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Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2016–2018

Open-File Report 2021–1124

U.S. Department of the Interior
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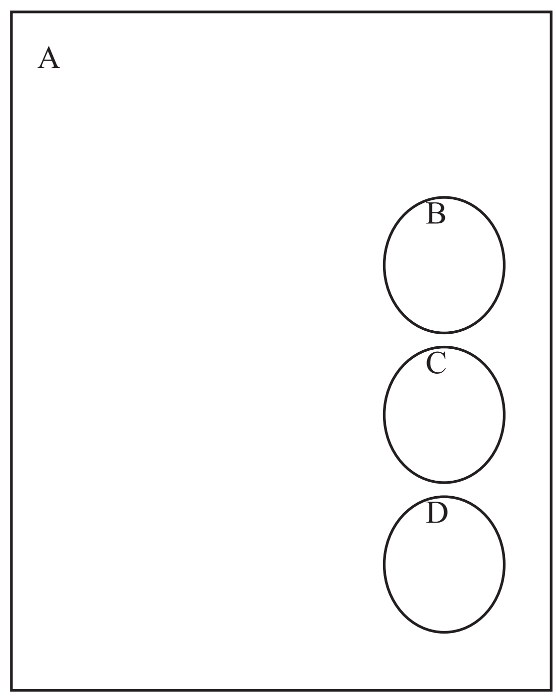

Cover. *A*, Unnamed Spring near Dennehotso, Arizona *B*, hydrologic technician collecting water-level measurement from a windmill powered stock well, *C*, base-flow discharge measurement using a Parshall flume at Dinnebito Wash near Sand Springs, Arizona streamflow gaging station, *D*, municipal well and storage tank at Kits'illi, Arizona. Photographs by Jon Mason, U.S. Geological Survey.

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per year	3.785	liter per year (L/yr)

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Supplemental Information

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

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

Abbreviations

ADWR	Arizona Department of Water Resources
BIA	Bureau of Indian Affairs
C aquifer	Coconino aquifer
D aquifer	Dakota aquifer
EPA	U.S. Environmental Protection Agency
MCL	Maximum Contaminate Level
N aquifer	Navajo aquifer
NTUA	Navajo Tribal Utility Authority
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
PWCC	Peabody Western Coal Company
QC	Quality control
SMCL	Secondary Maximum Contaminate Level
T aquifer	Toreva aquifer
USGS	United States Geological Survey

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By Jon P. Mason

Abstract

The Navajo (N) aquifer is the primary source of groundwater in the 5,400-square-mile Black Mesa area in northeastern Arizona. Availability of water is an important issue in the Black Mesa area because of continued water requirements for industrial and municipal use by a growing population and because of its arid climate. Precipitation in the area typically ranges from less than 6 to more than 16 inches per year depending on location.

The U.S. Geological Survey water-monitoring program in the Black Mesa area began in 1971 and provides information about the long-term effects of groundwater withdrawals from the N aquifer for industrial and municipal uses. This report presents results of data collected as part of the monitoring program in the Black Mesa area from November 2016 to December 2018. The monitoring program includes measurements of (1) groundwater withdrawals (pumping), (2) groundwater levels, (3) spring discharge, (4) surface-water discharge, and (5) groundwater and surface-water chemistry.

In calendar year 2017, total groundwater withdrawals were 3,710 acre-feet (acre-ft), industrial withdrawals were 1,110 acre-ft, and municipal withdrawals were 2,600 acre-ft. In calendar year 2018, total groundwater withdrawals were 3,670 acre-ft, industrial withdrawals were 1,170 acre-ft, and municipal withdrawals were 2,500 acre-ft. Total withdrawals during 2017 and 2018 were about 49 percent less than total withdrawals in 2005 because of Peabody Western Coal Company’s discontinued use of water to transport coal in a coal slurry pipeline.

From the prestress period (prior to 1965) to 2018, measured water levels available for comparison in wells completed in the unconfined areas of the N aquifer within the Black Mesa area declined in 8 of 14 wells, the changes ranged from +12.1 feet to −39.4 feet, and the median change was -0.6 feet. Water levels also declined in 15 of 18 wells measured in the confined area of the aquifer. The median change for the confined area of the aquifer was −40.2 feet (ft), with changes ranging from +14.2 ft to −189.0 ft. From the prestress period to 2018, the median water-level change for all 32 wells in both the confined and unconfined areas was −9.4 ft.

Spring flow was measured at four springs in 2017 and 2018. Flow fluctuated during the period of record for Burro Spring and Pasture Canyon Spring, but a decreasing trend was statistically significant ($p<0.05$) at Moenkopi School Spring and Unnamed Spring near Dennehotso. Discharge at Burro Spring has remained relatively constant since it was first measured in the 1980s and discharge at Pasture Canyon Spring has fluctuated for the period of record.

Continuous records of surface-water discharge in the Black Mesa area were collected from streamflow-gaging stations at the following sites: Moenkopi Wash at Moenkopi 09401260 (1976 to 2018), Dinnebito Wash near Sand Springs 09401110 (1993 to 2018), Polacca Wash near Second Mesa 09400568 (1994 to 2018), and Pasture Canyon Springs 09401265 (2004 to 2018). Median winter flows (November through February) of each water year were used as an index of the amount of groundwater discharge at the above-named sites. For the period of record, the median winter flows have generally remained constant at Dinnebito Wash and Polacca Wash, whereas a decreasing trend was indicated at Moenkopi Wash and Pasture Canyon Springs.

In 2017 and 2018, water samples collected from two wells, four springs, and three streams in the Black Mesa area were analyzed for selected chemical constituents. The results from wells and springs were compared with previous analyses from the same wells and springs. At the Peabody 2 well, a significant ($p<0.05$) decreasing trend in dissolved solids over time was found, while concentrations of dissolved solids have not varied significantly ($p>0.05$) at the Kykotsmovi PM2 well. Dissolved solids, chloride, and sulfate concentrations increased at Moenkopi School Spring during the more than 30 years of record at that site. Concentrations of dissolved solids, chloride, and sulfate at Pasture Canyon Spring have not varied significantly ($p>0.05$) since the early 1980s, and there is no increasing or decreasing trend in those data. Concentrations of dissolved solids, chloride, and sulfate at Burro Spring and Unnamed Spring near Dennehotso have varied for the period of record, but there is no statistical trend in the data. Baseflow water chemistry samples were collected from Moenkopi, Dinnebito, and Polacca washes in 2017. Samples from all three washes had total-dissolved solids concentrations higher than is typically found in the N aquifer water.

