Prepared in Cooperation with Utah Department of Natural Resources, Bureau of Land Management, and Central Iron County Water Conservancy District

Hydrogeologic and Geochemical Characterization of Groundwater Resources in Pine and Wah Wah Valleys, Iron, Beaver, and Millard Counties, Utah

Scientific Investigations Report 2019–5139

U.S. Department of the Interior
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Cover: Looking east across Pine Valley to the Wah Wah Mountains from near Willow Spring. Photograph by Philip Gardner, September 2013

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The authors gratefully acknowledge Hugh Hurlow and Stefan Kirby of the Utah Geological Survey for providing geochemical data for two wells and five springs in Pine and Wah Wah Valleys. These data account for nearly one-third of the sample sites discussed in this report and add great value to the geochemical dataset.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
Flow rate		
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
Specific capacity		
gallon per minute per foot ([gal/min]/ft)	0.2070	liter per second per meter ([L/s]/m)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)
Transmissivity		
foot squared per day (ft2/d)	0.09290	meter squared per day (m2/d)

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

$$°F = (1.8 \times °C) + 32.$$

Datum

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.

Supplemental Information

Concentrations of chemical constituents in water are reported in milligrams per liter (mg/L), micrograms per liter (µg/L), and in milliequivalents per liter. Milligrams per liter and micrograms per liter are units expressing the concentration of chemical constituents in solution as weight (grams) of solute per unit volume (liter) of water. A liter of water is assumed to weigh 1 kilogram, except for brines or water at high temperatures because of changes in the density of the water. For concentrations less than 7,000 mg/L or 7,000,000 µg/L, the numerical value is the same as for concentrations in parts per million or parts per billion, respectively. Milliequivalents per liter are units expressing concentrations that are chemically equivalent in terms of atomic or molecular weight and electrical charge.

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

Concentrations of dissolved gases are reported in cubic centimeters of gas at standard temperature and pressure per gram of water (ccSTP/g). Tritium concentration is reported in tritium units (TU) where one TU is equivalent to one molecule of tritiated water ($^{3}H^{1}HO$) in 1018 molecules of non-tritiated water ($^{1}H2O$) or 3.2 picocuries per liter. Carbon-14 activity is reported as percent modern carbon (pMC). Stable-isotope ratios are reported as delta (δ) values, which are parts per thousand or permil (‰) difference(s) from a standard.

Abbreviations

^{129}Xe	xenon-129
^{14}C	carbon-14 or radioactive isotope of carbon
^{18}O	oxygen-18
^{20}Ne	neon-20
^{2}H	deuterium
^{3}H	tritium
^{3}He	helium-3
$^{3}He_{trit}$	helium-3 from tritium decay
^{40}Ar	argon-40
^{4}He	helium-4
$^{4}He_{terr}$	terrigenic helium-4 (uranium/thorium-series decay)
^{84}Kr	krypton-84
BARCAS	Basin and Range carbonate-rock aquifer system

BP	before present
CO_2	carbon dioxide
EPA	Environmental Protection Agency
ET	evapotranspiration
ET_a	actual evapotranspiration
ET_g	groundwater evapotranspiration
EVI	Enhanced Vegetation Index
GBCAAS	Great Basin carbonate and alluvial aquifer study
GDA	groundwater discharge area
GIS	Geographic Information System
He	helium
HGU	hydrogeologic unit
H_{max}	maximum recharge altitude
H_r	recharge altitude
ID	identification
LCAU	lower carbonate aquifer unit
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
MCL	maximum contaminant level
MODIS	Moderate Resolution Imaging Spectroradiometer
MSAVI	Modified Soil-Adjusted Vegetation Index
NAIP	National Agriculture Imagery Program
NCCU	non-carbonate confining unit
NDVI	Normalized Difference Vegetation Index
NGT	noble-gas recharge temperature
NGT_{avg}	average noble-gas temperature
NGT_{max}	maximum noble-gas temperature
NGT_{min}	minimum noble-gas recharge temperature
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
R	3He/4He ratio in groundwater
r^2	coefficients of determination
R_a	atmospheric 3He/4He ratio
RASA	Regional Aquifer-System Analysis
RAWS	Remote Automated Weather Stations
TDS	total dissolved solids
TM	Thematic Mapper

UCAU	upper carbonate aquifer unit
USCU	upper siliciclastic confining unit
USGS	U.S. Geological Survey
WRS2	world reference system 2
$\delta^{13}C$	relative measured stable isotope of carbon
$\delta^{18}O$	relative measured stable isotope of oxygen
$\delta^{2}H$ or δD	relative measured stable isotope of hydrogen

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By Philip M. Gardner, Thomas M. Marston, Susan G. Buto, and Lynette E. Brooks

Abstract

Pine and Wah Wah Valleys are neighboring structural basins that encompass about 1,330 square miles in Beaver, Iron, and Millard Counties in Utah, approximately 50 miles northwest of Cedar City, Utah, and 50 miles southeast of Baker, Nevada. Perennial streamflow is limited and only exists in higher-altitude reaches of small mountain streams in both basins. Groundwater is in unconsolidated basin-fill aquifers and bedrock mountain aquifers. Groundwater in Pine and Wah Wah Valleys is being targeted for large-scale groundwater extraction and export to provide municipal supply to the growing population in Iron County, Utah. Concern about declining groundwater levels and spring flows from proposed groundwater withdrawals has increased interest in an improved understanding of the groundwater system. Previous studies have indicated that an average of 28,000 acre-feet per year of recharge occurs mostly as infiltration of precipitation in high-altitude regions in the two basins. Groundwater discharge in the mountain hydrologic systems was estimated to average 8,500 acre-feet per year and is assumed to be consumed before subsequently recharging the valley basin-fill aquifers. Subsurface groundwater outflow moves from basin-fill aquifers in Pine and Wah Wah Valleys northward to adjacent regional basins and was estimated to average 19,500 acre-feet per year.

An updated water-level map for the basin-fill aquifers in Pine and Wah Wah Valleys indicates that groundwater moves northward along the lengths of both valleys toward adjacent basins. Measured depths to water range from about 210 to 750 feet below land surface in Wah Wah Valley, and from about 300 to 620 feet below land surface in Pine Valley. Long-term water levels at seven wells completed in the basin-fill aquifers of Pine and Wah Wah Valleys with records spanning more than 40 years are generally stable with observed fluctuations of less than 5 feet. Observed discharge from two springs monitored between 2013 and 2016 also is generally stable.

Groundwater leaving Pine and Wah Wah Valleys through the subsurface moves northward, converges with regional groundwater flow, and discharges by evapotranspiration at regional groundwater discharge areas, likely Tule Valley, Utah. In this study, basin-scale groundwater discharge was estimated by (1) mapping the groundwater discharge areas in each valley; (2) evaluating the 2005–11 summer multispectral satellite images against the Basin and Range carbonate-rock aquifer system study evapotranspiration measurements to select scenes broadly representative of average conditions in the study area and partitioning the groundwater discharge areas into evapotranspiration units using the selected satellite images and field reconnaissance; and (3) scaling evapotranspiration to the evapotranspiration units using evapotranspiration-rate estimates from several studies in the Great Basin. The resulting updated estimates of average annual groundwater evapotranspiration in the Tule Valley and Sevier Lake groundwater discharge areas were 35,000 and 10,500 acre-feet per year, respectively, with a likely uncertainty of plus or minus 35 percent.

Groundwater samples from 13 sites in Pine Valley and 11 sites in Wah Wah Valley were analyzed for major ions and nutrients, to characterize geochemistry and water quality. Groundwater samples also were analyzed for the stable isotopes of oxygen, hydrogen, and carbon, the radioactive isotopes of carbon and hydrogen, and dissolved noble gases including helium-3, helium-4, neon, argon, krypton, and xenon. Groundwater sampling sites included 12 wells and 12 springs. Carbon-14 and tritium/helium groundwater age dating indicate that groundwater in the basin-fill aquifers is typically thousands to tens of thousands of years older than groundwater in the shallow mountain aquifers. Dissolved-solids concentrations are lower and noble-gas temperatures are warmer in the valley wells compared to almost all groundwater sampled from wells and springs in the surrounding mountains. These results indicate a hydraulic discontinuity between the mountain and valley aquifers throughout much of the study area, and that much of the valley recharge is not derived from direct infiltration of precipitation in the mountains.

Introduction

Pine and Wah Wah Valleys are rural valleys approximately 50 miles (mi) northwest of Cedar City, Utah, and approximately 50 mi southeast of Baker and Great Basin National Park, Nevada. Pine and Wah Wah Valleys are neighboring hydrologic/structural basins that encompass about 1,330 square miles (mi^2) in Beaver, Millard, and Iron Counties, Utah, and are east of Snake and Hamlin Valleys and south of Tule Valley and the Sevier Desert in western Utah (fig. 1). Both basins are bounded by surface-water drainage divides on all sides, but they are not closed groundwater basins. Groundwater resources aside from Wah Wah Springs are largely undeveloped with a limited number of wells completed in the basin-fill aquifer in both valleys. Groundwater levels in the valleys are generally hundreds of feet below land surface and neither basin contains areas in the valley lowlands where groundwater is shallow enough to be discharged by evapotranspiration (ET).

Total recharge for both basins has been estimated to be 28,000 acre-feet per year (acre-ft/yr) occurring as infiltration of precipitation that falls mostly on the mountains surrounding both valleys (Stephens, 1974, 1976). Groundwater discharge in Pine and Wah Wah Valleys occurs almost entirely as discharge to springs, small streams, and as ET in the surrounding mountains. Previous studies have hypothesized that groundwater that does not discharge in the surrounding mountains enters the adjacent basin-fill aquifers near the mountain front in both valleys and is subsequently discharged through the subsurface to other adjacent basins to the north (Stephens, 1974, 1976). Perennial streamflow is limited and only exists in high-altitude reaches of small mountain streams in both basins. Streamflow events that occur in ephemeral valley washes from intense rainfall are short in duration and represent an insignificant source of surface-water.

Recent proposals by the Central Iron County Water Conservancy District (CICWCD) to develop groundwater resources in and around Pine and Wah Wah Valleys have focused attention on the need for a better understanding of the groundwater resources in these valleys. The groundwater resources that sustain streams, springs, small wetlands, and local agricultural uses in these valleys are poorly understood. At the time of this study, minimal groundwater development had occurred in Pine and Wah Wah Valleys and anthropogenic impacts to the groundwater system had been negligible. Water-resource managers from the Utah Department of Natural Resources, CICWCD, and the Bureau of Land Management require additional information and an improved hydrogeologic conceptual model to make informed decisions about future water-resource development in the area.

Purpose and Scope

The purpose of this study was to assess groundwater resources in Pine and Wah Wah Valleys through improving the general understanding of groundwater presence, sources, and movement. Specifically, this study evaluated the hydrologic conditions at the time of this report, including groundwater levels, recharge to the groundwater system, and discharge from springs and evapotranspiration. This information has been combined with other data, including geochemical groundwater tracers, to determine sources of water to groundwater discharge areas, evaluate groundwater flow paths, and assess interbasin (subsurface) flow between adjacent valleys. Results from this study have been utilized to create an updated conceptual model of the groundwater flow system and then integrated into the existing updated Great Basin carbonate and alluvial aquifer study (GBCAAS) numerical groundwater flow model of the area, thus providing improved tools for use in future management decisions (Brooks, 2017a).

Previous Investigations

Initial hydrologic reconnaissance studies of Pine and Wah Wah Valleys were completed by Stephens (1974, 1976) and the results of these studies were incorporated in a hydrologic reconnaissance of the southern Great Salt Lake Desert (Gates and Kruer, 1981). Several more recent and ongoing regional investigations in east-central Nevada and western Utah have helped improve the understanding of groundwater resources in the eastern Great Basin, including Pine and Wah Wah Valleys. A Regional Aquifer-System Analysis (RASA) of the Great Basin was conducted by the U.S. Geological Survey (USGS) in Nevada and Utah, and included Pine and Wah Wah Valleys. This analysis, summarized by Harrill and Prudic (1998) provided a regional base of information including a description of the regional Great Basin aquifer systems (sources and rates of recharge and discharge), estimates of hydraulic properties of the groundwater flow system, and an understanding of the functioning of multi-basin flow.

Pine and Wah Wah Valleys are included within the boundaries of the GBCAAS and the Snake Valley numerical groundwater flow models (Brooks and others, 2014; Masbruch and others, 2014). Sensitivity analyses indicated that calibration of both numerical models is highly sensitive to recharge rates and aquifer hydraulic properties in and directly north of Pine and Wah Wah Valleys. Variations in these model parameters have substantial impacts on model-simulated water levels and discharge rates in surrounding valleys, illustrating the importance of refining these estimates. This is the same geographic area that Stephens (1974) was referring to when he stated that "the paucity of data on both subsurface lithology and water levels [in the areas north of Pine and Wah Wah Valleys] precludes a reliable estimate of volume or direction of groundwater flow."

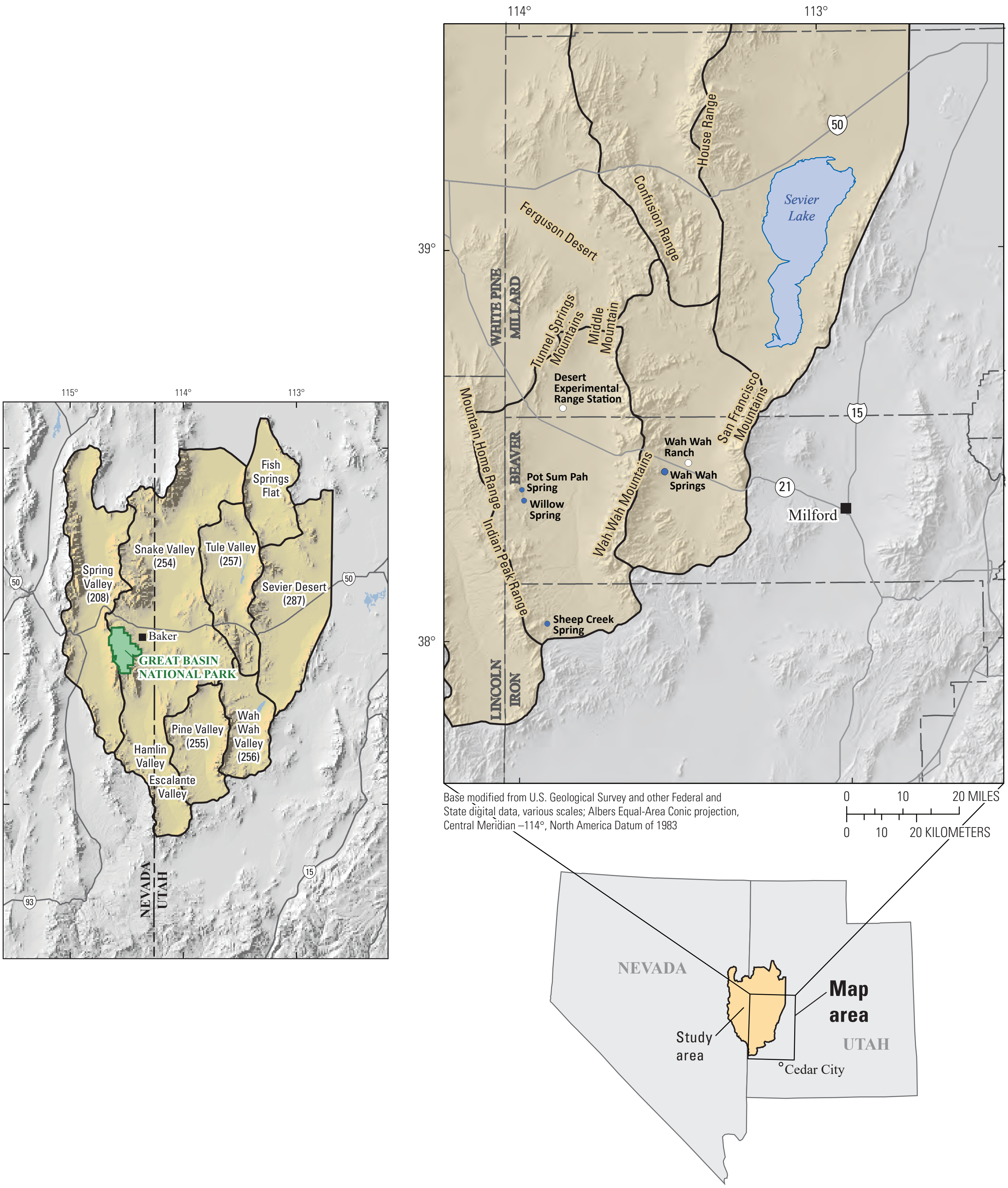


Figure 1. Location of Pine and Wah Wah Valleys, Iron, Beaver, and Millard Counties, Utah.

Results from initial investigations by Stephens (1974, 1976) indicated that a total of about 28,000 acre-ft/yr of water recharges Pine and Wah Wah Valleys in the form of infiltrating precipitation. The recharge estimates were made using a modified version of the Maxey-Eakin method described by Hood and Waddell (1968). Stephens reported that about 7,000 acre-ft/yr and 1,500 acre-ft/yr of groundwater is discharged in the Pine and Wah Wah Valley drainage basins respectively, at mountain locations as evapotranspiration and groundwater seepage to streams and springs that is subsequently consumed by evaporation, with a much smaller amount being pumped from existing wells. Stephens also reported that the groundwater discharged in the surrounding mountains contributed insignificant amounts of subsequent recharge to the valley-fill aquifers. In the studies conducted by Stephens, the groundwater flow systems were assumed to be in steady-state. Thus, the combined discharge from the basin-fill aquifers in Pine and Wah Wah Valleys was assumed to be the difference between the Maxey-Eakin estimated recharge and the reported consumptive discharge from mountain areas, together equaling 19,500 acre-ft/yr (Stephens, 1974, 1976).

Approach and Methods

The approach for investigation in this study included the following components (1) taking measurements of water levels at 63 new and previous identified well sites and spring discharge at 11 previously identified spring sites to produce a water-level map for Pine and Wah Wah Valleys; (2) utilizing water-level data and spring discharge data obtained during this study for comparison to historical data to establish a baseline dataset for groundwater conditions before significant development; (3) updating groundwater-evapotranspiration (ET_g) estimates in the hydrologically connected Tule Valley basin and Sevier Lake area to the north of the study area to improve the GBCAAS numerical model calibration for regional groundwater discharge related to the study area; (4) obtaining water samples from wells and springs for geochemical analyses of major-ions and selected trace elements, isotopic age-dating tracers, and noble gas recharge temperatures to improve the conceptual model of the groundwater system; and (5) providing updated groundwater budget estimates for Pine and Wah Wah Valleys using the GBCAAS v.3.0 numerical model (Brooks, 2017a, b) for comparison to previous estimates.

Data Collection Methods

Field parameters were measured with a multi-parameter sonde placed in a flow-through chamber connected to a discharge line near the well head for each of the 12 sampled wells, and in the 12 sampled springs at a submerged depth nearest the source of spring discharge.

Laboratory water-quality analyses of groundwater from Pine and Wah Wah Valleys included major and trace dissolved inorganic and organic constituents, tritium (^3H), carbon-14, stable isotopes of hydrogen and oxygen in water, and dissolved noble gases. The major inorganic ions included calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate. Trace ions included fluoride, bromide, iron, manganese, arsenic, molybdenum, nitrite, ammonia, and orthophosphate. Dissolved noble gases included helium-3 (^3He), helium-4 (^4He), neon-20 (^{20}Ne), argon-40 (^{40}Ar), krypton-84 (^{84}Kr), and xenon-129 (^{129}Xe).

Water-chemistry samples were collected from wells by using either installed submersible or top-mounted pumps or by temporary pumps used during pump tests. Before water-chemistry sample collection from monitoring wells, water was purged from each well until field parameters stabilized and a minimum of three casing volumes were removed. After purging each well, water was pumped into samples bottles and filtered as necessary. Water-chemistry samples were collected from springs by portable peristaltic pump as grab samples.

Samples for major and trace ions were filtered with 0.45-micron disposable filters and collected in clean polyethylene bottles according to procedures described by Wilde and Radtke (1998); samples for ion analysis were preserved with 7.7-normal nitric acid. Tritium samples were collected in 500 milliliter (ml) polyethylene bottles with polyseal caps without head space. Stable isotopes of hydrogen and oxygen were collected in 60-ml bottles with polyseal caps without head space. Carbon-14 samples were collected in 1-liter (L) glass bottles, according to procedures described by the USGS National Water Quality Laboratory. Noble gases were collected with diffusion sampler methods described by Sheldon (2002) and Gardner and Solomon (2009), and with copper tube methods described by Stute and Schlosser (2000).

Inorganic and organic chemical analyses (major and trace ions) were analyzed by the USGS at the National Water Quality Laboratory in Denver, Colorado. Stable isotopes of hydrogen and oxygen in water were analyzed by the USGS at the Stable Isotope Laboratory in Reston, Virginia. Tritium and noble gases were analyzed by the University of Utah's Dissolved Gas Laboratory using quadrupole and sector-field mass spectrometers; tritium concentrations were determined with the in-growth method (Clarke and others, 1976). Carbon-14 samples were analyzed by the Woods Hole Oceanographic Institution McLean Laboratory.

Physical Characteristics of the Study Area

Pine Valley

Pine Valley is a topographically closed basin bounded by the Wah Wah Mountains to the east, and the Needle Mountains to the west (fig. 1). Collectively, the Mountain Home Range and the Indian Peak Range are known as the Needle Mountains due to their jagged nature. The northern end of the basin is divided from Ferguson Desert by a broad low divide connecting the northern end of the Wah Wah Mountains with isolated Middle Mountain, Tunnel Spring Mountains, and the Needle Mountains. The southern end of the basin is divided from Escalante Valley to the south by a low divide between the Wah Wah Mountains and the Indian Peak Range in the Needle Mountains.

Most streams in Pine Valley are ephemeral. Sheep and Indian Creeks, in the southeastern Needle Mountains, and Pine Grove Creek, in the west central Wah Wah Mountains, are perennial in higher elevation reaches. These streams are usually ephemeral lower in their reaches as they approach alluvial deposits in the valley. Pine Valley Wash extends from the southern divide of the basin, north toward the playa in the lowest-altitude region in the valley.

Most of the known springs in Pine Valley are in the Needle Mountains and are associated with volcanic lithologies, with historical discharge rates for any given spring less than 60 gallons per minute (gal/min; Stephens, 1976, table 7). All known springs discharge at altitudes above 6,200 feet (ft). Pot Sum Pah, Willow, and Sheep Creek Springs were selected for monitoring during the course of this study.

Wah Wah Valley

Wah Wah Valley is a closed surface-water basin bounded by the Wah Wah Mountains to the west, the House and Confusion Ranges to the north, and the San Francisco Mountains to the east (fig. 1). The northeastern end of the basin is separated from the Sevier Desert by a broad low divide between the House Range and the San Francisco Mountains.

The are no perennial streams in Wah Wah Valley; all washes and streams are intermittent or ephemeral. Large stream channels and washes in the valley include Wah Wah Wash, Grover Wash, Willow Creek, Quartz Creek, and Frisco Wash. Streamflow has been historically observed in these channels during large high-intensity precipitation events, but typically does not persist for great distances owing to streambed seepage. Wah Wah Wash is the predominant wash that drains into the Wah Wah Valley playa at the north end of the basin.

Wah Wah Springs is the most well-known spring in the valley. The Springs are actually a complex of springs on the west side of the valley just south of Utah State Highway 21 that discharge from carbonate lithology at the base of the Wah Wah Mountains. Water from the spring has been used historically in early mining operations in the late 1800s associated with the San Francisco Mountains and the now abandoned town of Newhouse. At the time of this report, it was the sole source of water to a small agricultural ranch in the center of the valley. Stephens (1974) estimated the discharge of Wah Wah Springs at about 500 gal/min. Wah Wah Springs was selected for long-term monitoring as part of this study.

Population and Land Use

Pine and Wah Wah Valleys are very limited in their number of inhabitants. There are no named cities or towns in either valley. There is one agricultural establishment, Wah Wah Ranch, which is approximately one-half mile north of Utah State Highway 21 near the center of Wah Wah Valley. Primary land use in both basins consists of livestock grazing and open recreational activities on federally owned lands.

Climate and Precipitation

The climate of Pine and Wah Wah Valleys is arid and is characterized by moderate to little precipitation, large daily temperature changes, moderately cold winters, and warm dry summers. The average annual precipitation (1981–2010) estimated from Parameter-Elevation Regressions on Independent Slopes Model (PRISM) data for Pine and Wah Wah Valleys and most of the surrounding mountains ranges from about 8 to 16 inches (in.; Daly and others, 2008). Average annual precipitation reaches 24 in. in the highest altitudes of the Indian Peak Range of southwest Pine Valley (fig. 2). Total PRISM-estimated average annual precipitation for this period is 510,000 acre-feet for Pine Valley and 320,000 acre-feet for Wah Wah Valley.

