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Assessment of Artificial Recharge at Sand Hollow Reservoir, Washington County, Utah, Updated to Conditions through 2006

Scientific Investigations Report 2007-5023

Prepared in cooperation with the
WASHINGTON COUNTY WATER CONSERVANCY DISTRICT

U.S. Department of the Interior
U.S. Geological Survey

Cover: View of the North Dam of Sand Hollow Reservoir, Washington County, Utah. Photograph taken by Victor Heilweil.

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
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Conversion Factors, Datums, and Abbreviated Water-Quality Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
ounce, fluid (fl. oz)	29.57	milliliter (mL)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Viscosity	
pound per foot-second (lb/ft-s)	1,488	centipoise (kg/m-s)
	Intrinsic permeability	
square foot (ft^2)	0.0929	square meter (m^2)
	Hydraulic gradient	
foot per foot (ft/ft)	1.00	meter per meter (m/m)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88); horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Altitude, as used in this report, refers to distance above the vertical datum.

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

Concentrations of chemical constituents in water are reported either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Assessment of Artificial Recharge at Sand Hollow Reservoir, Washington County, Utah, Updated to Conditions through 2006

By Victor M. Heilweil and David D. Susong

Abstract

Sand Hollow, Utah, is the site of a surface-water reservoir completed in March 2002 and operated by the Washington County Water Conservancy District (WCWCD) primarily as an aquifer storage and recovery project. The reservoir is an off-channel facility that receives water from the Virgin River, diverted near the town of Virgin, Utah. Hydrologic data collected are described and listed in this report, including ground-water levels, reservoir stage, reservoir-water temperature, meteorology, evaporation, and estimated ground-water recharge.

Since the construction of the reservoir in 2002, diversions from the Virgin River have resulted in generally rising stage and surface area. Large spring run-off volumes during 2005-06 allowed the WCWCD to fill the reservoir to near capacity, with a surface area of about 1,300 acres in 2006. Reservoir stage reached a record altitude of about 3,060 feet in May 2006, resulting in a depth of nearly 90 feet and a reservoir storage of about 51,000 acre-feet. Water temperature in the reservoir shows large seasonal variation and has ranged from about 5 to 32°C.

Estimated ground-water recharge rates have ranged from 0.01 to 0.43 feet per day. Estimated recharge volumes have ranged from about 200 to about 3,500 acre-feet per month. Total ground-water recharge from March 2002 through August 2006 is estimated to be about 51,000 acre-feet. Estimated evaporation rates have varied from 0.05 to 0.97 feet per month, resulting in evaporation losses of 20 to 1,200 acre-feet per month. Total evaporation from March 2002 through August 2006 is estimated to be about 17,000 acre-feet. The combination of generally declining recharge rates and increasing reservoir altitude and area explains the trend of an increasing ratio of evaporation to recharge volume over time, with the total volume of water lost through evaporation nearly as large as the volume of ground-water recharge during the first 8 months of 2006. With removal of the viscosity effects (caused by seasonal water temperature variations), the intrinsic permeability indicates a large seasonal variation in clogging, with large winter increases likely caused by a combination of both decreased biofilms and the reduced volume of trapped gas bubbles.

Introduction

The population of Washington County in southwestern Utah has been rapidly growing. To help meet the demand for additional water resources, Sand Hollow Reservoir (*fig. 1*) was constructed in 2002 to provide both surface-water storage and artificial recharge to the underlying Navajo Sandstone. A previous report (Heilweil and others, 2005) documents both pre-reservoir ground-water conditions (prior to March 2002) and post-reservoir ground-water conditions and water budgets (March 2002- August 2004). That report also contains records of the wells within Sand Hollow and historical water-quality and precipitation data. Data presented here are an extension of data presented in the previous report and include water-level data, meteorology data, reservoir-water temperature, and physical properties and selected chemical constituents of ground water and surface water. The data collection was a cooperative effort by both the Washington County Water Conservancy District (WCWCD) and the U.S. Geological Survey (USGS). Support for this work was provided by both the USGS and the WCWCD.

Sand Hollow is a 20-mi^2 basin located in the southeastern part of Washington County, Utah, about 10 mi northeast of St. George (*fig. 1*). It is part of the Virgin River drainage basin of the Lower Colorado River Basin. Washington County is in the lowest-altitude part of Utah, where the altitudes range from about 3,000 to 4,200 ft. Sand Hollow is underlain primarily by Navajo Sandstone that is either exposed at the surface or covered by a veneer of soil or surface-flood basalts (Hurlow, 1998). Although the total stratigraphic thickness of the Navajo Sandstone in this region is more than 2,000 ft, erosion within the study area has resulted in sandstone thickness ranging from a few hundred to more than 1,200 ft.

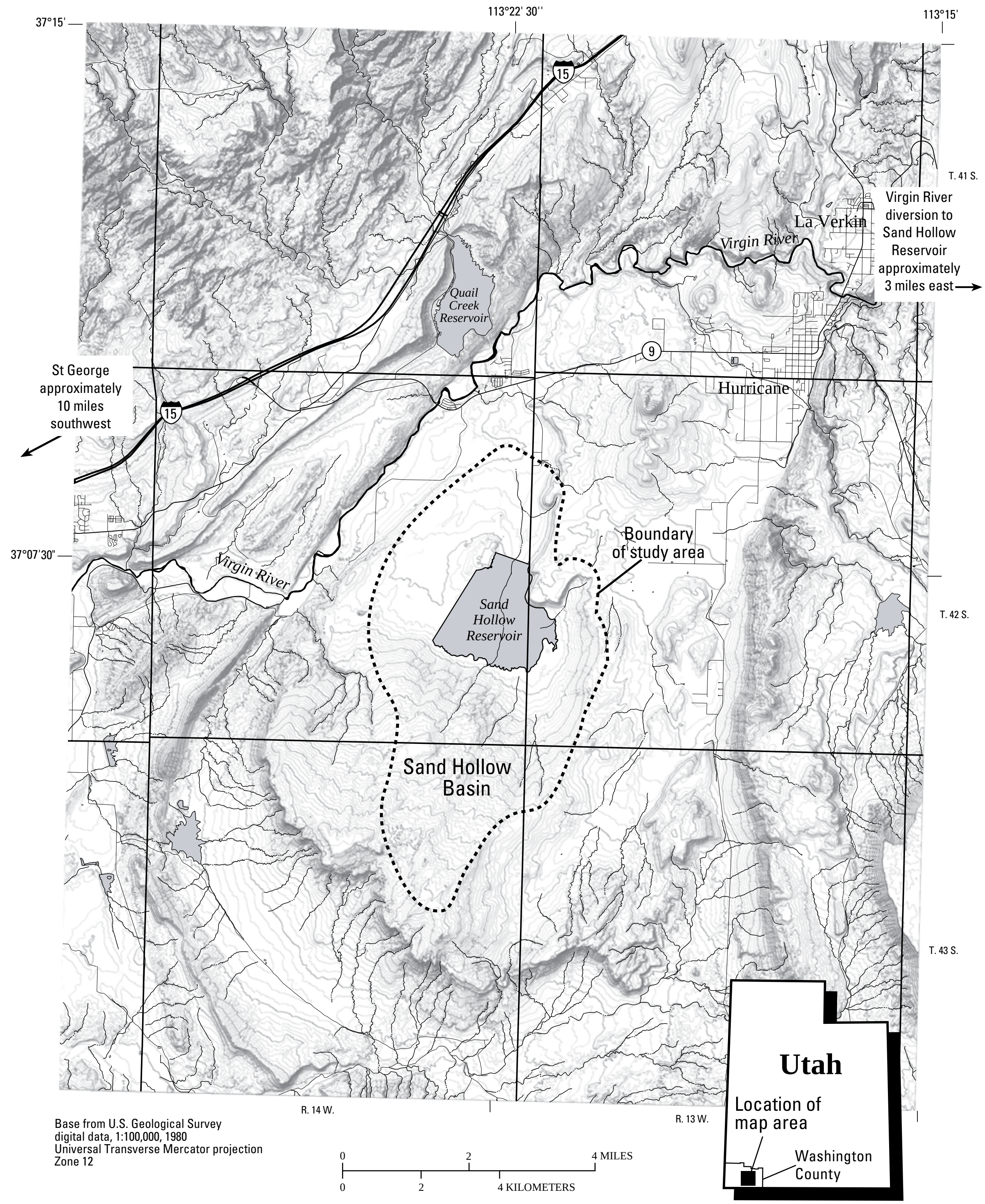

Figure 1. Location of the Sand Hollow study area, Washington County, Utah.