Introduction

The 5,400-square-mile (mi^2) Black Mesa study area is enclosed within the Navajo and Hopi Indian Reservations in northeastern Arizona (fig. 1). It contains diverse topography which includes flat plains, mesas, and incised drainages.

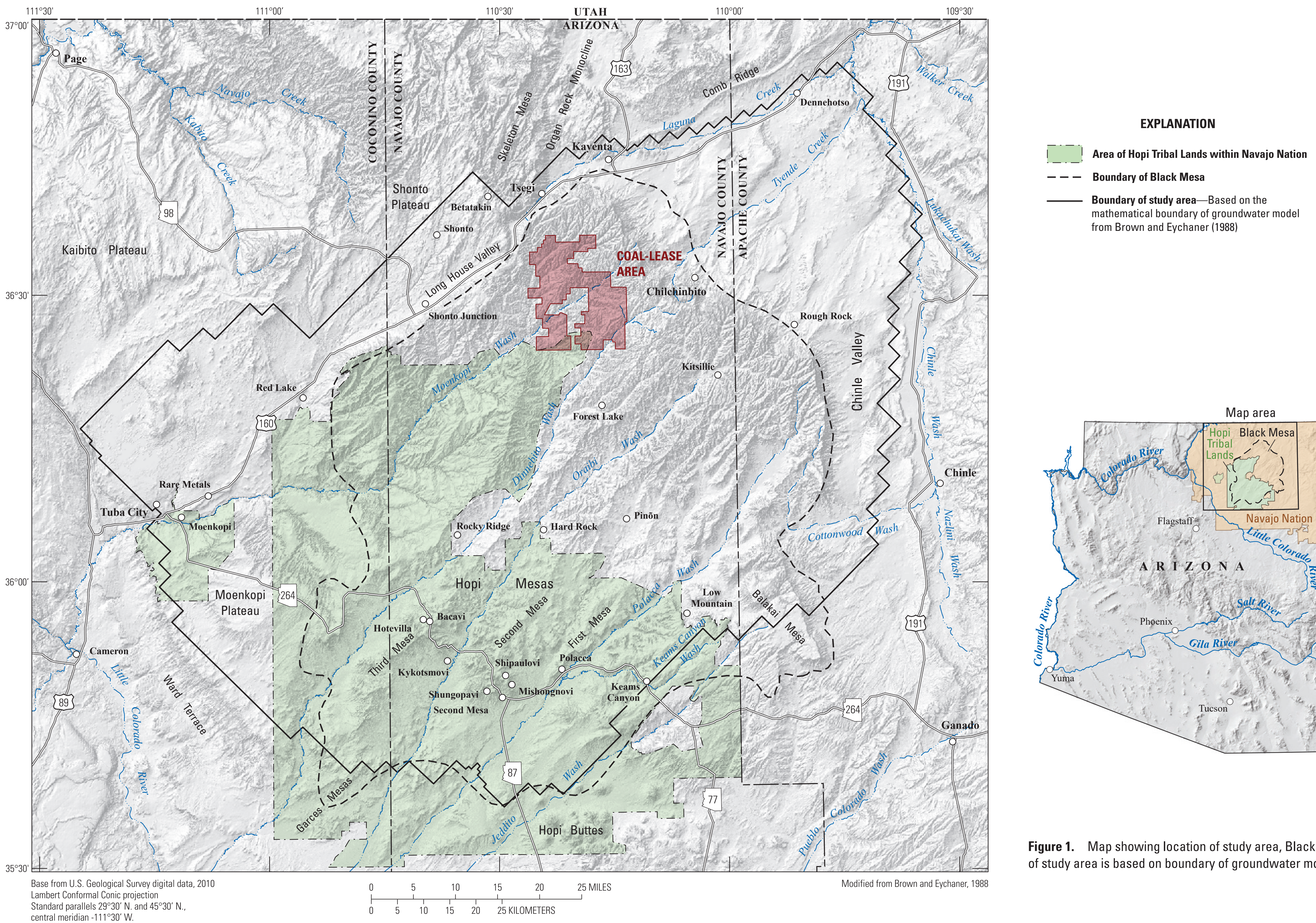


Figure 1. Map showing location of study area, Black Mesa area, northeastern Arizona. Boundary of study area is based on boundary of groundwater model from Eychaner, 1983.

Black Mesa, a topographic high at the center of the study area, encompasses about 2,000 mi^2. It has 2,000-foot-high cliffs on its northern and northeastern sides, but it slopes gradually down to the south and southwest. Availability of water is an important issue in the study area because of continued groundwater withdrawals, the growing population, and an arid to semiarid climate.

Aquifers that are utilized in the Black Mesa area include the Toreva (T), Dakota (D), and Navajo (N) aquifers (fig. 2). Shallow aquifers composed of surficial sediments or volcanic rock are used locally to supply small quantities of water. The N aquifer is the major source of water for industrial and municipal uses in the Black Mesa area. For this reason, groundwater data collected for this report was exclusively from the N aquifer. Water from the T and D aquifers are not used in substantial quantities in the Black Mesa area. Water from the T aquifer is used locally for livestock watering and to irrigate small plots of land, but it likely cannot produce enough water for municipal or industrial use. Water from the D aquifer is used locally for livestock watering and has contributed to some wells at the Peabody Western Coal Company (PWCC) well field, but water from the aquifer has elevated total-dissolved solids concentrations that make it unsuitable for municipal use. The deeper Coconino (C) aquifer is present throughout the Black Mesa area, but it is deeply buried and likely has total-dissolved solids concentrations above what can be used without treatment.

According to Eychaner (1983) the N aquifer is composed of three hydraulically connected formations—the Navajo Sandstone, Kayenta Formation, and Wingate Sandstone—that function as a single aquifer (fig. 2). However, more recent geologic mapping indicates the Wingate Sandstone is absent from much of the Black Mesa area. Outcrops of sandstone previously mapped as Wingate Sandstone in the Black Mesa area are now considered to be part of the Moenave Formation (Billingsley and others, 2012, 2013). Based on this recent geologic mapping it is unclear if the Wingate Sandstone is present at all in the Black Mesa area. If present it would only be in the northeastern part of the study area where it would be deeply buried. The N aquifer is confined under most of Black Mesa, and the overlying stratigraphy limits recharge to this part of the aquifer. The N aquifer is unconfined in areas surrounding Black Mesa, and most recharge occurs where the Navajo Sandstone is exposed in the area near Shonto (fig. 1) (Lopes and Hoffmann, 1997). From the recharge areas near Shonto, groundwater moves radially southwest toward Tuba City, south toward the Hopi Reservation, and east toward Rough Rock and Dennehotso (Eychaner, 1983).