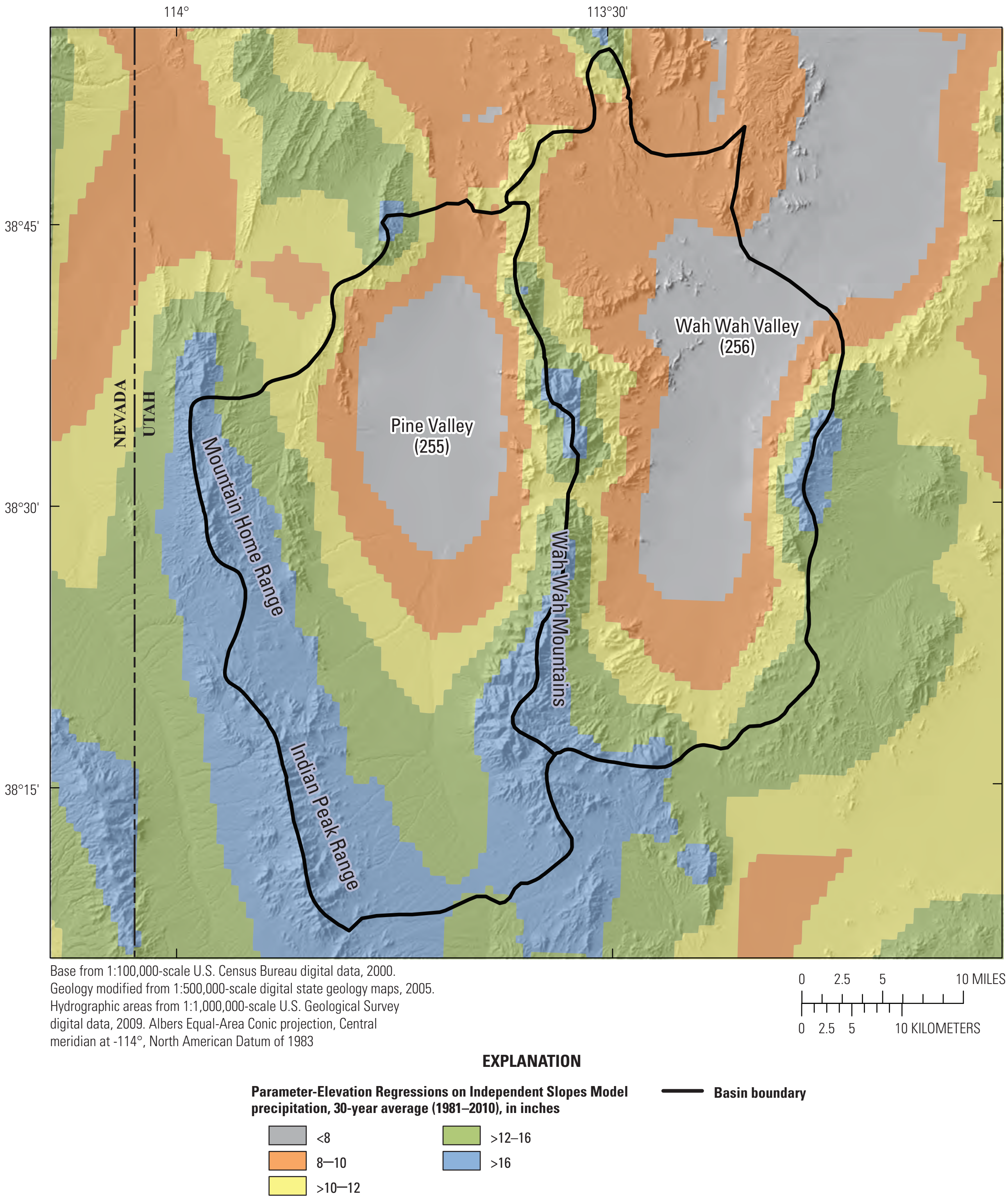


Figure 2. Average annual precipitation in Pine and Wah Wah Valleys, Utah, 1981–2010.

Two weather stations are in Pine and Wah Wah Valleys (fig. 1). The Desert Experimental Range station (NOAA COOP station 422116) is in Pine Valley at an altitude of 5,300 ft and has a historical period of record from January 1950 to September 1984. The Wah Wah Ranch station (NOAA COOP station 429152) is in Wah Wah Valley at an altitude of 4,900 ft and has a historical period of record from August 1955 to June 2008. Average monthly precipitation for each of the valleys for the period of record for both stations is shown in figure 3. The average monthly precipitation in Pine Valley during the period of record ranges from about 0.3 in. during the winter months of November, December, January, and February to about 0.9 in. during July and August. The average annual air temperature in Pine Valley was 9.5 degrees Celsius (°C) for the 34-year period of record from 1950 to 1984. The average monthly precipitation in Wah Wah Valley during the period of record was similar in magnitude and trend to the precipitation in Pine Valley and ranged from about 0.4 in. during the winter months of November, December, January, and February to about 1 in. during August. The average annual air temperature in Wah Wah Valley was 10.8 °C for the 53-year period of record from 1955 to 2008.

Geology

Pine and Wah Wah Valleys are part of a series of eastward-tilted fault blocks that are bounded on each side by normal faults associated with basin and range tectonic extension in the Great Basin physiographic region. Faulting extends along the lengths of each of the mountain ranges that divide the basins, including the San Francisco Mountains, Wah Wah Mountains, and the Needle Mountains. Lithologies in both valleys range in age from Precambrian to Holocene.

The Precambrian through Paleozoic units consist mainly of quartzites and carbonates with lesser amounts of shales, siltstones, and sandstones. They are the dominant lithologies that crop out on the western slopes of the San Francisco Mountains, Wah Wah Mountains, House Range, Confusion Range, and the northern portions of the Needle Mountains. They are generally low in primary permeability, but they can have moderate-to-high secondary permeability where fractured or solution derived openings are abundant.

The Cenozoic volcanic units that dominate the southern portion of Pine Valley as various tuffs and ignimbrites throughout the study area are the result of eruptive events associated with the Indian Peak Caldera Complex (Best and others, 2013). The southern portion of Pine Valley was the site of at least two calderas in the Indian Peak Caldera Complex: the Pine Valley caldera and the Mackleprang caldera. Best and others (2013) also infer that the southern parts of Pine Valley could have been the location of the caldera that produced the Marsden Tuff. Multiple eruptive events during the Cenozoic era have deposited thick sequences of tuffs and ignimbrites that could have backfilled earlier calderas.

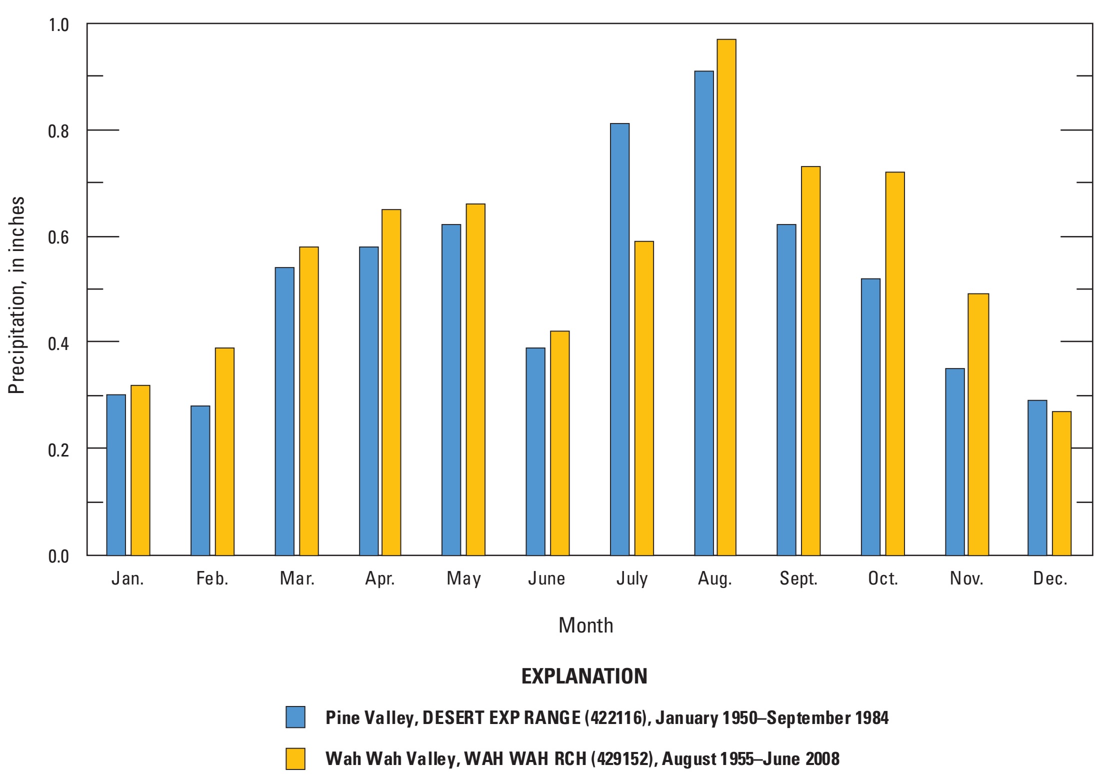


Figure 3. Average monthly precipitation for weather stations in Pine and Wah Wah Valleys, Utah.

Groundwater Hydrology

The groundwater system in the study area consists of water in unconsolidated deposits in the basins and water in consolidated rock (bedrock) underlying the basins and in the adjacent mountain blocks. The consolidated-rock and basin-fill aquifers have a limited connection hydraulically, with most of the recharge occurring in the consolidated-rock mountain blocks discharging in gaining streams and springs in the mountain areas. The hydrologic characteristics of the basin-fill aquifer water in Pine and Wah Wah Valleys indicate that the local mountain recharge zones do not contribute a significant amount of recharge to the basin-fill aquifers. The data and interpretation that yield this observation are addressed in the "Discussion" section below.

In the study area, groundwater divides do not coincide with surface-water divides in some areas. For example, Stephens (1976) observed that part of the Wah Wah Valley groundwater system was directly supported by recharge that occurred in the Pine Valley drainage basin. Specifically, quartzite and carbonate lithologies that crop out on the west side of the Wah Wah Mountains that dip to the east likely transfer recharge as seepage in Pine Valley to Wah Wah Valley through fractured bedrock. Stephens (1974) observed that the unique geologic structure of the carbonate lithology in the Wah Wah Mountains provides the recharge source and mode of transmission for water that discharges from Wah Wah Springs. Further investigation and results included in this study reinforce this observation.

Hydrogeology

As part of the GBCAAS study, a three-dimensional hydrogeologic framework of the eastern Great Basin was constructed (Cederberg and others, 2011; Sweetkind and others, 2011). The GBCAAS study area is inclusive of Pine and Wah Wah Valleys; therefore, this same hydrogeologic framework was used in this study. The framework was constructed using data from a variety of sources, including geologic maps and cross sections, drill-hole data, geophysical models, and stratigraphic surfaces created for other three-dimensional hydrogeologic frameworks within the GBCAAS study area. The framework was developed using a 1 mi^2 grid-cell size.

In the hydrogeologic framework developed for the GBCAAS study, the consolidated pre-Cenozoic-age rocks, Cenozoic-age sediments, and igneous rocks in the study area were subdivided into nine hydrogeologic units (HGUs; Sweetkind and others, 2011). An HGU has considerable lateral extent and reasonably distinct physical characteristics that could be used to infer the capacity of a sediment or rock to transmit water. The definition of HGUs is important in conceptualizing the hydrogeologic system and construction of a geologic framework for describing the groundwater flow system.

Of the nine HGUs defined in the hydrogeologic framework developed for the GBCAAS, five are in this study area (fig. 4). The HGUs in this study area are (1) a non-carbonate confining unit (NCCU) representing low-to-moderate permeability Precambrian-age siliciclastic formations as well as intrusive igneous rocks that are locally exposed in mountain ranges, and underlie parts of the study area; (2) a lower carbonate aquifer unit (LCAU) representing a thick succession of predominantly high-to-moderate permeability Cambrian through Devonian-age carbonate rocks that are locally exposed in the mountain ranges, and present beneath most of the valleys within the study area; (3) an upper siliciclastic confining unit (USCU) representing low-permeability Mississippian-age siliciclastic rocks, predominantly shales, that are limited in extent within the study area; (4) an upper carbonate aquifer unit (UCAU) representing a thick succession of low-to-high permeability Pennsylvanian- and Permian-age carbonate rocks that are locally exposed in the mountain ranges and exist beneath some of the valleys within the study area; and (5) a volcanic unit (VU) representing large volumes of low-to-high permeability Cenozoic-age volcanic rocks that are locally exposed in the mountain ranges and exist beneath some of the valleys in the study area. In this study the Cenozoic valley-fill sediments are referred to as the basin-fill aquifer.

Aquifer Properties

Aquifer properties describe the ability of a groundwater system to transmit and store water. The distribution of these properties in the study area is variable and depends on the depositional environment of sediments in the basin-fill aquifer and confining units, and on the degree of structural deformation, fracturing, and chemical dissolution in the bedrock aquifers and confining units. Aquifer properties can be estimated with aquifer tests and specific-capacity tests by pumping groundwater from a well and monitoring the water-level changes in the pumped well and in nearby observation wells. Aquifer tests and specific-capacity data are commonly used to estimate values of transmissivity, hydraulic conductivity, and storativity or the storage coefficient. Transmissivity and hydraulic conductivity describe the ease with which water can move through the pore space in an aquifer. More specifically, hydraulic conductivity is the volume of water flowing through a unit cross-sectional area of an aquifer under a unit hydraulic gradient in a given amount of time; and transmissivity is the volume of water flowing through a cross-sectional area that is one-unit wide multiplied by the aquifer thickness in a given amount of time. The storage coefficient is the volume of water released from storage per unit decline in hydraulic head (water level) in the aquifer (Freeze and Cherry, 1979).

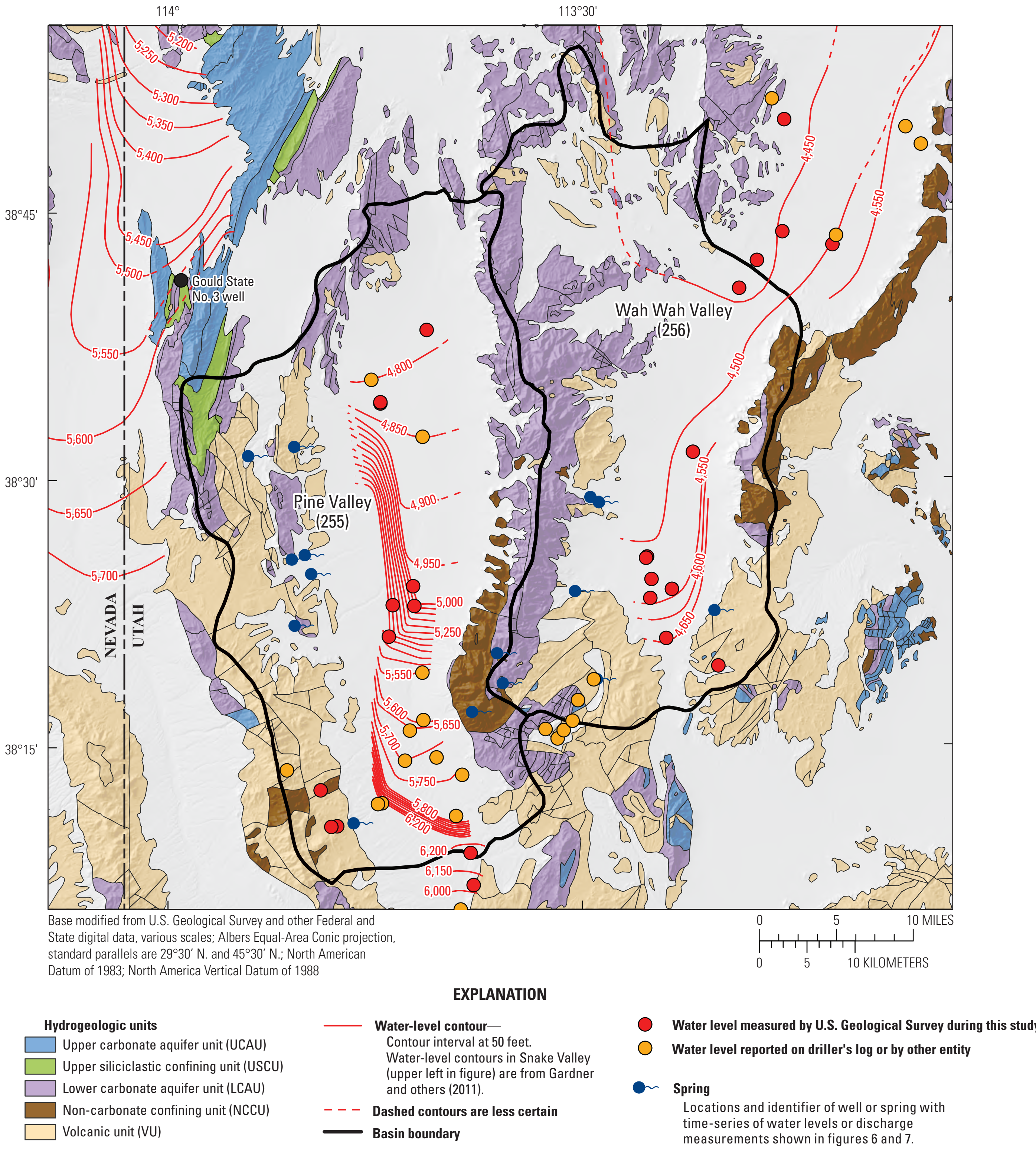


Figure 4. Surficial extent of hydrogeologic units and water-level (potentiometric) contours indicating the general direction of groundwater movement.

Basin Fill

Aquifer properties for the basin-fill aquifers in Pine and Wah Wah Valleys were determined from 10 single-well pump tests where a value for specific capacity was calculated. Transmissivity values were estimated from specific-capacity values by considering a range of storage coefficients representing unconfined conditions (0.075) to confined conditions (0.001). The transmissivity calculated for the basin-fill aquifer in Pine and Wah Wah Valleys mostly ranged from about 400 to 9,000 square feet per day (ft^2/d; table 1, fig. 5). One well, CICWCD #25, which is in the far southern portion of Pine Valley, yielded a transmissivity range of 20–30 ft^2/d. The driller's log indicates that the aquifer consists of sands and gravels at this location, but low yields could be the results of lower permeability volcanic lithologies and their weathering products in the area. Another well, CICWCD #11, which is in the center of the southern portion of Pine Valley, yielded a transmissivity range of 94,000–120,000 ft^2/d. The driller's log indicates a higher percentage and frequency of gravel/cobble layers, which can produce high values of transmissivity when saturated. The reported drawdown during the pumping test at CICWCD #11 after pumping at 189 gal/min for 24 hours was 0.5 ft. This value is significantly less than any other test in the area and could be erroneous.

Bedrock

Aquifer properties for the bedrock in Pine Valley were determined from two single-well pump tests at wells CICWCD #7 and #18 where a value for specific capacity was calculated. Transmissivity values were estimated from specific capacity values using the Cooper and Jacob (1946) solution for flow to a well in a confined aquifer by considering a range of storage coefficients representing unconfined conditions (0.075) and confined conditions (0.001). It is unclear from the driller's logs what rock type the wells were screened in. The transmissivity calculated from these two wells ranged from about 10 to 580 ft^2/d (table 1). Rock type, fracture density, and degree of fracture interconnection influence the value of transmissivity when considering fractured bedrock aquifers.

Presence and Movement of Groundwater

Sources of groundwater in Pine and Wah Wah Valleys are in the basin-fill and bedrock aquifers under confined and unconfined conditions. In the basin-fill aquifer, unconfined conditions generally exist in the upper portions of alluvial fans, with confined conditions in areas where fine-grained sediment is interlayered with more course gravels and sands, found near the centers of the valleys. Previous investigations (Stephens, 1974, 1976) have indicated that many of the bedrock aquifers in the mountains could be perched relative to the basin-fill aquifers. The connection between the bedrock aquifers and the basin-fill aquifers in the subsurface is not well understood.

A water-level map for the basin-fill aquifer in Pine and Wah Wah Valleys was constructed using water-level measurements taken at wells and considering springs in the low-altitude areas of the surrounding mountain regions totaling 63 sites (fig. 4; table A–1). Pine and Wah Wah Valleys are closed surface-water basins, but groundwater levels indicate that groundwater moves northward in both valleys toward adjacent basins.

Depth to water is generally deep in the basin-fill aquifers toward the center of the valleys. In Wah Wah Valley, water-level depths in wells (C-24-13)34ccb-1 and (C-28-14)26bbd-1 show a range from about 210 to 750 ft below land surface. In Pine Valley, depths to water are slightly shallower than in Wah Wah Valley with observed depths of about 620 ft at well (C-28-17) 1dbb-1 and 300 ft at (C-25-16)18bdd-1 (fig. 4; table A–1). Shallower water levels found in volcanic lithologies were observed at higher altitudes along the margins of both valleys as well as in local mountain bedrock aquifers.

Steep hydraulic gradients are inferred by water levels observed in Pine Valley. The areas of steepest hydraulic gradient are in the southern portion of Pine Valley and along the western margin of the valley in the central portion (fig. 4). It is possible that these areas represent the boundary between sediment types that make up the basin-fill aquifer in Pine Valley. The southern and western sides of Pine Valley likely contain fine-grained sediment that is a weathering product of the volcanic lithologies that dominates the Needle Mountains and southern portions of the Wah Wah Mountains, whereas the eastern sides of Pine Valley likely contain more course-grained sediment derived from quartzites that are found on the western slopes of the Wah Wah Mountains.

Table 1. Aquifer properties of basin-fill and bedrock aquifers from selected driller's logs in Pine and Wah Wah Valleys, Utah.

[Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). **Abbreviaitons**: USGS, U.S. Geological Survey; mm/dd/yyyy, month/day/year; —, no data; NR, not reported; ND, not determined]

Well name	USGS site name	Latitude (decimal degrees)	Longitude (decimal degrees)	Date of test (mm/dd/yyyy)	Well diameter (inches)	Screened interval of well (feet below land surface)	Bedrock or basin-fill	Pumping rate (gallons per minute)	Duration (hours)	Drawdown (feet)	Specific capacity (gallons per minute per foot of drawdown)	Transmissivity (feet squared per day[1])
CICWCD #6	—	38.275539	–113.691082	11/04/2016	6	600–1,000	Basin-fill	168	NR[2]	69	2.4	400–580
CICWCD #7	—	38.197012	–113.746362	02/02/2017	6	250–1,000	Bedrock	198	30	82	2.4	410–580
CICWCD #8	—	38.240485	–113.675263	10/31/2016	6	550–1,000	Basin-fill	168	NR[2]	58	2.9	490–690
CICWCD #11	—	38.265714	–113.707401	11/09/2016	6	500–1,000	Basin-fill	189	NR[2]	[3]0.5	380	[3]94,000–120,000
CICWCD #18	—	38.319833	–113.692094	11/02/2016	6	440–880	Bedrock	4	NR[2]	57	0.1	7–13
CICWCD #12	—	38.237688	–113.713291	01/24/2017	6	550–1,000	Basin-fill	168	29	24	7.0	1,300–1,800
CICWCD #25	—	38.185634	–113.651885	10/16/2016	6	700–1,000	Basin-fill	10	NR[2]	61	0.2	20–30
[4]Phelps Dodge #19	(C-28-17)11cca-1	38.383015	–113.727751	06/12/1978	12	ND–970	Basin-fill	402	44	139.5	2.9	450–650
[4]Phelps Dodge #27	(C-28-17)22dda-1	38.353571	–113.732473	06/12/1978	8	ND–2006	Basin-fill	503	44	35.2	14.3	2,800–3,800
Wah Wah #1	(C-28-14)11abb-1	38.397184	–113.389411	12/13/1974	12	680–1,475	Basin-fill / bedrock	1,353	28	113	12	2,100–2,900
Wah Wah #26	(C-28-14)10cbd-1	38.388806	–113.415500	06/04/1975	16	800–970	Basin-fill / bedrock	1,281	72	73	18	3,200–4,500
Wah Wah #29	(C-28-14)3bcd-1	38.406500	–113.414083	02/14/1975	12	700–1,480	Basin-fill / bedrock	1,401	48	44	32	6,300–8,500

[1]Range of transmissivity (T) based on a range of storage coefficients representing unconfined (0.075) and confined (0.001) aquifer conditions.

[2]Assumed to be 24 hours if not reported.

[3]Actual drawdown is reported as zero, which results in unrealistic transmissivity (T). This result should be considered suspect.

[4]Results from the drawdown associated with the highest pumping rate and longest duration during the step test reported by Phelps Dodge Corp.

