

Prepared in cooperation with the Bureau of Land Management

# Baseline Groundwater Hydrology and Water Quality In and Around Bluff, Utah



Open-File Report 2019–1076

**Cover photo:** View showing groundwater-fed hanging gardens east of Bluff, Utah. Bluff Sandstone overlies thin-bedded Summerville Formation. Photograph taken by Nora Nelson, U.S. Geological Survey, October 25, 2017.

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By Olivia L. Miller

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

**U.S. Department of the Interior**  
DAVID BERNHARDT, Secretary

**U.S. Geological Survey**  
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## Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Flow rate		
foot per day (ft/d)	0.3048	meter per day (m/d)

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

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8.$$

## Datums

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

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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 ( $\mu\text{S}/\text{cm}$  at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter ( $\mu\text{g}/\text{L}$ ).

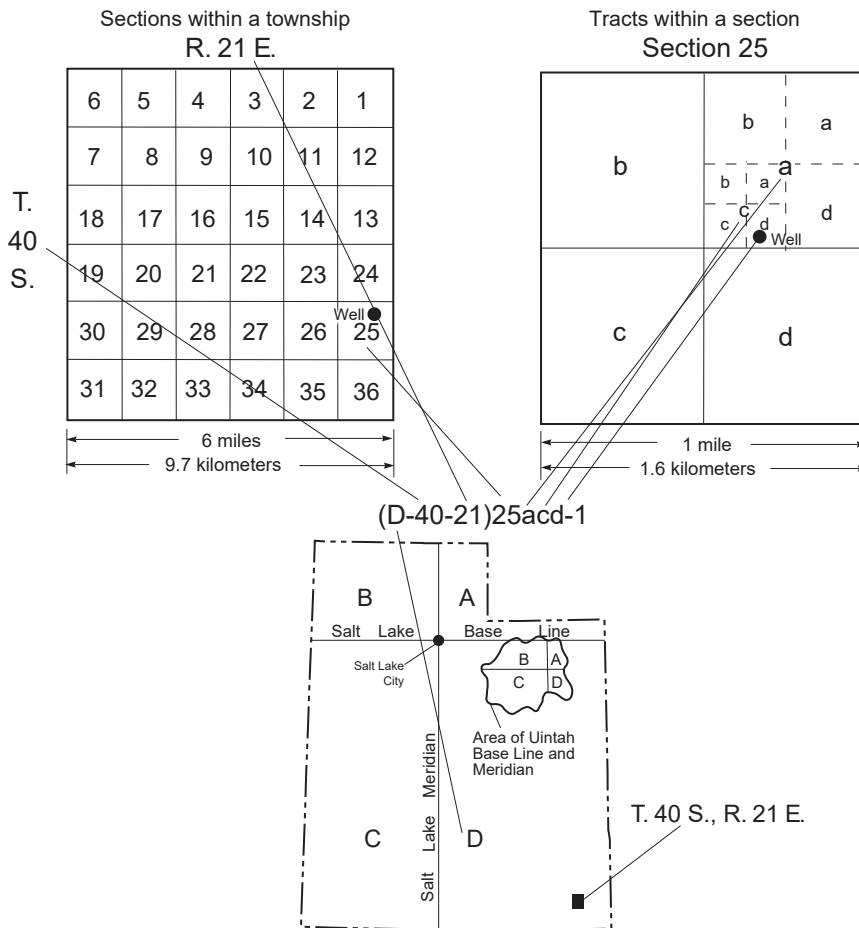
Radiochemical concentrations are given in units of picocurie per liter (pCi/L).

## Abbreviations

$^{14}\text{C}$	carbon-14
$\text{CO}_2$	carbon dioxide
$\delta^{13}\text{C}$	delta carbon-13
$\delta^{18}\text{O}$	delta oxygen-18
$\delta^2\text{H}$	delta deuterium
MCL	maximum contaminant level
NWIS	National Water Information System
pMC	percent modern carbon
SDWIS	Safe Drinking Water Information System
SMCL	secondary maximum contaminant level
USGS	U.S. Geological Survey

## Well-Numbering System

The system of numbering wells, springs, and other hydrologic-data sites in Utah is based on the cadastral land-survey system of the U.S. Government. The number, in addition to designating the site, describes its position in the land net. The land-survey system divides the State into four quadrants by the Salt Lake Meridian and Base Line. These quadrants are designated by the uppercase letters A, B, C, and D, indicating respectively, the northeast, northwest, southwest, and southeast quadrants. Numbers designating the township and range, in that order, follow the quadrant letter, and the three are enclosed in parentheses. The number after the parentheses indicates the section and is followed by three lowercase letters indicating the quarter section, the quarter-quarter section, and the quarter-quarter-quarter section, generally 10 acres for regular sections. The lowercase letters a, b, c, and d indicate, respectively, the northeast, northwest, southwest, and southeast quarters of each subdivision. The number after the letters is the serial number of the site within the 10-acre tract. The letter S preceding the serial number denotes a spring. Thus, (D-40-21)25acd-1 designates the first well constructed or cataloged in the southeast quarter of the southwest quarter of the northeast quarter of section 25, T. 40 S., R. 21 E.







# Baseline Groundwater Hydrology and Water Quality In and Around Bluff, Utah

By Olivia L. Miller

## Abstract

Southeastern Utah has a long history of oil and gas production. Two new hydrocarbon extraction wells have been proposed several miles northeast of the town of Bluff, Utah. In response to concern about the impacts of oil and gas extraction in the area on drinking-water quality, this study provides groundwater quality and hydrologic baseline data obtained before drilling the new hydrocarbon extraction wells. Data from future monitoring can be compared to these baseline water-quality data to identify changes in water quality. The quality of drinking water in Bluff is generally good, making changes in water quality more easily identifiable. Potential degradation of water quality from the proposed production wells could take hundreds to thousands of years to reach public-supply wells. Because of the limited water supply in this area, high-quality groundwater will continue to be an important resource into the foreseeable future.

## Introduction

The town of Bluff, Utah, primarily obtains its municipal water supply from wells completed in bedrock aquifers, including the Glen Canyon Group. The Glen Canyon Group includes the Entrada, Navajo, and Wingate aquifers. The region has a long history of oil and gas development centered on the Aneth Oil Field to the east of Bluff that began in the mid-1950s. New hydrocarbon production wells have been proposed 5 to 7 miles (mi) northeast of Bluff, east of highway 191 (fig. 1). These wells will be drilled through formations from which the town's municipal water supply is sourced and will be used for the injection of high-pressure fluids to hydraulically fracture deeper formations to enhance recovery. The new wells are expected to be completed at depths of 4,000 to 7,000 feet (ft). Residents of Bluff have expressed concern about future potential impacts on their municipal water supply from the proposed drilling activities and well operations.

Most groundwater degradation from oil and gas operations results from surface spills (Jackson and others, 2013). Surface spills or leaks can happen during storage,

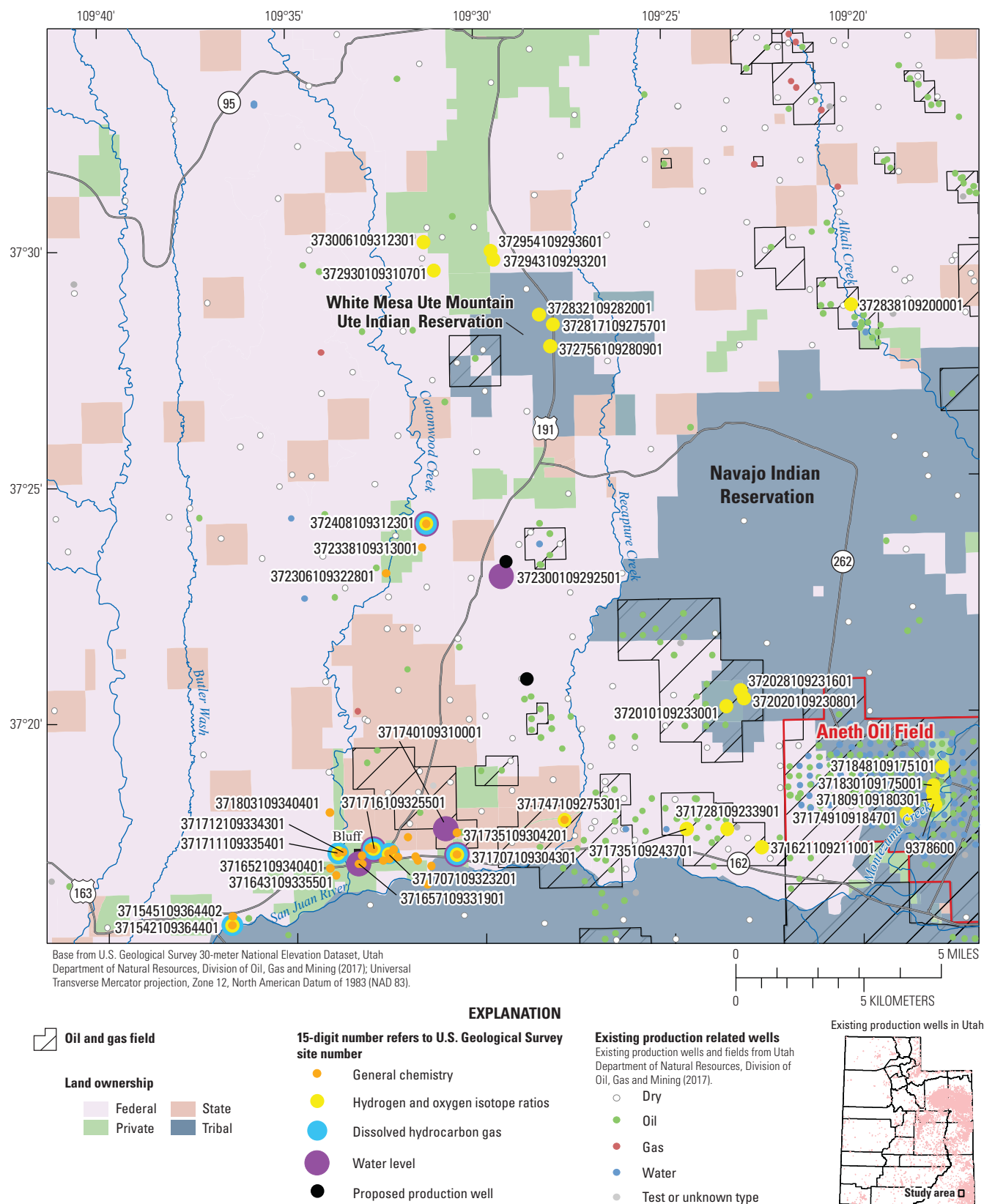
transportation, and handling of hydraulic fracturing fluids, produced water, oil-field brines, or extracted hydrocarbons. Another potential pathway for groundwater degradation related to hydrocarbon extraction is migration of fluids vertically along improperly constructed wells, compromised well casings, or geologic faults and fractures (natural or induced). The most common cause of stray gas migration is poor well construction (Gorody, 2012; Jackson and others, 2013). Contaminants can include hydraulic fracturing fluids, produced wastewater, and oil and gas.

Hydraulic fracturing fluids, which consist of water mixed with proppants and chemicals (for example, acids, viscosity adjusters, stabilizers, biocides, and surfactants), are injected into hydrocarbon reservoirs at high pressure to induce fracture formation to improve hydrocarbon recovery (Jackson and others, 2013). The composition of hydraulic fracturing fluids can vary; therefore, the fate, transport, and toxicity can vary. Few studies have evaluated the chemistry or assessed the health and environmental impacts of hydraulic fracturing fluids (Werner and others, 2015).

