Infiltration and Recharge at Sand Hollow, an Upland Bedrock Basin in Southwestern Utah

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Abstract

Permeable bedrock aquifers in arid regions of the southwestern United States are being used increasingly as a source of water for rapidly growing populations, yet in many areas little is known about recharge processes and amounts available for sustainable development. Environmental tracers were used in this study to investigate infiltration and recharge to the Navajo Sandstone at Sand Hollow in the eastern Mojave Desert of southwestern Utah. Average annual precipitation is about 210 millimeters per year. Tracers included bromide, chloride, deuterium, oxygen-18, and tritium. The basin-wide average recharge rate, based on ground-water chloride mass balance, is about 8 millimeters per year, or 4 percent of precipitation. However, infiltration and recharge are highly variable spatially within Sand Hollow. Recharge primarily occurs both as focused infiltration of runoff from areas of outcropping bedrock and as direct infiltration beneath coarse surficial soils. Locations with higher rates generally have lower vadose-zone and ground-water chloride concentrations, smaller vadose-zone oxygen-18 evaporative shifts, and higher ground-water tritium concentrations. Infiltration rates estimated from vadose-zone tritium concentrations at borehole sites within Sand Hollow range from 1 to more than 57 millimeters per year; rates calculated from average vadose-zone chloride concentrations between land surface and the bottom of the chloride bulge range from 0 to 9 millimeters per year; rates calculated from average vadose-zone chloride concentrations below the chloride bulge range from 0.5 to 15 millimeters per year; and rates calculated from ground-water chloride concentrations range from 3 to 60 millimeters per year. A two-end-member deuterium-mixing model indicates that about 85 percent of ground-water recharge in Sand Hollow occurs in the 50 percent of the basin covered by coarser soils and bedrock. Vadose-zone chloride concentrations at individual boreholes represent as much as 12,000 years of accumulation, whereas vadose-zone tritium has only been accumulating during the past 50 years. Environmental tracers at Sand Hollow indicate the possibility of a cyclical recharge pattern from higher infiltration rates earlier in the Holocene to lower rates later in the Holocene, back again to higher infiltration rates during the past 50 years.

Introduction

The Jurassic-age Navajo Sandstone is a regionally important bedrock aquifer in the southwestern United States. It is part of the Dakota - Glen Canyon aquifer system and is the principal source of ground water in the easternmost part of the Mojave Desert and Colorado Plateau (Robson and Banta, 1995). This aquifer system covers an area of about 210,000 km^2 in Utah, Arizona, Colorado, and New Mexico.

The 50-km^2 Sand Hollow study area (fig. 1) is situated on the Navajo Sandstone in Washington County in the southwestern corner of Utah. The population of this county has nearly doubled from about 48,000 in 1990 to about 90,000 in 2000 (U.S. Census Bureau, 2003) and is expected to increase to nearly 230,000 by 2020 (Washington County Water Conservancy District, 1995). This rapid growth is pressuring water agencies to actively develop ground water from the Navajo aquifer. To better manage this resource, an understanding of vadose-zone infiltration processes is needed for evaluating spatial and temporal variations in ground-water recharge. This information is critical for determining sustainable amounts of ground-water withdrawal, establishing effective land-use zoning for aquifer-source protection, and evaluating the potential for artificial recharge.

Unlike net infiltration and recharge in clastic sediments of alluvial desert basins (Phillips, 1994; Prudic, 1994; Tyler and others, 1996; Andraski, 1997; Izbicki and others, 2002; chapters D–F and H, this volume), direct and focused infiltration of precipitation away from major drainages is often the primary source of recharge to bedrock aquifers in arid settings (Cordova, 1978; Eychaner, 1983; Rasmussen and Evans, 1993; Flint and others, 2002). Infiltration along losing stream reaches can be readily quantified with discharge measurements and combined temperature measurements and modeling. Direct and focused infiltration of precipitation away from major streams is difficult to quantify. Regional watershed and ground-water-flow modeling often use empiri-

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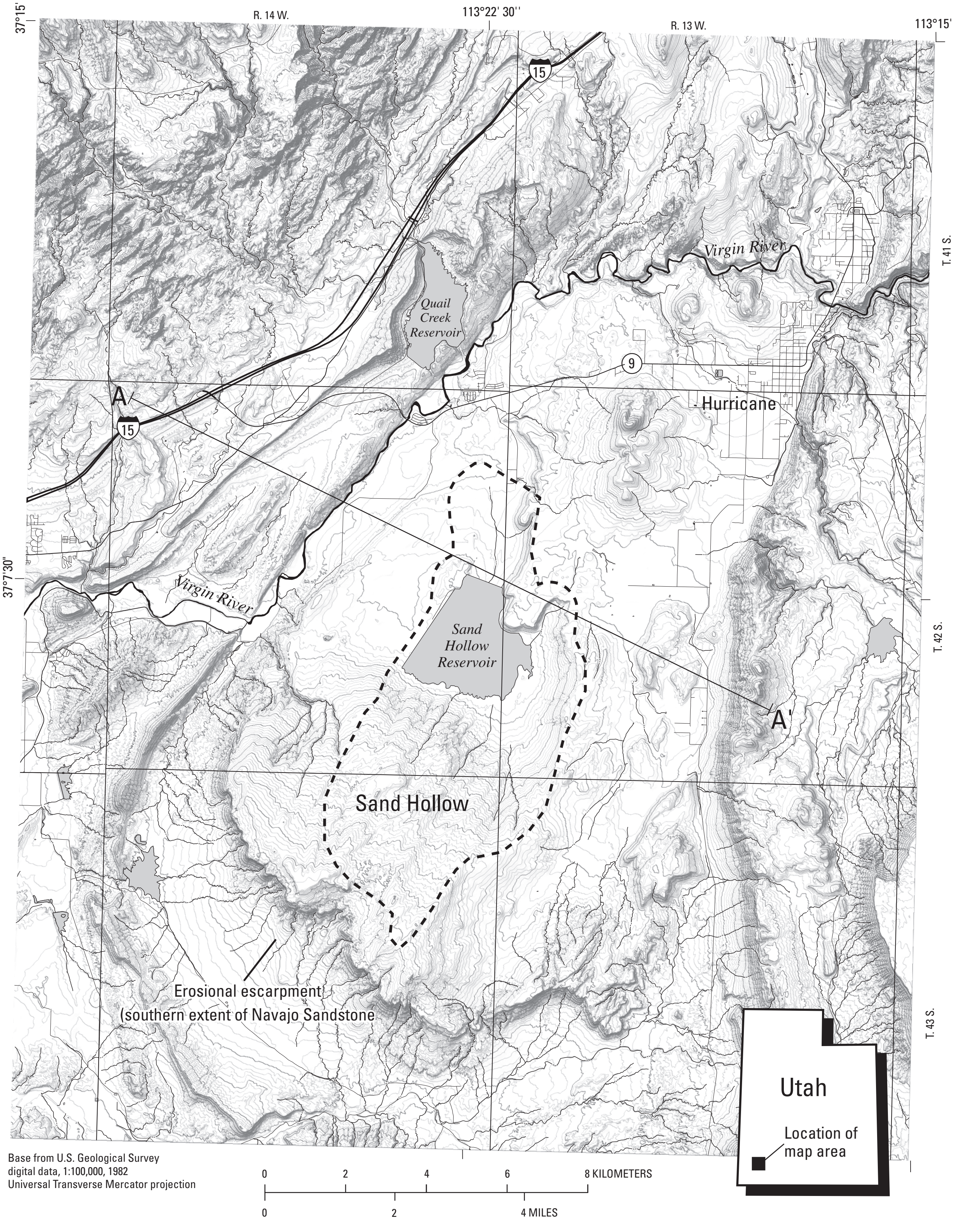


Base from U.S. Geological Survey
digital data, 1:100,000, 1982
Universal Transverse Mercator projection

Figure 1. Location of the Sand Hollow ground-water-recharge study area, Washington County, Utah.

cal methods for estimating infiltration and runoff (Maxey and Eakin, 1950) that are not well suited for evaluating the spatial and temporal heterogeneity in recharge caused by localized climatic, geomorphologic, and geologic variables. Conversely, soil-physics methods such as soil moisture and Darcy flux measurements (Nimmo and others, 1994) are limited by their time- and site-specific nature. Such methods may not accurately represent long-term average moisture conditions at the basin scale.

The use of multiple environmental-tracer methods, however, can integrate a range of temporal and spatial scales in the evaluation of infiltration and recharge processes, including the ability to identify primary recharge areas, quantify vadose-zone travel times, and investigate seasonal variations in infiltration and recharge. Also, the application of multiple recharge-estimation methods may yield results at varying temporal and spatial scales, providing different but individually correct flux estimates (Allison, 1988; Allison and others, 1994; Flint and others, 2002; Scanlon and others, 2002).

Prior to this investigation, borehole environmental tracer methods had not been extensively utilized for examining desert recharge processes to an upland bedrock aquifer. The objective of this study is to apply such methods to quantify recharge to the Navajo aquifer. Tracers included chloride (Cl), bromide (Br), tritium (^3H), deuterium (^2H), and oxygen-18 (^{18}O). In this chapter, these tracer techniques are used to investigate both infiltration processes and recharge rates. An important objective of the investigation was to compare the results of different techniques to illustrate the variation in temporal and spatial scales of the different methods. Vadose-zone ^3H (depth-to-peak and mass balance), vadose-zone Cl mass-balance, and ground-water Cl mass-balance methods are applied to evaluate vadose-zone spatial and temporal variations of net infiltration and recharge. Basin-averaged recharge rates are also estimated by using the ground-water Cl mass-balance method. Vadose-zone and ground-water stable isotopes (^2H and ^{18}O) are used both to identify active recharge areas within the basin and to evaluate seasonal/millennial temporal recharge variations. Cl/Br ratios are used to investigate the possibility of nonatmospheric sources of Cl and preferential uptake processes in the root zone.

Previous Investigations

Focused and direct infiltration of precipitation on exposed outcrop or shallowly buried bedrock has been identified as the primary source of recharge to the Navajo aquifer of southern Utah and northern Arizona (Cordova and others, 1972, Cordova, 1981; Hood and Danielson, 1981; Eychaner, 1983; Hood and Patterson, 1984). Cordova (1978) concluded that most infiltration to the Navajo Sandstone of the central Virgin Basin in southwestern Utah occurs on or near the outcrop area where the sandstone is exposed or covered with thin deposits of coarser-grained soils. This observation was supported by vadose-zone solute distributions observed along shallow trenches in the Navajo Sandstone at Sand Hollow (Heilweil and Solomon, 2004), indicating a connection between infiltration rates and surficial characteristics, such as soil coarseness, topographic slope, and runoff from outcropping bedrock.

Studies of the Navajo aquifer in other parts of Utah and Arizona also have estimated recharge from infiltration of precipitation. A study of data from tensiometers and neutron probes in shallow boreholes drilled into exposed sandstone of the Lower Dirty Devil River Basin of south-central Utah shows that infiltration of summer precipitation ranged from less than 1 percent to as much as 25 percent on bare rock (Danielson and Hood, 1984). Other ground-water studies of the Navajo Sandstone in southern Utah and northern Arizona by Blanchard (1986a, b), Thomas (1986), Weiss (1987), Heilweil and Freethey (1992), and Heilweil and others (2000) used ground-water budgets and modeling to estimate recharge rates of between 0.5 and 15 percent of precipitation.

Zhu (2000) combined ^{14}C-based aquifer residence times with ground-water flow modeling to estimate temporal variability in recharge rates in the Shonto recharge area of the Navajo aquifer of Black Mesa, Ariz.: 13 to 19 mm/yr during the late Holocene (0 to 6 ka), lower rates during the mid Holocene (6 to 11 ka), and 2 to 3 times higher recharge during the late Pleistocene and early Holocene (31 to 11 ka). More recently, Zhu and others (2003) used the Cl mass-balance method with variable Cl deposition rates based on chlorine-36 data to estimate recharge rates ranging from about 10 mm/yr for the late Holocene (4 percent of the current 305 mm annual precipitation) to about 40 mm/yr for the late Pleistocene (8 percent of the estimated 540 mm annual precipitation estimated from 31 to 11 ka). These findings are consistent with lake-sediment core data from the Kaibab Plateau of Arizona that indicate wetter conditions at various times during the Holocene (Weng and Jackson, 1999).

Other recharge studies conducted in the Mojave Desert can be divided into two categories of surficial geology: fractured bedrock and unconsolidated (clastic) basin-fill sediments. A variety of techniques including Darcy flux, soil moisture, borehole temperature, and environmental tracers were used at the potential nuclear-waste repository site at Yucca Mountain, Nev., to estimate recharge rates through fractured tuff deposits; values ranged from 3 to 12 mm/yr, or between 2 and 7 percent of annual precipitation (Flint and others, 2002). The Yucca Mountain study determined that recharge was quite variable, mostly occurring on hill slopes with thin soil cover; there was little evidence of active recharge through the thicker sediments of the wash channels or terrace deposits. In contrast, studies of recharge through unconsolidated basin-fill deposits in the Mojave Desert have detected active recharge only beneath ephemeral stream channels; boreholes away from active wash sites showed that little or no active recharge is currently occurring (Phillips, 1994; Prudic, 1994; Tyler and others, 1996; Andraski, 1997; Hartsough and others, 2001; Izbicki and others, 2002; chapters E and G, this volume).

Hydrogeologic Setting

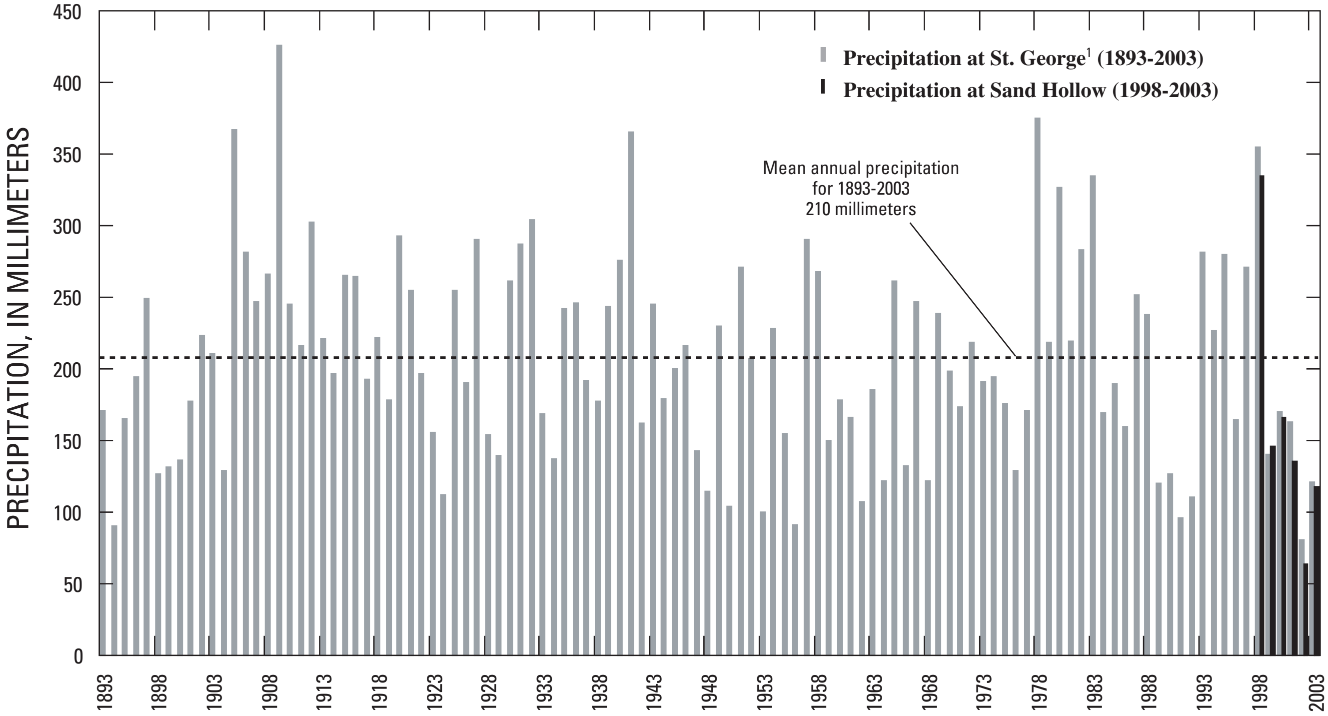
Climate

Although the geologic formations present in Sand Hollow are characteristic of the Colorado Plateau physiographic province, the study area is an upland basin within the lower-altitude and drier Mojave Desert ecosystem. Altitudes within Sand Hollow range from about 900 m to 1,300 m. Mean annual precipitation at St. George, Utah, from 1893 through 2003 was 210 ± 70 mm and ranged from 64 mm in 2002 to 419 mm in 1909. This historical precipitation record, along with precipitation measured at the Sand Hollow meteorological station during 1998 through 2002, is shown in figure 2. Total 5-year precipitation from 1998 through 2003 was 970 mm at Sand Hollow, compared with 1050 mm at St. George, about 10 miles to the southwest. Because of the close agreement (8 percent difference), it is assumed that long-term precipitation at St. George is representative of that at Sand Hollow.

