Prepared in cooperation with the National Park Service

Hydrogeology and Sources of Water to Select Springs in Black Canyon, South of Hoover Dam, Lake Mead National Recreation Area, Nevada and Arizona

Scientific Investigations Report 2015–5130

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

Cover: Photograph of Latos Pool looking west, Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona. (Photograph taken by Jon Wilson, U.S. Geological Survey, 2014.)

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
	Volume	
liter (L)	0.2642	gallon (gal)
	Mass	
milligram (mg)	0.00003527	ounce avoirdupois (lb)
kilogram (kg)	2.205	pound avoirdupois (lb)
microgram per gram (µg/g)	1	part per million

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

$$°F = (1.8 \times °C) + 32.$$

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) or the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27) and 1983 (NAD 83).

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

Supplemental Information

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

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

Activities for radioactive constituents in water are given in picocuries per liter (pCi/L).

Abbreviations

AR	activity ratio
CCC	Criteria Continuous Concentrations
δ^2H	hydrogen-2 to hydrogen-1 isotopic ratio relative to VSMOW
$\delta^{18}O$	oxygen-18 to oxygen-16 isotopic ratio relative to VSMOW
GMWL	Global Meteoric Water Line
$\delta^{34}S$	isotopic ratio of sulfur
$^{86}Sr/^{87}Sr$	isotopic ratio of strontium
$^{234}U/^{238}U$	isotopic ratio of uranium
ka	thousand years (ago)
LAKE	Lake Mead National Recreation Area
LMWL	Local Meteoric Water Line
MSW	modern sea water
NEL	no evaporation line
NWQL	National Water Quality Laboratory
PMC	percent modern carbon
TDS	total dissolved solids
EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water

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Abstract

Springs in Black Canyon of the Colorado River, directly south of Hoover Dam in the Lake Mead National Recreation Area, Nevada and Arizona, are important hydrologic features that support a unique riparian ecosystem including habitat for endangered species. Rapid population growth in areas near and surrounding Black Canyon has caused concern among resource managers that such growth could affect the discharge from these springs. The U.S. Geological Survey studied the springs in Black Canyon between January 2008, and May 2014. The purposes of this study were to provide a baseline of discharge and hydrochemical data from selected springs in Black Canyon and to better understand the sources of water to the springs.

Various hydrologic, hydrochemical, geochemical, and geologic data were collected and analyzed during this study. More than 100 hydrologic sites consisting of springs, seeps, pools, rivers, reservoirs, and wells were investigated, and measurements were taken at 75 of these sites. Water levels were measured or compiled for 42 wells and samples of water were collected from 36 unique sites and submitted for laboratory analyses of hydrochemical constituents. Measurements of discrete discharge were made from nine unique spring areas and four sites in Black Canyon were selected for continuous monitoring of discharge. Additionally, samples of rock near Hoover Dam were collected and analyzed to determine the age of spring deposits.

Results of hydrochemical analyses indicate that discharge from springs in Black Canyon is from two sources: (1) Lake Mead, and (2) a local and (or) regional source. Discharge from springs closest to Hoover Dam contains a substantial percentage (>50 percent) of water from Lake Mead. This includes springs that are between Hoover Dam and Palm Tree Spring. Discharge from springs south of Palm Tree Spring contains a substantial percentage (>50 percent) of the water that is believed to come from a combination of other local and regional sources, although the exact location and nature of these sources is not clear. The unique hydrochemistry of some springs, such as Bighorn Sheep Spring and Latos Pool, suggests that little if any water discharging from these springs comes from Lake Mead. Geochronological results of spring deposits at several sites near Hoover Dam indicate that most deposits are young and likely formed after the construction of Hoover Dam.

Several major faults, including the Salt Cedar Fault and the Palm Tree Fault, play an important role in the movement of groundwater. Groundwater may move along these faults and discharge where faults intersect volcanic breccias or fractured rock. Vertical movement of groundwater along faults is suggested as a mechanism for the introduction of heat energy present in groundwater from many of the springs. Groundwater altitudes in the study area indicate a potential for flow from Eldorado Valley to Black Canyon although current interpretations of the geology of this area do not favor such flow. If groundwater from Eldorado Valley discharges at springs in Black Canyon then the development of groundwater resources in Eldorado Valley could result in a decrease in discharge from the springs. Geology and structure indicate that it is not likely that groundwater can move between Detrital Valley and Black Canyon. Thus, the development of groundwater resources in Detrital Valley may not result in a decrease in discharge from springs in Black Canyon.

Introduction

Springs in Black Canyon of the Colorado River, directly south of Hoover Dam in the Lake Mead National Recreation Area (LAKE), Nevada and Arizona, are important hydrologic features. The springs are significant recreational aspects of LAKE and support a unique and important riparian ecosystem including habitat for endangered species. In 1964, the area around Lakes Mead and Mohave became the Lake Mead National Recreation Area, the first region in the Nation to be designated a national recreation area by the U.S. Congress. Lake Mead, located east of present-day Las Vegas, Nevada, was formed by the Hoover Dam impoundment of the Colorado River in 1935. Lake Mohave is a reservoir on the Colorado River in the southern part of LAKE and was created in 1951 following the completion of Davis Dam near present-day Laughlin, Nevada.

Black Canyon is a gorge on the Colorado River downstream of Hoover Dam in LAKE between Lakes Mead and Mohave. Black Canyon, as defined in this study, extends from Hoover Dam south to around Willow Beach (fig. 1). Numerous small springs and seeps discharge from various points in the canyon including the walls of the main canyon as well as areas within the tributary draws. A distinctive aspect of the springs in Black Canyon is that both hot and cold varieties are present near each other.

Numerous plant and animal species and subspecies that depend on springs or spring-fed wetlands and streams in Black Canyon are listed under the Federal Endangered Species Act (Rosen and others, 2012). For example, several species of endangered or threatened amphibians, including the relict leopard frog (*Rana onca*), are present in this area. Once occurring along the historical trace of the Colorado River in this region natural populations of this frog are now limited to a few spring and stream habitats in Black Canyon and in the region of the Overton Arm of Lake Mead (Jaeger and others, 2001; Bradford and others, 2004).

Over the past several decades the population in the area surrounding Black Canyon has increased substantially. Las Vegas, Nevada, to the northwest of Black Canyon, was among the 10 fastest-growing metropolitan areas in the Nation from 2000 to 2010 (Frey, 2012). There has been concern that this development could expand to the Eldorado Valley in Nevada. If this development occurs it is likely that groundwater will be used to provide potable water supplies to populations in Eldorado Valley. Additionally, the completion of the Hoover Dam Bypass has enabled increased future growth in the Detrital Valley of Arizona. Mohave County, in which Detrital Valley is located, was the fastest growing county in Arizona from 1990 to 2000; the population of this county grew by 24 percent from 2000 to 2010 (Williams and others, 2013). From 2013 to 2050 the population of Mohave County is anticipated to increase by an additional 34 percent (Arizona Department of Administration, 2014). Groundwater is expected to be the primary source of potable water for almost all of the population in Mohave County.

Recent rapid population growth in areas of southeastern Nevada and northwestern Arizona surrounding Black Canyon has caused concern among resource managers that such growth could lead to an increased demand for water, which would be obtained mainly from groundwater sources. An increase in pumping of groundwater in areas surrounding Black Canyon could have an effect on the springs in Black Canyon such as a decrease in discharge. Decreased discharge could have negative effects on the recreational aspects of the springs and could threaten habitat for endangered species.

Purpose and Scope

To address concerns regarding the potential for decreased discharge at springs in Black Canyon, the U.S. Geological Survey (USGS), in cooperation with the National Park Service, conducted a study of the springs in Black Canyon. This study will provide water resource managers at LAKE with baseline information on select springs in Black Canyon and give insights into the sources of water to the springs. Results from this study also may help to identify the specific natural or anthropogenic causes of any future changes in spring discharge or hydrochemistry. Information gained from this study will help water managers make effective decisions regarding spring resources in LAKE through the development of monitoring, management, and mitigation plans to protect water sources to the springs.

The scope of this report included the following tasks:

1. Documenting existing hydrologic conditions of select springs, including discharge and hydrochemistry;
2. Examining the hydrochemical conditions of select hot and cold springs that are near each other; and
3. Using a combination of geologic, hydrologic, and hydrochemical data to evaluate potential sources of water to the springs.

Various hydrologic, hydrochemical, geochemical, and geologic data were collected and analyzed during this study, including discharge and hydrochemistry data at the springs as well as geologic data in the form of mapping of lithologies and structures and kinematic analyses of faults. A USGS report by Beard and others (2014) contains results on geologic work completed as part of this study.

Study Area

The Black Canyon area, as defined in this study, encompasses a 1.2-mi-wide by 11.2-mi-long rectangular area that extends from Hoover Dam to Willow Beach in LAKE. To determine potential sources of groundwater to the springs, the study area also includes the region surrounding Black Canyon including Eldorado Valley and the area immediately east of Black Canyon (fig. 1). Most of Black Canyon is a deeply incised gorge eroded by the Colorado River into the mountain ranges south of Hoover Dam, such as the Eldorado Mountains in Nevada and the Black Mountains in Arizona. Eldorado Valley is west of the Eldorado Mountains in Nevada and Detrital Valley is east of Black Canyon and the Black Mountains in Arizona (fig. 1). The gorge carved by the Colorado River south of Hoover Dam, which includes Black Canyon, is part of a larger valley sometimes referred to as the Colorado River Valley that extends from Hoover Dam to around Needles, California (not shown in fig. 1) (Rush and Huxel, 1966).

Geology and Hydrogeology

Exposures of rock in Black Canyon are dominated by Miocene volcanic rocks underlain by Paleoproterozoic crystalline basement rocks. Alluvium and sedimentary rocks cover most of Eldorado and Detrital Valleys as well as smaller areas within Black Canyon. The main geologic units in the

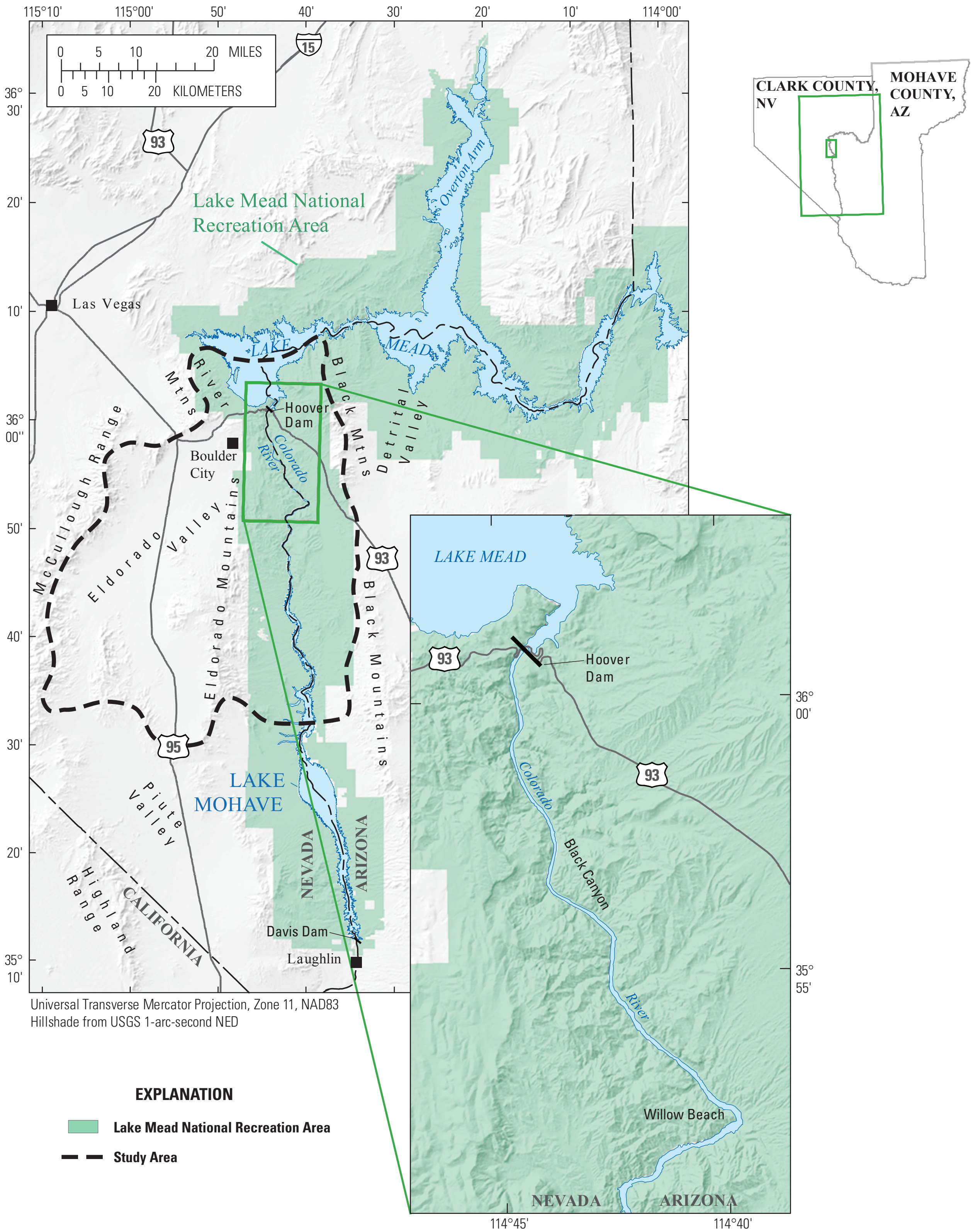


Figure 1. Location of the study area and Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

Black Canyon study area include Paleoproterozoic crystalline rocks, Cenozoic Patsy Mine volcanic rocks, Cenozoic Boulder City pluton, Cenozoic Mount Davis volcanic rocks, and Cenozoic sedimentary-rock basin fill (fig. 2).

Paleoproterozoic rocks in Black Canyon include various metamorphic and ultramafic rocks. These crystalline rocks are widely exposed at Willow Beach and on the west side of Black Canyon and plunge northward beneath overlying volcanic rocks. The Paleoproterozoic rocks are locally strongly fractured (Anderson, 1978). Depth-to-bedrock geophysical models suggest that Proterozoic crystalline basement is at a depth of a few tens of feet near surface exposures of the basement rock to a few hundred feet elsewhere in the Black Canyon area (Langenheim and Schmidt, 1996; Langenheim and others, 2010).

The Patsy Mine volcanic rocks consist of dacite flows, thick units of andesite and basaltic flows, and explosion breccias. The Boulder City pluton intrudes Patsy Mine volcanic rocks, although an obvious intrusive contact is rare because of faulting. The northern part of the pluton, which is well exposed in Goldstrike Canyon, is faulted, brecciated, and intruded by dikes. The Mount Davis volcanic rocks overlie the Patsy Mine rocks and are composed of rhyolite to basalt interbedded with clastic and volcaniclastic deposits (Beard and others, 2014).

In addition to these main rock units, other units have limited exposure in the Black Canyon area. The Tertiary Dam conglomerate is mostly composed of clasts of Patsy Mine andesite and granite porphyry that were identified as Boulder City pluton. The Tertiary tuff of Hoover Dam is a lithic ash flow tuff with moderately welded to poorly welded zones. The tuff is highly fractured and cut by many faults (Angelier and others, 1985). Both of these units occur mainly near Hoover Dam. Finally, Tertiary Mount Davis dacite intrudes along faults or occurs as flows and domes in various areas throughout Black Canyon (Beard and others, 2014).

Sedimentary rocks, consisting mainly of conglomerates, cover much of the basin areas of Eldorado Valley and Detrital Valley. These rocks are composed of coarse clastics shed from nearby ranges. East of Black Canyon and south of Hoover Dam, a thickness of more than 1,800 ft of sedimentary rock was measured by Williams (2003). However, based on a depth-to-bedrock model, the sedimentary rocks were estimated to be no more than 300–700 ft thick in the area south of Boulder City (Langenheim and others, 2010).

Structurally, Black Canyon is located south of the Lake Mead fault system and Las Vegas Valley shear zone at the north end of the Colorado River extensional corridor (Howard and John, 1987). Within Black Canyon, north-south striking normal faults of the corridor intersect with northeast- and northwest-striking strike-slip fault systems. Two major structures are notable in Black Canyon—the Palm Tree and the Salt Cedar Faults (fig. 2). The Palm Tree Fault is a right-lateral strike-slip fault that extends northwest across Black Canyon. The Salt Cedar Fault is a north-striking, west-side-down fault zone on the west side of Black Canyon with right-lateral slip displacement in some areas. Mount Davis dacite dikes, domes, and flows intrude along both faults (Beard and others, 2014).

From a hydrogeologic perspective, the crystalline and volcaniclastic rocks of Black Canyon and the surrounding area are relatively impermeable and probably are not important groundwater aquifers (Rush and Huxel, 1966). However, they may act as conduits for groundwater flow or as aquifers with low specific yields in areas where they are highly fractured. Rush and Huxel (1966) estimated that little groundwater movement occurs in the sedimentary or igneous rocks of the Eldorado-Piute Valleys. The alluvium of the area is believed to be the primary groundwater aquifer and most of the groundwater likely is contained within the coarse-grained alluvium. These materials mainly are located in mountain-front areas of Black Canyon or in washes cutting alluvial aprons.

Black Canyon is in the Mojave Desert ecoregion. The climate is typical of the Mojave Desert, with hot, dry summers and mild winters. Annual rainfall is relatively low but varies significantly depending on location. The mountainous areas of the Mojave Desert likely receive more precipitation than valley areas and most of the recharge probably occurs in the mountains of the Black Canyon area. A long-term precipitation measuring station in Black Canyon at Willow Beach (altitude about 800 ft) measured an average annual precipitation from October 1, 1967, to September 30, 2007, of about 5.6 in. (Western Regional Climate Center, 2014). Mountain areas near Black Canyon likely receive higher annual precipitation amounts. A station located in Red Rock Canyon National Conservation Area (altitude about 3,800 ft) measured an average annual precipitation from May 1, 1977, to March 28, 2013, of about 11.6 in. (Western Regional Climate Center, 2014). This is probably not representative of precipitation in the mountains of the immediate Black Canyon area, because this site is more than 15 mi west of the study area and at a significantly higher altitude. However, it is indicative of the higher precipitation that occurs in the mountains relative to the valleys of the Mojave Desert.

Only a small percentage of precipitation recharges groundwater in the study area. Early work in the Eldorado and Colorado River Valleys of Black Canyon indicated that the average annual groundwater recharge to the Eldorado Valley was about 1,100 acre-ft (about 1.5 ft^3/s), with 200 acre-ft (about 0.3 ft^3/s) of recharge in the adjacent part of the Colorado River Valley (Rush and Huxel, 1966). This represents only about 0.5 percent of precipitation in these areas. The primary areas of recharge in the Eldorado Valley were thought to be the McCullough Mountains to the west and southwest, respectively, and the Eldorado Mountains and the Highland Range to the south (Rush and Huxell, 1966).

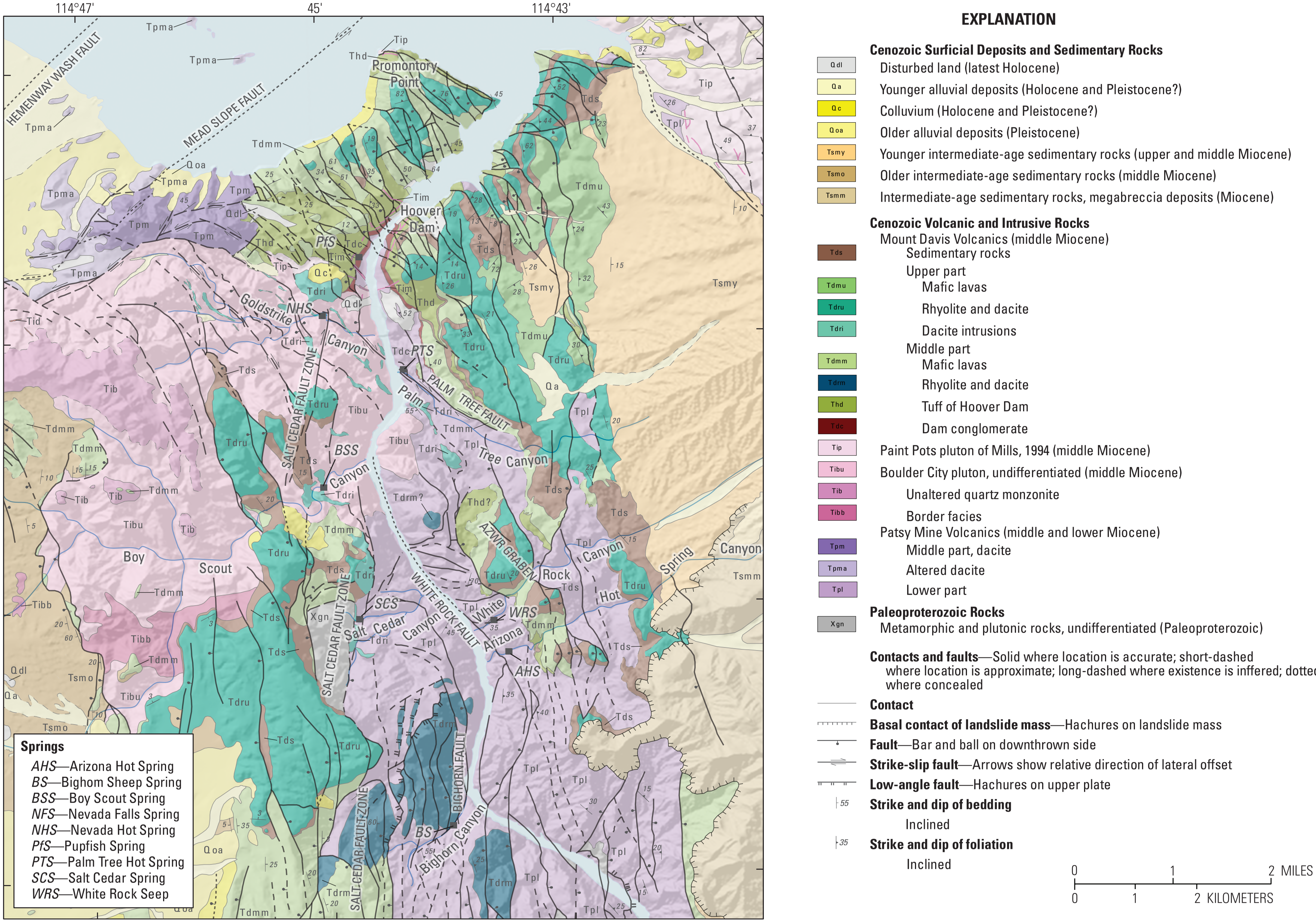


Figure 2. General geology and major structural features of Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona. From Beard and others (2014; figure 2).

Photograph (looking toward the bridge) of Black Canyon near Nevada Hot Spot looking north toward Hoover Dam, Lake Mead National Recreation Area, Nevada and Arizona. (Photograph taken by Michael Moran, U.S. Geological Survey, 2014.)

Previous Studies

The earliest known comprehensive hydrologic study of the Black Canyon area was done by the USGS in cooperation with the Nevada Department of Conservation and Natural Resources (Rush and Huxel, 1966). This report was one of the Water Resources Reconnaissance Series reports intended to appraise the water resources of the state of Nevada. The study area was confined to the Eldorado-Piute Valley area adjacent to Black Canyon; however, the report does provide an initial estimate of the water resource availability of the Black Canyon area. Rush and Huxel (1966) indicated that the unconsolidated alluvium of the area provides the best possible source for significant groundwater supplies and that the sedimentary and igneous rocks are relatively impermeable and are not important reservoirs of groundwater. They also suggested that groundwater discharge from Eldorado Valley occurs by subsurface outflow to the east through the volcanic rocks of the Eldorado Mountains to the Colorado River (Rush and Huxel, 1966).

Beginning in 1970, the USGS conducted a series of hydrologic reconnaissance studies in LAKE (Bentley, 1979a, 1979b, 1979c; Laney, 1979a, 1979b, 1979c; Bales and Laney, 1992; Laney and Bales, 1996). These studies evaluated the water resources in LAKE and identified areas with water-supply potential. Each of these studies included an inventory of wells and springs, geochemical analyses of groundwater from springs and wells, and an assessment of geologic controls on the occurrence and movement of groundwater in the area. The results of these studies indicated that significant quantities of groundwater likely are only present in coarse-grained alluvial deposits of the region. Much smaller quantities of groundwater were postulated to be present in fine-grained sedimentary rocks such as the Horse Spring or Muddy Creek Formations or in fractured areas of granitic, volcanic, or metamorphic rocks. Most of the evidence for groundwater occurrence from these studies was indirect and inferred as little data were available.

Several evaluations of the discharge and chemical composition of springs in Black Canyon were done. McKay and Zimmerman (1983) did a hydrochemical investigation of thermal springs in Black Canyon. They used environmental isotopes as well as other geochemical techniques to evaluate the possible origin of groundwater from the springs. The results of their study indicated that an estimated 1.24 ft^3/s (about 900 acre-ft/yr) of water discharges from springs along both sides of the Colorado River in Black Canyon. They noted that the springs discharged from highly faulted and fractured volcanic rocks exposed throughout the canyon. Chemical analyses of water from the springs indicated that the water could have various possible origins including (1) Lake Mead; (2) regional groundwater to the north, west, and east; (3) deep circulating hydrothermal fluids; and (4) locally-recharged groundwater.

McKay and Zimmerman (1983) also observed an overall trend of increasing anion concentrations with increasing distance downstream of Hoover Dam. They attributed this trend to increasing contributions from a component of chlorine-rich, non-thermal saline water of unknown origin. They also noted the presence of elevated tritium in springs closest to Hoover Dam, which was attributed to a component of rapidly circulated water derived at least partially from Lake Mead. Discharge from springs farther downstream generally contained no detectable tritium. Additionally, McKay and Zimmerman (1983) identified a separate hydrochemical origin for water discharging from Bighorn Sheep Spring and Nevada Falls relative to other springs in Black Canyon. They speculated that this water may come from Eldorado Valley or from local precipitation in the Eldorado Mountains.

Finally, McKay and Zimmerman (1983) observed little variation in discharge, temperature, or major constituent chemistry at most springs during a 5 percent variation in lake stage over the 16-month period of data collection. This lack of variation, especially with respect to spring discharge, was explained as the result of the large total head at the springs relative to the changes in Lake Mead water-level altitude and the restrictive forces limiting flow through the low permeability crystalline rocks of the area, including friction, turbulence, and tortuosity (McKay and Zimmerman, 1983).

In a later study, Pohlmann and others (1998) measured and described conditions at 36 springs in LAKE, including the Black Canyon area. The purpose of their study was to determine the hydrology and hydrochemistry of select springs in this area and to determine the source of water to the springs. They compiled historical hydrochemical data for the springs and collected new hydrochemical data. Additionally, Pohlmann and others (1998) considered regional hydrochemical data from studies associated with the Nevada Test Site and the USGS Regional Aquifer-System Analysis Program (Winograd and Friedman, 1972; Thomas and others, 1991; Hershey and Mizell, 1995; Laney and Bales, 1996).

The results of Pohlmann and others (1998) indicated that groundwater supplying the springs could have three possible sources. One-third of the springs were believed to have a source from a local groundwater system. These springs generally are not related to major structural features and their stable isotopic values (delta hydrogen [δ^2H] and delta oxygen [$\delta^{18}O$]) suggested that they receive recharge from low-altitude areas such as Eldorado Valley. Pohlmann and others (1998) concluded that hydrologic, geologic, and climatologic conditions can combine to support low-volume springs with a low-altitude source despite the negligible recharge in these areas as estimated by the Maxey-Eakin method (Maxey and Robinson, 1947; Maxey and Eakin, 1949).

A second set of springs was believed to discharge water that originates from a sub-regional flow system. Pohlmann and others (1998) attributed discharge from these springs to major regional structural features such as north-south striking faults. The stable isotopic values from water at these springs suggested that they receive recharge from higher altitudes. The source of water to these springs was presumed to be derived from a combination of groundwater flow from Eldorado and Detrital Valleys and locally recharged groundwater from the Black and Eldorado Mountains (Pohlmann and others, 1998).