Data Collection

Data collection techniques and methods are described in Heilweil and others (2005) and briefly summarized in the following sections.

Water-Level Data

The WCWCD has continued to measure water levels monthly at 15 monitoring wells (*fig. 2*) surrounding Sand Hollow Reservoir since previously reported measurements through January 2005 (Heilweil and others, 2005). Wells measured monthly by the WCWCD have had occasional check measurements performed by USGS personnel for quality assurance. Water-level measurements are presented in *figure 3*, which shows both recently measured (February 2005 through August 2006) and previously reported (1995-2005) monthly water-levels, along with reservoir altitude. Current (September 2006) water levels in the basin range from about 5 to 90 ft below land surface. From February 2005 through August 2006, water levels rose as much as 90 feet (site 5). The reservoir surface rose from about 3,000 feet in March 2002 to a maximum of about 3,060 feet in May 2006. Differences in hydraulic head between the reservoir and the 15 monitoring wells in Sand Hollow range from about 5 to 150 ft.

Water-Quality Data

Field parameters were measured in-situ and water-quality samples were collected for laboratory chemical analysis from eight monitoring wells and Sand Hollow Reservoir during January 2006 (*fig. 2*). Measured in-situ field parameters include water temperature, specific conductance, pH, and dissolved oxygen. Laboratory chemical analyses included chloride, bromide, and arsenic. Water-quality samples were collected from the 2-in.-diameter monitoring wells by using an air-operated submersible piston pump and from the 1-in.-diameter monitoring wells by using Waterra valves with 5/8-in.-diameter polyethylene tubing. A minimum of three casing volumes (or until specific conductance stabilized) was purged from all of the boreholes and wells prior to sample collection. Samples were collected in clean polyethylene bottles and filtered with 0.45-micron disposable filters. Samples for arsenic analysis were preserved with 7.7-normal nitric acid. Samples were analyzed by the USGS National Water Quality Laboratory in Denver, Colorado.

The chloride and bromide concentration in monitoring wells (*table 1*) ranged from 17.0 to 66.6 mg/L and 0.07 to 0.30 mg/L, respectively. Ground-water chloride:bromide ratios (Cl:Br) range from 150 to 680 and are significantly different from the sample of Sand Hollow Reservoir (1,100). As previously reported (Heilweil and others, 2005), the high Cl:Br ratio of water in the reservoir can be used to trace the movement of artificially recharged water through the aquifer. The highest ground-water Cl:Br ratios (≥500) are from the three monitoring wells closest to the reservoir (map numbers 28, 36, and 37) and have increased substantially from a baseline of about 150 prior to the inception of the reservoir. The other monitoring wells sampled during January 2006 (map numbers 8, 9, 32, 33, and 34) had low Cl:Br ratios of 150 to 220, consistent with previously reported background ratios prior to the reservoir (Heilweil and others, 2005) and thus do not yet show the arrival of artificial recharge. Assuming no density contrasts between the recharging water and the background ground water (such as a “diving” plume), the monitoring-well analyses indicate that artificial recharge has migrated less than 0.15 mi to the north of the reservoir and less than 0.5 mi to the west of the reservoir.

Arsenic concentrations of monitoring-well samples ranged from 2.3 to 43.5 µg/L; a concentration of 1.4 µg/L was measured in a water sample from the reservoir. Arsenic concentrations have generally remained stable in both the monitoring wells and reservoir since previous sampling in 2004. Arsenic concentrations in water from most of the monitoring wells during January 2006 were near or below the U.S. Environmental Protection Agency 10 µg/L maximum recommended concentration for drinking water. However, the 43.5 µg/L concentration in the North Dam 3A well sample (map number 28) shows continued persistence of arsenic, possibly caused by desorption from the surface of iron hydroxides (“Moki marbles”) present in the sandstone. Arsenic concentrations in water from this well decreased rapidly from 90 µg/L on October 8, 2002 to 42 µg/L on June 10, 2003, and have since only fluctuated slightly (Heilweil and others, 2005).

Meteorology and Precipitation Data

Meteorology data have been collected continuously at a weather station (*fig. 2*) in Sand Hollow since January 13, 1998, for evaluating evaporation and precipitation. Parameters measured include air temperature, wind speed, wind direction, precipitation, relative humidity, and solar radiation. Instrumentation includes a Vaisala Temperature and RH probe, a RM Young Wind Monitor, a Weathertronics tipping bucket rain gage, and a Matrix MK 1-G Sol-A-Meter with a spectral response from 0.35 to 1.15 microns. Sensors collect data every minute, with average hourly and daily values, except for cumulative precipitation, computed and stored on a data logger. From January 13, 1998, to May 6, 2006, daily average air temperature ranged from -1 to 37°C and daily average solar radiation ranged from 34 to 840 calories per square centimeter per day. Monthly precipitation from January 1998 to April 2006 ranged from 0 to almost 4 in. (*fig. 4*). A large amount of precipitation occurred during 2004 and 2005, allowing the WCWCD to divert large quantities of surface water from the Virgin River, nearly filling the reservoir to capacity in February 2006.