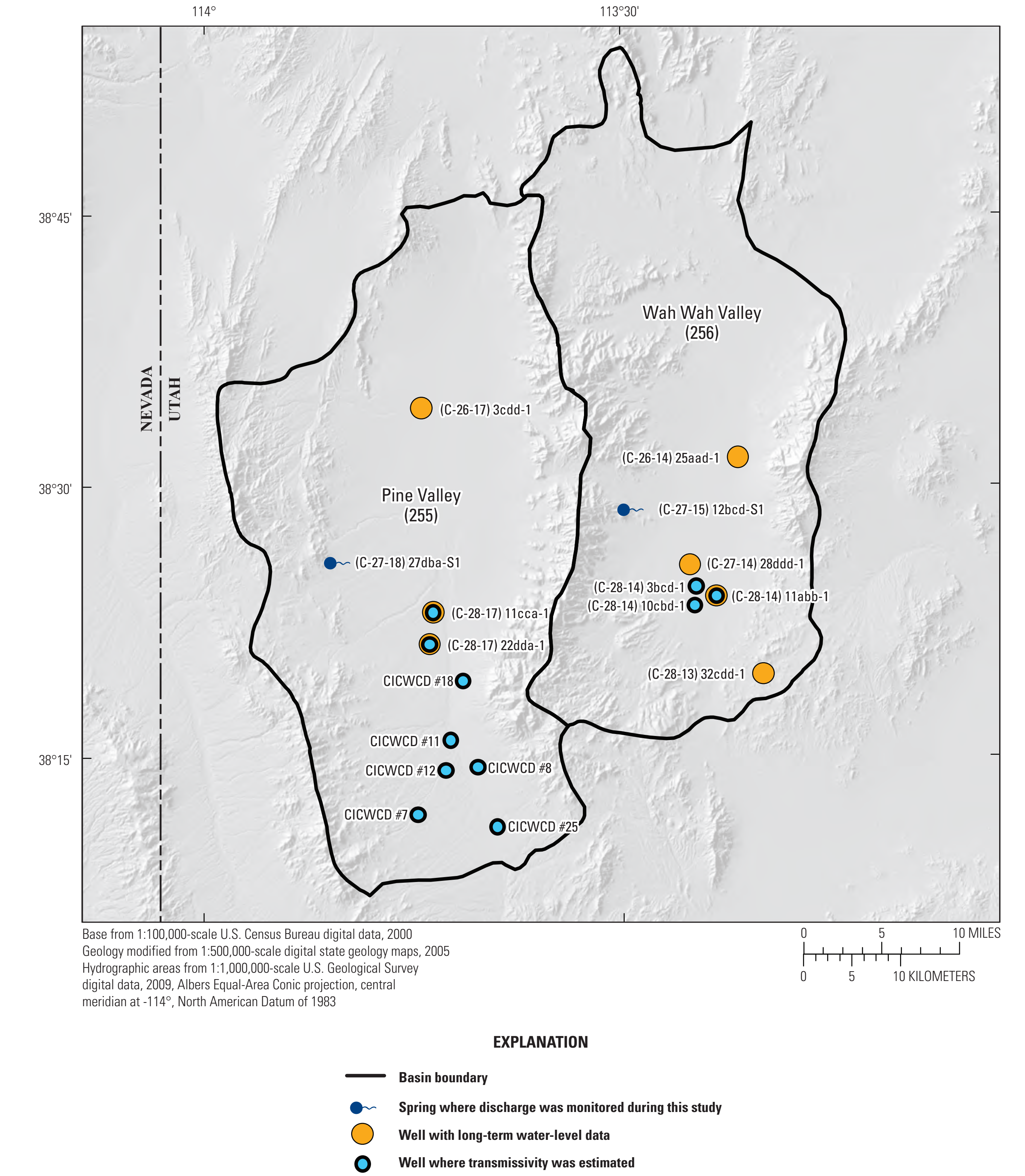


Figure 5. The locations of selected wells and springs with time-series records of water levels or discharge and wells where aquifer transmissivity was estimated in Pine and Wah Wah Valleys, Utah.

Water-Level and Spring-Discharge Trends

Water levels in wells and discharge from springs fluctuate in response to imbalances between groundwater recharge and discharge. Water levels rise and spring discharge increases when recharge exceeds discharge for a period of time and decline when the opposite occurs. Variations in recharge and discharge in Pine and Wah Wah Valleys are driven predominantly by natural processes, such as annual variability in precipitation and groundwater withdrawals from wells, and by anthropogenic (human-induced) processes, which have been historically negligible. Long-term water-level and spring discharge fluctuations in Pine and Wah Wah Valleys are presented for seven wells and two springs shown on figure 5. All water-level and discharge data are available through the USGS National Water Information System database (https://waterdata.usgs.gov/nwis). Six of the wells with long-term water-level data are completed in the deep basin-fill aquifers of Pine and Wah Wah Valleys; the remaining well, (C-28-13)32cdd-1 is completed in the volcanic-rock aquifer in the mountains of southeastern Wah Wah Valley. Both springs where discharge was measured are in bedrock aquifers in the mountains. In most of the seven wells, water levels were generally stable for the period of record represented at each site (fig. 6). The total water-level change at any of the sites that were observed was not greater than 5 ft. In well (C-28-13)32cdd-1, in the southeastern part of Wah Wah Valley, a steady decline in water level was observed from 2008 to 2017, which could represent response to drier than normal conditions that have occurred during this time. Conversely, in well (C-28-17)22dda-1, on the western side of central Pine Valley, a steady increase in water level was observed from 2013 to 2017, which could represent a delayed response through a large unsaturated zone to a period of above average recharge in the region. In both springs, discharge remained stable from 2013 to 2016 (fig. 7). Discharge from Pot Sum Pah Spring was relatively constant at about 15 gal/min from early 2013 to early 2016. There was only a slight decrease in discharge from Wah Wah Springs from about 2.3 cubic feet per second (ft^3/s) in early 2013 to about 2.2 ft^3/s in early 2016. This decrease could have been the result of drier than normal conditions that occurred during the period of record. The discharge measured at Wah Wah Springs was approximately twice that reported by Stephens (1974).

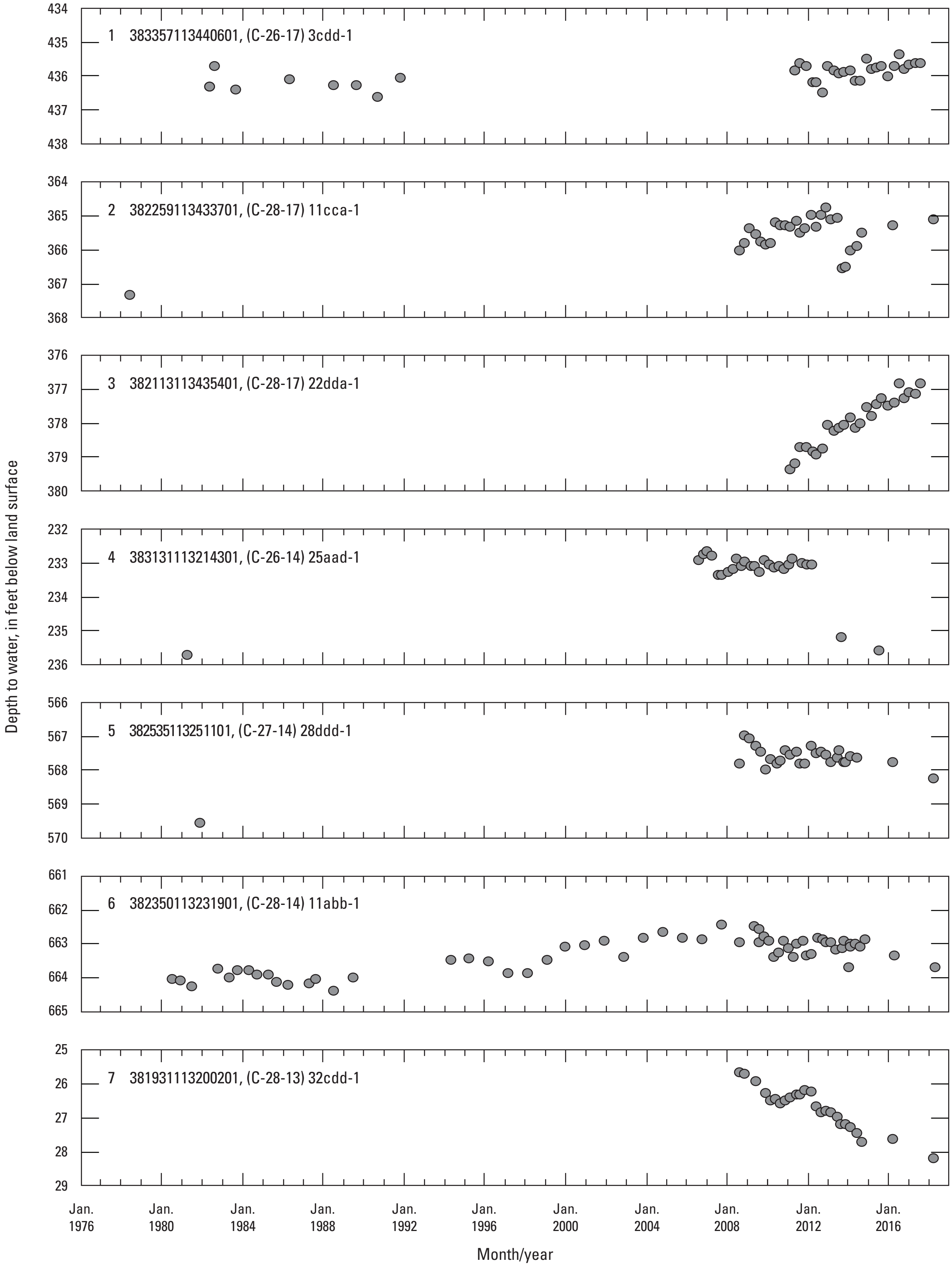


Figure 6. Long-term water-level fluctuations in selected wells in Pine and Wah Wah Valleys, Utah.

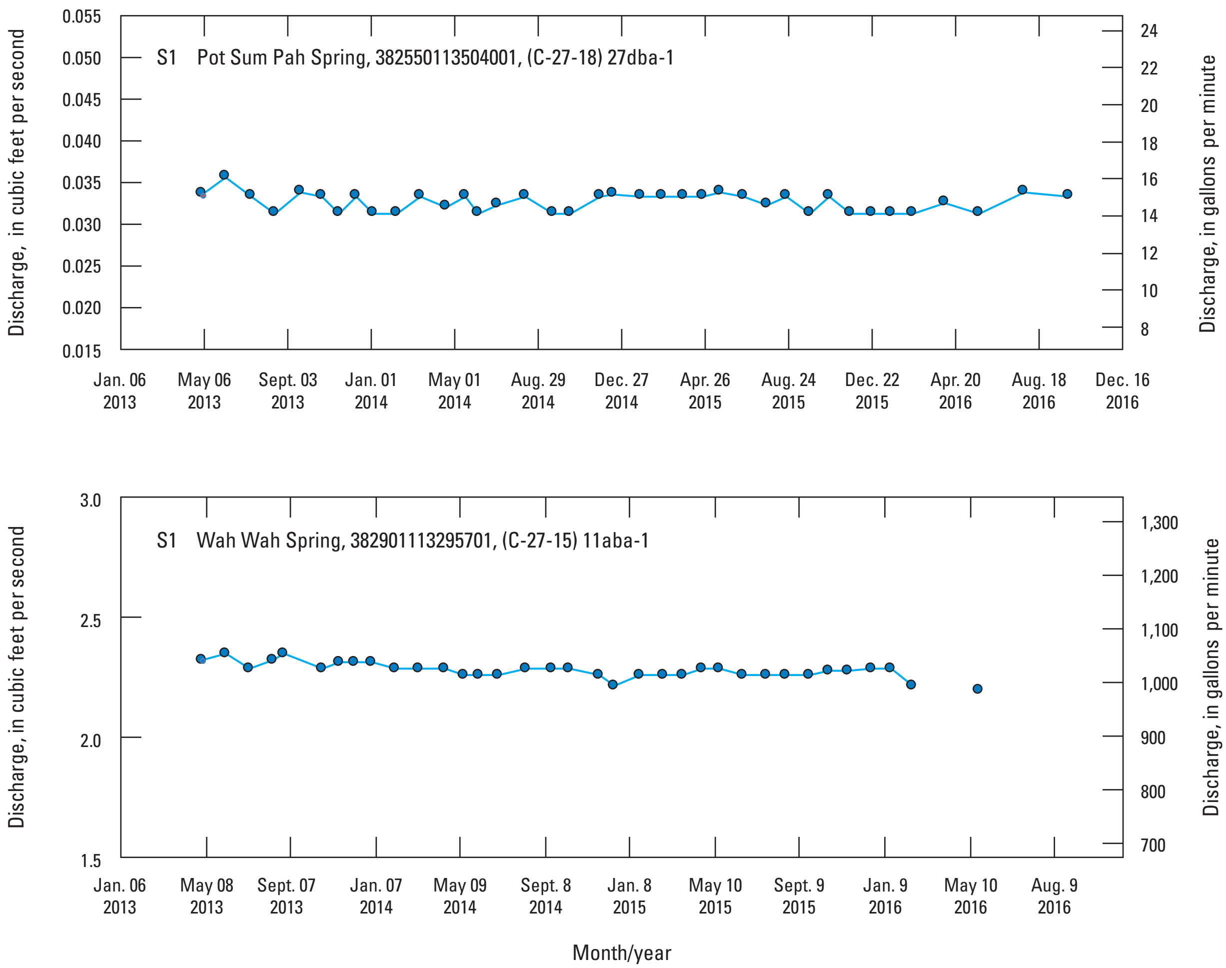


Figure 7. Discharge at springs in the mountains of the Pine and Wah Wah Valleys drainage basins, Utah.

Regional Evapotranspiration Occurring North of the Study Area

Groundwater discharge through ET is the largest natural outflow component of groundwater in most western Utah valleys; it consists of transpiration by phreatophytic vegetation, which uses shallow groundwater as a primary water source and evaporation from bare soil, Groundwater discharge from ET occurs in topographically low areas referred to as groundwater discharge areas (GDAs) where groundwater is at or near the surface. Pine and Wah Wah Valleys are unique when compared to surrounding valleys in western Utah in that no groundwater discharge by ET occurs from the basin-fill aquifers owing to the deep water tables in these valleys. Rather, nearly all discharge from the basin-fill aquifers occurs by subsurface outflow to other basins. Groundwater leaving Pine and Wah Wah Valleys through the subsurface moves northward, converges with regional groundwater flow from the east and possibly the west, and discharges by ET_g at regional GDAs, likely in Tule Valley or in the southern Sevier Desert near Sevier Lake (Gardner and others, 2011). Previous estimates of groundwater discharge by ET for these areas were based on reconnaissance-level study and could have had uncertainties as high as plus or minus 100 percent. Updated ET_g estimates for these two areas were made to better constrain Pine and Wah Wah Valley groundwater budgets using the groundwater model of the Great Basin carbonate and alluvial aquifer system Version 3.0 (Brooks, 2017a,b).

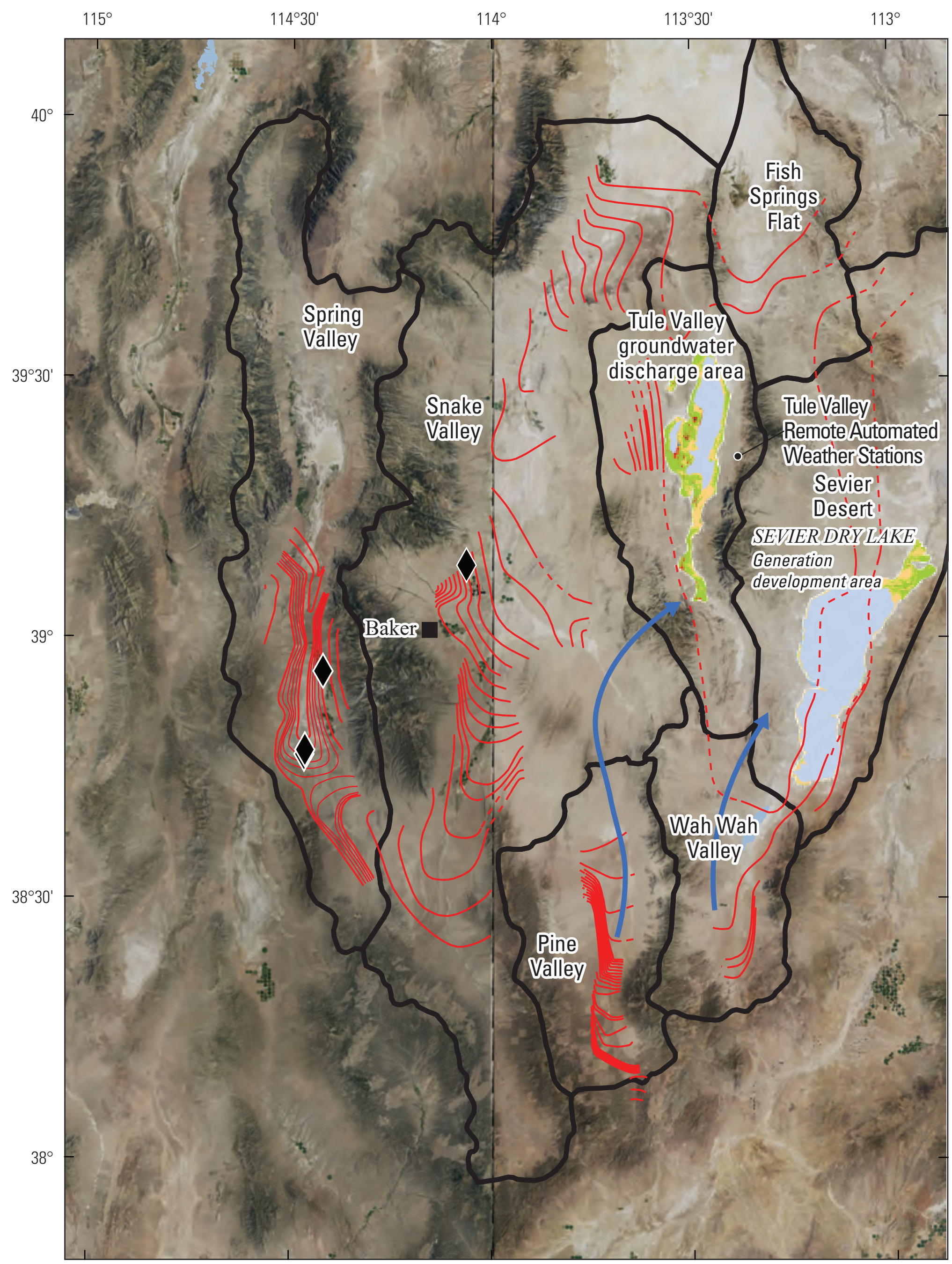
The total volume of water discharged by ET can be calculated as the product of the rate at which water is transferred from the land to the atmosphere (ET rate) and the area of the vegetation, open water, and soils that transfer this water. Groundwater ET, the fraction of total ET made up of groundwater, is calculated by subtracting precipitation from the total ET. The resulting updated estimates of average annual ET_g in the Tule Valley and Sevier Lake GDAs were 35,000 and 10,500 acre-ft/yr, respectively, with a likely uncertainty of plus or minus ±35 percent (Michael Moreo, U.S. Geological Survey, written comm., 2012).

Evapotranspiration rates were estimated from eddy-covariance measurements collected at six sites in nearby valleys west of the study area. The six eddy-covariance sites were installed in Spring, Snake, and White River Valleys from September 2005 through 2006 as part of the Basin and Range carbonate-rock aquifer system (BARCAS) study (Moreo and others, 2007). Data from the sites, that are in a range of phreatophytic vegetation assemblages, helped to select Landsat satellite imagery used to estimate groundwater discharge in Tule Valley and the area surrounding Sevier Lake. Groundwater discharge was estimated based on vegetation characteristics identified in the satellite imagery and during field mapping of the extent of the GDA in both valleys. In this study, basin-scale groundwater discharge was estimated by (1) mapping the GDA in each valley; (2) evaluating 2005–11 summer multispectral satellite images against BARCAS study ET measurements to identify images broadly representative of average conditions in the study area, and partitioning the GDA into ET units using the selected satellite images and field reconnaissance; and (3) scaling ET to the ET units using ET rate estimates from several studies in the Great Basin.

Scaling from Site Measurement to Basin-Scale Estimates

Delineation of Groundwater Discharge Areas

The GDAs for this study consist of discrete boundaries in Tule Valley and part of Sevier Desert surrounding Sevier Lake (fig. 8). The GDA boundaries represent the margin between areas where xerophytic shrubs that obtain water from precipitation and shallow soil moisture are predominant outside the boundary, and a mix of xerophytic and phreatophytic shrubs are inside the boundary. The GDAs were mapped using techniques similar to those used in studies throughout Nevada and eastern Utah (Nichols, 2000; Laczniak and others, 2001; Smith and others, 2007; Allander and others, 2009; Garcia and others, 2014). National Agriculture Imagery Program (NAIP) imagery from 2011 (U.S. Department of Agriculture, 2012), a digital elevation model (U.S. Geological Survey, 2017), and water-level data were used in conjunction with field visits to map the GDA at approximately 1:24,000-scale. During field visits, accessible roads were followed and the point at which xerophytic vegetation transitions to phreatophytic vegetation was marked on a digital map using a Global Positioning System unit connected to a computer running Geographic Information System (GIS) software. Photographs and notes were taken to document plant and soil conditions present at the marked location. Points, photographs, and notes also were used to document plant communities inside the mapped GDA boundaries where accessible. The final GDA boundary in each valley was digitized into a GIS feature class using the field mapped points, NAIP, and satellite imagery to help interpolate the location of the boundary between mapped field locations in areas where field reconnaissance was not possible because of limited access. Playa boundaries were mapped using a combination of field points, satellite imagery, and 2011 NAIP imagery. The final GDA boundary encompasses 81,659 acres in Tule Valley with 30,390 acres of that area covered by playa. The Tule Valley GDA is characterized by large areas of phreatophytic vegetation adjacent to the playa on the west and south and a thin band bordering the playa on the east. The Tule Valley playa is underlain by fresh water, hosts springs discharging fresh water, and is covered by very sparse phreatophytic vegetation. The Sevier Lake GDA encloses approximately 143,239 acres, of which 121,392 acres are lakebed playa. The Sevier Lake GDA is characterized by a narrow band of phreatophytic vegetation along the east, west, and southern margins of the playa and a more extensive expanse of phreatophytes following the course of the Sevier River northeast from its mouth. The Sevier Lake playa is underlain by dense brine and its salt-encrusted surface is devoid of vegetation. These are characteristics of playas where it has been shown that groundwater discharge by evapotranspiration is negligible (Jackson and others, 2018). The 121,392-acre Sevier Lake playa is excluded from the Sevier Lake GDA by assuming an ET rate equal to 0 feet per year (ft/yr). It had previously been assumed that the generally dry lakebed of Sevier Lake was a groundwater discharge playa with 3,800–4,100 acre-ft/yr of ET_g (Wilberg, 1991); however, new information obtained during exploratory drilling and groundwater sampling, by CH2M Hill and Peak Minerals during 2012 and 2013, illustrates that this is not the case (Stephen Hill, Peak Minerals, written commun., 2014). Sediment beneath the playa consists of thick (greater than 500 ft) terminal lake deposits with extremely low permeability (Hydraulic conductivity of less than 0.001 foot per day; ft/d), which is below approximately the upper 100 ft and limits groundwater movement. Groundwater samples from wells screened directly beneath the playa or playa edges have high total dissolved solids (TDS) concentrations (ranging from 33,000 to greater than 200,000 milligrams per liter; mg/L) and stable-isotope values of oxygen ($\delta^{18}O$) and hydrogen (δ^2H or δ^2D) that clearly indicate extensive evaporative enrichment (fig. 9). In contrast, low TDS groundwater samples from wells surrounding the Sevier Lake playa have meteoric stable-isotope values indicating that they have not undergone evaporation. The stable-isotope data indicate that the high TDS waters beneath the Sevier Lake playa must have spent considerable time undergoing evaporation on the paleosurface of this terminal lakebed. This pattern is the opposite of what would be observed if regional fresh groundwater was moving upward to discharge by ET or bare soil evaporation from the Sevier Lake playa.



Imagery from U.S. Department of Agriculture, National Agriculture Imagery Program. Base modified from U.S. Geological Survey and other Federal and State digital data, various scales; Albers Equal-Area Conic projection, standard parallels are 29°30′ N. and 45°30′ N.; North American Datum of 1983; North America Vertical Datum of 1988

0 5 10 15 20 MILES
0 5 10 15 20 KILOMETERS

EXPLANATION

Evapotranspiration unit (ET)

- Playa
- Open water
- Very sparse desert shrub
- Sparse-to-dense desert shrub
- Grassland
- Dense meadow and marshland

Basin boundary
Water-level contour (50-foot interval)
Dashed contours are less certain
General direction of groundwater flow
Eddy-covariance sites used to measure evapotranspiration rates by Moreo and others (2007)

Figure 8. Location and classification of evapotranspiration units used in the calculation of average annual evapotranspiration of groundwater in the Tule Valley and Sevier Lake groundwater discharge areas, Utah.

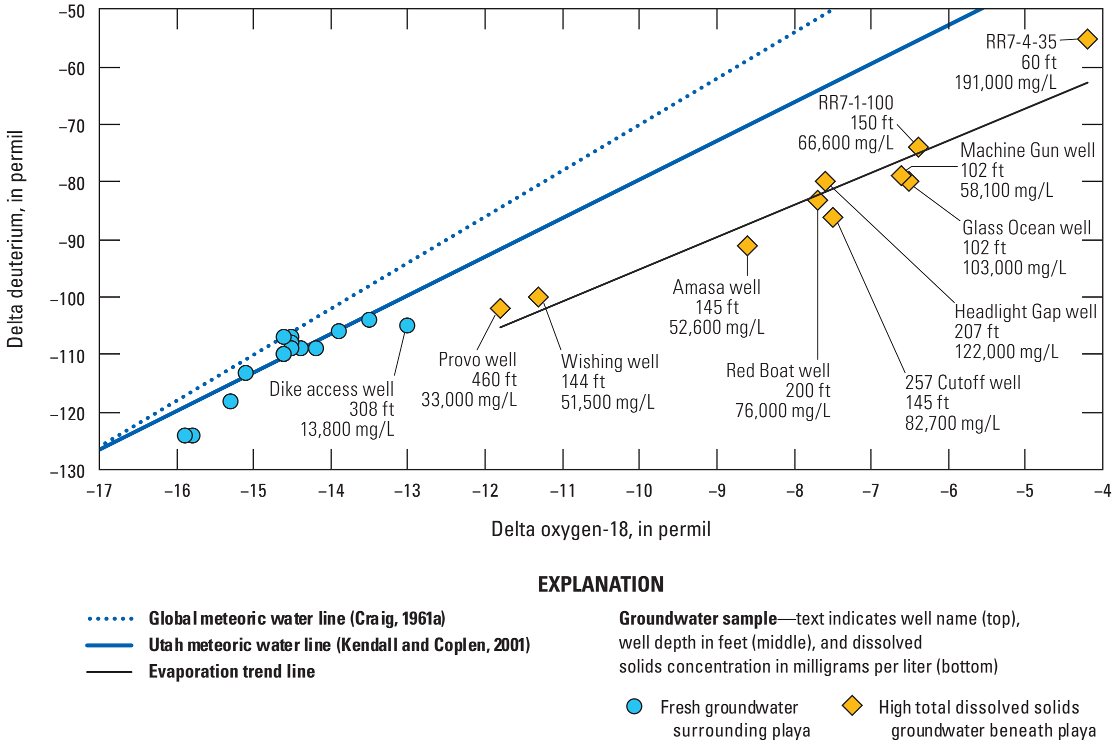


Figure 9. Stable isotopes of freshwater and brine showing evaporatively enriched waters in saturated sediments below the Sevier Lake playa, Utah.