Produced water refers to any water from a hydrocarbon production well, including flowback water, formation brine, and water condensing from the gas phase (Orem and others, 2014). Produced water typically contains high concentrations of dissolved solids, primarily sodium and chloride, but also can include other potentially harmful constituents, such as arsenic. Depending on the constituent and its concentration, leakage of produced waters into aquifers can degrade water quality in the aquifer, resulting in a range of possible impacts from poor taste to human health effects.

Gas in groundwater can consist of free gas in pore space or dissolved gas. Methane is the primary component of natural gas. Although no water-quality standards establish limits for methane in drinking water, the U.S. Department of the Interior, Office of Surface Mining, states that methane concentrations in groundwater over 28 milligrams per liter (mg/L) indicate that potentially explosive or flammable quantities of methane are being released from groundwater and that ventilation is necessary (Elt Schlager and others, 2001). Oxidation of methane in an aquifer is associated with changes in groundwater chemistry, particularly in confined aquifers (Vengosh and others, 2014; Roy and others, 2016).

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**Figure 1.** Study area, existing oil and gas wells, proposed production wells, and water wells with water-level and water-quality data, in and around Bluff, Utah.

The proposed production wells represent one potential source of groundwater degradation in the study area (fig. 1). In this report, the term “production well” is used to refer to oil and gas wells. Production wells can potentially allow formation waters to migrate along poorly sealed casings or through the borehole into adjacent aquifers. Surface activity related to oil and gas production represents another potential source of groundwater degradation. Chemicals and produced water stored and transported on the land surface can leak and potentially infiltrate into aquifers.

## Purpose and Scope

The Bureau of Land Management (BLM) requested that the U.S. Geological Survey (USGS) conduct a reconnaissance assessment of groundwater north of the San Juan River near Bluff, Utah, to provide data and information for the environmental compliance of several production wells proposed northeast of Bluff. The purpose of this report is to present baseline data on groundwater quality, water levels, and directions of groundwater movement for the area north of the San Juan River near Bluff, Utah. These baseline data, obtained before installation of the proposed production wells, can be used to assess potential changes in groundwater quality that could occur as a result of these activities.

The general approach for this assessment was to compile existing water-quality, water-level, and aquifer-property data and obtain several additional groundwater samples and water-level measurements to (1) establish baseline water-quality conditions and characterize potential contamination sources, (2) determine groundwater flow directions, (3) determine groundwater travel times, and (4) provide insights related to future monitoring.

## Study Area

The study area is in southeastern Utah, near the town of Bluff, located along the San Juan River (fig. 1). The lithology of the area mostly consists of relatively flat-lying sedimentary rocks that are composed of interbedded sandstone, siltstone, shale, mudstone, and conglomerate (fig. 2). Volcanic intrusions into these sedimentary rocks form mountainous areas north of the study area, including the Abajo Mountains, west of Monticello. Streams dissect the sedimentary rocks, forming canyons, and flow generally south into the San Juan River.

Water-yielding formations in the region have been grouped into multiple aquifer systems consisting of a sequence of bedrock aquifers and confining units underlying local alluvial aquifers (fig. 2). The principal bedrock aquifers include the Dakota Sandstone (D aquifer), Morrison Formation (including the Bluff Sandstone) (M aquifer), and the Entrada, Navajo, and Wingate Sandstones (N aquifer) (Avery, 1986). Aquifers in the Bluff, Entrada, Navajo, and Wingate Sandstones are typically confined in the study area. The Bluff Sandstone is the primary water-bearing unit of the Morrison Formation. Groundwater in the shallower D, M, and

N aquifers is typically fresh outside of the Aneth Oil Field, whereas water in deeper formations underlying the Cedar Mesa Sandstone (P aquifer) is typically briny (Whitfield and others, 1983; Avery, 1986). The Paradox Formation is the primary hydrocarbon-producing reservoir in the region.

Recharge to the principal aquifers occurs through infiltration of precipitation, seepage from streams, subsurface flow, and interformational leakage. Recharge from infiltration of precipitation occurs where aquifer formations crop out and is enhanced near mountainous areas where higher rates of precipitation occur. Fractures associated with intrusion of volcanic rocks can enhance recharge. Discharge from the principal aquifers is to the San Juan River, larger perennial streams, springs and wells, and as subsurface and interformational flow. Springs and flowing wells completed in these formations indicate that the potentiometric surface is at or above the land surface.

## Determining Baseline Conditions

Collecting baseline groundwater-quality data before installation of the two proposed production wells is part of a strategy to evaluate potential future impacts. Continued monitoring following production-well construction is also necessary to identify changes in water quality over time. Considering the multiple potential sources and pathways that could potentially impact Bluff’s drinking-water supply, a range of chemical constituents were evaluated to enable detection of changes that can happen because of hydrocarbon extraction processes. New and existing water-quality data from in and around Bluff, Utah, were compiled for this study to establish baseline water-quality conditions for constituents that have been used to evaluate water-quality degradation from hydrocarbon extraction activities. These baseline data provide a reference to which future water-quality data can be compared to determine if water quality has changed over time.

Produced water and oil-field brines can potentially be identified by dissolved-solids concentrations, bromide and chloride concentrations, and stable hydrogen (deuterium) and oxygen-18 isotope ratios (Breen and others, 1985; Osborn and McIntosh, 2010; Warner and others, 2012). Produced water can contain high concentrations of dissolved solids, and increases in dissolved solids in drinking water can indicate potential mixing with produced water. In the Uinta Basin, Utah, bromide and chloride concentrations in water along with hydrogen and oxygen isotope ratios have been used as signatures of produced water (Steiger, 2007). Bromide, chloride, and hydrogen and oxygen isotope ratios also have been used to distinguish water from the Navajo aquifer and formation brines in and near the Aneth Oil Field (Naftz and Spangler, 1994). Spangler and others (1996) used bromide-to-chloride ratios to show that the high salinity in the Navajo aquifer had geochemical signatures consistent with upward movement of saline water from the Upper Paleozoic aquifer or from local dissolution of evaporites in the Navajo aquifer, as opposed to mixing with oil-field brines.

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Era	System	Formation	Member	General lithology	Approximate maximum thickness (feet)	Aquifer
Cenozoic	Quaternary	Alluvium		Si, Sa, G	0–100	Alluvial aquifer
	Tertiary	Igneous intrusions		P		
Mesozoic	Cretaceous	Mancos Shale		Sh, M, Si		Confining
		Dakota Sandstone		Sa, Co	150	D a aquifer
		Burro Canyon Formation		Sa, Co, Sh	160	
	Jurassic	Morrison Formation	Brushy Basin	M, Si	700	Confining
			Westwater Canyon	f-c Sa	180	M a aquifer
			Recapture	f-m Sa	200	
			Salt Wash	f-m Sa, Si, L	400	
			Bluff Sandstone	f-m Sa	300	
			Summerville Formation	Sh, M, Si	200	Confining
		Entrada Sandstone		Sa	550	N a aquifer
		Carmel Formation		Sh, Si, Sa	100	
		Navajo Sandstone		f-m Sa	600	
		Kayenta Formation		Sa, Si	Average 150	
		Wingate Sandstone		Sa	650	Confining
		Chinle Formation		Si, Sa, Sh, M, Co	1,400	
	Triassic	Moenkopi Formation		Si, Sa	350	
Paleozoic	Permian	Cutler Formation	White Rim Sandstone	m-c Sa		
			De Chelly Sandstone	f Sa	400	C a aquifer
			Organ Rock Tongue	Si, Sa	650	
			Cedar Mesa Sandstone	f-c Sa, E, Si, Sh	1,200	P a aquifer
			Halgaito Tongue	Sh, Si, vf Sa	480	Brine
	Pennsylvanian	Rico Formation		L, f-m Sa, Si	300	
		Hermosa Formation	Honaker Trail	L, Sa, Si, Co	1,800	
			Paradox main oil-bearing unit	Si, Sh, Sa, L, E	11,000	
			Pinkerton Trail	L, Sh	300	

Adapted from Avery (1986), and Huffman, Jr., and Condon (1993).

#### EXPLANATION

<span style="background-color: #add8e6; border: 1px solid black; display: inline-block; width: 20px; height: 10px;"></span>	Principal bedrock aquifer
<span style="background-color: #f0f0f0; border: 1px solid black; display: inline-block; width: 20px; height: 10px;"></span>	Brine

#### General lithology grain size (lower case)

vf = very fine  
f = fine  
m = medium  
c = coarse

#### General lithology rock type (upper case)

Si = siltstone M = mudstone  
Sa = sandstone Co = conglomerate  
G = gravel L = limestone  
Sh = shale E = evaporite  
P = porphyritic

**Figure 2.** Generalized stratigraphy and aquifer systems in the study area in and around Bluff, Utah.

Methane, carbon and hydrogen isotopes, and other organic compounds such as ethane and propane also have been used to characterize produced waters, distinguish between gas sources in shallow aquifers, and determine formation processes (Osborn and McIntosh, 2010; Orem and others, 2014; Humez and others, 2016). Isotope ratios can be reported as delta ( $\delta$ ) values, which are parts per thousand or permil (‰) difference(s) from a standard. Isotope ratios of carbon-13 and hydrogen in methane can be used to distinguish between

biogenic gases produced in situ and thermogenic gases produced at higher pressures and temperatures. Biogenic methane  $\delta^{13}\text{C}$  values range from –50 to –110 permil, whereas thermogenic methane  $\delta^{13}\text{C}$  values typically range from –25 to –55 permil (Jackson and others, 2013). The gas composition of different sources varies as well. Biogenic natural gas mainly contains methane whereas thermogenic gas often contains ethane and propane, in addition to methane (Jackson and others, 2013).



## Methods

Before this study, a limited number of water samples collected from the study area had been analyzed for tracers typically used to identify water-quality degradation from hydrocarbon production. For this study, samples were collected from five wells and one site on the San Juan River in December 2017 and analyzed for general chemistry (including bromide and chloride concentrations), stable oxygen-18 and hydrogen (deuterium) isotope ratios, and methane (and carbon-13 and hydrogen isotope ratios of methane), propane, and ethane concentrations.

Understanding the direction of groundwater flow can be used to help determine contaminant movement through an aquifer. Vertical hydraulic gradients also can be used to evaluate susceptibility of an aquifer to degradation. Avery (1986) developed an initial potentiometric surface map of several bedrock aquifers in San Juan County in 1986. Groundwater conditions and flow systems, however, can change substantially over 30 years as the regional population and associated groundwater development increases. Although the area around Bluff has less groundwater development than other parts of Utah, with withdrawals less than 20,000 acre-feet per year (Burden and others, 2016), a reassessment of the potentiometric surface is still useful in conjunction with the baseline water-quality assessment. In addition, many wells in the study area only have one or two water-level measurements. Water-level measurements made since 2012, and for this study, were compiled to develop a new potentiometric surface map showing general directions of groundwater movement.