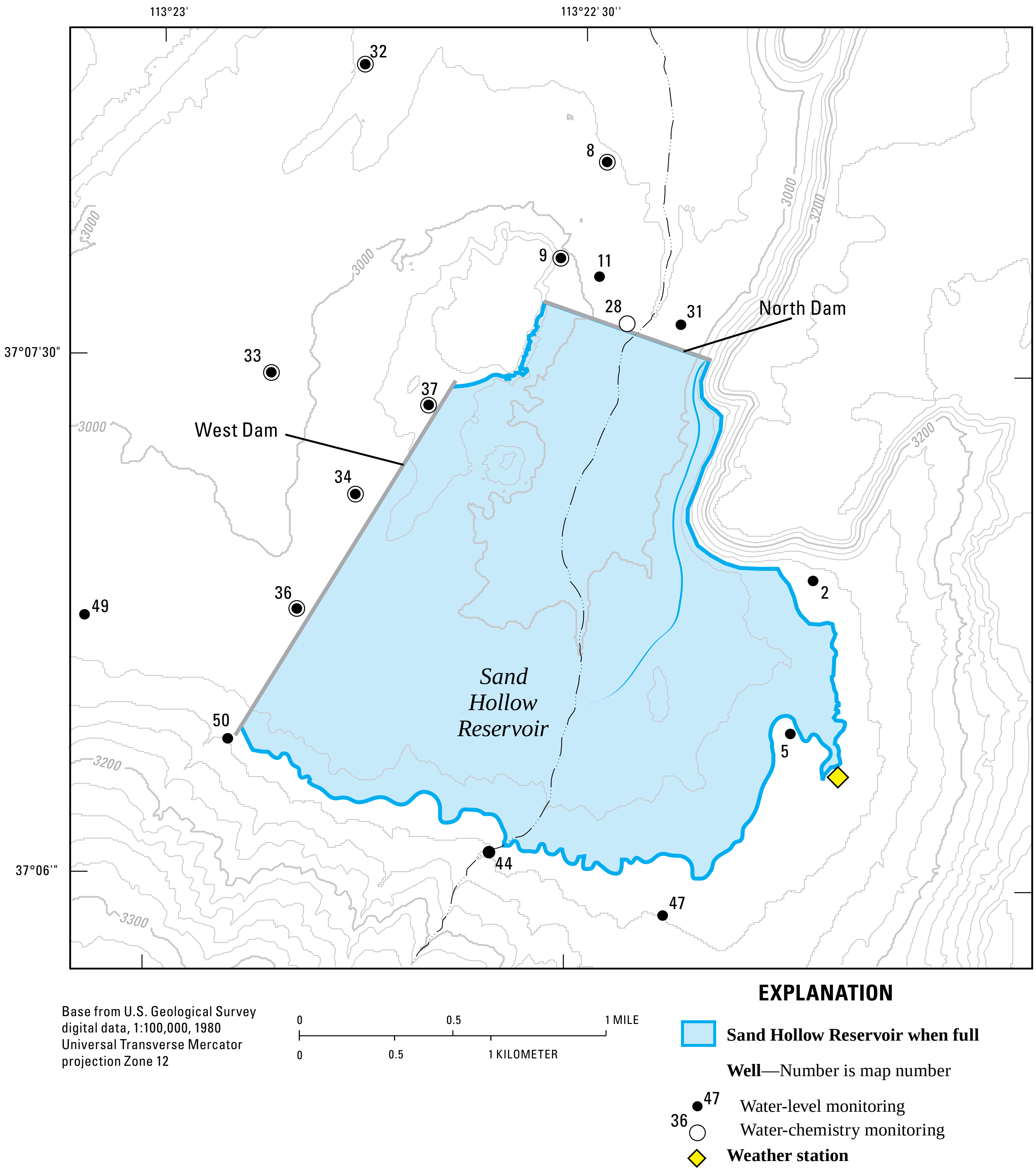

Figure 2. Location of wells and the weather station in Sand Hollow, Utah.

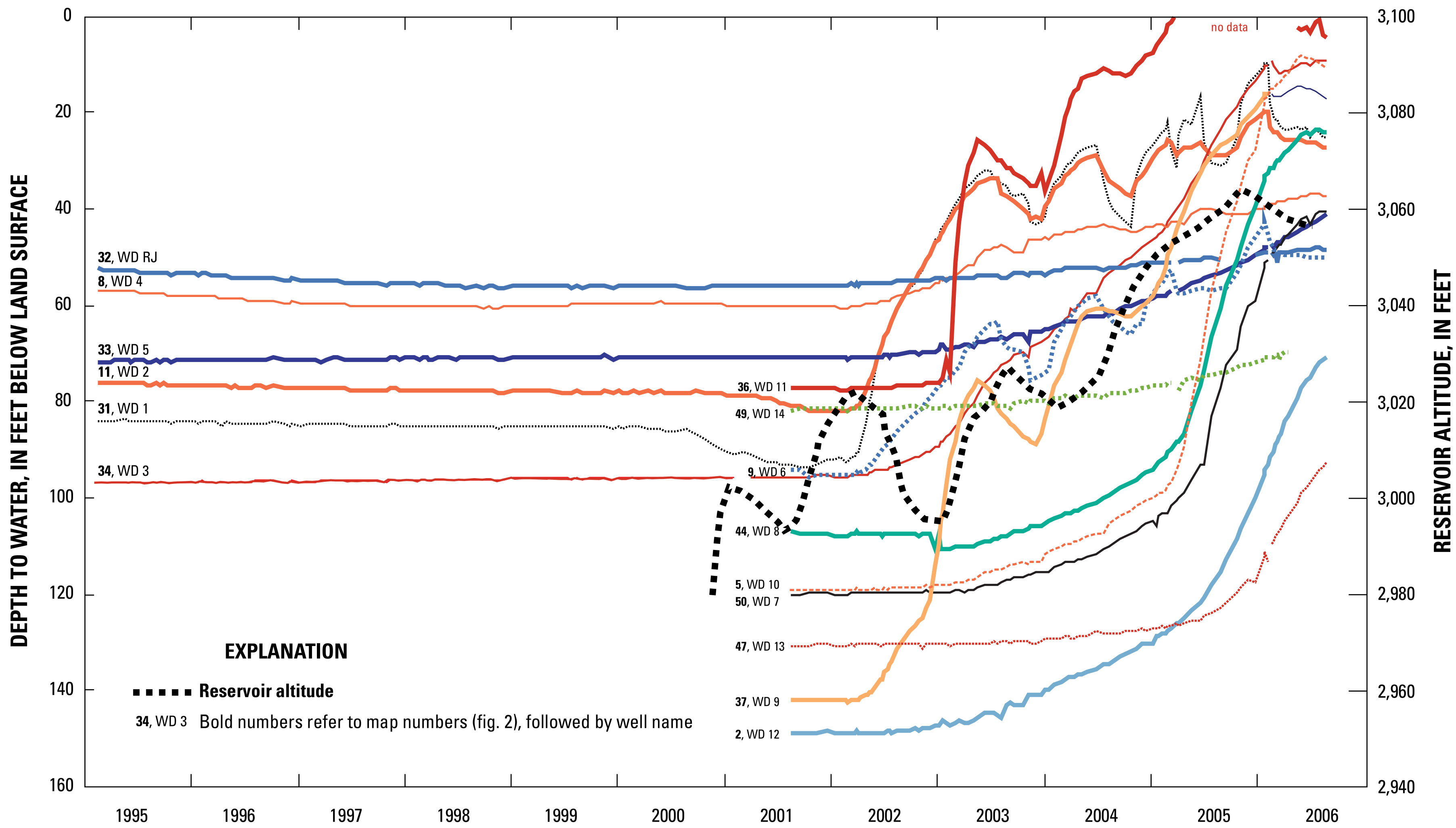

Figure 3. Relation between water level in selected wells and reservoir altitude, Sand Hollow, Utah, 1995-2006.

Table 1. Selected physical properties and concentration of chemical constituents in ground- and surface-water samples collected from selected sites in Sand Hollow, Utah, January 2006

[Map number: Refer to figure 2 and table 1 of Heilweil and others (2005). Water temperature: ˚C, degrees Celsius. Specific conductance: µS/cm, microsiemens per centimeter at 25 degrees Celsius. Analyzing agency: U.S. Geological Survey National Water Quality Laboratory in Denver, Colorado; mg/L, milligrams per liter; µg/L, micrograms per liter; —, no data available]

Map number	Well name	Date sampled	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen (mg/L) and percent saturation	Chloride (mg/L as Cl)	Bromide (mg/L as Br)	Chloride: bromide ratio	Arsenic (µg/L as As)
8	WD 4	1/19/2006	—	345	8.0	—	17.0	0.10	170	13.0
9	WD 6	1/19/2006	18.9	684	7.6	17.7 (213%)	66.6	.30	220	2.3
28	North Dam 3A	1/19/2006	—	835	8.0	—	61.6	.09	680	43.5
32	WD RJ	1/18/2006	—	550	7.7	—	47.9	.26	180	8.1
33	WD 5	1/18/2006	—	528	7.9	—	42.7	.23	190	7.6
34	WD 3	1/18/2006	—	460	7.9	—	27.7	.18	150	10.3
36	WD 11	1/18/2006	—	977	7.9	—	64.0	.13	500	10.7
37	WD 9	1/18/2006	—	1,233	7.9	—	42.4	.07	600	5.4
—	[1]Reservoir	1/18/2006	6.9	815	8.5	11.9 (108%)	44.8	.04	1,100	1.4

[1]Sample collected from Sand Hollow Reservoir.