Evapotranspiration Units and Estimates of Groundwater Evapotranspiration

Many studies have shown that the amount and rate of water lost to the atmosphere by ET in groundwater discharge areas varies with vegetation type and cover, depth to water, and soil characteristics (Laczniak and others, 1999, 2001, 2008; Nichols, 2000). Satellite imagery in combination with field mapping is often used to identify and group areas of similar vegetation and soil characteristics assuming that ET generally increases with increasing vegetation density and soil moisture (Laczniak and others, 2001; Moreo and others, 2007; Smith and others, 2007; Garcia and others, 2014; Berger and others, 2016). These areal groupings are referred to as ET units and are assumed to consist of areas with similar ET discharge rates (fig. 8).

Evapotranspiration rates for the study area were estimated on the basis of ET rate ranges from Welch and others (2007) supplemented with information gathered from more recent studies in Nevada (Garcia and others, 2014; Berger and others, 2016), net irrigation water requirements , and actual ET (ET_a) rates for alfalfa and open water, respectively, in Snake Valley, Nevada (Huntington and Allen, 2010). Ranges of ET_a rate estimates for ET units mapped in the Tule Valley and Sevier Lake GDAs during field work were assembled and used to estimate ET_g by subtracting 2006–09 mean annual precipitation (0.46 ft/yr) measured at the Tule Valley Remote Automated Weather Station (RAWS; table 2; fig. 8).

Table 2. Ranges of average annual actual evapotranspiration rates (ET_a) for evapotranspiration units (ET units) in the Tule Valley and Sevier Lake groundwater discharge areas, Utah.

[ft, feet]

Discharge area	Range of average annual ET_a rates (ft)	
	Low	High
Playa[1]	0.05	0.05
Very sparse desert shrub[2]	0.84	0.84
Sparse to dense desert shrub[3]	0.84	1.80
Grassland[4]	1.60	2.70
Dense meadow and marshland[5]	2.70	3.00
Open water[6]	4.70	4.70

[1]Based on playa rates from Garcia and others, 2014.

[2]Based on the mean annual evapotranspiration rate at the Spring Valley site (SPV1; Moreo and others, 2007) and the Kobeh Valley site 1 (Berger and others, 2016).

[3]Based on the range between the very sparse desert shrub rate and the upper end of the dense desert shrubland (Welch and others, 2007, fig. 27).

[4]Based on grassland range (Welch and others, 2007, fig. 27).

[5]Based on the upper end of the grassland (Welch and others, 2007, fig. 27) and the net irrigation water requirement for alfalfa in Snake Valley (Huntington and Allen, 2010).

[6]Open water rate for Snake Valley (Huntington and Allen, 2010).

Groundwater evapotranspiration rates were applied to vegetated ET units, open water, and the Tule Valley playa to estimate total ET_g for the study area. Vegetated ET units and open water were mapped using Landsat satellite imagery collected by the Thematic Mapper (TM) sensor aboard Landsat 5. The TM instrument collects information in six spectral bands with wavelengths ranging from the visible blue (0.45 micrometer, µm) to the short-wave infrared (2.35 µm), and in an additional seventh band with thermal infrared wavelengths between 10.4 and 12.5 µm. Continuous 112-mile-wide swaths of TM imagery are broken into overlapping “scenes” approximately 105 mi in length. Each scene is imaged by the sensor every 16 days at approximately 100-foot (30-meter) spatial resolution (394 feet [120 meters] for the thermal band) and covers approximately 11,800 mi^2. Landsat 5 TM scene locations are identified using a world reference system 2 (WRS2) path and row number. The Tule Valley and Sevier Lake GDAs and the ET stations used to evaluate scenes are in WRS2 path 39 row 33. As part of the BARCAS study, nine scenes were selected for evaluation against vegetation conditions and six stations were measured for ET in Spring, Snake, and White River Valleys, which are west of the study area (table 3; Moreo and others, 2007). Stations were installed in August 2005 and removed after September 30, 2006 (Moreo and others, 2007).

The selected scenes represent a subset of available images for each year where skies were cloud-free, vegetation canopies were green and active, and little to no antecedent precipitation was observed at nearby weather stations. All scenes were selected starting in 2005 through 2011 and acquired by the Landsat 5 TM sensor in the summer months to represent “growing-season” conditions when phreatophytic vegetation in the GDA is actively transpiring and shrubs have reached maximum growth. Early scene dates were selected to roughly coincide with installation of BARCAS study ET stations. No scenes were available for 2012 because of the failure of the TM sensor aboard Landsat 5 during the late winter of 2012. Landsat 8 scenes from 2013 were not evaluated because of slight spectral and radiometric differences between the sensors and because the atmospheric correction method used (described below) was not available for Landsat 8 at the time of processing. Data were assessed from 2005 through 2011 to provide a large group of data for comparison with the site-scale ET data.

Table 3. Landsat 5 Thematic Mapper scenes evaluated for use in basin-scale estimation of groundwater evapotranspiration in the Tule Valley and Sevier Lake groundwater discharge areas, Utah.

[ID, identification]

Image date	Landsat image entity ID
July 12, 2005	LT50390332005193PAC01
July 15, 2006	LT50390332006196PAC01
July 2, 2007	LT50390332007183PAC01
July 7, 2007	LT50390332009188PAC01
July 18, 2007	LT50390332007199PAC01
June 18, 2008	LT50390332008170PAC01
August 21, 2008	LT50390332008234PAC01
August 11, 2010	LT50390332010223EDC00
June 27, 2011	LT50390332011178PAC01

Each scene date was atmospherically corrected by the USGS Earth Resources Observation and Science (EROS) Center using Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) software. LEDAPS software applies atmospheric corrections to Landsat data to generate a surface reflectance product. The corrections are based on the Second Simulation of a Satellite Signal in the Solar Spectrum (6S) radiative transfer model used by the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Science Team (U.S. Geological Survey, 2012). The atmospherically corrected visible, near infrared, and short-wave infrared bands were combined to form a single 6-band image for each scene date.

Information from multispectral satellite imagery such as that collected by Landsat 5 TM can be used to characterize vegetation on the basis of light absorption and reflection characteristics unique to vegetated surfaces. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI; Rouse and others, 1974), Modified Soil-Adjusted Vegetation Index (MSAVI; Qi and others, 1994), and the Enhanced Vegetation Index (EVI; Huete and others, 1999) use the contrast between distinct absorption and reflectance features in vegetation to help identify vegetated areas and to characterize the health and spatial extent of vegetation communities. Calculation of a vegetation-index results in a unitless single-band image with valid values ranging between –1 and 1. Index values in vegetated areas are nearly always greater than 0 and, in general, the healthier and denser the vegetation, the higher the vegetation-index value. Different vegetation species at 100-percent cover can have different vegetation-index values as a result of varying chlorophyll content, internal leaf structure, and canopy structure (Glenn and others, 2008). These variations can reduce the significance of relationships between the vegetation index and vegetation cover. Vegetation indices that are based on a simple combination of the near infrared and red wavelengths such as the NDVI are sensitive to the quantity of green leaf vegetation in a scene, but also are influenced by the composite background reflectance of the soil surface, plant litter, and woody plant material, particularly in areas of moderate-to-sparse vegetation cover. The MSAVI and EVI are in a group of vegetation indices that use a canopy background adjustment factor to reduce the influence of soil and background reflectance on the index to increase the signal from healthy vegetation in the image.

The Normalized Difference Vegetation Index, NDVI, EVI, and MSAVI were calculated from nine atmospherically corrected 2005–11 summer Landsat 5 TM scenes selected for evaluation. Each calculated vegetation-index image was evaluated for its effectiveness in predicting ET_g, which is assumed directly proportional to phreatophytic shrub density. The evaluation was done by comparing area-weighted averages of vegetation-index values in the source area for each ET site with ET_g computed from each site (Moreo and others, 2007) using ordinary least-squares regression. Coefficients of determination (r^2) for all the vegetation indices evaluated were consistently above 0.8 (table 4). The Modified Soil-Adjusted Vegetation Index regularly exhibited r^2 equal to or better than the other vegetation indexes for all images evaluated and was selected for basin-scale ET_g estimation.

Vegetation assemblages, or ET units, outside the playa boundaries were determined from the MSAVI images. Each image was partitioned into five ET units (open water, very sparse desert shrub, sparse-to-dense desert shrub, grassland, and dense meadow and marshland; fig. 8) using threshold values determined from information gathered during field reconnaissance and mapping of the GDAs in conjunction with NAIP and Landsat imagery. Evapotranspiration estimates for vegetated ET units were calculated by linearly scaling the ET-rate range so that the highest ET rate was assigned to the highest MSAVI value in the ET unit and the lowest ET rate was assigned to the lowest MSAVI value in the ET unit, in the same manner as described in Welch and others (2007). Discharge for the Tule Valley playa and open water ET units were calculated using a single rate across the area of each unit (table 2). Calculations were made for each individual summer scene and for a 2007–08 midsummer mean scene calculated as the mean of MSAVI for the July 18, 2007, and August 21, 2008, scenes. These scenes were selected to calculate the midsummer average because they exhibited the highest r^2 values when compared with ET_g from the BARCAS study ET stations.

Table 4. Coefficients of determination describing relations between vegetation indexes and site-scale groundwater evapotranspiration (ET_g) in the Spring, Snake, and White River Valleys, Nevada and Utah.

[in/yr, inches per year; NDVI, normalized difference vegetation index; EVI, enhanced vegetation index; MSAVI, modified soil adjusted vegetation index]

Site	ET_g (in/yr)[1]	July 12, 2005	July 15, 2006	July 2, 2007	July 7, 2007	July 18, 2007	June 18, 2008	August 21, 2008	August 11, 2010	June 27, 2011
Mean source area, NDVI										
WRV-2	0.77	0.21	0.17	0.16	0.16	0.13	0.17	0.14	0.17	0.17
SPV-1	1.44	0.12	0.11	0.11	0.10	0.11	0.12	0.10	0.12	0.12
SPV-2	2.9	0.16	0.14	0.14	0.13	0.14	0.14	0.13	0.16	0.16
SNV-1	3.82	0.16	0.14	0.14	0.12	0.13	0.14	0.13	0.14	0.16
WRV-1	3.89	0.25	0.20	0.19	0.17	0.18	0.19	0.17	0.17	0.18
SPV-3	18.97	0.51	0.36	0.34	0.39	0.29	0.43	0.27	0.27	0.45
Coefficient of determination (r^2)		0.90	0.89	0.93	0.92	0.92	0.94	0.90	0.86	0.97
Mean source area, EVI										
WRV-2	0.77	0.16	0.13	0.13	0.12	0.11	0.13	0.10	0.14	0.13
SPV-1	1.44	0.12	0.11	0.12	0.10	0.11	0.12	0.10	0.13	0.12
SPV-2	2.9	0.14	0.13	0.13	0.12	0.12	0.13	0.12	0.14	0.14
SNV-1	3.82	0.14	0.12	0.12	0.10	0.11	0.12	0.11	0.12	0.13
WRV-1	3.89	0.19	0.15	0.15	0.14	0.14	0.15	0.13	0.13	0.14
SPV-3	18.97	0.39	0.27	0.28	0.29	0.23	0.34	0.20	0.22	0.35
Coefficient of determination (r^2)		0.94	0.95	0.98	0.95	0.97	0.97	0.96	0.90	0.98
Mean source area, MSAVI										
WRV-2	0.77	0.13	0.11	0.10	0.10	0.09	0.11	0.08	0.11	0.11
SPV-1	1.44	0.10	0.09	0.09	0.08	0.09	0.10	0.08	0.10	0.10
SPV-2	2.9	0.11	0.10	0.11	0.10	0.10	0.11	0.10	0.12	0.12
SNV-1	3.82	0.12	0.10	0.10	0.09	0.10	0.10	0.09	0.11	0.11
WRV-1	3.89	0.15	0.12	0.12	0.11	0.11	0.13	0.11	0.11	0.12
SPV-3	18.97	0.35	0.22	0.24	0.25	0.20	0.29	0.18	0.19	0.30
Coefficient of determination (r^2)		0.95	0.95	0.98	0.96	0.98	0.97	0.97	0.93	0.98

[1]Moreo and others (2007).

Vegetation variations owing to the presence of excess soil moisture, annual plants, and biological soil crusts may cause variation in ET_g calculations. At the Tule Valley RAWS station, examination of long-term precipitation records showed wetter than normal conditions in April and May of 2005 and 2010 as well as April–August 2011. Groundwater evapotranspiration calculated from the 2005, 2010, and 2011 scenes was discarded for that reason. The July 2, 2007, scene also resulted in anomalously high ET_g possibly because of the presence of annual plants (plants with a life cycle that lasts only one year) in the scene. Exact causes of scene variation are unknown, but they are thought to be associated with ecosystem response to precipitation pulses. Ecosystem function in arid environments is a function of precipitation timing and amount; and seed germination is typically triggered by rainfall that exceeds a minimum amount (Schwinning and Sala, 2004). It was observed during this study that a wetter than normal spring or fall appeared to trigger annual plants to germinate in larger numbers than in average years. In the end, MSAVI values for the 2007–08 midsummer mean scene were determined to best represent the long-term distribution of phreatophytic vegetation in the GDAs of interest and used to apply scaled ET-rate ranges to each ET unit.

Limitations of Methodology

Groundwater-evapotranspiration rates could vary due to varying hydrologic conditions including local precipitation amounts, soil texture, aquifer properties, surface morphology, and discharge area characteristics. This study assumes that the general rates applied to ET units are appropriate for the vegetation conditions and hydrologic properties of the valleys in the study area. Valleys in the study area are lower in elevation than valleys from which ET rates were estimated during the BARCAS study. Lower elevation valleys may experience warmer growing season temperatures and increased ET as a result. Variations in satellite imagery due to pixel shifts, incomplete atmospheric corrections, and local precipitation events also can result in variations in ET_g calculations.

Groundwater Geochemistry

Geochemical analyses are presented for water samples collected from 13 sites in Pine Valley and 11 sites in Wah Wah Valley. Groundwater sampling sites included a total of 12 observation, domestic, and stock wells and 12 perennial springs (table 5). The water samples were analyzed for major ions, nutrients, and selected trace metals to characterize general geochemistry and patterns of water quality. Water samples also were analyzed for a suite of environmental tracers that included the stable isotopes of oxygen ($\delta^{18}O$), and hydrogen ($\delta^{2}H$), and carbon ($\delta^{13}C$); the radioactive isotopes of carbon (^{14}C) and hydrogen (^{3}H); and dissolved noble gases including ^{3}He, ^{4}He, ^{20}Ne, ^{40}Ar, ^{84}Kr, ^{129}Xe, respectively. These environmental tracers and major-ion chemistry were used to investigate sources of recharge, groundwater flow paths, and groundwater ages to support the development of a conceptual model of the groundwater systems in these basins. What follows is an abridged description of the use of environmental tracer data in hydrologic conceptual model development; more detail is provided in Gardner and Heilweil (2014) and references therein.

Tritium is a radioactive isotope of hydrogen that can exist as part of a water molecule and is present in water worldwide in small concentrations. Tritium was used in this study to detect the presence of modern (post-1950s nuclear testing) groundwater and, combined with ^{3}He, evaluate groundwater age. Water containing greater than 0.4 tritium units (TU) is assumed to contain at least a fraction of modern water. The isotopes of ^{3}He and ^{4}He were apportioned into concentrations that originated from the atmosphere, tritium decay ($^{3}He_{trit}$), and uranium/thorium-series decay in the crust (terrigenic helium-4, $^{4}He_{terr}$). In this analysis of $^{4}He_{terr}$, the mantle was not considered as a source of helium (He) gas.

The $^{3}He_{trit}$ fraction is the radioactive decay product of ^{3}H and the concentration of both are used for $^{3}H/^{3}He_{trit}$ dating. Apparent $^{3}H/^{3}He_{trit}$ ages were computed for samples having concentrations greater than 0.4 TU where ^{3}He also was measured. Modern precipitation is assumed to contain 6–9 TU in the study area (Gardner and Heilweil, 2014). Because the addition of ^{3}H-free water does not appreciably alter the $^{3}H/^{3}He_{trit}$ ratio, apparent ^{3}H ages calculated for mixed waters only represent the age of the young fraction of that mixture.

Terrigenic helium-4 was used in this study as a qualitative dating tool that helped identify and categorize samples of mixed age when its abundance is considered along with $^{3}H/^{3}He$ and radiocarbon ages. Analysis of local $^{4}He_{terr}$ production rates was outside the scope of this study and no attempt was made to accurately date groundwater using $^{4}He_{terr}$. However, Solomon (2000) reported average crustal ^{4}He production rates ranging from 0.28 to 2.4 μccSTP (micro cubic centimeters at standard temperature and pressure) per cubic meter (m^3) per year; at these rates, groundwater will not acquire significant concentrations of $^{4}He_{terr}$ (more than about 2 x 10^{-8} cubic centimeters at standard temperature and pressure per gram [ccSTP/g] until it has been in contact with aquifer materials for more than 1,000 years. Therefore, even without precise knowledge of local production rates, $^{4}He_{terr}$ is particularly useful for identifying old water in samples of mixed age because it is often elevated by orders of magnitude in old waters and not easily disguised by dilution with young groundwater.

Table 5. Selected attributes of groundwater sites with chemical analyses from Pine and Wah Wah Valleys and surrounding areas, Utah.

[Sample identification (ID): See figure 10 for locations. Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). **Abbreviations**: USGS, U.S. Geological Survey; mm/dd/yyyy, month/day/year; LCAU, lower carbonate aquifer unit; VU, volcanic unit; —, no information; NCCU, non-carbonate confining unit; USCU, upper siliciclastic confining unit]

Sample ID	USGS site number	USGS site name	Site type	Latitude (decimal degrees)	Longitude (decimal degrees)	Well depth (feet)	Depth to top and bottom of openings (feet)	Altitude of land surface (feet)	Hydrogeologic unit	Sample date (mm/dd/yyyy)
1	382901113295701	(C-27-15)11aba-S1	Spring (piezometer)	38.483556	–113.499194	3.5	2.5–3.5	5,665	LCAU/VU	12/04/2012
2	382856113293301	(C-27-15)12bbc-1	Spring (piezometer)	38.482083	–113.492417	4.1	3.1–4.1	5,532	LCAU/VU	12/04/2012
3	382344113305901	(C-28-15)10abb-S1	Spring	38.395639	–113.517194	—	—	5,850	LCAU/VU	12/04/2012
4	382016113364001	(C-28-16)35bac-S1	Spring	38.337444	–113.611944	—	—	7,210	LCAU	12/05/2012
5	381045113470701	(C-30-17)19ddc-S1	Spring	38.179167	–113.785167	—	—	6,900	Basin fill/VU	12/06/2012
6	382445113501401	(C-27-18)35ccb-1	Spring (piezometer)	38.412611	–113.837139	2.5	1.5–2.5	6,275	Basin fill/VU/LCAU	12/05/2012
7	382550113504001	(C-27-18)27dba-1	Spring (piezometer)	38.430639	–113.844444	—	—	6,335	Basin fill/LCAU/VU	12/05/2012
8	383131113214301	(C-26-14)25aad-1	Observation well	38.525250	–113.362750	1,135	888–1,114	4,760	Basin fill	12/06/2012
9	383538113450801	(C-25-17)33dab-1	Domestic well	38.593861	–113.753028	628	—	5,275	Basin fill	12/03/2012
10	381344113512301	(C-30-18) 3bcc-1	Domestic well	38.228861	–113.856278	430	390–430	7,805	VU	10/23/2013
11	383402113440601	(C-26-17) 3cda-1	Observation well	38.572861	–113.742000	882	640–861	5,248	Basin fill	08/28/2013
12	382259113433701	(C-28-17)11cca-1	Observation well	38.383015	–113.727751	970	270–970	5,683	Basin fill	10/02/2013
13	381152113442801	(C-30-17)15cab-1	Domestic well	38.197833	–113.741167	385	365–385	6,550	Basin fill	08/29/2013
14	382539113250601	(C-27-14)28ddd-2	Observation well	38.427461	–113.419134	987	780–1,320	5,085	Basin fill	08/27/2013
15	382101113170801	(C-28-13)26bbd-1	Stock well	38.350306	–113.285500	200	100–200	6,160	VU	09/18/2013
16	381957113163701	(C-28-13)35acc-1	Stock well	38.332583	–113.277028	—	—	6,240	VU	09/18/2013
17	382423113243601	(C-28-14) 3bcd-1	Observation well	38.406500	–113.414083	1,480	700–1,480	5,210	Basin fill/VU	10/21/2013
[1]18	383825113410801	(C-25-16)18bdd-1	Stock/observation well	38.640300	–113.685684	340	—	5,085	Basin fill	06/15/2011
[1]19	384042113181601	(C-24-13)34ccb-1	Stock well	38.678154	–113.305320	294	—	4,655	Basin fill	06/15/2011
[1]20	381848113292701	(C-29-15) 2dad-S1	Spring	38.313130	–113.491750	—	—	6,150	VU	06/28/2011
[1]21	382238113205301	(C-28-13)18adb-S1	Spring	38.377350	–113.348880	—	—	5,530	Basin fill/VU	06/28/2011
[1]22	381702113383101	(C-29-16)16dbd-S1	Spring	38.283851	–113.642749	—	—	7,320	NCCU	10/02/2008
[1]23	382024113502101	(C-28-18)27dda-S1	Spring	38.339960	–113.839975	—	—	6,670	VU	10/02/2008
[1]24	383452113572301	(C-26-19) 3abc-S1	Spring	38.581160	–113.957250	—	—	7,150	USCU	06/16/2011

[1]Sample collected by the Utah Geological Survey and reported in Gardner and Heilweil (2014).

The source of He is distinguishable by the relative abundance of ^{3}He and ^{4}He isotopes, which can be expressed as R/R_a. With R defined as the $^{3}He/^{4}He$ ratio in groundwater and R_a as the atmospheric $^{3}He/^{4}He$ ratio, groundwater in contact with the atmosphere has an R/R_a value of 1, and groundwater containing crustal helium will have an R/R_a value less than 1 and approaching 0.01. Because He dissolved in groundwater is conservative and not subject to radioactive decay (unlike ^{3}H or ^{14}C) or dilution by chemical reaction (for example, ^{14}C reaction with carbonate [CO_3] minerals), R/R_a in groundwater generally decreases with age as it acquires crustal $^{4}He_{terr}$. Conversely, ^{3}H decay increases $^{3}He_{trit}$ in modern waters and can result in R/R_a values slightly greater than 1.

Carbon-14 was used to estimate the age of groundwater in Pine and Wah Wah Valleys that is more than about 2,000 years old. Unadjusted radiocarbon ages were calculated from non-normalized ^{14}C activities of dissolved inorganic carbon using the Libby half-life (5,568 years), assuming an initial ^{14}C activity of 100 percent modern carbon (pmC). Radiocarbon age adjustments were made using the formula-based inorganic adjustment model of Fontes and Garnier (1979). The adjustment model used standard assumptions for the ^{14}C activities of carbonate minerals and soil gas carbon dioxide (CO_2; 0 and 100 pmC, respectively) and $\delta^{13}C$ of carbonate minerals (0 permil; Plummer and Sprinkle, 2001; Kennedy and Genereux, 2007). Soil gas CO_2 was assumed to have a $\delta^{13}C$ value of –22 permil based on the reported average for similar terrain in Utah (Hart and others, 2010). Because it is recognized that atmospheric ^{14}C has not been constant (de Vries, 1958), radiocarbon ages were calibrated to years before present (BP) using the IntCal13 radiocarbon calibration curve (Stuiver and others, 2005; Reimer and others, 2013). Calibrated Fontes and Garnier (F&G) adjusted ages are considered conservative and representative of the true age of water in the region with an uncertainty of up to several thousand years (Gardner and Heilweil, 2014). If the model resulted in an unreasonable (negative) age, the adjusted age was designated as either modern (recharge after the mid-1950s), pre-modern (recharge before the mid-1950s), or as a mixture of modern and pre-modern water based on evaluating other age-related tracers.

The stable isotopes of water were used to better understand recharge sources to the groundwater basin. Stable isotopes are analyzed by measuring the ratio of the heavier, less abundant isotope (oxygen-18, ^{18}O; or deuterium, ^{2}H) to the lighter, more abundant (common) isotope (oxygen-16, ^{16}O; or ^{1}H). The values are reported as differences (δ, delta) relative to a reference standard known as Vienna Standard Mean Ocean Water (VSMOW) in parts per thousand (permil; Craig, 1961b; Coplen, 1994). The proportional variation in ^{2}H and ^{18}O results in isotopic compositions of precipitation (and groundwater sourced from precipitation) that plot along a linear trend referred to as a meteoric water line when $\delta^{2}H$ is plotted against $\delta^{18}O$. For a given area, where a sample plots on this trend is indicative of the season (winter versus summer) and altitude (mountain versus valley) that the precipitation fell in/at before recharging an aquifer.

Dissolved noble-gas samples (^{20}Ne, ^{40}Ar, ^{84}Kr, and ^{129}Xe) were used to determine noble-gas recharge temperatures (NGTs, assumed to equal the temperature of groundwater recharge as it crosses the water table) as an indicator of mountain versus valley recharge. Interpretation of NGTs for this purpose assumes a relationship exists between recharge altitude (H_r) and recharge temperature that mirrors a typical air-temperature lapse rate so that mountain recharge will have cooler temperatures than recharge occurring in adjacent valleys. The existence of this H_r-NGT relationship for the region including these basins is demonstrated in supplemental material provided in Gardner and Heilweil (2014). Noble gases dissolved in groundwater are primarily of atmospheric origin and their concentrations dissolved in water are a function of their solubility with the possible addition of excess air. Noble-gas concentrations and groundwater NGTs should be preserved along a groundwater flow path because most noble gases are geochemically inert and unlike physical temperatures and age tracers (^{14}C, $^{4}He_{terr}$, and $^{3}H/3He_{trit}$) that change with time.

