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Quality, Isotopes, and Radiochemistry of Water Sampled from the Upper Moenkopi Village Water-Supply Wells, Coconino County, Arizona

Open-File Report 2013–1162

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

FRONT COVER
Overview of Upper and Lower Moenkopi Villages from the south looking north across Moenkopi Wash. Photograph taken by D.J. Bills, Fall 2008.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to SI

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	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
	Flow rate	
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
gallon per minute (gal/min)	3.785	liter per minute (L/min)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

SI to Inch/Pound

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
	Volume	
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32

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

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

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

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 either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Quality, Isotopes, and Radiochemistry of Water Sampled from the Upper Moenkopi Village Water-Supply Wells, Coconino County, Arizona

By Robert L. Carruth, Kimberly Beisner, and Greg Smith

Abstract

The Hopi Tribe Water Resources Program has granted contracts for studies to evaluate water supply conditions for the Moenkopi villages in Coconino County, Arizona. The Moenkopi villages include Upper Moenkopi Village and the village of Lower Moencopi, both on the Hopi Indian Reservation south of the Navajo community of Tuba City. These investigations have determined that water supplies are limited and vulnerable to several potential sources of contamination, including the Tuba City Landfill and a former uranium processing facility known as the Rare Metals Mill. Studies are ongoing to determine if uranium and other metals in groundwater beneath the landfill are greater than regional groundwater concentrations.

The source of water supply for the Upper Moenkopi Village is three public-supply wells. The wells are referred to as MSW-1, MSW-2, and MSW-3 and all three wells obtain water from the regionally extensive N aquifer. The N aquifer is the principal aquifer in this region of northern Arizona and consists of thick beds of sandstone between less permeable layers of siltstone and mudstone. The relatively fine-grained character of the N aquifer inhibits rapid movement of water and large yields to wells. In recent years, water levels have declined in the three public-supply wells, causing concern that the current water supply will not be able to accommodate peak demand and allow for residential and economic growth.

Analyses of major ions, nutrients, selected trace metals, stable and radioactive isotopes, and radiochemistry were performed on the groundwater samples from the three public-supply wells to describe general water-quality conditions and groundwater ages in and immediately surrounding the Upper Moenkopi Village area. None of the water samples collected from the public-supply wells exceeded the U.S. Environmental Protection Agency primary drinking water standards.

The ratios of the major dissolved ions from the samples collected from MSW-1 and MSW-2 indicate water with a major ion composition of calcium and sulfate. There is no significant vertical distribution of ion concentrations in the samples collected from the upper and lower portion of the water column within the two wells. The samples collected at MSW-3 are higher in sodium and lower in calcium than the samples collected from MSW-1 and MSW-2, and contain a similar sulfate-ion percentage. There is a vertical distribution of ion concentrations in the samples collected from the upper and lower portion of the water column in MSW-3.

Groundwater samples from the three water-supply wells analyzed for oxygen-18 and deuterium stable isotopes plot on a local water line that is approximately parallel to the global meteoric water line. Tritium concentrations in samples from MSW-1 and MSW-3 were equal to or less than laboratory detection limits and were interpreted to contain no modern (post-1952) water. Tritium concentration in a sample from the top of the water column at MSW-2 was 0.41 tritium units, indicating that the composition is primarily pre-bomb (pre-1952) water, but may contain a small fraction of post-bomb modern water.

The calculated carbon-14 ages of groundwater in MSW-1 and MSW-2, both completed about 140 feet into the Navajo Sandstone, are about 3,000 years before present. The calculated carbon-14 age of groundwater in MSW-3, completed about 240 feet into the Kayenta Formation–Navajo Sandstone transition zone is about 5,000 years before present in the upper portion of the water column and about 8,500 years before present in the lower portion of the water column. The gross alpha radioactivity of samples collected from the three water-supply wells ranged from 5.1 to 9.8 picocuries per liter—less than the U.S. Environmental Protection Agency primary drinking water standard of 15 picocuries per liter. The gross beta radioactivity of samples collected from the wells ranged from 0.9 to 2.8 picocuries per liter and are not considered elevated relative to the U.S. Environmental Protection Agency primary drinking water standard.

Introduction

In 2010, the Hopi Tribe and the Indian Health Service (IHS) requested assistance from the U.S. Geological Survey (USGS) in evaluating the source of water to the public water supply and water quality as it relates to the possible migration of contaminated groundwater to supply wells in the

Upper Moenkopi Village area. Previous investigations have determined that local water supplies are limited and vulnerable to potential sources of contamination, including the Tuba City Landfill and a former uranium processing facility known as the Rare Metals Mill. Studies are ongoing to determine if uranium and other metals in groundwater beneath the landfill are greater than regional groundwater concentrations and if a flow path exists between the Tuba City Landfill area and the village water-supply wells.

This report documents the collection and analyses of depth-dependent water samples under pumping conditions from the three public water-supply wells in Upper Moenkopi Village, referred to as MSW-1, MSW-2, and MSW-3 (figs. 1 and 2). Samples from these wells were analyzed for a range of chemical and isotopic constituents including major ions, nutrients, trace elements, stable and radioactive isotopes, and radiochemistry. These data were collected to evaluate the quality of water that makes up the municipal water supply for Upper Moenkopi Village. The analytical results were reviewed to determine if degradation of water quality has occurred. The depth-dependent water-quality samples were analyzed to determine if any vertical distribution of water quality or contaminants exists within the Navajo Sandstone and Kayenta Formation (stratigraphic units of the N aquifer penetrated by the water-supply wells). Additionally, an attempt was made to collect well-bore flow data from the three wells to determine the flow distribution into the wells from the surrounding aquifer; however, limitations caused by the well construction and the relatively low permeability of the surrounding aquifer prohibited collection of well-bore flow data.

Purpose and Scope

The purpose of this report is to assess the source, distribution of flow, and quality of water from each of the three public water-supply wells under pumping conditions. Data collected during this study can be used to (1) assess the quality of the existing municipal water supply, (2) provide a baseline for comparison with future water-quality monitoring, (3) evaluate management options to address possible contaminant sources, and (4) provide information to design and locate future water-supply wells.

Previous Investigations

Previous investigations of the N aquifer have evaluated water availability for local needs. A study by Cooley and others (1969) provided the regional hydrogeologic characterization of the N aquifer in the Moenkopi and Tuba City area. Additional investigations by the USGS have added to this characterization over the years (Levings and Farrar, 1977; Farrar, 1980; Eychaner, 1983; Lopes and Hoffmann, 1997; Hoffmann and others, 2006; Macy, 2010; Macy and others, 2012). Additional studies have characterized the aquifer at the scale of individual test wells (Tetra Tech EM Inc., 2004; Carruth and Bills, 2012). Local geology and geologic structure also has been investigated (Macy, 2012) and is important because it affects the occurrence and movement of groundwater and movement of potential contaminants in the area. Additionally, geologic maps and cross sections, and geochemical analyses of rock, sediment, and groundwater have been done in the vicinity of the Tuba City landfill (Johnson and Wirt, 2009; Otton and others, 2009).

Description of Study Area

Upper Moenkopi Village is on the Hopi Indian Reservation south of the Navajo Nation community of Tuba City and west of Pasture Canyon on the southern side of U.S. Highway 160, approximately 80 mi northeast of Flagstaff, Arizona (figs. 1 and 2). Upper Moenkopi Village is one of 12 villages that make up the communities of the Hopi Nation in northeastern Arizona. Exposed rocks in the study area include the Jurassic Navajo Sandstone, and eolian sand and dunes eroded from the Navajo Sandstone. The surface deposits are covered with sparse desert grasses, cactus, and sagebrush. The regional dip of rock units at the surface is about 2 degrees northeast toward the Tuba City syncline, whose axis is about 5 miles from the study area (Cooley and others, 1969).

Upper Moenkopi Village Water-Supply Wells

Water for the Upper Moenkopi Village is supplied from three wells (MSW-1, MSW-2, and MSW-3) completed in the regionally extensive N aquifer, the principal aquifer in this region of northern Arizona. The N aquifer is a moderately productive groundwater-flow system that underlies most of the Navajo and Hopi Indian Reservations in northern Arizona. The Moenkopi Villages, however, are at the western edge of the N aquifer where rock units of the groundwater-flow system are thinned by exposure and erosion or locally pinch out. The N aquifer is composed of thick beds of sandstone between less permeable layers of siltstone and mudstone. The relatively fine-grained character of the N aquifer inhibits rapid movement of water and large yields to wells. In recent years, water levels have declined in the three public-supply wells, causing concern that the current water supply will not be able to accommodate peak demand and allow for residential and economic growth.