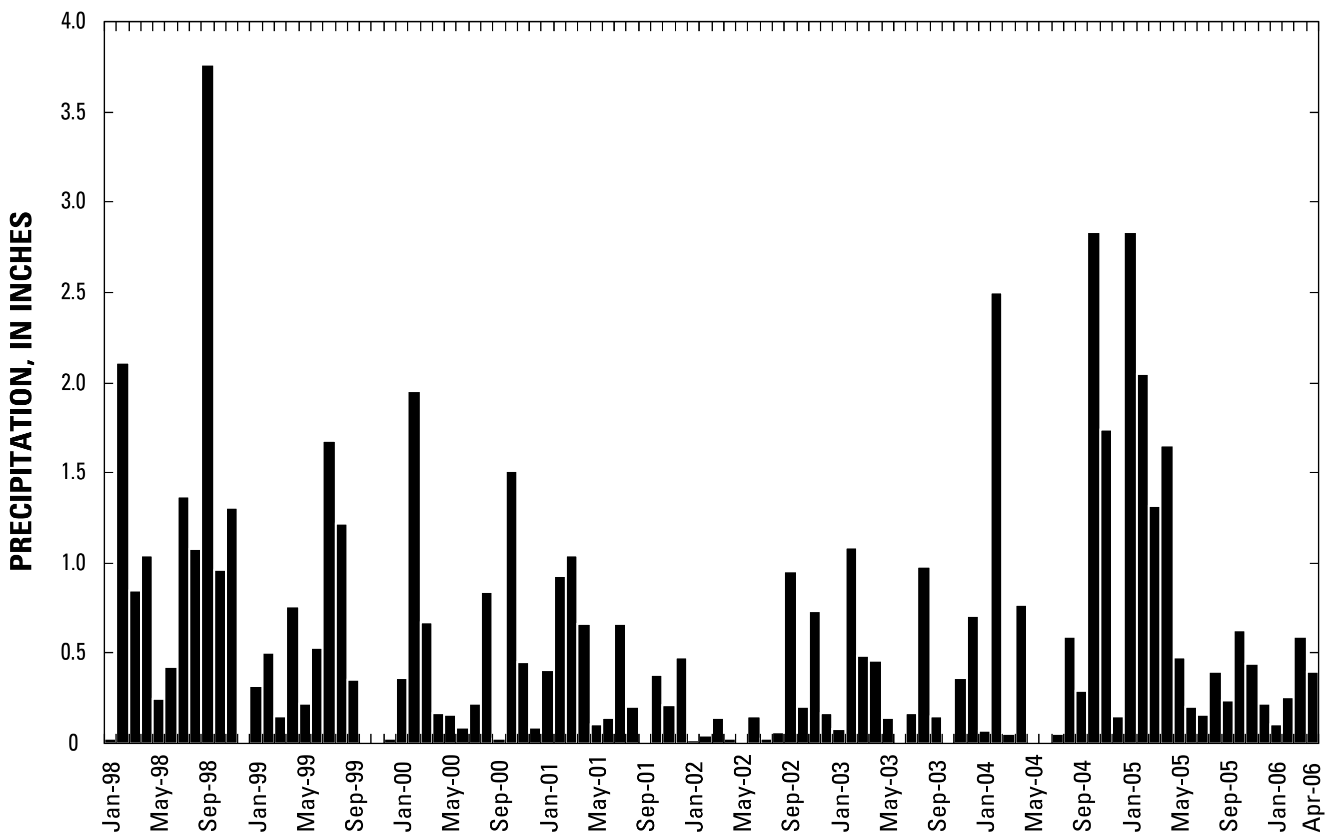

Figure 4. Monthly precipitation at Sand Hollow, Utah, 1998-2006.

Reservoir Water Temperature

Continuous water-temperature measurements were made in Sand Hollow Reservoir for evaluating effects of water viscosity changes on seepage rates beneath the reservoir. A string of five thermistors was installed in the deepest part of Sand Hollow Reservoir, about 300 ft from the North Dam. The thermistors were attached to a floating buoy at depths of 0.3, 3, 10, 16, and 33 ft or bottom of the reservoir, if shallower. The thermistors are reported to have an accuracy of better than 0.5ºC over the temperature range of 0 to 35ºC. Both the previous (January 2003 through August 2004) and current (September 2004 through May 2006) temperature data are shown in *figure 5*. Water temperature from January 2003 through May 2006 has ranged from about 3 to 32ºC. Water temperatures of the deepest thermistor (33 ft below the surface of the reservoir) show a smaller temperature range of 4 to 25ºC.

Surface-Water Inflow and Outflow to Sand Hollow Reservoir

Average daily surface-water inflow and outflow to Sand Hollow Reservoir was reported by the WCWCD. This data is collected at the pumping plant north of the north dam. Five turbines, each with Sparling Tigerman in-line totalizing flow meters, are linked to a computer system that combines and records total daily discharge in gallons. The in-line flow meters have electronic modules on which calibration diagnostics are performed monthly by the WCWCD. Each module is removed annually and factory recalibrated.

Calculation of Recharge from Sand Hollow Reservoir

Ground-water recharge to the Navajo aquifer underlying Sand Hollow Reservoir is calculated with the following water-budget equation (Heilweil and others, 2005):

$$R = I_{sw} - O_{sw} \pm \Delta S - E \qquad (1)$$

where:

R is recharge,
I_{sw} is surface-water inflow,
O_{sw} is surface-water outflow,
ΔS is change in surface-water storage, and
E is evaporation.

Changes in Reservoir Storage

Surface-water inflow and outflow to Sand Hollow Reservoir, along with reservoir-stage measurements, were recorded daily by the WCWCD. Changes in surface-water storage were calculated from reservoir-stage measurements and stage-volume relations for the reservoir (Washington County Water Conservancy District, written commun., 2006; RBG Engineering, written commun., 2002). Monthly total surface-water inflow during this study (September 2004 through August 2006) ranged from 0 to about 6,400 acre-ft (Washington County Water Conservancy District, written commun., 2006). There was no reported surface-water outflow during this period. Because of problems with monitoring equipment, inflows from October 2004 through February 2005 are estimated. These estimates are based on previous inflow history and changes in reservoir altitudes. On the basis of reported reservoir altitude-storage relations (RBG Engineering, written commun., 2002), the surface-water storage during this study ranged from about 11,000 acre-ft to about 51,000 acre-ft (*table 2*).

Reservoir Evaporation

On the basis of an earlier comparison of different methods (Heilweil and others, 2005), the McGuinness and Bordne (1971) version of the Jensen-Haise method was determined to be an accurate and appropriate method for calculating evaporation from Sand Hollow Reservoir and was used during this study. The method is based on the relation (McGuinness and Bordne, 1971)

$$PET = \{[((0.01Ta)- 0.37)(Qs)]0.000673\}2.54 \qquad (2)$$

where:

PET is potential evaporation, in centimeters per day,
T_a is air temperature, in degrees Farenheit, and
Q_s is solar radiation, in calories per square centimeter per day. The units for PET can be converted to feet per day by multiplying by 0.0328.

By using air temperature and solar radiation from the nearby weather station (*fig. 2*), daily evaporation rates were calculated with equation 2. These daily evaporation rates were added to determine total monthly evaporation rates, which ranged from 0.05 to 0.97 ft from March 2002 through August 2006 (*table 2*; Heilweil and others, 2005). Evaporation rates from May through August 2006 are estimated from average monthly 2002 through 2005 data because of the inability to download the weather station data for these months. On the basis of reservoir altitude-area relations (RBG Engineering, written commun., 2002), the monthly average reservoir surface area gradually increased to about 1,300 acres in 2006. Multiplying evaporation rates by average reservoir surface area yields monthly evaporation losses ranging from 20 to 1,200 acre-ft.