## Establishing Baseline Water-Quality Conditions

To establish baseline water-quality conditions in the study area, new and existing water-quality data were compiled and analyzed. Existing water-quality data were compiled from the USGS National Water Information System (NWIS) database and the Utah Safe Drinking Water Information System (SDWIS) database to describe groundwater quality in the Bluff area. Some sites contain data in both databases. These datasets contain records of groundwater-quality analyses of samples collected in and around Bluff from 1933 to 2017. Data from seven samples of oil-field brine (produced water) collected from water storage tanks at injection facilities and that represent composite samples of mixed waters from numerous production wells, were compiled from Spangler and others (1996). Mean annual oxygen and hydrogen isotope ratios of precipitation in Bluff and in Cortez and Silverton, Colorado, were calculated at WaterIsotopes.org (Waterisotopes Database, accessed April 16, 2018, at [http://wateriso.utah.edu/waterisotopes/pages/information/oipc\\_info.html](http://wateriso.utah.edu/waterisotopes/pages/information/oipc_info.html)). WaterIsotopes.org calculates the long-term average monthly and annual isotopic composition of precipitation based on global precipitation oxygen and hydrogen isotope data (Bowen and Wilkinson, 2002; Bowen and Revenaugh, 2003;

Bowen and others, 2005). These locations were selected because precipitation at these locations likely contributes to runoff that flows into the San Juan River. The isotope ratio data for these locations are general estimates and are meant to provide context for the isotope ratios of samples in the study area. Oxygen and hydrogen isotope ratios for wells were obtained over a larger area than the general chemistry samples because there were only a few isotope values from sites where general chemistry samples were obtained. The oxygen and hydrogen isotope ratios from a broader area highlight larger-scale hydrologic processes, whereas the general chemistry data from a more localized area around Bluff represent the water-quality characteristics of Bluff's drinking-water supply.

Water-quality data for wells outside the town limits of Bluff were limited, and some key water-quality parameters useful for identifying and determining sources of constituents associated with hydrocarbon production had not been sampled for. Additional water samples, therefore, were collected from five wells completed in aquifers used for drinking water and one site on the San Juan River. Samples were analyzed for major ions, selected trace elements, nutrients, stable oxygen-18 and hydrogen (deuterium) isotope ratios, and dissolved gases including ethane, propane, and methane concentrations (and carbon-13 and hydrogen isotope ratios of methane) to establish baseline data for future water-quality monitoring. Major ions and trace elements were also selected to complement continuous USGS water-quality sampling at the San Juan River at Bluff (USGS site number 09379500) streamgaging station. Sample isotope values are reported using  $\delta$  notation expressed as

$$\delta R = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1,000 \quad (1)$$

where

$\delta R$	is the value for a specific isotope in the sample,
$R_{\text{sample}}$	is the ratio of the less abundant isotope to the common isotope for a specific element in the sample, and
$R_{\text{standard}}$	is the ratio of the less abundant isotope to the common isotope for the same element in the reference standard.

Results are reported in permil (‰), which is equivalent to parts per thousand. Oxygen and hydrogen isotopic results are reported in permil relative to VSMOW (Vienna Standard Mean Ocean Water; Coplen, 1994).

Sampling was done December 4 to 7, 2017, and followed procedures described in the National Field Manual (U.S. Geological Survey, variously dated). Dissolved hydrocarbon gas samples were collected in IsoFlasks, following the procedures described by Isotech, and analyzed at the Isotech laboratory in Champagne, Illinois. Wells with prior water-quality or water-level data and wells that

contribute substantially to the public water supply were sampled. One well north of the proposed production wells (USGS site number 372408109312301) was sampled because it is unlikely to experience effects from the installation of the proposed production wells and could serve as a comparison to differentiate natural changes in the hydrologic system. This well is upgradient from the proposed production wells making it difficult for groundwater and potential contaminants to move toward this well. General chemistry, dissolved hydrocarbon gas, hydrogen and oxygen isotope, and water-level data for this site are summarized in [table 1](#). Holding times for nitrate-nitrite samples collected from the well exceeded the 30-day limit by 3 to 5 days. Results of the analyses are presented, however, because they are generally within the range of existing nitrate-nitrite concentrations in the study area.

Chemical signatures of water can be used to determine whether produced waters or other fluids have mixed with freshwater, such as that withdrawn for public supply in Bluff. Most of the oil and gas production is within the Paradox Member of the Hermosa Formation ([fig. 2](#)). A limited amount of data on the chemistry of water from these formations were compiled from Spangler and others (1996). Permission to collect new samples of produced water was not granted; therefore, no new samples were obtained.

## Determining Groundwater Flow Direction, Travel Times, and Age

Understanding the direction of groundwater flow can be used to determine where potential contaminants might move and to clarify the connection between the principal aquifers and the San Juan River. Water-level data from 2012 to 2017 for six wells in the study area were used to develop a potentiometric surface map for the study area to determine the direction of groundwater flow. Water levels at five of the six wells were from 2017. However, the water level at one well was from 2012. Water levels measured on different dates were used because relatively few measurements exist, and the spatial extent of the wells is limited. The potentiometric surface developed here could be different than a potentiometric surface developed from water levels measured on the same date. The altitude of the water table at each well was determined by subtracting the depth to water in each well from the land-surface altitude at that well, which was then used to develop a potentiometric surface map using kriging in ArcMap (Esri, version 10.5, <https://www.esri.com/en-us/home>). ArcMap is a program to represent and analyze geospatial information. Kriging was selected because it produced the most hydrologically realistic potentiometric surface. Other attempted methods (for example, inverse distance weighted and natural neighbor techniques) produced potentiometric surfaces with unusual distributions of the water-level altitude data points. The surface created with kriging was then contoured, and the contour lines were manually smoothed to reduce edge effects caused by the limited spatial extent of the wells.

Groundwater travel times can be used to estimate how quickly contaminants potentially could move through an aquifer toward drinking-water wells. Published Glen Canyon Group aquifer properties, along with the potentiometric surface map, were used to estimate groundwater travel times. Hydraulic conductivity, a measure of a materials ability to transmit water, has been estimated from aquifer tests to be between 0.02 and 0.34 feet per day (ft/d) in the N aquifer (Avery, 1986).

Travel time was calculated as

$$T = \frac{d}{\left(\frac{K}{\Phi_e}\right)\left(\frac{\Delta h}{\Delta l}\right)} \quad (2)$$

where

$T$	is travel time, in days,
$d$	is the length of a flow-line segment, in feet,
$K$	is hydraulic conductivity, in feet per day,
$\Phi_e$	is the effective porosity, unitless, and
$\Delta h/\Delta l$	is the hydraulic gradient, in foot per foot.

For estimates of travel time in this report, the maximum hydraulic conductivity of 0.34 ft/d was used. Effective porosity was estimated to be between 0.1 and 0.3, on the basis of reported Navajo Sandstone effective porosities from the Virgin River basin in southwestern Utah (Cordova, 1978; Heilweil and Solomon, 2004; Marston and Heilweil, 2012). The hydraulic gradient was determined by taking the average slope of the potentiometric surface. The flow-line segment length was measured from the potentiometric surface map.

Radiocarbon ages of groundwater in Bluff were calculated from alkalinity, pH, water temperature, and carbon isotope data of dissolved inorganic carbon species using the Tamers (1975) and Fontes and Garnier (1979) inorganic adjustment models. Radiocarbon ages are calculated from the known decay (half-life) of carbon-14 ( $^{14}\text{C}$ ) and adjusted because of changes in  $^{14}\text{C}$  activity from reactions with carbon dioxide ( $\text{CO}_2$ ) and carbonate minerals in the unsaturated and saturated zones in the subsurface. The radiocarbon-age adjustment models require values of  $^{14}\text{C}$  and  $\delta^{13}\text{C}$  of soil gas  $\text{CO}_2$  and carbonate minerals that can react with, or add to, the dissolved inorganic carbon in groundwater. The  $^{14}\text{C}$  activity of soil  $\text{CO}_2$  was assumed to be 100 percent modern carbon (pMC) because of the low  $^{14}\text{C}$  activities of the groundwater samples, which indicate that the samples pre-date the atomic bomb testing in the 1950s (Fontes and Garnier, 1979). The  $^{14}\text{C}$  activity of carbonate minerals was assumed to be 0 pMC (Plummer and Sprinkle, 2001). The  $\delta^{13}\text{C}$  of marine carbonate minerals is typically between 0 plus or minus 2 permil (Clark and Fritz, 1997; Gardner and Heilweil, 2014). Cerling and others (1991) reported the soil gas  $\delta^{13}\text{C}$  of  $\text{CO}_2$  to be  $-23.3$  permil in the Wasatch Mountains of Utah. The apparent  $^{14}\text{C}$  ages were compared to estimated travel times.



**Table 1.** Locations of groundwater and surface-water sites in and around Bluff, Utah, and date range for which general chemistry, dissolved hydrocarbon gas, hydrogen and oxygen isotope ratio, and water-level data were compiled or collected.

[Latitude and longitude geographic coordinates in decimal degrees. **Abbreviations:** mm/dd/yyyy, month/day/year; NWIS, National Water Information System; SDWIS, Safe Drinking Water Information System; USGS, U.S. Geological Survey; WM, White Mesa; NA, not applicable; —, no data]

Database	Station number	Site name	Latitude	Longitude	Date of first sample (mm/dd/yyyy)	Date of last sample (mm/dd/yyyy)	Site type	Well depth (feet)	Number of samples
General chemistry									
NWIS	371542109364401	San Juan River at Sand Island	37.261556	−109.612222	12/04/17	12/04/17	Stream	NA	20
NWIS	371545109364402	(D-40-21)33dbc- 2	37.264583	−109.611917	09/15/11	09/07/17	Groundwater	260	63
NWIS	371630109313001	(D-40-22)30aad- 2	37.275000	−109.525676	05/01/59	05/01/59	Groundwater	27	8
NWIS	371643109335501	(D-40-21)26daa- 2	37.278612	−109.565955	11/19/82	11/19/82	Groundwater	300	11
NWIS	371652109340401	(D-40-21)26ada- 1	37.281112	−109.568455	04/14/82	04/14/82	Groundwater	700	8
NWIS	371653109312301	(D-40-22)29bdb- 1	37.281389	−109.523732	11/21/82	11/21/82	Groundwater	325	11
NWIS	371657109331301	(D-40-21)25adb- 1	37.282501	−109.554288	11/19/82	11/19/82	Groundwater	590	11
NWIS	371657109331901	(D-40-21)25acd- 1	37.282501	−109.555955	07/23/82	08/23/12	Groundwater	450	115
NWIS	371700109314501	(D-40-22)30aad- 1	37.283334	−109.529843	10/24/57	11/21/82	Groundwater	440	44
NWIS	371701109324001	(D-40-21)25aac- 1	37.283612	−109.545121	05/04/82	05/04/82	Groundwater	550	12
NWIS	371703109323001	(D-40-22)30bbd- 1	37.284167	−109.542343	09/10/58	11/21/82	Groundwater	600	20
SDWIS and NWIS	371706109320001	1-96 well	37.284888	−109.530732	12/13/94	12/09/12	Groundwater	—	52
SDWIS and NWIS	371706109321901	2-96 well	37.284852	−109.538627	12/13/94	12/09/12	Groundwater	—	51
NWIS	371707109304301	(D-40-22)29aaa- 1	37.285278	−109.512620	05/21/58	12/05/17	Groundwater	599	46
SDWIS and NWIS	371707109323201	Corral well	37.285988	−109.542556	12/13/94	12/06/17	Groundwater	—	101
NWIS	371708109331301	(D-40-21)25aab- 1	37.285556	−109.554288	11/13/33	11/13/33	Groundwater	300	3
SDWIS and NWIS	371711109335401	1-94 well	37.286389	−109.565000	12/13/94	12/06/17	Groundwater	—	93
NWIS	371712109334301	(D-40-21)25bab- 1	37.286667	−109.562621	11/19/82	11/19/82	Groundwater	300	11
NWIS	371715109322301	(D-40-22)19cdc- 1	37.287500	−109.540399	11/21/82	11/21/82	Groundwater	350	11
NWIS	371716109325501	(D-40-22)30bbb- 1	37.287778	−109.549288	11/13/33	12/05/17	Groundwater	825	436
NWIS	371717109330201	(D-40-21)25aba- 1	37.288056	−109.551232	05/04/82	05/04/82	Groundwater	825	2
NWIS	371730109320001	(D-40-22)19 -S1	37.291667	−109.534010	04/29/59	04/29/59	Spring	NA	2
NWIS	371735109304201	(D-40-22)20ddd-S1	37.293056	−109.512343	04/26/47	05/01/59	Spring	NA	8
NWIS	371747109275301	(D-40-22)23aca- 1	37.296944	−109.464564	08/26/92	08/26/92	Groundwater	—	14
NWIS	371803109340401	(D-40-21)23aad- 1	37.300834	−109.568455	11/19/82	11/19/82	Groundwater	840	11
NWIS	372306109322801	(D-39-22)19bbd- 1	37.385001	−109.541788	04/29/82	04/29/82	Groundwater	1,450	12
NWIS	372338109313001	(D-39-22)17cbd- 1	37.393889	−109.525677	06/13/82	06/13/82	Groundwater	820	12
NWIS	372408109312301	(D-39-22)17bab- 1	37.402223	−109.523733	09/18/82	12/07/17	Groundwater	1,350	32
SDWIS	Arsenic treatment plant	Arsenic treatment plant	37.285972	−109.542741	05/14/15	12/20/17	Groundwater	—	3
SDWIS	Sand Island well	Sand Island well	37.264646	−109.612011	08/27/01	10/02/17	Groundwater	—	41