The wells generally are aligned east-west along the southern side of, and approximately parallel to, Highway 160 (fig. 2). MSW-1 (easternmost well) and MSW-2 (westernmost well) are separated by a distance of approximately 500 ft. MSW-3 is between MSW-1 and MSW-2, but closer to MSW-1. MSW-1 and MSW-2 were constructed in 1977 and 1982, respectively. Both wells were originally completed to about 140 ft below land surface. MSW-3 was constructed in 1991 to a depth of 280 ft below land surface. Construction details for the wells (including the screened intervals and depths to the pumps) were provided by the Hope Tribe Water Resources

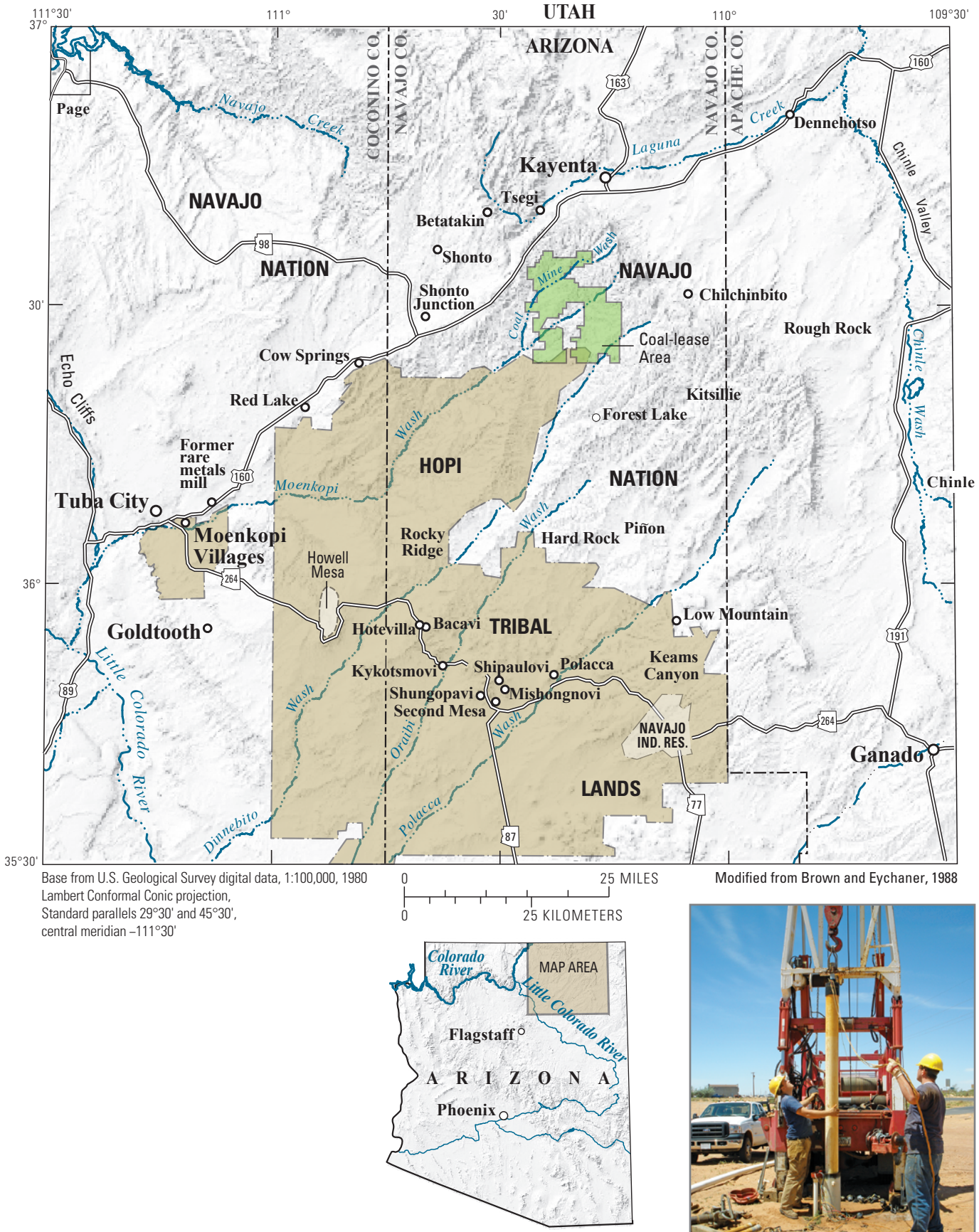
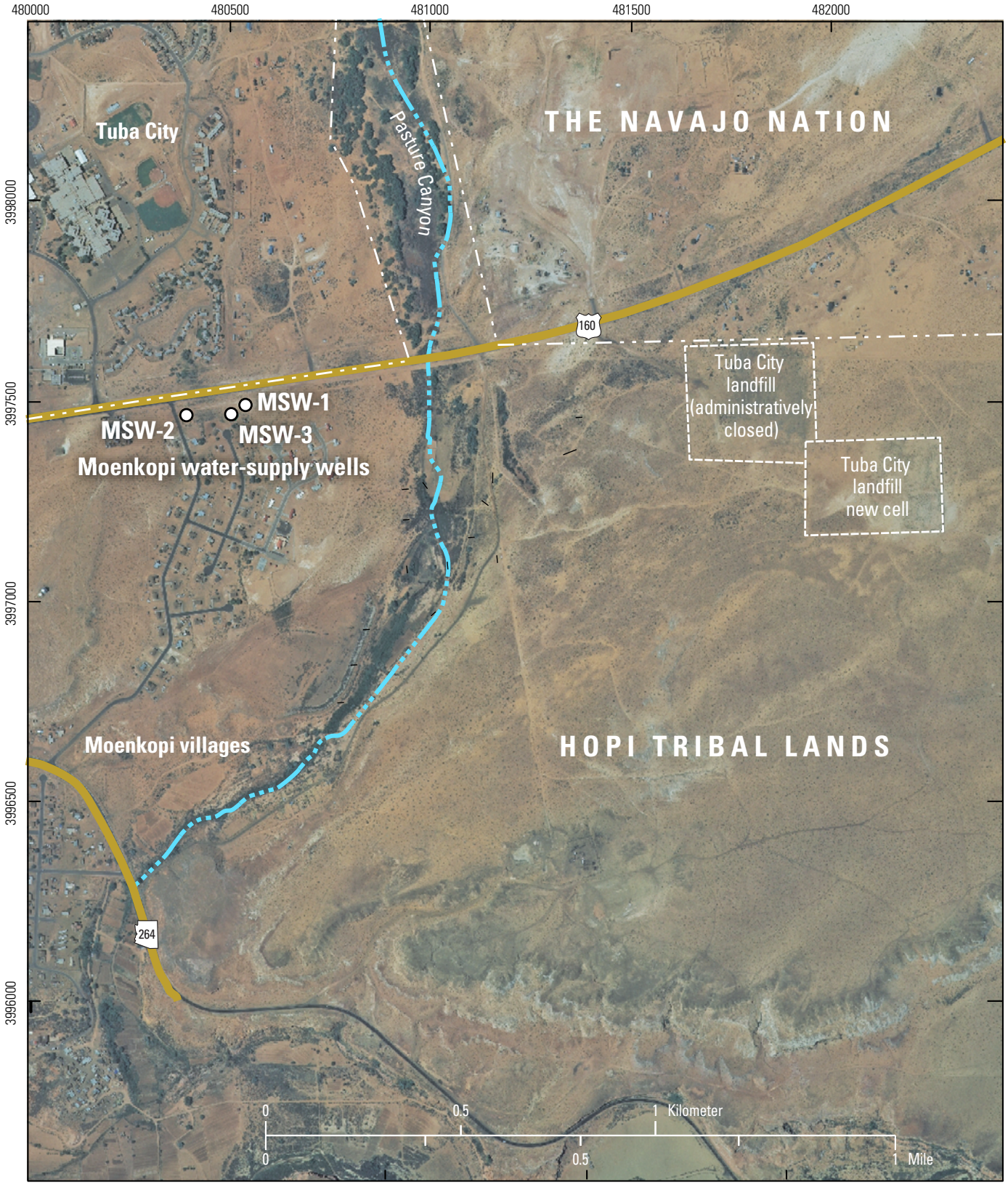


Figure 1. Map showing location of the study area in northeastern Arizona. Photograph shows pulling pump at well MSW-2.



Base from U.S. Department of Agriculture, National Agriculture Imagery Program, Universal Transverse Mercator Projection, North American Datum 1983, Zone 12 North

Figure 2. Map showing Upper Moenkopi water-supply wells near the Moenkopi villages, Coconino County, Arizona.

Table 1. Construction, water-level, and pumping data from the Upper Moenkopi Village water-supply wells, Coconino County, Arizona.