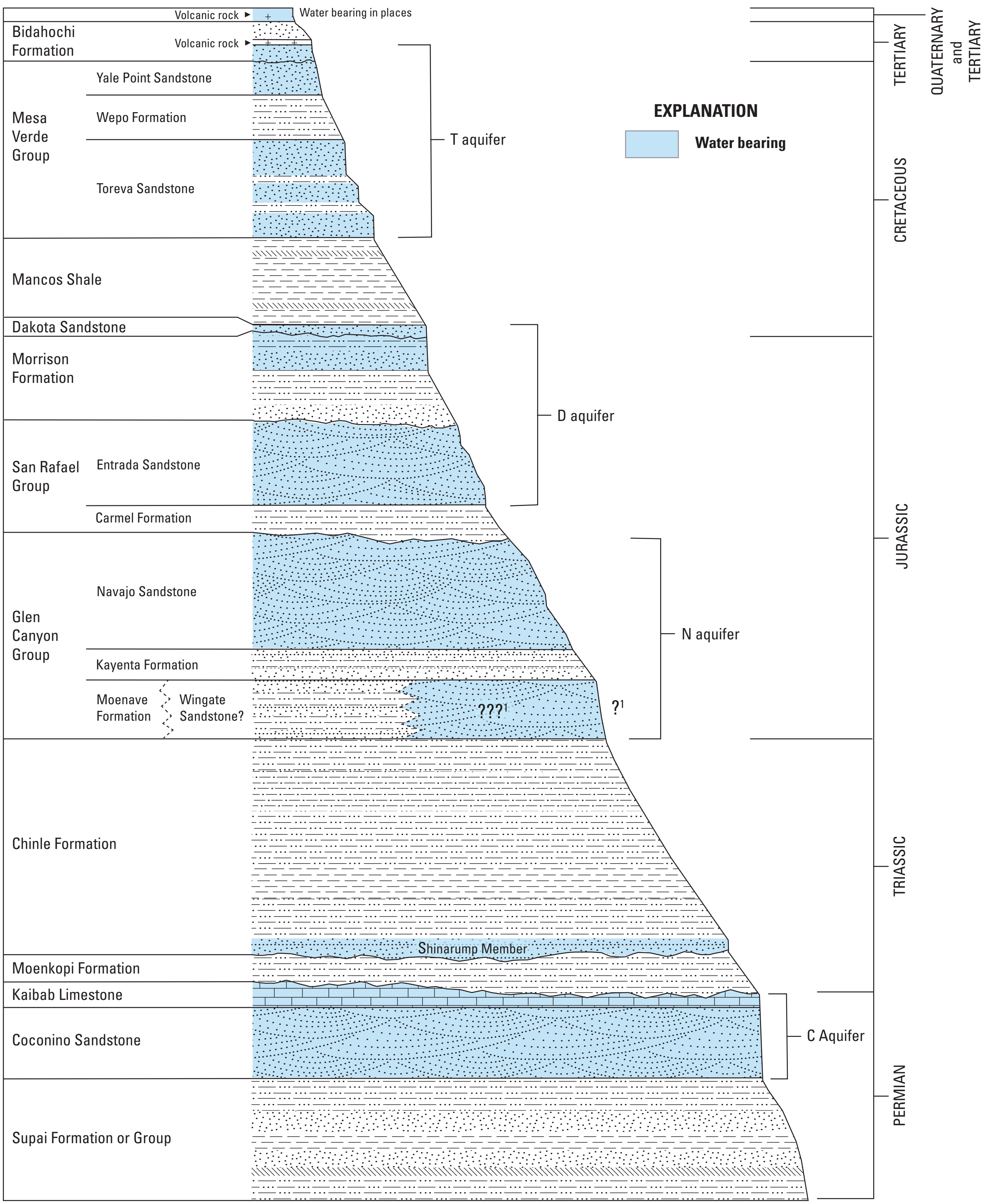
Within the Black Mesa study area, the Navajo Nation and Hopi Tribe are the principal municipal water users, and PWCC is the principal industrial water user. Withdrawals from the N aquifer in the Black Mesa area increased fairly consistently from 1965 through 2005 and then decreased markedly in 2006 (table 1). PWCC began operating a strip mine in the northern part of the study area in 1968 (highlighted red in fig. 1). PWCC's mining operation consisted of two mines on Black Mesa—the Kayenta mine, which transported coal to the Navajo Generating Station by train, and the Black Mesa mine, which transported coal 275 miles to the Mohave Generating Station by a water-based coal slurry pipeline.

PWCC operated both mines on Black Mesa from the 1970s until about 2005, when the Mohave Generating Station ceased operations. On December 31, 2005, PWCC reduced pumping of the N aquifer by approximately 70 percent as a result of discontinued use of the coal slurry pipeline that delivered water, in addition to coal, to the Mohave Generating Station. The two mines at PWCC have since been combined into the Black Mesa Complex, which still delivers coal to the Navajo Generating Station by an electric train. PWCC continued to pump about 1,100 to 1,600 acre-feet (acre-ft) per year after 2005, primarily for dust control (table 1).

There are four major stream systems that provide surface drainage for the Black Mesa area. They are Moenkopi Wash, Dinnebito Wash, Oraibi Wash, and Polacca Wash. All four stream systems have headwaters high on Black Mesa and eventually drain into the Little Colorado River to the south

Table 1. Withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2018.