Finally, a third set of springs directly south of Hoover Dam was thought to discharge water that originated from Lake Mead. Pohlmann and others (1998) recognized the same influence of Lake Mead on water discharging from springs near Hoover Dam that earlier was identified by McKay and Zimmerman (1983). They also noted that these springs seem to be related to faulting around the Boulder City pluton and hypothesized that the pluton could be the heat source for thermal springs (Pohlmann and others, 1998).

Anning and others (2007) examined water level changes in wells in the Detrital Valley as well as several other valleys in northwestern Arizona. They concluded that the potentiometric surface for groundwater in alluvium in Detrital Valley, as with other valleys in this area, generally is parallel to topography. Therefore, groundwater movement in Detrital Valley generally is from the mountain areas toward the basin center and then along the basin axis toward the Colorado River or Lake Mead. This conclusion suggests that groundwater movement within the alluvial basin-fill material of Detrital Valley generally is to the north toward Lake Mead and not to the west toward Black Canyon.

Sada and Jacobs (2008) inventoried springs in LAKE. Although they focused primarily on the ecological significance of the springs, they measured discharge at a number of springs in Black Canyon in 2007 including some of the same springs where discharge was measured in this study. This allowed for a comparison of discharge measured at these springs and provided an enhanced period of record of discharge for these springs.

Methods

Various physical measurements were made at wells and springs in the Black Canyon, including measurements of water levels, miscellaneous instantaneous discharge, and continuously measured stage. At many sites, land-surface altitude data were collected using a handheld Global Positioning System that was checked against a USGS 7.5′ quadrangle map. Water-level measurements in wells were made using calibrated electric tapes and steel tapes following standard USGS data-collection protocols (Cunningham and Schalk, 2011). Water-level measurements were recorded in feet below the measuring point at the well and then converted to altitude with reference to the ground surface at the well head. Average depth to groundwater from the land surface was computed for wells that had multiple measurements. The altitude of a spring orifice was considered as an approximation of the groundwater surface altitude in the immediate area of Black Canyon.

Miscellaneous measurements of discharge were made using flow-measurement instruments volumetrically, or were estimated based on channel cross-section and surface velocity. In cases where instruments were used to make instantaneous discharge measurements, a SonTek YSI FlowTracker Acoustic Doppler Velocimeter® was used to measure groundwater velocity and discharge was computed according to standard USGS methods (U.S. Geological Survey, 2004).

At four sites in Black Canyon, stage was measured continuously and discharge was computed using standard USGS methods and techniques (Rantz and others, 1982). Three-inch Parshall flumes were constructed at three of these sites and pressure transducers, capable of recording spring pool/stream stage and water temperature, were installed. Stage data were collected every 15 minutes. Discharge was computed using flume equations developed at other sites (Rantz and others, 1982). At one site, a French drain was installed in the natural channel and used in conjunction with a 2-in. stilling well for the collection of stage data. The discharge computed for this site was developed using standard USGS methods based on channel cross-section area and surface velocity. Each station where continuous stage data were collected was visited on a 4–6 week rotation for routine equipment maintenance and to obtain additional field measurements.

Samples for hydrochemical analyses were collected following standard USGS field sampling protocols (U.S. Geological Survey, variously dated). Samples were collected as close to the spring orifice as possible and were drawn from spring sites using a peristaltic pump and flow-through chamber. A water-quality sonde (In Situ Troll® 9500) within the flow-through chamber analyzed water for pH, temperature, specific conductance, and dissolved oxygen in the field. Samples were submitted for laboratory analyses of various hydrochemical constituents including major ions, trace elements, perchlorate (ClO_{4-}), nutrients, and isotopic ratios of sulfur ($\delta^{34}S$), strontium ($^{86}Sr/^{87}Sr$), uranium ($^{234}U/^{238}U$), hydrogen ($\delta^{2}H$), and oxygen ($\delta^{18}O$), as well as tritium and carbon-14 (^{14}C).

Major-ion, trace element, and nutrient concentrations were determined at the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado. The NWQL contracts with external organizations for the analysis of tritium and ^{14}C. Tritium was analyzed by the University of Miami and ^{14}C was analyzed at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts. Samples analyzed for $\delta^{2}H$ and $\delta^{18}O$ ratios were analyzed by the USGS Stable Isotope Laboratory in Reston, Virginia. Perchlorate analyses were completed at the U.S. Environmental Protection Agency (EPA) Regional Laboratory in Richmond, California. Samples analyzed for $\delta^{34}S$, $^{86}Sr/^{87}Sr$, and $^{234}U/^{238}U$ were completed at the USGS Denver Radiogenic Isotope Laboratory in Denver, Colorado. Samples of calcite from tufa and travertine deposits were analyzed using uranium-series disequilibrium at the USGS Denver Radiogenic Isotope Laboratory following methods described in Ludwig and Paces (2002). Analytical detection and reporting limits for each constituent, as reported by the NWQL and the EPA Regional Laboratory, are shown in appendix A.

Values of $\delta^{87}Sr$ were computed from reported $^{87}Sr/^{86}Sr$ values relative to the composition of modern sea water (MSW) using the following equation for delta notation:

$$\delta^{87}\text{Sr (in per mil units, ‰)} = \left[\left(\frac{^{87}\text{Sr}/^{86}\text{Sr}_{\text{sample}}}{^{87}\text{Sr}/^{86}\text{Sr}_{\text{MSW}}}\right) - 1\right] \times 1{,}000 \qquad (1)$$

where

$^{87}Sr/^{86}Sr_{MSW}$ is equal to 0.7091741 ± 0.0000024 (McArthur and others, 2006).

Use of 0.70920 instead of 0.7091741 results in $\delta^{87}Sr$ values that are 0.03–0.04 ‰ lower, which is at the level of 2σ analytical uncertainty. Sulfur (S)-isotopic results are reported in delta-notation relative to values obtained for the S-isotope standard using the equation:

$$\delta^{34}\text{S (in per mil units, ‰)} = \left[\left(\frac{^{34}\text{S}/^{32}\text{S}_{\text{sample}}}{^{34}/^{32}\text{S}_{\text{VCDT}}}\right) - 1\right] \times 1{,}000 \qquad (2)$$

where

$^{32}S_{VCDT}$ is the value of the standard Vienna Canyon Diablo Troilite.

As a check on the quality of the hydrochemical data, charge balance errors were computed. Charge balance errors deviated from zero by more than 5 percent in only four samples. These samples were not used in any subsequent analyses. As a measure of quality control, replicate samples were collected from seven sites and analyzed for some of the same constituents as environmental samples including major ions and trace elements. Replicate samples were collected sequentially on the same date as the environmental samples. Relative differences between replicate samples were computed as follows:

$$\text{Percent relative difference} = \text{absolute value}\left[\frac{(X_1 - X_2)}{X_1}\right] \times 100 \qquad (3)$$

where

X_1 is sample collected first in time and

X_2 is replicate sample collected.

A relative difference of 10 percent or less was considered as an acceptable level of variation between replicate samples. Most percent relative differences were less than 10 percent (appendix B). A few instances of relative differences greater than 10 percent in replicate samples occurred; however, all the instances of relative difference greater than 10 percent were for trace elements that were not used in any subsequent analyses.

In most cases, water samples to be analyzed for hydrochemical constituents were collected from each site on only one sample date. However, in some cases multiple samples were collected from a site on different dates or multiple samples were collected at a site on the same date but at slightly different locations at the site. In cases where more than one sample was collected at a site, multiple values of each individual hydrochemical constituent were averaged to produce a value used in the analyses.

Many of the analyses of hydrochemical data were done by distance of the springs from Hoover Dam in order to identify patterns. Past studies have shown a relation between hydrochemistry and distance of the springs in Black Canyon from Hoover Dam and have suggested Lake Mead as a source for much of the water discharging from springs near the dam (McKay and Zimmerman, 1983; Pohlmann and others, 1998). In this study, distances of each spring from Hoover Dam represent the map straight-line distances from the dam to the spring location. For two sets of springs, the distance from Hoover Dam to the spring is identical—Nevada Hot Spot–Sugarloaf Spring and Nevada Hot Spring–Arizona Hot Spot.

Water Level, Discharge, and Hydrochemistry

More than 100 hydrologic sites consisting of springs, seeps, pools, rivers, reservoirs, and wells were investigated during this study. Collection of physical measurements and (or) hydrochemical samples was attempted at all these sites. However, because of condition at some sites no physical measurements could be made and (or) no hydrochemical samples could be collected. Of the total number of sites visited, 75 were selected for some type of physical measurement or for collection of samples for hydrochemical analyses (fig. 3; table 1).

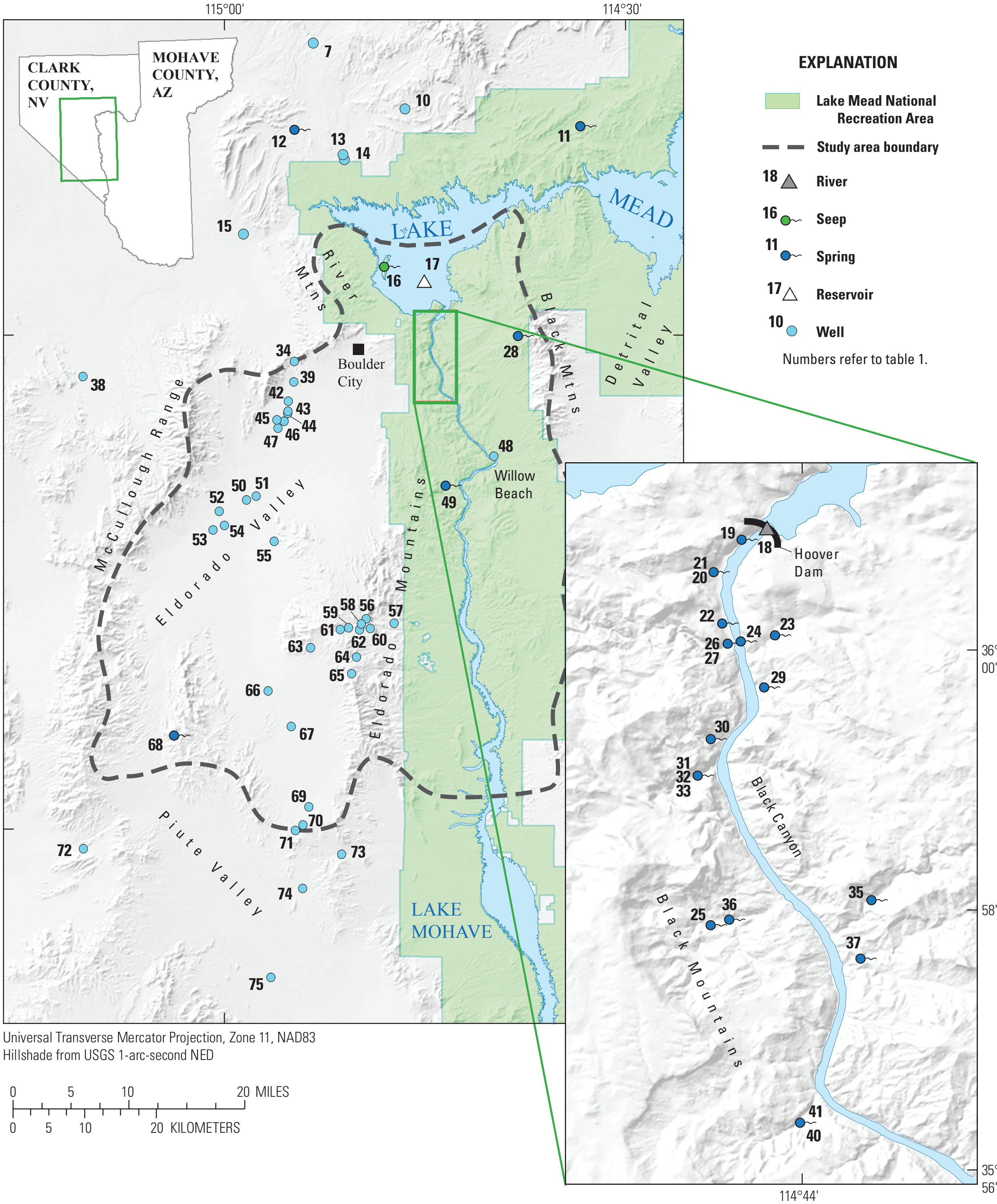


Figure 3. Location of sites where physical or hydrochemical samples were collected for analyses in and near Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona. (Numbers on map correspond to map numbers in table 3.)

Table 1. Study sites and sample types collected in and near Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[Data from U.S. Geological Survey National Water Information System (USGS site identifier); Nevada Department of Water Resources Well Log Database (NDWR log identifier). **Map No.** is shown in figure 3. **Altitude** refers either to feet above North American Datum of 1927 or feet above North American Datum of 1983. **Abbreviation:** USGS-BLM, U.S. Geological Survey-Bureau of Land Management]

USGS site/ NDWR log identifier	Map No.	Site name	Site type	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (feet)	Designated groundwater basin	Measurements, samples collected
363842114105401	1 (not shown)	Government Spring	Spring	36.64490	-114.18170	3,272	Virgin River Valley	Hydrochemical
363835114361901	2 (not shown)	Flame Spring	Spring	36.64310	-114.60540	1,644	California Wash	Hydrochemical
352805115061701	3 (not shown)	Clark's Well	Well	36.46480	-115.10770	4,849	Piute Valley	Water level
362735114154501	4 (not shown)	Red Bluff Spring	Spring	36.46200	-114.25220	1,627	Lake Mead Valley	Hydrochemical
362239114263501	5 (not shown)	Rogers Spring	Spring	36.37750	-114.44380	1,576	Lake Mead Valley	Hydrochemical
361804114084701	6 (not shown)	Garden Spring Well	Well	36.30100	-114.14640	3,754	Grease Wood Basin	Hydrochemical, water level
361736114531601	7	EBM-3	Well	36.29320	-114.88860	2,388	Black Mountains Area	Water level
361448114055201	8 (not shown)	New Spring	Spring	36.24670	-114.09770	3,314	Lake Mead Valley	Hydrochemical
361342114190201	9 (not shown)	Cataract Spring	Spring	36.22780	-114.31920	1,944	Lake Mead Valley	Hydrochemical
361335114463001	10	Rosen Oil	Well	36.22620	-114.77570	2,295	Black Mountains Area	Water level
361240114332001	11	Sandstone Spring	Spring	36.21070	-114.55610	1,889	Lake Mead Valley	Hydrochemical
361229114544001	12	Gypsum Spring	Spring	36.20730	-114.91180	1,750	Lake Mead Valley	Hydrochemical
93252	13	Sandia Gravel Well (south)	Well	36.17940	-114.85099	1,500	Black Mountains Area	Water level
361044114505601	14	Sandia Gravel Well (north)	Well	36.17553	-114.84960	1,500	Black Mountains Area	Water level
360832115060201	15	USGS-BLM Well	Well	36.10060	-114.97670	1,590	Las Vegas Valley	Water level
360412114480401	16	Lake Mead Intake No. 3 Connector Tunnel	Seep	36.07000	-114.80110	1,326	River Mountains Area	Hydrochemical
360314114450500	17	Lake Mead near Sentinel Island	Reservoir	36.05390	-114.75140	1,158	Lake Mead	Hydrochemical
9421500	18	Colorado River below Hoover Dam	River	36.01530	-114.73780	675	Colorado River Valley	Hydrochemical
360051114442801	19	Hoover Dam Seep	Spring	36.01410	-114.74100	902	Colorado River Valley	Hydrochemical
360036114444101	20	Pupfish Cold Spring	Spring	36.00990	-114.74470	803	Colorado River Valley	Hydrochemical, discrete discharge (combined)
360036114444102	21	Pupfish Hot Spring	Spring	36.00990	-114.74470	803	Colorado River Valley	Hydrochemical, discrete discharge (combined)

Table 1. Study sites and sample types collected in and near Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.—Continued

[Data from U.S. Geological Survey National Water Information System (USGS site identifier); Nevada Department of Water Resources Well Log Database (NDWR log identifier). **Map No.** is shown in figure 3. **Altitude** refers either to feet above North American Datum of 1927 or feet above North American Datum of 1983. **Abbreviation:** USGS-BLM, U.S. Geological Survey-Bureau of Land Management]

USGS site/ NDWR log identifier	Map No.	Site name	Site type	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (feet)	Designated groundwater basin	Measurements, samples collected
360010114443301	22	Sauna Cave	Spring	36.00330	-114.74350	689	Colorado River Valley	Hydrochemical
360007114441201	23	Sugarloaf Spring	Spring	36.00190	-114.73670	899	Colorado River Valley[1]	Hydrochemical, discrete discharge
360005114443001	24	Arizona Hot Spot	Spring	36.00110	-114.74110	690	Colorado River Valley[1]	Hydrochemical, continuous discharge and discrete discharge
355756114443401	25	Salt Cedar Spring	Spring	35.96453	-114.74604	709	Colorado River Valley	Hydrochemical, discrete discharge
360002114443201	26	Nevada Hot Spot	Spring	36.00080	-114.74300	828	Colorado River Valley	Hydrochemical, discrete discharge
355956114444401	27	Nevada Hot Spring	Spring	36.00070	-114.74290	797	Colorado River Valley	Hydrochemical
355956114375801	28	Horsethief Spring	Spring	35.99890	-114.63280	3,269	Colorado River Valley[1]	Hydrochemical
355942114441801	29	Palm Tree Spring (main channel)	Spring	35.99510	-114.73830	715	Colorado River Valley[1]	Hydrochemical, continuous discharge and discrete discharge
355919114444301	30	Dawn Hot Spring	Spring	35.98860	-114.74510	819	Colorado River Valley	Hydrochemical
355902114444801	31	Boy Scout Canyon—cold seep	Spring	35.98390	-114.74670	780	Colorado River Valley	Hydrochemical
355902114444802	32	Boy Scout Canyon—hot seep	Spring	35.98390	-114.74670	780	Colorado River Valley	Hydrochemical
355903114444401	33	Boy Scout Canyon Spring (Lower—combined flow)	Spring	35.98390	-114.74670	720	Colorado River Valley	Continuous discharge
355836114543701	34	Railroad Pass Well	Well	35.97158	-114.91178	2,950	Eldorado Valley	Water level
355804114432801	35	White Rock Spring	Spring	35.96780	-114.72440	892	Colorado River Valley[1]	Hydrochemical, discrete discharge
355756114443401	36	213 S23 E65 08CDD 1	Spring	35.96540	-114.74270	801	Colorado River Valley	Hydrochemical
355738114433301	37	Arizona Hot Spring	Spring	35.96050	-114.72580	862	Colorado River Valley[1]	Hydrochemical, discrete discharge
355718115103301	38	Sloan Well	Well	35.95510	-115.17590	2,540	Las Vegas Valley	Hydrochemical, water level
355706114545001	39	IRETEBA Well	Well	35.95167	-114.91389	2,050	Eldorado Valley	Water level
355621114440101	40	213 S23 E65 21CBC 1	Spring	35.93930	-114.73360	785	Colorado River Valley	Hydrochemical
355626114435701	41	Bighorn Sheep Spring	Spring	35.93930	-114.73360	950	Colorado River Valley	Hydrochemical, continuous discharge
355622114544101	42	Roger Ray Road Well	Well	35.93135	-114.92074	1,760	Eldorado Valley	Water level
47598	43	Unnamed well	Well	35.92282	-114.92120	1,760	Eldorado Valley	Water level
355519114551201	44	Unnamed well	Well	35.91956	-114.92174	1,750	Eldorado Valley	Water level
50654	45	NDOT Well	Well	35.91250	-114.93470	1,823	Eldorado Valley	Water level
62794	46	Unnamed well	Well	35.91201	-114.92596	1,750	Eldorado Valley	Water level
62792	47	Unnamed well	Well	35.90456	-114.93385	1,745	Eldorado Valley	Water level
355233114395101	48	Hatchery Well	Well	35.87590	-114.66410	698	Colorado River Valley[1]	Hydrochemical, water level
355050114432201	49	Latos Pool	Spring	35.84730	-114.72270	912	Lower Colorado River Valley	Hydrochemical, discrete discharge
355027114570801	50	Eldorado East Well	Well	35.83546	-114.96181	1,720	Eldorado Valley	Water level
355036114572501	51	Eldorado West Well	Well	35.83190	-114.97240	1,720	Eldorado Valley	Hydrochemical, water level

Table 1. Study sites and sample types collected in and near Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.—Continued

[Data from U.S. Geological Survey National Water Information System (USGS site identifier); Nevada Department of Water Resources Well Log Database (NDWR log identifier). **Map No.** is shown in figure 3. **Altitude** refers either to feet above North American Datum of 1927 or feet above North American Datum of 1983. **Abbreviation:** USGS-BLM, U.S. Geological Survey-Bureau of Land Management]

USGS site/ NDWR log identifier	Map No.	Site name	Site type	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (feet)	Designated groundwater basin	Measurements, samples collected
44207	52	Unnamed well	Well	35.82038	-115.00646	1,780	Eldorado Valley	Water level
64268	53	Unnamed well	Well	35.80607	-115.00097	1,780	Eldorado Valley	Water level
26942	54	Unnamed well	Well	35.80142	-115.01403	1,800	Eldorado Valley	Water level
25275	55	Unnamed well	Well	35.78977	-114.93831	2,190	Eldorado Valley	Water level
64302	56	Nelson Corner Well-1	Well	35.71080	-114.82350	3,035	Lower Colorado River Valley	Water level
76717	57	Jubilee Mine Well	Well	35.70690	-114.78870	2,156	Lower Colorado River Valley	Water level
354237114491701	58	WELL (REPORT R36)	Well	35.70625	-114.82944	3,110	Lower Colorado River Valley	Water level
354209114504301	59	Copper Canyon Well	Well	35.70270	-114.84510	3,456	Lower Colorado River Valley	Hydrochemical, water level
96768	60	Unknown well	Well	35.70180	-114.81870	2,847	Lower Colorado River Valley	Water level
354203114511701	61	Unknown well	Well	35.70070	-114.85560	3,679	Lower Colorado River Valley	Water level
96769	62	Nelson Well	Well	35.70040	-114.83060	3,107	Lower Colorado River Valley	Water level
23987	63	Stock Well	Well	35.68230	-114.89270	3,970	Eldorado Valley	Water level
354019114500401	64	Unknown (shallow) well	Well	35.67210	-114.83510	3,665	Lower Colorado River Valley	Water level
353921114503201	65	Knob Hill Well	Well	35.65580	-114.84210	4,144	Eldorado Valley	Water level
353817114563701	66	Unnamed well	Well	35.63863	-114.94540	2,848	Eldorado Valley	Hydrochemical, water level
87736	67	Unnamed well	Well	35.60244	-114.91645	3,065	Eldorado Valley	Water level
353547115033301	68	Highland Spring	Spring	35.59420	-115.06240	4,379	Eldorado Valley	Hydrochemical
64743	69	Unnamed well	Well	35.52028	-114.89549	3,585	Eldorado Valley	Water level
32989	70	Unnamed well	Well	35.50254	-114.90101	3,760	Eldorado Valley	Water level
64318	71	Jet Mine Stock Well	Well	35.49663	-114.91167	3,779	Eldorado Valley	Water level
68100	72	Unnamed well	Well	35.47820	-115.17612	4,300	Eldorado Mountains	Water level
No site number[2]	73	Cottonwood Cove Road Well	Well	35.47255	-114.85437	2,985	McCullough Range	Water level
106749	74	Unnamed well	Well	35.43767	-114.90232	3,315	Piute Valley	Water level
352047114563301	75	USBLM YKL 2 Well	Well	35.34720	-114.94260	2,896	Piute Valley	Water level

[1]Colorado River Valley in Arizona.

[2]Stock well, open hole.

Water-Level Measurements

More than 60 wells in the Black Canyon area were inspected and water-level measurements were made at 24 wells during this study. The sites were visited between August 11, 2007, and July 27, 2010. Site inspection included examination of the condition of the well and measurement of a water level in the well, where feasible. No wells were in the area immediately east of Black Canyon and only one well was in Black Canyon (Hatchery Well). Water-level measurements also were compiled from existing data for an additional 18 wells (fig. 3; table 2).

Water-level altitudes ranged from 682 feet at Hatchery Well in Black Canyon to 4,831 ft at Clark's Well in Piute Valley (table 2). Drillers' logs, where available, were examined to determine total depth and screened interval in the well. Additionally, lithologic information for wells, such as the lithology of the open casing interval, was compiled where available.

Most wells where water-level data were measured or compiled are in the Eldorado Mountains or the Eldorado Valley south of Black Canyon. Because of the sparse lithologic and hydrogeologic information available for most of the wells, it was difficult to identify a specific aquifer or lithology which contains open casing intervals. In mountainous areas, most wells likely have open casing intervals in fractured igneous or metamorphic rock that comprises the core of these ranges. In valley areas, wells likely have open casing intervals in alluvial basin fill; however, one well (Eldorado West Well) is known to have an open casing interval in volcanic rock. The lack of lithologic and hydrogeologic information available for many wells also made it difficult to identify if the groundwater surface at each well represents an unconfined water table or a potentiometric surface.

Discharge Measurements

Springs and seeps in Black Canyon occur in various forms and have varying discharge amounts. Some springs near the Colorado River discharge directly into the river whereas discharge from multiple individual springs and seeps in smaller side canyons often coalesces into a stream that ultimately discharges to the river. Springs with larger discharges are perennial whereas springs with smaller discharges can be either perennial or ephemeral. Occasionally, smaller seeps may provide water to localized vegetation and yield little water after evapotranspiration. For example, in side canyons and above river level, small seeps were observed in winter months whereas the same seeps were dry in summer months.

Nine spring areas had sufficient water for discrete measurements of discharge, which were made from September 21, 2007, to May 31, 2014 (table 1; appendix D). Additionally, four sites within Black Canyon were selected for continuous measurement of stage—Arizona Hot Spot, Palm Tree Spring, Boy Scout Canyon Spring, and Bighorn Sheep Spring. Continuous stage measurements were used to compute estimates of continuous discharge at each of these sites (fig. 4).

At three sites—Arizona Hot Spot, Palm Tree Spring, and Bighorn Sheep Spring—flumes were installed and continuous stage data were collected using pressure transducers deployed in the flume. At the site in Boy Scout Canyon, a French drain was installed in the natural channel and continuous stage data were collected using a pressure transducer deployed in the drain. Daily values of continuous discharge were computed from stage values at these sites (appendix C). Monthly and total average discharge measurements also were computed for each site (table 3).

Arizona Hot Spot is a collection of many small perennial seeps that occur along the base of a volcanic rock fracture. A 3-in. Parshall flume was installed at this site and a pressure transducer in a stilling well was used to collect stage data in the flume (fig. 5). Continuous stage data were collected at this site from October 3, 2008, until November 8, 2009. Stage record is missing for January 18–March 12, 2009 because of vandalism. Stage of water in the flume varied between 0.07 and 0.10 ft throughout the period of record and computed discharge varied between 0.01 and 0.03 ft^3/s with an average of 0.02 ft^3/s (table 3).

Palm Tree Spring is a series of thermal and non-thermal springs and seeps discharging from a right lateral strike-slip fault in the Patsy Mine volcanic rocks. Groundwater from multiple spring orifices coalesces into a single channel about 30–60 ft from the Colorado River. Measured discharge at this site represents a composite of discharge from all springs in the area that feed the discharge channel. A 3-in. Parshall flume was installed and a pressure transducer in a stilling well was used to collect stage data in the flume (fig. 6).

Continuous stage was measured at Palm Tree Spring from October 15, 2008, until December 30, 2009. Stage data are missing for November 26–28, 2008, and December 12–21, 2008, because of debris catching on the flume and water diverting around it. Computed average discharge for the period of record at the site was 0.08 ft^3/s (table 3). Displaced sediment and vegetation were noted during visits to this site as evidence of periodic flooding; however, the stage record does not show excessive discharge. For example, rainfall on February 7, 2009, produced 0.75-in. of precipitation but this resulted in less than a 0.01 ft^3/s increase in discharge.