[gpm, gallons per minute; ft, feet; water level and pumping data collected during fieldwork in April and May, 2010]

Year well constructed	USGS site identification number	Local identification number	Top of casing elevation (ft)	Depth to top and bottom of screened interval(s) (ft)	Constructed depth and actual depth to bottom of well (ft)	Depth to top of pump (ft)	Static depth to water[1] (ft) and date	Pumping depth to water[1] (ft) and date	Pumping discharge (gpm) and date
Upper Moenkopi Village water-supply well name									
MSW-1									
1977	360719111125901	A-32-11 28DCA1	4,847	69-129 (perforated 8-inch steel casing)	140 (backfilled with sediment to 125)	100	87.0 May 12, 2010	99.15 April 28, 2010	42.5 May 5, 2010
MSW-2									
1982	360719111130401	A-32-11 28DCA	4,846	72-77 105-125 (perforated intervals are 8-inch stainless steel well screen)	142 (backfilled with sediment to 127)	109	79.7 May 5, 2010	100[2] April 28, 2010	25 May 12, 2010
MSW-3									
1991	360719111130001	A-32-11 28DCA3	4,845	71-81 125-145 166-176 226-236 (perforated intervals are 8-inch stainless steel well screen)	280 (backfilled with sediment to 241)	220	72.75 May 5, 2010	88.5 April 28, 2010	10 April 28, 2010

[1] Measuring point at top of well casing

[2] Measurement error possible due to cascading water

Program and water levels were measured by the USGS during the fieldwork in April and May 2010 (table 1).

The wells produce groundwater from the Navajo Sandstone and the upper part of the Kayenta Formation-Navajo Sandstone transition zone, both units of the N aquifer (fig. 3). MSW-1 produced 60 gal/min upon completion in June 1977. The well discharge decreased to about 45 gal/min by October 2007, and was measured at 42.5 gal/min on May 5, 2010. MSW-2 produced about 40 gal/min upon completion in February 1982 and was measured at 25 gal/min on May 12, 2010. MSW-3 has been the lowest producing well of the three supply wells from the time it was completed in 1991. The well was originally reported to be capable of producing about 35 gal/min, but discharge has decreased with time; discharge at MSW-3 was measured at 8 gal/min in October 2007, and was measured at 10 gal/min on April 28, 2010. Water levels in the three wells also have declined in recent years (U.S. Department of Health and Human Services, 2008).

The close spacing of the wells may be leading to additional drawdown and decreased production from well interference when the wells are operated simultaneously. As a result, Upper Moenkopi Village water operators rotate the

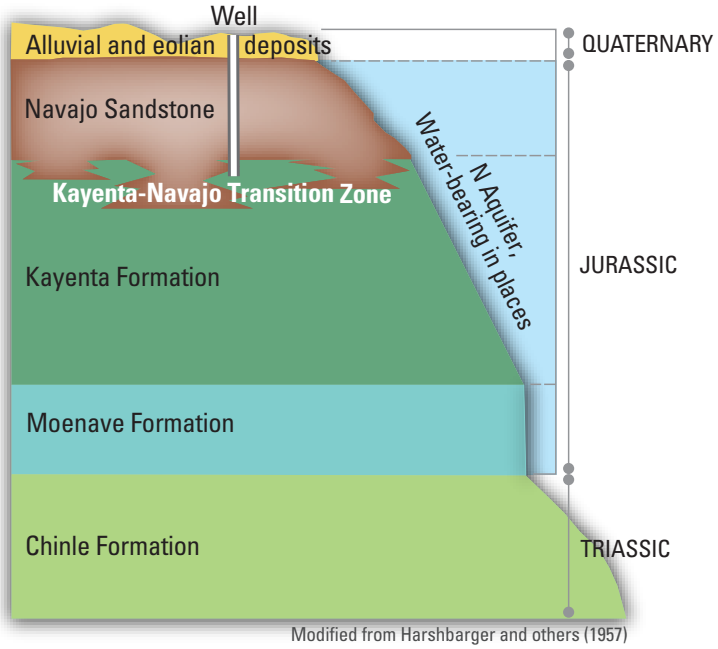


Figure 3. Generalized stratigraphic section for the area near the Upper Moenkopi Village water-supply wells, Coconino County, Arizona.

operation of the pumps on a nearly daily basis. The larger than predicted drawdown in the three wells and the resulting short column of water in the wells under pumping conditions—even during low pumping rates of 10–25 gal/min—resulted in the collection of fewer water-quality samples and prevented the collection of meaningful well-bore flow data.

Methods of Study

Depth-Dependent Sampling and Well-Bore Flow

Coupled well-bore flow and depth-dependent water-quality data that were collected from wells under pumping conditions can be used to directly measure the vertical distribution of flow and contaminants into wells from aquifers. Recent advancements in interpretation of these data use numerical groundwater-flow models and particle tracking at the well-bore scale to estimate aquifer hydraulic properties, and to predict the change in well yield and quality with changes in well construction (Halford, 2009). Collection of coupled well-bore flow and depth-dependent water-quality data can facilitate redesign of existing wells to improve water quality, or guide construction of future wells to ensure suitable-quality water (Izbicki and others, 1999).

Depth-dependent water samples were collected by the USGS from the three water-supply wells, (MSW-1, MSW-2, and MSW-3) for May 5–13, 2010. The samples were collected under pumping conditions to determine if there is a vertical distribution of water entering the wells from the surrounding aquifer. Depth-dependent samples were collected from the three production wells under pumping conditions using a gas-displacement sample pump (Izbicki, 2004). The pump used in this study is about 6 in. long, less than 1 in. in diameter, and operated through repeated application and release of compressed gas. The pump is intended for use in production wells having limited access that prevents the use of traditional geophysical tools (such as wire-line bailers) used to collect depth-dependent water samples. Data collected at different depths within the production well reflect water quality at those depths under actual pumping conditions.

The original scope of work called for the collection of water-quality samples at three positions within the water column of each well under pumping conditions—at the top, midpoint, and bottom portions of the screened interval. However, owing to the larger than predicted drawdown in the three wells and the resulting short column of water available to sample from in each well, a decision was made to collect water-quality samples from two positions in each well—at the top and bottom portions of the available water column.

The perforated interval within MSW-1 consists of a 60 ft section of 8-in. perforated steel casing from 69 to 129 ft below the top of the well casing (table 1). The pumping depth-to-water was about 99 ft on April 28, 2010, thus about one-half of the perforated interval is above the water column under pumping conditions. This information guided the collection of water samples at MSW-1—samples were collected from a depth of 105 ft near the top of the water column and from a depth of 120 ft near the bottom of the perforated interval. MSW-2 has two perforated intervals, the first from 72 to 77 ft and the second from 105 to 125 ft below the top of the well casing (table 1). Both perforated intervals consist of 8-in. stainless steel well screen. The pumping depth-to-water was about 100 ft on April 28, 2010—causing the upper perforated interval to be exposed above the water column under pumping conditions. Water samples from MSW-2 were collected from a depth of 107 ft near the top of the water column and from a depth of 120 ft near the bottom of the lower perforated interval. MSW-3 has four perforated intervals, the first from 71 to 81 ft, the second from 125 to 145 ft, the third from 166 to 176 ft, and the fourth from 226 to 236 ft below the top of the well casing (table 1). The four perforated intervals consist of 8-in. stainless steel well screen. The pumping depth-to-water was 88.5 ft on April 28, 2010, causing the upper perforated interval to be exposed above the water column under pumping conditions. Water samples from MSW-3 were collected from a depth of 135 ft, within the zone of the second perforated interval, and from a depth of 230 ft, within the zone of the lowermost perforated interval.

An attempt was made to collect well-bore flow data under pumping conditions in the three wells using a technique called the "tracer-pulse method" (Izbicki and others, 1999). The method uses a high-pressure hose equipped with valves for dye injection. The hose is filled with fluid containing an easily measured tracer, such as water colored with Rhodamine dye. The hose is lowered to a known depth in the well and a pulse of the tracer is injected into the water column. The travel time of the tracer to a detector on the surface is measured. The hose is then lowered to a deeper depth and another pulse of dye is released. The velocity is calculated as the difference in the travel times. The flow rate, given a known well diameter, is then calculated. A series of dye injections are released at different depths to construct a velocity profile for the well. If successful, the velocity profile can be used to guide the collection and interpretation of depth-dependent water-quality data.

In addition to the limitations observed during the water-quality sampling, well construction issues with the three water-supply wells prevented the collection of meaningful well-bore flow data. At MSW-1 and MSW-2, the high-pressure hose used for dye injection could not be lowered past the top of the pump because the pumps were fitted with sand shrouds with diameters close to the inside diameter of the well casing, and the small space between the two would not allow for the passage of the dye-injection hose. At MSW-2 and MSW-3, leaking fittings in the discharge pipes at the top of the wells caused pumped water to cascade back into the wells, resulting in erroneous values in the well-bore flow data. Additionally, groundwater-level decline coupled with the relatively low permeability of the surrounding aquifer resulted in larger than predicted drawdown in the three wells. This resulted in a short column of water in the wells

under pumping conditions, even during low pumping rates of 10–25 gal/min. The combination of these factors prevented the collection of meaningful well-bore flow data.