Calendar Year	Industrial[a]	Municipal[b,c]		Total withdrawals
		Confined	Unconfined	
1965	0	50	20	70
1966	0	110	30	140
1967	0	120	50	170
1968	100	150	100	350
1969	40	200	100	340
1970	740	280	150	1,170
1971	1,900	340	150	2,390
1972	3,680	370	250	4,300
1973	3,520	530	300	4,350
1974	3,830	580	360	4,770
1975	3,500	600	510	4,610
1976	4,180	690	640	5,510
1977	4,090	750	730	5,570
1978	3,000	830	930	4,760
1979	3,500	860	930	5,290
1980	3,540	910	880	5,330
1981	4,010	960	1,000	5,970
1982	4,740	870	960	6,570
1983	4,460	1,360	1,280	7,100
1984	4,170	1,070	1,400	6,640



[1]Unclear if present, some outcrops formerly mapped as Wingate Sandstone are now considered part of Moenave Formation (Billingsley and others, 2012, 2013).

Modified from Harshberger and others, 1966

Figure 2. Stratigraphic section showing rock formations and hydrogeologic units of the Black Mesa area, northeastern Arizona (not to scale). The N aquifer is approximately 1,000 feet thick.

Table 1.—Continued

Calendar Year	Industrial[a]	Municipal[b,c]		Total withdrawals
		Confined	Unconfined	
1985	2,520	1,040	1,160	4,720
1986	4,480	970	1,260	6,710
1987	3,830	1,130	1,280	6,240
1988	4,090	1,250	1,310	6,650
1989	3,450	1,070	1,400	5,920
1990	3,430	1,170	1,210	5,810
1991	4,020	1,140	1,300	6,460
1992	3,820	1,180	1,410	6,410
1993	3,700	1,250	1,570	6,520
1994	4,080	1,210	1,600	6,890
1995	4,340	1,220	1,510	7,070
1996	4,010	1,380	1,650	7,040
1997	4,130	1,380	1,580	7,090
1998	4,030	1,440	1,590	7,060
1999	4,210	1,420	1,480	7,110
2000	4,490	1,610	1,640	7,740
2001	4,530	1,490	1,660	7,680
2002	4,640	1,500	1,860	8,000
2003	4,450	1,350	1,440	7,240
2004	4,370	1,240	1,600	7,210
2005	4,480	1,280	1,570	7,330
2006	1,200	[d]1,300	[d]1,600	[d]4,100
2007	1,170	1,460	1,640	4,270
2008	1,210	[e,f]1,430	[e]1,560	[f]4,200
2009	1,390	1,440	1,400	4,230
2010	1,170	[d]1,450	1,420	[d]4,040
2011	1,390	[d]1,460	1,630	[d]4,480
2012	1,370	[d]1,380	1,260	[d]4,010
2013	1,460	[d]1,410	[d]1,110	[d]3,980
2014	1,580	[d]1,280	[d]1,310	[d]4,170
2015	1,340	[d]1,370	[d]1,260	[d]3,970
2016	1,090	[d]1,380	[d]1,070	[d]3,540
2017	1,110	1,330	[d]1,270	[d]3,710
2018	1,170	[d]1,370	1,130	[d]3,670

[a]Metered pumpage from the confined part of the aquifer by Peabody Western Coal Company.

[b]Does not include withdrawals from the wells equipped with windmills.

[c]Includes estimated pumpage 1965–73 and metered pumpage 1974–79 at Tuba City; metered pumpage at Kayenta and estimated pumpage at Chilchinbito, Rough Rock, Piñon, Keams Canyon, and Kykotsmovi before 1980; metered and estimated pumpage furnished by the Navajo Tribal Utility Authority and the Bureau of Indian Affairs and collected by the U.S. Geological Survey, 1980–85; and metered pumpage furnished by the Navajo Tribal Utility Authority, the Bureau of Indian Affairs, various Hopi Village Administrations, and the U.S. Geological Survey, 1986–2018.

[d]Meter data were incomplete; therefore, municipal withdrawals are estmated, and total withdrawal uses an estimation in the calculation.

[e]Confined and unconfined totals were reversed in previous reports.

[f]Confined withdrawals are about 90 acre-ft greater than previously reported.

and southwest of the study area (fig. 1). Most reaches of these streams are ephemeral, flowing only in response to runoff from precipitation events, but a few short reaches flow at least part of each year as a result of groundwater discharge.

The members of the Navajo Nation and the Hopi Tribe have been concerned about the long-term effects of withdrawals from the N aquifer on available groundwater supplies, on stream and spring discharge, and on groundwater chemistry. In 1971, these water-supply concerns led to the establishment of a monitoring program for the water resources in the Black Mesa area by the U.S. Geological Survey (USGS) in cooperation with the Arizona Water Commission, which was the predecessor to the present Arizona Department of Water Resources (ADWR). In 1983, the Bureau of Indian Affairs (BIA) joined the cooperative effort. Since 1983, the Navajo Tribal Utility Authority (NTUA), the PWCC, the Hopi Tribe, and the Western Navajo, Chinle, and Hopi Agencies of the BIA have assisted in the collection of hydrologic data.

Purpose and Scope

This report presents results of groundwater, surface-water, and water-chemistry monitoring in the Black Mesa area from November 2016 to December 2018. Continuous and periodic groundwater and surface-water data are collected to monitor the possible effects of industrial and municipal withdrawals from the N aquifer on groundwater levels, stream and spring discharge, and groundwater chemistry. Groundwater data include groundwater withdrawals (pumping), water levels, spring-discharge rates, and water chemistry. Surface-water data include discharge rates at four continuous-record streamflow-gaging stations and water chemistry from three of the gaging stations. Together, these data are compared with groundwater and surface-water data from 1965 to 2018 to describe the overall status of and change over time of groundwater conditions in the N aquifer, as well as to provide information on how the aquifer responds to groundwater development stresses. Some statistical analyses of the data are included in this report to examine trends in the data that characterize groundwater conditions in the N aquifer.

Previous Investigations

Progress reports on the Black Mesa area monitoring program have been prepared by the USGS since 1978, and these progress reports are summarized in table 2. The groundwater-level, surface-water discharge, and water chemistry data from the Black Mesa area monitoring program are contained in these progress reports and in the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/az/nwis/). Water-withdrawal data are presented in tables in the progress reports.