Noble-gas concentrations were used in the closed-system equilibration (CE) model (Aeschbach-Hertig and others, 2000; Kipfer and others, 2002) to calculate NGTs. Recharge altitude (the proxy for barometric pressure) was an unknown parameter in this model, which is a typical situation in locations with high topographic relief. Because the NGTs and H_r are correlated, a range of NGTs was calculated for each sample as described by Manning and Solomon (2003) and Manning (2011). This range consists of using a minimum recharge altitude (H_{min}), typically that of the sample site, to calculate a maximum noble-gas recharge temperature (NGT_{max}). Conversely, the maximum recharge altitude (H_{max}) in a basin is used to calculate a minimum noble-gas recharge temperature (NGT_{min}). The value of H_{max} for each sample was selected to include the highest water-table altitude where recharge could have occurred and is based on the altitude of the highest observed springs in a contributing area. For this study, H_{max} was assumed to be 8,400 and 8,000 ft for samples collected from valley wells in the Pine and Wah Wah Valley drainage basins, respectively. Maximum recharge altitude was assumed to be between 6,600 and 8,400 ft for samples collected from mountain springs and wells depending on their location. Average recharge altitude (H_{avg})and average noble-gas recharge temperature (NGT_{avg}) also are calculated using the mid-point altitude and are assumed to represent the actual recharge temperature of the sample with the minimum and maximum values representing a conservative range of uncertainty. Uncertainty in NGTs owing to noble-gas measurement precision is generally 0.5–1.5 °C (Manning and Solomon, 2003; Manning, 2009; Masbruch and others, 2012).

Major Ions, Nutrients, and Selected Trace Metals

Dissolved major-ion, nutrient, and selected trace-metal concentrations in groundwater samples were analyzed to assess general water-quality conditions and to evaluate groundwater source areas and flow paths in Pine and Wah Wah Valleys (table 6). Concentrations of dissolved solids for all sites ranged from 120 to 1,290 mg/L and exceeded the U.S. Environmental Protection Agency (EPA) secondary standard of 500 mg/L for drinking water (U.S. Environmental Protection Agency, 2014) at only six of the twenty-four sample sites (sites 3, 6, 16, 19, 20, and 24). Additional exceedances of EPA secondary standards include two sites with elevated manganese (sites 6 and 14) and one with elevated sulfate (site 24). Trace metals were sampled for only 17 of the 24 sites. Arsenic was reported to exceed the EPA maximum contaminant levels (MCL) of 10 micrograms per liter (µg/L) in a supply well at the Desert Experimental Range and an observation well in Pine Valley (sites 9 and 11), as well as in one stock well in the volcanic bedrock hills of southwestern Wah Wah Valley (site 16). Arsenic is likely derived from alluvial sediments eroded from extensive volcanic rocks in the surrounding mountains. Nutrient (nitrate plus nitrite) concentrations in all samples were well below the EPA MCL of 10 mg/L (table 6).

The principal dissolved constituents in most samples were calcium, sodium, bicarbonate, and chloride, all of which are directly derived from dissolution of the carbonate and volcanic rocks and alluvium eroded from these rocks that are abundant throughout the study area. Stiff diagrams and a piper plot illustrate the differences, often subtle, in water types across the study area (figs. 10, 11). There are notable differences in groundwater major-ion chemistry between the Pine and Wah Wah Valley drainage basins as well between mountain and valley groundwaters in each drainage basin. For this reason, further sample results are presented in the following four groups (1) Pine Valley-mountain groundwater (PV-mountain groundwater); (2) Pine Valley-valley groundwater (PV-valley groundwater); (3) Wah Wah Valley-mountain groundwater (WW-mountain groundwater); and (4) Wah Wah Valley-valley groundwater (WW-valley groundwater). Mountain groundwaters were sampled from springs and wells screened in bedrock or shallow alluvium in the foothills or mountains adjacent to the valleys and well above the valley floors. Valley groundwaters were all sampled from relatively deep (298–1,480-ft deep) alluvial wells generally along the central axis of each valley.

Samples representing PV-mountain groundwater (sites 4, 5, 6, 7, 10, 13, 22, 23, and 24) are dominantly calcium-bicarbonate (Ca-HCO_3) waters. Apart from one spring (site 22) that discharges from quartzite talus at more than 7,300 ft with a dissolved-solids concentration of 120 mg/L, all PV-mountain groundwaters had dissolved-solids concentrations ranging from 239 to 872 mg/L. Samples representing PV-valley groundwater (sites 9, 11, 12, and 18) were dominantly sodium-bicarbonate (Na-HCO_3) or calcium-sodium-bicarbonate (Ca-Na-HCO_3) water with dissolved-solids concentrations ranging from 212 to 234 mg/L, all lower than eight of the nine PV-mountain groundwaters sampled.

Samples representing WW-mountain groundwater (sites 1, 2, 3, 15, 16, 20, and 21) have major-ion chemical signatures that differ on the east and west sides of the basin. Sites 1 and 2 are different discharge points that are both a part of the Wah Wah Springs complex and separated by about 0.4 mi. These sites have nearly identical chemistry for all analytes except for elevated iron and manganese in site 2 that is likely associated with oxidation of the steel piezometer from which the sample was collected. Samples from the Wah Wah Range on the west side of the valley are all Ca-HCO_3 waters with dissolved-solids concentrations ranging from 336 to 575 mg/L. Samples collected from springs and wells in the hills that bound Wah Wah Valley to the southeast are calcium-chloride or sodium-calcium-chloride waters with dissolved-solids concentrations ranging from 387 to 712 mg/L. Samples representing WW-valley groundwater (sites 8, 14, 17, and 19) are dominantly sodium-chloride (Na-Cl) waters except for the southernmost (site 17), which is calcium-sodium-bicarbonate water. The northernmost of these (site 19) is on the edge of the Wah Wah Valley dry playa and within several miles of Sevier Lake. This site had 1,290 mg/L of dissolved solids, dominantly sodium-chloride, and likely caused by dissolution of evaporite minerals in the subsurface. The three southernmost WW-valley groundwater samples (sites 8, 14, and 17) had dissolved-solids concentrations ranging from 318 to 432 mg/L. These samples had major-ion chemical signatures that most closely resemble WW-mountain groundwaters in the southeast portion of the basin (sites 15 and 21) and that are distinctly different than WW-mountain groundwaters sampled in the Wah Wah Range on the west side of the basin (sites 1, 2, 3, and 20; fig. 10).

Table 6. Measured field parameters and dissolved concentrations of major ions, nutrients, and selected metals for groundwater sampled from Pine and Wah Wah Valleys and surrounding areas, Utah.

[Sample identificaiton (ID): See figure 10 for locations and table 5 for additional site information. Values shown in red exceed the U.S. Environmental Protection Agency (EPA) maximum contaminant level or secondary standard. **Abbreviations**: USGS, U.S. Geological Survey; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; E, estimated; —, no information; <, less than]

Sample ID	USGS site number	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Dissolved oxygen (mg/L)	Dissolved solids (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Bromide (mg/L as Br)	Calcium (mg/L as Ca)	Chloride (mg/L as Cl)	Fluoride (mg/L as F)	Iron (µg/L as Fe)
1	382901113295701	19.0	609	7.1	5.4	336	254	310	0.111	64.6	33.9	0.12	4.9
2	382856113293301	17.5	613	7.3	3.7	E 338	255	311	E 0.041	64.3	34.0	0.12	148
3	382344113305901	13.7	973	6.8	5.1	575	325	397	0.247	120	100	0.06	6.0
4	382016113364001	9.3	566	6.9	5.3	336	291	355	0.017	104	11.0	0.11	<4.0
5	381045113470701	11.4	588	6.8	8.0	E 345	239	292	E 0.031	86.2	26.9	0.47	<4.0
6	382445113501401	11.6	1,390	6.9	1.8	E 831	248	303	E 0.750	132	231	0.11	21.4
7	382550113504001	9.3	409	7.3	2.8	E 239	150	183	E 0.078	43.3	29.7	0.11	<4.0
8	383131113214301	19.9	777	8.1	0.6	E 432	92	112	E 0.096	35.7	114	0.57	208
9	383538113450801	16.6	284	7.7	7.5	205	115	141	0.050	19.1	8.4	1.1	4.0
10	381344113512301	12.5	473	7.6	1.4	271	205	250	0.074	54.6	18.4	0.90	91.0
11	383402113440601	19.5	307	8.3	6.0	234	103	126	0.075	20.0	19.9	0.83	19.4
12	382259113433701	20.0	325	7.7	—	219	98.7	120	0.112	35.5	28.8	0.36	34.5
13	381152113442801	16.7	498	7.3	5.9	316	153	187	0.205	61.4	50.3	0.42	95.4
14	382539113250601	21.9	546	8.9	0.6	318	77	94	0.180	36.4	78.0	0.28	38.6
15	382101113170801	14.6	632	7.3	6.8	387	105	128	0.230	58.1	106	0.41	25.5
16	381957113163701	15.1	1,180	7.1	3.6	712	190	232	0.453	93.1	186	0.52	45.7
17	382423113243601	23.7	583	7.6	6.0	391	113	138	0.138	42.9	56.5	0.42	48.2
18	383825113410801	16.7	303	7.6	—	212	100	122	—	23	26	—	—
19	384042113181601	16.2	2,120	7.6	—	1,290	129	157	—	51	614	—	—
20	381848113292701	12.3	866	6.6	—	570	298	364	—	109	101	—	—
21	382238113205301	18.6	622	7.9	—	448	108	132	—	54	125	—	—
22	381702113383101	14.8	167	7.2	—	120	57.4	70	—	18	11	—	—
23	382024113502101	15.4	525	7.6	—	340	197	240	—	49	36	—	—
24	383452113572301	9.5	1,170	6.8	—	872	315	384	—	198	93	—	—
EPA maximum contaminant level (MCL)													
—	—	—	—	—	—	—	—	—	—	—	—	—	—
EPA secondary standard													
—	—	—	—	—	—	500	—	—	—	—	250	2	300

Table 6. Measured field parameters and dissolved concentrations of major ions, nutrients, and selected metals for groundwater sampled from Pine and Wah Wah Valleys and surrounding areas, Utah.—Continued

[Sample identificaiton (ID): See figure 10 for locations and table 5 for additional site information. Values shown in red exceed the U.S. Environmental Protection Agency (EPA) maximum contaminant level or secondary standard. **Abbreviations**: USGS, U.S. Geological Survey; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; E, estimated; —, no information; <, less than]

Sample ID	USGS site number	Magnesium (mg/L as Mg)	Manganese (µg/L as Mn)	Potassium (mg/L as K)	Silica (mg/L as SiO_2)	Sodium (mg/L as Na)	Sulfate (mg/L as SO_4)	Nitrate plus nitrite (mg/L as N)	Ortho-phophate (mg/L as P)	Arsenic (µg/L as As)	Molybdenum (µg/L as Mo)	Selenium (µg/L as Se)	Uranium (µg/L as U)
1	382901113295701	30.3	<0.16	1.20	13.0	19.5	14.2	1.49	0.006	1.4	0.253	0.67	1.1
2	382856113293301	30.9	8.04	1.23	14.2	19.7	14.1	1.49	0.006	1.1	0.237	0.59	1.2
3	382344113305901	39.0	<0.16	1.45	38.8	32.5	37.1	2.45	0.026	2.4	0.378	1.4	10
4	382016113364001	13.5	0.20	0.60	12.6	9.83	10.6	<0.040	0.005	0.32	0.209	0.27	1.61
5	381045113470701	14.3	<0.16	1.57	19.7	23.8	27.6	0.152	0.014	0.49	1.06	0.37	5.7
6	382445113501401	52.7	55.4	1.09	45.0	82.1	138	<0.040	0.018	3.8	0.970	1.9	21
7	382550113504001	18.1	0.25	1.66	14.1	18.2	16.0	1.79	0.037	2.7	0.572	0.58	0.75
8	383131113214301	18.8	9.87	12.4	26.2	74.4	92.5	0.238	0.016	6.7	4.16	0.53	1.3
9	383538113450801	7.87	<0.16	5.21	47.4	28.1	11.8	1.53	0.023	46	2.87	0.50	5.0
10	381344113512301	17.2	18.9	1.31	13.8	20.7	15.9	0.374	<0.004	0.46	0.733	1.6	18
11	383402113440601	5.14	4.73	6.70	55.7	32.5	13.8	1.42	0.045	20	3.34	0.71	1.7
12	382259113433701	6.50	8.98	2.61	23.6	24.6	19.7	0.898	0.006	2.7	1.37	0.74	3.2
13	381152113442801	8.50	41.1	4.14	48.9	25.6	19.8	0.498	0.015	2.1	1.10	0.95	7.7
14	382539113250601	12.5	63.8	6.22	21.3	46.4	59.4	0.298	0.029	3.6	4.52	0.41	0.31
15	382101113170801	16.2	16	4.65	41.4	36.9	21.2	5.96	0.019	3.9	1.54	1.1	2.3
16	381957113163701	27.8	3.59	3.62	28.1	109	130	2.24	0.021	35	1.90	5.7	9.2
17	382423113243601	18.1	10.3	9.02	57.6	40.9	66.7	1.75	0.017	4.0	1.65	0.89	3.6
18	383825113410801	14.5	—	3.81	—	30	48.2	1.86	—	—	—	—	—
19	384042113181601	39.1	—	14.4	—	372	167	2.41	—	—	—	—	—
20	381848113292701	28.5	—	1.17	—	60	69.8	0.01	—	—	—	—	—
21	382238113205301	19.9	—	4.42	—	51	40.6	0.99	—	—	—	—	—
22	381702113383101	4.20	—	0.83	—	8.0	4	<0.5	—	—	—	—	—
23	382024113502101	4.40	—	2.30	—	53	15	3.1	—	—	—	—	—
24	383452113572301	46.4	—	4.23	—	48	334	0.06	—	—	—	—	—
EPA maximum contaminant level (MCL)													
—	—	—	—	—	—	—	—	—	—	10	—	50	30
EPA secondary standard													
—	—	—	50	—	—	—	250	10	—	—	—	—	—

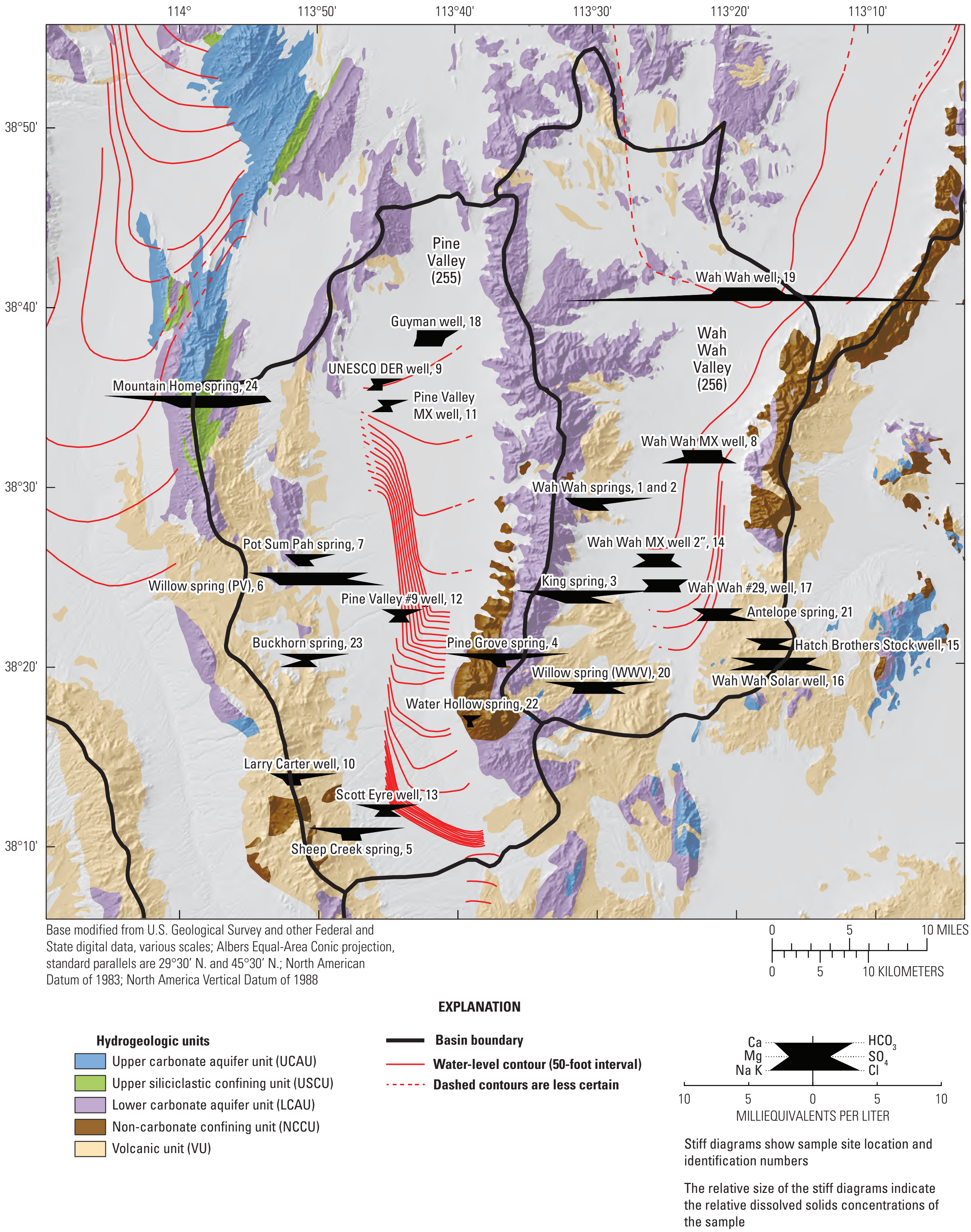


Figure 10. Locations of groundwater sample sites and corresponding stiff diagrams showing major-ion composition of groundwater in Pine and Wah Wah Valleys, Utah.

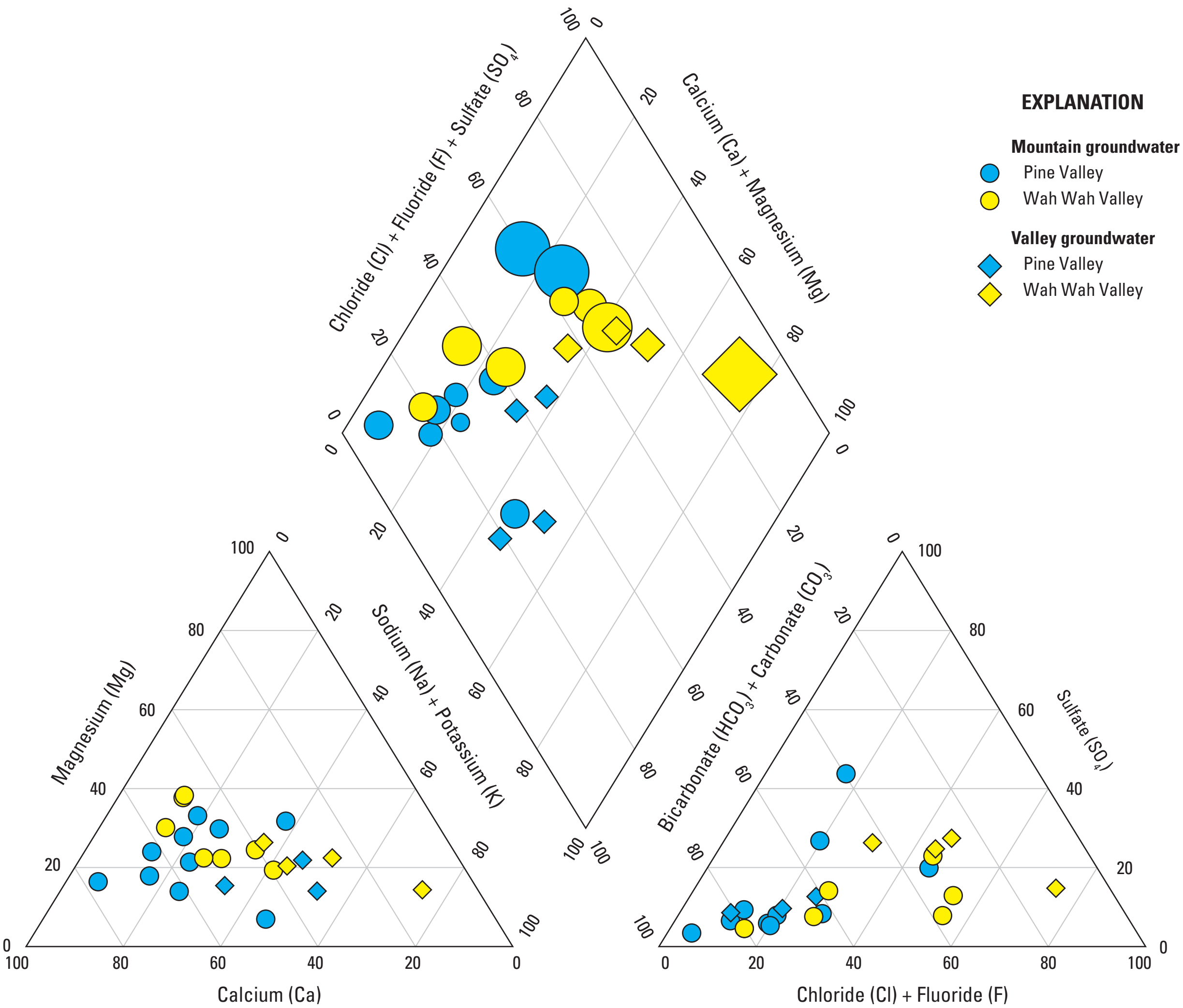


Figure 11. Major-ion composition of groundwater in Pine and Wah Wah Valleys and surrounding areas, Utah. The size of the symbol in the upper diamond represents the relative dissolved-solids concentration of the sample.

Tritium and Helium

Groundwater ^3H concentrations ranged from below detection (about 0.1 TU) to 5.2 TU (table 7). Terrigenic helium-4 concentrations ranged from not detected to 4.14×10^{-7} ccSTP/g and R/R_a values ranged from 0.15 to 1.05 for the 19 samples where dissolved noble gases were measured. The combined analysis of tritium and helium clearly identifies a component of "modern" water (less than about 60 years old) at 11 of the 24 sites sampled (sites 1–7, 10, 20, 22, and 24). All of these sites are in the mountains surrounding the valleys (PV-mountain and WW-mountain groundwater). The high end of the $^4He_{terr}$ concentrations and low end of the R/R_a values indicate that many of the samples contain water that is too old to be dated using ^3H. Some mountain samples appear to be pre-modern (more than 60 years old) or mixtures of modern and pre-modern water based on tritium and helium concentrations (sample identifications [IDs] 3, 10, 13, 15, 16, 21, 23, and 24), indicating areas of mountain residence times of 60 years or more. None of the valley samples (sample IDs 8, 9, 11, 12, 14, 17, 18, and 19; PV-valley and WW-valley groundwater) contained even a fraction of modern water (table 7).

Ratios of ^3H to $^3He_{trit}$ were used to calculate apparent ages of groundwater discharging from six mountain springs (sites 1, 2, and 4–7; table 7). Samples from Wah Wah Spring (sample IDs 1 and 2) had apparent $^3H/^3He_{trit}$ ages of 27 and 29 years, respectively. Samples from sites 4–7, which are springs in the mountains surrounding Pine Valley, had apparent $^3H/^3He_{trit}$ ages of 1–21 years. The remaining groundwater samples could not be dated by this method, either because they contained too little ^3H or because of complications owing to elevated $^4He_{terr}$.

Table 7. Stable- and radio-isotope data used to estimate ages of groundwater sampled from Pine and Wah Wah Valleys, Utah.