Located in the northeastern part of the Mojave Desert, Sand Hollow is in the transitional area between winter Pacific-storm dominated precipitation to the north and west and a bimodal combination of winter Pacific storms and summer Gulf of California and Gulf of Mexico monsoon precipitation to the east and south (Brenner, 1974; Weng and Jackson, 1999). It receives about 55 percent of its precipitation during November through March and 35 percent of its precipitation during August through October (fig. 3). Spring is extremely dry, accounting for only 10 percent of the annual precipitation (Western Regional Climate Center, 2003). Since recharge at Sand Hollow is very episodic and driven by large precipitation events spanning several days, moving 30-day precipitation totals were calculated, showing that ten of the fifteen 30-day periods during the 20th century with more than 100 mm of precipitation occurred between 1957 and 1997. This is consistent with the greater-than-average precipitation that occurred in the region from 1977 through 1998 associated with the positive Pacific Decadal Oscillation (PDO; Gray and others, 2003).

Geology

Sand Hollow is underlain by the Navajo Sandstone, which has been folded into a bowl-like shape as part of the Hurricane Bench Syncline (fig. 4). The upper part of the formation has been eroded away, associated with uplift on the flank of the nearby Virgin Anticline, and remaining Navajo Sandstone at Sand Hollow is as much as 350 m thick (Hurlow, 1998). The sandstone is well sorted, fine-to-medium quartz sand held together by calcite cement (Cordova, 1978). It was deposited under eolian conditions and has prominent primary cross-bedding structures, along with secondary fracturing. The average dip of nonbedding-plane fractures within Sand Hollow is 75 degrees (Alpha Engineering,



[1] St. George precipitation data from University of Nevada-Reno, Desert Research Institute, Western Region Climate Center (http://www.wrcc.sage.dri.edu), last accessed February 2003.

Figure 2. Annual precipitation at St. George, Utah, during 1893-2003, and at Sand Hollow, Utah, during 1998–2003.

Inc., written commun., 2001). Nonbedding-plane fractures in the Navajo Sandstone are unevenly distributed within the basin and occur in focused zones tens of meters wide, separated by areas with no fractures (Hurlow, 1998). The sandstone in Sand Hollow is either exposed at the surface or covered with a veneer of soils — generally less than 1.5 m. In the southern (upland) part of the basin where most of the sandstone outcrops occur, the soils are generally coarse-grained sands and sand-dune deposits. Finer grained loamy sand and sandy loams are present in the lower part of the basin. A thin layer of calcrete (generally less than 0.5 m) is often observed at the contact between the unconsolidated soils and the underlying sandstone, particularly beneath finer-grained soils.

Hydrology

The basin has a fairly gentle topographic relief. An erosional escarpment beyond the southern end of the drainage basin (fig. 1) marks the southern extent of the Navajo Sandstone. Most of the exposed sandstone is located along the perimeter of the basin. An ephemeral wash drains the higher-altitude southern part of the basin. Sand Hollow is essentially a closed basin under present climatic conditions. While the wash in the southern part of the basin flows during the largest storms, surface water spreads out and infiltrates into the permeable soils at the northern end (where the topographic slope decreases) rather than leaving the basin (L. Jessup, Washington County Water Conservancy District, oral commun., 2001).

As a porous medium, the fractured Navajo Sandstone shares characteristics of both clastic sediments and other consolidated rock formations. Because of its well-sorted nature and small amount of cementation, movement of water through the sandstone matrix is more similar to flow through unconsolidated soils than through other sedimentary formations with less primary permeability, such as siltstone, limestone, chalk, and tuff. Like other bedrock formations, the sandstone cannot be easily penetrated by roots, except where fractured. Therefore the sandstone matrix acts as a semipermeable medium, allowing moisture infiltration, but not root development. This limits transpiration losses, resulting in enhanced recharge compared to clastic sediments in similar arid settings.

The Navajo aquifer at Sand Hollow is unconfined, with depths to water in the central part of the basin ranging from 15 to 65 m below land surface. Ground water generally moves northward toward the Virgin River (fig. 5). The average horizontal hydraulic gradient is 0.006. Downward vertical hydraulic gradients calculated from nested piezometers at sites 14 and 43 (fig. 5) are 0.006 and 0.003, respectively. These downward gradients further support the conclusion that infiltration of precipitation through the vadose zone is the primary source of recharge to the Navajo aquifer in Sand Hollow.

Sample-Collection and Analytical Methods

Precipitation at Sand Hollow was measured from 1998 through 2003 at the Sand Hollow meteorology station (fig. 5) with a tipping bucket rain gauge connected to a data logger. Atmospheric-deposition samples for individual storms were collected for chemical analyses with a 150-mm-diameter brass funnel draining into a 250-mL high-density polyethylene bottle. Multiple-month composite atmospheric-deposition samples were collected with a 75-mm-diameter

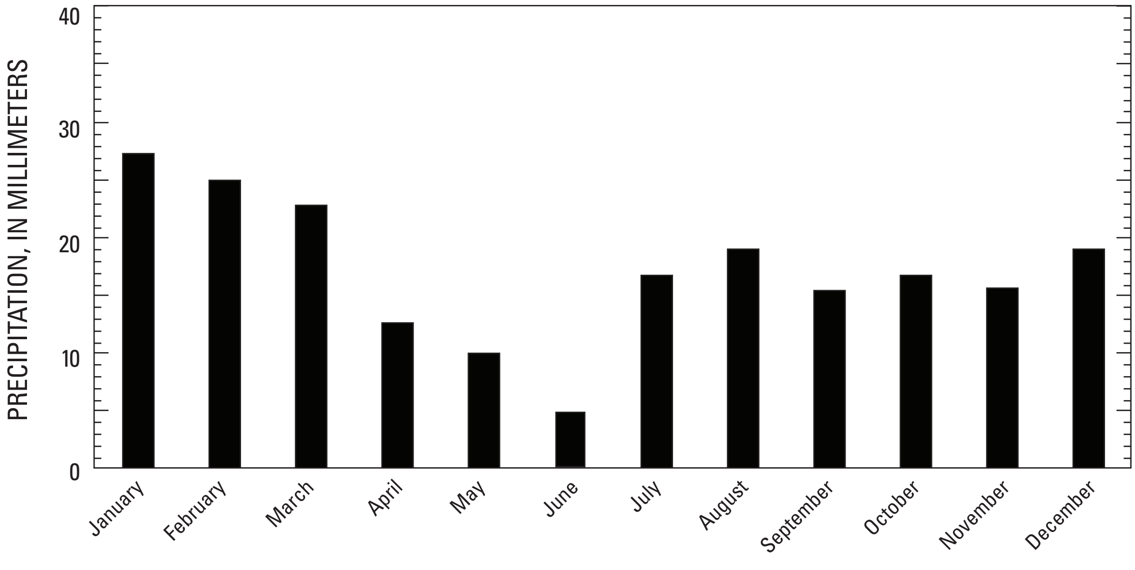


Figure 3. Monthly average precipitation at St. George, Utah, during 1893–2003.

straight-sided Buchner funnel at a height of about 1 m above ground supported by a stake and connected with copper tubing to a 1-L plastic sample bottle buried about 0.3 m below ground. A thin (10 mm) layer of mineral oil in the bottle was used to minimize evaporation of water (Friedman and others, 1992). To sample both wet fall and dust deposition between storms, the funnels for both the individual storms and the multiple-month composite samples were not rinsed between sample collections.

Vadose-zone core samples were collected at 18 sites in Sand Hollow (fig. 5) with an HQ-size triple-tube continuous coring system with air as the drilling fluid. The location of many of the boreholes was guided by a previous study of solute accumulations in shallow excavations within Sand Hollow (Heilweil and Solomon, 2004). Samples were immediately heat-sealed in a layered aluminum/plastic laminate. Pore waters were extracted for isotopic analysis by cryodistillation. Core samples for Cl and Br analysis were first oven-dried at 105°C for 24 hours to determine moisture content and then mixed with an equal mass of de-ionized water to leach the salts. This leachate was centrifuged to remove silts and then filtered to 0.45 µm for anion analysis by ion chromatography. Pore-water Cl and Br concentrations were then calculated from the leachate-concentration and core-sample moisture-content measurements.

Ground-water samples for analysis of cations and anions, as well as trace elements, were collected by using U.S. Geological Survey procedures described by Wilde and others (1998). Cl, Br, and sulfate concentrations in precipitation, pore-water leachates, and ground water were analyzed by the U.S. Geological Survey in San Diego, Calif.; the U.S. Geological Survey National Water Quality Laboratory (NWQL) in Denver, Colorado; and the Los Alamos National Laboratory (LANL) in Los Alamos, N. Mex. Deuterium (^{2}H) and ^{18}O isotopic ratios of precipitation, vadose-zone pore waters, and ground water were analyzed with an isotope-ratio mass spectrometer at the University of Utah Stable Isotope Ratio Facility for Environmental Research (SIRFER). ^{3}H was analyzed at the University of Utah Dissolved Gas Service Center (DGSC). ^{3}H concentrations in precipitation, vadose-zone pore water, and ground water were analyzed on a mass spectrometer with the helium in-growth method (Clark and others, 1976), which was preferable to the conventional radiometric method because of its lower detection limit (0.05 TU) and smaller minimum sample volume requirements (40 ml).

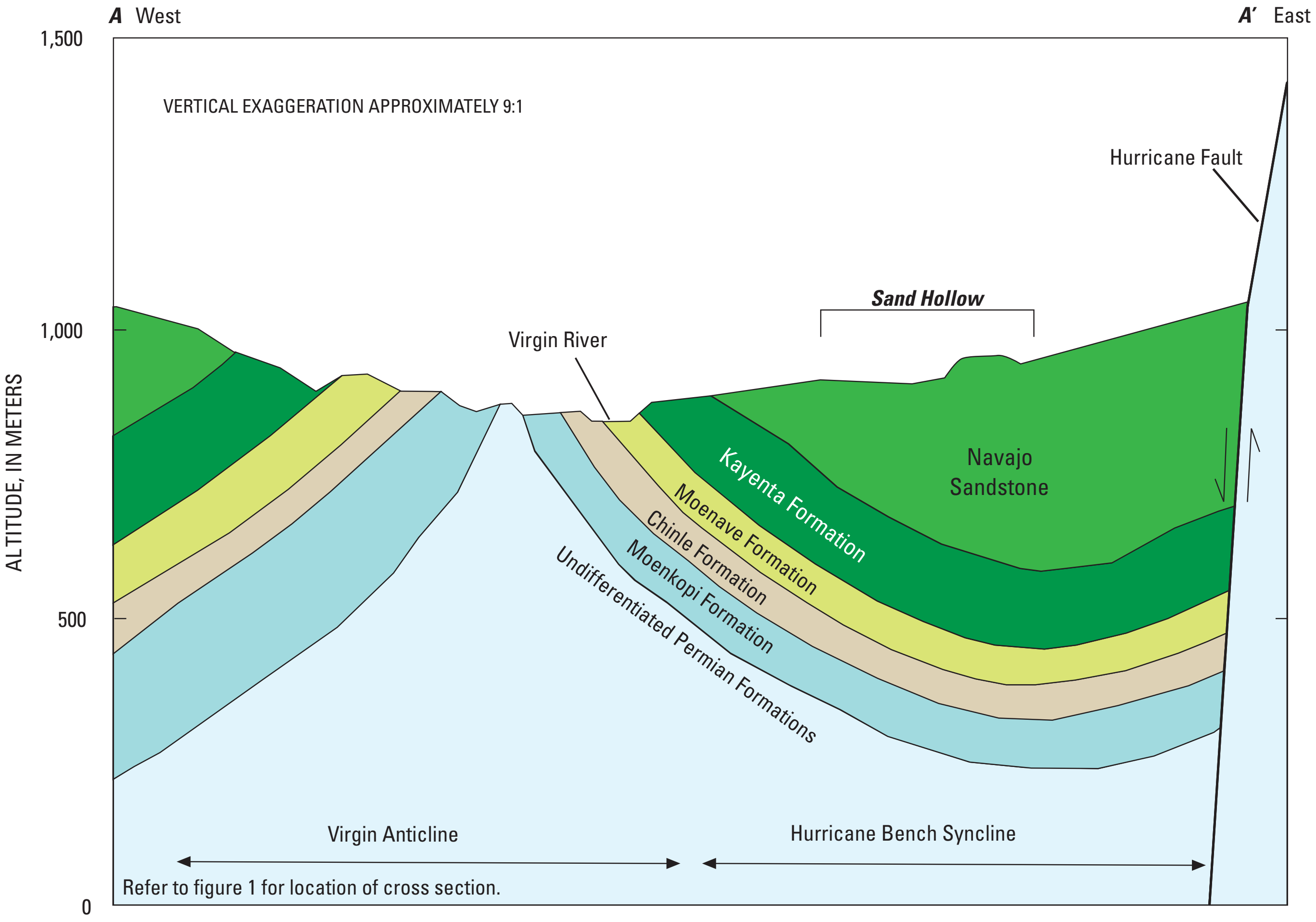


Figure 4. Generalized geologic cross section of the Navajo Sandstone and surrounding formations at the Sand Hollow ground-water-recharge study area, Utah. See figure 1 for location of A-A'

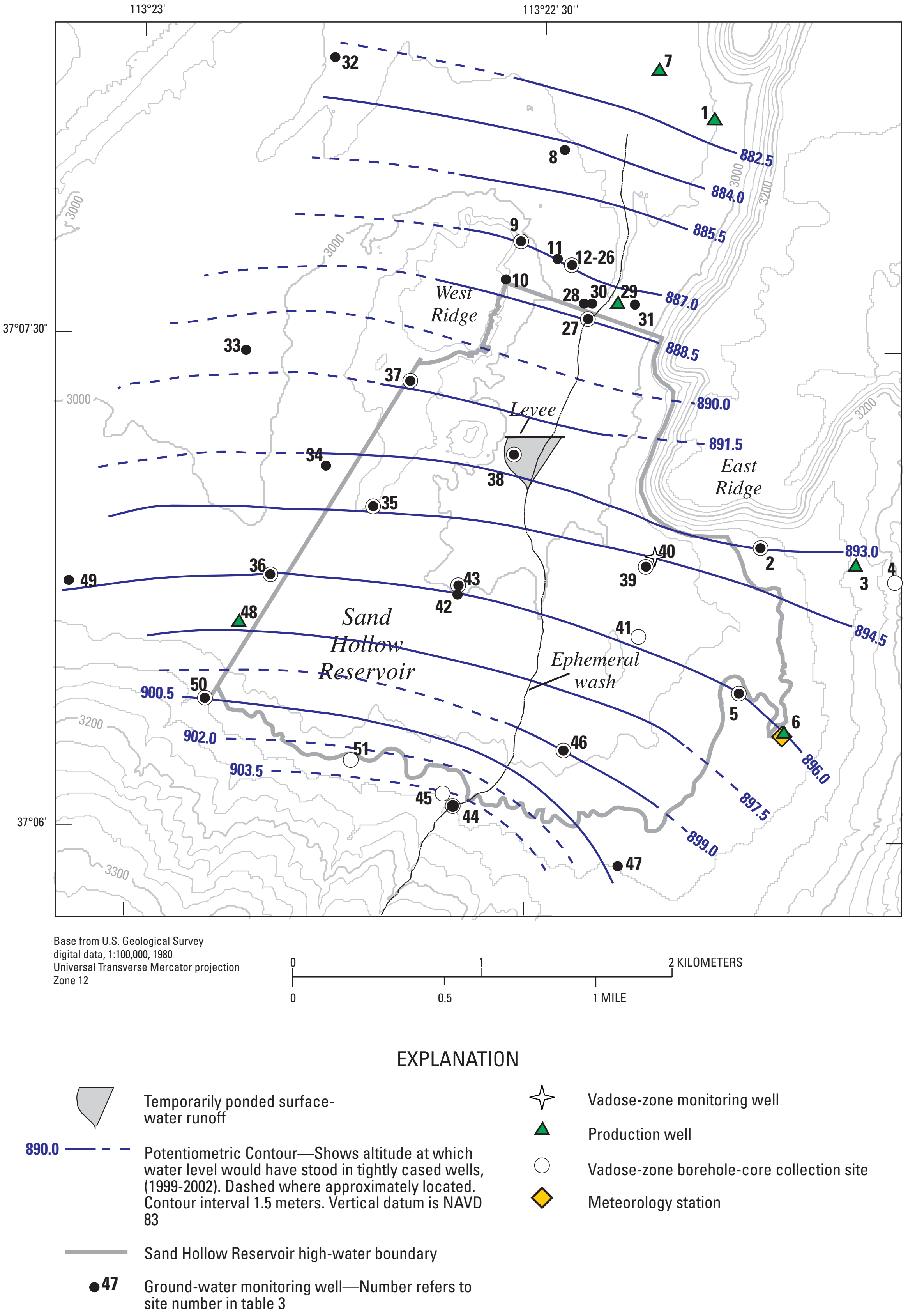


Figure 5. Location of wells, borehole-collection sites, meteorology station, and potentiometric surface of the Navajo Sandstone aquifer near the Sand Hollow ground-water-recharge study area, Utah.