Stream-discharge and periodic water-quality data collected from Moenkopi Wash before the 1982 water year were published by the USGS (1963–64a,b; 1965–74a,b; and 1976–83). Stream-discharge data from water years 1983 to 2005 for Moenkopi Wash at Moenkopi (09401260), Dinnebito Wash near Sand Springs (09401110), Polacca Wash near Second Mesa (09400568), Laguna Creek at Dennehotso (09379180), and Pasture Canyon Spring (09401265) in the Black Mesa area were published in White and Garrett (1984, 1986, 1987, 1988), Wilson and Garrett (1988, 1989), Boner and others (1989, 1990, 1991, 1992), Smith and others (1993, 1994, 1995, 1996, 1997), Tadayon and others (1998, 1999, 2000, 2001), McCormack and others (2002, 2003), Fisk and others (2004, 2005, 2006), and online for year 2006 to present (http://wdr.water.usgs.gov). Before the monitoring

Table 2. Tabulated list of progress reports for the Black Mesa monitoring program 1978–2018.

Year published	Author(s)	Title	USGS report type and number
1978	U.S. Geological Survey	Progress report on Black Mesa monitoring program—1977	Open-File Report 78–459
1985	Hill, G.W.	Progress report on Black Mesa monitoring program—1984	Open-File Report 85-483
1986	Hill, G.W., and Whetten, M.I.	Progress report on Black Mesa monitoring program—1985–86	Open-File Report 86-414
1987	Hill, G.W., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987	Open-File Report 87–458
1988	Hart, R.J., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987–88	Open-File Report 88–467
1989	Hart, R.J., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1988–89	Open-File Report 89–383
1992	Sottilare, J.P.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1989–90	Water-Resources Investigations Report 92–4008
1992	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1990–91	Water-Resources Investigations Report 92–4045
1993	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1991–92	Water-Resources Investigations Report 93–4111
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1992–93	Water-Resources Investigations Report 95–4156
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-chemistry monitoring, Black Mesa area, northeastern Arizona—1994	Water-Resources Investigations Report 95–4238
1996	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1995	Open-File Report 96–616
1997	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1996	Open-File Report 97–566

Table 2.—Continued

Year published	Author(s)	Title	USGS report type and number
1999	Littin, G.R., Baum, B.M., and Truini, Margot	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1997	Open-File Report 98–653
2000	Truini, Margot, Baum, B.M., Littin, G.R., and Shingoite-wa-Honanie, Gayl	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1998	Open-File Report 00–66
2000	Thomas, B.E., and Truini, Margot	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona–1999	Open-File Report 00–453
2002a	Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2000–2001, and performance and sensitivity of the 1988 USGS numerical model of the N aquifer	Water-Resources Investigations Report 02–4211
2002b	Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2001–02	Open-File Report 02–485
2004	Truini, Margot, and Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2002–03	Open-File Report 03–503
2005	Truini, Margot, Macy, J.P., and Porter, T.J.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2003–04	Open-File Report 2005–1080
2006	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2004–05	Open-File Report 2006–1058
2007	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2005–06	Open-File Report 2007–1041
2008	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2006–07	Open-File Report 2008–1324
2009	Macy, J.P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2007–2008	Open-File Report 2009–1148
2010	Macy, J.P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2008–2009	Open-File Report 2010–1038
2011	Macy, J.P., and Brown, C.R.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2009–2010	Open-File Report 2011-1198
2012	Macy, J.P., Brown, C.R., and Anderson, J.R.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2010–2011	Open-File Report 2012-1102
2014	Macy, J.P., and Unema, J.A.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2011–2012	Open-File Report 2013-1304
2015	Macy, J.P. and Truini, Margot	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2012–2013	Open-File Report 2015-1221
2017	Macy, J.P., and Mason, J.P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2013–2015	Open-File Report 2017-1127
2018	Mason, J.P., and Macy, J.P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2015–2016	Open-File Report 2018-1193

program, a large data-collection effort in the 1950s resulted in a compilation of well and spring data for the Navajo and Hopi Indian Reservations (Davis and others, 1963).

Many interpretive studies have investigated the hydrology of the Black Mesa area. Cooley and others (1969) made the first comprehensive evaluation of the regional hydrogeology of the Black Mesa area. Eychaner (1983) developed a two-dimensional numerical model of groundwater flow in the N aquifer. Brown and Eychaner (1988) recalibrated Eychaner's model by using a finer grid and by using revised estimates of selected aquifer characteristics. GeoTrans, Inc. (1987) also developed a two-dimensional numerical model of the N aquifer in the 1980s. In the late 1990s, HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering (1999) developed a three-dimensional numerical model of the N aquifer and the overlying D aquifer.

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water collected from wells and springs in the Black Mesa area. HSIGeoTrans, Inc. (1993) evaluated the major-ion and isotopic chemistry of the D and N aquifers. Lopes and Hoffmann (1997) analyzed groundwater ages, recharge, and hydraulic conductivity of the N aquifer by using geochemical techniques. Zhu and others (1998) estimated groundwater recharge in the Black Mesa area by using isotopic data and flow estimates from the N-aquifer model developed by GeoTrans, Inc. (1987). Zhu (2000) estimated recharge using advective transport modeling and the same isotopic data from the GeoTrans model. Truini and Longsworth (2003) described the hydrogeology of the D aquifer and the movement and ages of groundwater in the Black Mesa area by using data from geochemical and isotopic analyses. Truini and Macy (2005) looked at possible leakage through the confining unit between the D aquifer and the N aquifer as part of an investigation of the Carmel Formation.

Description of Study Area

The availability and chemistry of water resources within the Black Mesa area are directly related to physiography, climate, and geology. Physiography affects the movement of both surface water and groundwater in the area, and climate affects the water budget. The complex geologic history of the area has resulted in the accumulation of abundant coal resources and influences the movement and chemistry of surface water and groundwater.

Physiography

The Black Mesa area is in the Colorado Plateau Physiographic Province of the Rocky Mountain Region (Raisz, 1972). The dominant physiographic feature in the study area is Black Mesa itself, but numerous smaller features play an important role in the movement of surface water and groundwater (fig. 1). Black Mesa is the remnant of a large sedimentary basin that has undergone substantial tectonic deformation and uplift during the past 70 million years. Parts of Black Mesa which were once below sea level now rise over 8,000 feet above sea level. As a result of this uplift, the region has gone from a depositional cycle to an erosional cycle. Much of the erosion responsible for present day topography likely occurred in the past 10 million years (Lazear and others, 2013). Since uplift occurred, Black Mesa has been dissected by streams, resulting in the formation of numerous smaller mesas such as the Hopi Mesas.