Estimated Artificial Recharge

To estimate ground-water recharge beneath Sand Hollow Reservoir, evaporation (E), total monthly inflows (I_{sw}),

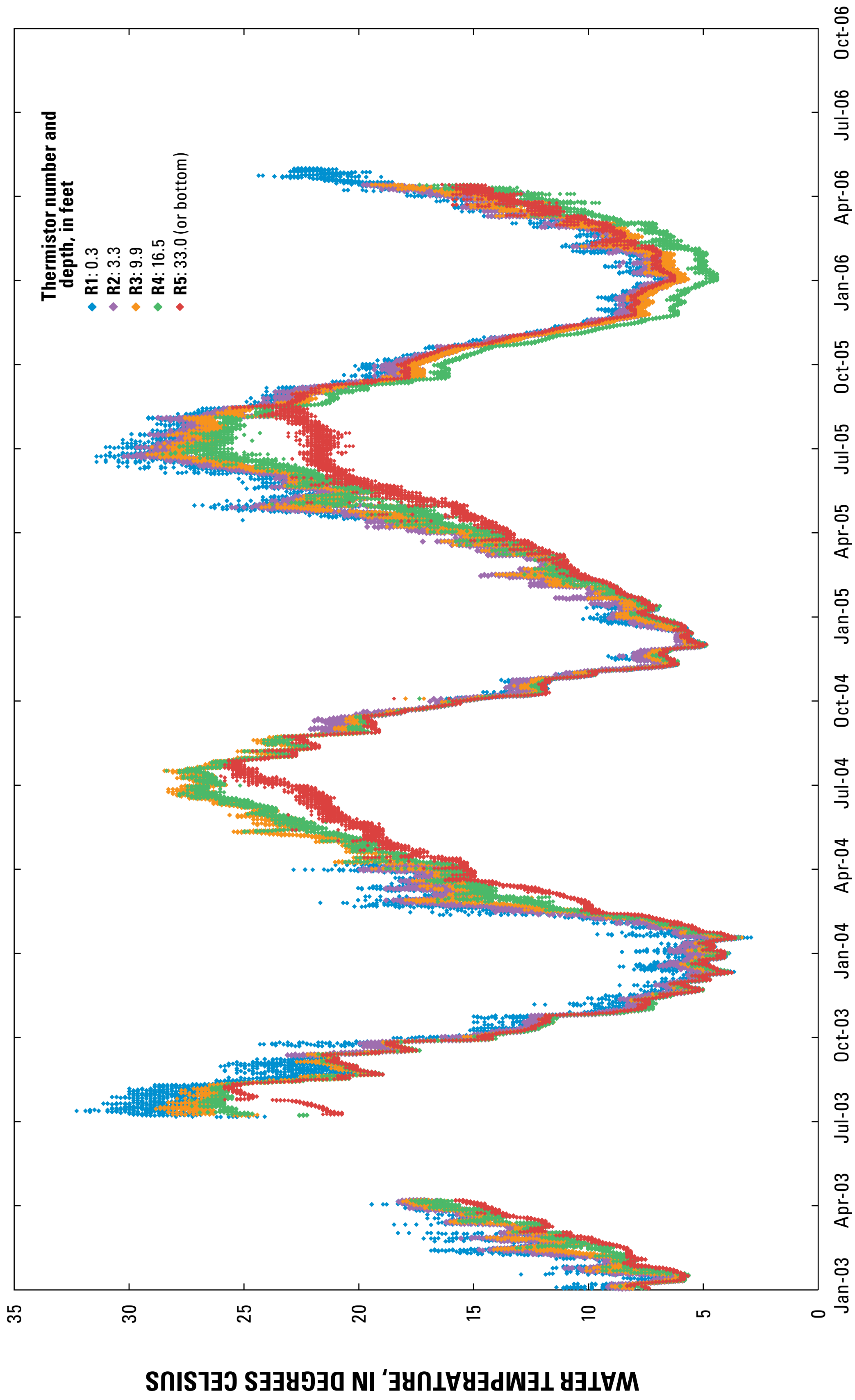

Figure 5. Average hourly water temperature at various depths in Sand Hollow Reservoir, Utah, 2003-06.

Table 2. Reservoir data and estimated evaporation and ground-water recharge at Sand Hollow, Utah, 2002-06

[Reservoir altitude and storage: specified at end of each month; Average bottom water temperature: from R5 thermistor]

Month	Reservoir altitude (feet)	Reservoir storage (acre-feet)	Monthly surface-water inflow (+) or outflow (-) (acre-feet)	Monthly reservoir storage change (acre-feet)	Reservoir surface area (acres)	[1]Monthly evaporation rate (feet)	Monthly evaporation (acre-feet)	Monthly recharge (acre-feet)	Estimated recharge rate and hydraulic conductivity (foot/day)	Average bottom water temperature (degrees Celsius)	[2]Intrinsic permeability (square feet)
March-2002	3,001.0	3,090	[3]6,620	3,090	260	0.24	60	3,470	0.43	[4]10	0
April-2002	3,002.5	3,500	3,690	410	280	.46	130	3,150	.38	[4]16	2.13E-12
May-2002	3,001.0	3,090	2,450	-410	260	.68	170	2,690	.33	[4]22	1.61E-12
June-2002	2,998.5	2,480	0	-610	230	.91	210	400	.06	[4]22	1.21E-12
July-2002	2,996.5	2,050	0	-430	210	.90	190	240	.04	[4]23	2.09E-13
August-2002	2,994.5	1,650	0	-400	180	.81	150	250	.04	[4]24	1.29E-13
September-2002	2,993.7	1,300	0	-350	140	.47	70	280	.07	[4]21	1.53E-13
October-2002	2,994.7	1,500	790	200	160	.26	40	550	.11	[4]15	2.50E-13
November-2002	3,005.5	4,220	3,590	2,720	320	.11	30	840	.09	[4]9	4.78E-13
December-2002	3,011.7	7,000	3,930	2,780	400	.05	20	1,130	.09	[4]6	4.46E-13
January-2003	3,017.3	9,760	4,580	2,760	590	.09	50	1,770	.10	[4]5	5.16E-13
February-2003	3,019.0	10,670	2,850	910	570	.10	60	1,880	.12	7	5.55E-13
March-2003	3,019.5	10,930	1,930	260	580	.24	140	1,530	.09	10	6.32E-13
April-2003	3,019.0	10,680	540	-250	570	.37	210	580	.03	16	4.21E-13
May-2003	3,017.6	9,930	0	-750	540	.66	350	400	.02	22	1.46E-13
June-2003	3,010.3	6,040	-3,120	-3,890	390	.89	350	420	.04	[4]22	8.70E-14
July-2003	3,001.8	3,200	-2,020	-2,840	240	.92	220	600	.08	[4]23	1.29E-13
August-2003	2,998.8	2,540	0	-660	230	.75	170	490	.07	24	2.83E-13
September-2003	2,997.4	2,100	0	-440	220	.58	130	310	.05	21	2.35E-13
October-2003	2,996.4	1,850	0	-250	170	.36	60	190	.04	15	1.76E-13
November-2003	2,994.0	1,560	0	-290	200	.09	20	270	.05	9	1.55E-13
December-2003	3,006.5	4,700	3,590	3,140	330	.06	20	430	.04	6	2.30E-13
January-2004	3,013.0	7,600	3,990	2,900	480	.06	30	1,060	.07	5	2.38E-13
February-2004	3,016.0	8,840	2,320	1,240	600	.08	50	1,030	.06	6	4.14E-13
March-2004	3,018.5	10,400	2,400	1,560	630	.38	240	600	.03	11	3.42E-13
April-2004	3,025.3	15,070	5,620	4,670	750	.42	310	640	.03	15	1.49E-13
May-2004	3,026.2	15,830	2,050	760	780	.72	560	730	.03	18	1.23E-13
June-2004	3,025.3	14,400	0	-1,430	750	.87	650	780	.03	21	1.20E-13
July-2004	3,023.0	13,000	0	-1,400	680	.94	640	760	.04	23	1.28E-13
August-2004	3,020.8	11,670	0	-1,330	680	.78	520	810	.04	24	1.25E-13
September-2004	3,019.3	11,260	3,600	-410	620	.53	340	670	.04	22	1.32E-13
October-2004	3,019.0	11,040	3,630	-220	610	.25	150	700	.04	18	1.30E-13
November-2004	3,021.5	12,650	[3]2,300	1,610	650	.10	60	610	.03	12	1.49E-13
December-2004	3,022.6	13,390	[3]1,400	740	670	.06	40	620	.03	7	1.48E-13
January-2005	3,026.6	16,200	[3]3,500	2,810	740	.07	50	640	.03	6	1.62E-13
February-2005	3,031.8	20,280	[3]5,200	4,080	830	.11	90	1,030	.04	8	1.56E-13
March-2005	3,037.1	25,030	6,430	4,750	920	.24	210	1,470	.05	11	2.34E-13
April-2005	3,041.4	29,220	5,900	4,190	1,000	.39	370	1,340	.04	13	2.51E-13
May-2005	3,044.1	31,970	4,670	2,750	1,040	.70	720	1,200	.04	15	2.06E-13
June-2005	3,047.5	35,750	5,830	3,780	1,110	.75	810	1,240	.04	19	1.62E-13
July-2005	3,048.9	37,280	3,400	1,530	1,130	.97	1,080	790	.02	22	1.46E-13
August-2005	3,050.1	38,670	3,350	1,390	1,150	.75	850	1,110	.03	22	8.12E-14
September-2005	3,050.9	39,590	2,980	920	1,170	.54	630	1,440	.04	23	1.12E-13
October-2005	3,052.0	40,990	2,900	1,400	1,190	.28	330	1,170	.03	18	1.43E-13
November-2005	3,054.7	44,310	4,650	3,320	1,240	.11	140	1,190	.03	15	1.27E-13
December-2005	3,056.1	46,120	3,270	1,810	1,260	.05	60	1,400	.04	8	1.40E-13
January-2006	3,058.8	49,640	4,650	3,520	1,310	.08	100	1,030	.03	8	1.89E-13
February-2006	3,058.8	49,580	1,170	-60	1,310	.12	160	1,070	.03	7	1.34E-13
March-2006	3,058.0	48,590	0	-990	1,300	.18	240	750	.02	9	1.58E-13
April-2006	3,058.7	49,490	2,010	900	1,310	.45	580	530	.01	12	9.57E-14