Table 2. Generalized lithology and water-level measurements made or compiled from wells in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[Data from U.S. Geological Survey National Water Information System (USGS site identifier); Nevada Department of Water Resources Well Log Database (NDWR log identifier). **Map No.** is shown in figure 3. **Altitude** refers either to feet above North American Datum of 1927 or feet above North American Datum of 1983. **Abbreviation**: USGS-BLM, U.S. Geological Survey-Bureau of Land Management]

USGS site/ NDWR log identifier	Map No.	Site name	Site type	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (feet)	Designated groundwater basin	Measurements, samples collected	Generalized lithology of open interval	Water-level date	Water level (feet below land surface)	Altitude of water level (feet)
352805115061701	3 (not shown)	Clark's Well	Well	36.46480	-115.10770	4,849	Piute Valley	Water level	Volcanic rock	02-27-08	18	4,831
361804114084701	6 (not shown)	Garden Spring Well	Well	36.30100	-114.14640	3,754	Grease Wood Basin	Hydrochemical, water level	Sedimentary rock	07-01-08	14	3,740
361736114531601	7	EBM-3	Well	36.29320	-114.88860	2,388	Black Mountains Area	Water level	Sedimentary rock	05-06-08	579	1,809
361335114463001	10	Rosen Oil	Well	36.22620	-114.77570	2,295	Black Mountains Area	Water level	Volcanic rock	04-03-08	510	1,786
93252	13	Sandia Gravel Well (south)	Well	36.17940	-114.85099	1,500	Black Mountains Area	Water level	Sedimentary rock	04-02-08	248	1,267
361044114505601	14	Sandia Gravel Well (north)	Well	36.17553	-114.84960	1,500	Black Mountains Area	Water level	Sedimentary rock	04-02-08	363	1,122
360832115060201	15	USGS-BLM Well	Well	36.10060	-114.97670	1,590	Las Vegas Valley	Water level	Valley fill	04-02-08	21	1,569
355836114543701	34	Railroad Pass Well	Well	35.97158	-114.91178	2,950	Eldorado Valley	Water level	Volcanic rock	09-01-73	820	2,130
355718115103301	38	Sloan Well	Well	35.95510	-115.17590	2,540	Las Vegas Valley	Hydrochemical, water level	Sedimentary rock	07-28-08	381	2,159
355706114545001	39	IRETEBA Well	Well	35.95167	-114.91389	2,050	Eldorado Valley	Water level	Volcanic rock	08-29-84	530	1,520
355622114544101	42	Roger Bay Road Well	Well	35.93135	-114.92074	1,760	Eldorado Valley	Water level	Carbonate rock	10-21-58	300	1,460
47598	43	Unnamed well	Well	35.92282	-114.92120	1,760	Eldorado Valley	Water level	Valley fill	04-25-95	343	1,417
355519114551201	44	Unnamed well	Well	35.91956	-114.92174	1,750	Eldorado Valley	Water level	Valley fill	11-15-84	470	1,280
50654	45	NDOT Well	Well	35.91250	-114.93470	1,823	Eldorado Valley	Water level	Valley fill	04-24-08	307	1,516
62794	46	Unnamed well	Well	35.91201	-114.92596	1,750	Eldorado Valley	Water level	Valley fill	01-20-97	230	1,520
62792	47	Unnamed well	Well	35.90456	-114.93385	1,745	Eldorado Valley	Water level	Valley fill	01-27-97	210	1,535
355233114395101	48	Hatchery Well	Well	35.87590	-114.66410	698	Colorado River Valley[1]	Hydrochemical, water level	Volcanic rock	08-11-07	16	682
355027114570801	50	Eldorado East Well	Well	35.83546	-114.96181	1,720	Eldorado Valley	Water level	Valley fill	02-24-64	275	1,445
355036114572501	51	Eldorado West Well	Well	35.83190	-114.97240	1,720	Eldorado Valley	Hydrochemical, water level	Volcanic rock	07-27-10	266	1,454
44207	52	Unnamed well	Well	35.82038	-115.00646	1,780	Eldorado Valley	Water level	Valley fill	02-22-94	313	1,467
64268	53	Unnamed well	Well	35.80607	-115.00097	1,780	Eldorado Valley	Water level	Valley fill	03-22-68	350	1,430
26942	54	Unnamed well	Well	35.80142	-115.01403	1,800	Eldorado Valley	Water level	Valley fill	10-23-84	318	1,482
25275	55	Unnamed well	Well	35.78977	-114.93831	2,190	Eldorado Valley	Water level	Valley fill	02-15-84	700	1,490
64302	56	Nelson Corner Well-1	Well	35.71080	-114.82350	3,035	Lower Colorado River Valley	Water level	Valley fill	03-31-08	7	3,023
76717	57	Jubilee Mine Well	Well	35.70690	-114.78870	2,156	Lower Colorado River Valley	Water level	Volcanic rock	03-31-08	18	2,132
354237114491701	58	WELL (REPORT R36)	Well	35.70625	-114.82944	3,110	Lower Colorado River Valley	Water level	Valley fill	02-22-64	74	3,036
354209114504301	59	Copper Canyon Well	Well	35.70270	-114.84510	3,456	Lower Colorado River Valley	Hydrochemical, water level	Unknown	03-31-08	11	3,431
96768	60	Unknown Well	Well	35.70180	-114.81870	2,847	Lower Colorado River Valley	Water level	Unknown	04-01-08	36	2,834
354203114511701	61	Unknown Well	Well	35.70070	-114.85560	3,679	Lower Colorado River Valley	Water level	Unknown	04-01-08	10	3,669
96769	62	Nelson Well	Well	35.70040	-114.83060	3,107	Lower Colorado River Valley	Water level	Volcanic rock	04-01-08	47	3,050

Table 2. Generalized lithology and water-level measurements made or compiled from wells in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.—Continued

[Data from U.S. Geological Survey National Water Information System (USGS site identifier); Nevada Department of Water Resources Well Log Database (NDWR log identifier). **Map No.** is shown in figure 3. **Altitude** refers either to feet above North American Datum of 1927 or feet above North American Datum of 1983. **Abbreviation**: USGS-BLM, U.S. Geological Survey-Bureau of Land Management]

USGS site/ NDWR log identifier	Map No.	Site name	Site type	Latitude (decimal degrees)	Longitude (decimal degrees)	Altitude (feet)	Designated groundwater basin	Measurements, samples collected	Generalized lithology of open interval	Water-level date	Water level (feet below land surface)	Altitude of water level (feet)
23987	63	Stock Well	Well	35.68230	-114.89270	3,970	Eldorado Valley	Water level	Volcanic rock	02-25-08	48	3,927
354019114500401	64	Unknown (shallow) well	Well	35.67210	-114.83510	3,665	Lower Colorado River Valley	Water level	Volcanic rock	04-08-08	2	3,663
353921114503201	65	Knob Hill Well	Well	35.65580	-114.84210	4,144	Eldorado Valley	Water level	Unknown	04-08-08	23	4,124
353817114563701	66	Trespass Well	Well	35.63863	-114.94540	2,848	Eldorado Valley	Water level	Valley fill	05-02-85	380	2,468
87736	67	Unnamed well	Well	35.60244	-114.91645	3,065	Eldorado Valley	Water level	Volcanic rock	01-25-03	670	2,395
64743	69	Unnamed well	Well	35.52028	-114.89549	3,585	Eldorado Valley	Water level	Volcanic rock	04-07-97	316	3,269
32989	70	Unnamed well	Well	35.50254	-114.90101	3,760	Eldorado Valley	Water level	Valley fill	06-26-85	89	3,671
64318	71	Jet Mine Stock Well	Well	35.49663	-114.91167	3,779	Eldorado Valley	Water level	Volcanic rock	02-26-08	54	3,725
68100	72	Unnamed well	Well	35.47820	-115.17612	4,300	Eldorado Valley	Water level	Volcanic rock	09-10-97	31	4,269
No site number[2]	73	Cottonwood Cove Road Well	Well	35.47255	-114.85437	2,985	Eldorado Valley	Water level	Valley fill	03-07-08	0	2,985
106749	74	Unnamed well	Well	35.43767	-114.90232	3,315	Piute Valley	Water level	Sedimentary rock	08-21-08	380	2,935
352047114563301	75	USBLM YKL 2 Well	Well	35.34720	-114.94260	2,896	Piute Valley	water level	Valley fill	02-26-08	640	2,256

[1]Colorado River Valley in Arizona.

[2]Stock well, open hole.

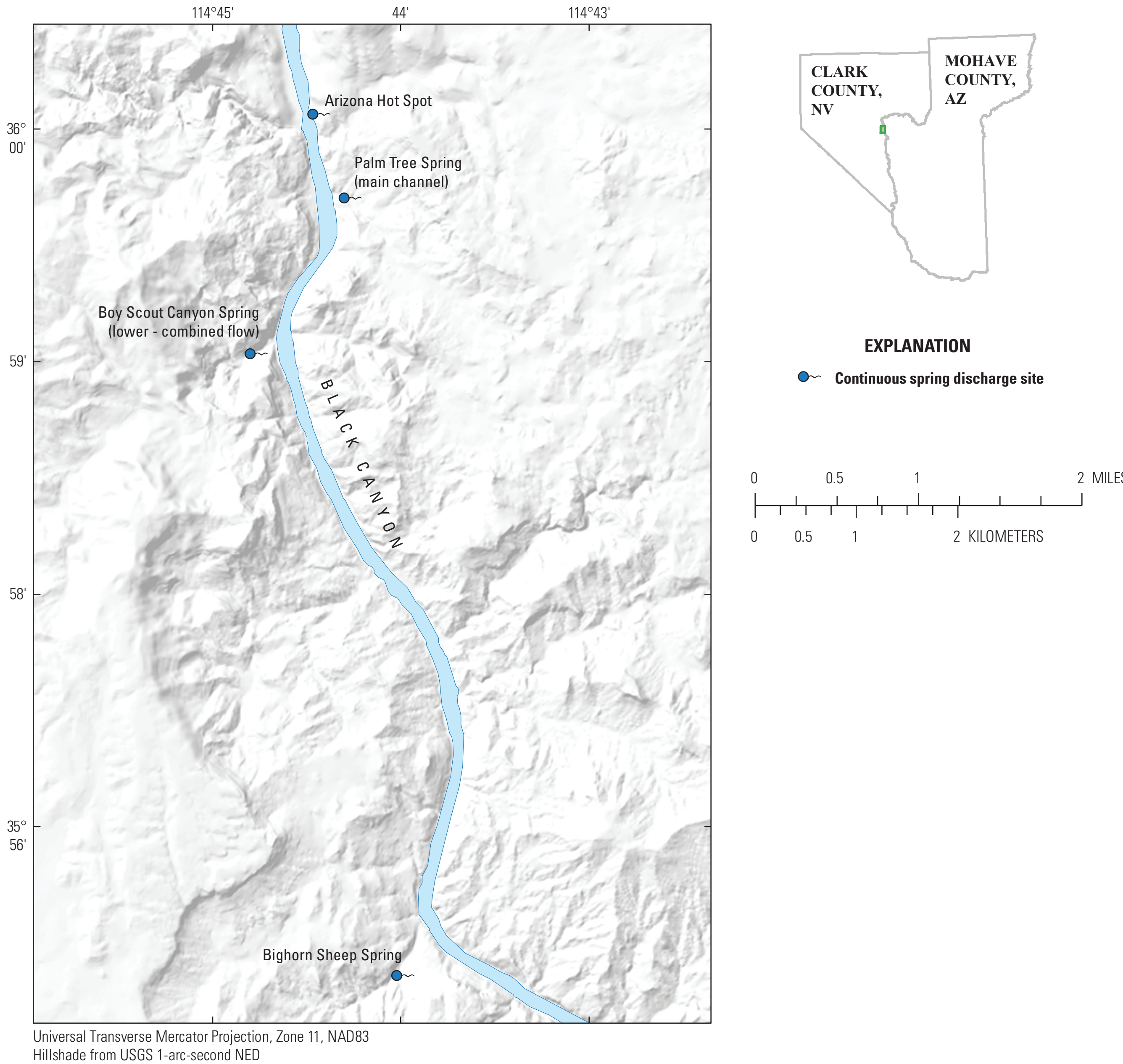


Figure 4. Locations of sites where discharge was computed from continuous measurements of stage in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

Table 3. Summary of monthly and total average discharge values for selected sites where stage was measured continuously in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[**Average discharge:** For period of record. **Abbreviations:** ft, foot; ft^3/s, cubic foot per second; acre-ft/yr, acre-foot per year; NA, not analyzed]

Site name	Monitoring date		Daily average discharge (ft^3/s [acre-ft/yr])				Average discharge (ft^3/s [acre-ft/yr])		Monthly average discharge (ft^3/s) 2008		
	Begin	End	Highest		Lowest				October	November	December
Arizona Hot Spot	10-02-08	11-09-09	0.03	[23]	0.01	[10]	0.02	[14]	0.02	0.02	0.02
Palm Tree Spring	10-14-08	12-29-09	0.10	[73]	0.07	[49]	0.08	[60]	0.08	0.07	0.07
Boy Scout Canyon Spring	01-15-09	12-31-09	0.54	[388]	0.28	[205]	0.36	[264]	NA	NA	NA
Bighorn Sheep Spring	10-14-08	12-31-09	0.12	[87]	0.03	[20]	0.04	[31]	0.06	0.06	0.06
Total average discharge	–	–	–		–		**0.5**	**[369]**	**NA**	**NA**	**NA**

Site name	Monitoring date		Monthly average computed discharge values (ft^3/s) 2009					
	Begin	End	January	February	March	April	May	June
Arizona Hot Spot	10-02-08	11-09-09	0.02	NA	0.03	0.03	0.02	0.02
Palm Tree Spring	10-14-08	12-29-09	0.08	0.08	0.08	0.08	0.08	0.08
Boy Scout Canyon Spring	01-15-09	12-31-09	0.36	0.42	0.38	0.32	0.37	0.39
Bighorn Sheep Spring	10-14-08	12-31-09	0.04	0.04	0.04	0.04	0.04	0.04
Total average discharge	–	–	**0.50**	**NA**	**0.53**	**0.47**	**0.51**	**0.53**

Site name	Monitoring date		Monthly average computed discharge values (ft^3/s) 2009					
	Begin	End	July	August	September	October	November	December
Arizona Hot Spot	10-02-08	11-09-09	0.02	0.02	0.02	0.02	0.02	NA
Palm Tree Spring	10-14-08	12-29-09	0.09	0.09	0.08	0.08	0.09	0.09
Boy Scout Canyon Spring	01-15-09	12-31-09	0.38	0.37	0.37	0.32	0.34	0.34
Bighorn Sheep Spring	10-14-08	12-31-09	0.04	0.03	0.04	0.04	0.04	0.05
Total average discharge	–	–	**0.53**	**0.51**	**0.51**	**0.44**	**0.49**	**NA**

Figure 5. Monitoring site showing flume and stilling well, looking (*A*) toward seep, and (*B*) toward the Colorado River at Arizona Hot Spot in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona. Photographs taken by Jon Wilson, U.S. Geological Survey, 2008.

Figure 6. Monitoring site showing (*A*) waterfall immediately downstream of monitoring site, and (*B*) monitoring site with flume and stilling well installed at stream at Palm Tree Spring in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona. Photographs taken by Jon Wilson, U.S. Geological Survey, 2008.

The discharge at Boy Scout Canyon is a series of thermal and non-thermal springs and seeps that occur along fractured-rock walls in the canyon. Water from multiple spring orifices coalesces and flows in a small channel. In order to characterize discharge, a streamgage was constructed in the natural channel 5 ft above a cemented weir structure about 400 ft from the Colorado River. Stage measurements at this site were taken by placing a transducer in a 2 in. French drain that was buried in the coarse gravel channel (fig. 7). Stage data were measured at the drain and physical discharge measurements were made 2 ft downstream of the drain so a theoretical rating could be developed.

The streamgage was operational on January 16, 2009, and continuous stage data were collected until December 30, 2009. Computed average discharge for the period of record at this site was 0.36 ft^3/s, with a minimum computed discharge of 0.28 ft^3/s and a maximum of 0.54 ft^3/s. A decrease in discharge in March through April was observed that may be the result of springtime vegetation growth and increased water consumption by evapotranspiration.

The discharge at Bighorn Sheep Spring consists of several seeps emanating from faults in tuffaceous sedimentary rock and Patsy Mine volcanic rocks. The main spring in the canyon originates about 1,800 ft from the Colorado River and discharge flows through coarse alluvial material along the canyon bottom to the Colorado River. A 3-in. Parshall flume was installed at this site about 600 ft from the Colorado River and a pressure transducer in a stilling well was used to collect stage data in the flume (fig. 8).

Continuous stage measurements were collected at this site from October 15, 2008, until December 30, 2009. Computed average discharge for the period of record was 0.04 ft^3/s, with a minimum computed discharge of 0.03 ft^3/s and a maximum of 0.12 ft^3/s. Peak discharge during periods of flooding was computed at 0.65 ft^3/s on December 25, 2008, and also on February 7, 2009.

The total average discharge computed from the continuously measured sites for 2009 was approximately 0.5 ft^3/s (about 370 acre-ft/yr; table 3). The total average discharge from discrete discharge measurements made during the study period, excluding the discharge from discrete measurements taken at continuously monitored sites, was approximately 0.6 ft^3/s (appendix D; about 430 acre-ft/yr). The total unmeasured discharge in the canyon was estimated at 0.4 ft^3/s (about 290 acre-ft/yr). This discharge estimate was made for all small and unmeasurable springs and seeps observed during the study. Thus, an estimate of the total discharge of all springs in Black Canyon is about 1.5 ft^3/s (about 1,100 acre-ft/yr). This value is regarded as a minimum total average discharge in Black Canyon as it does not include discharge from evapotranspiration.

McKay and Zimmerman (1983) and Sada and Jacobs (2008) also made estimates of total discharge for springs in Black Canyon. McKay and Zimmerman (1983) estimated a total discharge of about 1.2 ft^3/s (about 900 acre-ft/yr), and Sada and Jacobs (2008) estimated a total discharge of about 1.5 ft^3/s. The estimate made here is in agreement with those previous estimates. In December of 2006, Sada and Jacobs (2008) measured discharge at the same sites where continuous stage data were collected in this study. Discharge computed in this study was compared to discharge measured by Sada and Jacobs (2008) to give insight into the variability in discharge that may occur at these springs.

The discharge from springs in Boy Scout Canyon, as measured by Sada and Jacobs (2008), was identical to the annual average discharge computed in this study. At every other site, discharge measured by Sada and Jacobs (2008) was 3 to 13 times lower than the discharge computed in this study. A comparison of discharges measured by Sada and Jacobs (2008) and those measured in this study is difficult for two reasons: (1) they made only one-time measurements of discharge, and (2) they may have made measurements of discharge at specific spring orifices at each site. The reason for the good agreement between discharge values at Boy Scout Canyon may be that the discharge measurements made by Sada and Jacobs (2008) were for an aggregate of discharge from many springs and seeps in the area, as was done in this study.

Hydrochemistry

Hydrochemical data, consisting of either field parameters or samples for laboratory analyses, were collected from 38 unique locations in Black Canyon (table 1). At two unnamed springs only field hydrochemical measurements were taken. At 36 of these sites, water samples were collected and submitted for laboratory hydrochemical analyses (appendix D). In appendix D, the sampling location at Lake Mead Sentinel Island platform is divided into four sites associated with different sampling depths in the lake. However, for analyses purposes the platform site is considered as a single, unique sampling location. Sixteen spring sites were selected to help identify potential sources of water to other spring sites in Black Canyon (fig. 9). All these sites, with the exception of Hatchery Well and Hoover Dam Seep, are springs. Hatchery Well is one of several wells that provides water to the Willow Beach National Fish Hatchery (U.S. Fish and Wildlife Service), which is near Willow Beach in the southern part of Black Canyon. Hoover Dam Seep is a water seep in the diversion tunnel at Hoover Dam on the Nevada side of the river. Water was sampled from a small pipe that passes through the concrete lining of the diversion tunnel on the west side of the dam. This site is not considered here as a spring but is still included in the analyses.

Figure 7. Monitoring site showing (*A*) hot and cold springs that contribute to the main channel upstream of monitoring site; and (*B*) French-drain pipe, transducer, and rock/concrete control at Boy Scout Canyon in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona. Photographs taken by Jon Wilson, U.S. Geological Survey, 2009.

Figure 8. Monitoring site showing (*A*) flume and stilling well installed at stream, and (*B*) rock/concrete control downstream of monitoring site at Bighorn Sheep Spring in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona. Photograph taken by Jon Wilson, U.S. Geological Survey, 2009.

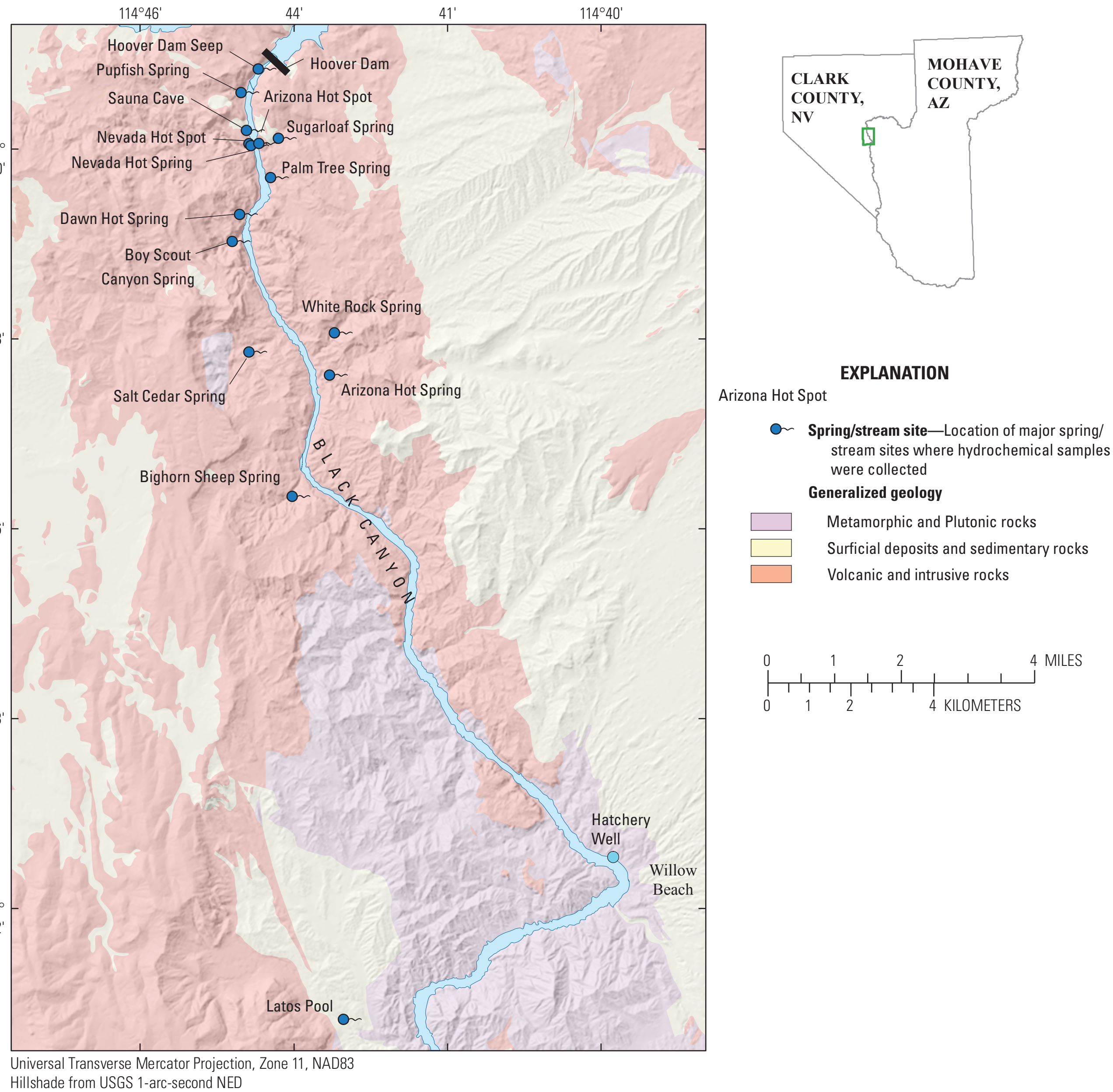


Figure 9. Locations of spring sites where hydrochemical samples were collected in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

Water Temperature

Water temperatures at most springs in Black Canyon were greater than 32 °C (table 4). However, water temperatures at three sites were less than 32 °C—Hoover Dam Seep, Sugarloaf Spring, and White Rock Spring. The lower water temperatures at these sites may be the result of the difficulty in identifying orifices where water issues directly from rock. In these situations, water temperatures were taken from areas of running water or even stagnant pools and probably do not represent the temperature of water at the spring orifice. For example, a water temperature of 9.1 °C measured at Latos Pool on January 6, 2010, was from a pool in which water was allowed to equilibrate with air temperature and thus does not represent the true temperature of water discharging from the spring.

Previous observations in Black Canyon have indicated that springs with both hot and cold water are near each other at several Black Canyon sites. During this study, a stream of flowing water in Boy Scout Canyon, assumed to be from a cold spring, was observed to be far from a spring orifice. An unsuccessful attempt was made to locate the orifice of this spring. However, the temperature of water in the stream increased as the stream was followed toward the orifice. In this case, the cold water observed in the stream does not represent a cold spring but instead likely represents water discharging from a spring orifice and then thermally equilibrating with air temperatures before being measured.

Relative differences in the concentrations of individual hydrochemical constituents in samples from cold and hot springs at Boy Scout Canyon were compared. Average values of individual constituents were used when multiple values existed. The relative differences in the concentrations of most individual constituents are less than 10 percent. For example, the relative difference of total dissolved solids was 1.4 percent and the relative difference between δ^2H values was 1.7 percent. Relative differences of greater than 10 percent were only noted in trace elements such aluminum, barium, beryllium, chromium, manganese, selenium, and uranium.

Hydrochemical analyses for both cold and hot springs were available for only one additional site, Pupfish Spring. Like the springs in Boy Scout Canyon, the relative differences in the concentrations of most individual constituents in Pupfish Spring were less than 10 percent. Only two constituents, fluoride and cadmium, had relative concentration differences of greater than 10 percent. The relative difference of total dissolved solids was 2.6 percent, the relative difference of perchlorate was 6 percent, and the relative difference of δ^2H values was 0.8 percent.

The physical examination of springs and the analyses of hydrochemical results at Boy Scout Canyon and Pupfish Spring suggest that the water discharging from hot and cold springs at these sites is from the same source. As a result, all hydrochemical data from hot and cold springs at individual sites were combined throughout the remainder of the analyses.