The geologic units that comprise the N aquifer occur at or near the land surface in a large extent around the periphery of Black Mesa. In these areas the aquifer is generally unconfined. West of Kayenta, exposed N aquifer units form Skeleton Mesa and the Shonto Plateau. At the southeast edges of these features, the aquifer units are folded by the Organ Rock monocline (fig. 3) and plunge steeply to the southeast below the younger Cretaceous rocks of Black Mesa forming Long House Valley. The N aquifer units continue to the southeast under Black Mesa eventually reappearing south of the Hopi Mesas. The aquifer units pinch out not far from where they reappear. In general, the confined portion of the N aquifer occurs where the aquifer units are deeply buried beneath Black Mesa.

The paths of stream channels also are influenced by physiography. Geologic structural folds, joint patterns, rock type, and topography all affect the flow of surface water in the study area. Major streams of the study area are shown in figure 1. The surface topography of Black Mesa slopes downhill from northeast to southwest. Likewise, the major streams that drain Black Mesa flow from northeast to southwest toward the Little Colorado River.

Climate

The climate in most of the Black Mesa area is broadly classified by Hendricks (1985) as steppe, which is characterized by limited amounts of precipitation. Much of the precipitation in steppe regions evaporate before it can infiltrate to groundwater. As a result, the vegetation cover consists

Figure 3. Aerial photograph of Organ Rock monocline and folding strata of Skeleton Mesa near Kayenta, Arizona. The Navajo Sandstone is truncated in this part of the monocline, forming the flatirons along the lower part of the monocline. Photograph by Jodi Norris.

mostly of mesquite, pinyon-juniper, and various grasses (Hendricks, 1985). A small area around Tuba City is classified by Hendricks (1985) as desert, signifying even less annual rainfall and a vegetative cover consisting mostly of creosote bush, cacti, and sagebrush.

Mean annual precipitation for the Black Mesa area was estimated using spatial regression methods that incorporated precipitation data from traditional weather stations and high-altitude meteorological sites (Daly and others, 1994). Based on 30-year averages from 1981–2010, annual precipitation in the Black Mesa area ranges from less than 6 inches (in) in the lower elevation regions around the mesa to more than 16 in at the highest elevations on the mesa (fig. 4; PRISM Climate Group, 2018).

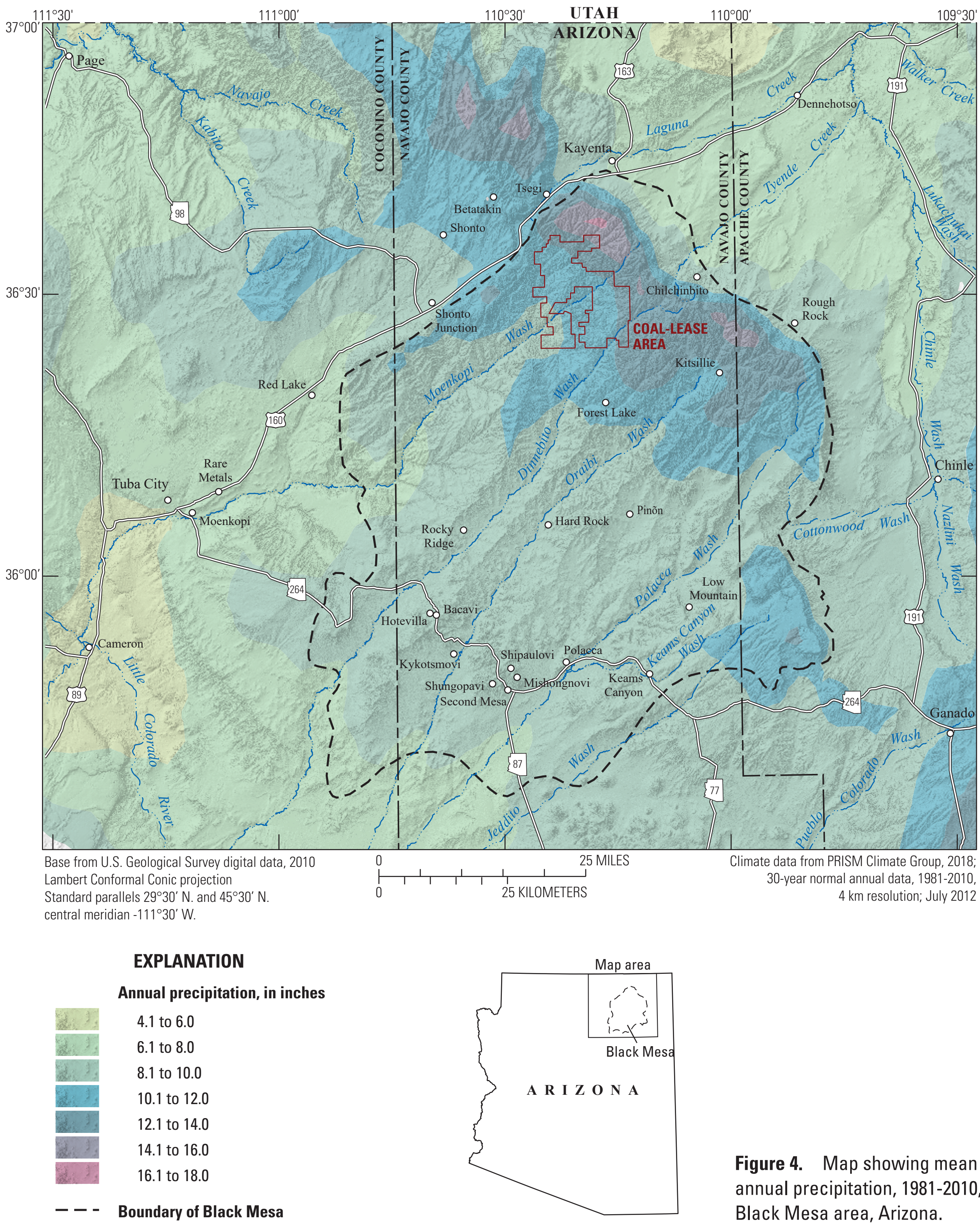


Figure 4. Map showing mean annual precipitation, 1981-2010, Black Mesa area, Arizona.