Water-Chemistry Data Collection and Analysis

Sampling procedures followed standard protocols for collection and preservation established in the USGS National Field Manual for the Collection of Water Quality Data (U.S. Geological Survey, variously dated). The major ion, nutrient, and trace metal water samples were analyzed by the USGS National Water-Quality Laboratory in Denver, Colorado. The radiochemistry water samples were analyzed by the Eberline Analytical Services in Richmond, California, and the carbon-14 (^{14}C) water samples were analyzed by the McLean Laboratory at the Woods Hole Oceanographic Institute in Woods Hole, Massachusetts.

Field parameters including temperature, pH, and specific conductance were measured with a Hydrolab MS5 multi-parameter water-quality monitoring probe (manufactured by Hach Hydromet). Dissolved-oxygen concentrations were measured with an InSitu Troll® 9500 water-quality monitoring probe (InSitu, Inc.). The water-quality monitoring probes were calibrated each day of the sampling fieldwork. Titrations to determine total alkalinity and bicarbonate concentrations of the water samples were conducted in the field within 4 hours of sample collection using the inflection point method (Rounds, 2012). Buffer solutions for the titrations were provided by the USGS National Water Quality Laboratory and pH was measured during the titrations with a ThermoOrion 5 Star pH meter (Thermo Scientific Orion).

Chemical constituents from the water-supply wells were compared to the U.S. Environmental Protection Agency (USEPA) primary and secondary drinking-water standards (U.S. Environmental Protection Agency, 2009). Maximum contaminant levels (MCLs), which are the primary regulations, are legally enforceable standards that apply to public water systems. MCLs protect drinking-water quality by limiting the levels of specific contaminants that can adversely affect public health. Secondary maximum contaminant levels (SMCLs) provide guidelines for the control of contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. The USEPA recommends compliance with SMCLs for public water systems; however, compliance is not enforced (U.S. Environmental Protection Agency, 2009).

Results of Water-Quality, Isotope, and Radiochemistry Analysis

Results of the water-quality, stable isotope, and radiochemistry sample analyses are shown in tables 2 and 3 and also are available online at http://nwis.waterdata.usgs.gov/az/nwis/qwdata by entering the USGS well site identification numbers listed in table 1. For comparison, table 2 also contains water-quality data for MSW-2 from samples collected in January 1992 and October 1993.

Water Quality

Field Parameters and Inorganics

At MSW-1, specific conductance was 533 and 603 µS/cm for samples collected from the top and bottom portions of the water column, respectively. The pH was 8.7 and 7.3 for samples collected from the top and bottom portions of the water column, respectively. Dissolved oxygen was not determined for the sample collected from the top of the water column and was 5.75 mg/L for the sample collected from the bottom portion of the water column. The total dissolved solids (TDS) was 332 mg/L for the sample collected from the top portion of the water-column sample and slightly higher at 374 mg/L for the sample from the bottom portion of the water column. Alkalinity was similar for the two samples collected at MSW-1, measuring 135.1 and 136.5 mg/L for the samples collected from the top and bottom portions of the water column, respectively. At MSW-1, bicarbonate concentrations were 164.7 and 166.4 mg/L for samples collected from the top and bottom portions of the water column, respectively.

For MSW-2, specific conductance was 525 and 561 µS/cm for the samples collected from the top and bottom portions of the water column, respectively. The pH was 8.06 and 7.19 for the samples collected from the top and bottom portions of the water column, respectively. Dissolved oxygen was not determined for the sample collected from the top of the water column; however, a value of 7.86 mg/L was measured for the sample collected from the lower portion of the water column. TDS was not determined for the sample collected from the top of the water column; however, a value of 318 mg/L was measured for the sample from the bottom portion of the water column. Alkalinity also was similar for the two samples collected at MSW-2— 98.7 and 96.6 mg/L for the samples collected from the top and bottom portions of the water column, respectively. At MSW-2, bicarbonate concentrations were 120.3 and 117.8 mg/L for the samples collected from the top and bottom portions of the water column, respectively.

For MSW-3, specific conductance was 596 and 488 µS/cm for the samples collected from the top and bottom portions of the water column, respectively. The pH was 8.6 for samples collected from the top and bottom portions of the water column. Dissolved oxygen was not determined for the sample collected from the top of the water column; however, a value of 5.3 mg/L was measured for the sample collected from the bottom portion of the water column. TDS was not determined for the sample collected from the top portion of the water column; however, a value of 303 mg/L was measured for the sample from the bottom portion of the water column.

Alkalinity was similar for the two samples collected at MSW-3, measuring 136.1 and 132.0 mg/L for the samples collected from the top and bottom portions of the water column, respectively. At MSW-3, bicarbonate concentrations were 157.3 and 135.1 mg/L for the samples collected from the top and bottom portions of the water column, respectively. None of the water samples collected at MSW-1, MSW-2, and MSW-3 and analyzed for TDS were greater than the USEPA SMCL standard of 500 mg/L. The USEPA SMCL range for pH is 6.5–8.5. At MSW-1, the pH for the sample collected from the top of the water column was 8.65, slightly exceeding the SMCL. Additionally, at MSW-3, pH was 8.55 and 8.63 for the samples collected from the top and bottom portions of the water column, respectively. These pH values also slightly exceeded the USEPA SMCL and indicate that the water is alkaline.

The ratios of the major dissolved ions from the samples collected from MSW-1 and MSW-2 indicate water with a calcium and sulfate-ion composition (figs. 4*A* and 4*B*; table 2). MSW-1 and MSW-2 are completed to similar depths in the Navajo Sandstone (table 1). There is not a significant vertical distribution of the major ion concentrations in the samples collected from the top and bottom portion of the water column in the two wells. Concentrations of the major dissolved ions for the four samples collected from MSW-1 and MSW-2 ranged from 49.9 to 56.5 mg/L for calcium, 30.8 to 44.5 mg/L for sodium, 11.3 to 13.3 mg/L for magnesium, 1.96 to 2.13 mg/L for potassium, 41.6 to 52.7 mg/L for chloride, 0.15 to 0.29 mg/L for fluoride, and 62.5 to 81.7 mg/L for sulfate. The major ion concentrations for the samples collected at MSW-2 as part of this study are similar to the samples collected in January 1992 and October 1993 (table 2).

The samples collected at MSW-3 were higher in sodium and lower in calcium than the samples collected from MSW-1 and MSW-2 and contained a similar sulfate-ion percentage (fig. 4; table 2). MSW-3 is about 140 ft deeper than MSW-1 and MSW-2, with the lower portion of the well completed in the Kayenta Formation-Navajo Sandstone transition zone (fig. 3). Additionally, there was a vertical distribution of ion concentrations in the samples collected at MSW-3. Calcium concentrations for the samples collected at MSW-3 were 30.6 mg/L for the sample collected from the top portion of the water column (135 ft below the top of the casing) and 8.21 mg/L for the sample collected from the bottom portion of the water column (230 ft below the top of the casing). In contrast, the sodium concentration increased with depth in the water column. Sodium concentrations were 78.8 and 96.6 mg/L for the

Table 2. Water quality data from Upper Moenkopi Village water-supply wells, Coconino County, Arizona.

[--, no data; <, less than; E, estimated; R, radchem non-detect, below ssLc; mg/L, milligrams per liter; mm, millimeters; gpm, gallons per minute; µs/cm, microsiemens per centimeter; °C, degrees Celsius]

Barometric pressure, (mm of mercury)	Dissolved oxygen, (mg/L)	Flow rate, (gpm)	pH, field, (standard units)	pH, laboratory, (standard units)	Specific conductance, (µS/cm at 25 °C)	Temperature, (25 °C)	Depth of well, feet below land surface datum	Sampling condition	Sampling method
Moenkopi water-supply well name and sample date									
MSW-1, May 6, 2010									
633	5.8	--	7.3	7.9	603	18.6	--	Pumping	Submersible pump
MSW-1, May 13, 2010									
--	--	--	8.7	8.2	533	18.4	--	Pumping	Other
MSW-2, January 31, 1992									
574	5	100	8	7.9	589	16.3	--	--	--
MSW-2, October 18, 1993									
643	5.6	106	7.8	7.9	522	17	180	--	--
MSW-2, May 5, 2010									
634	7.9	--	7.2	7.6	525	24.3	--	Pumping	Submersible pump
MSW-2, May 12, 2010									
--	--	--	8.1	8.1	561	18.8	--	Pumping	Other
MSW-3, May 6, 2010									
634	5.3	--	8.6	9.2	488	19.9	--	Pumping	Submersible pump
MSW-3, May 11, 2010									
--	--	--	8.6	8.7	596	19.1	--	Pumping	Other