Table 4. Air and water temperatures measured at spring sampling sites in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[**Abbreviations:** NWIS, National Water Information System; ft^3/s, cubic foot per second; °C, degrees Celsius; POR, period of record; NA, not analyzed; –, no data; <, less than]

Site name	NWIS identifier	Sample date	Time	Spring discharge (ft^3/s)	Air temperature (°C)	Water temperature (°C)
Arizona Hot Spot	360005114443001	07-15-08	1210	–	38.5	54.5
		12-02-08	1138	–	20.0	54.2
		09-10-09	–	[1]0.02	–	–
		05-07-14	1105	[1]0.01	–	–
		POR	–	[2]0.02	–	–
Arizona Hot Spring	355738114433301	11-19-07	–	[1]0.20	41.0	49.0
		07-10-08	1310	–	41.0	49.0
		12-04-08	1332	–	20.5	49.0
		12-04-08	1339	–	20.5	49.0
		05-07-14	1311	[1]0.07	–	–
Bighorn Sheep Spring	355621114440101	02-02-97	–	[1]0.02	–	–
		07-31-08	1150	–	34.5	34.2
		12-04-08	1224	–	18.5	33.4
		POR	–	[2]0.04	18.5	33.4

Table 4. Air and water temperatures measured at spring sampling sites in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.—Continued

[**Abbreviations:** NWIS, National Water Information System; ft^3/s, cubic foot per second; °C, degrees Celsius; POR, period of record; NA, not analyzed; –, no data; <, less than]

Site name	NWIS identifier	Sample date	Time	Spring discharge (ft^3/s)	Air temperature (°C)	Water temperature (°C)
Boy Scout Canyon Cold Spring	355902114444801	07-15-08	1035	–	41.0	32.7
		12-01-08	1240	–	21.0	42.2
		POR	–	[2]0.36		
Boy Scout Canyon Hot Spring	355902114444802	07-15-08	1020	–	39.50	56.3
		12-01-08	1418	–	23.00	56.2
		POR	–	[2]0.36		
Dawn Hot Spring	355919114444301	04-15-09	1113	–	12.0	50.1
Hatchery Well	355233114395101	07-29-08	1040	–	36.0	25.7
Hoover Dam Seep	360051114442801	07-16-08	1140	–	27.0	23.2
		12-09-08	1040	–	16.5	23.0
Latos Pool	355050114432201	05-06-97	–	[1]<0.01		
		09-10-09	1058	–	38.0	33.7
		01-06-10	1033	–	10.0	9.1
Nevada Hot Spot	360002114443201	07-10-08	1100	–	37.5	56.3
		12-02-08	1227	–	18.0	56.5
		05-07-14	1008	[1]0.05	32.0	56.5
Nevada Hot Spring	355956114444401	03-19-08	1020	–	NA	NA
		07-14-08	0930	–	NA	NA
		12-03-08	1206	–	19.5	48.5
Palm Tree Spring	355942114441801	02-27-08	1515	–	NA	NA
		02-27-08	1230	–	NA	NA
		07-10-08	1020	–	41.0	52.6
		12-02-08	1031	–	22.0	46.5
		09-10-08	1031	[1]0.09	–	–
		POR	–	[2]0.08	–	–
Pupfish Cold Spring	360036114444101	07-16-08	1020	–	42.0	35.4
		08-19-14	0930	[1]0.09	–	–
Pupfish Hot Spring	360036114444102	03-19-08	1400	–	NA	NA
		07-16-08	0950	–	40.5	36.5
		07-16-08	1000	–	40.5	36.5
		12-09-08	1122	–	16.5	35.7
Salt Cedar Spring	355756114443401	07-15-08	1342	–	38.5	44.5
		12-04-08	1055	–	21.5	44.0
		05-07-14	1234	[1]0.21	32.0	31.3
Sauna Cave	360010114443301	02-01-97	–	[1]0.01	20.5	42.3
		12-02-08	1328	–	20.5	42.3
		05-05-09	NA	–	NA	NA
Sugarloaf Spring	360007114441201	02-27-08	1645	–	NA	NA
		02-27-08	1615	–	NA	NA
		12-03-08	0948	–	19.5	24.9
White Rock Spring	355804114432801	02-28-08	0930	–	NA	NA
		05-05-09	1110	–	27.0	29.1

[1]Instantaneous discharge, in cubic feet per second.

[2]Average yearly discharge, in cubic feet per second.

Total Dissolved Solids and Alkalinity

Concentrations of total dissolved solids (TDS) in water from springs ranged from about 500 to 3,000 mg/L (table 5). Concentrations of TDS at Bighorn Sheep Spring and Latos Pool were the lowest at around 500 mg/L, and were substantially lower than other springs and even lower than TDS values in the Colorado River. Concentrations of alkalinity in water from springs ranged from about 24 to 320 mg/L (table 5). Unlike TDS, the concentrations of alkalinity at Bighorn Sheep Spring and Latos Pool were not the lowest; in fact, the concentration of alkalinity at Latos Pool (248 mg/L) was among the highest measured at any spring. The spring site closest to Hoover Dam, Pupfish Spring, had concentrations of TDS and alkalinity similar to concentrations measured in the Colorado River. As distance from Hoover Dam increases, there is a general increase in TDS and a decrease in alkalinity except for Bighorn Sheep Spring and Latos Pool (fig. 10).

The nature of the changes in TDS and alkalinity with increasing distance from Hoover Dam suggests that the water supplying springs could be a gradually changing mixture of different sources as distance from the dam increases. There are statistically significant correlations (Spearman correlation) between the distance of each main spring from Hoover Dam and the concentrations of TDS and alkalinity when the values of Bighorn Sheep Spring, Hatchery Well, and Latos Pool are excluded from the analyses. The moving average lines in figure 10 have not been extended to include data from Bighorn Sheep Spring, Hatchery Well, and Latos Pool. The correlation of spring distance with TDS is positive (rho = 0.68, $p = 0.009$), whereas the correlation of spring distance and alkalinity was negative (rho = -0.84, $p = 0.0003$).

Major Ions

Major ions were defined in this study as bicarbonate, carbonate, sulfate, chloride, calcium, magnesium, sodium, and potassium (table 6). The Stiff diagrams of major ion concentration profiles shows a clear change in spring hydrochemistry as the distance from Hoover Dam increases (fig. 11). Water from the Colorado River and Lake Mead has a sodium-sulfate composition, and water from Pupfish Spring, the closest spring to Hoover Dam, is similar in composition. Farther from Hoover Dam, water from Sauna Cave, Nevada Hot Spot, and Nevada Hot Spring also has a sodium-sulfate composition but shows increased concentrations of sulfate and chloride relative to Pupfish Spring. Water from Arizona Hot Spot, Sugarloaf Spring, Palm Tree Spring, Dawn Spring, Boy Scout Canyon Spring, Salt Cedar Spring, and Arizona Hot Spring has a sodium chloride-sulfate composition and shows increased concentrations of sodium, chloride, and sulfate relative to springs closer to Hoover Dam (fig. 11).

Table 5. Concentrations of total dissolved solids and alkalinity for spring sampling sites in Black Canyon and distance of each spring from Hoover Dam, Lake Mead National Recreation Area, Nevada and Arizona.

[**Abbreviations:** mi, mile; mg/L, milligram per liter; –, no data]

Site name	Approximate distance from Hoover Dam (mi)	Total dissolved solids (mg/L)	Alkalinity (mg/L)
Colorado River/Lake Mead	–	638	138
Hoover Dam Seep	0.0	847	124
Pupfish Hot/Cold Spring	0.2	797	92
Sauna Cave	0.5	1,201	114
Nevada Hot Spot	0.9	1,383	84
Sugarloaf Spring	0.9	2,257	320
Arizona Hot Spot	1.0	2,185	59
Nevada Hot Spring	1.0	1,081	113
Palm Tree Spring	1.4	2,227	56
Dawn Hot Spring	1.9	2,992	24
Boy Scout Canyon Hot/Cold Spring	2.2	2,713	30
White Rock Spring	3.0	907	44
Salt Cedar Spring	3.4	3,007	38
Arizona Hot Spring	3.8	2,916	25
Bighorn Sheep Spring	5.2	518	91
Hatchery Well	10.3	1,663	163
Latos Pool	11.3	557	248

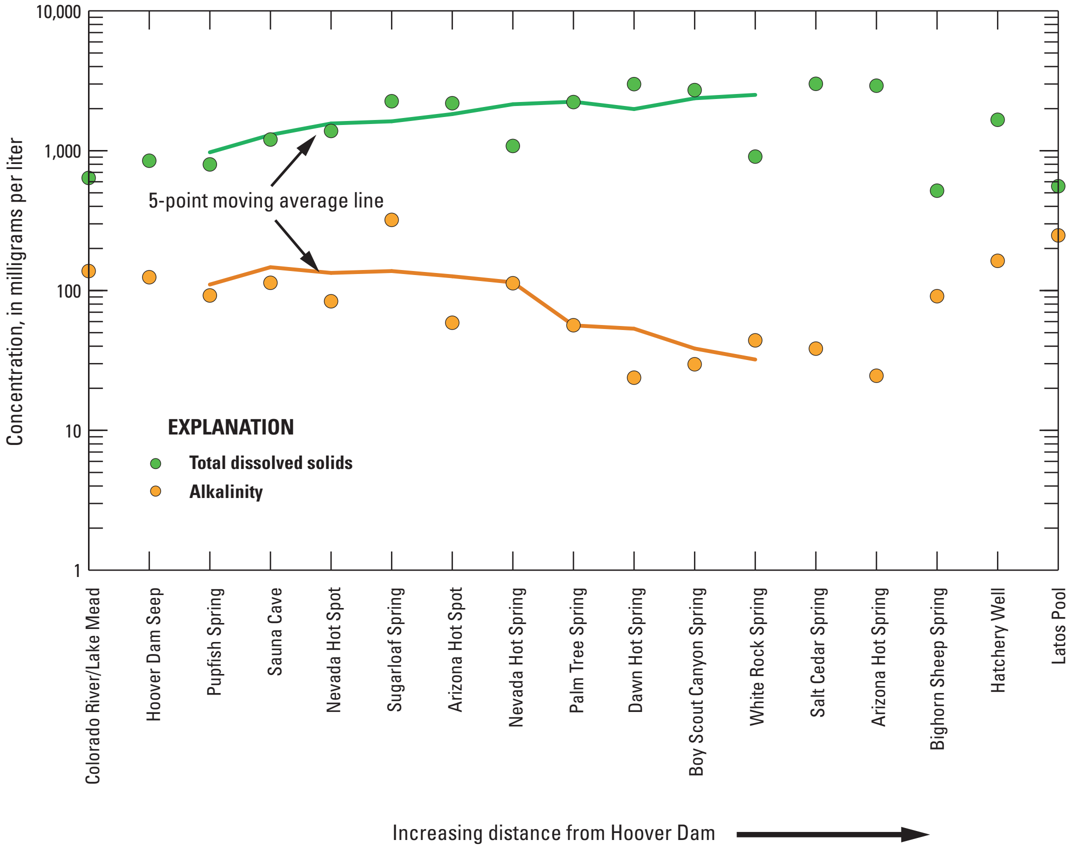
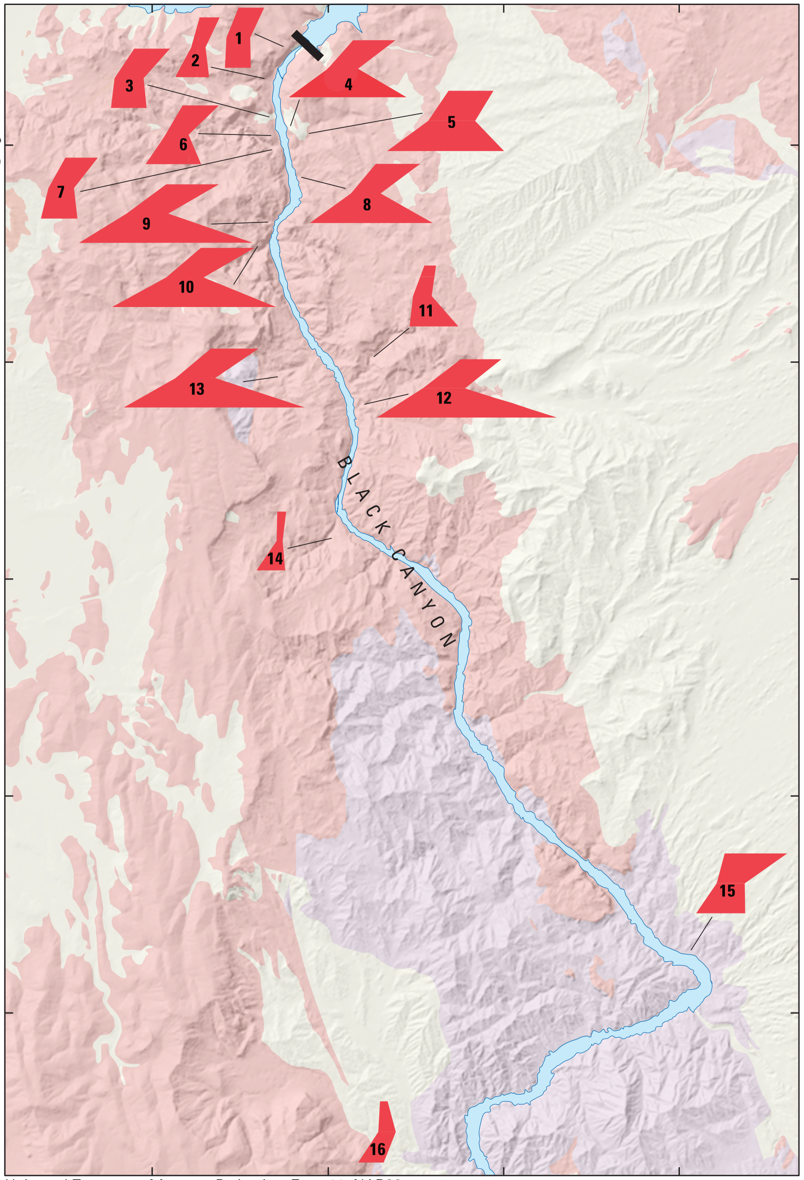


Figure 10. Average concentrations of total dissolved solids and alkalinity in samples collected from springs by distance from Hoover Dam, Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona. Distances of each spring from Hoover Dam, in miles, are shown in table 5.

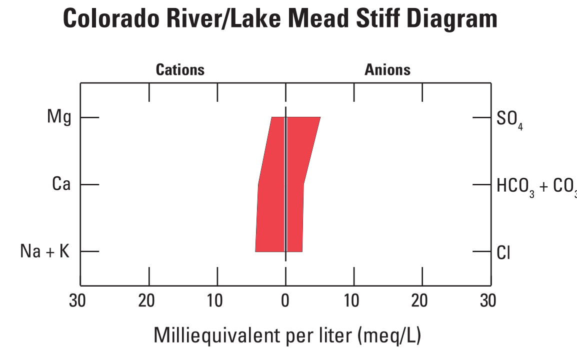
Table 6. Average concentrations of major ions in water samples collected from main springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

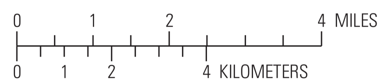
[**Abbreviations:** mi, mile; mg/L, milligram per liter; –, no data; <, less than]

Site name	Approximate distance from Hoover Dam (mi)	Bicarbonate (mg/L)	Carbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)
Colorado River/Lake Mead	–	159	1.4	244	85	76	26.7	92	4.9
Hoover Dam Seep	0.0	151	< 1.0	344	97	106	16.2	132	3.8
Pupfish Hot/Cold Spring	0.2	111	< 1.0	313	107	59	2.8	189	4.4
Sauna Cave	0.5	138	< 1.0	531	115	151	11.2	196	7.1
Nevada Hot Spot	0.9	102	< 1.0	574	209	123	4.0	291	7.0
Sugarloaf Spring	0.9	389	< 1.0	598	565	184	29.1	515	11.0
Arizona Hot Spot	1.0	72	< 1.0	686	643	187	6.8	522	9.7
Nevada Hot Spring	1.0	137	< 1.0	482	119	122	7.2	194	6.0
Palm Tree Spring	1.4	69	< 1.0	691	662	177	6.2	517	9.4
Dawn Hot Spring	1.9	29	< 1.0	850	1,040	275	2.5	678	14.4
Boy Scout Canyon Hot/Cold Spring	2.2	36	<1.0	813	844	227	3.2	653	13.1
White Rock Spring	3.0	53	< 1.0	109	338	105	18.5	143	7.0
Salt Cedar Spring	3.4	47	< 1.0	742	1,101	252	8.1	685	13.7
Arizona Hot Spring	3.8	30	< 1.0	616	1,128	277	11.1	663	13.8
Bighorn Sheep Spring	5.2	101	4.6	144	94	4	0.2	161	0.8
Hatchery Well	10.3	198	< 1.0	833	118	122	41.6	290	11.8
Latos Pool	11.3	290	5.7	106	35	15	2.2	164	6.2



Universal Transverse Mercator Projection, Zone 11, NAD83
Hillshade from USGS 1-arc-second NED





EXPLANATION

Generalized Geology

- Metamorphic and Plutonic rocks
- Surficial deposits and sedimentary rocks
- Volcanic and intrusive rocks

Mg	Magnesium
Ca	Calcium
Na + K	Sodium and potassium
SO_4	Sulfate
$HCO_3 + CO_3$	Bicarbonate and carbonate
Cl	Chloride

Location of major spring/stream sites where hydrochemical samples were collected

Site No.	Site name
1	Hoover Dam Seep
2	Pupfish Spring
3	Sauna Cave
4	Arizona Hot Spot
5	Sugarloaf Spring
6	Nevada Hot Spot
7	Nevada Hot Spring
8	Palm Tree Spring
9	Dawn Hot Spring
10	Boy Scout Spring
11	White Rock Spring
12	Arizona Hot Spring
13	Salt Cedar Spring
14	Bighorn Sheep Spring
15	Hatchery Well
16	Latos Pool

Figure 11. Major ion concentrations for water samples collected from main springs in Black Canyon, Lake Mead, and the Colorado River, Lake Mead National Recreation Area, Nevada and Arizona.

Water from White Rock Spring, Bighorn Sheep Spring, and Latos Pool has a distinctly different profile of major ion concentrations compared to other springs. Sodium, chloride, and sulfate concentrations are significantly less relative to other springs although sodium is the dominant species in most cases. Water from Hatchery Well has a sulfate-sodium composition and is somewhat intermediate in composition relative to other springs (fig. 11).

There are statistically significant correlations (Spearman correlation) between the distance of each spring from Hoover Dam and the concentrations of bicarbonate (rho = -0.84; *p*-value = 0.0003), chloride (rho = 0.87; *p*-value = 0.000), calcium (rho = 0.64; *p*-value = 0.02), sodium (rho = 0.67; *p*-value = 0.001), and potassium (rho = 0.71; *p*-value = 0.006), when values for Bighorn Sheep Spring, Hatchery Well, and Latos Pool are excluded from the analyses. There was no statistically significant relation between the distance of each spring from Hoover Dam and the concentrations of sulfate or magnesium.

Figure 12 shows several groupings of major ion ratios on a Piper diagram and indicates a potential evolution in water from the Colorado River and Lake Mead as distance

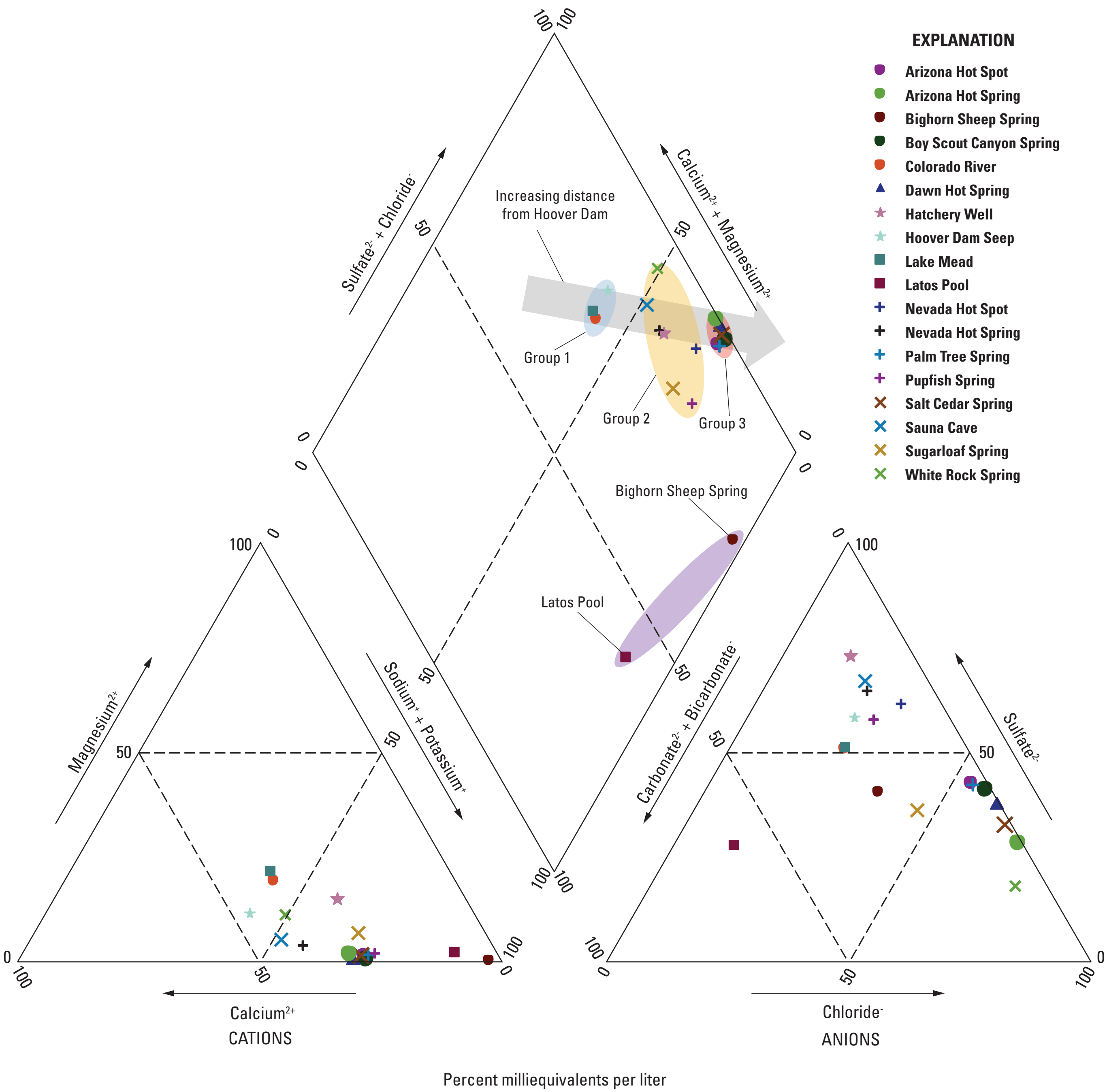


Figure 12. Major ion concentration ratios for water samples collected from springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

from Hoover Dam increases. Group 1 includes the Colorado River, Lake Mead, and Hoover Dam Seep. Water from these sites is most enriched in bicarbonate relative to sulfate and chloride and in calcium and magnesium relative to sodium and potassium. Group 2 includes White Rock Spring, Sauna Cave, Nevada Hot Spot, Nevada Hot Spring, Hatchery Well, Sugarloaf Spring, and Pupfish Spring. Water from these springs has an intermediate composition between water from Lake Mead and springs farther from Hoover Dam and has a sodium chloride-sulfate composition. Group 3 includes Palm Tree Spring, Salt Cedar Spring, Arizona Hot Spring, Arizona Hot Spot, Dawn Hot Spring, and Boy Scout Canyon Spring. Water from these springs is most different from Lake Mead and other springs, but is further enriched in sodium and sulfate relative to other springs. As distance from Hoover Dam increases, the major ion composition ratios seem to show an evolution from Group 1 to Group 3. Bighorn Sheep Spring and Latos Pool plot far from any other springs in Black Canyon in figure 12. Water from these springs is much lower in calcium and magnesium relative to other springs and has a sodium-bicarbonate composition (fig. 12).

Figure 13 shows a plot of major anion species concentration ratios indicating that water from the Colorado River/Lake Mead through and including Palm Tree Spring

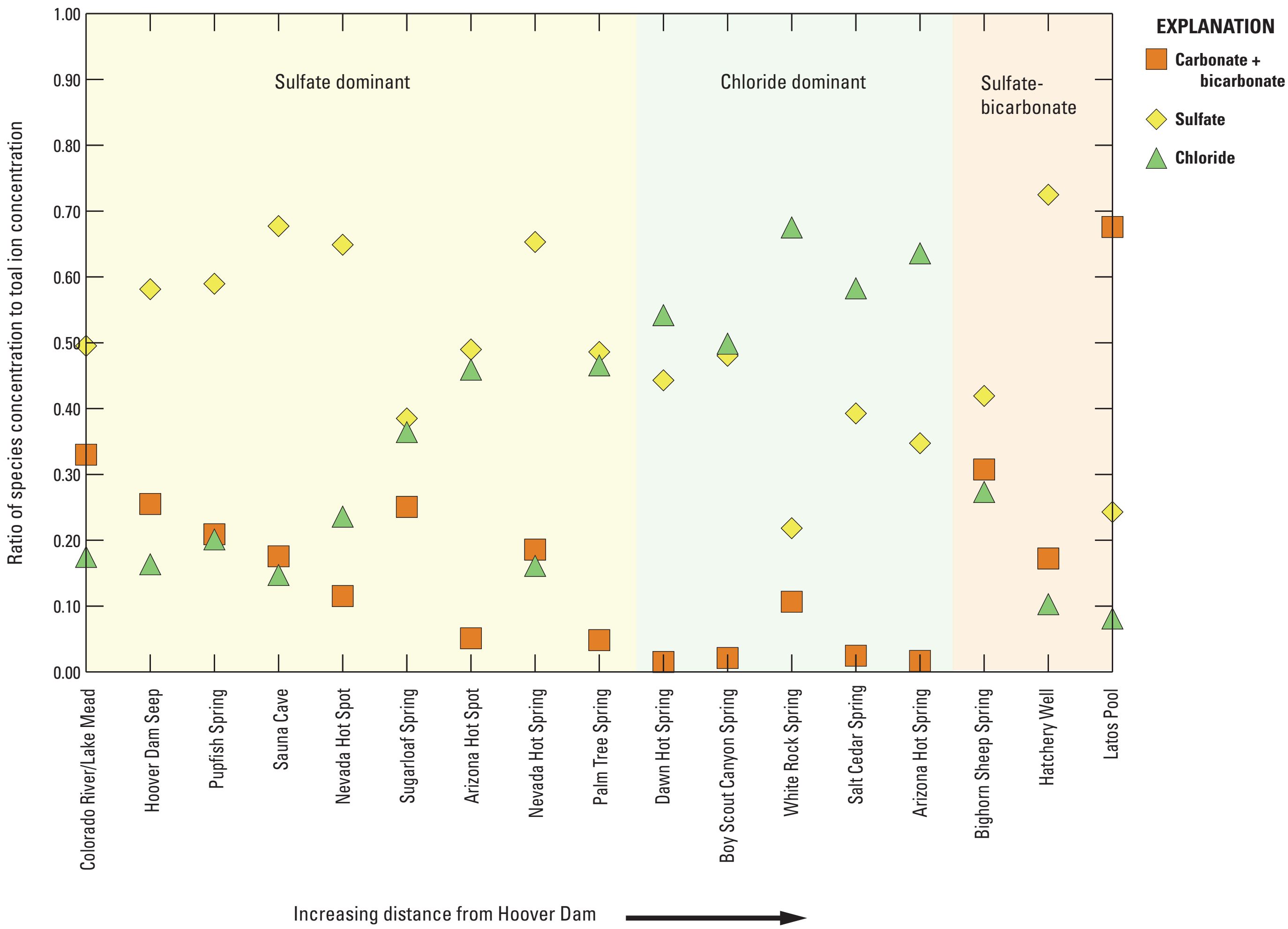


Figure 13. Concentration ratios of major anion species in water samples collected from springs in Black Canyon with increasing distance from Hoover Dam, Lake Mead National Recreation Area, Nevada and Arizona. Distances of each spring from Hoover Dam, in miles, are shown in table 5.

is classified as sulfate dominant. Chloride ratios generally increase and carbonate/bicarbonate ratios generally decrease in these springs with increasing distance from Hoover Dam. Water from springs south of Palm Tree Spring, including Dawn Hot Spring through Arizona Hot Spring, is classified as chloride dominant. In general, sulfate and carbonate/bicarbonate ratios are lower in these springs relative to springs closer to Hoover Dam. Water from Bighorn Sheep Spring, Hatchery Well, and Latos Pool is classified as sulfate-bicarbonate with no clearly dominant anion. The ratio of bicarbonate to other anions generally is higher at these sites relative to other springs and chloride ratios are significantly lower (fig. 13).