According to Sellers and Hill (1974), about 60 percent of average annual precipitation in northeastern Arizona falls between the months of May and October (primarily in July and August). They report that, on average, the plateaus and mesas of northeastern Arizona are the driest part of the state during the colder half of the year and rarely receive heavy winter precipitation. Using more recent precipitation data, an analysis of 30-year normal precipitation for the period 1981–2010 (PRISM Climate Group, 2018) in the Black Mesa area show that about 55 percent of precipitation occurred from May–October. An important factor when thinking about recharge to the N aquifer is that much of the groundwater contained in the N aquifer was recharged during the late Pleistocene when the temperature was cooler and precipitation amounts were higher (Zhu and Kipfer, 2010).

Geology

The stratigraphic section (fig. 2) used in the current and previous Black Mesa monitoring reports was modified from Harshbarger and others (1966). The original stratigraphic section showed the Wingate Sandstone occurring between the Chinle Formation and the Kayenta Formation and did not have the Moenave Formation present. More recently, Billingsley and others (2012, 2013) concluded that sandstones in the Black Mesa area formerly mapped in outcrop as Wingate Sandstone are in fact part of the Moenave Formation. It is unclear if the Wingate Sandstone could be present in the subsurface under parts of the Black Mesa area. Since the two geologic units are considered coeval, the Moenave Formation is shown as present and possibly intertongued with the Wingate Sandstone in figure 2. Harshbarger and others (1966) considered the eolian facies of the Wingate Sandstone to be a water-bearing unit of the N aquifer. It is unclear if any of the sandstones now mapped as Moenave Formation could be water bearing.

Rocks of Triassic age and older are not discussed in detail in this report because they are not significant sources of groundwater in the Black Mesa area. Instead, this section focusses on Jurassic and younger rocks that are part of hydrologic systems utilized in the Black Mesa area.

The Black Mesa area is the remnant of a large sedimentary basin that has been uplifted and dissected by streams since its original formation. When the sedimentary rock units (fig. 2) in the Black Mesa area were deposited the region had a much lower surface elevation nearer to, and sometimes below, sea level. As the thick sequence of sedimentary rock units was being deposited, the basin was slowly subsiding, allowing more sediments from nearby highlands to be deposited. The entire Colorado Plateau including Black Mesa was tectonically uplifted a mile above sea level during the Tertiary by processes that are still not fully understood. According to Flowers (2010), Colorado Plateau "elevation gain could have occurred in early Tertiary time associated with [the] Sevier-Laramide contraction, middle-Tertiary time synchronous with the proposed demise of the Laramide flat slab, [or] late Tertiary time coeval with regional extensional tectonism in adjacent provinces."

Geologic Units Below the N Aquifer

The geologic units below the N aquifer system are Triassic and older in age (fig. 2) and generally are not suitable as a water supply in the Black Mesa area and will not be discussed in detail. The Permian Coconino Sandstone and Kaibab Limestone (fig. 2) can produce adequate quantities of water in the Black Mesa area, but they are deeply buried and likely have total-dissolved solids concentrations above what can be used without treatment.

Geologic Units of the N Aquifer

The geologic units that make up the N aquifer are members of the Glen Canyon Group and include the Moenave Formation, Wingate Sandstone, Kayenta Formation, and Navajo Sandstone (fig. 2). The group is named after Glen Canyon of the Colorado River in southeastern Utah where these units are typically exposed (Harshbarger and others, 1957). The Glen Canyon Group was originally thought to be Late Triassic to Early Jurassic in age (Harshbarger and others, 1957), but more recent paleontological and stratigraphic discoveries strongly suggest the group is largely Early Jurassic in age (Peterson and Pipiringos, 1979). According to Blakey and Ranney (2008), when the Glen Canyon group was deposited, the Black Mesa Basin was slightly above sea level and the climate was windy and dry. This led to widespread deposition of eolian and fluvial deposits (Blakey and Ranney, 2008) that now compose the sandstone units of the N aquifer.

Where the N aquifer is confined it is capped by the Carmel Formation (fig. 2), which is considered part of the San Rafael Group; the Carmel Formation is discussed in this section since it both confines the aquifer in places and hydraulically separates the N aquifer from the overlying D aquifer, where the D aquifer is present.

Moenave Formation

The Moenave Formation (fig. 2) contains several members with the most prominent one in the Black Mesa area being the Dinosaur Canyon Member. Blakey and Ranney (2008) described the Moenave Formation as being deposited by northwest flowing streams, concurrently the Wingate Sandstone was being deposited to the northeast. Billingsley and others (2012) described the lithology of the formation as reddish-brown, thin, flat, and crossbedded, fine to coarse-grained fluvial siltstone and silty sandstone.

The Moenave Formation forms distinctive orange-red cliffs along the southwest edge of the Moenkopi Plateau and west of Oraibi Wash on Garces Mesas (figs. 1 and 5). The Moenave Formation is not known to yield economic quantities of water in the Black Mesa area.

Figure 5. Aerial photograph of Moenave Formation outcropping on Garces Mesas, northeastern Arizona. White caprock on top of the Moenave Formation is silicified sandstone of the Kayenta Formation. Photograph by Jon Mason, USGS.

Wingate Sandstone

It is uncertain if the Wingate Sandstone is present in the Black Mesa area. Billingsley and others (2012 and 2013) considered the Wingate Sandstone to be absent from the Moenkopi Plateau and the Hopi Buttes area and concluded that sandstones in these areas formerly mapped as Wingate are in fact part of the Moenave Formation. The Wingate Sandstone may be present deep in the subsurface of the northeastern part of the Black Mesa area, but there is no corroborating information to verify this. Historically the Wingate Sandstone was divided into two members. The upper unit was the Lukachukai Member, which consisted mostly of eolian, large-scale crossbedded sandstone, while the lower Rock Point Member mainly consisted of flat-bedded fluvial and lacustrine sediments (McKee and MacLachlan, 1959). More recently, the Rock Point Member has been assigned to the underlying Chinle Formation and the Lukachukai Member has been dropped, leaving the name Wingate Sandstone (Dubiel, 1989). At its type locality near Fort Wingate, New Mexico, Harshbarger and others (1957) described the Wingate Sandstone as “pale-reddish-brown fine- to very fine-grained quartz sandstone.” Harshbarger and others (1966) considered the eolian facies of the Wingate Sandstone to be a water-bearing unit of the N aquifer where present.