Table 2. Water quality data from Upper Moenkopi Village water-supply wells, Coconino County, Arizona.—Continued

Dissolved solids dried at 180 °C, (mg/L)	Calcium, (mg/L)	Magnesium, (mg/L)	Potassium, (mg/L)	Sodium, (mg/L)	Alkalinity, as calcium carbonate (mg/L)	Bicarbonate, (mg/L)	Bromide, (mg/L)	Carbonate, (mg/L)	Chloride, (mg/L)
Moenkopi water-supply well name and sample date									
MSW-1, May 6, 2010									
374	56.5	13.3	2.13	44.5	136	166	0.431	--	52.7
MSW-1, May 13, 2010									
332	49.9	11.3	1.99	40	135	165	0.336	--	41.6
MSW-2, January 31, 1992									
345	56	13	2.1	42	130	159	--	0	59
MSW-2, October 18, 1993									
290	51	12	1.9	36	104	127	--	0	48
MSW-2, May 5, 2010									
318	51.5	11.6	1.96	33.3	96.6	118	0.46	--	51.1
MSW-2, May 12, 2010									
--	52.4	11.9	1.99	30.8	98.7	120	0.538	--	59.2
MSW-3, May 6, 2010									
303	8.21	2.09	1.16	96.6	132	135	0.128	12.7	31.5
MSW-3, May 11, 2010									
--	30.6	7.57	1.71	78.8	136	157	0.373	4.2	51

Table 2. Water quality data from Upper Moenkopi Village water-supply wells, Coconino County, Arizona.—Continued

Fluoride, (mg/L)	Silica, (mg/L) as SiO_2	Sulfate, (mg/L)	As nitrogen (mg/L)				As phosphorus (mg/L)		Aluminum, (µg/L)
			Ammonia plus organic nitrogen	Ammonia	Nitrate plus nitrite	Nitrite	Ortho phosphate	Phospho-rus	
Moenkopi water-supply well name and sample date									
MSW-1, May 6, 2010									
0.24	14.4	81.7	0.21	< .020	1.24	< .002	0.011	< .04	< 3.4
MSW-1, May 13, 2010									
0.29	13.6	62.5	< .10	< .020	1.07	< .002	0.01	< .04	< 3.4
MSW-2, January 31, 1992									
0.3	14	80	--	0.01	1.2	< .010	< .01	--	--
MSW-2, October 18, 1993									
0.2	15	69	--	0.02	1.8	< .010	< .01	--	--
MSW-2, May 5, 2010									
0.15	13	73.8	E .05	< .020	2.06	< .002	0.011	< .04	< 3.4
MSW-2, May 12, 2010									
0.16	13.1	81.7	0.1	< .020	2.24	E .001	0.01	< .04	< 3.4
MSW-3, May 6, 2010									
0.94	12.1	51.1	E .05	< .020	1.63	< .002	0.029	E .02	7
MSW-3, May 11, 2010									
0.58	13.6	86.9	0.14	< .020	1.84	< .002	0.039	< .04	5.1

Table 2. Water quality data from Upper Moenkopi Village water-supply wells, Coconino County, Arizona.—Continued

Barium, (µg/L)	Beryllium, (µg/L)	Cadmium, (µg/L)	Chromium, (µg/L)	Cobalt, (µg/L)	Copper, (µg/L)	Iron, (µg/L)	Lead, (µg/L)	Lithium, (µg/L)	Manganese, (µg/L)
Moenkopi water-supply well name and sample date									
MSW-1, May 6, 2010									
91.7	< .20	< .6	< 1.2	< 1.6	< 2.8	< 6.0	0.259	45.6	0.22
MSW-1, May 13, 2010									
80.3	< .20	< .6	< 1.2	< 1.6	< 2.8	15.8	E .018	48.5	1.11
MSW-2, January 31, 1992									
--	--	--	--	--	--	< 3.0	--	--	--
MSW-2, October 18, 1993									
--	--	--	--	--	--	7	--	--	--
MSW-2, May 5, 2010									
94.5	< .20	< .6	< 1.2	< 1.6	< 2.8	E 5.8	0.222	36.6	0.73
MSW-2, May 12, 2010									
104	< .20	< .6	< 1.2	< 1.6	< 2.8	12.7	E .021	44.3	1.8
MSW-3, May 6, 2010									
12.2	< .20	< .6	< 1.2	< 1.6	< 2.8	15.8	0.044	59.7	1.78
MSW-3, May 11, 2010									
44.4	< .20	< .6	< 1.2	< 1.6	< 2.8	13.2	< .030	69.8	3.13

Table 2. Water quality data from Upper Moenkopi Village water-supply wells, Coconino County, Arizona.—Continued

Mercury, (µg/L)	Molybdenum, (µg/L)	Nickel, (µg/L)	Silver, (µg/L)	Strontium, (µg/L)	Vanadium, (µg/L)	Zinc, (µg/L)	Antimony, (µg/L)	Arsenic, (µg/L)	Boron, (µg/L)
Moenkopi water-supply well name and sample date									
MSW-1, May 6, 2010									
< .010	< 4.4	< 4.2	< 4.0	1,030	6.6	14.9	< .054	2.4	75
MSW-1, May 13, 2010									
< .010	< 4.4	< 4.2	< 4.0	864	5.9	26.9	E .052	2	71
MSW-2, January 31, 1992									
--	--	--	--	--	--	--	--	2	80
MSW-2, October 18, 1993									
--	--	--	--	--	--	--	--	2	70
MSW-2, May 5, 2010									
< .010	< 4.4	< 4.2	< 4.0	884	7.6	18	< .054	2.1	69
MSW-2, May 12, 2010									
< .010	< 4.4	< 4.2	< 4.0	883	7.2	93.5	0.056	1.8	74
MSW-3, May 6, 2010									
< .010	7.1	< 4.2	< 4.0	234	13.5	5	< .054	6.8	323
MSW-3, May 11, 2010									
< .010	< 4.4	< 4.2	< 4.0	682	10.3	8.7	E .041	4.1	219

Table 2. Water quality data from Upper Moenkopi Village water-supply wells, Coconino County, Arizona.—Continued

Selenium, (µg/L)	Organic carbon, (mg/L)	Suspended sediment, dry weight, (pC/gm)			Carbon-14 (percent modern)		Gross alpha activity curve (pC/L)		Gross beta activity curve (pC/L)	
		Uranium-234	Uranium-235	Uranium-238	Counting error, filtered	Filtered	30-day count, Th-230	72-hour count, Th-230	30-day count, Cs-137	72-hour count, Cs-137
Moenkopi water-supply well name and sample date										
MSW-1, May 6, 2010										
2.1	0.72	0.005	R -.0003	0.0036	0.26	69.27	7.3	9.8	2.4	2.3
MSW-1, May 13, 2010										
1.4	E .49	0.05	R .02	R .000	0.24	67.34	6	7.2	2.4	1.4
MSW-2, January 31, 1992										
--	--	--	--	--	--	--	--	--	--	--
MSW-2, October 18, 1993										
--	--	--	--	--	--	--	--	--	--	--
MSW-2, May 5, 2010										
3.5	0.82	0.0031	R .0000	0.0012	0.22	65.2	5.1	8.1	2.8	1.6
MSW-2, May 12, 2010										
3.9	0.97	R -.009	R -.011	R .009	0.23	65.24	6.4	8.7	2.6	1.9
MSW-3, May 6, 2010										
1.1	E .64	0.0078	R .0004	0.003	0.18	33.44	6.4	5.1	1.4	1.3
MSW-3, May 11, 2010										
2.2	1.1	R -.03	R -.031	R .000	0.2	52.72	8.6	9.1	2.3	0.9

Table 2. Water quality data from Upper Moenkopi Village water-supply wells, Coconino County, Arizona.—Continued

Thorium-228, (pC/L)	Thorium-230, (pC/L)	Thorium-232, (pC/L)	Tritium, (pC/L)	Uranium (natural), (µg/L)	δ Carbon-13, (per mil)	δ Oxygen-18, (per mil)	Deuterium/protium ratio, (per mil)
Moenkopi water-supply well name and sample date							
MSW-1, May 6, 2010							
R -.01	R .02	R .000	R .1	3.85	-8.04	-8.61	-74.7
MSW-1, May 13, 2010							
0.04	0.09	R .000	R .3	3.16	-7.1	-8.73	-74.7
MSW-2, January 31, 1992							
--	--	--	--	--	--	--	--
MSW-2, October 18, 1993							
--	--	--	--	--	--	--	--
MSW-2, May 5, 2010							
R -.02	R .01	R .000	1.3 (0.41 TU)	3.4	-8.06	-9.03	-74.9
MSW-2, May 12, 2010							
0.07	R -.10	R .000	R .3	3.52	-8.03	-9.09	-75.5
MSW-3, May 6, 2010							
R .01	R -.01	0.034	R -.7	4.51	-7.52	-9.52	-79.1
MSW-3, May 11, 2010							
0.15	R -.05	R .000	R -.2	4.88	-8.37	-9.12	-76.7