Unlike anions, the concentration ratios of major cation species do not significantly change with distance from Hoover Dam (fig. 14). Only two groupings can be identified. Water from the Colorado River and Hoover Dam Seep have similar and nearly identical ratios of sodium/potassium and calcium/magnesium. The water from these sites is classified as having no dominant cation. Water from all other spring sites is classified as sodium/potassium dominant. Within this group of springs, there is little variation in the concentration ratios of the two cation groups with increasing distance from Hoover Dam with the exception of water from Bighorn Sheep Spring and Latos Pool. At these springs, the ratios of calcium/magnesium are substantially less relative to other springs (fig. 14).

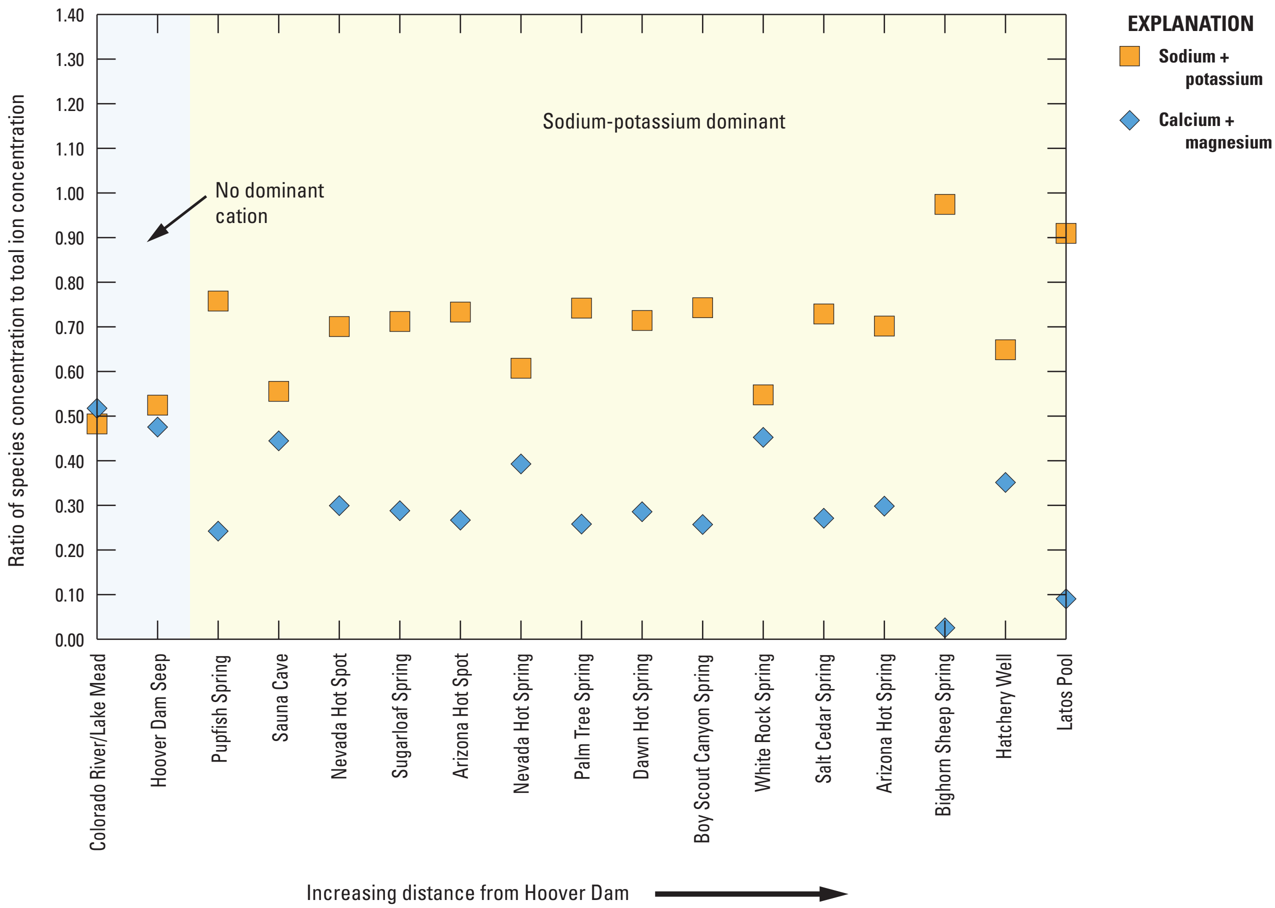


Figure 14. Concentration ratios of major cation species in water samples collected from springs in Black Canyon with increasing distance from Hoover Dam, Lake Mead National Recreation Area, Nevada and Arizona. Distances of each spring from Hoover Dam, in miles, are shown in table 5.

Perchlorate

Samples of water from five springs in Black Canyon and samples from Lake Mead were collected and analyzed for perchlorate (table 7). Water samples were collected from Lake Mead at the Sentinel Island platform operated by the USGS from depths of 10 and 45 m below water surface (Veley and Moran, 2012). Detectable concentrations of perchlorate were observed at only 3 sites—Hoover Dam Seep, Pupfish Spring, and Lake Mead. The highest concentration of perchlorate was in the sample from Hoover Dam Seep (8.2 µg/L). The lowest detected concentrations of perchlorate were observed in water samples from Lake Mead (3.9 µg/L at 10 m and 1.8 µg/L at 45 m). Concentrations of perchlorate were lower than the analytical detection level of 1 µg/L in samples collected from all other sites (table 7).

Trace Elements

Most concentrations of trace elements were less than the laboratory reporting level; however, 50 percent of the concentrations of eight trace elements were more than the laboratory reporting level (table 8; appendix D). Of these, only three trace elements (fig. 15) had concentrations that were significantly positively correlated with distance from Hoover Dam: barium (rho = 0.76, p = 0.003), boron (rho = 0.58, p = 0.04), and strontium (rho = 0.7, p = 0.007). No other distinct patterns in occurrence could be identified. The concentrations of both barium and strontium in water from Bighorn Sheep Spring and Latos Pool are lower relative to other springs by about 1 order of magnitude. As a result, the moving average lines were not extended to these springs (fig. 15).

The concentrations of trace elements in water from the main springs in Black Canyon were compared to aquatic life criteria as established by the EPA Criteria Maximum Concentrations (CMC) and Criteria Continuous Concentrations (CCC) (U.S. Environmental Protection Agency, 2015). Several instances of exceedances were noted at Latos Pool; the CCC for arsenic was exceeded (275 µg/L) on September 10, 2009, and the CCC for cadmium was exceeded (0.28 µg/L) on September 10, 2009 (appendix D). One exceedance was noted at Sugarloaf Spring; the CCC for selenium was exceeded (20.1 µg/L) on December 3, 2008.

Nutrients

Water samples were collected from five springs and the Colorado River and were analyzed for various nutrients including ammonia, nitrate, nitrite, orthophosphate, and phosphorous (table 9). Multiple nutrient samples were collected from the Colorado River site during the study period and then averaged. No nitrate concentrations were greater than the background concentration of nitrate (<5.0 mg/L) that might be expected in undeveloped areas of the Lower Colorado River biotic community (Anning and others, 2012). One sample of water from Boy Scout Canyon Spring on December 1, 2008, had a low concentration of ammonia (0.012 mg/L). One sample of water from Latos Pool on January 6, 2010, had a low concentration of phosphorous (0.012 mg/L). Numerous samples contained low concentrations of orthophosphate (table 9).

Table 7. Perchlorate concentrations from spring sampling sites in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[**Abbreviations:** mi, mile; µg/L, microgram per liter; m, meter; ND, not detected; –, no data]

Site name	Map No. (see fig. 3)	Approximate distance from Hoover Dam (mi)	Sample date	Perchlorate (µg/L)
Boy Scout Canyon Hot Spring	32	0.0	07-15-08	ND
Hoover Dam Seep	19	–	07-16-08	8.2
Lake Mead - Sentinel Island Platform (10 m)	17	–	07-17-08	3.9
Lake Mead - Sentinel Island Platform (45 m)	17	–	07-10-08	ND
			07-14-08	ND
			07-17-08	1.8
Pupfish Cold Spring	20	0.2	07-16-08	6.8
Pupfish Hot Spring	21	0.2	07-16-08	6.4
Boy Scout Canyon Cold Spring	31	2.2	07-15-08	ND
Salt Cedar Spring	25	3.4	07-15-08	ND
Arizona Hot Spring	37	3.8	07-10-08	ND

Table 8. Average concentrations of selected trace elements in water samples collected from springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[Only those trace elements with 50 percent or more concentrations above the laboratory reporting level are shown; <, less than]

Site name	Approximate distance from Hoover Dam (mi)	Arsenic (µg/L)	Barium (µg/L)	Boron (µg/L)	Molybdenum (µg/L)	Nickel (µg/L)	Selenium (µg/L)	Strontium (µg/L)	Uranium (µg/L)
Colorado River/Lake Mead	–	2	144	128	5	1.1	1.2	1,129	4.2
Hoover Dam Seep	0	16	15	213	6	0.7	3.7	3,702	0.9
Pupfish Spring	0.2	51	18	354	23	0.3	3.7	1,414	0.8
Sauna Cave	0.5	3	19	350	25	1.2	1.6	2,612	1.3
Nevada Hot Spot	0.9	45	25	525	19	0.7	0.0	2,552	0.2
Sugarloaf Spring	0.9	14	74	1,155	14	1.5	20.1	4,041	5.2
Arizona Hot Spot	1	34	27	776	20	1.2	0.0	3,815	<0.1
Nevada Hot Spring	1	21	24	410	13	0.7	0.5	2,896	1.2
Palm Tree Spring	1.4	35	28	776	21	1.1	0.1	3,738	0.2
Hatchery Well	1.6	42	9	1,871	23	0.6	2.7	4,299	6.7
Dawn Hot Spring	1.9	57	27	1,648	32	1.8	0.1	5,693	<0.1
Boy Scout Canyon Spring	2.2	34	32	1,298	28	1.4	0.2	4,685	0.2
White Rock Spring	3	9	103	267	2	0.2	1.0	2,942	1.1
Salt Cedar Spring	3.4	51	39	1,312	32	1.7	0.5	5,238	0.3
Arizona Hot Spring	3.8	52	43	1,153	20	1.8	0.4	7,428	0.3
Bighorn Sheep Spring	5.2	63	< 0.4	503	34	0.4	2.3	79	1.1
Latos Pool	11.3	275	7	924	75	0.5	0.6	186	1.5

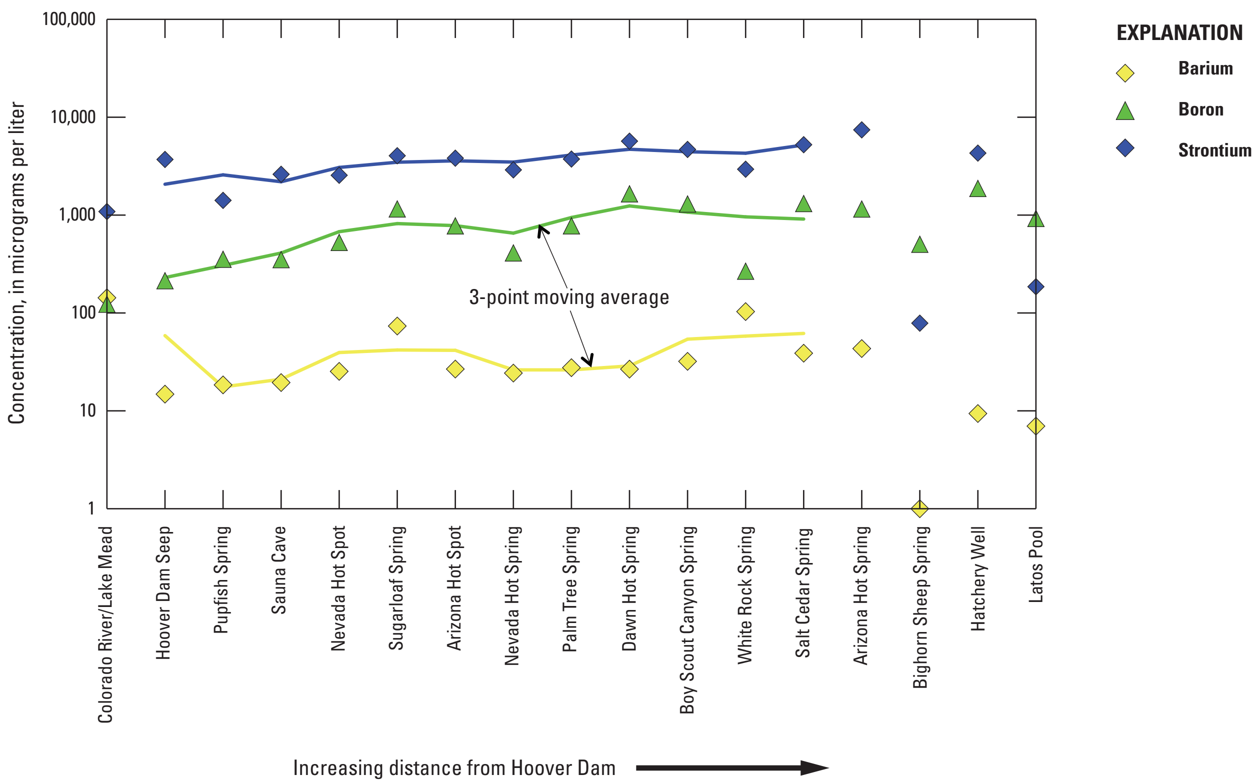


Figure 15. Average concentrations of barium, boron, and strontium in water samples collected from springs in Black Canyon with increasing distance from Hoover Dam, Lake Mead National Recreation Area, Nevada and Arizona. Distances of each spring from Hoover Dam, in miles, are shown in table 5.

Table 9. Average concentrations of nutrients in water samples collected from springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[**Abbreviations:** N, nitrogen; P, phosphorus; mg/L, milligram per liter; NO_3, nitrate; NO_2, nitrite; <, less than]

Site name	Ammonia (mg/L as N)	Nitrate (NO_3+NO_2) (mg/L as N)	Orthophosphate (mg/L as P)	Phosphorous (mg/L as P)
Arizona Hot Spot	< 0.020	< 0.04	0.013	< 0.006
Bighorn Sheep Spring	< 0.02	2.667	0.014	< 0.006
Boy Scout Canyon Spring	0.012	0.032	0.011	< 0.006
Colorado River	0.012	0.548	0.005	0.004
Latos Pool	< 0.02	0.066	0.058	0.012
Palm Tree Spring	< 0.02	< 0.04	0.013	< 0.006

Hydrogen and Oxygen Isotopes

Figure 16 shows isotopic ratios of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) water samples collected from springs in Black Canyon. The Global Meteoric Water Line (GMWL) is from Craig (1961) and the line has an equation of $\delta^2H = (8\times\delta^{18}O) + 10$. The Local Meteoric Water Line (LMWL) is from Friedman and others (1992) and represents the stable isotope results for precipitation falling at 32 sites in southeastern California between April 1986 and October 1987. The equation for this line is $\delta^2H = (6.5\times\delta^{18}O) - 9.7$. The no evaporation line (NEL) is from Pohlmann and others (1998) and the equation for this line is $\delta^2H = (8\times\delta^{18}O) + 0$. Points that plot to the right of NEL indicate water that has undergone significant evaporation prior to recharge whereas points that plot between the NEL and the GMWL indicate water that has undergone only a small amount of evaporation prior to recharge (Pohlmann and others, 1998).

In addition to springs in Black Canyon, a sample of water from an intake tunnel was analyzed for isotopic ratios of δ^2H and $\delta^{18}O$ (table 10). The Lake Mead intake tunnel, between Lake Mead and Las Vegas, will provide drinking water supply to Las Vegas. A sample of water from Sugarloaf Spring, collected on December 3, 2008, indicated a δ^2H value of -79.70 and a $\delta^{18}O$ value of -13.16 (appendix D). This δ^2H value is extremely enriched relative to similar $\delta^{18}O$ values at other springs in Black Canyon and may represent an error in either sampling or analysis. As a result, the values of δ^2H and $\delta^{18}O$ from Sugarloaf Spring were not included in subsequent analyses.

All the δ^2H and $\delta^{18}O$ values from springs plot to the right of both the GMWL and the LMWL (fig. 16). This indicates that the water discharging from the springs in Black Canyon has undergone some evaporation prior to being recharged. Stable isotope values from Bighorn Sheep Spring, Latos Pool, Boy Scout Canyon Spring, Pupfish Spring, and Hoover Dam Seep plot to the right of the NEL. Water from these springs has undergone significant evaporation prior to being recharged. However, most of the points plot to the left of the NEL, suggesting that recharged water at these sites has not undergone substantial evaporation (Pohlmann and others, 1998). Two distinct groupings of springs are evident—a group that is relatively depleted in δ^2H and $\delta^{18}O$ (Lake Mead influence) and a group that is relatively enriched in δ^2H and $\delta^{18}O$ (local and [or] regional influence). The springs grouped by Lake Mead influence include Sauna Cave, Nevada Hot Spot, Nevada Hot Spring, Pupfish Spring, Hoover Dam Seep, Arizona Hot Spot, and Palm Tree Spring. The springs grouped by local and (or) regional influence include Hatchery Well, Boy Scout Canyon Spring, Dawn Hot Spring, Salt Cedar Spring, Arizona Hot Spring, Bighorn Sheep Spring, Latos Pool, and White Rock Spring (fig. 16).

Within the Lake Mead influence group, samples from Sauna Cave, Nevada Hot Spot, and Nevada Hot Spring are less enriched in δ^2H and $\delta^{18}O$ relative to other springs. Within the local and (or) regional influence group, samples from Bighorn Sheep Spring, Latos Pool, and White Rock Spring are more enriched in δ^2H and $\delta^{18}O$ relative to other springs. The separation of springs in these groups may indicate a different source of recharge (fig. 16).

Strontium and Uranium Isotopes

Strontium isotopes, and particularly the $^{87}Sr/^{86}Sr$ ratio, can be used to help determine certain aspects of hydrology that cannot be obtained by studying other physical and chemical properties. Water from most springs has a relatively restricted range of $^{87}Sr/^{86}Sr$ values but these values are notably more radiogenic than values associated with water from the Colorado River or Lake Mead (table 11). These differences are readily apparent in a plot of $^{87}Sr/^{86}Sr$ compared with reciprocal Sr concentration (1/Sr), which commonly is used to evaluate groundwater-mixing relations. The Colorado River and Lake Mead sites plot far from any of the springs whereas Bighorn Sheep Spring and Latos Pool plot in a group that is separate from other springs. Hatchery Well and Sugarloaf Spring also plot in a group that is separate from other springs (fig. 17).

Table 10. Average values of isotopic ratios of hydrogen (δ²H) and oxygen (δ¹⁸O) in water samples collected from springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[**δ²H:** deuterium (²H) to protium (¹H) isotopic ratio relative to VSMOW. **δ¹⁸O**: oxygen-18 to oxygen-16 isotopic ratio relative to VSMOW. **Symbol and abbreviation:** ‰ VSMOW, parts per thousand Vienna Standard Mean Ocean Water]

Site name	δ²H (‰ VSMOW)	δ¹⁸O (‰ VSMOW)
Arizona Hot Spot	-99.16	-12.56
Arizona Hot Spring	-87.74	-11.09
Bighorn Sheep Spring	-82.35	-10.19
Boy Scout Canyon Spring	-91.55	-11.61
Colorado River	-98.18	-12.39
Dawn Hot Spring	-91.00	-11.58
Hatchery Well	-92.30	-11.52
Hoover Dam Seep	-100.10	-12.43
Lake Mead - Sentinel Island Platform	-96.40	-12.07
Latos Pool	-81.24	-9.95
Nevada Hot Spot	-104.67	-13.33
Nevada Hot Spring	-103.56	-13.27
Palm Tree Spring	-98.67	-12.46
Pupfish Spring	-101.43	-12.55
Salt Cedar Spring	-89.50	-11.45
Sauna Cave	-103.06	-13.16
Sugarloaf Spring	-79.70	-13.16
White Rock Spring	-75.10	-9.61

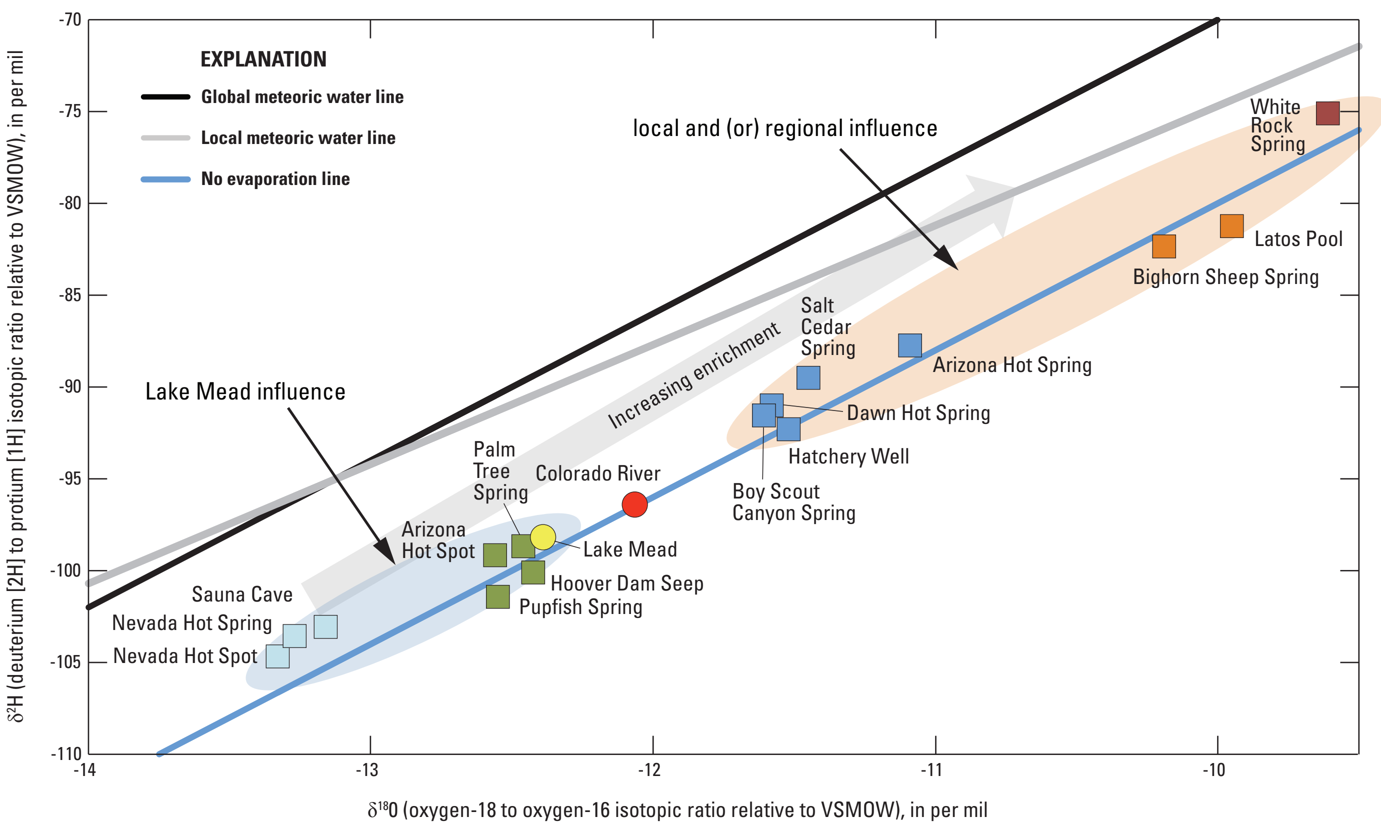


Figure 16. Hydrogen-2 to hydrogen-1 isotopic ratio relative to Vienna Standard Mean Ocean Water (VSMOW) compared with oxygen-18 to oxygen-16 isotopic ratio relative to VSMOW in water samples collected from springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

Table 11. Isotope ratio values for strontium ($\delta^{87}Sr/\delta^{86}Sr$) and uranium ($^{234}U/^{238}U$), and average strontium and uranium concentrations for springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[**Abbreviations and symbols:** ‰ MSW, parts per thousand Model Sea Water; AR, activity ratio; µg/L, microgram per liter; ND, not detected; <, less than]

Site name	$\delta^{87}Sr/\delta^{86}Sr$	$\delta^{87}Sr$ (‰ MSW)	$^{234}U/^{238}U$ (AR)	Strontium (µg/L)	Uranium (µg/L)
Arizona Hot Spot	0.71152	3.310	2.1120	3,815	<0.1
Bighorn Sheep Spring	0.71155	3.350	1.8230	79	1.1
Boy Scout Canyon Spring	0.71169	3.545	1.6810	4,685	0.2
Colorado River	0.71026	1.523	1.7025	1,087	4.4
Dawn Hot Spring	0.71167	3.520	ND	5,693	<0.1
Hatchery Well	0.71232	4.440	1.5490	4,299	6.7
Hoover Dam Seep	0.71160	3.420	5.3690	3,702	0.9
Lake Mead	0.71023	1.475	1.7140	1,172	4.1
Latos Pool	0.71141	3.150	1.6310	186	1.5
Nevada Hot Spot	0.71171	3.580	1.1570	2,552	0.2
Nevada Hot Spring	0.71155	3.350	2.7050	2,896	1.2
Palm Tree Spring	0.71141	3.155	1.8035	3,738	0.2
Pupfish Spring	0.71147	3.240	4.1350	1,414	0.8
Salt Cedar Spring	0.71127	2.960	1.4860	5,238	0.3
Sauna Cave	0.71164	3.480	1.6340	2,612	1.3
Sugarloaf Spring	0.71216	4.205	1.9770	4,041	5.2
White Rock Spring	0.71054	1.870	2.2695	2,942	1.1

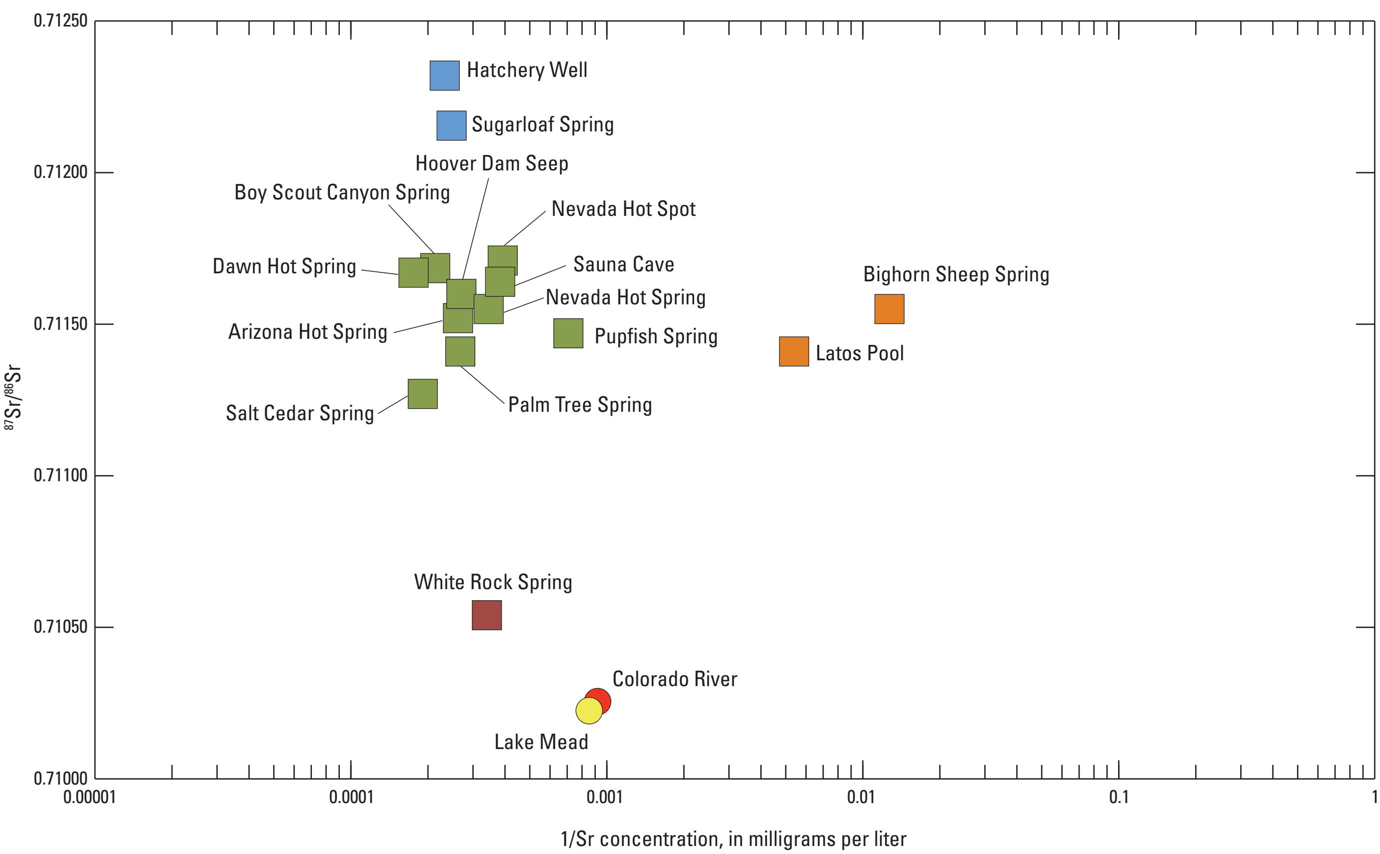


Figure 17. Isotope ratio of strontium ($^{87}Sr/^{86}Sr$) compared with reciprocal strontium (1/Sr) concentrations in water from springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

Like strontium, the ratio of certain uranium isotopes, in particular $^{234}U/^{238}U$, varies considerably in natural waters because of differences in uranium isotope ratios in various types of rocks and soil (Plater and others, 1992; Riotte and Cabaux, 1999). Therefore, differences in $^{234}U/^{238}U$ in water from springs in Black Canyon could indicate unique water sources. Figure 18 shows $^{234}U/^{238}U$ compared with reciprocal U concentration (1/U), which commonly is used to evaluate different groundwater sources. Hatchery Well and Sugarloaf Spring are clustered in the uranium isotope graph (fig. 18) just as they are in the strontium isotope graph (fig. 17). However, Bighorn Sheep Spring and Latos Pool are clustered with Sauna Cave, White Rock Spring, and Nevada Hot Spring. These springs are separated by relatively large physical distances from each other. Hoover Dam and Pupfish Spring form a group and the remaining springs form a group consisting of Boy Scout Canyon Spring, Arizona Hot Spring, Palm Tree Spring, Nevada Hot Spot, and Salt Cedar Spring (fig. 18).