[Sample identification (ID): See figure 10 for locations. Pre-modern, groundwater that recharged prior to the mid-1950s. Modern, groundwater that recharged after the mid-1950s. Mixture is a sample that contains a mixture of pre-modern and modern groundwater. **Abbreviations**: USGS, U.S. Geological Survey; $\delta^{18}O$, oxygen-18; permil, per million; D, deuterium; ^{3}H, tritium; TU, tritium units; ^{4}He, measured helium-4; ccSTP/g, cubic centimeters per gram of water at standard temperature and pressure; $^{4}He_{terr}$, terrigenic helium-4; $^{3}He_{trit}$, tritiogenic helium-3, $^{3}H/^{3}He_{trit}$, tritium/tritiogenic helium-3; BP, before present; ^{14}C, Carbon-14; pmC, percent modern carbon; ^{13}C, carbon-13; F&G, Fontes and Garnier (1979) model; +/–, plus or minus; —, no information; ND, not detected; <, less than]

Sample ID	USGS site number	$\delta^{18}O$ (permil)	δD (permil)	^{3}H and precision (TU)	R/Ra[1]	^{4}He (ccSTP/g)	$^{4}He_{terr}$ [2] (ccSTP/g)	$^{3}He_{trit}$ [2] (TU)	Apparent $^{3}H/^{3}He_{trit}$ age (years BP)	^{14}C (pmC)	$\delta^{13}C$ (permil)	Unadjusted ^{14}C age (thousands of years BP)	^{14}C age F&G (years BP)	Calibrated age (years BP)[3]	Age category
1	382901113295701	–14.5	–109	0.6 +/– 0.2	1.00	4.47E–08	3.74E–09	2.0	27	39	–8.7	8,000	100	—	Mixture[4]
2	382856113293301	–14.4	–110	0.5 +/– 0.2	1.00	4.39E–08	3.61E–09	2.0	29	38	–8.5	8,000	40	—	Mixture[4]
3	382344113305901	–12.6	–100	0.7 +/– 0.1	0.75	6.24E–08	1.93E–08	1.8	Mixture	97	–11.6	300	Mixture	—	Mixture[4]
4	382016113364001	–14.2	–106	5.2 +/– 0.3	1.00	4.01E–08	4.02E–09	2.2	6.3	99	–12.1	Modern	Modern	—	Modern
5	381045113470701	–13.2	–99.2	3.6 +/– 0.3	1.00	4.27E–08	ND	0.0	<1	103	–12.6	Modern	Modern	—	Modern
6	382445113501401	–12.3	–99.0	0.8 +/– 0.1	0.98	4.21E–08	4.15E–09	1.7	21	107	–9.9	Modern	Modern	—	Modern
7	382550113504001	–13.7	–104	2.6 +/– 0.2	1.05	4.13E–08	5.17E–09	4.0	17	61	–9.9	4,000	Modern	—	Modern
8	383131113214301	–14.7	–110	–0.1 +/– 0.1	0.37	1.39E–07	1.06E–07	—	Pre-modern	3.2	–5.6	28,000	16,000	19,000	Pleistocene
9	383538113450801	–14.7	–112	0.3 +/– 0.1	0.39	1.15E–07	7.61E–08	—	Pre-modern	17	–7.8	14,000	6,000	7,000	Holocene
10	381344113512301	–13.5	–102	1.5 +/– 0.1	0.23	5.23E–07	4.14E–07	—	Mixture	83	–11.8	2,000	Mixture	—	Mixture[4]
11	383402113440601	–14.4	–109	–0.01 +/– 0.2	0.57	1.48E–07	5.94E–08	—	Pre-modern	10	–6.8	19,000	9,000	10,000	Holocene
12	382259113433701	–13.8	–105	0.03 +/– 0.1	0.43	2.47E–07	2.09E–07	—	Pre-modern	36	–9.8	8,000	2,000	2,000	Holocene
13	381152113442801	–13.5	–102	0.05 +/– 0.1	0.15	2.35E–07	1.99E–07	—	Pre-modern	62	–11.1	4,000	Pre-modern	—	Late Holocene
14	382539113250601	–13.2	–102	0.02 +/– 0.1	0.72	6.66E–08	—	—	Pre-modern	48	–5.6	6,000	Pre-modern	—	Late Holocene
15	382101113170801	–13.5	–103	0.01 +/– 0.1	0.84	4.81E–08	1.73E–08	11.2	Pre-modern	60	–7.1	3,000	Pre-modern	—	Late Holocene
16	381957113163701	–13.5	–107	0.01 +/– 0.1	0.30	1.60E–07	1.24E–07	—	Pre-modern	37	–7.9	8,000	Pre-modern	—	Holocene
17	382423113243601	–13.5	–103	0.04 +/– 0.1	0.25	1.70E–07	1.32E–07	—	Pre-modern	45	–8.4	6,000	Pre-modern	—	Late Holocene
18	383825113410801	–13.8	–105	0.1 +/– 0.1	0.49	7.95E–08	4.04E–08	—	Pre-modern	11	–9.6	18,000	11,000	13,000	Pleistocene
19	384042113181601	–14.1	–106	0.1 +/– 0.1	0.43	9.83E–08	7.48E–08	—	Pre-modern	7.4	–9.2	21,000	14,000	17,000	Pleistocene
20	381848113292701	–13.1	–102	5.2 +/– 0.2	—	—	—	—	Modern	104	–11.9	Modern	Modern	—	Modern
21	382238113205301	–12.7	–113	0.1 +/– 0.1	—	—	—	—	Pre-modern	54	–12.2	5,000	500	—	Late Holocene
22	381702113383101	–14.8	–104	4.6 +/– 0.2	—	—	—	—	Modern	106	–13.0	Modern	Modern	—	Modern
23	382024113502101	–14.2	–105	0.1 +/– 0.1	—	—	—	—	Pre-modern	75	–7.9	2,000	Pre-modern	—	Late Holocene
24	383452113572301	–14.6	–111	1.6 +/– 0.1	—	—	—	—	Modern or Mixture	49	–9.9	6,000	Mixed	—	Mixture[4]

[1]R is the $^{3}He/^{4}He$ ratio of the sample, and Ra is the $^{3}He/^{4}He$ ratio of air (1.384×10^{-6}).

[2]Interpreted value derived using the closed-equilibrium dissolved-gas model (Aeschbach-Hertig and others, 2000; Kipfer and others, 2002).

[3]Radiocarbon ages calibrated using the program CALIB (Stuiver and others, 2005) with the IntCal13 radiocalibration curve (Reimer and others, 2013).

[4]Water samples categorized as mixed are dominantly mixtures of modern and Late Holocene groundwater.

Carbon-14 and Age Categories

Carbon-14 activity measured from dissolved inorganic carbon (DIC) in groundwater samples ranged from 3.2 to 107 pmC (table 7). A clear distinction is seen in ^{14}C activities between mountain and valley groundwaters. Pine Valley-mountain groundwater (sample IDs 4, 5, 6, 7, 10, 13, 22, 23, and 24) ranged from 49 to 107 pmC and WW-mountain groundwater (sample IDs 1, 2, 3, 15, 16, 20, and 21) ranged from 37 to 104 pmC, whereas PV-valley groundwater (sample IDs 9, 11, 12, and 18) ranged from 10 to 36 pmC and WW-valley groundwater (sample IDs 8, 14, 17, and 19) ranged from 3.2 to 48 pmC.

Adjusted and calibrated radiocarbon ages were calculated for the six samples with the lowest ^{14}C activities (sample IDs 8, 9, 11, 12, 18, and 19) and ranged from 2,000 to 19,000 years BP. These six sites are either PV-valley or WW-valley groundwaters. The remaining two valley samples (sites 14 and 17, WW-valley groundwater) yielded unreasonable (negative) adjusted radiocarbon ages indicating that they are too young to be reliably dated using ^{14}C. The combination of low ^{14}C activity, lack of ^{3}H, and elevated $^{4}He_{terr}$ in these two samples clearly indicate that they are pre-modern and possibly as old as several thousand years (table 7). Samples from Wah Wah Springs (sites 1 and 2) have adjusted radiocarbon ages of 100- and 40-years BP, respectively. However, given that the uncertainty of radiocarbon dates in these carbonate waters is as much as several thousand years, these ages are merely evidence that these samples contained a fraction of pre-modern water. Reliable adjusted radiocarbon ages could not be calculated for the remaining 14 samples (all PV-mountain and WW-mountain groundwaters), indicating that they are all modern, pre-modern, or mixed waters no more than about 2,000 years old.

Despite only being able to calculate ages (either $^{3}H/^{3}He$ or ^{14}C based) of groundwater for half of the sample sites, general age categories were assigned to all 24 samples based on evaluation of ^{3}H, He-isotope, and ^{14}C data (table 7). This categorization is modified from that presented by Gardner and Heilweil (2014) recognizing that significant variability can exist in isotope concentrations caused by mixing dynamics, variable crustal He production rates, and variable degrees of carbonate chemical reactions. Groundwater samples were categorized as one of the following:

(1) Modern (post-1950s),

(2) Mixture (modern and Late Holocene),

(3) Late Holocene (more than 60 and less than about 2,000 years),

(4) Holocene (more than 2,000 and less than about 11,700 years), and

(5) Pleistocene (more than about 11,700 years).

The criteria used to categorize the samples are summarized in table 8.

All modern and mixed groundwater is found in the mountains surrounding the valleys (sample IDs 1–7, 10, 20, 22, and 24; table 7; fig. 12). Four mountain samples were categorized as Late Holocene (sample IDs 13 and 23, PV-mountain groundwater; and sample IDs 15 and 21, WW-mountain groundwater) and one as Holocene (sample ID 16, WW-mountain groundwater). All five of these sites discharge from volcanic bedrock or alluvium eroded from volcanic rocks in the hills and mountains bordering the valleys. The presence of water this old in the mountains indicates that these are areas of low bedrock permeability, that they receive little recharge, or both. No modern groundwater or mixtures containing modern water were reported in valley wells in either valley. Samples representing PV-valley groundwater were either Holocene (sample IDs 9, 11, and 12) or Pleistocene (site 18). Samples representing WW-valley groundwater were either Late Holocene (sample IDs 14 and 17) or Pleistocene (sample IDs 8 and 19). The groundwater ages in both basins display expected patterns with the youngest samples being from high-altitude mountain sites and valley groundwater increasing in age in a downgradient direction (generally south to north; table 7; fig. 12).

Table 8. Criteria used to assign age categories to groundwater samples from Pine and Wah Wah Valleys, Utah.

[^{3}H, tritium; TU, tritium unit; $^{4}He_{terr}$, terrigenic helium-4; ccSTP/g, cubic centimeters at standard temperature and pressure per gram of water; ^{14}C, carbon-14; pmC, percent modern carbon; >, greater than; <, less than]

Groundwater age category	Criteria
Modern (post-1950s)	^{3}H greater than 0.4 TU, no significant $^{4}He_{terr}$ (less than about 1x10^{-8} ccSTP/g), and ^{14}C greater than about 60 pmC.
Mixture (modern and Late Holocene)	^{3}H greater than 0.4 TU and either elevated $^{4}He_{terr}$ (more than about 1x10^{-8} ccSTP/g) or ^{14}C less than than about 60 pmC or both.
Late Holocene (>60 and <2,000 years)	^{3}H less than 0.4 TU, elevated $^{4}He_{terr}$ (more than about 1x10^{-8} ccSTP/g), and carbon isotope data suggesting ages of less than about 2,000 years.
Holocene (>2,000 and <11,700 years)	^{3}H less than 0.4 TU, elevated $^{4}He_{terr}$ (more than about 4x10^{-8} ccSTP/g), and carbon isotope data suggesting ages of more than about 2,000 years.
Pleistocene (>11,700 years)	^{3}H less than 0.4 TU, elevated $^{4}He_{terr}$ (more than about 4x10^{-8} ccSTP/g), and carbon isotope data suggesting ages of more than about 11,700 years.

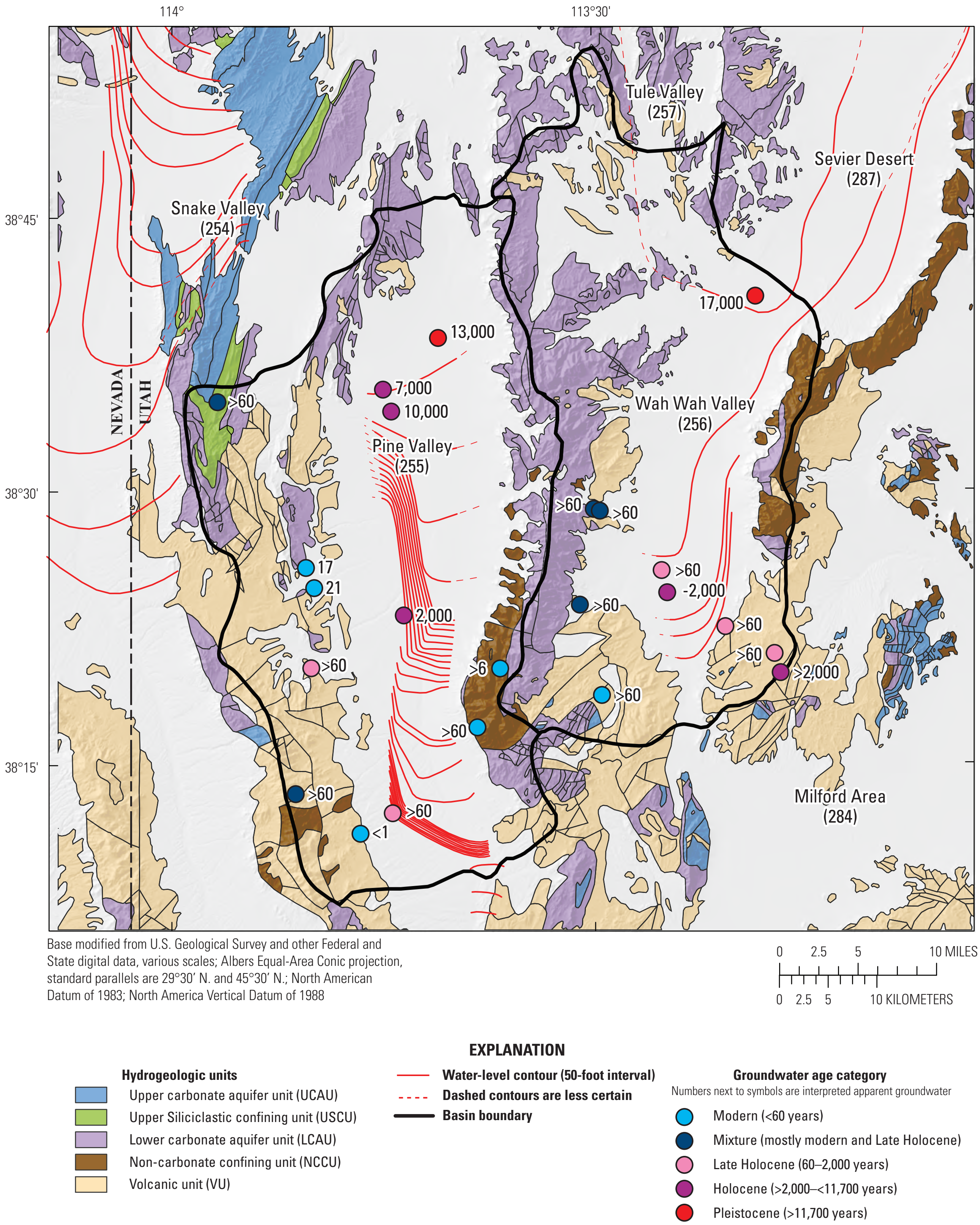


Figure 12. Groundwater-age categories and apparent groundwater ages based on multiple age-related environmental tracers for selected groundwater samples from Pine and Wah Wah Valleys, Utah.

Oxygen-18 and Deuterium

Stable-isotope compositions for the groundwater sampled from Pine and Wah Wah Valley drainage basins ranged from –14.8 to –12.3 permil and from –113 to –102 permil for $\delta^{18}O$ and δD, respectively (table 7). All waters plot near the Utah or Global Meteoric Water Line except for Antelope Spring (site 21) in the southeast foothills of Wah Wah Valley (fig. 13). This sample was preferentially enriched in $\delta^{18}O$ relative to δD because of evaporation, which is not surprising because this is a diffuse discharge spring that feeds a large, nearly stagnant pool. There were no significant differences between samples collected from Pine or Wah Wah Valleys or between samples collected from mountain or valley locations; all of the groups had a similar range in measured δD and $\delta^{18}O$ compositions.

Samples sourced from precipitation falling at higher altitudes or during the winter months will be isotopically lighter (more negative values) and plot lower and farther to the left along a meteoric water line, whereas samples sourced from precipitation falling at lower altitudes or during the summer months should be isotopically heavier (fewer negative values) and plot higher and farther to the right (fig. 13). When compared to 135 groundwater samples from 7 neighboring or nearby basins, Pine and Wah Wah Valley groundwaters were isotopically heavier than many of them. A subset (16) of eastern Great Basin mountain springs with modern ^{3}H-^{3}He ages defines a zone of modern mountain precipitation that generally aligns with the range of $\delta^{2}H$ values for modern cumulative winter precipitation (–120 to –110 permil) in these valleys presented by Friedman and others (2002) indicating that much of the geographic region is recharged by high-altitude winter precipitation. This recharge occurs as snow melt and either infiltrates in the mountains or generates runoff that infiltrates basin-fill aquifers near the mountain front. Twenty-one of 24 samples from Pine and Wah Wah Valleys were isotopically heavier than cumulative winter precipitation, clearly falling in the $\delta^{2}H$ range of cumulative annual precipitation and indicating that winter rain and melting snow is not the dominant source of recharge in Pine and Wah Wah Valleys.

Noble Gas- and Water-Table Temperatures

Because NGTs represent estimates of recharge temperature (the water-table temperature at the location of recharge), they can be compared to valley water-table temperatures to evaluate whether samples represent mountain or valley recharge. In many parts of the eastern Great Basin, mountain water-table temperatures are notably cooler than valley water-table temperatures, providing a clear contrast between the two (Gardner and Heilweil, 2014). And because of the conservative nature of dissolved noble gases in saturated freshwater systems, NGTs can be used to identify continuous groundwater flow between recharge and sample locations. For example, if samples collected from valley wells have NGTs that are clearly cooler than valley water-table temperatures, then they likely originated as mountain recharge and moved into the valley aquifer through the subsurface along a continuous flow path.

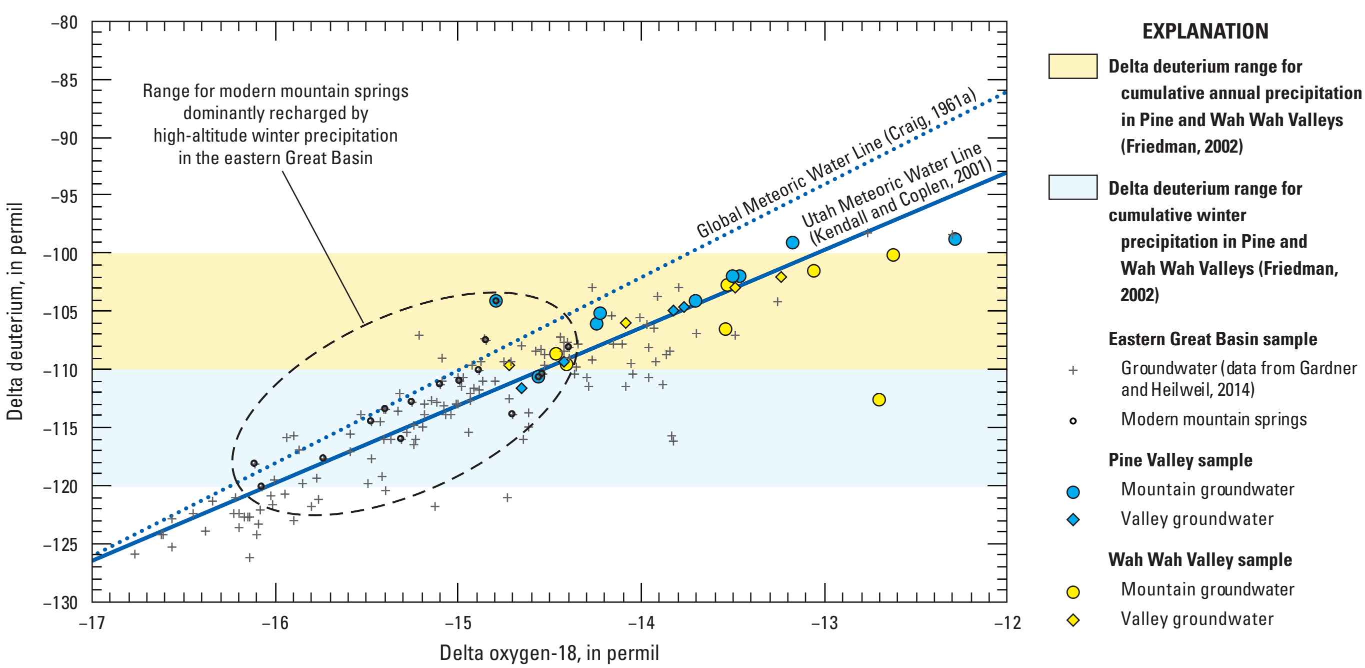


Figure 13. Stable-isotope values for selected samples from wells and springs in Pine and Wah Wah Valleys compared to stable-isotope values from seven neighboring basins and ranges of modern cumulative winter and annual precipitation for Pine and Wah Wah Valleys, Utah.

Groundwater temperatures measured near the water table from 20 valley wells in Pine and Wah Wah Valleys ranged from 14.5 to 24.9 with average of 18.9 °C (table 9). These valley water-table temperatures average 8.1 to 9.4 °C warmer than mean annual air temperatures for Pine and Wah Wah Valleys (9.5 and 10.8 °C, respectively). Eight mountain springs and one mountain well selected to represent mountain water-table temperatures in Pine and Wah Wah Valleys ranged from 9.3 to 16.7 °C with an average of 11.6 °C. With the mountain and valley water-table temperature ranges overlapping by 2.2 °C, the contrast between mountain and valley water-table temperatures is not as clear in Pine and Wah Wah Valleys as in other basins in the region.

Dissolved noble-gas concentrations and NGTs are presented in table 10. Average noble-gas temperatures computed for 18 sites ranged from 7.5 to 16.6 °C and were cooler than measured water temperatures at all but 2 of the sample sites (sample IDs 5 and 7). Noble-gas recharge temperatures typically are cooler than measured water temperatures given that recharge areas are higher in altitude (and generally cooler at the water table) than the corresponding sample locations. Average noble-gas recharge temperature was greater than measured water temperatures at sites 5 and 7 by 0.8 and 1.0 °C, respectively. These are both springs where water is in contact with the air before it can be sampled, likely resulting in gases re-equilibrating with atmosphere and leading to the warmer than expected NGTs. The range of possible NGT values calculated for each site is shown on figure 14 in which the left and right points for each sample represent NGT_{min} and NGT_{max}, respectively.

Except for Wah Wah Springs (sites 1 and 2), which are noted as being classified as “thermal” or “warm” by Stephens (1974), most mountain waters have cooler NGTs than most valley waters. There is an apparent distinction where NGT_{avg} for eight of nine mountain waters are cooler, and NGT_{avg} for six of seven valley waters are warmer than about 12.5 °C (fig. 14). Only one sample collected from a valley well in Pine Valley (site 12) had a cool NGT_{avg} (11.3 °C) that fell in the range of the majority of NGT_{avg} values for samples collected from mountain wells and springs. The cool NGT of this single valley sample indicates that mountain recharge does contribute to a fraction of valley groundwater at this site. One sample collected from a well in the hills southeast of Wah Wah Valley (site 16) had a warm NGT_{avg} (14.0 °C) that falls in the range of NGT_{avg} values for samples collected from deep valley wells. Although surprisingly warm for a mountain water table, this NGT_{avg} was cooler than the measured temperature of 15.1 °C at this site. The sample provides an example of warmer than expected, mountain water-table temperatures, which are likely related to elevated and variable ground temperatures near the Indian Peak Caldera Complex (Henrikson and Chapman, 2002; Blackett R.E., 2004).

Table 9. Water temperatures from wells and springs selected to represent the water table in the valley and temperatures from Pine and Wah Wah Valleys, Utah.