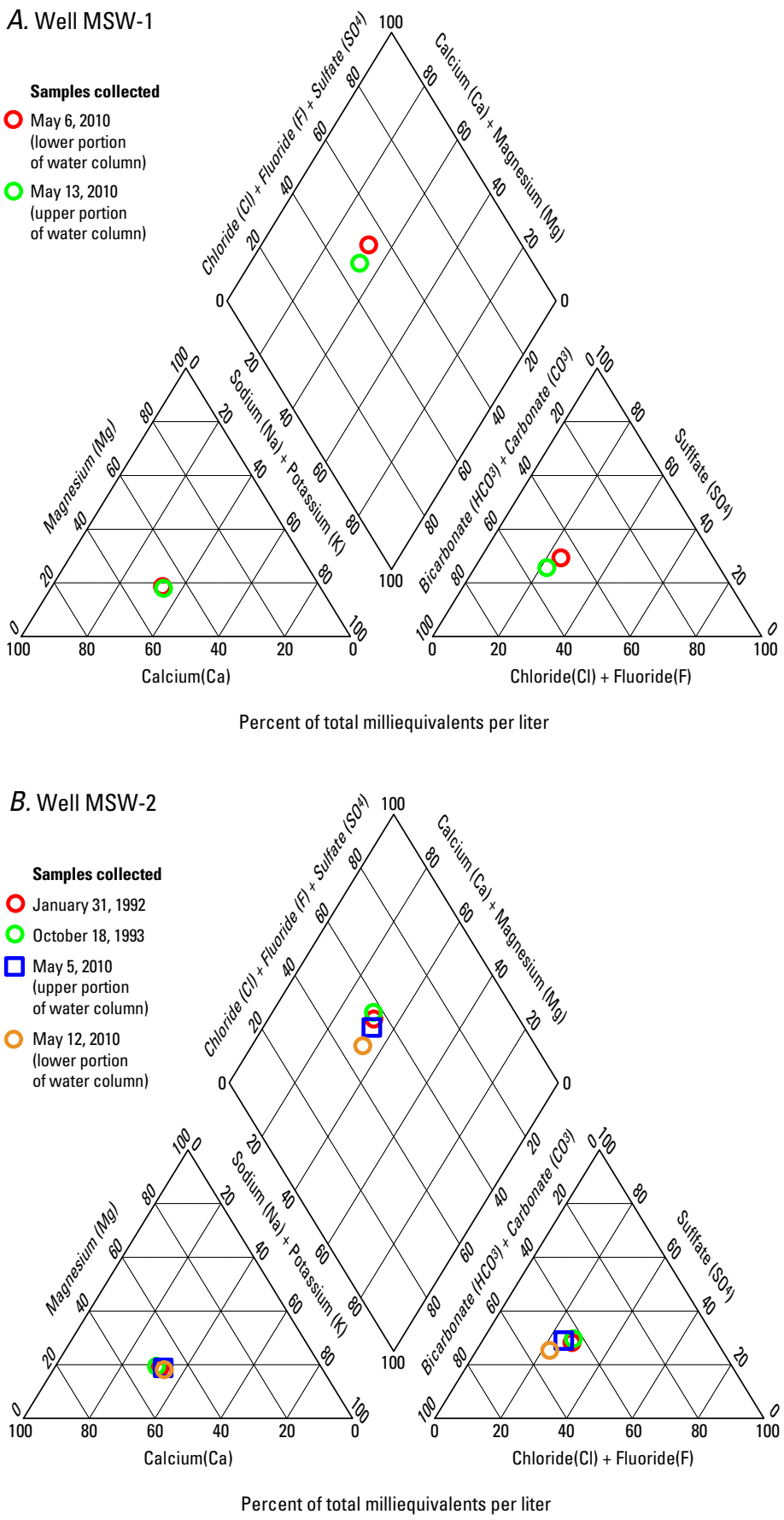


Figure 4. Trilinear diagram showing relative compositions of groundwater samples collected from the Upper Moenkopi Village water-supply wells in Coconino County, Arizona, under pumping conditions; *A.* Well MSW-1; *B.* Well MSW-2; *C.* Well MSW-3.

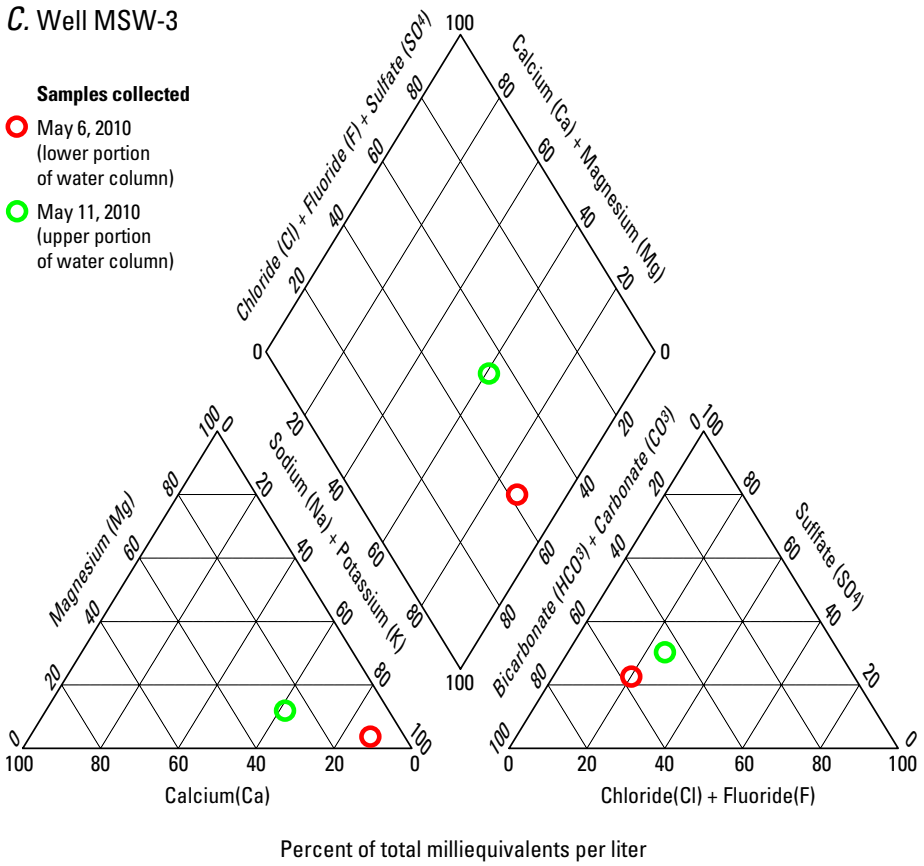


Figure 4.—Continued

samples collected from the top and bottom portions of the water column, respectively. Magnesium concentrations decreased from 7.57 to 2.09 mg/L for the samples collected from the top and bottom portions of the water column, respectively. Potassium concentrations were 1.71 and 1.16 mg/L for the samples collected from the top and bottom portions of the water column, respectively. Carbonate increased from 4.2 to 12.7 mg/L for the samples collected from the top and bottom portions of the water column, respectively. Chloride decreased from 51 to 31.5 mg/L for the samples collected from the top and bottom portions of the water column, respectively. Fluoride concentrations were higher for the samples collected at MSW-3 than the samples collected at MSW-1 and MSW-2, and increased with depth from 0.58 to 0.94 mg/L for the samples collected from the bottom portion of the water column. Sulfate concentrations for the samples collected at MSW-3 decreased with depth from 86.9 to 51.1 mg/L for the samples collected from the top and bottom portions of the water column, respectively.

Previous studies of the Navajo Sandstone and the Kayenta Formation-Navajo Sandstone transition zone portions of the N aquifer generally reported calcium bicarbonate to sodium bicarbonate type water with low-to-moderate TDS and other trace elements (Cooley and others, 1969; Eychaner, 1983; Lopes and Hoffmann, 1997; Tetra Tech EM Inc., 2004; Carruth and Bills, 2012). Additionally, Cooley and others (1969) reviewed 140 groundwater samples from the Navajo Sandstone and found the principal chemical constituents to be calcium and sodium, and bicarbonate, sulfate, and chloride ions. TDS of the 140 samples ranged from about 90 to 1,000 ppm, and the most common minor chemical constituents were fluoride, nitrate, magnesium, silica, and iron.