Tritium and Carbon-14

Water from four sites was analyzed for tritium: (1) Lake Mead intake tunnel (21.5 picocuries per liter [pCi/L]), (2) Flame Spring (0.5 pCi/L), (3) Eldorado West Well (1.1 pCi/L), and (4) an unnamed well (0.4 pCi/L). The tritium result from the Lake Mead intake tunnel is substantially greater than 5 pCi/L suggesting that some component of the groundwater in this area may have been recharged after 1952. The remaining sites have tritium values less than 5 pCi/L, suggesting that only a small component of groundwater recharge in this area has occurred after 1952.

The results of ^{14}C are given as conventional radiocarbon ages (percent modern carbon [PMC]) and represent uncorrected apparent ages of the water. Water from three sites was analyzed for ^{14}C: (1) Flame Spring (30.4 PMC), (2) an unnamed well (21.32 PMC), and (3) Eldorado West Well (2.78 PMC). Flame Spring is north of Hoover Dam near Moapa Springs and the other two wells are in Eldorado Valley (fig. 3). These results yield uncorrected apparent water ages of 9,850, 12,800, and 29,600 years respectively.

U-Series Disequilibrium Dating

McKay and Zimmerman (1983) noted the small amounts of groundwater discharge deposits at most springs in Black Canyon and speculated that their absence implied that discharge has only occurred in the recent past. However, small amounts of gypsum, tufa, and travertine are present at

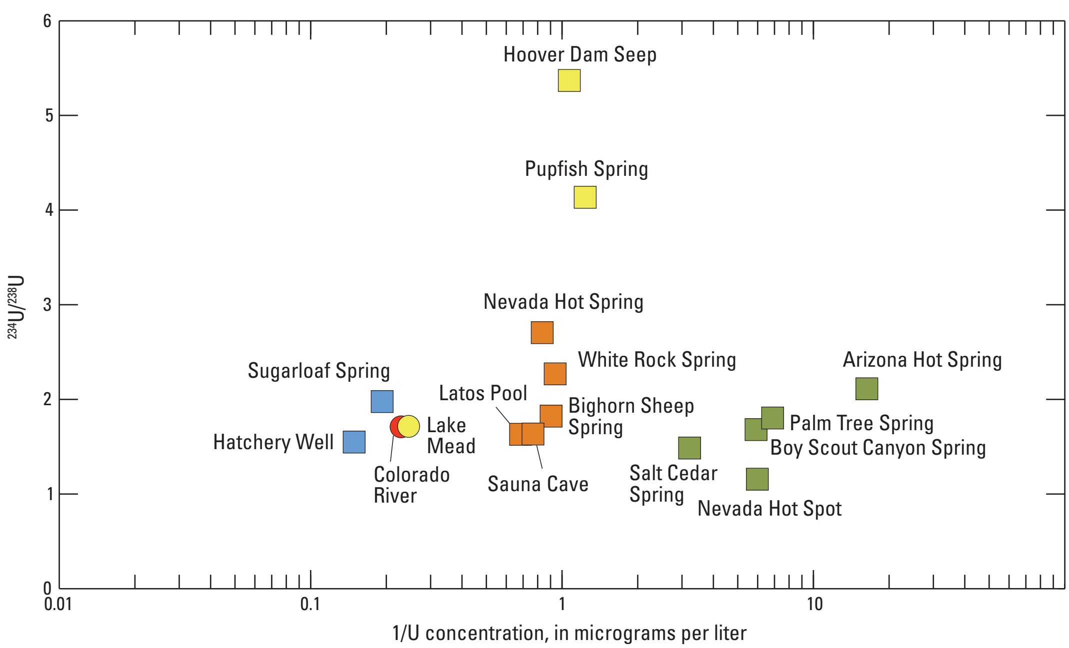


Figure 18. Isotope ratio of uranium ($^{234}U/^{238}U$) compared with reciprocal uranium (1/U) concentrations in water from main springs in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

Pupfish Spring, Nevada Hot Spring, and in Sauna Cave, and were collected in order to date the deposits using U-series disequilibrium methods. Thin crusts of secondary gypsum more commonly are present at Black Canyon springs, particularly those nearest to Hoover Dam. Despite being relatively enriched in dissolved sulfate, Black Canyon water is near equilibrium with respect to calcium-sulfate minerals. The presence of gypsic crusts near the fringes of wet areas is consistent with the formation of those crusts by evaporative concentration of dissolved solids near wet-dry interfaces.

Sulfate crusts were identified at many springs in Black Canyon. These deposits tend to be most thickly accumulated and occupy the widest zone around springs and seeps closest to Hoover Dam. Samples of these deposits were collected for geochemical analysis from seeps forming wet walls in Boy Scout Canyon and lower Goldstrike Canyon. These crusts vary from less than 1 cm to more than several centimeters in thickness; are only crudely layered; and typically have irregular, popcorn-like surfaces. Semi-quantitative X-ray fluorescence maps indicate that these crusts are composed mostly of calcium (Ca) and sulfur (S), with only minor amounts of sodium (Na), aluminum (Al), and magnesium (Mg), and trace amounts of silicon (Si), potassium (K), manganese (Mn), and iron (Fe). These data are interpreted as evidence that crusts consist mainly of gypsum, with lesser amounts of Na-Mg-Al sulfates and silicates.

Uranium concentrations in sulfate crusts are low, ranging from 0.013 to 0.12 microgram per gram (µg/g). Attempts to date these deposits using U-series disequilibrium methods were unsuccessful because measurements of the minor isotopes of uranium and thorium were difficult in low-concentration materials, and because samples show evidence of post-depositional uranium mobility resulting in open-system behavior. Evidence of the youthfulness of these crusts, especially in areas where wet walls are nearly vertical, is indicated by slabs of mineral crusts that have peeled away and fallen into the active tributary channel. Deposits in more protected areas are less susceptible to mechanical erosion.

Deposits dominated by calcite were identified only at a few springs in Black Canyon, including Sauna Cave, Nevada Hot Spring, and Pupfish Spring. These deposits show a wide range of forms, from porous tufa with remnant textures from original vegetative matter to dense, banded travertine commonly associated with speleothem deposits. In Sauna Cave, an exploratory tunnel excavated prior to dam construction, the adit face is covered with botryoidal calcite consisting of coarse, sparry crystals that form a white botryoidal coating at least 2 cm thick. No gypsum is present within this coating, although thin crusts of gypsum cover adit walls away from the flowing face. Uranium concentrations of the calcite are 1–2 orders of magnitude higher than those in gypsum crusts, and are sufficient to allow dating by U-series disequilibrium methods.

Because the calcite in Sauna Cave formed after tunnel excavation, its age should be younger than about 80 years. Measured U-series dates for two separate samples of material subsampled near the base of the coating are young (396.0±82.0 and 36.0±122.0 years, respectively; table 12). One of the two dates is outside the limits of analytical uncertainty of the age of the adit. However, material this young has low thorium-230 (^{230}Th) contents, and measured ^{230}Th/^{238}U compositions are more susceptible to analytical artifacts of spike subtraction, blank correction, and assumptions about the amount of ^{230}Th present at the time of formation compared to older samples with larger amounts of ^{230}Th. Therefore, these relatively young results are considered at least broadly consistent with calcite that has formed in place since the tunnel was excavated.

The most significant deposits of secondary calcite minerals are associated with discharge in upper Goldstrike Canyon near Nevada Hot Spring (fig. 19). Near the uppermost limit of discharge within the canyon, a low-lying carbonate spring mound anchored by several large boulders is present on the north side of the channel. Material forming the carapace of the mound consists of porous tufa that preserves textures of original plant debris. Vugs between boulders underlying the carapace contain speleothem-like banded travertine with dripstone and flowstone textures. The mound was dry when visited in March 2008; however, an active seep was discharging water at a temperature of about 43 °C at an altitude above the deposit near the canyon wall a few meters away.

Several samples of different materials from this location were analyzed for U-series isotopes (fig. 20). All samples had U concentrations ranging from 1.2 to 1.8 µg/g and much lower Th concentrations (0.001–0.080 µg/g), making them good dating candidates. Resulting ^{230}Th/U ages range from 23±14 years to 136±50 years before present (table 12). Ages of ^{230}Th/U for individual millimeter-thick layers within a 28-mm thick banded flowstone are all younger than the 113±47-year-old date obtained for the basal layer adjacent to the rock substrate; however, they are not all consistent with their microstratigraphic positions. Therefore, it is unclear whether the deposit formed rapidly over a short episode or more-or-less continuously during the last 100 years. Nevertheless, all material sampled and dated from this mound is consistent with discharge under modern hydraulic conditions rather than during more ancient Holocene or Pleistocene conditions.

Samples of porous tufa coating the lee side of boulders downstream of the main Nevada Hot Spring discharge area also were analyzed (fig. 19). Dates for basal layers of the 3-cm-thick crust were less precise than those for travertine associated with the upgradient spring mound because of larger detrital-Th corrections, but also resulted in young ages of 99±157 and 470±388 years before present (table 12) that are indistinguishable from the age of Hoover Dam construction.

Table 12. Uranium-series disequilibrium results for samples of rock from various spring sample locations in Black Canyon, Lake Mead National Recreation Area, Nevada and Arizona.

[**Abbreviations:** UTM, Universal Tranverse Mercator; Th, thorium; U, uranium; AR, activity ratio; ka, thousand years; m, meter; NA, not analyzed]

Sample location	Sample No.	Sample location (UTM/zone)	$^{230}Th/^{238}U$ (AR)	±2σ[a]	$^{234}U/^{238}U$ (AR)	±2σ[a]	ρ_{48-08}[b]	$^{230}Th/U$ age (ka)	±2σ[c]	Initial $^{234}U/^{238}U$ (AR)	±2σ[c]	$\rho_{age-\gamma}\gamma_o$[d]
Pupfish Spring Ledge, about 15 m above main pool	PF-v1a	NA	1.6805	0.0127	1.7000	0.0050	0.0000	240.0000	5.8000	2.3800	0.0200	0.9000
	PF-v2a		1.5382	0.0616	1.6890	0.0160	0.1700	195.0000	18.0000	2.1900	0.0600	0.9100
	PF-v1b		0.4860	0.0640	1.7530	0.0700	-0.6900	34.6000	6.5000	1.8300	0.0700	-0.7200
	PF-v2b		0.6051	0.0474	1.7830	0.0600	-0.6000	43.8000	5.4000	1.8900	0.0600	-0.7000
Pupfish Spring, main pool	PF-U1	703,314E/3,987,205N/11	0.0053	0.0025	4.0400	0.0140	-0.4000	0.1430	0.0690	4.0400	0.0140	-0.3700
	PF-U2		0.0106	0.0061	4.0450	0.0190	-0.7900	0.2860	0.1670	4.0500	0.0180	-0.7600
Upper Goldstrike, spring mound	NHS-1A-U1	702,855E/ 3,986,442N/11	0.0038	0.0022	3.7610	0.0120	-0.4100	0.1120	0.0650	3.7600	0.0110	-0.3800
	NHS-1B-U3		0.0046	0.0017	3.6730	0.0090	-0.3900	0.1360	0.0500	3.6700	0.0090	-0.3600
	NHS-1B-U1		0.0037	0.0015	3.5740	0.0110	-0.2800	0.1130	0.0470	3.5700	0.0110	-0.2600
	NHS-1B-U2		0.0018	0.0001	3.7850	0.0100	-0.0300	0.0520	0.0040	3.7900	0.0100	-0.0600
	NHS-1B-U4		0.0009	0.0004	3.6000	0.0100	-0.0900	0.0280	0.0130	3.6000	0.0100	-0.0800
	NHS-1B-U5		0.0018	0.0009	3.6490	0.0080	-0.2700	0.0550	0.0270	3.6500	0.0080	-0.2500
	NHS-1B-U6		0.0008	0.0005	3.6870	0.0080	-0.1300	0.0230	0.0140	3.6900	0.0080	-0.1200
Upper Goldstrike, streambed tufa	NHS-2-U1	703,201E/ 3,986,185N/11	0.0026	0.0042	2.9180	0.0130	-0.5000	0.0990	0.1570	2.9200	0.0120	-0.4500
	NHS-2-U2		0.0127	0.0104	2.9510	0.0190	-0.8400	0.4700	0.3880	2.9500	0.0180	-0.8000
Sauna Cave	SC-1.1	NA	0.0066	0.0014	1.8190	0.0050	-0.1600	0.3960	0.0820	1.8200	0.0100	-0.1400
	SC-1.2		0.0006	0.0020	1.8290	0.0040	-0.3200	0.0360	0.1220	1.8300	0.0000	-0.2500

[a] Detritus-corrected ^{230}Th-^{234}U-^{238}U activity ratios (ARs) assume a Th-bearing detrital component with atomic Th/U of 4 and activity ratios (±2σ) of $^{232}Th/^{238}U$ = 1.20±0.60, $^{234}U/^{238}U$ = 1.00±0.10, and $^{230}Th/^{238}U$ = 1.00±0.25.

[b] Error correlation between $^{234}U/^{238}U$ AR and $^{230}Th/^{238}U$ AR (Ludwig, 2003).

[c] $^{230}Th/U$ age, initial $^{234}U/^{238}U$ ratio, and associated errors calculated using detritus-corrected activity ratios.

[d] Error correlation between the calculated age and initial $^{234}U/^{238}U$ AR (Ludwig, 2003).

Figure 19. Calcite sampling site showing a low carbonate spring mound including a porous tufa carapace (insets on left side) and vugs containing dripstones and flowstones (insets on right side), in Goldstrike Canyon near Nevada Hot Spring, Lake Mead National Recreation Area, Nevada. Photographs taken by James Paces, U.S. Geological Survey, 2009.

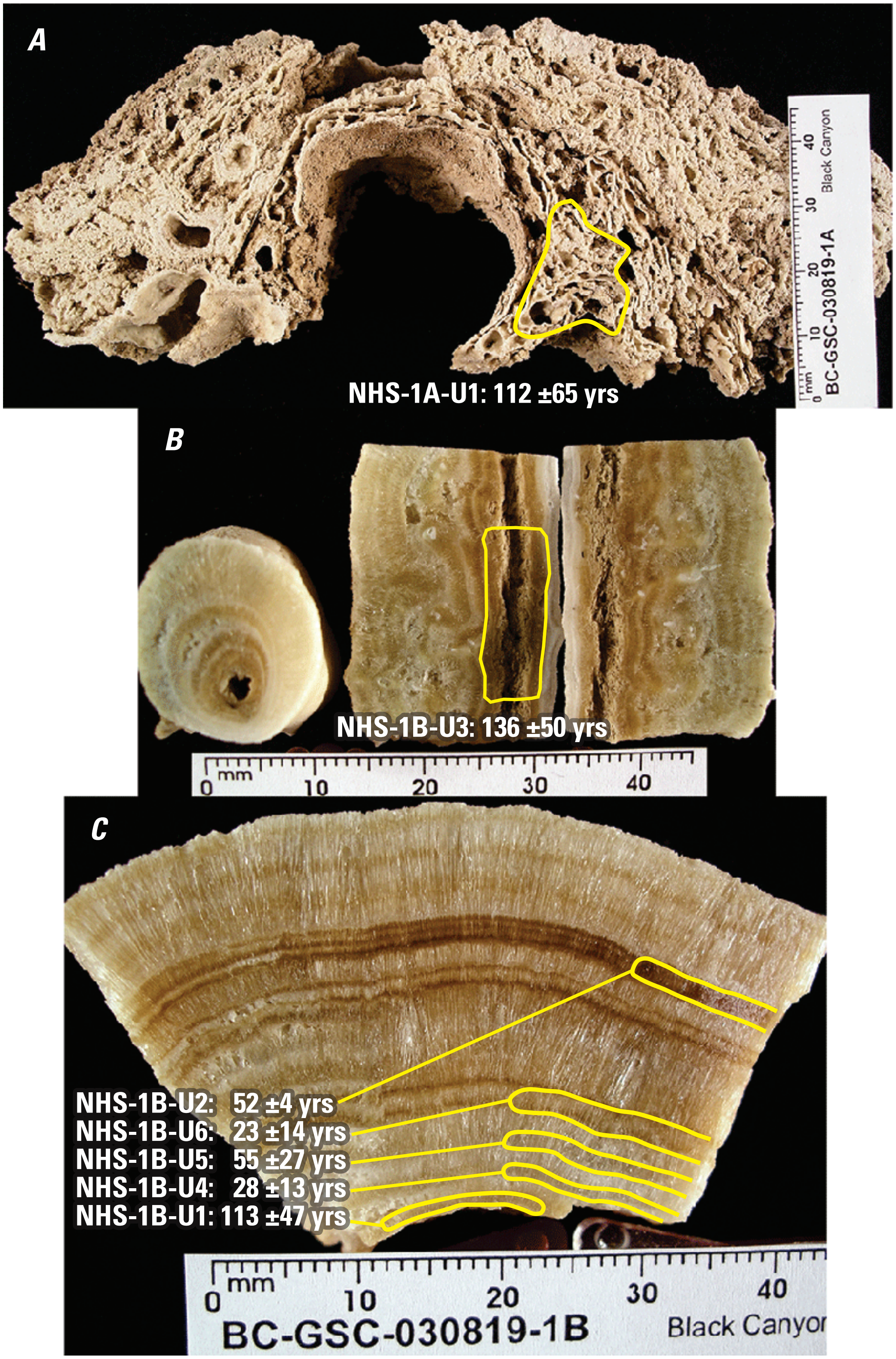


Figure 20. Various materials collected and analyzed for uranium (U)-series isotopes, from Goldstrike Canyon, Lake Mead National Recreation Area, Nevada. (*A*) Porous tufa replacing plant debris, (*B*) small stalactite, and (*C*) banded travertine flowstone with multiple analyses. Areas subsampled for U-series dating are outlined; ages are given in years before present. Photograph taken by James Paces, U.S. Geological Survey, 2009.

At Pupfish Spring, the most obvious discharge deposits consist of 5- to 10-cm-thick porous tufa levees that have built up on either side of a narrow rivulet of water cascading down the vertical rock headwall (fig. 21). Two separate analyses of material from near the base of the levee give ^{230}Th/U dates of 143± 69 and 286± 167 years (table 12). No other deposits were identified around the main pool; however, an approximately 15-mm-thick tabular vein of calcite was discovered in place under an overhanging ledge about 15 m above the main pool (fig. 22). The vein contains complex textures that may indicate several generations of vein material including clear, sparry calcite, reddish- to buff-colored microlayered calcite, and brownish, calcite-cemented soil-like material (fig. 22).

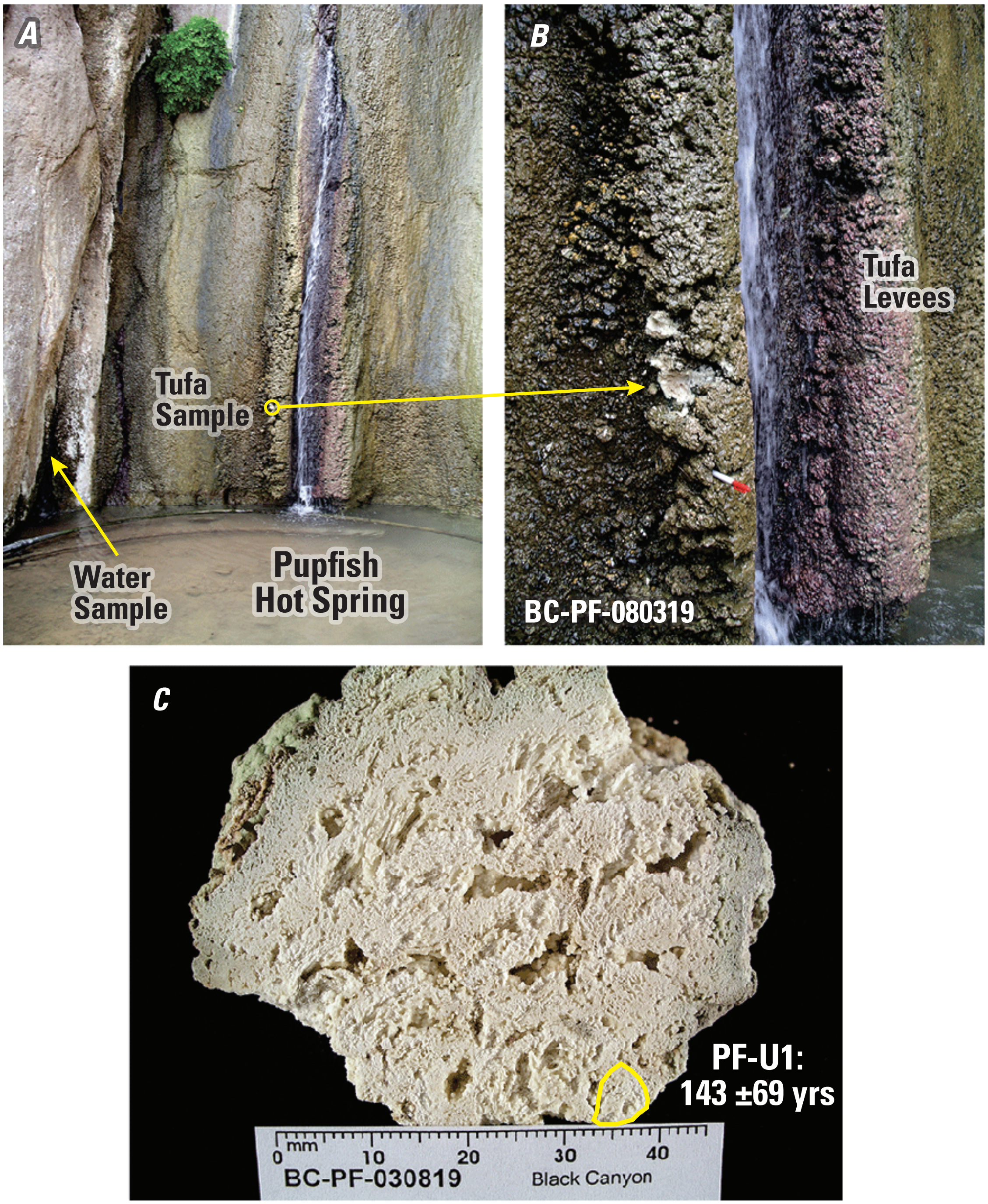


Figure 21. Material collected and analyzed for uranium (U)-series isotopes, at the main pool calcite sampling site, Pupfish Hot Spring, Lake Mead National Recreation Area, Arizona and Nevada. (*A*) Main pool at Pupfish Hot Spring, (*B*) close-up of tufa levees formed on both sides of a cascading rivulet, and (*C*) cross section of tufa-levee sample with location of sample dated using U-series isotopes and ages obtained. Photograph taken by James Paces, U.S. Geological Survey, 2009.

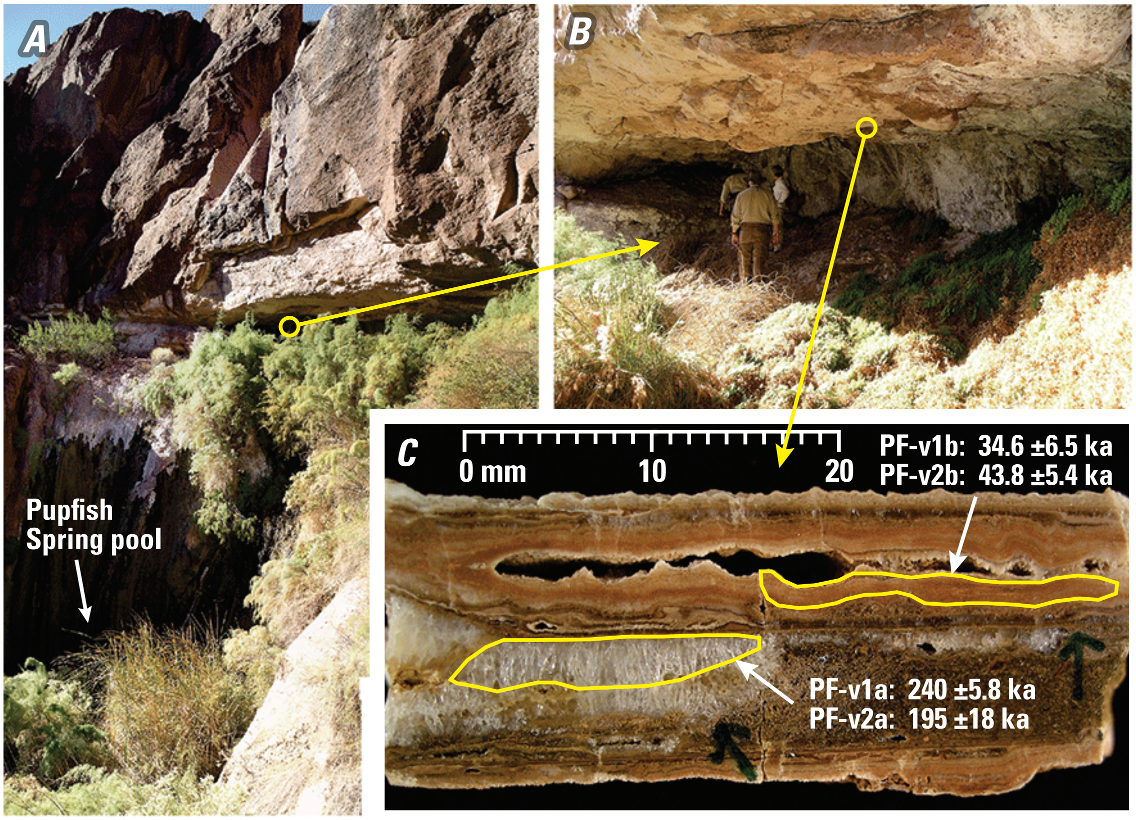


Figure 22. Material collected and analyzed for uranium (U)-series isotopes, at the ledge calcite sampling site, Pupfish Spring, Lake Mead National Recreation Area, Arizona and Nevada. (*A*) Main pool at Pupfish Spring, (*B*) the overhanging ledge, and (*C*) a 15-millimeter-thick tabular vein of calcite sampled for U-series dating. General areas sampled from this and adjacent slabs are outlined, along with resulting thorium-230/uranium ($^{230}Th/U$) ages given in thousands of years before present (ka). Photograph taken by James Paces, U.S. Geological Survey, 2009.