Net Infiltration and Recharge Rates

Chloride

The ratio of the Cl concentrations in atmospheric deposition and ground water can be used with the Cl mass-balance method to provide an estimate of the recharge rate to an aquifer (Allison and Hughes, 1978; Allison, 1988; Dettinger, 1989; Wood and Sanford, 1995). Similarly, vadose-zone Cl concentrations beneath the root zone can be used to estimate rates of net infiltration (Allison and Hughes, 1978).

Chloride in Atmospheric Deposition

The precipitation-weighted mean concentration of atmospheric Cl deposition at Sand Hollow is 0.8 (± 0.3) mg/L from data collected during this study. This is based on the uncorrected Cl concentrations of eight multiple-month atmospheric-deposition samples collected between June 1999 and September 2004, which ranged from 0.5 to 1.2 mg/L (table 1). Three other multiple-month periods were excluded because of high sulfate concentrations (greater than 4.0 mg/L), which indicate possible contamination from bird droppings, decaying insect debris, or dust associated with construction. Because some evaporation from the sample container likely occurred, precipitation amounts from the atmospheric-deposition collector were often less than rain-gauge measurements at the same site. Therefore, a correction factor (the ratio of weather-station precipitation to atmospheric-deposition sample precipitation) was used to adjust the Cl concentration for this evaporative concentration of the sample. Similar Cl concentrations were measured in atmospheric-deposition samples collected during 12 individual storms from October 2000 to July 2001 (not including seven storms with sulfate concentrations greater than 4.0 mg/L), which ranged from 0.3 to 2.9 mg/L (table 1), with a mean of 0.8 mg/L. Assuming an average precipitation rate of 210 mm/yr, the mean 0.8 mg/L Cl concentration of atmospheric deposition corresponds to an average Cl deposition rate of 17 μg/cm^2/yr.

Chloride in the Vadose Zone

Leachates prepared from borehole-core samples show that accumulation of atmospheric Cl in the vadose zone at Sand Hollow is quite variable. Total Cl accumulation ranged from 4 mg/cm^2 at sites 9 and 35 to at least 230 mg/cm^2 at site 4. Assuming an annual Cl deposition rate of 17 ± 8.5 μg/cm^2, this mass of Cl in the vadose zone at Sand Hollow represents from 200 to at least 12,000 years of accumulation (table 2).

Pore-water chloride concentrations were calculated based on the mass of chloride in the leachate sample and the volumetric water content determined by oven-drying the core sample. Vadose-zone water content of the borehole-core samples is generally consistent with trends in Cl and ^{3}H accumulation (tables 2, 3). Mean vadose-zone volumetric water content, calculated from land surface to the capillary fringe, ranged from 1.7 to 7.8 percent. Site 4 had the lowest average vadose-zone moisture content, consistent with the largest Cl accumulation of the sites within Sand Hollow. Site 4 is located on the East Ridge (fig. 5) and is exposed to more wind, resulting in more bare-soil evaporation than at the other sites. Site 9 had the highest average vadose-zone moisture content, consistent with having very little Cl accumulation. Located along a small side wash, this site regularly receives focused infiltration of surface-water runoff from the exposed sandstone of the West Ridge.

The profiles generally show shallow Cl accumulations, with peak concentrations occurring less than 15 m below land surface. The peak concentrations range from 28 mg/L at site 35 to 29,900 mg/L at site 4 (table 2). The profiles generally have the characteristic bulge shape observed in many desert soils (figs. 6, 7).

Site-specific vadose-zone infiltration rates were calculated with the Cl mass-balance method (Phillips, 1994; Scanlon, 2004) by dividing the average Cl concentration of atmospheric deposition by either [1] the average vadose-zone Cl concentration of pore water from borehole samples between land surface and the bottom of the Cl bulge or [2] the average vadose-zone Cl concentration of pore water from borehole samples below the Cl bulge. In unconsolidated sediments, pore-water concentrations within the shallow Cl bulge generally are not used for calculating net infiltration rates because the depth of salt accumulation associated with root-zone transpiration often overlaps the depth of the bulge. However, at Sand Hollow there is minimal root penetration into the Navajo Sandstone, which is either exposed or covered by less than about 1.5 m of soil. Peak vadose-zone Cl concentrations are generally located in sandstone below the root zone at depths ranging from 1.2 to 14.5 m below land surface, with an average depth of about 5 m (table 2). Therefore, calculations based on Cl concentrations within the bulge should be representative of net infiltration rates. Infiltration rates ranged from 0.03 to 8 mm/yr based on pore-water Cl concentrations between land surface and the bottom of the Cl bulge; rates ranged from 0.5 to 13 mm/yr based on pore-water Cl concentrations below the bottom of the Cl bulge (table 4).

The boreholes can be divided into low- and high-recharge sites on the basis of total Cl accumulation, peak vadose-zone Cl concentration, and infiltration rates. Sites 2, 4, 12, 27, 37, 38, 39, and 46 have lower vadose-zone Cl net infiltration rates, with more than 20 mg/cm^2 total Cl accumulation and peak vadose-zone Cl concentrations of more than 300 mg/L. Conversely, sites 9, 35, 43, 44, and 50 have higher vadose-zone Cl net infiltration rates, with less than 20 mg/cm^2 total Cl accumulation and peak vadose-zone Cl concentrations of less than 200 mg/L (tables 2, 4).

Chloride in Ground Water

The mean Cl concentration from 31 ground-water sites in Sand Hollow (fig. 8) is 22.5 mg/L with a standard deviation of 12.5 mg/L. It is assumed that all of the Cl in the unsaturated zone and the underlying aquifer is of atmo-

Table 1. Selected chemical constituents in precipitation, Sand Hollow ground-water recharge study area, Utah.

[Site locations refer to figure 5. Anions analyzed by U.S. Geological Survey, San Diego, Calif., unless otherwise noted. Abbreviations: mg/L, milligrams per liter; δ^2H, deuterium; $\delta^{18}O$, 18-oxygen; ^3H, tritium; TU, tritium units; —, no data available; <, less than; ±, plus or minus]

Site number	Sample day or period	Chloride, in mg/L	[1] Bromide, in mg/L	[1] Sulfate, in mg/L	Chloride/bromide ratio	δ^2H, in per mil	$\delta^{18}O$, in per mil	^3H, in TU
2	4/30/1999	—	—	4.7	—	—	—	21.0 ± 1.0
6	[2] 6/3/1999–10/12/1999	[3] 6	—	—	—	−76.0	−7.5	—
6	[2] 10/12/1999–4/13/2000	1.2	[4] 0.007	3.0	171	−82.0	−11.0	—
6	[2] 4/13/2000–10/11/2000	0.9	0.016	4.0	56	−21.0	−4.3	—
6	[2] 10/11/2000–4/30/2001	1.2	< 0.016	4.0	—	−86.0	−11.8	—
6	[2] 4/30/2001–10/3/2001	[3] 3.5	—	[3] 14	—	−1.0	2.8	—
6	[2] 10/3/2001–5/8/02	0.9	—	3.0	—	—	—	—
6	[2] 5/8/02–9/11/02	1.0	—	4.0	—	—	—	—
6	[2] 9/11/02–5/8/03	0.5	0.05	< 3.0	—	−97.6	−13.0	—
6	[2] 5/08/03–10/8/03	0.5	< 0.3	3.0	—	—	—	—
6	[2] 10/08/03–5/4/04	0.4	< 0.3	2.3	—	—	—	—
6	[2] 5/04/04–9/22/04	[3] 1.6	[3] < 0.3	[3] 11	—	—	—	—
12	10/10/2000	—	—	—	—	−43.0	−7.1	—
12	10/11/2000	1.7	[4] 0.007	2.6	243	−16.9	−2.6	—
12	10/23/2000	[3] 7.2	[3] 1.129	[3] 10.8	—	−122.1	−13.8	—
12	10/27/2000	—	—	—	—	−72.1	−11.1	—
12	10/28/2000	—	—	—	—	−116.9	−15.3	—
12	11/1/2000	—	—	—	—	−79.2	−10.7	—
12	11/10/2000	0.8	0.023	1.6	37	−52.3	−9.2	—
12	11/13/2000	—	—	—	—	−49.1	−8.8	—
12	12/12/2000	—	—	—	—	−84.6	−10.5	—
12	1/9/2001	0.8	—	3.95	—	−84.6	−10.8	—
12	1/12/2001	0.3	< 0.016	0.7		−91.0	−11.6	—
12	2/14/2001	—	—	—	—	−87.0	−12.7	9.14 ± 0.5
12	2/27/2001	—	—	—	—	−126.4	−15.5	—
12	3/1/2001	0.3	< 0.016	0.7	—	−104.1	−14.2	—
12	3/5/2001	0.4	< 0.016	1.3	—	—112.1	−15.1	—
12	3/7/2001	0.4	< 0.016	1.6	—	−104.5	−12.0	—
12	3/9/2001	—	—	—	—	−100.6	−13.7	9.28 ± 0.5
12	3/12/2001	0.4	< 0.016	1.3	—	−100.6	−13.7	—
12	4/6/2001	[3] 2.2	[3] < 0.016	[3] 11.2	—	−34.2	−6.2	—
12	4/9/2001	—	—	—	—	−51.6	−7.2	—
12	5/14/2001	[3] 16.6	[3] 0.615	[3] 29.9	—	4.2	0.5	—
12	5/17/2001	0.5	[4] 0.007	1.5	71	—	—	—
12	5/28/2001	[3] 1.8	0.020	4.7	—	—	—	—
12	6/26/2001	[3] 2.1	0.028	8.4	—	—	—	—
12	7/5/2001	0.6	[4] 0.007	2.2	84	—	—	—
12	7/9/2001	2.9	[4] 0.010	3.0	287	—	—	—
12	7/11/2001	[3] 16.7	[3] 0.620	[3] 28.4	—	—	—	—
12	10/7/2001	[3] 4.3	[3] 0.190	[3] 25.1	—	−54.3	−6.7	—
12	11/13/2001	—	—	—	—	−39.0	−5.6	—
12	11/25/2001	—	—	—	—	−73.0	−9.2	—
12	11/30/2001	—	—	—	—	−103.0	−14.6	—
12	12/4/2001	—	—	—	—	−59.0	−8.5	—
12	12/15/2001	—	—	—	—	−84.0	−11.5	—
12	12/23/2001	—	—	—	—	−103.0	−13.3	—
42	09/11/2001	—	—	—	—	−3.1	3.3	—
[5] 44	11/09/2002	0.32	[6] 0.006	2.3	53	−48.2	−6.6	2.3 ± 0.1

[1] Analyzed by Los Alamos National Laboratory, Los Alamos, New Mex.

[2] Multiple-month atmospheric deposition sample collected at meteorologic station.

[3] Value is suspect; high sulfate or phosphate concentration suggests contamination.

[4] Reported bromide concentration is less than the 0.016 parts per milion detection limit because of evaporative concentration.

[5] Sample of streamflow collected during ephemeral runoff.

[6] Analyzed by the USGS National Water-Quality Laboratory in Denver, Colo.

spheric origin. The Navajo Sandstone is a clean, well-sorted, eolian sandstone containing no evaporite or other salt deposits. However, because of the upward advective movement into the Navajo Sandstone of Cl-rich brines from underlying formations documented at other study sites (Kimball, 1992; Naftz and others, 1997; Heilweil and others, 2000), Cl-to-Br ratios were examined to evaluate potential Cl contributions from geologic sources. Such geologic sources of Cl typically have Cl-to-Br ratios exceeding 1,000 and the ratios increase with increasing Cl concentration (Davis and others, 1998). However, no such trend is evident in ground water from Sand Hollow and ground-water Cl-to-Br ratios are always less than 500 (fig. 9). Furthermore, vadose-zone pore water Cl-to-Br ratios generally increase from land surface to the water table (fig. 10; Heilweil, 2003), consistent with a doubling in the mean Cl-to-Br ratio from 120 for atmospheric-deposition samples to 230 for ground-water samples. This indicates that some unsaturated-zone process, such as preferential uptake of Br by plant roots, influences ground-water Cl-to-Br ratios rather than a geologic source of Cl.

By using mean Cl concentrations of 0.8 mg/L (with a standard deviation of 0.3 mg/L) for atmospheric deposition (Cl_{dep}) and 22.5 mg/L (with a standard deviation of 12.5 mg/L) for ground water (Cl_{gw}), along with the 210 mm (with a standard deviation of 70 mm) of mean annual precipitation (P) at Sand Hollow, the estimated Cl mass-balance recharge rate is 7.5 mm/yr (with a standard deviation of 5.6 mm/yr, or about 4 (± 3) percent of precipitation. The mean and variance (square of the standard deviation) in the recharge rate were evaluated with a truncated (linear terms only) Taylor series expansion (chapter appendix).

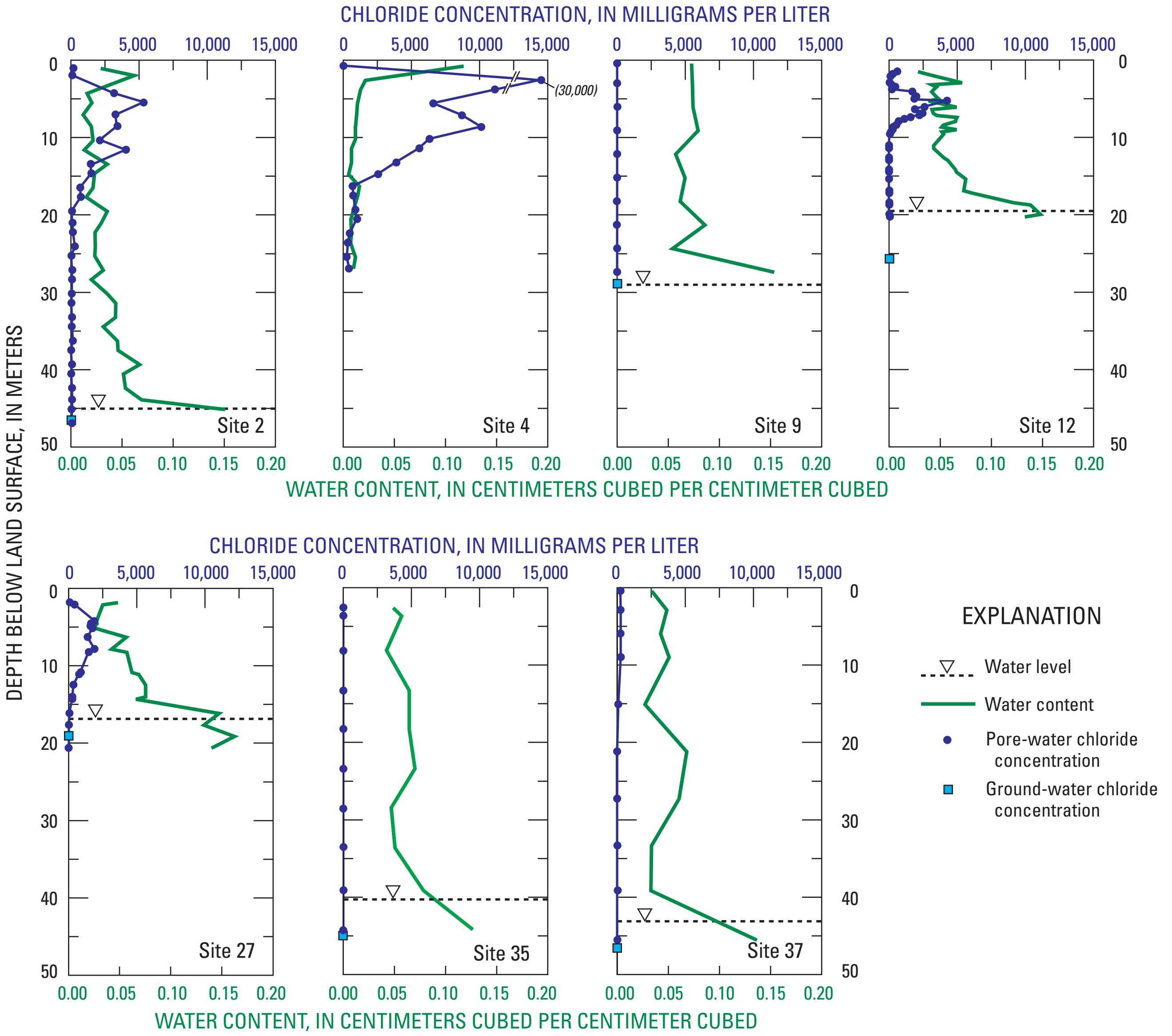


Figure 6. Chloride concentration and volumetric water content of pore-water and ground-water samples collected from selected boreholes at the Sand Hollow ground-water-recharge study area, Utah.