**Table 1.** Locations of groundwater and surface-water sites in and around Bluff, Utah, and date range for which general chemistry, dissolved hydrocarbon gas, hydrogen and oxygen isotope ratio, and water-level data were compiled or collected.—Continued

[Latitude and longitude geographic coordinates in decimal degrees. **Abbreviations:** mm/dd/yyyy, month/day/year; NWIS, National Water Information System; SDWIS, Safe Drinking Water Information System; USGS, U.S. Geological Survey; WM, White Mesa; NA, not applicable; —, no data]

Database	Station number	Site name	Latitude	Longitude	Date of first sample (mm/dd/yyyy)	Date of last sample (mm/dd/yyyy)	Site type	Well depth (feet)	Number of samples
Dissolved hydrocarbon gases									
NWIS	371542109364401	San Juan River at Sand Island	37.2615556	−109.612222	12/04/17	12/04/17	Stream	NA	1
NWIS	371707109304301	(D-40-22)29aaa- 1	37.2852781	−109.512620	12/05/17	12/05/17	Groundwater	599	2
NWIS	371716109325501	(D-40-22)30bbb- 1	37.2877783	−109.549288	12/05/17	12/05/17	Groundwater	825	1
NWIS	371707109323201	Corral well	37.2859880	−109.542556	12/06/17	12/06/17	Groundwater	—	1
NWIS	371711109335401	1-94 well	37.2863889	−109.565000	12/13/94	12/06/17	Groundwater	—	1
NWIS	372408109312301	(D-39-22)17bab- 1	37.4022228	−109.523733	09/18/82	12/07/17	Groundwater	1,350	1
Hydrogen and oxygen isotope ratios									
NWIS	9378600	Montezuma Creek near Bluff, UT	37.299998	−109.300671	04/20/94	04/20/94	Stream	NA	1
NWIS	371542109364401	San Juan River at Sand Island	37.261556	−109.612222	12/04/17	12/04/17	Stream	NA	1
NWIS	371621109211001	(D-40-23)27baa- 1	37.286110	−109.377895	08/25/92	08/25/92	Groundwater	672	1
NWIS	371707109304301	(D-40-22)29aaa- 1	37.285278	−109.512620	12/05/17	12/05/17	Groundwater	599	1
NWIS	371707109323201	(D-40-22)30bab- 1	37.285889	−109.542556	08/02/17	12/06/17	Groundwater	580	2
NWIS	371711109335401	1-94 well	37.286389	−109.565000	12/06/17	12/06/17	Groundwater	—	1
NWIS	371716109325501	(D-40-22)30bbb- 1	37.287778	−109.549288	12/05/17	12/05/17	Groundwater	825	1
NWIS	371728109233901	(D-40-23)21dbc- 1	37.292777	−109.392895	08/28/92	08/28/92	Groundwater	777	1
NWIS	371735109243701	(D-40-23)20db - 1	37.293055	−109.410951	06/24/92	06/24/92	Groundwater	5,520	1
NWIS	371747109275301	(D-40-22)23aca- 1	37.296944	−109.464564	08/26/92	08/26/92	Groundwater	—	1
NWIS	371749109184701	(D-40-24)19ada- 1	37.296943	−109.313727	10/09/89	10/09/89	Groundwater	—	1
NWIS	371809109180301	(D-40-24)17dcd- 1	37.302498	−109.301504	06/23/92	06/23/92	Groundwater	—	1
NWIS	371818109180401	(D-40-24)17dca- 1	37.304998	−109.301782	06/23/92	06/23/92	Groundwater	—	1
NWIS	371830109175001	(D-40-24)17dbd- 1	37.306943	−109.301504	06/06/84	06/06/84	Groundwater	925	1
NWIS	371848109175101	(D-40-24)17aac- 1	37.313332	−109.297615	08/25/92	08/25/92	Groundwater	—	1
NWIS	372010109233001	(D-40-23) 4dbd- 1	37.336111	−109.392340	04/03/93	04/03/93	Groundwater	—	1
NWIS	372020109230801	(D-40-23) 3bcc- 1	37.338888	−109.384562	06/24/92	06/24/92	Groundwater	—	1
NWIS	372028109231601	(D-40-23) 4ada- 1	37.341666	−109.385951	06/24/92	06/24/92	Groundwater	—	1
NWIS	372408109312301	(D-39-22)17bab- 1	37.402223	−109.523733	12/07/17	12/07/17	Groundwater	1,350	1
NWIS	372756109280901	(D-38-22)23cda- 1 WM South well	37.464194	−109.467750	09/11/07	11/12/08	Groundwater	1,739	4
NWIS	372817109275701	(D-38-22)23acb- 1 WM North well	37.471861	−109.466194	09/11/07	11/11/08	Groundwater	1,385	4
NWIS	372832109282001	(D-38-22)23bba-S1 Right Hand Fork seep	37.475472	−109.472333	03/12/08	03/12/08	Spring	NA	1

**Table 1.** Locations of groundwater and surface-water sites in and around Bluff, Utah, and date range for which general chemistry, dissolved hydrocarbon gas, hydrogen and oxygen isotope ratio, and water-level data were compiled or collected.—Continued

[Latitude and longitude geographic coordinates in decimal degrees. **Abbreviations:** mm/dd/yyyy, month/day/year; NWIS, National Water Information System; SDWIS, Safe Drinking Water Information System; USGS, U.S. Geological Survey; WM, White Mesa; NA, not applicable; —, no data]

Database	Station number	Site name	Latitude	Longitude	Date of first sample (mm/dd/yyyy)	Date of last sample (mm/dd/yyyy)	Site type	Well depth (feet)	Number of samples
Hydrogen and oxygen isotope ratios—Continued									
NWIS	372838109200001	(D-38-23)13ddc- 1	37.477222	−109.334005	04/21/94	04/21/94	Groundwater	3,680	1
NWIS	372930109310701	(D-38-22) 8dcd- 1 WM West monitoring well	37.491583	−109.518583	09/11/07	11/13/08	Groundwater	110	5
NWIS	372943109293201	(D-38-22)10cbc Anasazi Pond near spillway	37.495222	−109.492139	09/18/08	09/18/08	Lake	NA	1
NWIS	372954109293601	(D-38-22)10bcc- 1 WM East monitoring well	37.498222	−109.493417	09/11/07	11/13/08	Groundwater	90	5
NWIS	373006109312301	(D-38-22) 8bad-S1 Ruin Spring	37.501667	−109.523056	09/11/07	11/11/08	Spring	NA	6
Water levels									
USGS	371657109331901	(D-40-21)25acd- 1	37.282501	−109.555955	NA	03/22/2012	Groundwater	450	1
USGS	371707109304301	(D-40-22)29aaa- 1	37.285278	−109.512620	NA	12/05/2017	Groundwater	599	1
USGS	371716109325501	(D-40-22)30bbb- 1	37.287778	−109.549288	NA	03/21/2017	Groundwater	825	1
USGS	371740109310001	(D-40-22)20bdc- 1	37.294445	−109.517343	NA	03/21/2017	Groundwater	240	1
USGS	372300109292501	(D-39-22)22bcd- 1	37.383334	−109.490954	NA	12/07/2017	Groundwater	475	1
USGS	372408109312301	(D-39-22)17bab- 1	37.402223	−109.523733	NA	12/07/2017	Groundwater	1,350	1

## Groundwater Hydrology and Water Quality

The following subsections summarize the results of the data analysis completed for this study to determine baseline water-quality conditions and groundwater flow direction, age, and travel times.

### Physical Properties, Major Ions, Trace Elements, and Nutrients

The groundwater quality in and around Bluff, Utah, is generally good. The physical properties of water samples collected for this study are shown in [table 2](#). Concentrations of major ions, trace elements, and nutrients in samples collected for this study are shown in [table 3](#). To put the water-quality conditions for this study in context, they were compared to (1) existing water-quality data from the NWIS and SDWIS databases for wells no deeper than 2,000 ft, (2) the San Juan River, and (3) springs in the study area ([figs. 3 and 4](#)). The water-quality data also were compared to the U.S. Environmental Protection Agency maximum contaminant levels (MCLs) or secondary maximum contaminant levels (SMCLs) when concentrations approached or exceeded these standards (U.S. Environmental Protection Agency, 2018). Maximum contaminant levels are enforceable standards for contaminants that could affect human health. Secondary maximum contaminant levels are unenforceable guidelines for contaminants that could cause cosmetic or aesthetic effects.

The concentrations of major ions, trace elements, and nutrients, and physical properties of samples collected previously and samples collected during this study were below the MCLs or SMCLs, except for pH and concentrations of arsenic, iron, sulfate, and dissolved solids in a few samples. Physical properties and solute concentrations of samples collected for this study generally fall within the range of existing values and concentrations. The MCL for arsenic is 0.01 milligrams per liter (mg/L; U.S. Environmental Protection Agency, 2018), which is equivalent to 10 micrograms per liter (µg/L). Micrograms per liter are also included in this report because arsenic is commonly reported in µg/L in regulatory documents and in the scientific literature. Arsenic concentrations ranged from 0.00046 to 0.0701 mg/L (0.46 to 70.1 µg/L), with a median concentration of 0.009 mg/L (9.0 µg/L), a mean concentration of 0.01586 mg/L (15.86 µg/L), and a standard deviation of 0.01810 mg/L (18.10 µg/L; number of samples (n) = 66). The SMCL for iron is 0.3 mg/L. Iron concentrations ranged from less than 0.003 to 0.96 mg/L, with a median concentration of 0.01 mg/L, a mean concentration of 0.11 mg/L, and a

standard deviation of 0.28 mg/L (n = 44). The SMCL for sulfate is 250 mg/L. Sulfate concentrations ranged from 26 to 1,170 mg/L, with a median concentration of 48 mg/L, a mean concentration of 62 mg/L, and a standard deviation of 115 mg/L (n = 105). The SMCL for pH is 6.5 to 8.5. The pH ranged from 7.5 to 9.6, with a median of 8.8, a mean of 8.7, and a standard deviation of 0.4 (n = 87). The SMCL for total dissolved solids is 500 mg/L. Dissolved-solids concentrations ranged from 166 to 726 mg/L, with a median concentration of 270 mg/L, a mean concentration of 303 mg/L, and a standard deviation of 107 mg/L (n = 56). In water samples collected from the Paradox Member, dissolved-solids concentrations ranged from 6,730 to 381,436 mg/L, chloride ranged from 3,660 to 238,000 mg/L, and sulfate ranged from 145 to 4,601 mg/L (Whitfield and others, 1983). Summary statistics for an expanded list of analytes with respect to primary and secondary drinking-water standards are shown in [table 4](#). Only one measurement of bromate, a byproduct of drinking-water disinfection, has been made, and it exceeded the MCL of 0.01 mg/L at 0.03 mg/L.