Table 2. Reservoir data and estimated evaporation and ground-water recharge at Sand Hollow, Utah, 2002-06—Continued

Month	Reservoir altitude (feet)	Reservoir storage (acre-feet)	Monthly surface-water inflow (+) or outflow (-) (acre-feet)	Monthly reservoir storage change (acre-feet)	Reservoir surface area (acres)	[1]Monthly evaporation rate (feet)	Monthly evaporation (acre-feet)	Monthly recharge (acre-feet)	Estimated recharge rate and hydraulic conductivity (foot/day)	Average bottom water temperature (degrees Celsius)	[2]Intrinsic permeability (square feet)
May-2006	3,060.0	51,240	3,650	1,750	1,340	[5]0.69	920	980	0.02	[6]15	6.39E-14
June-2006	3,058.8	49,610	0	-1,630	1,310	[5].86	1,000	630	.02	[6]19	1.03E-13
July-2006	3,057.5	47,910	0	-1,700	1,290	[5].93	1,200	500	.01	[6]22	6.27E-14
August-2006	3,056.2	46,180	0	-1,730	1,260	[5].77	970	760	.02	[6]22	4.50E-14
Total	—	—	114,000	—	—	—	17,000	51,000			

[1]Calculated using the Jensen-Haise method.

[2]Assuming a unit hydraulic gradient.

[3]Estimated.

[4]2004 water temperatures.

[5]Estimated using 2002 through 2005 monthly average.

[6]2005 water temperatures.

outflows (O_{sw}), and changes in surface water storage (ΔS) were used in equation (1) to calculate monthly estimates of ground-water recharge. Monthly recharge from September 2004 through August 2006 ranged from about 500 acre-ft to 1,500 acre-ft (*table 2*, *fig. 6*), totaling about 23,000 acre-ft. Since the inception of the reservoir (March 2002) through August 2006, monthly recharge volumes have ranged from about 200 to 3,500 acre-ft. From March 2002 through August 2006, total net surface-water inflow into the reservoir was about 114,000 acre-ft, evaporative loss was about 17,000 acre-ft, and estimated recharge to the underlying Navajo aquifer was about 51,000 acre-ft. Total annual inflow, estimated evaporation, and ground-water recharge are shown in *figure 7*. Annual inflow has ranged from about 8,000 to 52,000 acre-ft; annual estimated evaporation has ranged from about 1,000 to 5,000 acre-ft; annual ground-water recharge has ranged from about 9,000 to 14,000 acre-ft (not including 2006, which is incomplete).

Equation (1) does not account for precipitation falling directly on the surface of the reservoir or runoff to the reservoir. Because of high evaporation rates and permeable surficial soils, precipitation events seldom produce runoff that reaches the lower part of Sand Hollow basin (L. Jessop, Washington County Water Conservancy District, oral commun., 2001). On the basis of monthly total precipitation data from the weather station (*fig. 4*) and reservoir surface areas (*table 2*), the largest amount of monthly precipitation falling directly on the reservoir surface water is only 180 acre-ft. This amount is small relative to the average monthly inflow of more than 2,000 acre-ft and, therefore, was not considered during the recharge calculations.

The monthly recharge volume was divided by the surface area of the reservoir, resulting in monthly average recharge rates. Assuming a unit hydraulic gradient of 1ft/ft, this yields monthly average hydraulic conductivity values ranging from 0.01 to 0.43 ft/d. Monthly average hydraulic conductivity values from 2002 through 2006 indicate a general downward trend in hydraulic conductivity, even as the reservoir altitude (driving head) increased. The general decline in hydraulic conductivity during the 4-year period since initial filling (*fig. 8*) is a typical pattern observed at most artificial recharge facilities. This decline is likely caused by a combination of (1) a lower horizontal hydraulic gradient once the ground-water table connected with the base of the surface-water reservoir, and (2) clogging (siltation, biofilm development, gas generation) of the sediments beneath the reservoir. Superimposed on this is a second-order effect of winter peaks for recharge rates. The combination of generally declining recharge rates and generally increasing reservoir altitude and area explains the trend of an increasing ratio of evaporation to recharge volume over time, with the total volume of water lost through evaporation nearly as large as the volume of ground-water recharge during the first 8 months of 2006 (*fig. 7*).

Long-Term and Seasonal Variation in Recharge Rates

In order to more closely examine clogging at Sand Hollow, specific changes in aquifer properties can be separated from changes in water properties by calculating intrinsic permeability. Hydraulic conductivity is a function of both aquifer and fluid properties. Intrinsic permeability is the aquifer-properties component of hydraulic conductivity. Intrinsic permeability, therefore, removes the seasonal changes caused by variations in temperature-dependent viscosity of water.

Intrinsic permeability is defined as (Freeze and Cherry, 1979):

$$\kappa = K \frac{\mu}{\rho g} \quad (3)$$

where:

κ is intrinsic permeability in ft^2,
K is hydraulic conductivity (Darcy velocity) in ft/s,
μ is dynamic viscosity in lb/ft-s, where 1 lb/ft-s equals 1,488 centipoise or 1.49 kilogram per meter-second,
ρ is the density of water (77,880.2 lb/ft^3), and
g is the acceleration of gravity (32.2 ft/s^2). This equation yields intrinsic permeability in ft^2, which can be converted to square meters by multiplying by 0.093.