The wide range of Cl concentration in ground water, from 2.9 to 61.1 mg/L (fig. 8, table 4), indicates that the amount of evaporative concentration of infiltrating precipitation in the shallow root zone is quite spatially variable. The Cl mass-balance method can be applied to these individual ground-water sites, resulting in recharge rates ranging from 3 to 60 mm/yr (table 4), or about 1 to 28 percent of average annual precipitation.

Tritium

Tritium in Precipitation

The estimated ^{3}H concentration of precipitation in southwestern Utah from 1950 to 2000 is shown in figure 11. This estimation is based on a distance-weighted average from Global Network of Isotopes In Precipitation (GNIP) monitoring stations operated by the International Atomic Energy Agency (IAEA) at Albuquerque, N. Mex.; Flagstaff, Ariz.; and Salt Lake City, Utah. The maximum ^{3}H concentration of precipitation at Sand Hollow during the above-ground nuclear testing in the early 1960s was estimated to exceed 2,000 TU. Present ^{3}H concentrations in precipitation at Sand Hollow are near or slightly above the prebomb background levels. Three samples of recent precipitation (1999–2001) had measured ^{3}H concentrations ranging from 9.1 to 21.0 TU (table 1). A surface-water sample collected during a ephemeral flow event on 11/09/2002 had a ^{3}H concentration of only 2.3 TU, possibly caused by a dilution with older (lower ^{3}H) shallow vadose-zone pore waters flushed into the wash by the infiltrating precipitation.

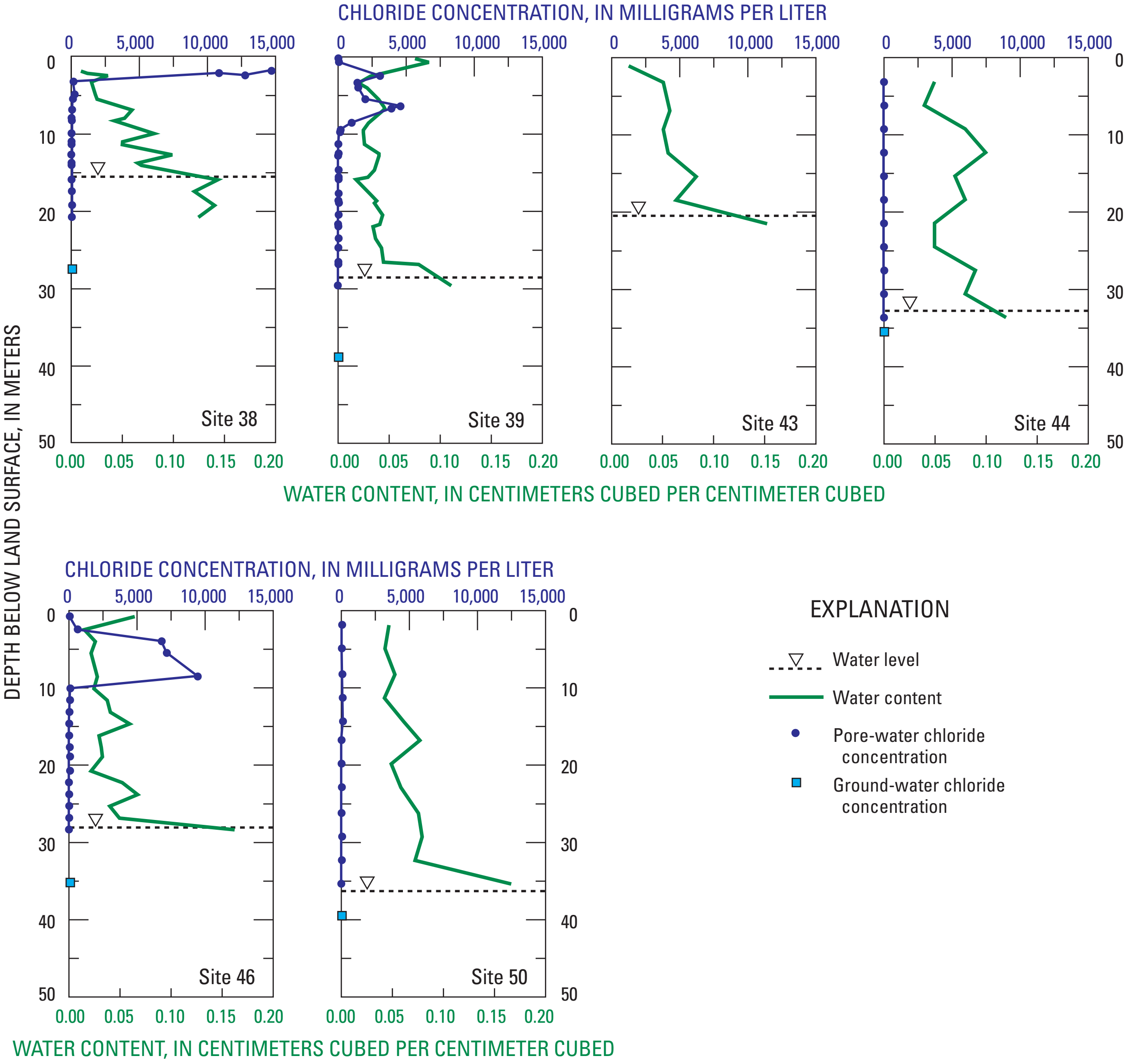


Figure 6.—Continued.

Table 2. Vadose-zone chloride parameters and water content from borehole samples, Sand Hollow ground-water-recharge study area, Utah.

[Site numbers refer to figure 5. Abbreviations: mg/cm^2, milligrams per centimeter squared; mg/L, milligrams per liter; m, meters; mm/yr, millimeters per year; —, no data available]

Site number	Total chloride accumulation, in mg/cm^2	[1] Chloride accumulation time, in years	[2] Peak chloride concentration, in mg/L	Depth of chloride peak concentration, in m	[3] Mean volumetric water content, in percent	Chloride accumulation time for bulge, in years	Mean chloride concentration in Cl bulge, in mg/L	Depth interval from chloride bulge to water table, in m	[4] Mean chloride concentration below bulge, in mg/L
High-recharge sites									
9	4	200	41	8	7.8	100	22	9 to 28.8	13
35	4	200	28	5	5.9	50	20	18 to 24.4	21
44	5	300	36	6	6.8	100	21	12 to 32.7	23
43	5	300	141	1	5.4	150	76	12 to 20.2	38
50	15	800	138	15	6.0	400	100	17 to 36.6	51
Low-recharge sites									
37	22	1,200	336	5	4.4	800	240	21 to 43.3	41
38	55	3,000	14,700	2	4.7	2,500	6,500	7 to 15.6	44
12	56	3,000	4,300	5	5.6	3,000	1,100	11 to 19.6	36
39	70	4,000	4,600	7	4.0	3,500	1,600	11 to 28.2	48
27	72	4,000	1,900	8	4.6	3,500	1,100	16 to 17.7	59
2	91	7,000	5,400	6	3.3	4,000	2,200	20 to 45.4	109
46	140	7,000	9,500	9	3.8	7,000	3,500	13 to 28.3	58
4	[5] 230	12,000	29,900	3	1.7	—	5,600	25 to [6] 137.0	354

[1] For entire vadose zone, assuming a 17 microgram per square centimeter annual chloride atmospheric deposition rate.

[2] Shown in figure 6.

[3] Calculated between land surface and the capillary fringe.

[4] For depths below the chloride bulge and above the water table, except for site 4, which did not reach water table.

[5] Minimum because borehole was not drilled to water table.

[6] Depth to water table extrapolated from potentiometric map (fig. 5).

Table 3. Vadose-zone tritium parameters and water content from borehole-core samples, Sand Hollow, Utah.

[Abbreviations: m, meters; mm/yr, millimeters per year; TU-m, tritium unit meters; —, no data available; >, greater than]

Site number	Bore-hole name	Collection date	Depth to tritium peak in vadose zone, in m	Mean volumetric water content to tritium peak, in percent	Time since peak atmospheric tritium concentration, in years	[1] Recharge rate from depth of tritium peak, in mm/yr	Total tritium in vadose zone, in TU-m	[2] Recharge rate from tritium mass balance, in mm/yr	Correction factor for mass balance recharge rate
				High-recharge sites					
9	WD 6	2001/05/14	> 28.7	7.9	38	[3] > 57	12.9	[3] > 11	—
35	Hole N	2001/05/25	20.3	4.9	38	26	15.3	13.1	2.0
44	WD 8	2001/05/17	18.6	7.0	38	34	17.2	14.7	2.3
43	Hole O	2001/06/10	17.4	5.9	38	27	13.6	11.6	2.3
50	WD 7	2001/05/15	8.4	4.7	38	10	6.9	5.9	1.8
				Low-recharge sites					
37	WD 9	2001/05/22	3.8	4.6	38	4.6	3.5	3.0	1.5
38	Basin 1	1999/04/22	—	—	—	—	1.5	1.2	—
12	IFP 1	1999/04/19	—	—	—	—	1.9	1.4	—
39	Slope 1a	1999/04/26	3.5	2.7	36	2.6	2.2	1.7	1.6
27	Wash 1	1999/04/15	—	—	—	—	2.7	2.0	—
2	WD 12	1999/05/03	—	—	—	—	2.8	2.1	—

[1] Based on equation 1.

[2] Based on equation 2; the decay-corrected tritium mass in precipitation since 1950 is 274 tritium-unit meters for wells drilled in 1999 and 246 tritium-unit meters for wells drilled in 2001.

[3] Based on assumption that tritium peak is already below water table.

Table 4. Summary of recharge rates and environmental-tracer data for individual borehole sites, Sand Hollow ground-water-recharge study area, Utah.

[Site numbers refer to figure 5. Abbreviations: mm/yr, millimeters per year; TU, tritium units; >, greater than; —, no data available]

Site number	Depth to bedrock, in m	Environmental tracer data					Infiltration or recharge rate				Site description
		Vadose-zone chloride accumulation time, in years	Ground-water chloride concentration, in mg/L	[1] Ground-water tritium concentration, in TU	Average vadose-zone 18-oxygen shift, in per mil	Ground-water deuterium ratio, in per mil	Chloride, land surface to bottom of bulge, in mm/yr	Chloride, bottom of bulge to water table, in mm/yr	Ground-water chloride, in mm/yr	Vadose-zone tritium, in mm/yr	
High-recharge sites											
9	0.0	200	2.9	6.9	2.1	–79	8	13	60	> 57	Fine sand/ exposed sandstone beneath wash
35	0.4	200	6.5	4.3	—	–82	8	8	26	26	Sand dunes
44	0.0	300	[2] 10.0	4.1	2.3	[2]–83	8	7	17	34	Fine sand/ exposed sandstone beneath wash
43	0.0	300	[2] 16.5	1.0	2.8	[2]–84	2	4	10	27	Exposed sandstone
50	1.2	800	18.0	0.21	3.4	–85	2	3	9	10	Loamy fine sand
Low-recharge sites											
37	0.2	1,000	[2] 20.4	0.00	3.0	[2]–88	0.7	4	8	4.6	Loamy very fine sand on ridge
38	0.9	3,000	[2] 61.1	0.07	2.2	[2]–86	0.03	4	3	[3] 2.4	Silty clay loam near wash
12	0.8	3,000	19.9	[4] 0.00	3.5	[2]–84	0.2	5	8	[3] 2.8	Loamy very fine sand
39	0.8	4,000	[2] 11.3	0.07	3.5	[2]–85	0.1	4	15	2.6	Fine sandy loam
27	0.8	4,000	28.1	0.27	4.1	[2]–86	0.2	3	6	[3] 4.0	Fine sandy loam beneath wash
2	1.5	7,000	[2] 21.0	0.02	3.8	[2]–85	0.08	2	8	[3] 4.2	Fine sandy loam
46	1.2	7,000	[2] 10.9	0.18	3.7	[2]–87	0.05	3	15	—	Fine sandy loam
[5] 4	1.5	12,000	—	—	4.7	—	0.03	0.5	—	—	Fine sandy loam on ridge
Mean											
	[2] 0.7	[6] 1,500	[6] 15	[2] 1.4	[2] 3.3	[2]–85	[6] 0.4	[6] 4	[6] 11	[6] 9	

[1] See table 5 for tritium precision; analysis with highest precision listed when multiple analyses available.

[2] Arithmetic mean of multiple values.

[3] Calculated using ^{3}H-mass-balance method multiplied by a correction factor of 2.

[4] From shallowest port (site 17) in same borehole.

[5] Borehole was not drilled to water table.

[6] Geometric mean.

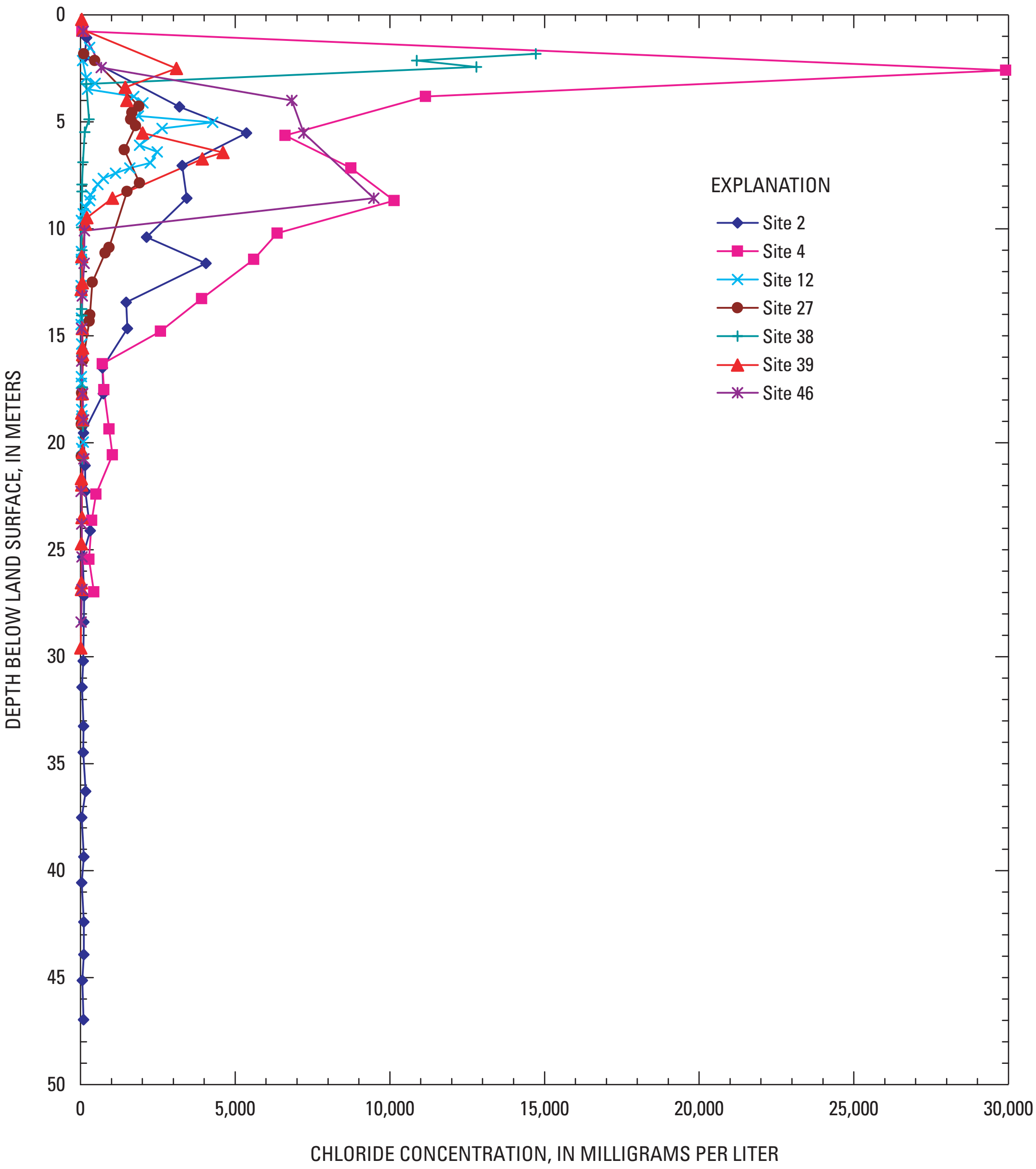


Figure 7. Vadose-zone chloride concentration obtained from borehole-core samples collected from locations with low values of recharge, Sand Hollow ground-water-recharge study area, Utah.