Bromide and chloride concentrations can be useful in identifying sources of groundwater that have potentially mixed with freshwater. Bromide and chloride concentrations in water samples collected from the principal bedrock aquifers, San Juan River, and the adjacent alluvial aquifer were compared to bromide and chloride concentrations in oil-field brines (Spangler and others, 1996; [fig. 5](#)). Bromide concentrations in water samples collected from study sites ranged from 0.01 to 0.056 mg/L, with a median concentration of 0.023 mg/L, a mean concentration of 0.023 mg/L, and standard deviation of 0.01 mg/L (n = 20). Chloride concentrations in water samples collected from study sites ranged from 0.8 to 125 mg/L, with a median concentration of 4.0 mg/L, a mean concentration of 9.4 mg/L, and standard deviation of 14.8 mg/L (n = 86). The bromide and chloride concentrations in the principal bedrock aquifers, San Juan River, and the adjacent alluvial aquifer are distinct from the bromide and chloride concentrations in oil-field brines, which ranged from 200 to 480 mg/L and 44,000 to 110,000 mg/L, respectively (Spangler and others, 1996). This difference can be used to determine if oil-field brines could be a source of these constituents in the Bluff water supply.

Bromide-to-chloride ratios can also be useful in assessing changes to groundwater, such as from mixing. Of the three sites where multiple bromide and chloride values are available, the calculated bromide-to-chloride ratios have remained relatively stable. The maximum change in the bromide-to-chloride ratio occurred at USGS site number 371657109331901. The ratio in water from this well increased from 0.04 to 0.11 between 2005 and 2012 because of an increase in bromide concentration from 0.01 mg/L to 0.021 mg/L and a decrease in chloride concentration from 2.19 mg/L to 1.89 mg/L.

**Table 2.** Physical properties of water samples collected from selected wells in the principal bedrock aquifers and from the San Juan River in and around Bluff, Utah, December 4 to 7, 2017.

[mm/dd/yyyy, month/day/year; —, no data]

Site name	Site number	Date (mm/dd/yyyy)	Alkalinity, field, milligrams per liter as calcium carbonate	Bicarbonate, field, milligrams per liter	Carbonate, field, milligrams per liter	Acid neutralizing capacity, milligrams per liter as calcium carbonate
Corral well	371707109323201	12/06/2017	164	197	1.0	165
Cottonwood Wash well	372408109312301	12/07/2017	190	230	0.7	191
1-94 well	371711109335401	12/06/2017	161	189	3.6	167
San Juan River at Sand Island	371542109364401	12/04/2017	—	—	—	139
St. Christopher well	371707109304301	12/05/2017	138	163	2.4	141
Twin Rocks well	371716109325501	12/05/2017	347	389	16.4	355

Site name	Site number	Date (mm/dd/yyyy)	pH, field, standard units	pH, laboratory, standard units	Specific conductance, field, microsiemens per centimeter at 25 degrees Celsius	Specific conductance, laboratory, microsiemens per centimeter at 25 degrees Celsius
Corral well	371707109323201	12/06/2017	8.0	8.3	364	457
Cottonwood Wash well	372408109312301	12/07/2017	7.8	8.2	388	394
1-94 well	371711109335401	12/06/2017	8.8	8.7	391	396
San Juan River at Sand Island	371542109364401	12/04/2017	8.4	8.2	739	741
St. Christopher well	371707109304301	12/05/2017	8.6	8.6	366	375
Twin Rocks well	371716109325501	12/05/2017	9.0	9.0	778	799

Site name	Site number	Date (mm/dd/yyyy)	Dissolved oxygen, milligrams per liter	Flow rate, gallons per minute	Water temperature, degrees Celsius
Corral well	371707109323201	12/06/2017	4.1	—	14.7
Cottonwood Wash well	372408109312301	12/07/2017	0.5	7.5	16.4
1-94 well	371711109335401	12/06/2017	0.5	—	17.8
San Juan River at Sand Island	371542109364401	12/04/2017	10.2	—	6.3
St. Christopher well	371707109304301	12/05/2017	0.4	—	17.0
Twin Rocks well	371716109325501	12/05/2017	0.5	20	19.3

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**Table 3.** Concentrations of major ions, and selected trace elements and nutrients in water samples collected from selected wells in the principal bedrock aquifers and from the San Juan River in and around Bluff, Utah, December 4 to 7, 2017.

[mm/dd/yyyy, month/day/year; ROE, residue on evaporation at 180 degrees Celsius; <, less than]

Site name	Site number	Date (mm/dd/yyyy)	Bromide, milligrams per liter	Calcium, milligrams per liter	Chloride, milligrams per liter	Dissolved solids, ROE, milligrams per liter	Fluoride, milligrams per liter	Iron, milligrams per liter
Corral well	371707109323201	12/06/2017	0.01	7.2	3.2	284	0.1	0.015
Cottonwood Wash well	372408109312301	12/07/2017	<0.01	30.4	0.8	224	0.2	0.247
1-94 well	371711109335401	12/06/2017	<0.01	3.2	1.1	249	0.1	<0.01
San Juan River at Sand Island	371542109364401	12/04/2017	0.06	81.3	19.5	514	0.3	<0.01
St. Christopher well	371707109304301	12/05/2017	0.01	4.0	1.2	238	0.1	0.013
St. Christopher replicate	371707109304301	12/05/2017	<0.01	4.1	1.2	235	0.1	0.042
Twin Rocks well	371716109325501	12/05/2017	0.03	1.2	15.2	483	0.4	0.011

Site name	Site number	Date (mm/dd/yyyy)	Magnesium, milligrams per liter	Manganese, milligrams per liter	Potassium, milligrams per liter	Silica, milligrams per liter	Sodium, milligrams per liter
Corral well	371707109323201	12/06/2017	0.7	0.0077	1.4	11.5	99.3
Cottonwood Wash well	372408109312301	12/07/2017	19.3	0.0284	2.8	18	29.5
1-94 well	371711109335401	12/06/2017	0.8	0.0143	1.3	11.7	90.2
San Juan River at Sand Island	371542109364401	12/04/2017	19.5	0.0018	2.5	4.77	51.9
St. Christopher well	371707109304301	12/05/2017	0.9	0.0163	1.5	11.9	82.7
St. Christopher replicate	371707109304301	12/05/2017	0.9	0.0157	1.5	11.8	82.3
Twin Rocks well	371716109325501	12/05/2017	0.4	0.0019	1.0	11.1	195

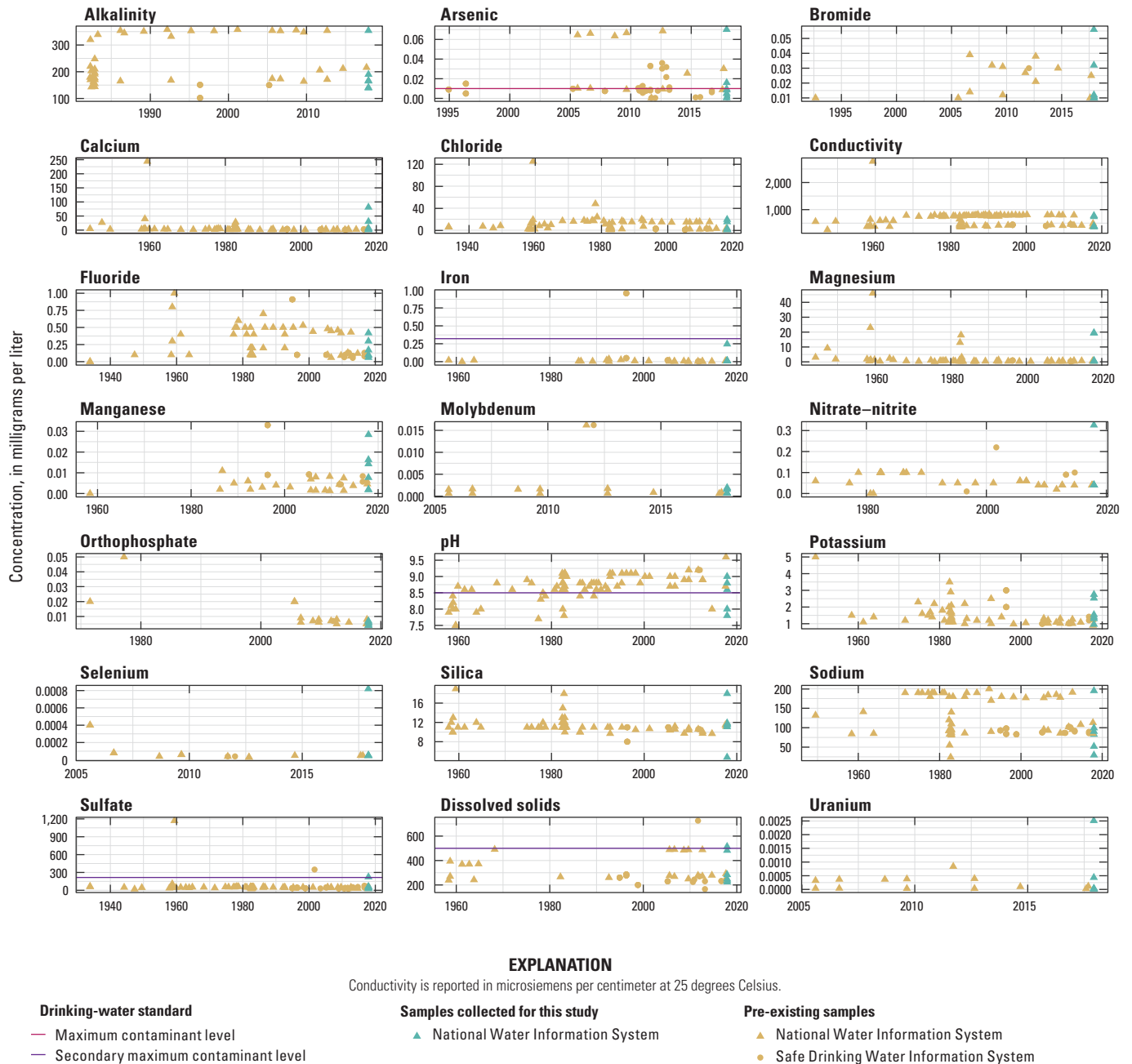
  

Site name	Site number	Date (mm/dd/yyyy)	Strontium, milligrams per liter	Sulfate, milligrams per liter	Nitrate plus nitrite, milligrams per liter as nitrogen	Orthophosphate, milligrams per liter as phosphorus
Corral well	371707109323201	12/06/2017	0.111	63.2	<0.04	<0.004
Cottonwood Wash well	372408109312301	12/07/2017	1.48	26.2	<0.04	0.006
1-94 well	371711109335401	12/06/2017	0.103	38.8	<0.04	0.006
San Juan River at Sand Island	371542109364401	12/04/2017	1.05	224	0.33	<0.004
St. Christopher well	371707109304301	12/05/2017	0.134	49.6	<0.04	0.005
St. Christopher replicate	371707109304301	12/05/2017	0.135	49.8	<0.04	0.005
Twin Rocks well	371716109325501	12/05/2017	0.077	51.7	<0.04	0.007