[NAD 83, North American Datum of 1983; mm/dd/yyyy, month/day/year; hhmm, hour minute; —, no information; °C, degrees Celsius]

Site name	Site number	Site type	Latitude (decimal degrees, NAD 83)	Longitude (decimal degrees, NAD 83)	Water level date (mm/dd/yyyy)	Water level time (hhmm)	Water level (feet below land surface)
				Valley			
(C-23-12) 6ccd-1	385008113145301	Well	38.835512	–113.248853	09/07/2012	1315	205
(C-24-12)15cdc-1	384306113112601	Well	38.718292	–113.191350	09/07/2012	1138	83
(C-24-13)13aac-1	384351113150501	Well	38.730791	–113.252186	09/07/2012	1215	96
(C-24-13)23ccd-1	384215113165701	Well	38.704124	–113.283298	09/07/2012	1105	177
(C-24-13)34ccb-1	384042113181601	Well	38.678167	–113.305222	09/07/2012	1035	210
(C-27-14)28ddd-1	382535113251101	Well	38.426349	–113.420523	09/05/2012	1640	568
(C-27-14)28ddd-2	382539113250601	Well	38.427461	–113.419134	09/05/2012	1645	562
(C-28-14) 3bcd-1	382423113243601	Well	38.406500	–113.414083	09/04/2012	—	682
(C-28-14)10cbd-1	382311113244901	Well	38.388806	–113.415500	09/04/2012	—	781
(C-28-14)11abb-1	382350113231901	Well	38.397184	–113.389411	09/04/2012	1720	663
(C-28-14)26bbd-1	382105113234801	Well	38.351333	–113.396556	09/04/2012	—	747
(C-26-14)25aad-1	383131113214301	Well	38.525237	–113.362744	09/07/2012	0924	233
(C-25-16)18bdd-1	383825113410801	Well	38.640361	–113.685667	09/06/2012	—	300
(C-25-17)33dab-1	383538113450801	Well	38.593845	–113.753032	07/01/1933	—	466
(C-26-17) 3cda-1	383402113440601	Well	38.572861	–113.742000	09/06/2012	1810	433
(C-26-17) 3cdd-1	383357113440601	Well	38.571639	–113.741972	09/06/2012	1740	436
(C-28-17) 1cca-1dbb	382402113421101	Well	38.400667	–113.702944	09/06/2012	—	620
(C-28-17)11cca-1	382259113433701	Well	38.383015	–113.727751	09/06/2012	1218	365
(C-28-17)12dcc-1	382256113420501	Well	38.382194	–113.701500	09/06/2012	—	609
(C-28-17)22dda-1	382113113435401	Well	38.353571	–113.732473	09/06/2012	1250	378
				Mountain			
(C-29-16) 2dcd-S1	381835113361701	Spring	38.309684	–113.605526	—	—	—
(C-28-15)10abb-S1	382344113305901	Spring	38.395639	–113.517194	—	—	—
(C-29-15) 2dad-S1	381848113292701	Spring	38.313130	–113.491750	—	—	—
(C-28-16)35bac-S1	382016113364001	Spring	38.337444	–113.611944	—	—	—
(C-30-17)19ddc-S1	381045113470701	Spring	38.179167	–113.785167	—	—	—
(C-27-18)35ccb-1	382445113501401	[2]Spring	38.412611	–113.837139	—	—	—
(C-27-18)27dba-1	382550113504001	Spring	38.430639	–113.844444	—	—	—
(C-26-19) 3abc-S1	383452113572301	Spring	38.581160	–113.957250	—	—	—
(C-30-17)15cab-1	381152113442801	Well	38.197833	–113.741167	11/22/1995	—	—

Table 9. Water temperatures from wells and springs selected to represent the water table in the valley and temperatures from Pine and Wah Wah Valleys, Utah.—Continued

[NAD 83, North American Datum of 1983; mm/dd/yyyy, month/day/year; hhmm, hour minute; —, no information; °C, degrees Celsius]

Site name	Site number	Well depth (feet below land surface)	Top of open interval (feet below land surface)	Bottom of open interval (feet below land surface)	Water table temperature date (mm/dd/yyyy)	[1]Water table temperature (°C)	Hydrographic area
				Valley			
(C-23-12) 6ccd-1	385008113145301	560	—	—	09/07/2012	18.1	Sevier Desert
(C-24-12)15cdc-1	384306113112601	532	—	—	09/07/2012	16.6	Sevier Desert
(C-24-13)13aac-1	384351113150501	145	—	—	09/07/2012	17.6	Sevier Desert
(C-24-13)23ccd-1	384215113165701	201	178	201	09/07/2012	14.5	Sevier Desert
(C-24-13)34ccb-1	384042113181601	294	236	294	09/07/2012	16.1	Wah Wah Valley
(C-27-14)28ddd-1	382535113251101	1,399	—	—	09/05/2012	20.8	Wah Wah Valley
(C-27-14)28ddd-2	382539113250601	987	—	—	09/05/2012	20.7	Wah Wah Valley
(C-28-14) 3bcd-1	382423113243601	1,480	700	1,480	09/04/2012	24.9	Wah Wah Valley
(C-28-14)10cbd-1	382311113244901	970	800	970	09/04/2012	22.8	Wah Wah Valley
(C-28-14)11abb-1	382350113231901	1,475	680	1,475	09/04/2012	24.8	Wah Wah Valley
(C-28-14)26bbd-1	382105113234801	1,104	715	1,104	09/04/2012	20.8	Wah Wah Valley
(C-26-14)25aad-1	383131113214301	1,135	888	1,114	09/07/2012	16.2	Wah Wah Valley
(C-25-16)18bdd-1	383825113410801	340	—	—	06/15/2011	16.7	Pine Valley
(C-25-17)33dab-1	383538113450801	628	—	628	12/03/2012	16.6	Pine Valley
(C-26-17) 3cda-1	383402113440601	882	640	861	09/06/2012	18.1	Pine Valley
(C-26-17) 3cdd-1	383357113440601	870	560	850	09/06/2012	18.7	Pine Valley
(C-28-17) 1cca-1dbb	382402113421101	1,460	500	1,460	09/06/2012	19.0	Pine Valley
(C-28-17)11cca-1	382259113433701	970	270	970	09/06/2012	18.6	Pine Valley
(C-28-17)12dcc-1	382256113420501	1,120	400	1,120	09/06/2012	17.8	Pine Valley
(C-28-17)22dda-1	382113113435401	2,006	500	2,006	09/06/2012	18.2	Pine Valley
				Mountain			
(C-29-16) 2dcd-S1	381835113361701	—	—	—	10/11/1972	11.0	Wah Wah Valley
(C-28-15)10abb-S1	382344113305901	—	—	—	12/04/2012	13.7	Wah Wah Valley
(C-29-15) 2dad-S1	381848113292701	—	—	—	06/28/2011	12.3	Wah Wah Valley
(C-28-16)35bac-S1	382016113364001	—	—	—	12/05/2012	9.3	Pine Valley
(C-30-17)19ddc-S1	381045113470701	—	—	—	12/06/2012	11.4	Pine Valley
(C-27-18)35ccb-1	382445113501401	2.5	1.5	2.5	12/05/2012	11.6	Pine Valley
(C-27-18)27dba-1	382550113504001	—	—	—	12/05/2012	9.3	Pine Valley
(C-26-19) 3abc-S1	383452113572301	—	—	—	06/16/2011	9.5	Pine Valley
(C-30-17)15cab-1	381152113442801	385	365	385	08/29/2013	16.7	Pine Valley

[1]Water-table temperatures in wells were measured just below the free surface of the water using a Solnist 1,000-foot electric water-level tape equiped with a temperature sensor except in wells (C-25-17)33dab-1 and (C-30-17)15cab-1, where the temperature is of pumped water assumed to approximate the water table. Springs selected to represent water-table temperature had sufficient flow to accurately represent ground temperature at their location. Wah Wah Springs were excluded due to being classified as "warm" or "thermal springs" by Stephens (1974).

[2]Spring temperature measured from the shallow well completed in sediments at the discharge location.

Table 10. Dissolved-gas concentrations and related noble-gas temperature data for groundwater sampled from Pine and Wah Wah Valleys, Utah.

[Sample identification (ID): See figure 10 for locations and table 5 for additional information. Dissolved-gas sample collection method: CT, copper tube; DS, diffusion sampler. **Abbreviations**: USGS, U.S. Geological Survey; mmHg, millimeters of mercury; °C, degrees Celsius; ^{20}Ne, Neon-20; ccSTP/g, cubic centimeters at standard temperature and pressure per gram of water; ^{40}Ar, Argon-40; ^{84}Kr, Krypton-84; ^{129}Xe, Xenon-129; —, no information; H_{min}, minimum recharge altitude; NGT_{max}, dimensionless ratio of the total volume of trapped (moist) air at the pressure and temperature of the free atmosphere to the volume of water; A, average noble-gas recharge temperature; F, fractionation factor for partial dissolution of trapped air bubbles; $\sum\chi^2$, sum of error-weighted misfit for each of the noble gases; H_{avg}, average recharge altitude; NGT_{avg}; H_{max}, maximum recharge altitude; NGT_{min}, minimum noble-gas recharge temperature]

Sample ID	USGS site number	Sample method	Dissolved-gas pressure (mmHg)	Water temperature (°C)	Dissolved noble-gas concentrations (ccSTP/g)			
					^{20}Ne	^{40}Ar	^{84}Kr	^{129}Xe
1	382901113295701	DS	608	19.0	1.56E–07	2.93E–04	3.76E–08	2.33E–09
2	382856113293301	DS	594	17.5	1.54E–07	2.95E–04	3.82E–08	2.39E–09
3	382344113305901	DS	636	13.7	1.70E–07	3.17E–04	4.21E–08	2.76E–09
4	382016113364001	DS	577	9.3	1.44E–07	3.19E–04	4.09E–08	2.93E–09
5	381045113470701	DS	582	11.4	1.61E–07	2.81E–04	3.86E–08	2.49E–09
6	382445113501401	DS	539	11.6	1.49E–07	3.10E–04	3.95E–08	2.72E–09
7	382550113504001	DS	542	9.3	1.42E–07	3.03E–04	3.99E–08	2.67E–09
8	383131113214301	CT	537	19.9	3.19E–08	2.50E–04	1.34E–07	2.51E–09
9	383538113450801	CT	699	16.6	1.47E–07	2.68E–04	3.34E–08	2.34E–09
10	381344113512301	CT	716	12.5	3.93E–07	4.93E–04	5.59E–08	3.23E–09
11	383402113440601	CT	813	19.5	3.66E–07	3.72E–04	4.34E–08	2.72E–09
12	382259113433701	CT	—	20.0	5.10E–07	4.86E–04	5.25E–08	3.11E–09
13	381152113442801	CT	—	16.7	1.82E–07	3.43E–04	4.34E–08	2.74E–09
[1]14	382539113250601	CT	683	21.9	1.83E–07	2.77E–04	9.74E–09	2.22E–09
15	382101113170801	CT	683	14.6	1.55E–07	2.98E–04	4.03E–08	2.56E–09
16	381957113163701	CT	726	15.1	1.79E–07	3.28E–04	3.89E–08	2.59E–09
17	382423113243601	CT	705	23.7	1.63E–07	2.89E–04	3.92E–08	2.44E–09
18	383825113410801	CT	—	16.7	1.56E–07	2.81E–04	3.62E–08	2.50E–09
19	384042113181601	CT	—	16.2	1.55E–07	2.84E–04	3.99E–08	2.56E–09

Sample ID	USGS site number	Sample method	Modeled recharge parameters								
			H_{min} (feet)	NGT_{max} (°C)	A	F	$\sum\chi^2$	H_{avg} (feet)	NGT_{avg} (°C)	H_{max} (feet)	NGT_{min} (°C)
1	382901113295701	DS	5,666	17.3	0.0009	0.88	0.13	6,833	16.6	8,000	15.9
2	382856113293301	DS	5,531	16.2	0.0007	0.90	0.14	6,766	15.5	8,000	14.8
3	382344113305901	DS	5,850	10.6	0.0010	0.00	0.12	6,925	9.5	8,000	8.4
4	382016113364001	DS	7,211	7.8	0.0001	0.99	1.24	7,606	7.5	8,000	7.2
5	381045113470701	DS	6,900	13.1	0.0014	0.00	2.07	7,650	12.2	8,400	11.3
6	382445113501401	DS	6,276	11.1	0.0003	0.95	0.56	6,938	10.5	7,600	9.9
7	382550113504001	DS	6,335	10.7	0.0000	0.96	0.24	6,968	10.3	7,600	9.9
8	383131113214301	CT	4,760	14.8	0.0000	1.18	6.90	6,380	14.2	8,000	13.4
9	383538113450801	CT	5,276	17.6	0.0003	0.00	1.79	6,638	15.9	8,000	14.2
10	381344113512301	CT	7,805	8.7	0.0300	0.17	0.22	8,103	8.4	8,400	8.2
11	383402113440601	CT	5,249	16.8	0.0120	0.00	4.66	6,825	14.9	8,400	13.1
12	382259113433701	CT	5,682	12.8	0.0220	0.00	0.53	7,041	11.3	8,400	9.8
13	381152113442801	CT	6,548	12.2	0.0480	0.73	0.01	7,474	11.3	8,400	10.5
[1]14	382539113250601	CT	5,085	—	—	—	—	—	—	—	—
15	382101113170801	CT	6,161	12.1	0.0031	0.70	0.38	6,381	11.8	6,600	11.6
16	381957113163701	CT	6,240	14.2	0.0290	0.71	0.81	6,420	14.0	6,600	13.8
17	382423113243601	CT	5,210	15.0	0.0010	0.00	0.91	6,605	13.4	8,000	11.7
18	383825113410801	CT	5,089	15.7	0.0010	0.00	1.47	6,744	13.7	8,400	11.7
19	384042113181601	CT	4,655	14.8	0.0000	0.00	2.53	6,528	12.8	8,400	10.8

[1]Noble gas concentrations yielded no acceptable NGT model, which was likely due to erroneously low ^{84}Kr and ^{129}Xe concentrations.

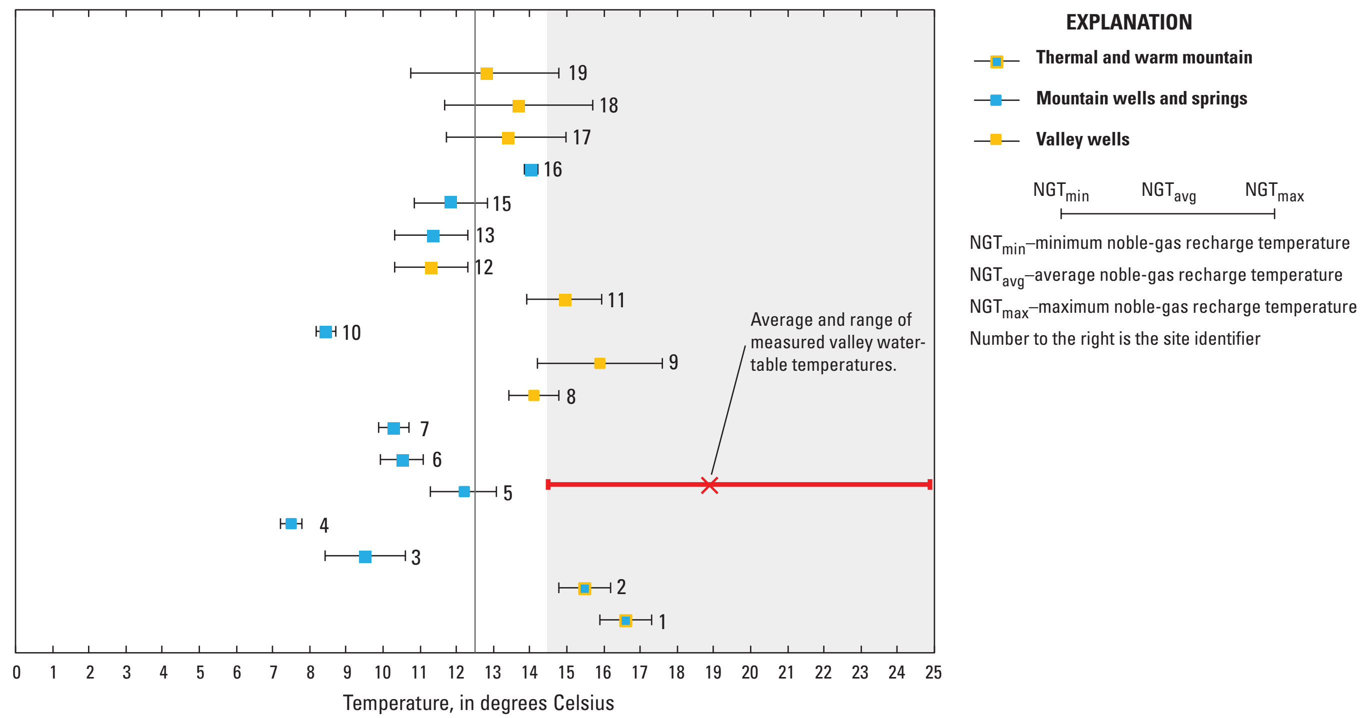


Figure 14. Computed noble-gas recharge temperatures compared to measured valley water-table temperatures for groundwater sites sampled in Pine and Wah Wah Valleys, Utah.

Discussion

In many ways, the Pine and Wah Wah Valleys are like many watersheds in the eastern Great Basin. Both are internally drained, surface-water basins bounded by steep normal faults. The valleys contain thick basin-fill deposits that form the principal source of available groundwater and are surrounded by bedrock mountain highlands. Precipitation rates are generally too low to provide in-place groundwater recharge at low altitudes. Instead, most recharge originates as precipitation falling on the mountains surrounding the valleys.

In many comparable nearby basins, mountain precipitation exceeds consumptive use (evaporation and transpiration by plants) in the mountains so that a fraction of the precipitation is available to recharge the aquifer. This is a function of the amount and timing of the precipitation. Most precipitation in these basins occurs in the mountains during the winter. Whether or not it is stored as snowpack and released as snowmelt in the spring, more of it is available for groundwater recharge because ET rates are much lower during the cooler months, seasonally reducing consumptive-use rates. In these areas, recharge enters the aquifer system as direct infiltration where mountains are composed of permeable bedrock at the surface. If the permeable bedrock extends to the mountain front, this infiltration can recharge the basin-fill aquifer directly through the subsurface. In mountain areas with less-permeable bedrock, precipitation and snowmelt form runoff that gathers in stream channels and infiltrates permeable basin-fill deposits near the mountain front to recharge basin-fill aquifers.

Despite some similarities, Pine and Wah Wah Valleys also differ from typical regional watersheds in ways that have important implications regarding groundwater resource evaluation and management. A few of these basin characteristics that have notable effects on the groundwater hydrology are (1) igneous rocks associated with the Indian Peak Caldera Complex resulting in extensive perched (or semi-perched) mountain aquifers that are disconnected from the adjacent basin-fill aquifers, (2) a smaller fraction of the precipitation in these valleys occurs during winter months leading to a larger fraction of annual precipitation being consumed by evapotranspiration during the summer and leaving less available for groundwater recharge, and (3) the majority of groundwater discharge from Pine and Wah Wah Valleys occurs through the subsurface and is therefore not observable or measurable, precluding the use of discharge measurements to constrain independent estimates of groundwater recharge.

Hydrologic Characteristics of the Basins

Approximately the southern two-thirds of the mountains surrounding Pine and Wah Wah Valleys are composed of extrusive and intrusive igneous rocks, quartzite, and metasedimentary rocks (VU and NCCU in fig. 4). These rocks typically have low primary permeability and only localized, near-surface secondary permeability. Stephens (1976) reported that these conditions created perched (or semi-perched[1]) mountain aquifers where significant discharge occurs to mountain springs, noting "Examination of spring locations, topography, and geology on maps and in the field indicates that many of the springs that discharge from the extrusive igneous rocks on the eastern flank of the Needle Mountains probably are perched. They issue either from a surficial weathered zone or from permeable interbeds within the volcanic rocks."

Stephens (1974, 1976) also mentions the shallow water-table conditions in stream-channel alluvium along the major washes and streams draining the Needle and Wah Wah Ranges and states "These shallow water table areas probably do not represent a regional water table. Instead, they appear to be perched zones resulting from the accumulation of ground water in permeable unconsolidated deposits underlain by less permeable, unsaturated consolidated rocks." Early evidence for extensive perched groundwater in the mountains was based on field inspection and the observation that the 80 or more springs in the Pine Valley drainage basin all discharge at altitudes above 6,200 ft, which is above the mountain-bedrock, basin-fill transition zone. Although the number of springs is fewer and the altitude of the mountain-bedrock, basin-fill transition is lower (5,400 ft), the same pattern is apparent in Wah Wah Valley. Furthermore, comparing groundwater altitudes from wells and springs in the mountains to groundwater levels measured in valley wells anywhere in Pine or Wah Wah Valleys shows that a hydraulic gradient across the mountain-bedrock, basin-fill transition zone would be unusually steep for any well-connected flow system (fig. 4), reinforcing that perched mountain groundwater is widespread. The Gould State No. 3 oil and gas exploration well, about six miles outside of the Pine Valley drainage basin at the northern end of the Mountain Home Range (fig. 4), provides a direct observation supporting the concept of perched mountain groundwater. During drilling of this well, fresh water was encountered in carbonate rocks with a static water level at 750-ft below the land surface of 6,362 ft, confirming that the regional water table in bedrock at this location is about 5,612 ft and well beneath the altitude of "shallow water-table areas" in the Mountain Home and Indian Peak Ranges to the south.

A significant implication of extensive perched mountain groundwater is a degree of hydraulic disconnection between groundwater that recharged in the mountains and groundwater in the adjacent basin-fill aquifers. In addition to the geologic and hydrologic evidence discussed above, groundwater geochemistry also indicates discontinuous flow between mountain recharge areas and basin-fill aquifers. Groundwater samples from valley wells in Pine Valley clearly have lower dissolved-solids concentrations than almost all the groundwater sampled from wells and springs in the surrounding mountains (fig. 10; table 6). A similar pattern is seen when comparing mountain versus valley groundwater samples in Wah Wah Valley, although with slightly more overlap in dissolved-solids concentration. Groundwater should acquire solutes over time as it moves downgradient along a flow path. In areas where flow paths are continuous between mountain and valley groundwater, dissolved-solids concentrations in water from valley wells should be higher than upgradient mountain waters, especially given the long travel time indicated by the groundwater ages (fig. 12).

In a similar way, NGTs also indicate a hydraulic discontinuity between mountain and valley groundwaters. Because NGTs are derived from dissolved noble-gas concentrations representing the temperature of a water sample at its point of recharge, and because the noble gases are generally preserved in the saturated zone, NGTs should remain constant along continuous groundwater flow paths. This pattern, however is not generally observed in Pine or Wah Wah Valleys. Excluding the thermal waters discharging from Wah Wah Springs, the NGT_{avg} for all but one of the valley groundwater samples are notably warmer than the NGT_{avg} for all but one of the mountain groundwater samples (fig. 14). The contrast is not wholly conclusive on its own; NGTs for several of the samples overlap when the complete range (NGT_{min} to NGT_{max}) is considered (fig. 14). However, this represents a conservative range of uncertainty given that samples are unlikely to have recharged at the highest or lowest altitudes used in their calculation. Consequently, this pattern further supports the premise that much of valley recharge is not derived from direct infiltration of precipitation in the mountains. The cool NGT of one sample from Pine Valley (site 12) indicates, however, that permeable pathways do exist allowing mountain recharge to reach the valley aquifers in some places. This is expected given that the low-permeability volcanic rocks responsible for perched mountain groundwater are not continuous across the whole of the surrounding mountains.

[1]Meinzer (1923, p. 40) defines perched groundwater as that which is separated from an underlying body of groundwater by unsaturated rock stating that "Perched water belongs to a different zone of saturation from that occupied by the underlying ground water." Perched groundwater is sometimes confused with semi-perched groundwater, which Meinzer (1923, p. 41) defines as groundwater that "has greater pressure head than an underlying body of ground water, from which it is, however, not separated by any unsaturated rock."

Stable-isotope values for 7 out of the 23 meteoric waters sampled (excluding the highly evaporated sample from site 21) were isotopically enriched (heavier) compared to modern mountain springs dominantly recharged by winter precipitation in nearby parts of the eastern Great Basin (fig. 13). This indicates that much of the groundwater in the study basins originated as either low-altitude or warm-season precipitation. However, because many of the enriched waters were samples collected from mountain springs, all that can be concluded is that warm season rather than winter precipitation is the source of much of the groundwater in the mountain and valley aquifers.

Of the samples that did have isotopic values representing high-altitude winter precipitation, four of the samples (1, 2, 22, and 24) are mountain springs that are directly downgradient from mountain catchments between 8,600 and 9,300 ft in altitude (fig. 10). One of them (sample 19) is Pleistocene in age and represents water recharged during a cooler and wetter climate (fig. 12). The remaining two (sample IDs 9 and 11) are basin-fill waters that are downgradient of an exposed block of permeable carbonate (the Needles) surrounded by low-permeability igneous and metasedimentary rocks on the eastern flank of the Needle Mountains in western Pine Valley. This isolated carbonate block is one of the likely locations where mountain infiltration can move through permeable rock at depth and become recharge to the basin-fill deposits beneath the valley floor.

Stable-isotope data provide useful information about the seasonality of precipitation occurring in Pine and Wah Wah Valleys. Twenty-one of 24 samples had δ^2H values indicative of cumulative annual rather than cumulative winter precipitation (fig. 13). This makes sense considering that about half of all precipitation at the Desert Experimental Range Station and Wah Wah Ranch occurs during May–September (fig. 3). Furthermore, Stephens (1974) noted that winter precipitation (mostly snowfall) during December–March accounts for less than one-fourth of the annual precipitation in the valleys and probably not more than one-third of the annual precipitation in the mountains.

The timing of precipitation has important implications for valley recharge. More than 80 percent of recharge previously estimated using a modified Maxey-Eakin method (Hood and Waddell, 1968) is from precipitation occurring above the altitude of the mountain-bedrock, basin-fill transition in both valleys where normal annual precipitation exceeds 10–12 in/yr (Stephens, 1974, 1976). However, much of the area where recharge occurs is below the mountain-bedrock, basin-fill transition where runoff from the higher parts of the drainage basin infiltrates the relatively permeable sand and gravel deposits in and along the stream channels. If most precipitation occurs during winter months when evapotranspiration rates are lowest, much less of it is consumptively used in the mountains, and more is available to recharge the basin-fill aquifers at the mountain front. If, however, most precipitation occurs during the warm months, natural consumptive use in the mountains could leave little available for recharge by the time water arrives at the permeable sand and gravel deposits below the mountain-bedrock, basin-fill transition.

Another unique characteristic of the Pine and Wah Wah Valley drainage basins is their lack of natural discharge at the lowest altitudes of the valley floors. Most comparable valleys in the eastern Great Basin have extensive areas of lowland discharge where groundwater levels are near the land surface and the bulk of the basin's groundwater discharge occurs through springs and by phreatophyte evapotranspiration. Groundwater levels in Pine and Wah Wah Valleys, however, are hundreds of feet below land surface, even beneath dry playas at the lowest valley altitudes. A consequence of the deep groundwater levels is that all discharge from the basin-fill aquifers in both valleys must occur through the subsurface where it is not observable and cannot be measured.

Groundwater Budget

As of 2014 there were approximately 54,000 acre feet (acre-ft) of outstanding, unapproved water-right applications for groundwater from Pine and Wah Wah Valleys. Recent proposals to develop groundwater resources in Pine and Wah Wah Valleys are focused on extraction of groundwater from their extensive basin-fill aquifers. The long-standing estimate of annual groundwater recharge to these valleys combined is 28,000 acre-ft/year (Stephens, 1974, 1976). However, it has never been formally recognized that the groundwater budgets presented by Stephens clearly indicate that substantially less than the full 28,000 acre-ft recharges the basin-fill aquifers. Although various other groundwater budget estimates have been reported in the recent decade (Masbruch, 2011a; Brooks and others, 2014; Masbruch and others, 2014, tables A3–2, 14), they have come out of large-scale or multi-basin studies not focused on Pine and Wah Wah Valleys. This study collected new hydrologic data with the specific intention of re-evaluating the conceptual model of the groundwater flow and providing information to update groundwater budgets using the GBCAAS v. 3.0 numerical model (Brooks, 2017a, b).

