites, located beneath the deepest parts of the reservoir and having the thickest layer of recently deposited sediments. It may be coincidence that the newer sediments at these two sites have similar coarseness to the pre-existing finer-grained deposits. Further study of the sources of incoming silt and the development of a sediment budget are needed to confirm preliminary findings.

The positive or near-zero excess TDG pressures calculated for four of the 11 samples indicate the presence of gas bubbles in the shallow sediments beneath Sand Hollow Reservoir. These higher excess TDG pressures, in general, were found at piezometers located in shallow water (<3.5 m) for water temperatures between 13 to 20° C. Three repeat TDG pressures at site P1-14 confirm the relation between higher excess TDG pressure and warmer water temperature. TDG pressure was not measured beneath Sand Hollow Reservoir during the warmest or coolest months (August, January), when reservoir water temperatures generally reach a maximum and minimum of 30° C and 5° C, respectively. Measured dissolved gas concentrations from the eight diffusion samplers collected during early May and June, however, were used with Henry's Law solubility relations for calculating theoretical TDG pressures at these minimum and maximum reservoir water temperatures. These calculations show that at 30ºC, all but the deepest piezometer (P1-18 at 6-m water depth) would have had positive or near-zero excess TDG pressure, indicating bubble formation. In contrast, calculations for the minimum water temperature of 5ºC indicate no bubble formation during this cooler period. This confirms the hypothesis that a donut-shaped area of trapped gas in sediments forms beneath the shallower parts of the reservoir (water depths of less than 6 m) during the warmest months and dissipates during the coolest months. Elevated concentrations of carbon dioxide and methane in water from the shallow piezometers (table 3) support the theory that these gas bubbles are formed from biological decay and respiration of benthic algae and aquatic plants, which are prevalent beneath the shallower parts of the reservoir during the warmer months, but decline during the cooler months.

Conclusions

Vertical hydraulic conductivity measurements of core samples collected beneath Sand Hollow Reservoir are similar to or larger than previously reported values for soil and sandstone samples collected in Sand Hollow basin, indicating that silt accumulation during 2002-2007 has not caused substantial permeability reduction. This was an unexpected finding and counter to the initial hypothesis that the deposition of silts from either the suspended sediments in the inflow to the reservoir or from eolian dust transport has caused

a gradual decrease in artificial recharge rates beneath the reservoir. Additional studies are needed to investigate other potential causes for the general decline in recharge rates at Sand Hollow Reservoir, such as decreasing hydraulic gradients away from the reservoir as the regional water table rises in response to recharge.

Artificial recharge rates at Sand Hollow during 2002 to 2007 show much seasonal variability. Calculations of apparent intrinsic permeability show that these variations are only partly caused by variation in water viscosity associated with seasonal changes in water temperature. The lack of consistent seasonal trends in both artificial recharge rates and apparent intrinsic permeability during 2002-2004 could possibly be explained by spatial and temporal heterogeneity associated with (1) soil permeability, (2) air entrapment in the sediments beneath the reservoir, or (3) hydrostatic pressure changes, all of which could have been caused by the large fluctuation in reservoir elevation and wetted area during this initial period of reservoir operation. Also, benthic algae and aquatic plants (potentially causing seasonal biogenic gas clogging) were not immediately present in the reservoir; it took a several years for these plant communities to become established.

Seasonal patterns of variation in artificial recharge rates and apparent intrinsic permeability show more consistency during 2005-2007. Dissolved-gas analyses of ground water collected from piezometers indicate the presence of biogenic gas bubbles in the sediments beneath the shallower parts of Sand Hollow Reservoir when the water is warmer. This supports the hypothesis of seasonal bubble formation and gas clogging in a donut-shaped area beneath the shallow part of the reservoir during the summer. Cooling water temperatures, coupled with the seasonal die off and/or reduced respiration of aquatic vegetation, likely cause partial or complete dissolution of these bubbles and the increase in artificial recharge rates in autumn. The subsequent decrease in recharge rates during the winter and spring, however, cannot be explained by biogenic gas bubble formation/dissipation. Other possible factors affecting the seasonal variation in recharge rates that require further investigation include: (1) increased seasonal silt deposition associated with larger inflows to the reservoir during winter and spring snowmelt runoff, (2) increased eolian dust transport associated with higher seasonal wind speeds, (3) re-working of silt deposits by wave action, and (4) physical biofilm clogging and subsequent seasonal dissipation and decay.

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