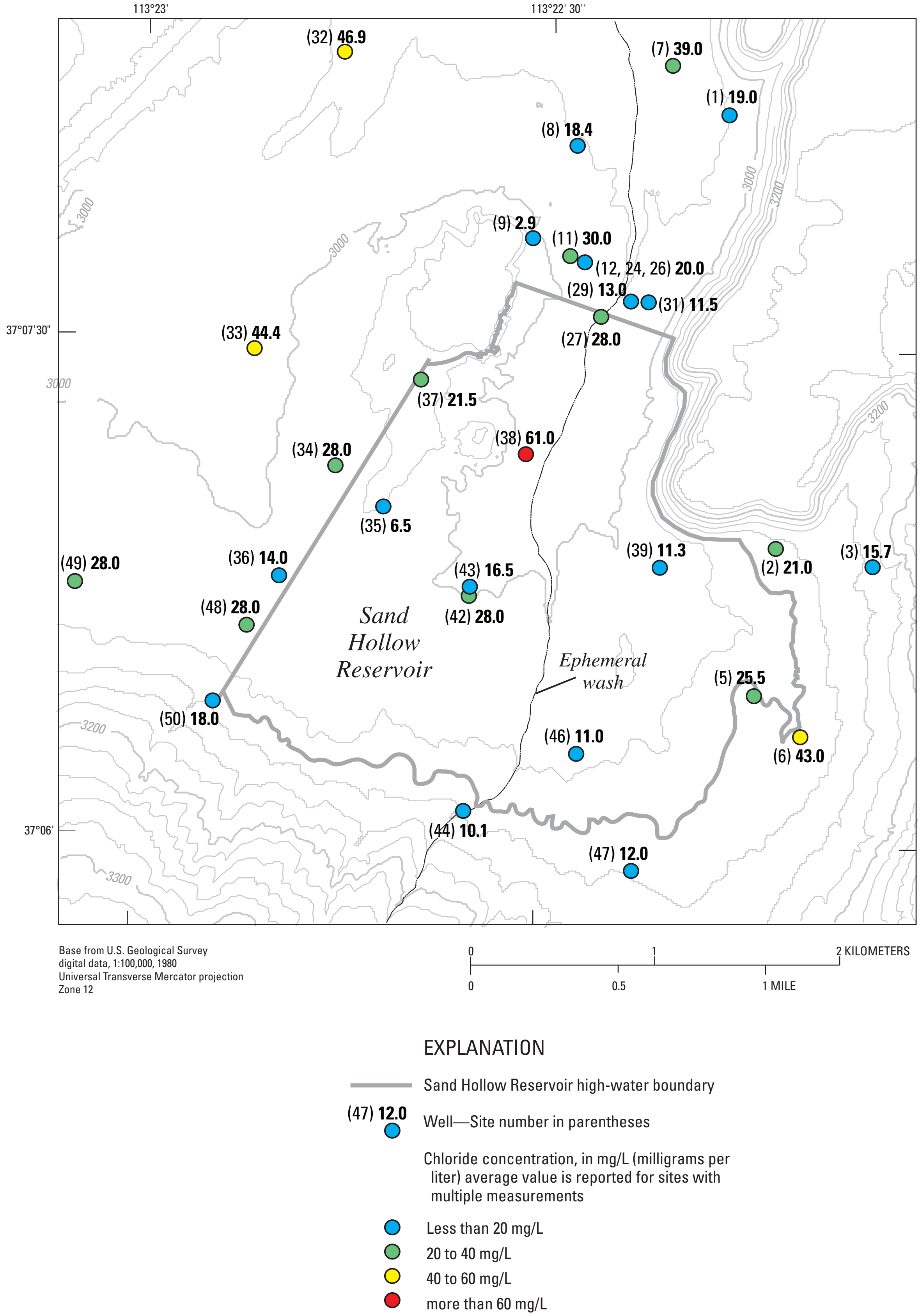


Figure 8. Chloride concentration in water from selected wells at the Sand Hollow ground-water-recharge study area, Utah.

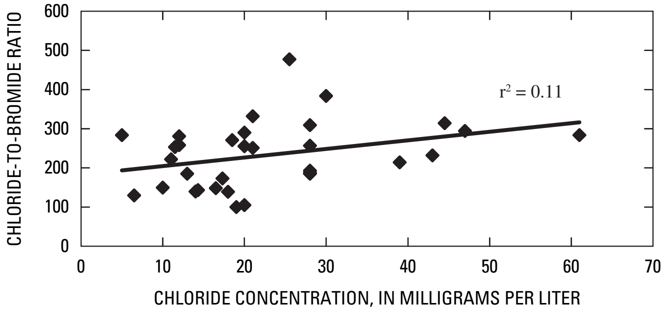


Figure 9. Relation of chloride-to-bromide ratio to chloride concentration in water from selected wells at the Sand Hollow ground-water-recharge study area, Utah.

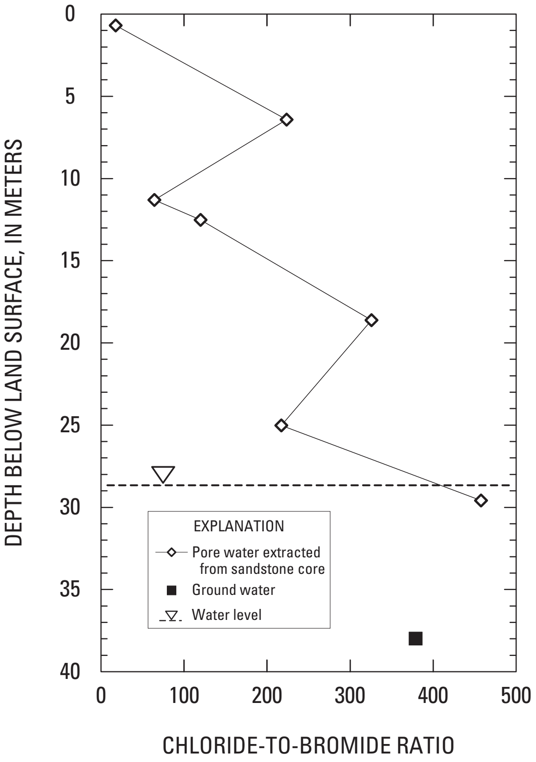


Figure 10. Chloride-to-bromide ratio with depth in vadose-zone pore-water and ground-water samples collected at site 39, Sand Hollow ground-water-recharge study area, Utah.

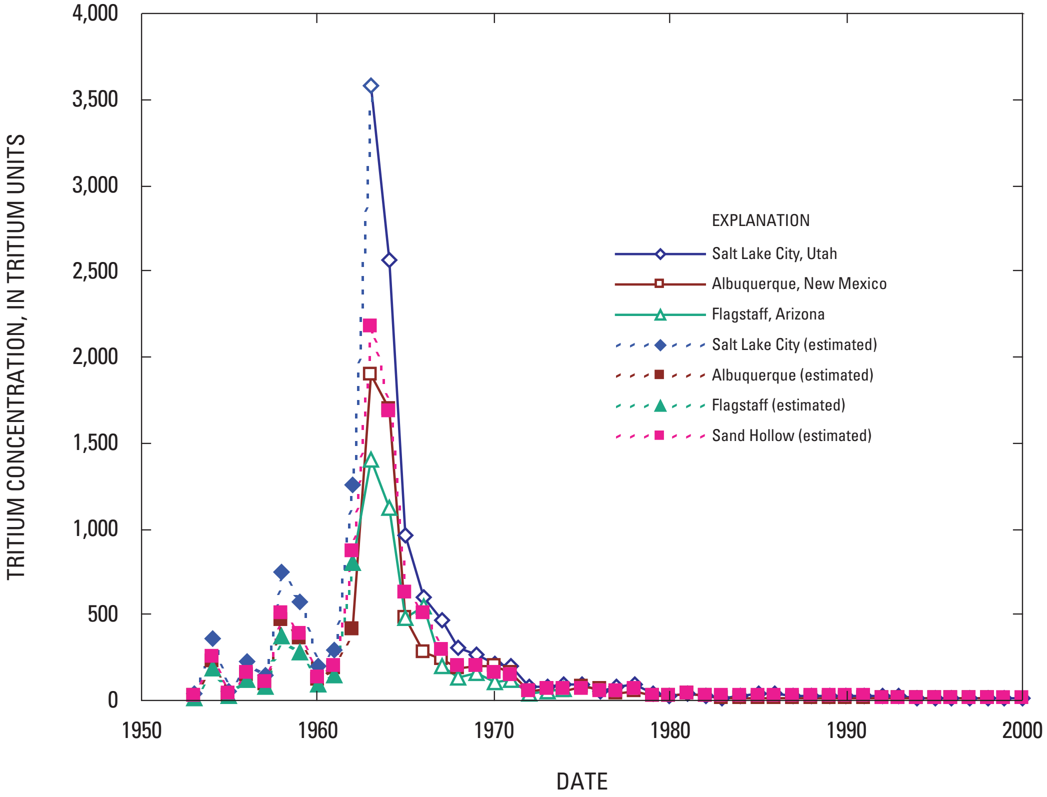


Figure 11. Estimated tritium concentration of precipitation at the Sand Hollow ground-water-recharge study area, Utah.

Tritium in the Vadose Zone

^{3}H concentrations in vadose-zone pore water from boreholes within Sand Hollow ranged from 0 to 17.9 TU (fig. 12). ^{3}H concentrations of 4 to 12 TU were typically measured within the first few meters of the boreholes and likely represent recent precipitation. Profiles at sites 35, 37, 39, 43, 44, and 50 show vadose-zone peaks consistent with the peak atmospheric-^{3}H concentrations of the early 1960s. Profiles at sites 2, 12, 37, and 38 do not display a subsurface ^{3}H peak. The profile at site 9 has consistently high concentrations throughout the entire vadose zone, indicating that the 1960s peak has already been flushed down to the water table. ^{3}H concentrations of ground-water at each site (also shown in fig. 12) are generally similar to concentrations in pore waters from borehole cores at or near the water table.

Both the ^{3}H depth-to-peak (TDTP) and ^{3}H mass-balance (TMB) methods were used to determine net infiltration rates at various borehole locations within Sand Hollow. The TDTP method uses the depth of the 1963 ^{3}H peak in the vadose zone and the average soil-moisture content to estimate a net infiltration flux rate, q (L T^{-1}), with the following equation (Cook and others, 1994):

$$q = \frac{z}{t}\theta_v \ , \qquad (1)$$

where z is the vertical distance between land surface and the 1963 ^{3}H peak (L),
t is the length of time between the ^{3}H peak and the sample collection time (T),
and θ is the depth-weighted volumetric water content of the vadose zone between land surface and the ^{3}H peak.

Similar to the Cl mass-balance method, the ^{3}H mass-balance (TMB) method is based on the assumption that precipitation falling at the borehole site either becomes net infiltration or is lost from the site as evapotranspiration or runoff. The ratio of [1] the mass of ^{3}H between the root zone and the water table to [2] the mass of decay-corrected ^{3}H that fell as precipitation provides the percent of moisture that has infiltrated the subsurface. Multiplying this ratio by the average annual precipitation yields the average annual infiltration rate. The following TMB equation (Cook and others, 1994) was used to estimate net infiltration rates at Sand Hollow:

$$q = \frac{\int_0^\infty \theta(z)c\,(z)d\,z}{\sum_{i=1}^{\infty} w_i c_i e^{-i\lambda}} \ , \qquad (2)$$

where q is the net infiltration flux rate (L T^{-1}),
$c(z)$ is the pore-water ^{3}H concentration at depth z (M L^{-3}),
$\theta(z)$ is the volumetric moisture content at depth z (L^3 L^{-3}),
w_i is a weighting function to correct for variations in annual net infiltration flux (the weighting function used for Sand Hollow was the ratio of precipitation during each year (i) to mean annual precipitation),
and $c^ie^{-i\lambda}$ is the decay-corrected ^{3}H concentration in precipitation i years before present (M L^{-3}).

The TDTP method is considered more accurate than the TMB method. However, at borehole sites without the presence of a clearly discernable 1963 vadose-zone ^{3}H peak, the TMB method must be used to estimate net infiltration. The TMB method [1] requires knowledge of the ^{3}H input function (the historical record of ^{3}H in precipitation), which is generally not known for each site and must be interpolated from sparsely-located GNIP stations at other locations having different wind and climate patterns, [2] it may overpredict net infiltration at sites where surface-water runon has occurred, [3] part of the ^{3}H within the shallow root zone may eventually be recycled into the atmosphere rather than becoming net infiltration, causing an overestimate of net infiltration rates when ^{3}H in the root zone is included in the total mass of vadose-zone ^{3}H.

For estimating the ^{3}H input function at Sand Hollow, the nearest GNIP stations are Flagstaff, Ariz., Salt Lake City, Utah, and Albuquerque, N. Mex., located at distances of 270, 425, and 650 km, respectively. Also, since no early ^{3}H precipitation measurements were made at any of these stations, the Sand Hollow ^{3}H input function prior to the early 1960's is based only on correlations with the Ottawa, Canada station located more than 3,000 km to the northeast at a much more northerly latitude. Error associated with root zone ^{3}H in the mass-balance calculation is not considered an important factor at the borehole sites in Sand Hollow because of the exposed or shallowly buried sandstone, where minimal root penetration occurs.

Net infiltration was calculated at seven borehole sites by using the TDTP method, with rates ranging from 2.6 to more than 57 mm/yr (table 3). Net infiltration was calculated at 11 borehole sites by using the TNB method, with rates ranging from 1.2 to 14.7 mm/yr. At the seven sites where both ^{3}H methods were applied, the ratio of the mass-balance to depth-to-peak net infiltration rates was used as a correction factor for the sites where only the mass-balance method was applied. This correction factor ranged from 1.5 to 2.3. Therefore, the reported infiltration rates based on borehole ^{3}H in Table 4 for the four sites without TDTP rates (2, 12, 27, 38) are the TMB method rates of Table 3 multiplied by an average correction factor of 2.0. The use of this correction factor assumes that the TDTP method is more accurate than the TMB method, which requires an estimate of historical ^{3}H precipitation concentrations and may underestimate net infiltration because of runoff.