Nutrients

Nutrients including nitrogen, phosphorus, and ammonia compounds can be a water-quality concern in concentrations that exceed USEPA MCLs. Major sources of nutrients include fertilizers, sewage effluent, and dissolution of naturally occurring minerals (Mueller and Helsel, 1996). For the samples collected at MSW-1, MSW-2, and MSW-3, nitrate (as nitrogen) ranged from 1.07 to 2.24 mg/L—less than the USEPA MCL of 10 mg/L. Additionally, concentrations of nitrite (as nitrogen), orthophosphate (as phosphorus), phosphorus, and ammonia (as nitrogen) generally were low or less than detection limits for samples from all three water-supply wells (table 2). None of the water samples collected at MSW-1, MSW-2, and MSW-3 exceeded the USEPA MCL standards for nutrients (U.S. Environmental Protection Agency, 2009).

Table 3. Carbon-14 radioisotope data used to estimate ages of groundwater sampled from the upper Moenkopi Village water-supply wells, Coconino County, Arizona.

[--, no data; pM, percent modern carbon; mg/L, milligrams per liter; mm, millimeters; gpm, gallons per minute; µs/cm, microsiemens per centimeter; °C, degrees Celsius]

Carbon-14, normalized		Carbon-14, de-normalized		Calculated Carbon-14 age, in years before present	
pM,	Error 1 σ pM	pM,	Error 1 σ pM	normalized	de-normalized
Moenkopi water-supply well name and sample date					
MSW-1, May 6, 2010					
67.34	0.24	69.84	0.24	3176	2884
MSW-1, May 13, 2010					
69.27	0.26	71.70	0.26	2949	2672
MSW-2, May 5, 2012					
65.24	0.23	67.53	0.23	3431	3154
MSW-2, May 12, 2012					
65.2	0.22			3436	
MSW-3, May 6, 2010					
52.72	0.2	54.53	0.20	5143	4871
MSW-3, May 11, 2010					
33.44	0.18	34.65	0.18	8799	8514

Trace Elements

The samples collected from MSW-1, MSW-2, and MSW-3 also were analyzed for selected trace elements, some of which can cause negative health effects if there is long-term exposure above the USEPA MCL (U.S. Environmental Protection Agency, 2009). Samples from the three water-supply wells analyzed for arsenic did not contain concentrations that exceeded the USEPA MCL of 10 µg/L. Arsenic concentrations ranged from 1.8 to 2.4 µg/L for the samples collected from MSW-1 and MSW-2. For MSW-3, arsenic concentrations ranged from 4.1 to 6.8 µg/L—the higher arsenic sample was collected from the bottom portion of the water column, 230 ft below the top of the casing.

Uranium is an element of concern in the vicinity of Upper Moenkopi Village. Studies are ongoing to determine if elevated concentrations of uranium occur in the vicinity of the Tuba City Landfill and Open Dump Site and if groundwater from these sites could migrate toward the Upper Moenkopi Village water-supply wells (Morgan, 2002; Johnson and Wirt, 2009; Otton and others, 2009). Uranium is a naturally occurring radioactive element and can occur in groundwater when uranium deposits are present in the groundwater-flow system. Previous studies have indicated that uranium deposits occur at levels of economic importance in the surrounding area (Johnson and Wirt, 2009). Uranium ore mined from the Chinle Formation was processed in a nearby facility known as the Rare Metals Mill. In December 2003, the USEPA began regulating uranium in community water supplies in order to reduce the risk of cancer and kidney disease. For the samples collected from MSW-1 and MSW-2, uranium concentrations ranged from 3.16 to 3.85 µg/L. For MSW-3, uranium concentrations ranged from 4.51 to 4.88 µg/L. There is no significant vertical distribution of uranium concentrations in samples collected from the water-supply wells and no sample exceeded the USEPA MCL for uranium of 30 µg/L (table 2).

The samples collected from MSW-1, MSW-2, and MSW-3 were analyzed for other trace metals including aluminum, barium, chromium, copper, lead, mercury, nickel, selenium, silver, and zinc (table 2). Trace metals in groundwater may be derived from a variety of natural and anthropogenic sources. Many of these metals are required by humans in trace amounts but in larger, persistent dosages that exceed the USEPA MCL, these heavy metals can become toxic when they are not metabolized by the body (U.S. Environmental Protection Agency, 2009). None of the samples collected from MSW-1, MSW-2, or MSW-3 exceeded the USEPA MCL or SMCL for trace metals (table 2 and U.S. Environmental Protection Agency, 2009).

Isotopes

Water samples from the three water-supply wells were analyzed for a suite of environmental tracers that included the stable isotopes of oxygen and hydrogen, and radioactive isotopes of carbon and hydrogen. The isotope data can be used to develop and refine conceptual models of groundwater-flow systems. They also can be used to investigate sources

of recharge and to determine rates of movement and ages of groundwater (Clark and Fritz, 1997).

The use of oxygen- 18 (^{18}O) and deuterium (^{2}H) stable isotopes are helpful in estimating groundwater recharge sources (Coplen, 1993). In general, water recharged under cooler climatic conditions is more depleted in ^{18}O and ^{2}H; such stable isotope signatures have been observed in the nearby Black Mesa area (Truini and Longsworth, 2003). Additionally, evaporation during recharge and (or) evaporation from the top of the water table can produce a waterline with a lower slope (Coplen, 1993). Groundwater samples from the three Upper Moenkopi Village water-supply wells aligns with a local waterline (LWL) that is approximately parallel to the global meteoric water line (fig. 5). These signatures are similar to other reported data for shallow wells and springs in the area that discharge from N aquifer (Johnson and Wirt, 2009).

Sampling of the radioactive isotope of hydrogen (^{3}H or tritium) was done to approximate the age of groundwater pumped by the wells. Tritium was released into the Earth's atmosphere in large quantities during nuclear bomb testing in the 1950s (Michel, 1989). The current level of tritium in the atmosphere in the Southwestern United States is approximately 5 tritium units (TU) (A. Manning, U.S. Geological Survey, oral commun., 2007). A surface-water sample in Pasture Canyon less than 0.5 mi from the Moenkopi water-supply wells (fig. 2) had a tritium concentration of 4.9 TU, which probably represents current exchange with the atmosphere (Johnson and Wirt, 2009). Water samples with values of tritium less than 1 TU are interpreted to be primarily pre-bomb water (pre-1952). Samples with 1–2 TU may have a significant portion of pre-bomb water but also may have some post-bomb water due to mixing. All but one sample collected during this study had ^{3}H concentrations at or less than the detection limit for tritium and are interpreted to contain no modern water. The sample from the top of the water column in MSW-2 had a ^{3}H concentration of 1.3 pC/L (0.41 TU), indicating that composition is primarily pre-bomb (pre-1952), but may contain a small fraction of post-bomb modern water water (table 2).

Carbon-14 (^{14}C) is a naturally occurring radioactive isotope of carbon used to estimate the age of waters in the 500–50,000 years before present range. Carbon-14 is produced in the upper atmosphere as cosmic rays react with atmospheric nitrogen-14 (^{14}N) to produce ^{14}C and hydrogen-1 (^{1}H). In the upper atmosphere, ^{14}C is rapidly oxidized to CO_2 which readily mixes into the lower atmosphere. Any material using or reacting with atmospheric CO_2 (plants and water) has a ^{14}C activity equal to atmospheric ^{14}C while it is in equilibrium with the atmospheric carbon reservoir (Pearson and White, 1967). Carbon-14 activity is reported as percent modern carbon (pmc) and, by convention, the modern pre-1950 (pre-nuclear weapons testing) activity of atmospheric ^{14}C is 100 pmc.

Carbon-14 generally enters the hydrologic cycle through the following pathways: (1) dissolution of atmospheric CO_2 into rainwater and surface water, (2) plant respired CO_2 in the soil zone that dissolves into water, (3) CO_2 resulting from oxidation of organic material in the soil that dissolves