Uranium-series data confirm that the vein upstream of Pupfish Spring, unlike all other samples collected in this study, contains much older calcite that precipitated during the Pleistocene. Apparent $^{230}Th/U$ ages range from about 40,000 years (40 ka) for the reddish layer to more than 195 ka for the white, sparry layer (table 12). Although textures imply that calcite may have formed as at least two distinct generations, U-series isotope systematics also permit the older age for the white vein material to be an artifact of U-loss from calcite formed around 40 ka before present. Because U is much more mobile in low-temperature, oxygen-rich solutions than Th, relatively recent U-loss can cause an increase in the $^{230}Th/^{238}U$ activity ratio (AR), leading to erroneously old $^{230}Th/U$ ages and higher initial $^{234}U/^{238}U$. Therefore, a late Pleistocene date between about 35 and 44 ka with an initial $^{234}U/^{238}U$ value between 1.8300 and 1.8900 is considered to be the most likely age and U-isotopic composition for this material.

Given the limited information available from this single sample of vein material, the origin of solutions responsible for its formation remains unclear. The vein could be derived from downward-percolating vadose-zone flow or upwelling groundwater discharge. Studies of secondary mineral veins in fractured volcanic rocks at Yucca Mountain, about 120 mi northwest of Black Canyon, showed that below a depth of about 15 m but still within the vadose zone, the fine-grained, earthy cements characteristic of the soil-zone transition to coarser-grained sparry calcite and water-clear hyalitic opal (Whelan and others, 1994; Vaniman and Chipera, 1996). Furthermore, the initial $^{234}U/^{238}U$ AR of 1.8300–1.8900 obtained from the vein above Pupfish Spring is consistent with other pedogenic materials throughout the region (Ludwig and Paces, 2002; Lundstrom and others, 2008; Paces and Whelan, 2012). The large difference in initial $^{234}U/^{238}U$ between this vein material (1.8300–1.8900) and the younger levee material (4.0400–4.0500) or modern groundwater $^{234}U/^{238}U$ (4.1350) from the main spring pool, indicates a different source of water responsible for the vein calcite. The lack of additional vein material or other discharge-related deposits at this well-sheltered site, the large difference between the initial $^{234}U/^{238}U$ of vein material and modern discharge, and the consistency of the observed initial $^{234}U/^{238}U$ and a vadose-zone source of water forming the vein are all interpreted as evidence that, despite the older ages obtained for this vein, there was no significant groundwater discharge at Pupfish Spring during the Pleistocene.

Deposits in settings favorable to preservation are equally sparse at other spring settings throughout the canyon. Where datable deposits have been sampled, ages were consistently young. The weighted mean age of all aliquots analyzed (n=13 with one outlier) is only 49±11 years (fig. 23*A*); however, this date is strongly influenced by the younger and more precisely determined ages obtained from banded travertine layers in flowstone from the upper Goldstrike Canyon carbonate spring mound. If only basal layers of hand specimens from calcite deposits in upper Goldstrike Canyon and Pupfish Spring are considered, a weighted mean age of 130±38 years is obtained (fig. 23*B*). This mean age is only slightly older than the 70-plus years since completion of Hoover Dam. The inherent difficulties in measuring material this young by U-series methods were not rigorously evaluated in this study and, therefore, numerical ages reported here are considered approximate. Nevertheless, these ages are considered strong evidence that (1) Pleistocene-aged material was not present at any of the sites with discharge deposits, and (2) all deposits sampled generally are consistent with initiation of surface discharge starting at about the time that Lake Mead was created.

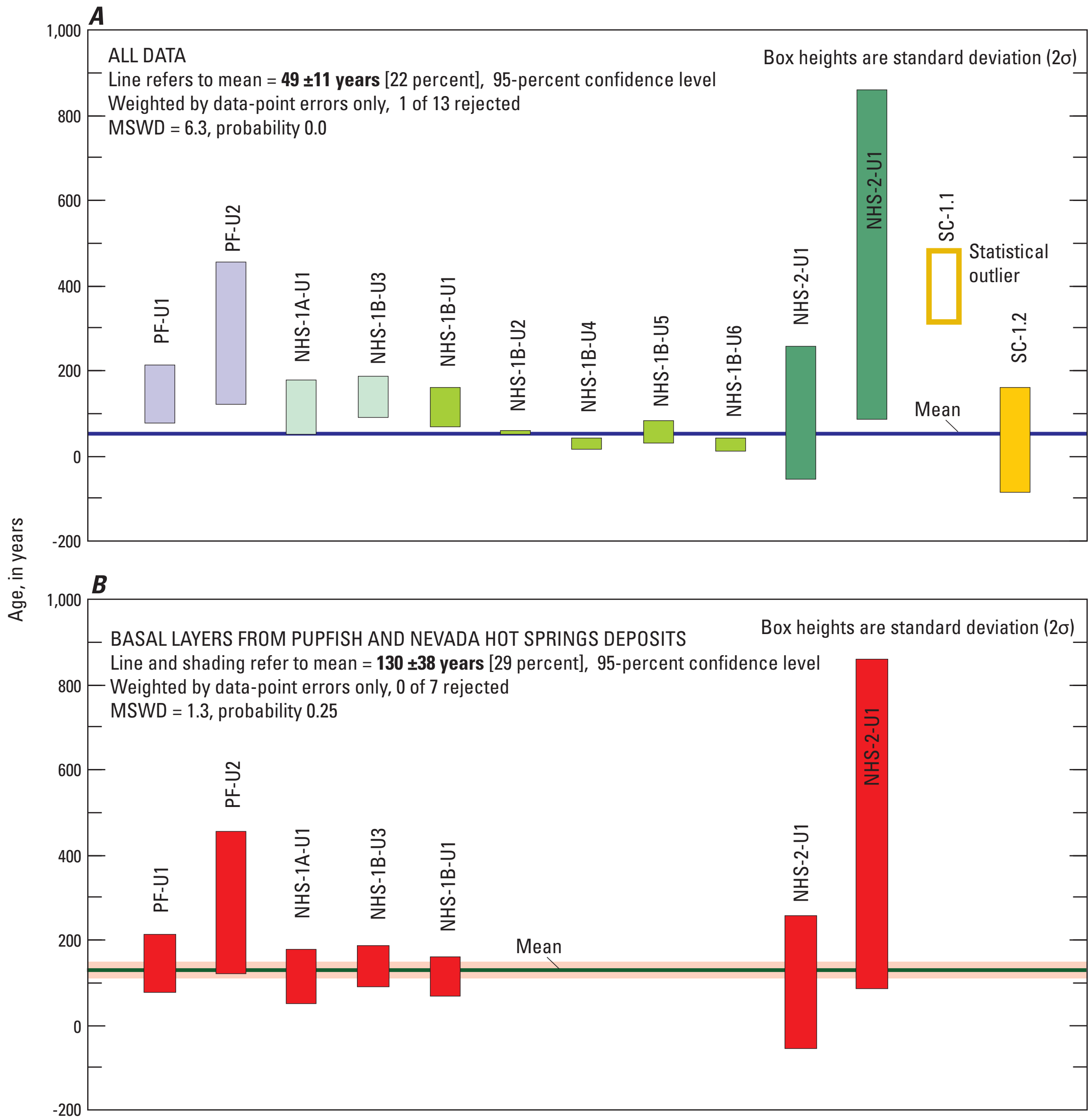


Figure 23. Comparison of ages of uranium (U)-series isotope analyses obtained for carbonate samples from Pupfish Spring (PF), Nevada Hot Springs (NHS) in upper Goldstrike Canyon, and Sauna Cave (SC), Lake Mead National Recreation Area, Arizona and Nevada. (*A*) Weighted mean age for all analyses. Colors indicate multiple determinations from the same samples. (*B*) Weighted mean age for basal layers from samples from Pupfish Spring and Nevada Hot Springs. MSWD, Mean square weighted deviation.

Photograph of Black Canyon near Salt Cedar Spring looking south, Lake Mead National Recreation Area, Nevada and Arizona. (Photograph taken by Michael Moran, U.S. Geological Survey, 2014.)

Hydrogeology and Sources of Water to Springs in Black Canyon

No significant correlation was observed between the distance of springs in Black Canyon from Hoover Dam and discharge rate. The lack of correlation between distance of the spring from Hoover Dam and discharge rate is likely due to many different factors. The conclusion from this result is that discharge alone does not convey any important information to understanding the source of water to the springs.

Numerous results strongly indicate that water from springs near Hoover Dam has a source in Lake Mead. Major ions in the Colorado River and Lake Mead are similar to major ions in springs closest to Hoover Dam (figs. 11–12). Perchlorate results also support this interpretation. Perchlorate was detected only in springs closest to Hoover Dam. Although perchlorate can have some natural sources such as atmospheric precipitation (Dasgupta and others, 2005), the concentrations present in these natural sources are much lower than those at Pupfish Spring. Perchlorate has been entering Lake Mead through the Las Vegas Wash since the 1950s (Nevada Division of Environmental Protection, 2014). The most likely source of perchlorate in Pupfish Spring is Lake Mead water which has moved through the rocks that separate Lake Mead from the spring. Finally, the results of the U-series dating of material deposited at select springs near Hoover Dam supports Lake Mead as a source of water. The results indicate that the deposits are relatively young and close to the age of the completion of Hoover Dam.

Springs south of Palm Tree Spring likely have a significant proportion of discharge that is not from Lake Mead but from a local and (or) regional source. Results of major ions and stable isotopes of hydrogen and oxygen support this interpretation. Concentrations of TDS, alkalinity, and major ions show a distinct change in composition with increasing distance from Hoover Dam (figs. 10–13). In fact, significant correlations (when excluding Bighorn Sheep Spring, Hatchery Well, and Latos Pool) exist between the distance of springs from Hoover Dam and the concentrations of some of these constituents. These results suggest that either a change in the source of groundwater or a geochemical evolution of groundwater occurs as distance from Hoover Dam increases, or a combination of these two factors is at work. The most notable result is the unique chemical characteristics of water from Bighorn Sheep Spring and Latos Pool, which is significantly different from the characteristics of water at other springs.

Springs closest to Hoover Dam cluster together and show the least enrichment of δ^2H and $\delta^{18}O$ relative to other springs (fig. 16). Depletion of δ^2H and $\delta^{18}O$ indicates a source for this water at high altitudes or latitudes such as the Rocky Mountains, which is consistent with a source for much of the water in the Colorado River. In contrast, springs farther from Hoover Dam cluster together and show more enrichment in δ^2H and $\delta^{18}O$ relative to other springs (fig. 16).

Based primarily on hydrochemical results, groundwater discharging from springs in Black Canyon has two sources: (1) Lake Mead, and (2) a local and (or) regional source. These two sources combine at the springs in a complex flow system. Discharge occurring from Pupfish Spring to Palm Tree Spring likely contains a substantial percentage (>50 percent) of water from Lake Mead whereas discharge south of Palm Tree Spring likely contains a substantial percentage (>50 percent) of water from other sources; however, the exact location and nature of these other sources is not clear. Enrichment in δ^2H and $\delta^{18}O$ in water from springs south of Pam Tree Spring suggests a source in the low-altitude mountain ranges surrounding Black Canyon. Pohlmann and others (1998) noted that groundwater from springs in the McCullough Range and Eldorado Mountains surrounding Black Canyon plotted with substantially enriched δ^2H and $\delta^{18}O$ compared to higher-altitude springs in the Spring and Sheep Mountains near Las Vegas, Nevada.

Binary and ternary mixing calculations were done to determine if the hydrochemical composition of groundwater discharging from springs in Black Canyon could be the result of mixing of two or more end members. For binary mixing, the end members selected were Lake Mead/Colorado River and Arizona Hot Spring (fig. 24). For ternary mixing, the end members selected were Lake Mead/Colorado River, Bighorn Sheep Spring, and Arizona Hot Spring (fig. 25). The measured values of most constituents show significant scatter about the mixing lines or mixing areas. However, some constituents, such as calcium compared with chloride, δ^2H compared with chloride, and $\delta^{34}S$ compared with chloride, plot close to the binary mixing line or within the ternary mixing boundaries (figs. 24 and 25). These results generally support the interpretation that the change in composition of groundwater in springs in Black Canyon could be the result of mixing of two or more separate sources of water.

Samples of water from springs and wells located in areas away from Black Canyon, but within an area of potential regional groundwater flow, were collected and analyzed for various constituents. Results of major ion ratios are included in figure 26. The purpose of this analysis was to include or exclude regional groundwater sources to springs in Black Canyon.

Most samples of water from areas outside Black Canyon do not plot in locations near springs in Black Canyon with the following exceptions: Eldorado West Well, Cataract Spring, and the Lake Mead Intake Tunnel (fig. 26). Eldorado West Well, located in Eldorado Valley (fig. 3; table 1), has major ion ratios that are similar to those present in Bighorn Sheep Spring. According to the driller’s log this well is completed in volcanic rock.

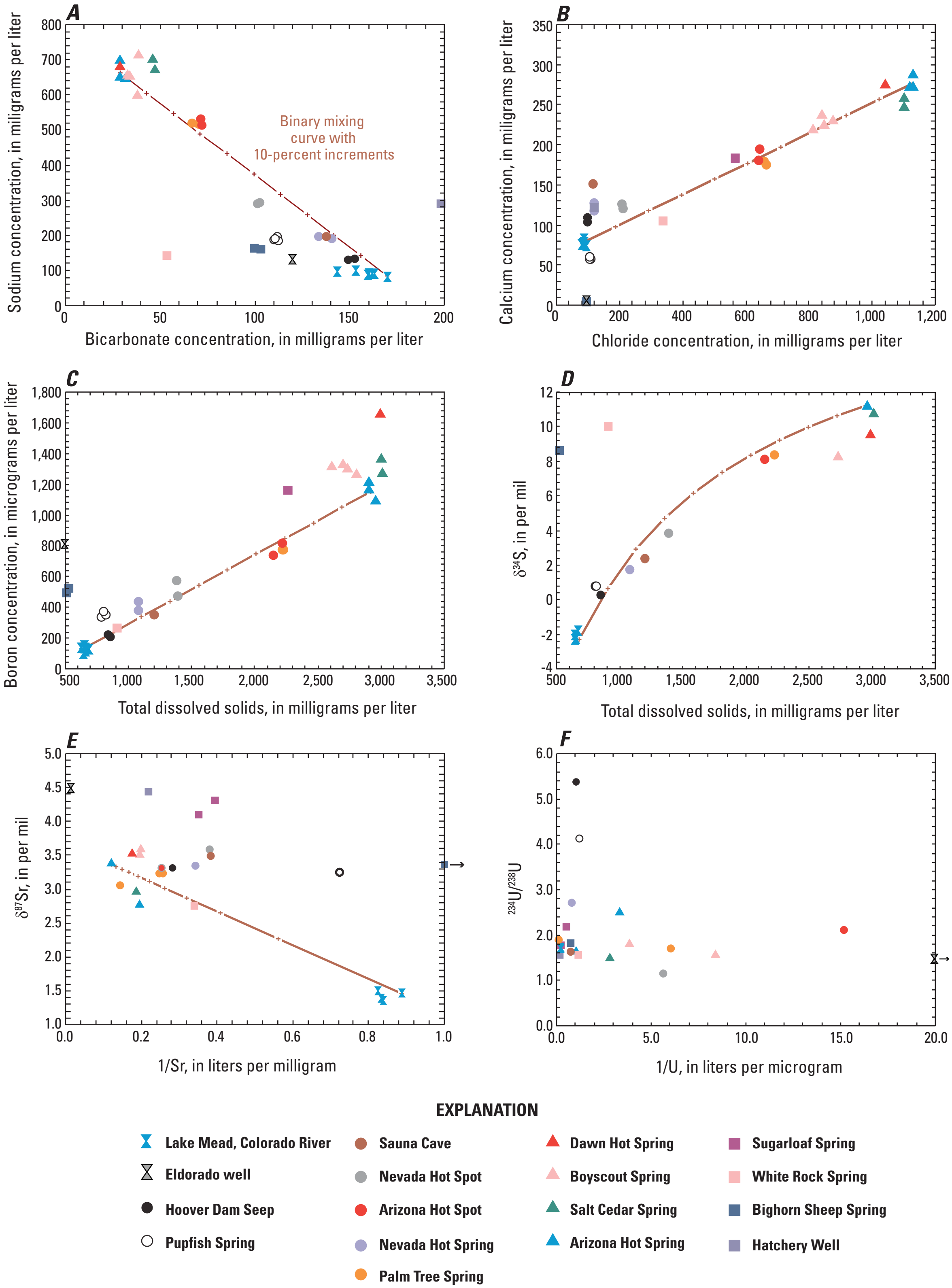


Figure 24. Binary mixing diagrams for various constituents with end members of Lake Mead/Colorado River water and water from Arizona Hot Spring and mixing curves in 10-percent increments for (*A*) sodium and bicarbonate, (*B*) calcium and chloride, (*C*) boron and total dissolved solids, (*D*) delta-34-sulfur ($\delta^{34}S$) and total dissolved solids, (*E*) delta-87-strontium ($\delta^{87}Sr$) and reciprocal strontium concentration (1/Sr), and (*F*) 234-uranium/238-uranium ($^{234}U/^{238}U$) activity ratio and reciprocal uranium concentration (1/U), Black Canyon, Lake Mead National Recreation Area, Arizona.

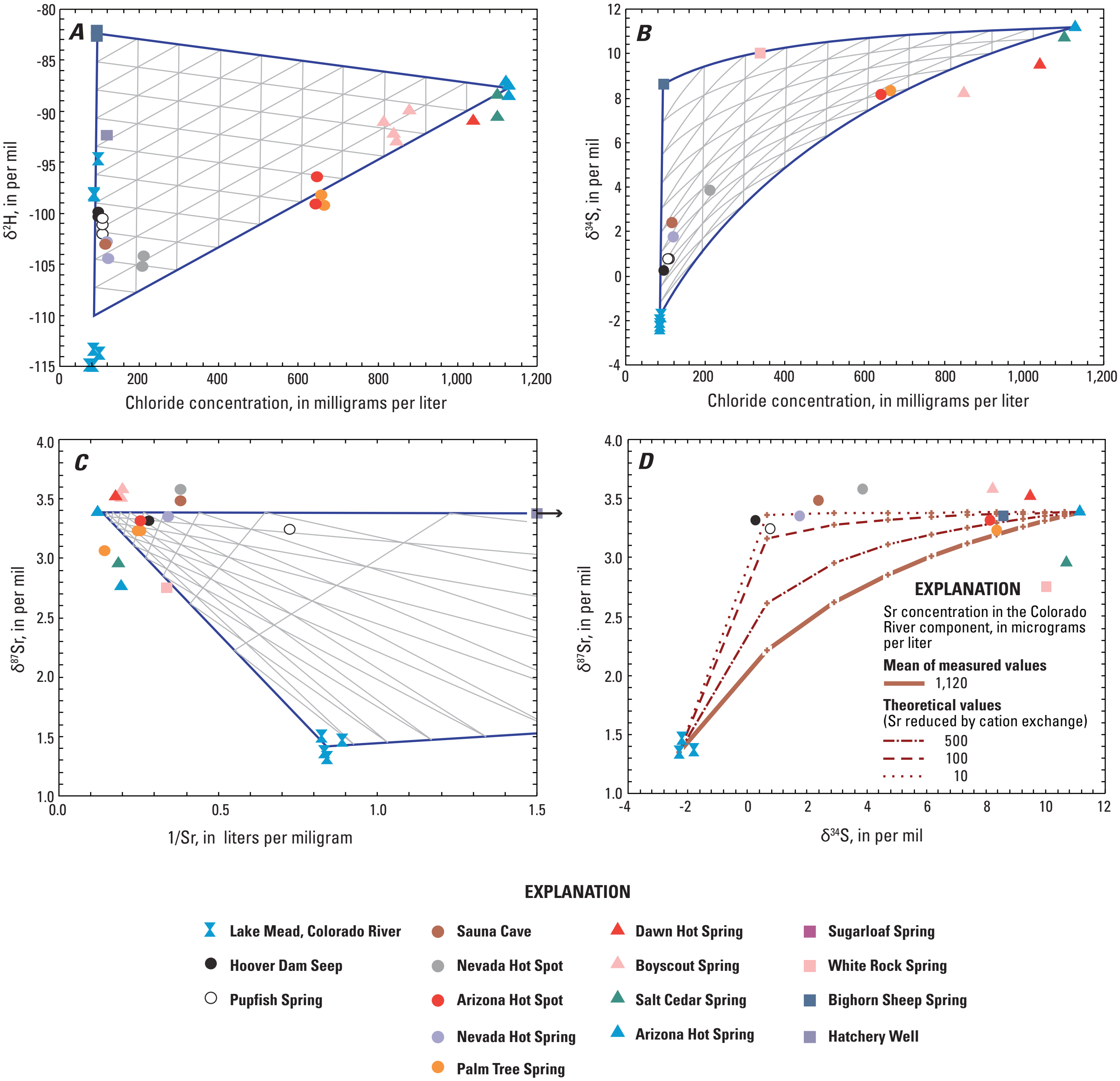


Figure 25. Ternary mixing diagrams for various constituents with end members of Lake Mead/Colorado River water and water from Arizona Hot Spring and mixing boundaries for (*A*) delta hydrogen-2 (δ^2H) and chloride, (*B*) delta-34-sulfur (δ^{34}S) and chloride, (*C*) delta-87-strontium (δ^{87}Sr) and reciprocal strontium concentration (1/Sr), and (*D*) delta-87-strontium (δ^{87}Sr) and delta-34-sulfur (δ^{34}S), Black Canyon, Lake Mead National Recreation Area, Arizona and Nevada.

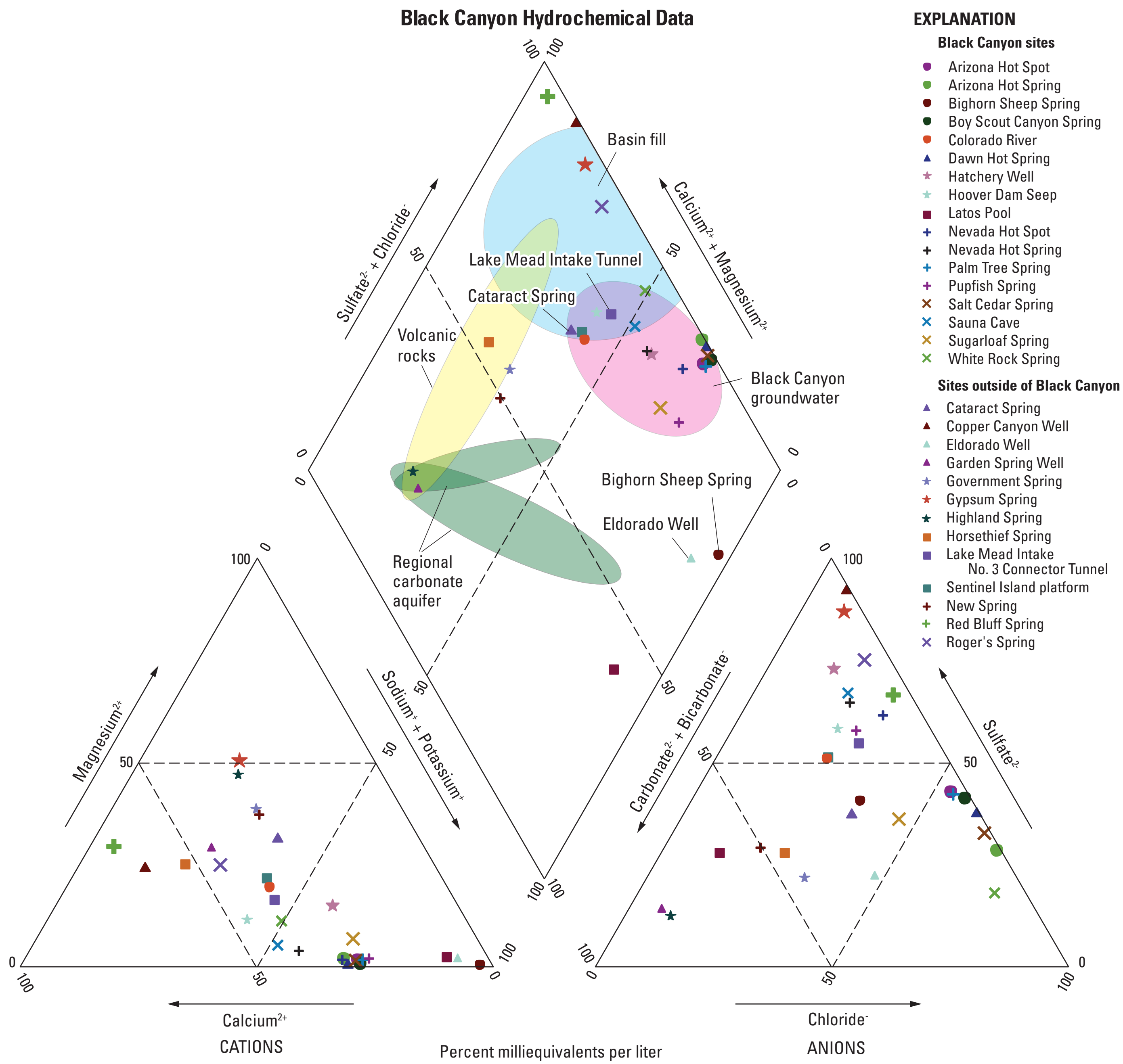


Figure 26. Major ion concentration ratios for water samples collected from springs in Black Canyon as well as various wells and springs outside Black Canyon (shaded areas, from Pohlmann and others, 1998), Lake Mead National Recreation Area, Nevada and Arizona.

The similarity in major ion ratios between these two sites suggests that Eldorado Valley may be a source of water discharging at Bighorn Sheep Spring. Cataract Spring is located northeast of Hoover Dam and east of the Overton Arm of Lake Mead (not shown in fig. 3). Because of its great distance from Black Canyon it is not likely that groundwater in this area could be a source of water to the springs. The Lake Mead intake tunnel point plots near points for Hoover Dam Seep and Sauna Cave. Much of the water in this area is Lake Mead water that has infiltrated rocks surrounding the lake. Thus, the sample from this site would be expected to have a major ion composition similar to that of springs close to Hoover Dam.

The compositions of regional water samples can exclude some areas as viable sources of groundwater to springs in Black Canyon. Pohlmann and others (1998) plotted the compositions of numerous water samples from the regional carbonate aquifer (see fig. 26). None of the water samples from springs in Black Canyon overlaps with the compositions in the regional carbonate aquifer (fig. 26). Water from springs in Black Canyon is too depleted in carbonate and bicarbonate to represent groundwater in the carbonate aquifer (fig. 26). Relative to samples from the carbonate aquifer, water samples from Black Canyon springs are dominated by sodium-potassium and sulfate-chloride. Hess and Mifflin (1978) noted that sodium, potassium, chloride, and sulfate could increase in groundwater in the regional carbonate aquifer as the groundwater moves along regional flow paths in southern Nevada. This change in hydrochemistry is believed to be due to the presence of other minerals, such as gypsum and halite, in small quantities in the carbonate rocks (Maxey and Mifflin, 1966). However, many of the samples from springs in Black Canyon are more enriched in these elements than most samples from the regional carbonate aquifer (fig. 26).