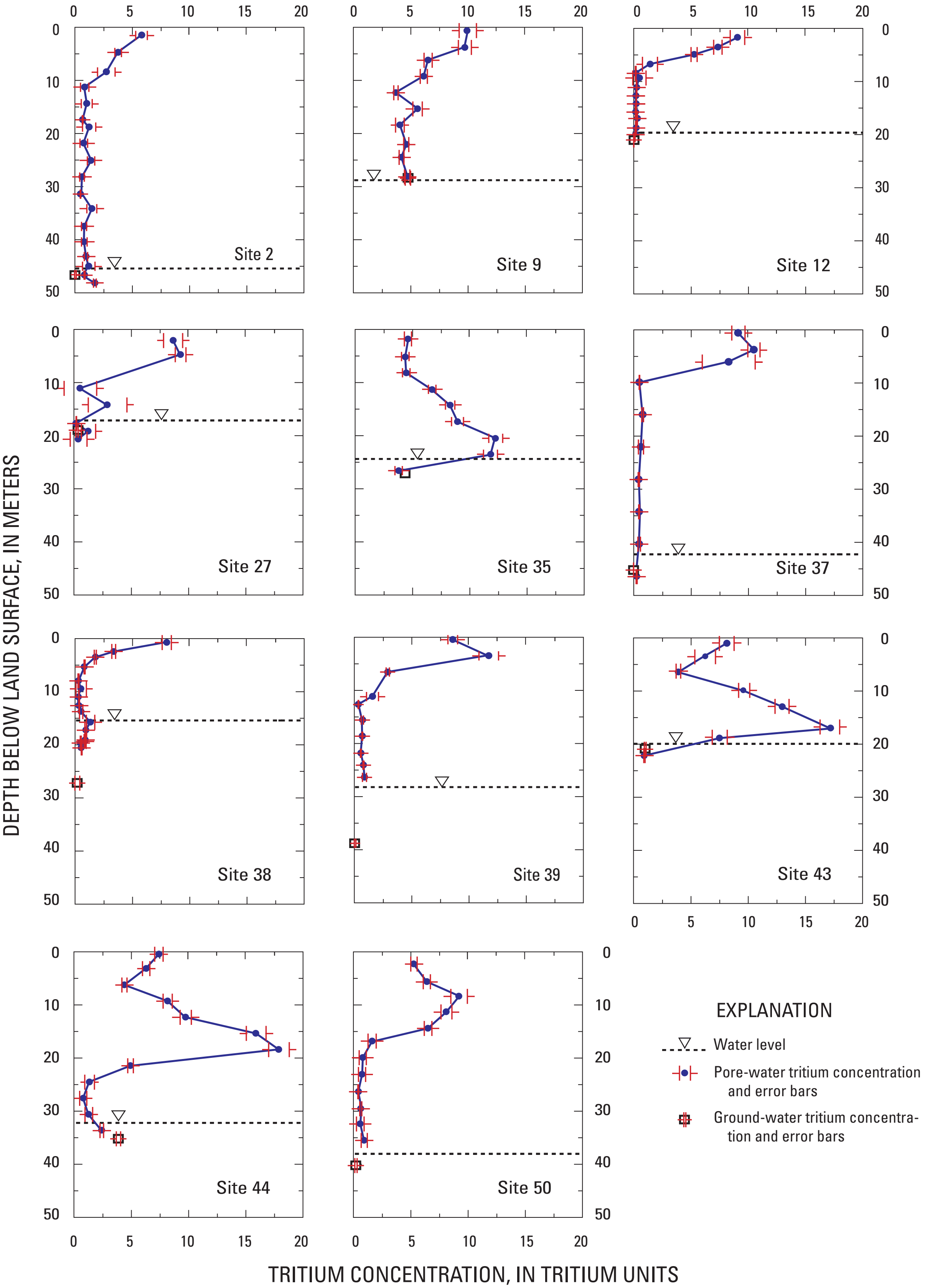


Figure 12. Tritium concentration of pore-water and ground-water samples collected from selected boreholes at the Sand Hollow ground-water-recharge study area, Utah.

The highest TDTP net infiltration rates were determined to be beneath exposed bedrock sites 9, 35, 43, and 44. Sites 9 and 44 are located in ephemeral washes or rivulets that receive surface-water runoff from nearby exposed sandstone during storms. Site 43 is located on nearly flat lying exposed sandstone away from the ephemeral wash channel, thus not receiving as much surface-water runoff. Site 35 is located on coarser-grained sand dune deposits. Because the 1960s ^{3}H peak has already been flushed out of the 29-m-thick vadose zone at site 9, a minimum TDTP net infiltration rate of 57 mm/yr is estimated from equation 6 with the mean water content of 7.9 percent. Sites 35, 43 and 44 have ^{3}H peaks at depths between 17 and 20 m (fig. 12) and water contents above the ^{3}H peaks of 5.9 to 7.0 percent, resulting in calculated TDTP net infiltration rates of 26 through 34 mm/yr. It is assumed that steeply dipping areas of exposed sandstone away from ephemeral wash channels in Sand Hollow would have net infiltration rates of less than about 25 mm/yr because of the potential for higher runoff than at site 43. Unfortunately, this could not be confirmed because of inaccessibility to drilling. TDTP net infiltration rates are lower at sites 35, 37, 39, and 50, which are covered by unconsolidated finer-grained soils. ^{3}H peaks at these sites are determined to be at depths of about 3 to 20 m and water contents ranged from 2.7 to 4.9 percent, resulting in net infiltration rates from 2.6 to 26 mm/yr. The other four sites without discernable ^{3}H peaks all have loamy very fine sand or fine sandy loam soil cover and low uncorrected TMB net infiltration rates, ranging from 1.2 to 2.1 mm/yr.

Tritium in Ground Water

The ^{3}H concentration of ground water within Sand Hollow ranged from below detection (0.01) to almost 7 TU (table 5; fig. 13). Higher concentrations of ^{3}H indicate areas where substantial amounts of recent precipitation have reached the water table. Because of its 12.3-year half-life, ground water originating as precipitation at Sand Hollow more than 50 years ago would likely have a ^{3}H concentration of less than 0.5 TU. Therefore, shallow ground-water ^{3}H concentrations greater than 0.5 TU indicate areas where active recharge has recently occurred either at or upgradient of the borehole. All of the wells that contain water with ^{3}H concentrations of more than 0.5 TU are screened within 10 m of the water table. A correlation of lower ground-water Cl concentration with higher ground-water ^{3}H concentration (fig. 14) indicates that areas of the aquifer receiving active recharge correspond to areas where infiltrating precipitation undergoes less solute enrichment in the root zone by evaporation and transpiration.

Stable Isotopes

Stable Isotopes in Precipitation

Stable-isotope ratios of precipitation at Sand Hollow range from +4.2 to –126.4 per mil for δ^2H and from +3.3 to –15.5 per mil for δ^{18}O (table 1). A local meteoric water line (LMWL) was constructed by linear curve-fitting to the stable-isotope ratios of precipitation samples collected at Sand Hollow between 1999 and 2002 (fig. 15; table 1). The equation for this LMWL is:

$$\delta^2H = 7.61\,\delta^{18}O - 0.03\,, \qquad (3)$$

This LMWL has a shallower slope and a smaller y-intercept than the global meteoric water line, which has a slope of 8 and a y-intercept of 10 (Craig, 1961). The slope and intercept of the LMWL is similar to other published precipitation-isotope data from other arid locations in the southwestern United States (Welch and Preissler, 1986).

Stable Isotopes in the Vadose Zone

Vadose-zone pore-water stable-isotope ratios range from –46 to –113 per mil for δ^2H and from +0.5 to –14.0 per mil for δ^{18}O (Heilweil, 2003). Although this range of values is smaller than the range in precipitation values, the vertical borehole profiles generally show much variability in the shallower part of the vadose zone, varying less and converging to the ground-water value at or near the water table (fig. 16). This indicates that little pore-water mixing occurs in the vadose zone.

Pore-water samples from high-recharge sites (9, 43, 44, 50) have a mean δ^2H concentration of –88 per mil, whereas pore waters from low-recharge sites (2, 4, 12, 27, 37, 38, 46) have a mean δ^2H concentration of –75 per mil and follow an evaporative trend below the LMWL (fig. 15). This evaporative shift was quantified by calculating the expected δ^{18}O concentration with the measured δ^2H concentration and the LMWL given in equation 3. The evaporative shift calculated for each site is the average value from land surface to the water table (table 4). The smallest shift of 2.1 per mil at the highest recharge site and the largest shift of 4.7 per mil at the lowest recharge site support the hypothesis that less evaporative loss occurs where infiltration can quickly move beneath the root zone in the more active recharge areas of the basin.

Stable Isotopes in Ground Water

Ratios of stable isotopes in ground water at Sand Hollow range from –79 to –94 per mil for δ^2H (mean of –86 per mil) and –9.7 to –11.9 per mil for δ^{18}O (mean of –11.1 per mil; table 5). These ratios are within a much narrower range than in precipitation and vadose-zone pore waters. These values also plot closer to the local meteoric water line, showing less evaporative effects than the vadose-zone pore waters (fig. 15).

Table 5. Isotope and chloride concentrations of ground-water samples collected at the Sand Hollow ground-water-recharge study area, Utah.

[Site numbers refer to figure 5. Abbreviations: δ^{2}H, deuterium; δ^{18}O, 18-oxygen; ^{3}H, tritium; TU, tritium units; mg/L, milligrams per liter; ±, plus or minus; —, no data available]

Site number	Well name	Date sampled	δ^{2}H, in per mil	δ^{18}O, in per mil	^{3}H, in TU	Chloride, in mg/L
1a	Well 1 (Wayne Wilson)	1/4/2000	–83	–11.5	0.03 ± 0.05	18.6
2	WD 12	[1] 4/30/1999	–85	–11.3	0.53 ± 0.38	22.0
2	WD 12	[1,2] 4/30/1999	–83	–11.0	—	—
2	WD 12	[1,2] 4/30/1999	–86	—	—	—
2	WD 12	9/12/2002	–85	–10.8	0.02 ± 0.06	20.0
3a	Well 2 (east side of reservoir) at 75 m	10/9/2002	–89	–11.7	0.33 ± 0.02	17.3
3b	Well 2 (east side of reservoir) at 122 m	10/10/2002	–89	–11.5	0.55 ± 0.20	17.8
3c	Well 2 (east side of reservoir) at 152 m	10/10/2002	–92	–11.7	—	—
3d	Well 2 (east side of reservoir) at 187 m	10/10/2002	–92	–11.8	0.02 ± 0.02	13.2
3e	Well 2 (east side of reservoir) at 229 m	10/10/2002	–94	–11.9	0.22 ± 0.06	14.3
5	WD 10	[1] 6/12/2001	–85	–11.0	0.45 ± 0.25	25.0
5	WD 10	[1,2] 6/12/2001	–84	–11.1	—	—
5	WD 10	9/13/2001	–85	–11.2	0.73 ± 0.35	25.6
6	Well 4 (Sky Ranch 2)	3/30/1999	–84	–11.6	0.52 ± 0.36	20.4
6	Well 4 (Sky Ranch 2)	8/29/2001	–85	–11.1	0.26 ± 0.21	44.4
6	Well 4 (Sky Ranch 2)	9/11/2002	–86	–11.0	—	42.0
7	Dale Wilson	4/28/1999	–84	–10.2	0.40 ± 0.26	39.0
7	Dale Wilson	[2] 4/28/1999	–83	—	—	—
8	WD 4	4/2/1999	–86	–11.0	0.22 ± 0.10	18.1
8	WD 4	2002/12/18	-85	–10.8	—	18.8
9	WD 6	2001/05/15	[3]–82	[3]–10.7	[3] 4.77 ± 0.24	[3] 7
9	WD 6	2001/08/28	–79	–10.5	6.88 ± 0.34	2.9
11	WD 2	1999/04/02	–90	–11.3	0.38 ± 0.45	30.0
12	IFP 1	[1] 4/20/1999	–86	–11.0	0.00 ± 0.66	19.9
12	IFP 1	[1,2] 4/20/1999	–82	–11.1	—	—
12	IFP 1	[1,2] 4/20/1999	–84	—	—	—
13	IFP 1 (port 1)	5/18/2002	—	—	0.12 ± 0.05	—
16	IFP 1 (port 4)	5/18/2002	—	—	0.03 ± 0.03	—
17	IFP 1 (port 5)	5/17/2002	—	—	0.00 ± 0.01	—
18	IFP 5 shallow	5/17/2002	–87	–10.5	0.08 ± 0.08	—
18	IFP 5 shallow	[2] 5/17/2000	–84	–10.7	—	—
18	IFP 5 shallow	[2] 5/17/2000	–85	–10.7	—	—
19	IFP 5 medium	5/17/2002	–85	–11.0	0.18 ± 0.14	—
20	IFP 5 deep	5/17/2002	–86	–11.0	0.08 ± 0.05	[4] 21.1
26	IFP 2	4/21/1999	–84	–11.6	—	21.3
26	IFP 2	[2] 4/21/1999	–85	—	—	—
27	Wash 1	4/20/1999	–86	–11.2	0.27 ± 0.10	28.1
27	Wash 1	[2] 4/20/1999	–85	—	—	—
29	Well 9 (east side of north dam)	8/30/1999	–86	–11.4	0.10 ± 0.04	13.0
31	WD 1	4/2/1999	–83	–10.6	0.37 ± 0.50	11.6
31	WD 1	[2] 4/2/1999	–84	—	—	—
31	WD 1	9/10/2002	–85	–10.9	—	—
32	WD RJ	4/2/1999	–83	–10.7	0.02 ± 0.05	46.0
32	WD RJ	12/17/2002	–84	–10.3	—	47.8
33	WD 5	4/3/1999	–85	–11.2	0.19 ± 0.06	43.5
33	WD 5	12/17/2002	–85	–10.6	—	44.8
34	WD 3	12/19/2000	–89	–10.6	0.28 ± 0.20	28.2
35	Hole N	5/25/2001	–82	–10.6	4.27 ± 0.21	6.6
36	WD 11	[1] 6/14/2001	–85	–9.7	1.19 ± 0.77	14.0
36	WD 11	9/14/2001	–86	–10.8	0.53 ± 0.08	22.5
37	WD 9	[1] 5/23/2001	–88	–11.5	0.00 ± 0.01	22.0
37	WD 9	9/14/2001	–86	–11.4	0.20 ± 0.15	17.9
37	WD 9	9/11/2002	–89	–11.5	—	21.4
38	Basin 1	[1] 7/22/1999	–88	–10.9	0.07 ± 0.21	58.3
38	Basin 1	9/10/2001	–84	–10.7	0.18 ± 0.21	64.0
39	Slope 1a	[1] 4/28/1999	–85	—	—	12.1
39	Slope 1a	7/20/1999	–85	–11.1	0.39 ± 0.18	—
39	Slope 1a	[2] 7/20/1999	–87	–11.1	—	—
39	Slope 1a	9/12/2001	–83	–11.4	0.44 ± 0.36	11.7
39	Slope 1a	9/9/2002	–86	–11.4	0.07 ± 0.06	10.1
42	Terracor 3	4/23/1999	–82	–10.9	0.53 ± 0.09	26.9
42	Terracor 3	[2] 4/23/1999	–82	—	—	—
42	Terracor 3	9/11/2001	–85	–11.0	0.28 ± 0.08	28.7
43	Hole O	[1] 6/11/2001	–84	–10.1	1.03 ± 0.07	21.0
43	Hole O	9/11/2001	–85	–10.3	1.09 ± 0.20	11.9
44	WD 8	[1] 5/21/2001	–81	–10.6	4.13 ± 0.38	9.2
44	WD 8	[1,2] 5/21/2001	–81	–10.6	—	—
44	WD 8	9/12/2001	–86	–10.9	2.98 ± 0.15	10.8
44	WD 8	9/9/2002	–85	–10.9	3.89 ± 0.19	10.1
46	Basin 2	[1] 5/5/1999	–87	—	—	—
46	Basin 2	7/21/1999	–86	–11.6	0.23 ± 0.35	11.8
46	Basin 2	[2] 7/21/1999	–86	–11.7	—	—
46	Basin 2	8/27/2001	–88	–11.1	0.18 ± 0.06	9.9
47	WD 13 (corral)	1/5/2000	–86	–11.6	0.43 ± 0.36	—
47	WD 13 (corral)	8/30/2001	–86	–11.4	0.29 ± 0.15	12.1
48	Well 17 (west dam)	5/18/2000	–87	–11.2	—	28.2
49	WD 14 (Terracor 2)	12/18/2002	–88	–11.4	0.32 ± 0.04	28.3
50	WD 7	9/10/2001	–85	–10.6	0.21 ± 0.09	18.0

[1] Collected prior to well installation.

[2] Replicate sample.

[3] Value affected by drilling and not considered representative.

[4] Collected on 11/29/2000.