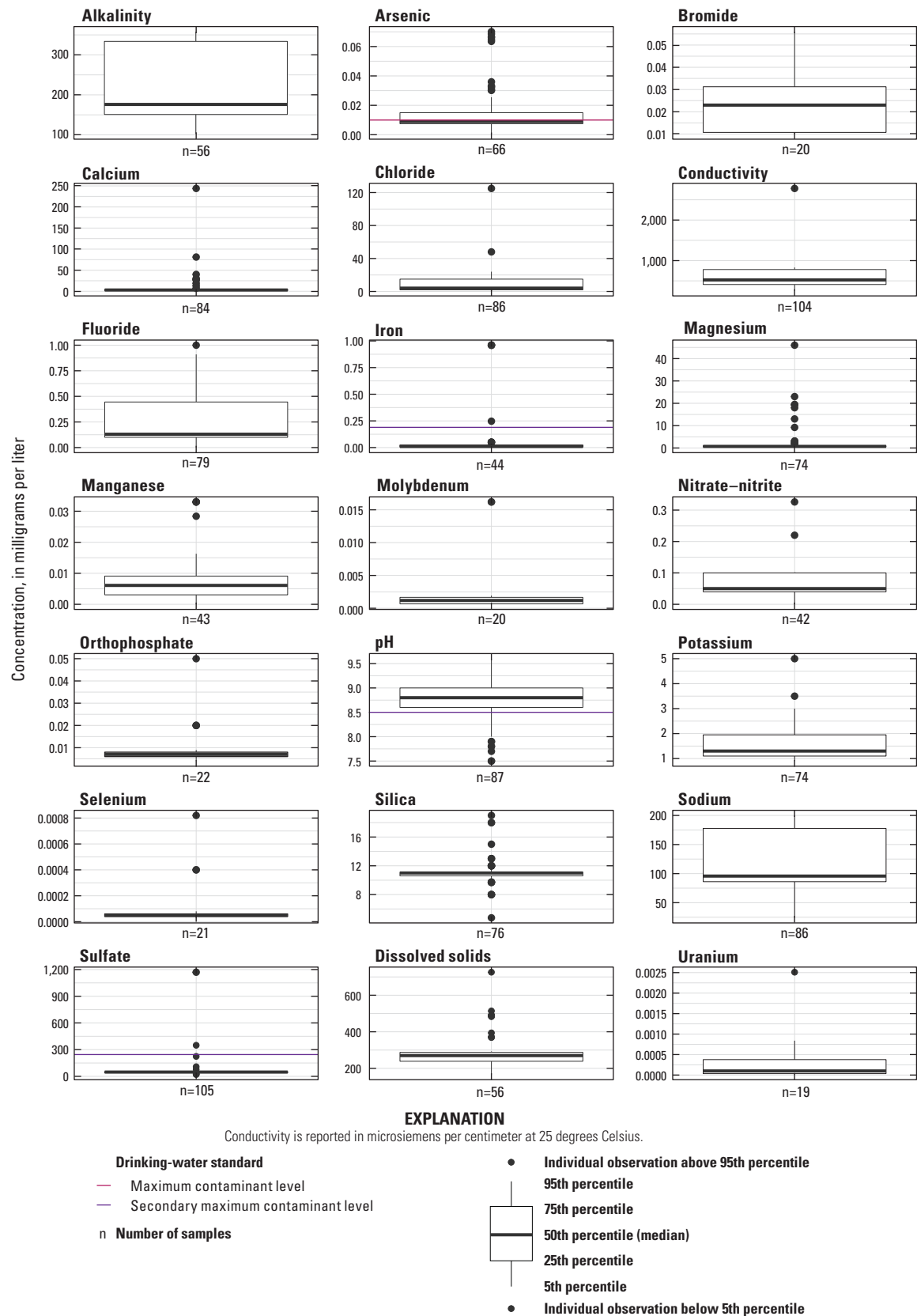
  

Site name	Site number	Date (mm/dd/yyyy)	Arsenic, milligrams per liter	Molybdenum, milligrams per liter	Selenium, milligrams per liter	Uranium, milligrams per liter
Corral well	371707109323201	12/06/2017	0.0050	0.00069	<0.00005	0.00003
Cottonwood Wash well	372408109312301	12/07/2017	0.0160	0.00193	<0.00005	0.00001
1-94 well	371711109335401	12/06/2017	0.0085	0.00070	<0.00005	0.00003
San Juan River at Sand Island	371542109364401	12/04/2017	0.0006	0.00155	0.00082	0.00251
St. Christopher well	371707109304301	12/05/2017	0.0097	0.00068	<0.00005	0.00002
St. Christopher replicate	371707109304301	12/05/2017	0.0090	0.00069	<0.00005	0.00002
Twin Rocks well	371716109325501	12/05/2017	0.0701	0.00168	<0.00005	0.00044





**Figure 3.** Physical properties and concentrations of major ions, and selected trace elements and nutrients in water samples collected in and around Bluff, Utah, for this study compared to pre-existing data.

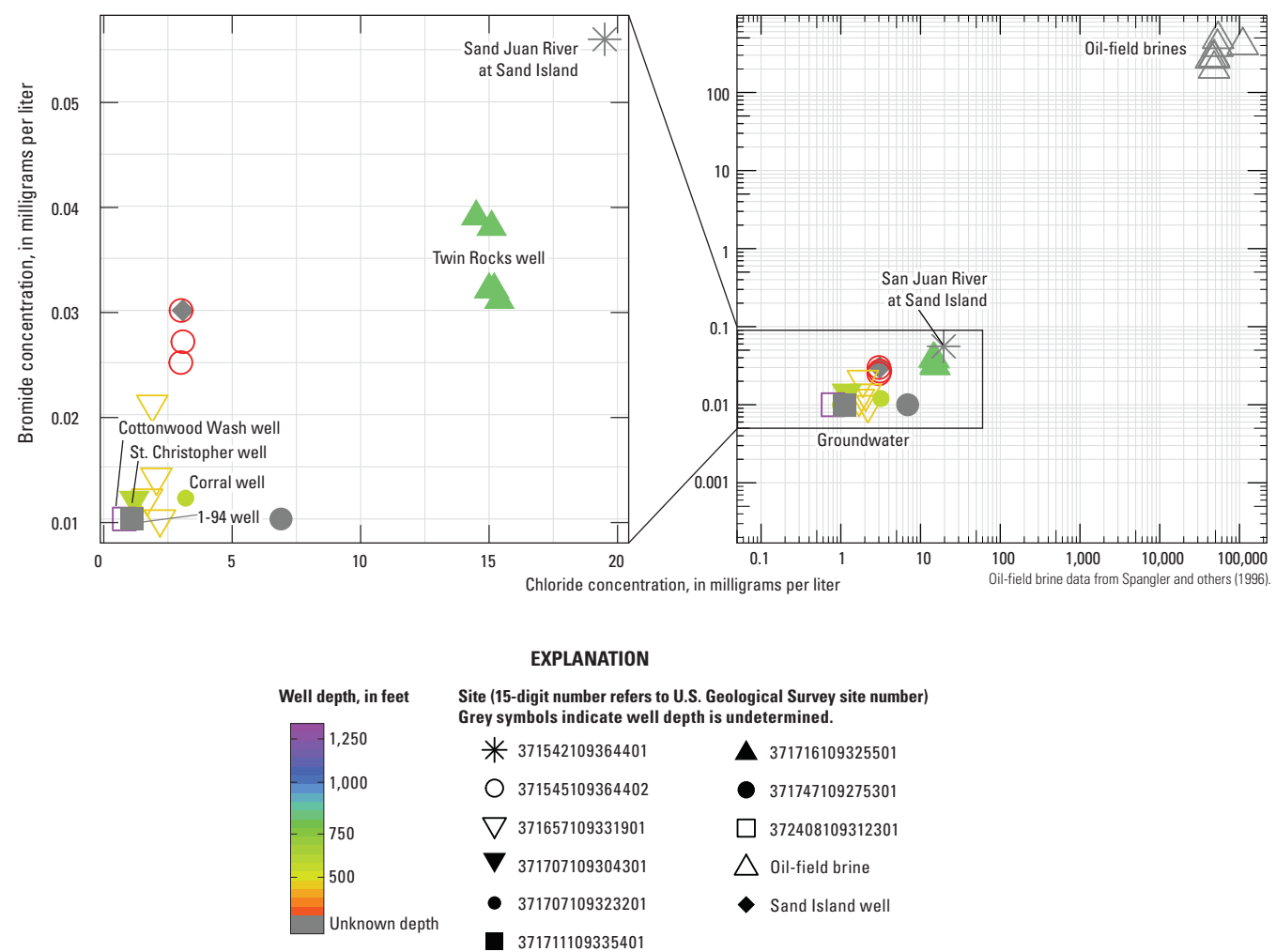


**Figure 4.** Statistical distribution of physical properties, major ions, and selected trace elements and nutrients in filtered and unfiltered water samples collected from wells, springs, and surface-water sites in and around Bluff, Utah.

**Table 4.** Summary statistics for selected chemical constituents for which drinking-water standards have been established from water samples collected in and around Bluff, Utah, compared to drinking-water standards.

[Results are reported in milligrams per liter unless otherwise noted. Maximum contaminant level (MCL) and secondary maximum contaminant level (SMCL) from U.S. Environmental Protection Agency (2018). **Abbreviations:** pCi/L, picocurie per liter; NA, not applicable; <, less than]

Analyte	Minimum concentration, milligrams per liter	Maximum concentration, milligrams per liter	Median concentration, milligrams per liter	Mean concentration, milligrams per liter	Standard deviation, milligrams per liter	Number of samples	Maximum contaminant level, milligrams per liter	Secondary maximum contaminant level, milligrams per liter	Regulatory exceedance type
Antimony	0.00100	0.00370	0.00100	0.00190	0.00156	3	0.006	NA	None
Arsenic	0.0005	0.0701	0.009	0.0160	0.0181	66	0.01	NA	MCL
Barium	0.0040	0.0300	0.0200	0.0183	0.0092	16	2	NA	None
Bromate	0.03	0.03	0.03	0.03	NA	1	0.01	NA	MCL
Cadmium	<0.0006	0.0010	0.0006	0.0006	0.0005	4	0.005	NA	None
Chloride	0.80	125	4.00	9.41	14.84	86	NA	250	None
Chromium	<0.0006	0.0100	0.0032	0.0053	0.0044	5	0.1	NA	None
Copper	0.0009	0.0109	0.0030	0.0039	0.0032	7	1.3	1	None
Cyanide	0.003	0.003	0.003	0.003	NA	1	0.2	NA	None
Dissolved solids	166	726	270	303	107	56	NA	500	SMCL
Fluoride	<0.01	1.00	0.13	0.28	0.25	79	NA	2	None
Foaming agents (surfactants)	0.02	0.02	0.02	0.02	0	3	NA	0.5	None
Iron	<0.01	0.96	0.01	0.11	0.28	44	NA	0.3	SMCL
Lead	0.00011	0.01040	0.00041	0.00234	0.00451	5	0.015	NA	None
Manganese	<0.0004	0.0330	0.0061	0.0089	0.0092	43	NA	0.05	None
Nitrate-Nitrite	<0.04	0.33	0.05	0.07	0.06	42	10	NA	None
p-Dichlorobenzene	<0.0001	0.0047	0.0047	0.0035	0.0023	4	0.075	NA	None
pH (standard units)	7.5	9.6	8.8	8.7	0.4	87	NA	8.5	SMCL
Radium-228 (pCi/L)	0.4	0.9	0.7	0.7	0.3	8	5	NA	None
Selenium	<0.00005	0.00082	0.00005	0.00012	0.00019	21	0.05	NA	None
Sulfate	20.0	1,170	48.0	61.5	115	105	NA	250	SMCL
Thallium	0.00002	0.00100	0.00100	0.00076	0.00040	6	0.002	NA	None
Toluene	<0.0002	0.0011	0.0011	0.0009	0.0005	5	1	NA	None
Uranium	<0.00003	0.00251	0.00010	0.00032	0.00057	19	0.03	NA	None
Zinc	0.006	0.082	0.007	0.027	0.035	11	NA	5	None



**Figure 5.** Bromide and chloride concentrations in water samples collected from the principal bedrock aquifers, San Juan River, and the adjacent alluvial aquifer in and around Bluff, Utah, between 1992 and 2017, compared to bromide and chloride concentrations in oil-field brines from the Aneth Oil Field.