Of the fluid properties, the density of water does not vary substantially within the normal range of surface-water temperatures and the acceleration of gravity is not temperature-dependent. Dynamic viscosity, however, is very temperature dependent. In order to calculate intrinsic permeability, therefore, temperature data from thermistor R5 at a depth of about 33 ft in the reservoir (*fig. 5*) was used to first calculate dynamic viscosity. On the basis of monthly average measured water temperatures (*table 1*), the calculated dynamic viscosity of water in the reservoir has varied by about a factor of two, from 0.0010 lb/ft-s (1.5 centipoise) at 5ºC to 0.00059 lb/ft-s (0.88 centipoise) at 24°C.

With equation 3, average monthly intrinsic permeability beneath the reservoir has ranged from 4.5 x 10^{-14} to 1.2 x 10^{-12} ft^2 from 2002 through 2006 (*table 2*). The large seasonal variation in intrinsic permeability, which increases in the winter is shown in *figure 8*. This increase may be caused by either the dissipation of biofilms and algal mats (decreased biological activity) or the reduction in the size of trapped gas bubbles in the aquifer. As an example, there would be an approximate 10-percent decrease in the volume of trapped gas bubbles in sediments beneath the reservoir as bottom water temperatures cool from 24ºC in the summer to 5ºC in the winter. It was shown earlier (Heilweil and others, 2004) that small changes in the volume of trapped gas bubbles can cause substantial effects on the relative hydraulic conductivity of the sandstone.

Summary

This study was a cooperative effort by both the Washington County Water Conservancy District and the U.S. Geological Survey to evaluate ground-water recharge from infiltration beneath Sand Hollow Reservoir from September 2004 through August 2006 as an update to USGS Scientific Investigations Report 2005-5185 (Heilweil and others, 2005). Wet conditions during 2005-06 allowed the WCWCD to fill the reservoir to near capacity. Consequently, the surface area of the reservoir gradually increased to about 1,300 acres during 2006. Reservoir stage reached a peak altitude of about 3,060 ft in May 2006, resulting in a depth of nearly 90 feet and a surface-water storage of about 51,000 acre-ft. Water temperatures at the surface of Sand Hollow Reservoir have ranged seasonally from about 5°C in the winter months to about 32°C in the summer months, whereas water temperatures deeper in the reservoir have generally only risen to about 25°C.

Current (August 2006) ground-water levels in monitoring wells in the basin range from about 5 to 90 ft below land surface. From August 2004 through August 2006, water levels rose as much as 90 ft nearest the reservoir, but less than 5 ft at wells farthest from the reservoir.

Ground-water Cl:Br, a geochemical indicator of recharge from Sand Hollow Reservoir, have increased at the three monitoring wells closest to the reservoir from background ratios of about 150 to as much as 680 (compared with a ratio of 1,100 in the recharging reservoir water). The other monitoring wells sampled during January 2006 did not show the arrival of artificial recharge. This indicates that artificial recharge from the reservoir has migrated less than 0.5 mi to the north of the reservoir and less than 0.15 mi to the west of the reservoir. Arsenic concentrations of monitoring-well samples ranged from 2.3 to 43.5 µg/L and have generally remained stable in both the monitoring wells and reservoir since previous sampling during 2004.

To estimate ground-water recharge beneath Sand Hollow Reservoir, a water-budget approach was used. Components of the water budget include surface-water inflow and outflow to and from the reservoir, evaporation, and changes in surface-water storage. Estimated evaporation rates since the inception of the reservoir, based on the Jensen-Haise method using air temperature and solar radiation from the nearby weather station have varied from 0.05 to 0.97 ft per month, resulting in evaporation losses of 20 to 1,200 acre-ft per month. Total evaporation from March 2002 through August 2006 is estimated to be about 17,000 acre-ft. Estimated recharge rates have ranged from 0.01 to 0.43 ft/d. Estimated ground-water recharge volumes have ranged from about 200 to more than 3,000 acre-ft per month. Monthly recharge from September 2004 through August 2006 ranged from about 500 acre-ft to 1,500 acre-ft, totaling about 23,000 acre-ft. Since the inception of the reservoir (March 2002) through August 2006, monthly recharge volumes have ranged from about 200 to 3,500 acre-ft. Total recharge from March 2002 through August 2006 is estimated to be about 51,000 acre-ft, with annual recharge ranging from about 9,000 to 14,000 acre-ft. There has been a general downward trend in recharge rates from 2002 through 2006, even as the reservoir altitude (driving head) increased. This is likely caused by a combination of lower hydraulic gradients once the ground-water table connected with the surface-water reservoir, and clogging (siltation, biofilm development, trapped air, gas generation).

In order to more closely examine clogging at Sand Hollow, intrinsic permeability (representing the aquifer-properties component of hydraulic conductivity) was calculated in order to remove seasonal changes caused by variations in temperature-dependent viscosity of water. Average monthly intrinsic permeability beneath the reservoir has ranged from 4.5 x 10^{-14} to 1.2 x 10^{-12} ft^2 from 2002 through 2006 and shows a large seasonal variation, with generally higher values in the win-