The groundwater budgets reported by Stephens (1974, 1976) are summarized in table 11 to clarify what fraction of recharge contributes to the basin-fill aquifer in each valley. Total annual recharge from precipitation to Pine and Wah Wah Valleys is estimated to be 21,000 and 7,000 acre-ft/yr, respectively. It is important to note that 3,000 acre-ft/yr of this recharge is reported to leave the Pine Valley drainage basin (discharge from Pine Valley) and move into the Wah Wah Valley drainage basin (recharge to Wah Wah Valley) through permeable carbonate rocks along the drainage divide in the Wah Wah Mountains. Recognizing that this amount not be double counted, the total annual recharge to both basins remains 28,000 acre-ft. An additional 7,100 acre-ft of discharge from Pine Valley is reported to occur in perched zones in the surrounding mountains and is clearly inferred to be lost to consumptive uses, mostly evapotranspiration. The difference between the recharge from precipitation (21,000 acre-ft) and the sum of mountain discharge (7,100 acre-ft) in the Pine Valley drainage, plus the subsurface discharge to Wah Wah Valley through consolidated rocks in the Wah Wah Mountains (3,000 acre-ft) is assumed to leave the basin-fill aquifer as subsurface discharge (11,000 acre-ft, rounded) to the north. The same reasoning is used in reporting the Wah Wah Valley groundwater budget where the sum of mountain discharge components (150 and 1,400 acre-ft) is subtracted from the sum of recharge from precipitation (7,000 acre-ft) and the component of Pine Valley recharge that moves into Wah Wah through consolidated rocks in the Wah Wah Mountains (3,000 acre-ft) to arrive at the amount leaving the basin-fill aquifer as subsurface discharge (8,500 acre-ft, rounded) to the north. These budget estimates are based on the premise of significant perched or semi-perched conditions in the mountains surrounding both valleys, which is substantiated by geochemical and physical evidence presented in this study. Assuming steady-state conditions, recharge to the basin-fill aquifers is equal to the subsurface discharge from the basin-fill aquifers in each valley (11,000 and 8,500 acre-ft for Pine and Wah Wah Valleys, respectively).

Steady-state groundwater budgets for Pine and Wah Wah Valleys from simulations by the GBCAAS v. 3.0 model (Brooks, 2017a, b) are compared to the average annual groundwater budgets of only the basin-fill aquifers from Stephens (1974, 1976) in table 12. The basin-fill only portions of these budgets are equal to the "unconsumed recharge that moves northward through the basin-fill aquifer and leaves as subsurface outflow" shown in the final row of the Pine and Wah Wah Valley sections of table 11. Moreover, this comparison is made because only the basin-fill portions of the budgets presented by Stephens (1974, 1976) are physically available for withdrawal. Wah Wah Springs is the only spring or spring complex where groundwater discharge is simulated by the numerical model. Discharge of groundwater was not simulated by the model for other mountain springs or by phreatophytic ET in areas of shallow mountain groundwater and the calibrated model did not include recharge to supply them. Therefore, recharge simulated by the model is equal to the amount of water that remains in the groundwater system and either discharges at Wah Wah Springs or moves through the basin-fill aquifers before leaving as subsurface discharge toward the north. To compare recharge estimates for the basin-fill only, the Wah Wah Springs discharge (750 acre-ft) that is simulated by the GBCAAS v. 3.0 model was subtracted from the total recharge simulated for Wah Wah Valley (3,200 acre-ft; Brooks, 2017a, table 8) to yield the model-estimated recharge to the basin-fill (2,500 acre-ft, rounded).

The reason that Wah Wah Springs is uniquely represented in the GBCAAS v. 3.0 model is given by Brooks and others (2014): "Springs with flow rates less than 300 gal/min were not simulated unless they were near other springs. These smaller springs could represent local conditions that are not simulated in this regional model, such as perched conditions or irrigation return flow. Discharge from springs that are less than 300 gal/min accounts for less than 2 percent of the discharge for the [GBCAAS] study area..." Wah Wah Springs is the only spring discharging more than 300 gal/min in all of Pine and Wah Wah Valleys. It is actually a collection of discrete springs, seeps, and an area of ET_g that is controlled by local geologic structure and thought to capture recharge from an area that extends across the drainage divide into Pine Valley as described in detail by Stephens (1974). The discharge from Wah Wah Springs measured during this study is approximately 1,000 gal/min (2.3–2.2 ft^3/s or 1,600 acre-ft/yr), which is two times the discharge reported by Stephens (1974) and two times that discharge simulated using the GBCAAS v. 3.0 model. This discharge was measured through a rectangular weir in a collection box and is thought to represent nearly all of the spring flow from the complex. Because the water from Wah Wah Springs principally is used for irrigation on the valley floor, it is reasonable to assume that 50 percent of measured discharge is consumptively used and that the remaining water recharges the basin-fill aquifer. And because the discharge of spring flow from Wah Wah Springs reported by Stephens (1974; 800 acre-ft) and that simulated using the GBCAAS v. 3.0 model (750 acre-ft), both are approximately 50 percent of what was measured during 2013–16; it is assumed for this budget analysis that those estimates represent consumptive discharge.

Table 11. Summary of conceptual steady-state groundwater budgets reported by Stephens (1974, 1976) for Pine and Wah Wah Valleys, Utah.

[All values rounded to two significant figures, in acre-feet per year (acre-ft/yr) unless otherwise noted.]

Value	Description
	Pine Valley
Groundwater recharge	
[1]21,000	Recharge from precipitation.
Groundwater discharge	
[2]7,100	Sum of consumed groundwater discharge occurring in the mountains.
[3]3,000	Eastward moving subsurface discharge into the Wah Wah Valley drainage basin from parts of the Wah Wah Mountains in the Pine Valley drainage basin.
[4]11,000	Unconsumed recharge that moves northward through the basin-fill aquifer and leaves as subsurface outflow.
	Wah Wah Valley
Groundwater recharge	
[1]7,000	Recharge from precipitation.
[3]3,000	Eastward moving subsurface recharge from parts of the Wah Wah Mountains in the Pine Valley drainage basin and into the Wah Wah Valley drainage basin.
Groundwater discharge	
[5]150	Sum of consumed groundwater discharge occurring in the mountains.
[6]1,400	Combined discharge from Wah Wah Springs and groundwater evapotranspiration from the surrounding discharge area.
[4]8,500	Unconsumed recharge that moves northward through the basin-fill aquifer and leaves as subsurface outflow.

[1]Modified Maxey-Eakin estimate of groundwater recharge from precipitation in the drainage basin in Stephens (1974, p. 11; 1976, p. 12).

[2]Sum of groundwater discharge occurring in the mountains in the Pine Valley drainage basin that is consumed by evapotranspiration without reaching the basin-fill aquifer is summarized in Stephens (1976, p. 17).

[3]Estimate of recharge occurring in the Wah Wah Mountains within the Pine Valley drainage basin that flows under the topographic divide into the Wah Wah Valley drainage is described in Stephens (1974, p. 12; 1976, p. 12). This same 3,000 acre-ft is reported as discharge from Pine Valley and recharge to Wah Wah Valley.

[4]Estimate of subsurface discharge out of the basin-fill aquifer calculated as the difference between total recharge and groundwater discharge consumed in the mountains surrounding the basin-fill aquifer is described in Stephens (1974, p. 30; 1976, p. 17).

[5]Sum of small components of discharge occurring in the mountains within the Wah Wah Valley drainage basin that is consumed by evapotranspiration without reaching the basin-fill aquifer, excluding spring or groundwater evapotranspiration discahrge associated with Wah Wah Springs is summarized in Stephens (1974, p. 13, 20, and 26).

[6]Combined estimates of Wah Wah Springs discahrge and groundwater discharged by evapotranspiration in the area surrounding Wah Wah Springs (Stephens, 1974, p. 21).

Table 12. Conceptual and simulated (using the GBCAAS v. 3.0 groundwater model) steady-state groundwater budgets for the basin-fill aquifers of Pine and Wah Wah Valleys, Utah.

[All values rounded to two significant figures, in acre-feet per year unless otherwise noted.]

Source	Annual groundwater recharge/discharge		
	Pine Valley	**Wah Wah Valley**	**Combined**
Conceptual (Stephens, 1976) basin-fill only	[1]11,000	[1]8,500	20,000
Simulated (Brooks, 2017) basin-fill only	11,000	[2]2,500	14,000

[1]Unconsumed recharge that moves northward through the basin-fill aquifer and leaves as subsurface outflow is reported in table 11.

[2]With the exception of Wah Wah Springs, Brooks (2017) does not simulate recharge to supply spring discharge and groundwater evapotranspiration occurring in the mountains surrounding Pine and Wah Wah Valleys. The model-simulated discharge from Wah Wah Springs is assumed to represent a consumptive loss and is subtracted from the total recharge to Wah Wah Valley.

The simulated groundwater budget for the Pine Valley basin-fill aquifer appears essentially unchanged from the reconnaissance study of Stephens (1976). The simulated groundwater budget for Wah Wah Valley basin-fill aquifer is significantly reduced. These reductions in recharge resulted in (1) lower simulated water levels on the west side of Sevier Lake that more closely matched measured water levels and (2) accurate simulation of the revised conceptual model having no regional groundwater discharging as ET directly from the Sevier Lake playa. There is one nuance associated with the GBCAAS v. 3.0 model groundwater budgets that complicates a basin-by-basin comparison; the model-simulated budgets represent recharge occurring within the basin boundary and do not address the fate of the 3,000 acre-ft of Pine Valley recharge that moves into the Wah Wah Valley drainage basin. This complication is irrelevant when comparing the combined simulated recharge for the two basins. At 14,000 acre-ft (rounded), the combined annual steady-state recharge to the basin-fill aquifers simulated using the GBCAAS v. 3.0 model is about 30 percent less than the 20,000 acre-ft (rounded) reported in Stephens (1974, 1976).

The conceptual and simulated estimates are uncertain because recharge is notoriously difficult to quantify (Bredehoeft, 2007), verification of independent recharge estimates using methods like Maxey-Eakin (Maxey and Eakin, 1949) and the Basin Characterization Model (Flint and Flint, 2007a) relies on accurate discharge measurements. If, for example, coefficients determining the fraction of precipitation that becomes recharge in a Maxey-Eakin estimate were determined for a basin dominated by winter precipitation, they could overestimate recharge in basins where most precipitation occurs at other times of the year. Measuring discharge to verify a Maxey-Eakin recharge estimate is not possible in either Pine or Wah Wah Valleys where most basin-wide discharge occurs through the subsurface and is not measurable. And, for reasons given by Brooks (2017a, p. 50), the GBCAAS v. 3.0 model would require significant revision to accurately simulate shallow mountain aquifers and their interaction with the adjacent basin-fill aquifers. Regardless of the uncertainties, the basin-fill aquifers in Pine and Wah Wah Valley are recharged by an amount that very likely lies between the estimates presented in table 12.

Because all groundwater in the basin-fill aquifers leaves as subsurface outflow, Pine and Wah Wah Valleys are clearly part of a larger, multiple-basin groundwater flow system. Although the recharge estimates presented could help water managers define a conceptual limit on groundwater withdrawal, it should be noted that pumping in the Pine and Wah Wah basins will have to capture discharge from neighboring basins because there is no groundwater discharging from the valleys in either of these basins. With the springs and ET areas in the mountains present in perched aquifers, the principal effect of increased groundwater withdrawal in the Pine and Wah Wah Valleys basin-fill aquifers would be a reduction in the quantity of subsurface outflow. This, in turn would result in reduced discharge in areas outside of the basin, most likely in Tule Valley and the Sevier Desert.

Summary

A groundwater resources assessment was conducted in Pine and Wah Wah Valleys to provide a better understanding of groundwater presence, sources, and movement. Groundwater in Pine and Wah Wah Valleys is being targeted for large-scale extraction and export to provide municipal supply to growing populations in Iron County, Utah. Concern about potential declining groundwater levels and spring flows resulting from proposed groundwater withdrawals necessitates an improved understanding of the Pine and Wah Wah Valleys groundwater system. This study evaluated hydrologic conditions including groundwater levels, recharge to the groundwater system, discharge from springs, and evapotranspiration (ET). Geochemistry and environmental groundwater tracers were used to determine sources of water to groundwater discharge areas, evaluate groundwater flow paths, and assess interbasin flow between adjacent valleys. Previous studies estimated that an average of 28,000 acre-feet per year (acre-ft/yr) of recharge occurs as infiltration of precipitation in the two basins (Stephens, 1974, 1976). Groundwater discharge that occurs in mountain hydrologic systems was estimated to average 8,500 acre-ft/yr and assumed to be consumed before subsequently recharging the valley basin-fill aquifers. Subsurface groundwater discharge from basin-fill aquifers in Pine and Wah Wah Valleys that moves northward to adjacent regional basins was estimated to average 19,500 acre-ft/yr.

Aquifer properties for the basin-fill aquifers in Pine and Wah Wah Valleys were determined from 10 single-well pump tests where a value for specific capacity was calculated. The transmissivity calculated for the basin-fill aquifer in Pine and Wah Wah Valleys mostly ranged from about 400 to 9,000 square feet per day (ft^2/d; table 1). One well, CICWCD #25, in the far southern portion of Pine Valley, yielded a transmissivity of about 20–30 ft^2/d. Another well, CICWCD #11, in south-central Pine Valley, yielded a transmissivity range of 94,000–120,000 ft^2/d.

A water-level map for the basin-fill aquifers in Pine and Wah Wah Valleys was constructed using water-level measurements taken at wells and springs in the surrounding mountain regions totaling 64 sites (fig. 4; table A–1). Pine and Wah Wah Valleys are closed surface-water basins, but groundwater levels indicate that groundwater moves northward out of both valleys toward adjacent basins. Water-level and spring discharge fluctuations in Pine and Wah Wah Valleys are presented for seven wells and two springs. In all seven wells, water levels are generally stable for the period of record at each site with maximum observed fluctuations of less than 5 feet (ft). Sites with shorter periods of record (less than 10 years) show short-term increases and decreases, which could be delayed responses to climatic variability. In both springs, discharge remained stable from 2013 to 2016.

New estimates of groundwater ET (ET_g) in Tule Valley and the Sevier Lake basin were made by (1) mapping the groundwater discharge areas in each basin; (2) evaluating 2005–11 summer multispectral satellite images against the Basin and Range carbonate-rock aquifer system, studying ET measurements to select scenes broadly representative of average conditions in the study area, and partitioning the groundwater discharge areas into ET units using the selected satellite images and field reconnaissance; and (3) scaling ET to the ET units using ET rate estimates from comparable study areas in the Great Basin. The resulting updated estimates of average annual ET_g in the Tule Valley and Sevier Lake groundwater discharge areas are 35,000 and 10,500 acre-ft/yr, respectively, with a likely uncertainty of plus or minus 35 percent. Updated ET_g estimates for these two areas were made to better constrain Pine and Wah Wah Valley groundwater budgets using the Great Basin carbonate and alluvial aquifer system Version 3.0 groundwater flow model (Brooks, 2017a,b).

Groundwater samples from 13 sites in Pine Valley and 11 sites in Wah Wah Valley were analyzed for major ions and nutrients to characterize geochemistry and water quality. Groundwater samples also were analyzed for the stable isotopes of oxygen, hydrogen, and carbon; the radioactive isotopes of carbon and hydrogen; and dissolved noble gases including helium-3, helium-4, neon, argon, krypton, and xenon. Groundwater sampling sites included 12 wells and 12 springs.

Carbon-14 and tritium/helium groundwater age dating indicate that groundwater in the basin-fill aquifers is typically thousands to tens of thousands of years older than groundwater in the shallow mountain aquifers. Dissolved-solids concentrations are lower and noble-gas temperatures are warmer in valley wells compared to almost all groundwater sampled from wells and springs in the surrounding mountains. These results, combined with the steep hydraulic gradients observed between mountain and valley locations, indicate a widespread hydraulic discontinuity between mountain and valley aquifers throughout much of the study area, and that much of the valley recharge is not derived from direct infiltration of precipitation in the mountains. However, noble-gas recharge temperatures from one and stable-isotope values from two Holocene-aged groundwater samples indicate that areas exist where mountain infiltration can move through permeable rock at depth and recharge adjacent basin-fill valley aquifers. Furthermore, the geology within the mountains and between the mountains and valleys is complex, and areas of hydraulic connections between valley aquifers and mountain springs cannot be ruled out completely. Groundwater levels are deep throughout the basin-fill aquifers of Pine and Wah Wah Valleys and neither contains areas of measurable groundwater discharge that can be used to verify groundwater budget estimates. As such, the steady-state average annual recharge to and discharge from the combined valleys is best bracketed between the simulated estimate of Brooks (2017,a,b) and the reconnaissance estimates of Stephens (1974, 1976) at 14,000–20,000 acre-ft.

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Appendix A: Hydrologic Site Information

Table A–1. Selected attributes of wells and water levels measured in wells used in constructing the water-level surface map for Pine and Wah Wah Valleys and surrounding areas, Utah.

[Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). **Abbreviations**: USGS, U.S. Geological Survey; mm/dd/yyyy, month/day/year; —, no information; <, less than]

USGS site number	Site name	Latitude (decimal degrees)	Longitude (decimal degrees)	Well depth (feet)	Altitude of land surface (feet)	Measurement date (mm/dd/yyyy)	Depth to water below land surface (feet)	Water-level altitude (feet)
382402113421101	(C-28-17) 1dbb-1	38.400667	–113.702944	1,460	5,585	09/06/2012	620.2	4,965
382256113420501	(C-28-17)12dcc-1	38.382194	–113.701500	1,120	5,657	09/06/2012	609.2	5,048
382259113433701	(C-28-17)11cca-1	38.383015	–113.727751	970	5,683	09/06/2012	365.2	5,318
382113113435401	(C-28-17)22dda-1	38.353571	–113.732473	2,006	5,775	09/06/2012	377.6	5,397
381931113200201	(C-28-13)32cdd-1	38.325333	–113.333833	194	5,845	09/04/2012	26.8	5,818
382105113234801	(C-28-14)26bbd-1	38.351333	–113.396556	1,104	5,385	09/04/2012	747.5	4,638
382311113244901	(C-28-14)10cbd-1	38.388806	–113.415500	970	5,320	09/04/2012	781.4	4,539
382350113231901	(C-28-14)11abb-1	38.397184	–113.389411	1,475	5,195	09/04/2012	663.0	4,532
382423113243601	(C-28-14) 3bcd-1	38.406500	–113.414083	1,480	5,210	09/04/2012	682.0	4,528
381037113474001	(C-30-17)30bab-1	38.176306	–113.795500	286	7,193	09/06/2012	17.1	7,176
382539113250601	(C-27-14)28ddd-2	38.427461	–113.419134	987	5,085	09/05/2012	562.4	4,523
382535113251101	(C-27-14)28ddd-1	38.426349	–113.420523	0	5,090	09/05/2012	567.7	4,522
380904113380101	(C-30-16)34cca-1	38.151075	–113.634414	170	6,230	09/05/2012	41.9	6,188
380716113374901	(C-31-16)10cab-1	38.121076	–113.631080	150	6,135	09/05/2012	8.9	6,126
381033113480701	(C-30-18)25aad-1	38.175796	–113.802750	0	7,098	09/06/2012	5.0	7,093
383357113440601	(C-26-17) 3cdd-1	38.571639	–113.741972	870	5,245	09/06/2012	435.8	4,809
383402113440601	(C-26-17) 3cda-1	38.572861	–113.742000	882	5,248	09/06/2012	433.4	4,815
383303113343201	(C-25-16)18bdd-1	38.640361	–113.685667	340	5,085	09/06/2012	299.8	4,785
383131113214301	(C-26-14)25aad-1	38.525237	–113.362744	1,135	4,760	09/07/2012	233.4	4,527
384042113181601	(C-24-13)34ccb-1	38.678167	–113.305222	294	4,645	09/07/2012	209.5	4,436
384215113165701	(C-24-13)23ccd-1	38.704124	–113.283298	201	4,619	09/07/2012	177.0	4,442
384306113112601	(C-24-12)15cdc-1	38.718292	–113.191350	532	4,595	09/07/2012	83.3	4,512
384351113150501	(C-24-13)13aac-1	38.730791	–113.252186	145	4,555	09/07/2012	95.6	4,460
385008113145301	(C-23-12) 6ccd-1	38.835512	–113.248853	560	4,632	09/07/2012	205.5	4,427
[2]383538113450801	(C-25-17)33dab-1	38.593845	–113.753032	628	5,265	07/01/1933	466.0	4,799
—[1]	(C-31-16)32aca	38.066798	–113.658773	217	5,980	07/08/2008	185	5,795
—[1]	(C-31-16)21abb	38.098263	–113.646686	300	6,050	02/10/2004	180	5,870
381152113442801	(C-30-17)15cab-1	38.197880	–113.741408	385	6,550	11/22/1995	350	6,200
[2]383226113412401	(C-26-16)19bbd-1	38.540513	–113.690808	394	5,205	01/01/1960	355	4,850
382016113364001	(C-28-16)35bac-S1	38.337739	–113.611915	—	7,210	—[4]	—	7,210
381700113383001	(C-29-16)16dca-S1	38.283295	–113.642471	—	7,280	—[4]	—	7,280
381045113470701	(C-30-17)19ddc-S1	38.179129	–113.786083	—	6,900	—[4]	—	6,900
382151113512301	(C-28-18)22bbc-S1	38.364126	–113.857198	—	6,585	—[4]	—	6,585

Table A–1. Selected attributes of wells and water levels measured in wells used in constructing the water-level surface map for Pine and Wah Wah Valleys and surrounding areas, Utah.—Continued

[Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). **Abbreviations**: USGS, U.S. Geological Survey; mm/dd/yyyy, month/day/year; —, no information; <, less than]

USGS site number	Site name	Latitude (decimal degrees)	Longitude (decimal degrees)	Well depth (feet)	Altitude of land surface (feet)	Measurement date (mm/dd/yyyy)	Depth to water below land surface (feet)	Water-level altitude (feet)
382445113501401	(C-27-18)35ccb-1	38.412459	–113.836921	—	6,260	—[4]	—	6,260
382550113504001	(C-27-18)27dba-S1	38.430236	–113.844421	—	6,340	—[4]	—	6,340
383153113512301	(C-26-18)22cbb-S1	38.531345	–113.857201	—	6,570	—[4]	—	6,570
383122113544401	(C-26-19)25aad-S1	38.522734	–113.913035	—	6,910	—[4]	—	6,910
382238113205301	(C-28-13)18adb-S1	38.377184	–113.348855	—	5,535	—[4]	—	5,535
381848113292701	(C-29-15) 2dad-S1	38.313296	–113.491635	—	6,150	—[4]	—	6,150
381835113361701	(C-29-16) 2dcd-S1	38.309684	–113.605526	—	8,050	—[4]	—	8,050
382534113513401	(C-27-18)28ddb-S1	38.426069	–113.860255	—	6,660	—[4]	—	6,660
382344113305901	(C-28-15)10abb-S1	38.395516	–113.517192	—	5,850	—[4]	—	5,850
382901113295101	(C-27-15)11aba-S	38.483570	–113.498303	—	5,640	—[4]	—	5,640
382843113291401	(C-27-15)12bcd-S1	38.478570	–113.488025	—	5,460	—[4]	—	5,460
381344113512301	(C-30-18) 3bcc-1	38.228861	–113.856278	430	7,805	09/01/2012	92	7,713
381236113485601	(C-30-18)12cdb-1	38.210028	–113.815500	300	7,190	07/23/2014	39	7,151
—[3]	Dike Access (SEV-12-027)	38.726955	–113.186820	380	4,542	05/20/2013	—	4,494
—[3]	Bonneville (SEV-12-026)	38.827966	–113.101015	315	4,769	05/22/2013	—	4,592
—[3]	Coyote Well (SEV-11-013)	38.855061	–113.263763	765	4,781	09/17/2012	—	4,431
—[3]	Monument Point Well	38.811554	–113.082527	1,215	4,888	09/17/2012	—	4,594
—[1]	CICWCD # 6	38.275539	–113.691082	1,000	6,088	11/07/2016	514	5,574
—[1]	CICWCD # 7	38.197012	–113.746362	1,000	6,600	02/02/2017	220	6,380
—[1]	CICWCD # 8	38.240485	–113.675263	1,000	6,200	11/02/2016	468	5,732
—[1]	CICWCD #11	38.265714	–113.707401	1,000	6,080	11/11/2016	404	5,676
—[1]	CICWCD #18	38.319833	–113.692094	880	5,984	11/02/2016	419	5,565
—[1]	CICWCD #12	38.237688	–113.713291	1,000	6,220	01/24/2017	508	5,712
—[1]	CICWCD #24	38.224235	–113.644278	—	6,427	02/09/2017	DRY	<6,817
—[1]	CICWCD #25	38.185634	–113.651885	1,000	6,290	10/29/2016	512	5,778
—[1]	Utah Allunite MW-1	38.266729	–113.543286	145	7,000	10/06/2012	38.0	6,962
—[1]	Utah Allunite MW-4	38.257836	–113.528621	255	6,845	10/05/2012	140.0	6,705
—[1]	Utah Allunite MW-2	38.293592	–113.503849	170	6,650	10/04/2012	165.0	6,485
—[1]	Utah Allunite MW-6	38.265466	–113.521390	300	6,900	08/08/2013	40.0	6,860
—[1]	Utah Allunite MW-9	38.274424	–113.510472	61	6,720	08/08/2013	30.0	6,690
—[1]	Utah Allunite MW-13	38.312988	–113.484588	220	6,080	08/08/2013	15.0	6,065

[1]Water level was not in the USGS database. It was obtained from drillers log filed with the Utah State Division of Water Rights and available at https://waterrights.utah.gov/.

[2]Water level was obtained from the driller's log and reported in the USGS database.

[3]Water level was not in the USGS database. The water-level altitudes were reported by Stephen Hill with CH2MHill (written commun., January 21, 2014).

[4]Land-surface altitude is used to approximate the altitude of the groundwater level at springs; no date is associated.

For more information concerning the research in this report, contact the
Director, Utah Water Science Center
U.S. Geological Survey
2329 West Orton Circle
Salt Lake City, Utah 84119-2047
801-908-5000
https://ut.water.usgs.gov

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