### Dissolved Hydrocarbon Gases

Water samples collected during this study from bedrock and alluvial aquifers, and from the San Juan River had concentrations of dissolved hydrocarbon gases close to or below the analytical detection limit. Dissolved hydrocarbons, produced through fermentation, carbon dioxide reduction metabolic pathways, or thermogenic processes, can be detected in most anoxic aquifers (Gorody, 2012). The mole percentage of dissolved gas and gas concentrations is shown in [table 5](#). Methane was detected in samples collected from all sites. The minimum methane concentration was 0.00042 mg/L (Corral well, USGS site number 371707109323201), and the maximum concentration was 0.0089 mg/L (Twin Rocks well, USGS site number 371716109325501). The methane concentrations in water from the Twin Rocks and 1-94 (USGS site number 371711109335401) wells (about 0.001 mg/L)

were an order of magnitude greater than the concentrations in water from the other wells (about 0.0001 mg/L). After averaging the methane concentrations of the replicate samples collected at the St. Christopher well (USGS site number 371707109304301), the median value for all sites was 0.00074 mg/L. The methane concentrations in these samples were too low for carbon-13 and hydrogen isotope ratio analysis. Concentrations of ethane and propane in all Bluff water samples were below the detection limit of 0.0002 mg/L for both gases.

The San Juan River sample had the highest dissolved oxygen concentration, as expected for a surface-water sample compared to groundwater samples. The pump in the Corral well was running while sampling was taking place, which could explain the elevated dissolved oxygen relative to that in other samples.

**Table 5.** Composition of dissolved gases in water samples collected from selected wells in the principal bedrock aquifers and from the San Juan River in and around Bluff, Utah, December 4 to 7, 2017.

[mm/dd/yyyy, month/day/year; &lt;, less than]

Site name	Site number	Date (mm/dd/yyyy)	Argon	Carbon dioxide	Carbon monoxide	Dinitrogen	Hydrogen	Oxygen	Propene	C6 and higher- molecular-weight hydrocarbons
mole percent of dissolved gases										
Corral well	371707109323201	12/06/2017	1.47	0.49	<0.010	84.51	<0.01	13.53	<0.0001	<0.0001
Cottonwood Wash well	372408109312301	12/07/2017	1.82	1.66	<0.010	92.16	<0.01	4.36	<0.0001	<0.0001
1-94 well	371711109335401	12/06/2017	1.84	0.2	<0.010	94.31	<0.01	3.61	<0.0001	<0.0001
San Juan River at Sand Island	371542109364401	12/04/2017	1.49	0.47	<0.010	65.86	<0.01	32.18	<0.0001	<0.0001
St. Christopher well	371707109304301	12/05/2017	1.81	0.28	<0.010	92.79	<0.01	5.12	<0.0001	<0.0001
St. Christopher replicate	371707109304301	12/05/2017	1.86	0.29	<0.010	92.98	<0.01	4.87	<0.0001	<0.0001
Twin Rocks well	371716109325501	12/05/2017	1.72	0.19	<0.010	91.45	<0.01	6.59	<0.0001	<0.0001

Site name	Site number	Date (mm/dd/yyyy)	n-Butane	Ethane	Ethene	Methane	2-Methylbutane (isopentane)	2-Methylpropane (isobutane)	n-Pentane	Propane
recoverable, mole percent of dissolved gases										
Corral well	371707109323201	12/06/2017	<0.0001	<0.0001	<0.0001	0.0012	<0.0001	<0.0001	<0.0001	<0.0001
Cottonwood Wash well	372408109312301	12/07/2017	<0.0001	<0.0001	<0.0001	0.0027	<0.0001	<0.0001	<0.0001	<0.0001
1-94 well	371711109335401	12/06/2017	<0.0001	<0.0001	<0.0001	0.0417	<0.0001	<0.0001	<0.0001	<0.0001
San Juan River at Sand Island	371542109364401	12/04/2017	<0.0001	<0.0001	<0.0001	0.004	<0.0001	<0.0001	<0.0001	<0.0001
St. Christopher well	371707109304301	12/05/2017	<0.0001	<0.0001	<0.0001	0.0035	<0.0001	<0.0001	<0.0001	<0.0001
St. Christopher replicate	371707109304301	12/05/2017	<0.0001	<0.0001	<0.0001	0.0032	<0.0001	<0.0001	<0.0001	<0.0001
Twin Rocks well	371716109325501	12/05/2017	<0.0001	<0.0001	<0.0001	0.049	<0.0001	<0.0001	<0.0001	<0.0001

Site name	Site number	Date (mm/dd/yyyy)	Ethane	Methane	Propane
recoverable, milligrams per liter					
Corral well	371707109323201	12/06/2017	<0.0002	0.00042	<0.0002
Cottonwood Wash well	372408109312301	12/07/2017	<0.0002	0.00049	<0.0002
1-94 well	371711109335401	12/06/2017	<0.0002	0.0078	<0.0002
San Juan River at Sand Island	371542109364401	12/04/2017	<0.0002	0.00085	<0.0003
St. Christopher well	371707109304301	12/05/2017	<0.0002	0.00067	<0.0002
St. Christopher replicate	371707109304301	12/05/2017	<0.0002	0.0006	<0.0002
Twin Rocks well	371716109325501	12/05/2017	<0.0002	0.0089	<0.0002

## Hydrogen and Oxygen Isotope Ratios

The hydrogen and oxygen isotope ratios of groundwater samples and the sample collected from the San Juan River ranged from  $-118.06$  to  $-89.61$  permil and from  $-16.04$  to  $-12.1$  permil, respectively (table 6). The hydrogen ( $\delta^2\text{H}$ ) and oxygen ( $\delta^{18}\text{O}$ ) isotope values for groundwater and surface-water samples fell within the normal range of meteoric waters (fig. 6); samples generally plot along or slightly above both the Global and Salt Lake Valley meteoric water lines (Craig, 1961; Jameel and others, 2016). The isotope values of groundwater samples were similar and decreased with depth, whereas the San Juan River sample values were higher. The difference between the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of groundwater and surface-water samples reflects different precipitation, recharge conditions, and mixing patterns. The lower isotope values of the deeper groundwater samples were similar to isotope values of snow samples collected in the Abajo Mountains, approximately 40 mi north of Bluff (Spangler and others, 1996), indicating that recharge to the deeper principal bedrock aquifers was in or near the Abajo Mountains or that recharge occurred under cooler or higher-altitude conditions. The higher  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of shallower groundwater samples

indicate warmer or lower-altitude recharge. Downward movement of surface water with higher  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values, which could also cause the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values in shallower aquifers to increase, is not likely because hydraulic gradients and the presence of flowing wells near the San Juan River indicate that groundwater moves upward and discharges around the San Juan River. The  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of the San Juan River reflect either discharge of groundwater that recharged under warmer, lower-altitude conditions and (or) mixing of precipitation and runoff of precipitation occurring in Bluff, Silverton, and Cortez.

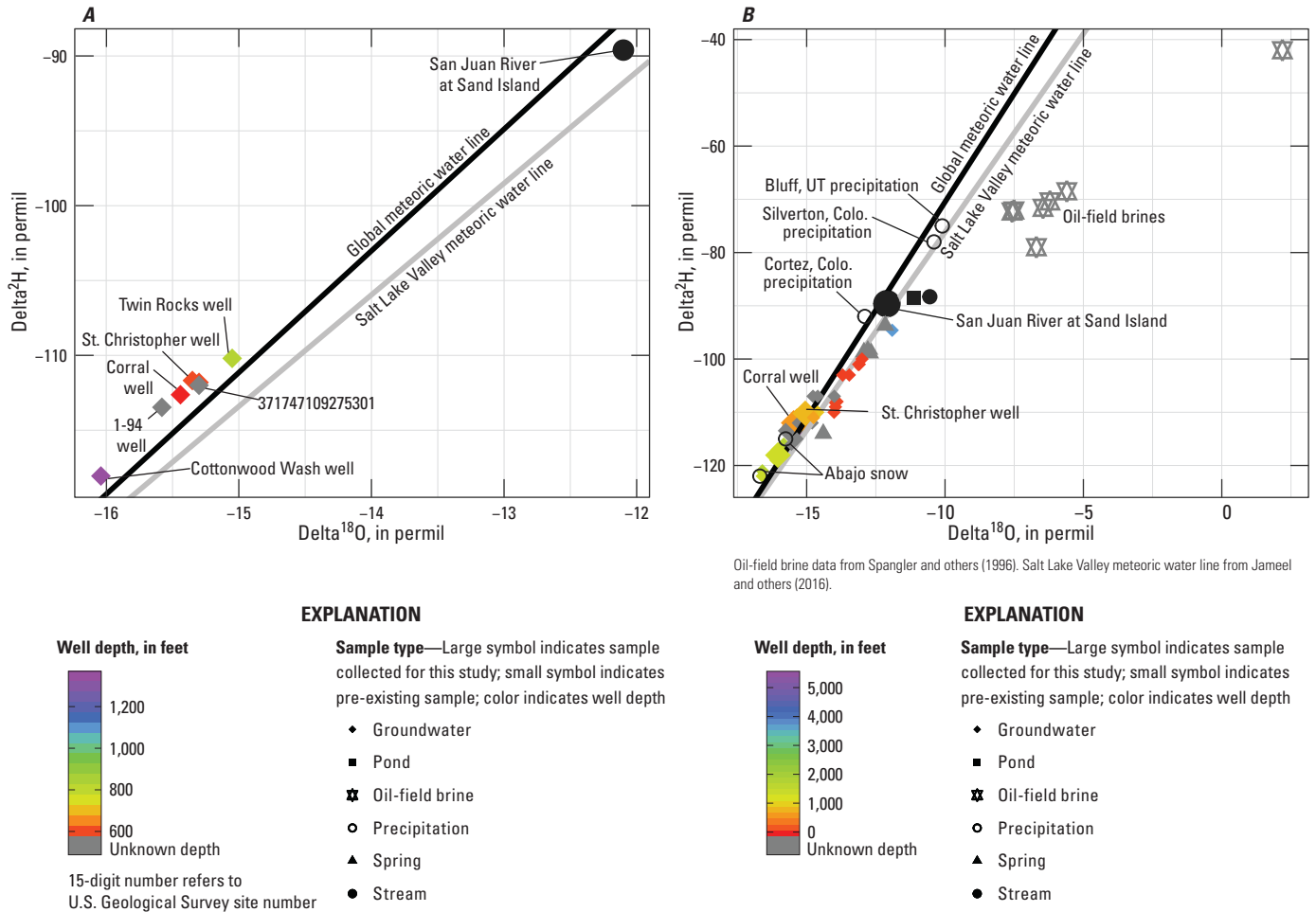
The isotopic composition of oil-field brines is distinct from water in the principal bedrock aquifers, indicating that mixing of the water in these aquifers, which supply drinking water, with oil-field brines potentially can be identified (fig. 6). The hydrogen and oxygen isotope ratios of oil-field brine samples ranged from  $-79.0$  to  $-42.0$  permil and from  $-7.58$  to  $2.19$  permil, respectively (Spangler and others, 1996). Changes in the isotopic composition of principal bedrock aquifer water along a mixing line with brine water could indicate that water in the principal bedrock aquifers has mixed with oil-field brine and that drinking water for public supply might have been affected.