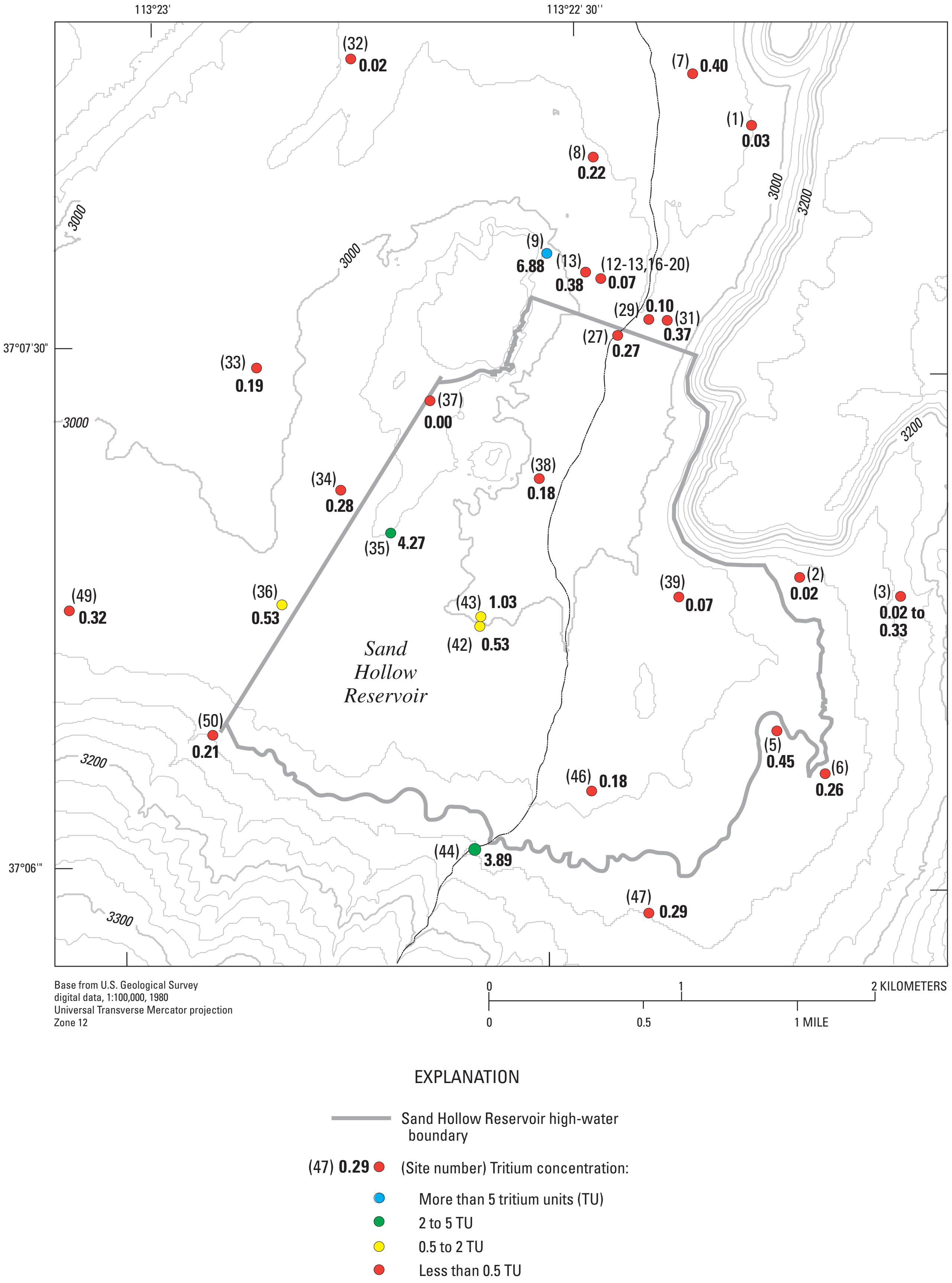


Figure 13. Tritium concentration in water from selected wells at the Sand Hollow ground-water-recharge study area, Utah.

Spatial and Temporal Variations in Recharge

Multiple environmental tracers were used at Sand Hollow in order to compare/contrast various independent lines of evidence regarding net infiltration and recharge rates. The combination of multiple tracer methods provides a higher level of confidence than any one method by itself. In addition, the individual methods can be used to investigate particular spatial and temporal patterns. Although both vadose-zone ^{3}H and Cl provide site-specific net infiltration estimates, ^{3}H targets modern (post 1950s) net infiltration whereas Cl provides a longer term record (up to about 12,000 years). Ground-water Cl yields more regionally averaged recharge estimates than vadose-zone methods because of horizontal hydraulic gradients and mixing in the well screen. Stable isotopes (δ^2H and δ^{18}O), although not providing direct recharge rates, are useful for evaluating spatial and temporal differences in infiltration and recharge processes.

Spatial Variation in Recharge

Recharge within Sand Hollow is highly variable. Large differences likely are caused by local focusing of surface-water runoff, as well as variations in both surficial soil cover and topographic slope. This is illustrated by contrasting vadose-zone ^{3}H-based net infiltration rates at sites 12 (2.8 mm/yr) and 9 (more than 57 mm/yr), located less than 300 m apart. Site 9 is located along a small ephemeral wash with exposed sandstone and some coarse-grained sand deposits at the base of a steep sandstone outcrop that regularly receives surface-water runoff. Conversely, site 12 is located away from any potential pathway of surface-water runoff and is covered by relatively fine-grained soil (loamy fine sand, table 4). In general, relatively high net infiltration and recharge rates were observed at sites with focused surface-water runoff, coarse-grained soils, or shallowly sloping exposed bedrock. Low net infiltration and recharge rates were observed at sites with no surface-water runoff and fine-grained soils.

An initial hypothesis of infiltration and recharge at Sand Hollow, based on other vadose-zone bedrock studies, was that water would move preferentially along sandstone fractures to the water table. However, there is no correlation between higher net-infiltration rates, based on vadose-zone ^{3}H, and fracture density (fig. 17). To the contrary, rates are higher at borehole sites with less fracturing. This finding is supported by a recent modeling study of vadose-zone fracture flow (Ludwig, 2003), which determined that an open sandstone fracture with an aperture of 1 mm (typical of those measured in trenches in Sand Hollow) would not saturate and become preferential flow conduits, even during periods of intense precipitation. Rather, the numerical simulations showed that [1] surface infiltration through fractures is quickly imbibed by the highly porous sandstone; and [2] the larger pore-throat diameters of fractures act as capillary barriers to flow, especially in arid settings.

Although recharge rates at individual sites vary depending on the particular environmental-tracer method, the various environmental tracers used in this study generally show similar trends. Higher recharge rates are generally correlated with smaller vadose-zone δ^{18}O shifts, smaller vadose-zone Cl accumulation, higher shallow ground-water ^{3}H concentrations, and less depleted δ^2H values (table 4).

Net infiltration and recharge rates based on all three Cl mass-balance methods generally were well correlated, although the vadose-zone Cl rates were generally lower than the ground-water Cl rates. Two exceptions to this were sites 39 and 46, which had much higher ground-water Cl rates (15 mm/yr) than those based on vadose-zone Cl within the bulge (0.05 to 0.1 mm/yr), vadose-zone Cl beneath the bulge (4 mm/yr and 3 mm/yr, respectively), and vadose-zone tritium (2.6

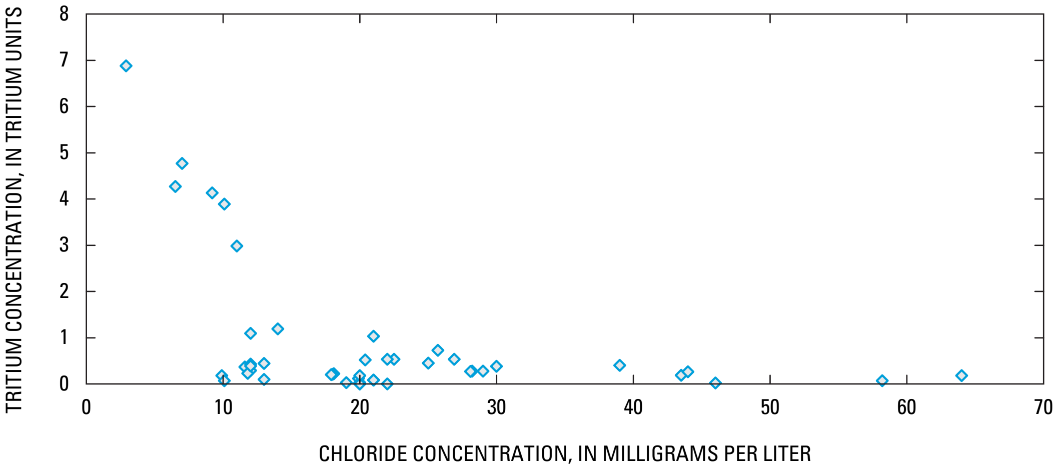


Figure 14. Relation of tritium concentration to chloride concentration in water from selected wells at the Sand Hollow ground-water-recharge study area, Utah.

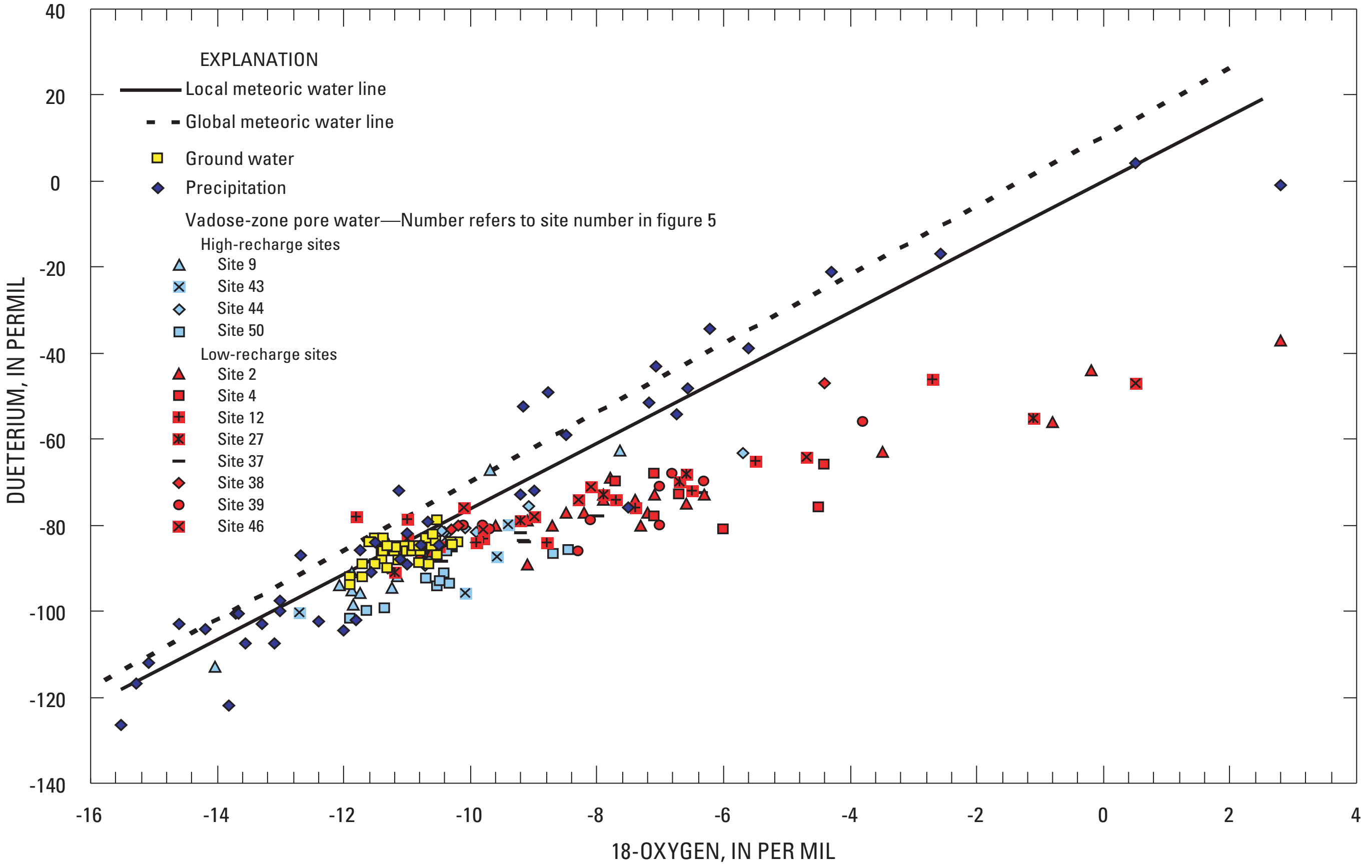


Figure 15. Relation between the stable-isotope ratios of hydrogen and oxygen in vadose-zone pore water, water samples from selected wells, and precipitation at the Sand Hollow ground-water-recharge study area, Utah.

mm/yr at site 39). Vadose-zone water potential measurements at four depths at site 39 were consistent with these low vadose zone environmental tracer-based recharge rates, showing no substantial infiltration events between January 2000 and September 2002 (fig. 18). At both sites, pore-water Cl concentrations decrease dramatically when crossing from the deep vadose zone into the underlying water table (Heilweil, 2003). These anomalies may be caused by upgradient areas having higher recharge rates than the vadose zones at each of these two sites. An upgradient high-recharge area would result in ground-water mounding and a large horizontal component of flow beneath the water table at the downgradient site. Therefore, the low Cl concentration of shallow ground water at these two sites likely represents upgradient recharge conditions, whereas the higher Cl concentration of the deep vadose-zone represents in-situ recharge conditions.

Stable-isotope ratios were also used for evaluating spatial variability of recharge in Sand Hollow. Assuming average δ^2H values of –75 per mil for the low-recharge site vadose-zone pore waters, –88 per mil for the high-recharge site vadose-zone pore waters, and –86 per mil for ground water, a two-end-member mixing model indicates that about 85 percent of ground-water recharge in Sand Hollow occurs at high-recharge sites.

Temporal Variations in Recharge

The vadose zone at Sand Hollow is an archive of past climate. Vadose-zone Cl bulges characteristic of those occurring in unconsolidated desert soils were observed in many of the boreholes, an unusual finding for bedrock. This Cl has been accumulating in the vadose zone of Sand Hollow for as much as 12,000 years (since the early Holocene; table 2), whereas ^{3}H has only been accumulating for the past 50 years. Thus, the two tracers can be used for looking at net infiltration during different time intervals.

For the group of 11 sites having vadose-zone tritium information, vadose-zone ^{3}H-based infiltration rates are always higher (2.4 to more than 57 mm/yr; geometric mean of 9 mm/yr) than infiltration rates calculated by using shallow vadose-zone Cl within the bulge (0.08 to 8 mm/yr; mean of 2.1 mm/yr; table 4). Since the total mass of Cl within the bulge represents from 50 to 12,000 years of accumulation, this implies that infiltration rates during the past few decades were generally higher than during previous centuries to millennia. Such recently higher net infiltration may have flushed down Cl that previously accumulated in the shallow root zone, a possible reason why the average depth

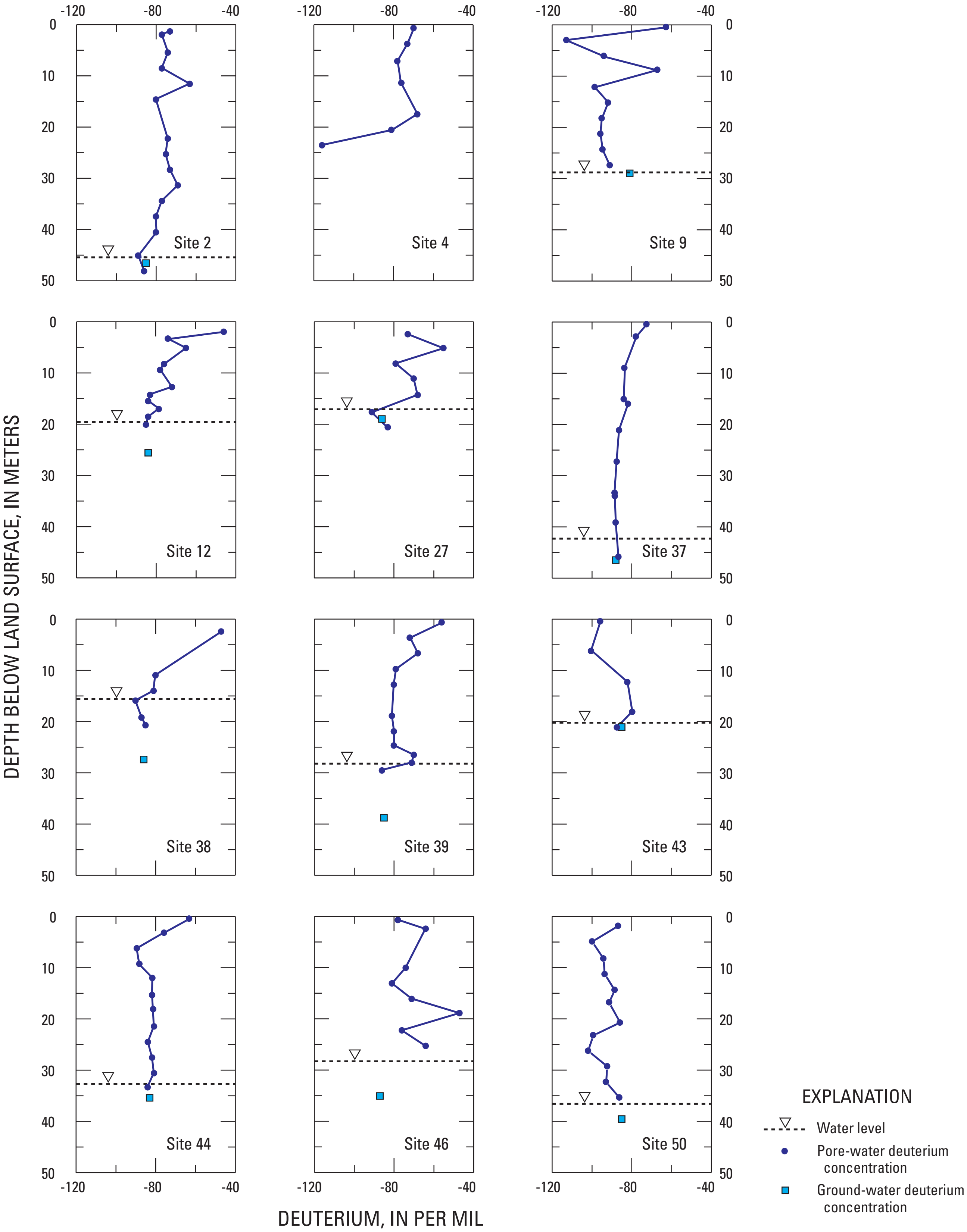


Figure 16. Stable-isotope ratio of hydrogen in pore-water and ground-water samples collected from selected boreholes at the Sand Hollow ground-water-recharge study area, Utah.