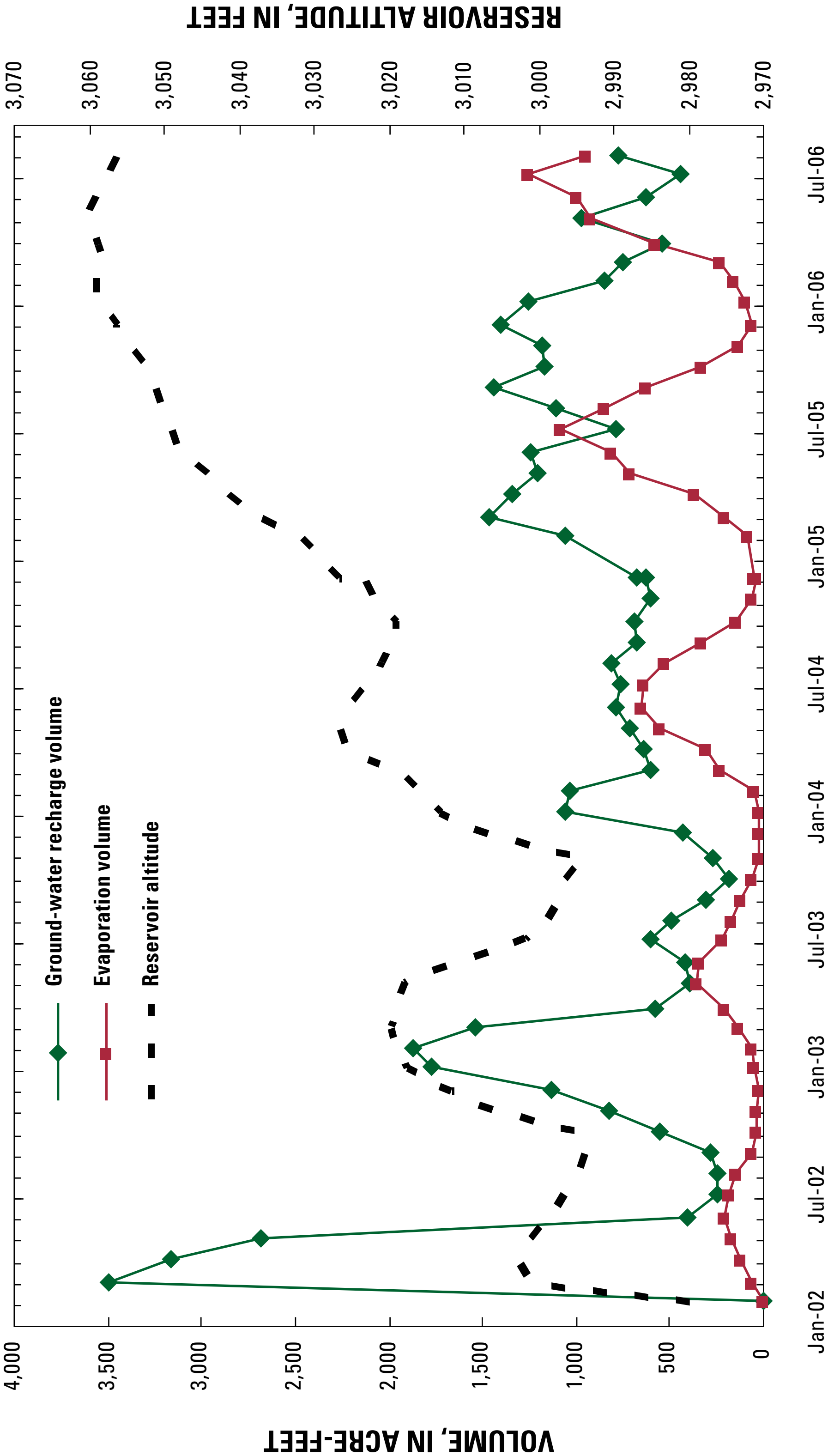

Figure 6. Monthly estimated evaporation, estimated ground-water recharge, and reservoir altitude, Sand Hollow Reservoir, Utah, 2002-06.

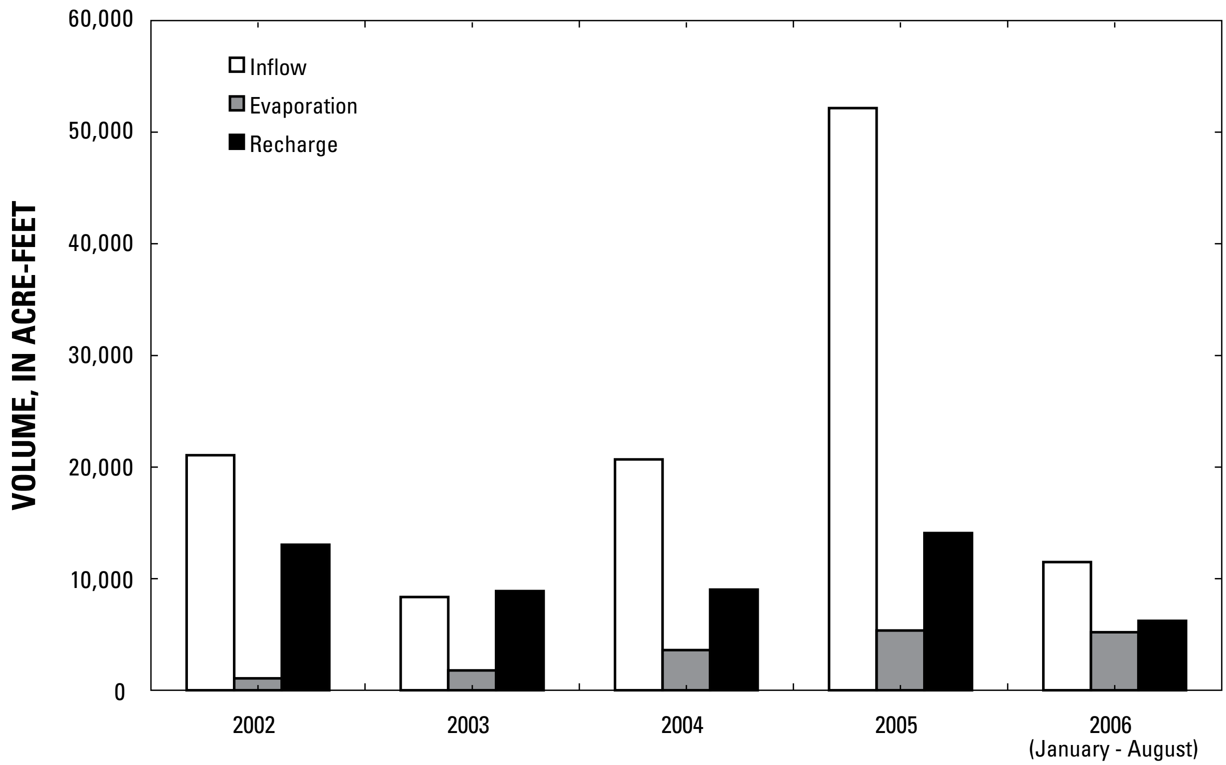

Figure 7. Annual inflow, estimated evaporation, and estimated ground-water recharge, Sand Hollow Reservoir, Utah, 2002-06.

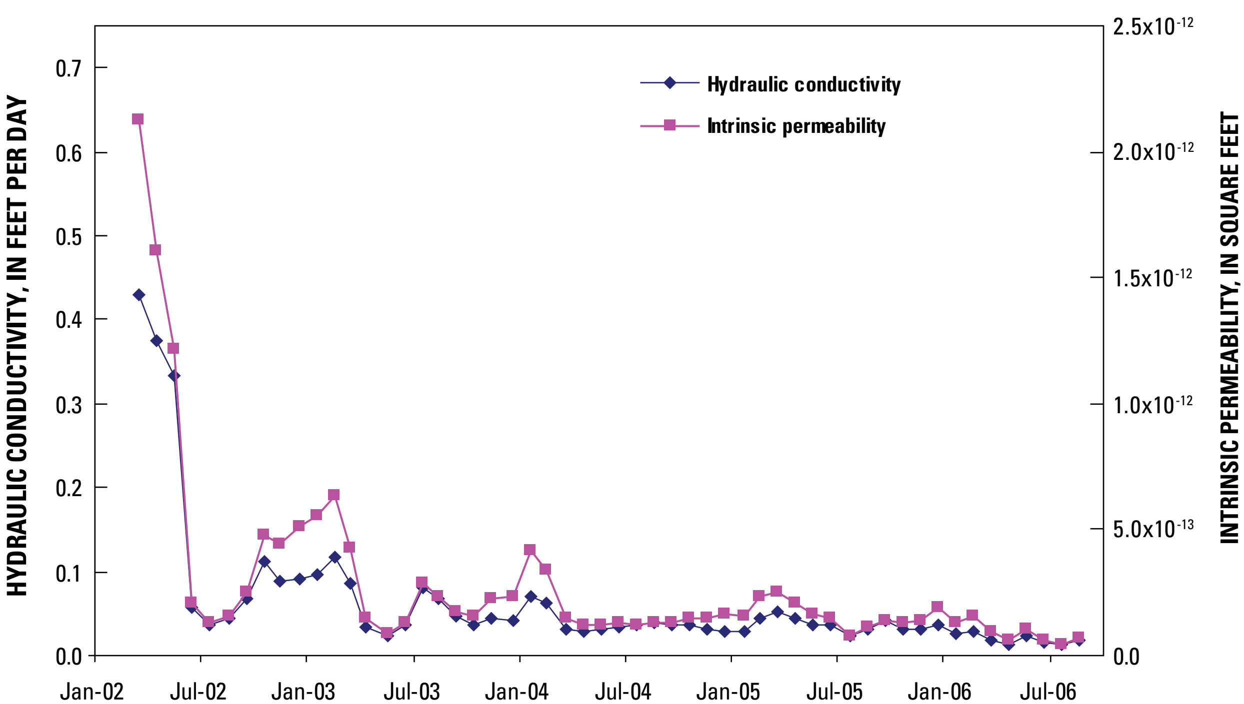

Figure 8. Average monthly hydraulic conductivity and intrinsic permeability, Sand Hollow Reservoir, Utah, 2002-06.

ter. This increase may be caused by either the dissipation of biofilms and algal mats (decreased biological activity) or the reduction in the size of trapped gas bubbles in the aquifer.

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