**Table 6.** Hydrogen and oxygen isotope ratios of water samples collected from selected wells in the principal bedrock aquifers and from the San Juan River in and around Bluff, Utah, December 4 to 7, 2017.

[ $\delta^{18}\text{O}$ , ratio of ratio of oxygen-18 to oxygen-16 in sample to ratio of oxygen-18 to oxygen-16 in reference material  $-1 \times 1,000$ ;  $\delta^2\text{H}$ , ratio of ratio of hydrogen-2 to hydrogen-1 in sample to ratio of hydrogen-2 to hydrogen-1 in reference material  $-1 \times 1,000$ ; permil, per thousand. **Abbreviation:** mm/dd/yyyy, month/day/year]

Site name	Site number	Date (mm/dd/yyyy)	$\delta^{18}\text{O}$ , in permil	$\delta^2\text{H}$ , in permil
Corral well	371707109323201	12/06/2017	$-112.63$	$-15.44$
Cottonwood Wash well	372408109312301	12/07/2017	$-118.06$	$-16.04$
1-94 well	371711109335401	12/06/2017	$-113.47$	$-15.58$
San Juan River at Sand Island	371542109364401	12/04/2017	$-89.61$	$-12.1$
St. Christopher well	371707109304301	12/05/2017	$-111.68$	$-15.35$
St. Christopher replicate	371707109304301	12/05/2017	$-111.81$	$-15.3$
Twin Rocks well	371716109325501	12/05/2017	$-110.2$	$-15.05$





**Figure 6.** A, The isotopic composition of groundwater and surface-water samples collected in and around Bluff, Utah, in relation to the global ( $\delta^2\text{H} = 8 \times \delta^{18}\text{O} + 10$ ) and Salt Lake Valley ( $\delta^2\text{H} = 7.45 \times \delta^{18}\text{O} - 1.66$ ) meteoric water lines, and B, the isotopic composition of groundwater, surface-water, and precipitation samples, and oil-field brines in relation to the global and Salt Lake Valley meteoric water lines.

## Groundwater Flow Direction, Travel Times, and Age

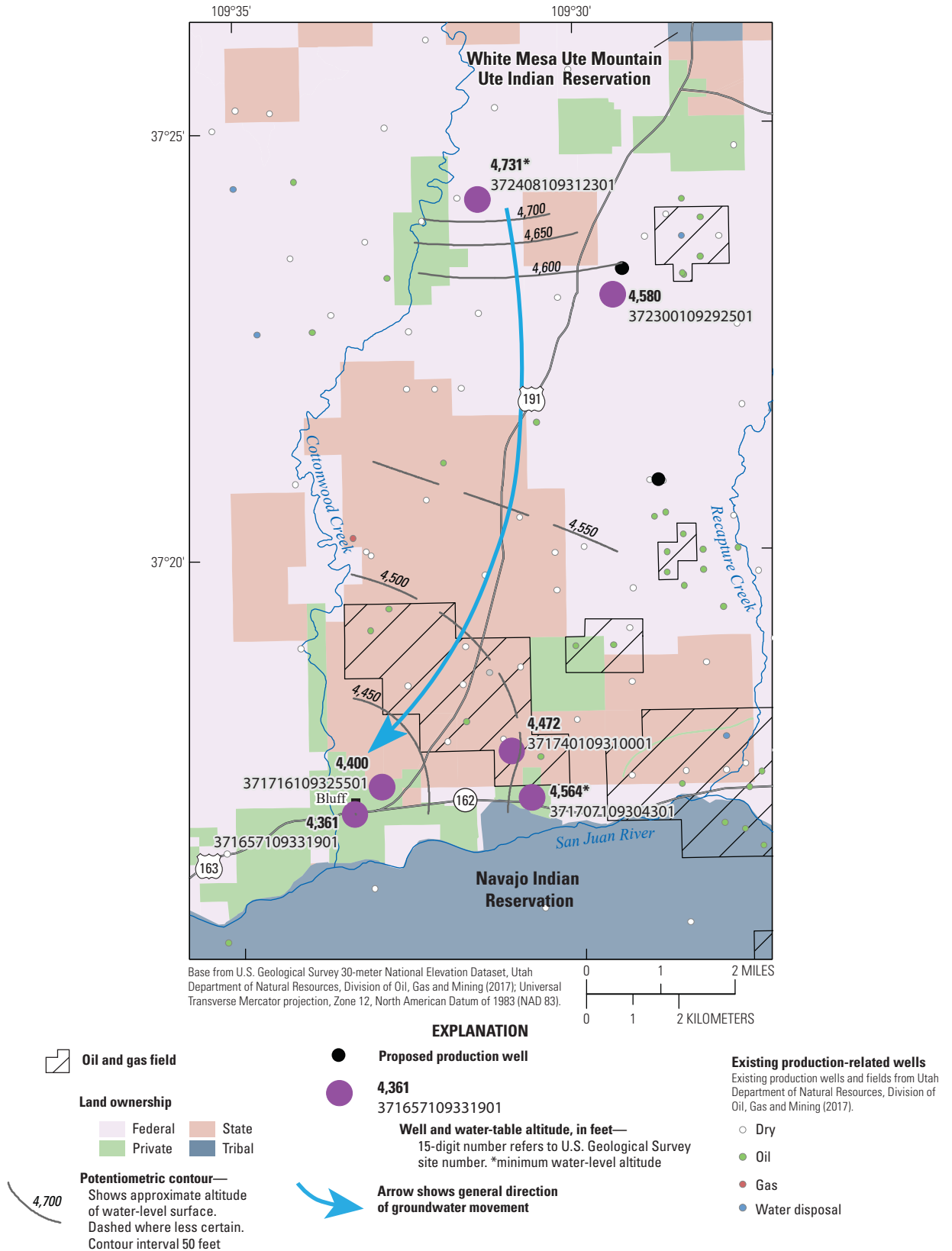
Groundwater in the principal bedrock aquifers generally moves from north to south based on water-level measurements made between 2012 and 2017 in the study area. The proposed production-well boreholes are upgradient from the town of Bluff and the San Juan River (fig. 7). Thus, contaminants originating at either of the proposed production wells have the potential to move toward the San Juan River and Bluff. The overall pattern of the potentiometric surface is similar to the generalized direction of groundwater movement shown in Spangler and others (1996).

The mean hydraulic gradient in the area covered by the potentiometric surface contour lines is 0.006. For effective porosities between 0.1 and 0.3, the average linear velocity is between 7 and 2 feet per year, respectively. The distance along an idealized flow path from the southern proposed production well to the Corral well is approximately 31,400 ft, and the distance from the northern proposed production well is approximately 44,000 ft. Using these distances, effective porosities, and average linear velocities, the estimated groundwater travel times from the southern production well ranged from 4,214 to 12,642 years, and travel times from the northern production well ranged from 5,905 to 17,716 years. This method of calculating travel times is simplistic, and a more precise estimate could be obtained by developing a numerical groundwater flow model. This calculation does not account for any chemical reactions and assumes that the hydraulic-head distribution in the study area remains constant during this time. Chemical reactions, particularly for petroleum-based constituents, tend to consume the compounds and can increase travel times. Changes in pumping at wells could also alter the hydraulic gradient, which would affect travel times. For example, doubling the hydraulic gradient from 0.006 to 0.012 (by pumping enough water in Bluff to reduce the hydraulic head by approximately 190 ft) would reduce travel times by half to between 2,107 and 6,321 years from the southern production well. Groundwater flow along

fractures could also substantially reduce travel times. The distribution of travel times varies based on site-specific aquifer properties, and the travel times estimated using the simple equation applied in this report have substantial uncertainties. This method, however, gives a general first-order estimate and indicates that contaminants originating at the proposed production wells would not immediately affect the water quality of Bluff's drinking-water supply wells.

The  $^{14}\text{C}$  apparent age of water sampled from the Corral well (USGS site number 371707109323201) in 2017 indicates that recharge to the aquifer that provides water to the well could have occurred during the Pleistocene. The  $^{14}\text{C}$  age using the Tamers adjustment model is 37,946 years since recharge. The  $^{14}\text{C}$  age using the Fontes and Garnier adjustment model is 33,231 to 35,957 years, using soil  $\text{CO}_2$   $\delta^{13}\text{C}$  values of  $-2$  or  $2$  permil, respectively. These ages are consistent with recharge occurring near the Abajo Mountains and moving through the subsurface at the estimated average linear velocities and effective porosities calculated previously. These ages indicate that a substantial amount of time would be required for drinking-water quality in Bluff to be affected by contaminants in surface or groundwaters several miles away; however, these ages, and the low rates of precipitation in the area, also highlight the vulnerability of groundwater in the area to depletion if pumping outpaces recharge.

Groundwater can transport contaminants in the direction dictated by the hydraulic gradient. Within 10 to 15 mi of the San Juan River, Spangler and others (1996) identified upward hydraulic gradients, indicating vertical movement of groundwater from the Navajo aquifer to the Morrison aquifer and San Juan River. Downward vertical hydraulic gradients also indicate that movement of water from the Morrison aquifer to the Navajo aquifer is possible. Low-permeability confining layers overlying deeper aquifers and upward hydraulic gradients close to the San Juan River can impede the downward movement of contaminants from the surface. Thus, the potential for water-quality degradation in deeper aquifers from surface spills is greater in areas of downward hydraulic gradients.



**Figure 7.** Potentiometric surface contours from water-level measurements made between 2012 and 2017 at wells in and around Bluff, Utah.

## Conclusions and Future Monitoring

The drinking-water supply from bedrock aquifers for the town of Bluff, Utah, is generally of good quality. Overall, concentrations of most constituents analyzed were low (below EPA drinking-water standards), making them sensitive indicators of changes to the groundwater system, potentially resulting from human activities upgradient from public-supply wells. The concentrations of ethane and propane in water from wells in the principal bedrock aquifers were below the analytical detection limit. Increases in concentrations of ethane or propane, therefore, might prove to be useful indicators of hydrocarbon gases migrating into the principal bedrock aquifers. Further, increases in methane concentrations to the level that isotopic analysis of methane carbon and hydrogen isotope ratios is possible could yield insights into hydrocarbon sources and processes in the aquifers. Changes in concentrations of dissolved solids, bromide and chloride, and oxygen and hydrogen isotope ratios could also prove to be indicators of mixing with produced waters or fluids in this area as has been shown in other areas.

To determine the source of potential contaminants related to hydrocarbon extraction, data on potential sources are required. Some data on oil-field brine chemistry from the Aneth Oil Field (bromide and chloride concentrations, dissolved-solids concentrations, major anions, and stable isotopes) were collected in the early 1990s; however, more recent and comprehensive data (for example, hydrocarbon concentrations or isotopic compositions) and data for other sources (for example, hydraulic fracturing fluids) do not exist or are not publicly available. Nonetheless, baseline water-quality data compiled during this study in conjunction with data collected previously, can now be used as a tool to help determine and evaluate potential changes in, and sources of, water-quality degradation from man-made activities including those that occur in oil-field operations.

Groundwater in the study area generally moves toward Bluff and the San Juan River. Potential contaminants in groundwater near the proposed production wells could take thousands of years to arrive at water-supply wells in Bluff if the hydrologic conditions remain constant, and increased groundwater withdrawals could reduce travel time in the vicinity of the wells. Water-quality degradation from surface activities near Bluff, such as transport or storage of produced waters or hydraulic fracturing fluids, could affect the town's water supply more quickly, particularly in areas where downward vertical hydraulic gradients exist. Numerical modeling would inform contaminant transport scenarios in greater detail.

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