Likewise, none of the water from springs in Black Canyon overlaps with the compositions found in the volcanic-rock aquifers of the region (fig. 26). Groundwater from springs in Black Canyon is too enriched in sodium and potassium to represent most groundwater in these aquifers (fig. 26). Nonetheless a possible source for the enrichment in sodium and potassium in water from springs in Black Canyon may be movement through the volcanic rocks. Groundwater in volcanic rocks northwest of Las Vegas has a sodium- and potassium-bicarbonate composition, indicating dissolution of feldspar and mafic minerals along relatively long flow paths (Winograd and Thordardson, 1975; Lyles and others, 1987).

The compositions of a few samples of water from springs in Black Canyon overlap with compositions in basin-fill aquifers of the region (fig. 26). Groundwater in basin-fill areas in southern Nevada generally is classified as having a composition of calcium and magnesium-bicarbonate mixed cation-sulfate, and sodium and potassium-bicarbonate (Lyles and others, 1987). In general, groundwater in these aquifers is depleted in carbonate-bicarbonate relative to volcanic-rock aquifers or the regional carbonate aquifer and this more closely matches the composition of water from springs in Black Canyon. Sulfate in the basin-fill material may be derived from dissolution of evaporite minerals such as gypsum and thenardite while sodium, potassium, and chloride may be derived from dissolution of halite and sylvite (Lyles and others, 1987). These minerals are present in Tertiary sedimentary rocks of basin fill in the region and possibly within unconsolidated alluvium. But samples from springs in Black Canyon are still more enriched in sodium-potassium and depleted in calcium-magnesium than most samples from the basin-fill aquifers (fig. 26).

Recharge likely is occurring in the mountainous areas surrounding Eldorado Valley. Pohlmann and others (1998) noted that tritium activities measured at two springs in the Eldorado Mountains indicated that most groundwater in this area was recharged after about 1952 (Southern Nevada Water Authority, unpub. data, 1998). Such recharge could be a source for some of the water discharging at springs in Black Canyon. However, age-dating tracers indicate that the water in Eldorado West Well in the Eldorado Valley may be significantly older than the date of the construction of Hoover Dam. Pohlmann and others (1998) noted that much of the groundwater in the central areas of the Eldorado Valley may have been recharged during a wetter period in the past, perhaps at the end of the last North American glacial period.

Estimates of recharge in the study area were compiled to identify the potential groundwater sources to springs in Black Canyon. For this analysis, only recharge occurring within the Eldorado Valley Basin portion of the study area was considered. The presence of a large core of crystalline metamorphic rock in the Black Mountains, as well as several bounding normal faults, make it unlikely that groundwater can move between Detrital Valley and Black Canyon (Beard and others, 2014, pl. 1, section C-C′).

Two existing recharge estimates for the Eldorado Valley Basin were available (Rush and Huxel, 1966; Epstein and others, 2010). The average of recharge from these two studies in the Eldorado Valley Basin was 2,200 acre-ft/yr. Although this is more than the total discharge estimated to be occurring in Black Canyon (1,100 acre-ft/yr) data from the Nevada Division of Water Resources indicate that about 2,256 acre-ft/yr of groundwater are withdrawn from the Eldorado Valley each year. Based on this information, a groundwater source from Eldorado Valley alone cannot account for all of the discharge in Black Canyon.

Recharge in the Eldorado Valley Basin part of the study area was computed using average precipitation values from 1981 to 2010 (PRISM Climate Group, 2015), which were organized into zones representative of 1-in. annual precipitation intervals (fig. 27). The precipitation in these 11 zones ranged from about 4.75 to about 15 in. per year. Total annual precipitation volume was computed by multiplying the average annual precipitation by the geographic area encompassed by each of these zones. Geographic areas were computed using ARCMap™ (ESRI 2014 ArcGIS Desktop, Release 10.2.2, Environmental Systems Research Institute [ESRI], Redlands, California). Recharge was then determined by multiplying the total annual precipitation volume in each zone by a recharge coefficient (table 13). Recharge coefficients were derived from Nichols (2000) and Hevesi and others (2003).

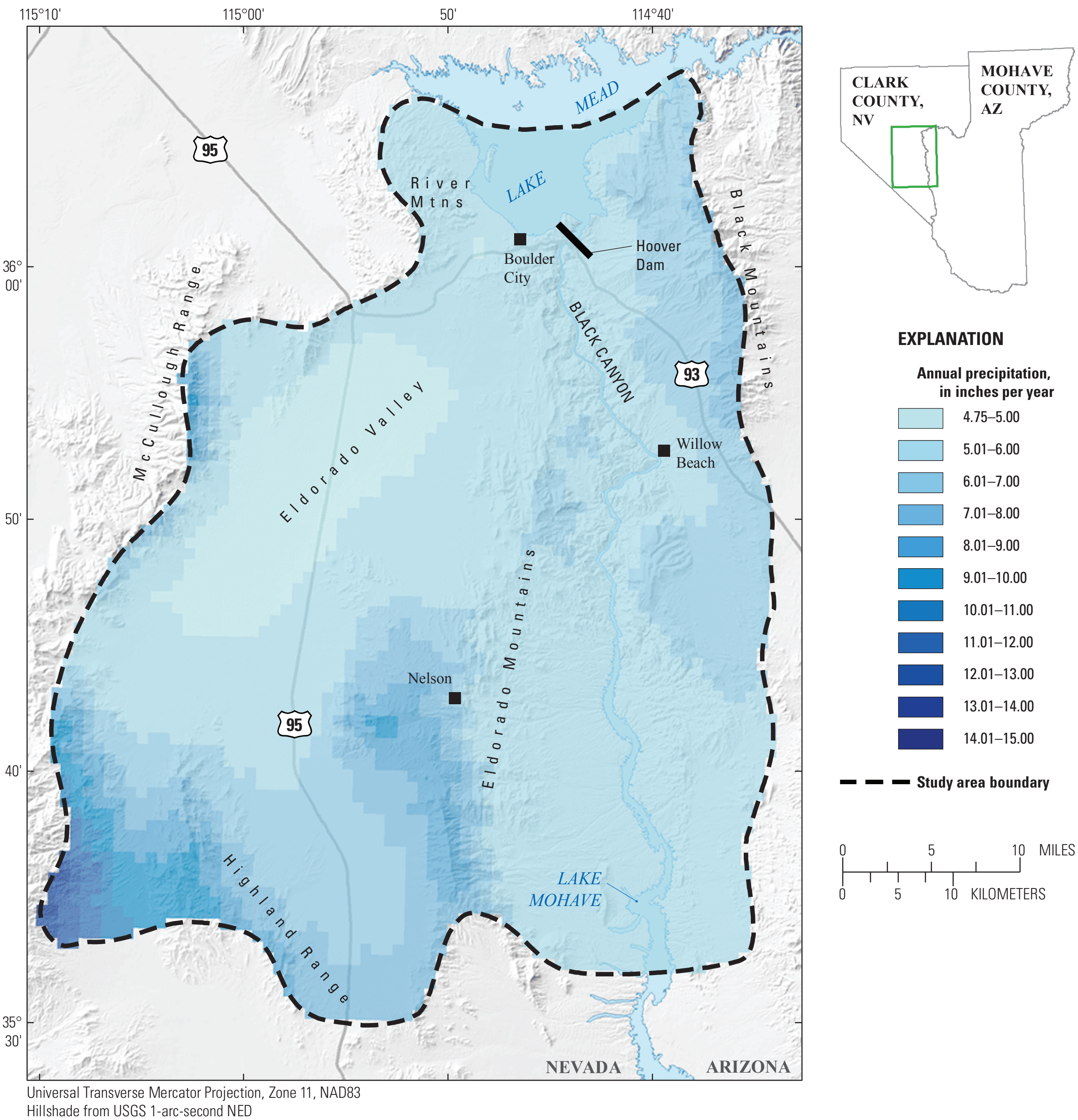


Figure 27. Annual precipitation zones used to compute potential recharge in the Black Canyon study area, Lake Mead National Recreation Area, Nevada and Arizona.

Table 13. Estimated recharge to the Eldorado Valley Basin part of the Black Canyon study area, Lake Mead National Recreation Area, Nevada and Arizona.

[**Abbreviations:** in/yr, inch per year; acre-ft/yr; acre-foot per year]

Annual precipitation zone (in/yr)	Zone area (acres)	Total precipitation range (acre-ft/yr)	Recharge coefficient	Recharge range (acre-ft/yr)
4.75–5.00	57,091	22,620–23,788	[1]0.0009	20–21
5.01–6.00	355,515	148,131–177,757	[1]0.0009	133–160
6.01–7.00	127,625	63,812–74,448	[1]0.0009	57–67
7.01–8.00	58,514	34,133–39,010	[1]0.0009	31–35
8.01–9.00	27,043	18,028–20,282	[2]0.008	144–162
9.01–10.00	12,968	9,726–10,807	[2]0.008	78–86
10.01–11.00	3,637	3,031–3,334	[2]0.008	24–27
11.01–12.00	3,163	28,99–3,163	[2]0.008	23–25
12.01–13.00	1,898	1,897–2,056	[2]0.13	247–267
13.01–14.00	1,423	1,541–1,661	[2]0.13	200–216
14.01–15.00	316	369–395	[2]0.13	48–51
Total	–	–	–	**1,005–1,117**

[1]Recharge coefficient based on average of Model 1, 2, and 3 of INFIL v3 (Hevesi and others, 2003).

[2]Recharge coefficient from Nichols (2000).

The method described by Nichols (2000) follows Maxey and Eakin (1949) and Eakin and Maxey (1951) who suggest that no recharge is available from areas that annually receive less than 8 in. of precipitation. Geographically, areas receiving less than 8 in. of annual precipitation are located in the lower altitudes that include basins lowlands and surrounding alluvial fans and in southern Nevada these areas are generally believed to contribute very little recharge to groundwater. However, Hevesi and others (2003) suggested that infiltration occurs in these areas as a result of stream-channel losses. Net infiltration values from Hevesi and others (2003) were averaged and used as recharge coefficients in this study for areas receiving less than 8 in. of annual precipitation.

Results of the recharge computations indicate that a total of 1,005–1,117 acre-ft/yr of recharge could be occurring in the study area (table 13). Additional computations indicate that between 0.33 ft^3/s (239 acre-ft/yr) and 0.39 ft^3/s (282 acre-ft/yr) of recharge could also be coming from areas that receive less than 8 in. of precipitation annually. Thus, the total amount of recharge that could be occurring in the Eldorado Valley Basin portion of the study area ranges from about 1,245 acre-ft/yr to 1,400 acre-ft/yr. As stated before, since about 2,256 acre-ft/yr of groundwater are withdrawn from the Eldorado Valley each year a groundwater source from this area alone cannot account for all the discharge from springs in Black Canyon.

Groundwater altitudes in the Eldorado Valley Basin part of the study area support a groundwater source to Black Canyon from Eldorado Valley. A groundwater altitude map suggests that groundwater is recharged in the Eldorado Mountains south of Black Canyon and flows into Eldorado Valley toward Black Canyon (fig. 28). This is in agreement with estimated groundwater flow in Eldorado Valley as suggested by Rush and Huxel (1966). Although data are sparse in this area, most springs in Black Canyon have an altitude of less than 900 ft whereas groundwater altitudes in Eldorado Valley are higher than 1,200 ft. This indicates a potential for groundwater flow from Eldorado Valley to Black Canyon. However, the presence of numerous strike-slip and normal faults, as well as Tertiary intrusive rocks, in the area between Eldorado Valley and Black Canyon may impede groundwater flow between them (Beard and others, 2014, pl. 1, section D-D′).

Additional evidence for a local and (or) regional source to springs in Black Canyon comes from historical accounts. A map produced as part of an expedition to explore the Colorado River, known as the Ives Expedition, shows a hot spring on the Arizona side of Black Canyon (Ives, 1861; fig. 29). The map was produced sometime between 1857 and 1858. Although the topography shown on the map is crude, the hot spring is believed to be near either Arizona Hot Spring or White Rock Spring. This suggests that some groundwater discharge was occurring in Black Canyon prior to the construction of Hoover Dam.

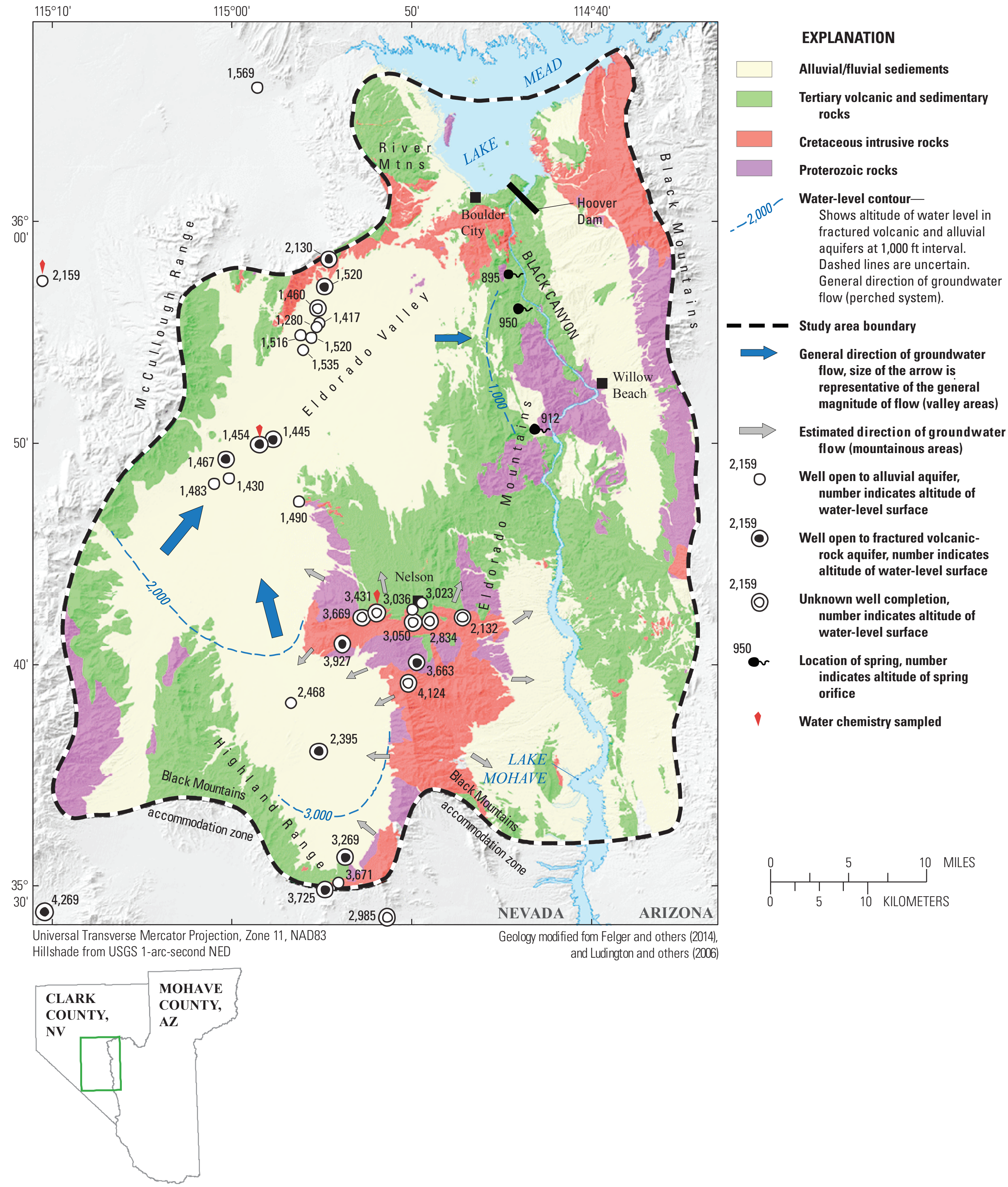


Figure 28. Groundwater altitudes and potential flow directions in the Eldorado Valley Basin, Lake Mead National Recreation Area, Nevada and Arizona.

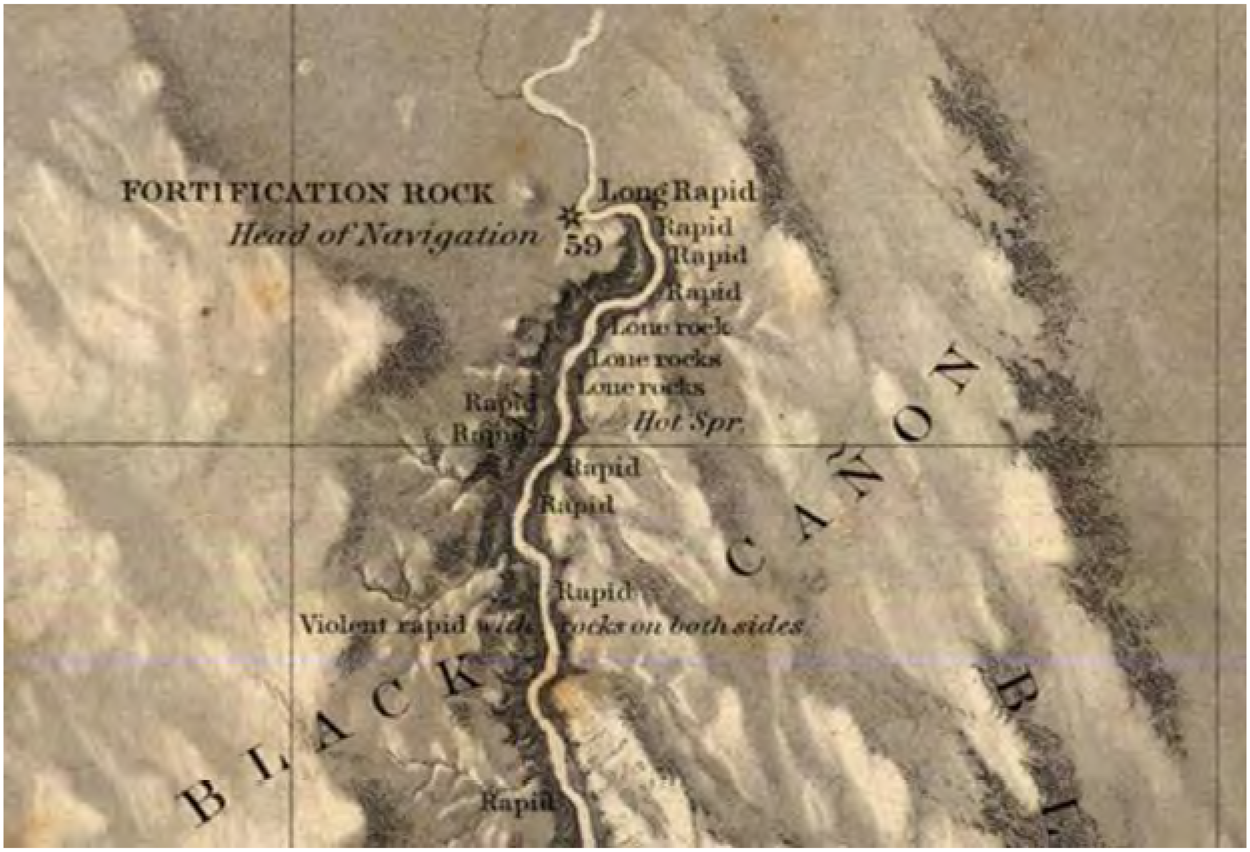


Figure 29. Historical map of area produced during the Ives Expedition of 1857–58 showing location of a hot spring in Black Canyon. (From Ives, 1861.)

Several major faults play an important role in the movement of groundwater in Black Canyon. The first is the northwest-striking right-lateral Palm Tree Fault in north Black Canyon (fig. 2). Groundwater movement may be flowing along the strike of the Palm Tree Fault resulting in discharge where Mount Davis dikes intrude the fault (Beard and others, 2014). The second fault is the north-striking, west-side-down Salt Cedar Fault. Several springs in Black Canyon are located near or along this fault including Boy Scout Canyon Spring, Nevada Hot Spring, and Salt Cedar Spring (Beard and other, 2014).

In many areas of Black Canyon, discharge from springs does not occur directly at fault planes but in areas where faults intersect volcanic breccias or fractured rock. For example, in Salt Cedar Canyon groundwater discharges from multiple points in the stratified Patsy Mine volcanic sequence near the Salt Cedar Fault. In Goldstrike Canyon, groundwater discharges from fractured Boulder City pluton where these rocks are near the Salt Cedar Fault (Beard and others, 2014). The major faults of Black Canyon may act as conduits for movement of groundwater whereas igneous rocks and breccias may act as both barriers to flow and as outlets for the transmission of groundwater to the surface. Caine and others (1996) noted that groundwater flow often occurs in the damage zone of fractured rock associated with faulting and outside an impermeable fault-core zone.

Groundwater possibly flows vertically down faults and then returns to the surface. The median temperature of groundwater discharging from the major springs in Black Canyon is 42.3 °C. This is about 12.9 °C higher than the average temperature of groundwater in Eldorado West Well (29.4 °C). The simplest explanation for this additional heat would be magmatic sources or residual heat from tectonic activity. However, according to Beard and others (2014), the additional heat cannot be accounted for by shallow magmatic sources because the local volcanic and intrusive rocks are too old to be a viable source of this heat. Therefore, it is more likely that the additional heat is due to the natural geothermal gradient as groundwater moves vertically along faults.

Water from Lake Mead may be moving along normal faults that separate the lake from Black Canyon, especially along Promontory Point (fig. 2). Although the modern stress field does not favor flow along the strike of these faults, many are west-dipping and could transmit water from Lake Mead to other faults such as the Salt Cedar Fault (Beard and others, 2014). Another pathway for movement of water from Lake Mead to Black Canyon is a series of west-down normal faults on the east side of Black Canyon (fig. 2). Again, the modern stress field does not favor flow along the strike of these faults but it is possible they could transmit water to other faults (Beard and others, 2014).

Sedimentary rocks, the Boulder City pluton, and volcanic rocks including the Patsy Mine and Mount Davis volcanic rocks separate Eldorado Valley from Black Canyon. Although these rocks are highly faulted in this area, the orientation of the faults in conjunction with the modern stress field does not support groundwater flow along them in a west-east direction (plate 1, Beard and others, 2014). Nonetheless a groundwater altitude difference exists between Eldorado Valley and Black Canyon and groundwater may move from Eldorado Valley to Black Canyon. If such groundwater does occur, the development of groundwater resources in Eldorado Valley could result in a decrease in discharge from springs in Black Canyon.

To the east of Black Canyon, groundwater recharged in the Black Mountains likely flows east to Detrital Valley. No wells were located in the area immediately east of Black Canyon. Because there are no groundwater data immediately east of Black Canyon, no conclusions can be drawn about groundwater flow in this area (fig. 28). The northern core of the Black Mountains is composed of Tertiary intrusive rocks whereas the southern core is composed of Proterozoic crystalline rocks. In addition, the entire Black Mountain range is bounded on the west and east sides by steeply dipping north-south normal faults (Beard and others, 2014, pl. 1, section C-C′). The northern Detrital Valley subbasin, which underlies the northern Detrital Valley, consists of tilted and faulted middle Miocene volcanic rocks and older sedimentary deposits that overlie crystalline bedrock (Anning and others, 2007). Given this geology, the possibility of groundwater flow from Detrital Valley to Black Canyon is unlikely. Additionally, Anning and others (2007) note that groundwater flow in the basin-fill material of Detrital Valley is to the north-northeast toward Lake Mead along the axis of the basin. As a result, the development of groundwater resources in Detrital Valley may not result in a decrease in discharge from springs in Black Canyon.

Summary

Springs in Black Canyon of the Colorado River, south of Hoover Dam in the Lake Mead National Recreation Area, Nevada and Arizona, are important hydrologic features supporting a unique riparian ecosystem that includes habitat for endangered species. Rapid population growth in areas surrounding Black Canyon has caused concern among resource managers that such growth could have an effect on the discharge from these springs. The U.S. Geological Survey studied the springs in Black Canyon between January 2008, and May 2014.

Based primarily on results of hydrochemical analyses, groundwater discharging from springs in Black Canyon has two sources: (1) Lake Mead, and (2) a local source and (or) a regional source. These two sources likely combine at the springs in a complex flow system. Discharge from Pupfish Spring to Palm Tree Spring likely contains a substantial percentage (>50 percent) of water from Lake Mead, whereas discharge south of Palm Tree Spring likely contains a substantial percentage (>50 percent) of water from local and (or) regional sources. Analyses of hydrochemical results including total dissolved solids, alkalinity, major ions, perchlorate, and stable isotopes of hydrogen and oxygen support these interpretations. Results of the uranium-series disequilibrium dating suggest that spring deposits at several sites near Hoover Dam are relatively young and likely formed after the construction of Hoover Dam.

As discharge is examined from springs near Hoover Dam to the south, major ion ratios indicate a change in the source of groundwater or a geochemical evolution of groundwater along a flow path. Results from binary and ternary mixing computations support the interpretation that the change in composition of groundwater in springs in Black Canyon could be the result of mixing of two or more separate sources of water. The specific location and nature of the sources of local or regional water to springs south of Palm Tree Spring is not clear, but enrichment in isotopes of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) in water from these springs suggests a source in the low-altitude mountain ranges surrounding Black Canyon. The compositions of regional water samples can exclude some areas as viable sources of water to springs in Black Canyon. None of the water from springs in Black Canyon overlaps with water compositions present in either the regional carbonate aquifer or the volcanic rocks of the region. However, there is some overlap with water compositions present in basin fill of the region.

Based on recharge estimates, a groundwater source from Eldorado Valley is possible but cannot account for all of the discharge from springs in Black Canyon. Groundwater altitudes in the Eldorado Valley Basin part of the study area support a regional groundwater source to Black Canyon from Eldorado Valley. A groundwater altitude map suggests that groundwater is recharged in the Eldorado Mountains south of Black Canyon and flows into Eldorado Valley toward Black Canyon. However, the presence of numerous strike-slip and normal faults, as well as Tertiary intrusive rocks, in the area between Eldorado Valley and Black Canyon do not favor groundwater flow between them. Age-dating tracers indicate that the water in Eldorado West Well in the Eldorado Valley may be significantly older than the date of the construction of Hoover Dam.

Several major faults play an important role in the movement of groundwater in Black Canyon including the Palm Tree and Salt Cedar Faults. In many areas of Black Canyon, discharge from springs does not occur directly at fault planes but in areas where faults intersect volcanic breccias or fractured rock. Groundwater possibly flows vertically down faults and then returns to the surface as indicated by the median temperature of groundwater discharging from the major springs in Black Canyon which is higher than the estimated temperature of recharge water.

Although a groundwater altitude difference exists between Eldorado Valley and Black Canyon, an unknown volume of groundwater may move between them. Sedimentary rocks, the Boulder City pluton, and volcanic rocks including the Patsy Mine and Mount Davis volcanic rocks separate Eldorado Valley from Black Canyon. Although these rocks are highly faulted in this area, the orientation of the faults in conjunction with the modern stress field does not support groundwater flow in a west-east direction. If groundwater does move from Eldorado Valley to Black Canyon, the development of groundwater resources in Eldorado Valley could result in a decrease in discharge from springs in Black Canyon.

To the east of Black Canyon, groundwater recharged in the Black Mountains likely flows east to Detrital Valley. The northern core of the Black Mountains is composed of Tertiary intrusive rocks whereas the southern core is composed of Proterozoic crystalline rocks. Given the geology of this area, the possibility of groundwater flow from Detrital Valley to Black Canyon is unlikely. As a result, the development of groundwater resources in Detrital Valley may not result in a decrease in discharge from springs in Black Canyon.

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Appendixes

Appendixes A–D are included as Excel files and can be downloaded from http://dx.doi.org/10.3133/sir20155130.

Appendix A. Analytical Detection and Reporting Limits for Water Samples Collected from Black Canyon, Nevada and Arizona

Appendix B. Replicate Samples Collected and Percent Relative Difference between Samples, Black Canyon, Nevada and Arizona

Appendix C. Daily Average Discharge Computed for Each Site where Stage was Monitored Continuously, Black Canyon, Nevada and Arizona

Appendix D. Sampling Site Information, Physical Hydrologic Measurements, and Hydrochemical Results for all Sites Sampled in Black Canyon and Surrounding Area, Nevada and Arizona

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