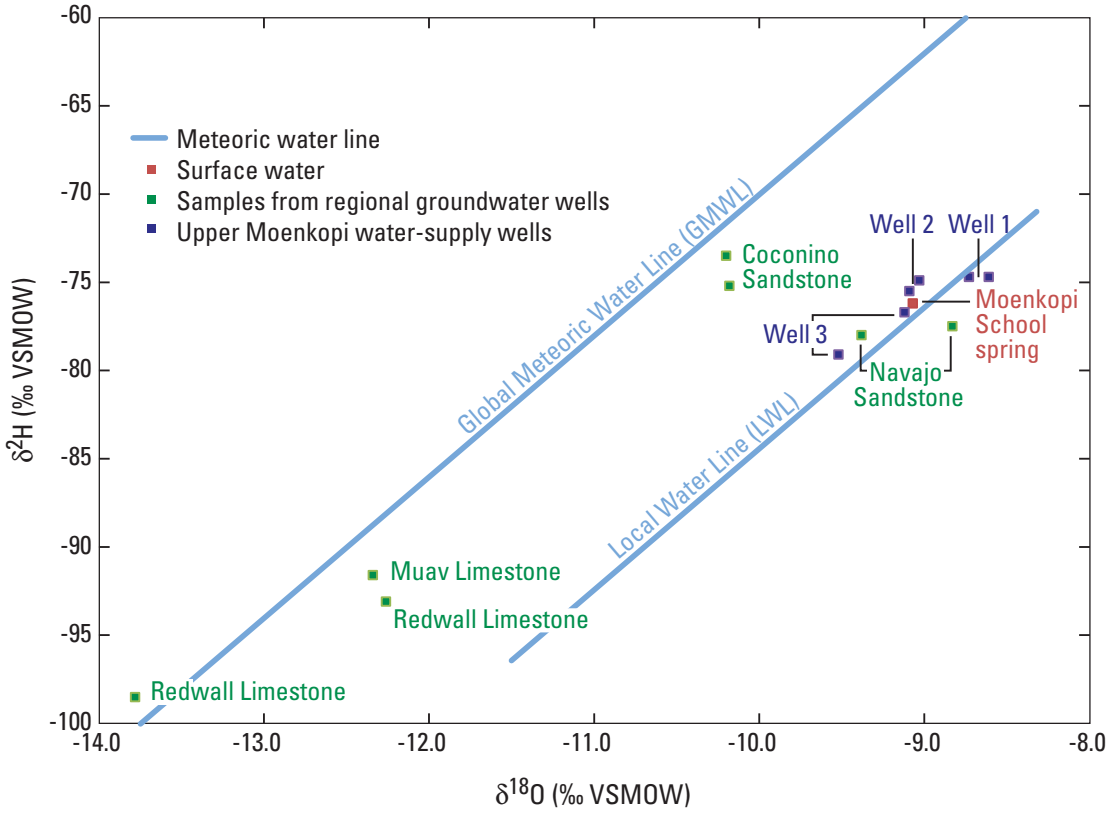


Figure 5. Graph showing oxygen-18 (^{18}O) and deuterium (^{2}H) data from the Upper Moenkopi village water-supply wells and comparison with other water sources in the surrounding area, Coconino County, Arizona.

into water, and (4) dissolution of mineral phases containing geologically young carbon, particularly in carbonate rocks. Kalin (2000) provides a comprehensive review of the radiocarbon groundwater dating method. Table 3 shows the ^{14}C radioisotope data used to estimate ages of groundwater sampled from Upper Moenkopi Village water-supply wells. Data were used to estimate the pmc and ages of groundwater in the wells. The estimated ^{14}C age of groundwater in MSW-1 and MSW-2, both completed about 140 ft into the Navajo Sandstone, is about 3,000 years before present. The estimated ^{14}C age of groundwater in MSW-3, completed about 240 ft into the Navajo Sandstone-Kayenta Formation transition zone is older, about 5,000 years before present in the upper portion of the water column and about 8,500 years before present in the lower portion of the water column (table 3).

Radiochemistry

Radioactive elements are naturally present in a wide range of concentrations in rocks, soil, and water and the occurrence and distribution of radionuclides in groundwater is controlled primarily by the local geology and geochemistry (Zapecza and Szabo, 1988). In the vicinity of Upper Moenkopi Village, uranium processed at the Rare Metals Mill (RMM) was not derived from the local Navajo Sandstone, but from the Chinle Formation near Cameron and from other formations in northeastern Arizona (Johnson and Wirt, 2009).

Measurements of gross alpha and beta activities serve as a useful screening technique that can provide information about natural and mined sources of radiation in the water supply and to estimate the corresponding potential public health impact. Gross alpha particle activity is a measure of the total amount of radioactivity in a water sample attributable to the radioactive decay of alpha-emitting elements. Gross alpha can be a concern for natural radioactivity in water as it refers to the radioactivity of uranium (U), thorium (Th), radium (Ra), as well as radon (Rn) and descendants (U.S. Environmental Protection Agency, 2009). Alpha particles are highly ionizing, but the particles travel short distances in air (< 2 in.) before being absorbed. Alpha particles have little ability to penetrate objects; thus, they can be stopped by a sheet of paper or the outer layer of skin. The external hazard from alpha particles is minimal, but the internal hazard when they are inhaled or ingested may be significant (U.S. Environmental Protection Agency, 2009). The USEPA MCL for gross alpha particle activity in drinking water is 15 pCi/L (U.S. Environmental Protection Agency, 2009). The gross alpha radioactivity of all samples collected from the three water-supply wells were less than the USEPA MCL and ranged from about 5.1 to 9.8 pCi/L (table 2).

Gross beta particle activity is a measure of the total amount of radioactivity in a water sample attributable to the radioactive decay of beta-emitting elements. Beta particles usually travel greater distances in air than alpha particles (about 6 ft) before being absorbed. Beta particles are more penetrating than alpha particles, and some are capable of penetrating the skin and causing radiation damage (U.S. Environmental Protection Agency, 2009). Gross beta particle activity is reported in pCi/L as cesium-137 (Cs-137). The USEPA MCL for gross beta particle activity states that the average annual concentration of beta particle activity from radionuclides in drinking water shall not produce an annual dose equivalent to the total body or any internal organ greater than 4 millirems per year. The gross beta radioactivity of samples collected from the three water-supply wells are not considered elevated and ranged from about 0.9 to 2.8 pCi/L (table 2).

Summary

This report documents the collection and analysis of depth-dependent water samples under pumping conditions from the three public water-supply wells in Upper Moenkopi Village, referred to as MSW-1, MSW-2, and MSW-3. Samples from these wells were analyzed for a range of chemical and isotopic constituents including major ions, nutrients, trace elements, stable and radioactive isotopes, and radiochemistry. The study assessed the source, distribution of flow, and quality of water from each of the three public water-supply wells. Data collected during this study can be used to (1) assess the quality of the existing municipal water supply, (2) provide a baseline for comparison with future water-quality monitoring, (3) evaluate management options to address possible contaminant sources, and (4) provide information to design and locate future water-supply wells.

Previous hydrologic and geochemical investigations have determined that water supplies for the Upper Moenkopi Village are limited and vulnerable to potential sources of contamination including the Tuba City Landfill and a former uranium processing facility known as the Rare Metals Mill. Studies are ongoing to determine if uranium and other metals in groundwater beneath the landfill are greater than regional groundwater concentrations and if a flow path exists between the Tuba City Landfill area and the village water-supply wells.

Analyses of major ions, nutrients, selected trace metals, isotopes, and radiochemistry were done on the groundwater samples from the three wells to describe general water-quality conditions and groundwater ages in and immediately surrounding the Upper Moenkopi Village public-supply wells. Chemical constituents from the water-supply wells were compared to the U.S. Environmental Protection Agency (USEPA) primary and secondary drinking water standards. None of the water samples collected at MSW-1, MSW-2, and MSW-3 exceeded USEPA primary drinking water standards. The pH for a water sample collected from the top of the water column in MSW-1 measured 8.65, exceeding the USEPA secondary drinking water standard for a pH range of 6.5–8.5. Additionally, at MSW-3, the pH ranged from 8.55 and 8.63

for the samples collected from the top and bottom portion of the water column—these pH values also exceeded the USEPA secondary drinking water standard.

The ratios of the major dissolved ions from the samples collected from MSW-1 and MSW-2 indicate water with a calcium and sulfate-ion composition and no significant vertical distribution of ion concentrations within the wells. Samples collected at MSW-3 are higher in sodium and lower in calcium than the samples collected from MSW-1 and MSW-2 and contain a similar sulfate-ion percentage. MSW-3 is about 140 ft deeper than MSW-1 and MSW-2 and there is a vertical distribution of ion concentrations in the samples collected at the well.

Groundwater samples from the three water-supply wells analyzed for oxygen-18 and deuterium stable isotopes appear to align with a local water line that is approximately parallel to the global meteoric water line. Tritium concentrations in samples from MSW-1 and MSW-3 were at or less than laboratory detection limits; these samples were interpreted to contain no modern water. A sample from the top of the water column at MSW-2 had a tritium concentration of 0.41 tritium units, indicating that the composition is primarily pre-bomb (pre-1952) water, but may contain a small fraction of post-bomb modern water.

The estimated carbon-14 age of groundwater sample from MSW-1 and MSW-2, both completed about 140 feet into the Navajo Sandstone, is about 3,000 years before present. The estimated carbon-14 age of groundwater sampled from MSW-3, completed about 240 feet into the Kayenta Formation-Navajo Sandstone transition zone is older, about 5,000 years before present in the top portion of the water column and about 8,500 years before present in the bottom portion of the water column. The gross alpha radioactivity of samples collected from the three water-supply wells ranged from 5.1 to 9.8 picocuries per liter (pCi/L)—less than USEPA primary drinking water standard of 15 pCi/L. The gross beta radioactivity of samples collected from the wells ranged from 0.9 to 2.8 pCi/L and are not considered elevated relative to the USEPA primary drinking water standard.

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