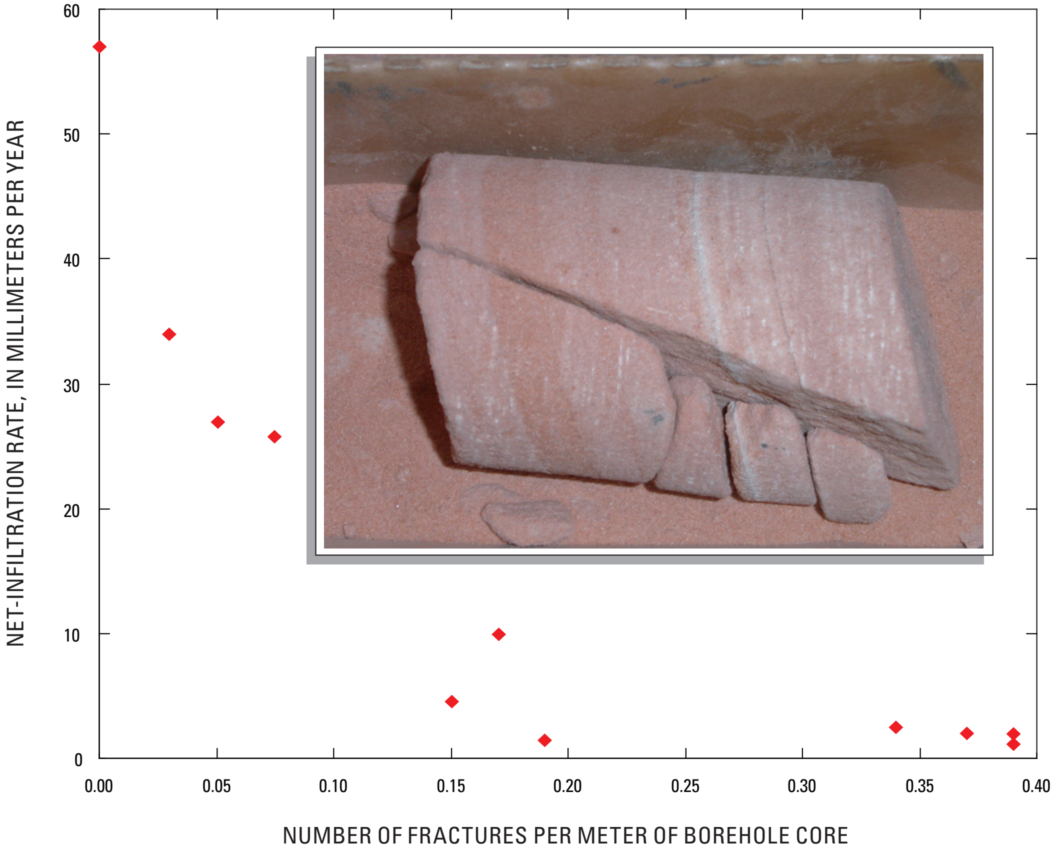


Figure 17. Relation of net infiltration rate, based on vadose-zone tritium concentration, to fracture density obtained from core samples at the Sand Hollow ground-water-recharge study area, Utah.

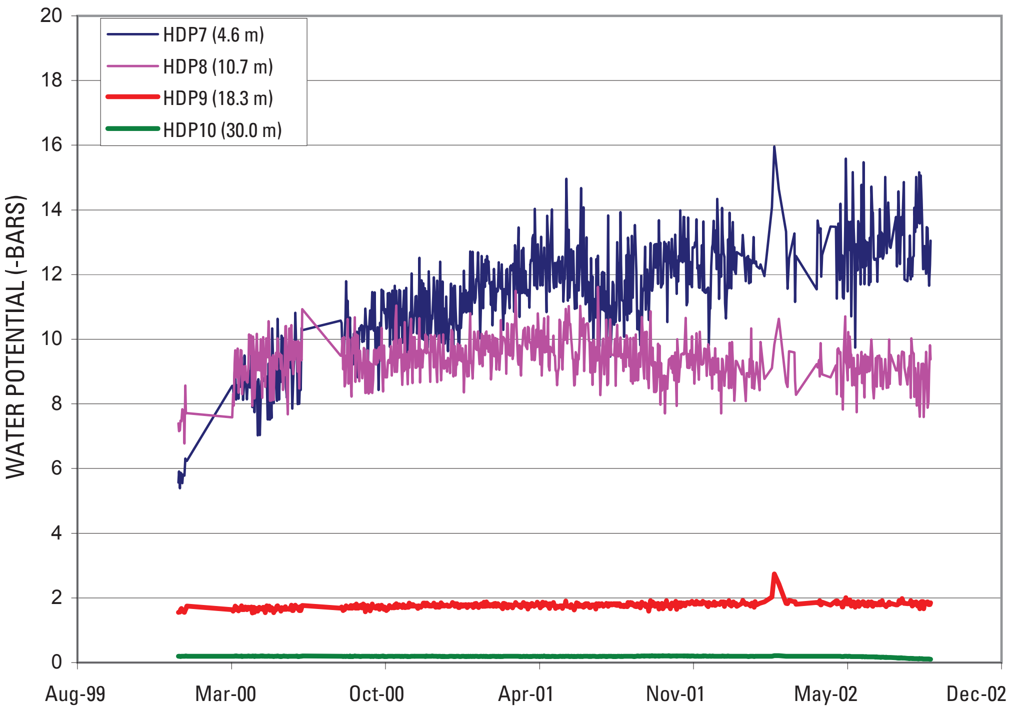


Figure 18. Vadose-zone water potential measured with heat dissipation probes at various depths below land surface at site 39, Sand Hollow ground-water-recharge study area, Utah.

of 5 m to the Cl bulge peaks at the borehole sites is much greater than the maximum soil thickness and root zone depth of about 1.5 m.

Comparison of ^{3}H-based net infiltration rates to deeper vadose-zone Cl-based net infiltration rates beneath the bulge is not as straightforward. For the group of high-recharge sites (9, 35, 43, 44, 50), vadose-zone ^{3}H-based infiltration rates are higher (9 to more than 57 mm/yr) than vadose-zone Cl-based rates from beneath the bulge (3 to 13 mm/yr; table 4). These sites contain up to about 800 years of total vadose-zone Cl accumulation and this deeper Cl represents 50 to 80 percent of this accumulation, indicating that infiltration rates in high-recharge settings during recent decades was higher than during previous centuries. However, for the group of low-recharge sites (2, 12, 27, 37, 38, 39), vadose-zone ^{3}H-based infiltration rates (2.4 to 4.6 mm/yr) are similar to vadose-zone Cl-based rates from beneath the bulge (2 to 5 mm/yr). The total amount of Cl beneath the bulge at these low-recharge sites represents only a small fraction of the total vadose-zone Cl accumulation (0 to 40 percent), but represents the oldest preserved vadose-zone information regarding infiltration and indicates that rates earlier in the Holocene were similar to the higher rates of recent decades.

Eight of the 12 borehole sites drilled to the water table have shallow ground-water ^{3}H concentrations of less than 0.5 TU, indicating recharge that occurred more than 50 years ago. Modern ^{14}C ages indicate that these ground waters are of Holocene age (Heilweil, 2003). Recharge rates based on ground-water Cl concentrations at these 8 boreholes range from 3 to 15 mm/yr, much higher than the 0.05 to 0.7 mm/yr vadose-zone Cl bulge recharge rates or the 2 to 5 mm/yr Cl-based net infiltration rates below the bulge (table 4). Higher ground-water Cl-based recharge rates may be caused by higher recharge in upgradient areas. However, another possibility is that the ground-water Cl-based recharge rates indicate a wetter climatic period earlier in the Holocene than recharge rates represented by both the shallow and deep vadose-zone Cl. If so, this implies that a full swing in climatic cycle has occurred, with higher recharge rates earlier in Holocene changing to lower rates in the later Holocene, returning again to higher rates during the past 50 years. This is consistent with Holocene variations in recharge to the Navajo Sandstone observed at Black Mesa, Ariz. (Zhu, 2000) and is supported by the meteorological record, which shows an anomalously large number of 30-day periods between 1957 and 1997 with over 100 mm of precipitation at St. George.

Recent changes in infiltration rates resulting from changing soil cover or land use may have occurred at sites 27 and 38, resulting in vadose-zone environmental tracer concentrations that are not in equilibrium with current net infiltration conditions. Unlike the other 11 boreholes in table 2, these sites are located in or near the main ephemeral wash of Sand Hollow and do not fit the trend of increasing peak concentration of the shallow Cl bulge with increasing total vadose-zone Cl accumulation. Considering the total accumulation of Cl in the vadose zone, the peak Cl concentration of 1,900 mg/L at site 27 is lower than expected. Although this site is presently situated in the ephemeral wash, solute distributions in nearby trench excavations indicate that the wash had recently migrated from a location farther to the east (Heilweil and Solomon, 2004). The lower-than-expected peak concentration of the shallow Cl bulge at this site is consistent with a recent shift to higher net infiltration beneath the active wash channel, which would push downward and dilute a preexisting shallow Cl bulge. The high cumulative vadose-zone Cl at the site indicates that the previously accumulated Cl has not yet been flushed out of the vadose zone.

The very shallow (1.8 m depth) and higher-than-expected peak Cl concentration of 14,700 mg/L (table 2) at site 38 may indicate a recent change to lower net infiltration rates and increased runon of Cl. This site is located adjacent to a section of the ephemeral wash that was impounded by a small levee built by cattle ranchers about 50 years ago (L. Jessup, Washington County Water Conservancy District, oral commun., 2001) and is now covered with about 0.5 m of fine-grained silts that have settled out of surface-water runoff. Prior to the existence of the levee, the site was likely a higher recharge site on the natural wash channel. This would explain the low Cl concentrations measured below a 3-m depth, the poor correlation between total Cl accumulation and peak Cl concentration, the low vadose-zone ^{3}H-based net infiltration rate, and a small average vadose-zone δ^{18}O evaporative (2.2 per mil) similar to the highest recharge sites (table 4). The very high Cl concentration in the shallow subsurface likely represents a combination of salt accumulation from runon and evaporative enrichment associated with decreased infiltration through the shallow, low-permeability silts at the site.

The uniformity of ground-water stable-isotope ratios at the more negative end of the range of precipitation values indicates that most of the net infiltration reaching the water table comes from cooler-season precipitation. The more depleted δ^2H values (–84 to –88 per mil) of ground water having ages between about 50 years and a few thousand years (based on ^{3}H concentrations less than 0.5 TU and modern apparent ^{14}C ages) from the low-recharge sites compared to less depleted δ^2H values (–79 to –85 per mil) of ground water at high-recharge sites (table 4) may indicate that the source of this older shallow ground water was cooler-temperature recharge. One scenario hypothesis for this is a higher percentage of winter precipitation prior to the 1950s, indicating less summer monsoonal precipitation relative to winter Pacific storms than at present.

Conclusions

The combination of multiple vadose-zone and ground-water environmental tracer techniques is used to evaluate various aspects of infiltration and recharge at Sand Hollow, including basin-average rates, site-specific (spatial) processes, and seasonal to millennial temporal variations. Spatial variations in infiltration and recharge rates show that most recharge occurs in areas with coarse soils or exposed bedrock that receive focused runoff. However, substantial amounts of direct infiltration and recharge also occur beneath coarse-grained sandy soils away from washes. This is contrary to findings generally reported from alluvial desert basins receiving similar amounts of precipitation, where little or no basin-floor recharge away from washes is generally thought to occur. This indicates that more moisture is able to pass beyond the maximum rooting depth and become net infiltration where permeable bedrock formations are exposed or shallowly buried. Bedrock prevents substantial root penetration and plant transpiration. Also, lower ground-water Cl concentrations are clearly correlated with higher ground-water ^{3}H concentrations, indicating that areas of the aquifer receiving active recharge correspond to areas where infiltrating precipitation is able to bypass the concentration of solutes in the shallow root zone.

Tritium and chloride were also used to explore temporal variations in infiltration and recharge. Vadose-zone Cl concentrations at some borehole locations represent up to 12,000 years of accumulation, whereas vadose-zone ^{3}H has only been accumulating during the past 50 years. Net-infiltration rates at individual borehole sites range from 2.4 to at least 57 mm/yr calculated from vadose-zone ^{3}H concentrations, 0.03 to 8 mm/yr from vadose-zone Cl concentrations within the Cl bulge, 0.5 to 13 mm/yr from vadose-zone Cl concentrations beneath the Cl bulge, and 3 to 60 mm/yr from ground-water Cl concentrations. Because of the different time periods represented by these environmental tracers, it is inferred that recharge rates at Sand Hollow have changed from higher rates during the early Holocene to lower rates during the past few centuries/millenia, back to higher rates during the latter part of the 20th century, illustrating the cyclical nature of desert bedrock recharge.

Ground-water tracer concentrations provide a more spatially averaged recharge flux than vadose-zone tracers. The basin-wide average recharge rate calculated from the ground-water Cl mass-balance method is about 8 mm/yr, or about 4 percent of precipitation. Ground-water stable-isotope ratios are generally more depleted (isotopically lighter) than the seasonally weighted mean value of local precipitation samples, indicating that net infiltration and recharge occurs predominantly during the cooler winter months. The seasonally weighted mean value of δ^2H in precipitation is -79 per mil, compared to the -86 per mil mean of shallow ground water. A two-end-member mixing model of stable-isotope ratios from vadose-zone pore waters indicates that about 85 percent of recharge occurs in high-infiltration areas of Sand Hollow. Similarly, calculated δ^{18}O evaporative shifts of pore waters from low-infiltration sites are larger than from the high-infiltration sites. Stable isotopes in ground water show that most infiltration occurs during cooler months and that a larger percent of cooler-season recharge occurred prior to the 1950s than during recent decades.

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Chapter I Appendix—Determination of Mean and Variance of Ground-Water Recharge

For a function Y composed of n statistically independent variables:

$$Y = f(X_{1,} X_2, ..., X_n), \tag{I–1}$$

the first order approximation of the mean, $\overline{Y}$, and variance, Var (Y) can be defined, respectively, as

$$\overline{Y} \approx f\ (\overline{X}_{1.}\ \overline{X}_2, ..., \overline{X}_n)\text{, and} \tag{I–2}$$

$$Var(Y) = \left[\frac{\partial Y}{\partial X_1}\right]^2 Var(X_1) + \left[\frac{\partial Y}{\partial X_2}\right]^2 Var(X_2) + ... + \left[\frac{\partial Y}{\partial X_n}\right]^2 Var(X_n), \tag{I–3}$$

where the partial derivatives are evaluated at the mean value of the respective parameter (Ang and Tang, 1975).

Therefore, the variance in the net infiltration or recharge rate, q, is defined as

$$Var(q) = \left[\frac{\partial q}{\partial [Cl_{dep}]}\right]^2 Var[Cl_{dep}] + \left[\frac{\partial q}{\partial [Cl_{gw}]}\right]^2 Var[Cl_{gw}] + \left[\frac{\partial q}{\partial P}\right]^2 Var[P]. \tag{I–4}$$