Kayenta Formation

According to Blakey and Ranney (2008), the Wingate sand dunes were eventually “overwhelmed everywhere by a sandy, braided fluvial system preserved as the Kayenta Formation” (fig. 2). Imlay (1980) reported that the Kayenta Formation consists of light-gray to reddish-orange sandstone and siltstone. The sandstone layers in the Kayenta Formation tend to form ledges whereas the siltstone layers form slopes. Wilson (1965) described the thickness of the Kayenta Formation in south-central Utah as increasing progressively from east to west in part owing to intertonguing with the overlying Navajo Sandstone. Intertonguing of the Kayenta Formation and Navajo Sandstone can be seen clearly in outcrops of the two units along Moenkopi Wash near Tuba City. The Kayenta Formation does not yield economic quantities of water in the Black Mesa area and is therefore not considered an aquifer.

Navajo Sandstone

The Navajo Sandstone is the principal water-bearing unit of the N aquifer (fig. 2). According to Harshbarger and others (1957) it is an eolian deposit made up of sediments derived in part from fluvial deposits of the underlying Kayenta Formation. Beitler and others (2005) described the Navajo Sandstone as a “subrounded, fine- to medium grained, well-sorted, quartz arenite to subarkose sandstone.” The type and amount of cement in the sandstone varies considerably and includes quartz, calcite, dolomite, kaolinite, goethite, and hematite. It is characterized by high-angle, large scale cross-stratification and striking red to white color variations. The red pigment in Navajo Sandstone comes from thin hematite grain coatings, when these coatings are reduced by hydrocarbons migrating through, the sandstone is bleached to a lighter color (Beitler and others, 2003). Bedding features in the Navajo Sandstone are identical to those in modern dunes of the transverse and barchan types. In the Black Mesa area, the Navajo Sandstone contains many lenticular beds of cherty limestone deposited in interdune lakes that can be seen between Tuba City and the Hopi Buttes (Harshbarger and others, 1957).

The thickness of the Navajo Sandstone was reported by Harshbarger and others (1957) as 950 feet (ft) near Shonto, 478 ft near Dennehotso, 335 ft at Rock Point, and 15 ft northwest of Chinle. Well log data indicate that the top of the Navajo Sandstone is about 2,500 ft below the Black Mesa Mine Complex and has a thickness in the mine area of around 700 ft. In the Tuba City area, where the Navajo Sandstone and Kayenta Formation are intertongued, well log data suggest the combined thickness of the intertongued portion to be greater than 500 ft. Interpretation of the well log from Black Mesa observation well 3 (BM 3) located in Kayenta indicate the top of the Navajo Sandstone is about 155 ft below land surface and that the unit is about 700 ft thick. In the Keams Canyon area, well logs indicate the top of the Navajo Sandstone is about 900 ft below land surface and has a thickness of around 150 ft. Well logs from Kykotsmovi Village indicate the top of the Navajo Sandstone is around 850 ft below land surface with a thickness of over 200 ft.

Carmel Formation

The Carmel Formation (fig. 2) is part of the San Rafael Group. Harshbarger and others (1957) reported the formation in northeastern Arizona as Middle and Late Jurassic in age and consisting of resistant ledge-forming sandstone beds 1 to 3 ft thick separated by slope-forming siltstone strata 5 to 20 ft thick. They further described the siltstone beds as weakly cemented grayish red, weathering to pale reddish brown in color, and the sandstone beds as light greenish gray, weathering to pale yellow (Harshbarger and others, 1957). In most places in northeastern Arizona the Carmel Formation is 100 to 200 ft thick but is thinner at the limits of its deposition (Harshbarger and others, 1957).

According to Blakey and others (1983), the Carmel Formation was deposited in two major transgressive-regressive cycles of the Jurassic Western Interior Seaway, resulting in varied depositional facies including fluvial, eolian, coastal sabkha, and marine. Where present in the Black Mesa area, the Carmel Formation overlies the Navajo Sandstone, forming a confining layer when the Navajo is fully saturated. In most of the study area where the N aquifer is unconfined, the Carmel Formation is absent.

The Carmel Formation also hydraulically separates the N aquifer from the overlying D aquifer in areas where both aquifers are present. In the southern part of Black Mesa there may be some leakage from the D aquifer through the Carmel Formation into the N aquifer (Truini and Macy, 2005). Because the D aquifer has higher total-dissolved solids concentrations than the N aquifer, leakage between the two could degrade the water quality of the N aquifer.

Geologic Units of the D Aquifer

Entrada Sandstone

The Entrada Sandstone (fig. 2) is part of the San Rafael Group and was deposited during the Middle Jurassic in widespread eolian sand seas that were adjacent and inland from a restricted marine seaway (Blakey, 2008; Peterson, 1988). Harshbarger and others (1957) described two general facies of the Entrada Sandstone in the Black Mesa area. The first is a red silty sandstone which often weathers into hoodoos, the second is a clean, sandy facies which weathers into rounded massive cliffs. Where resistant cap rocks are present, the second facies weathers into prominent cliffs. Billingsley and others (2012) described the sediments in the Entrada Sandstone as crossbedded, white and interbedded white and red in color.

Harshbarger and others (1951) named a unit overlying the Entrada Sandstone near Cow Springs, Arizona, as the Cow Springs Sandstone. Peterson (1988) reported the Cow Springs is closely related to the Entrada Sandstone and often difficult to differentiate from it, but states that the Cow Springs can serve as a useful stratigraphic marker. For this reason, Peterson (1988) reduced the rank of the Cow Springs to a member of the Entrada Sandstone. The Entrada Sandstone is a water-bearing unit of the D aquifer in the Black Mesa area.

Morrison Formation

The Morrison Formation (fig. 2) was deposited by streams draining uplands in Nevada and central Arizona during Late Jurassic time (Blakey and Ranney, 2008). Harshbarger and others (1957) described the Morison Formation as primarily fluvial, consisting of alternating flood-plain and channel deposits. There are several recognized members within the Morrison Formation, but only a general description for the formation will be presented here. The Morrison Formation is often very colorful. Cooley and others (1969) reported formation colors include white, gray, green, red, orange, purple, tan, yellow, and brown. They reported the lithology as having mudstone, siltstone, sandstone, conglomerate, and limestone (Cooley and others, 1969). The extent of the Morrison Formation is not fully known in the Black Mesa area. On the west side of Black Mesa there are areas such as Coal Mine Canyon and Blue Canyon where the adjacent units of Entrada Sandstone and Dakota Sandstone (fig. 2) outcrop, but the Morrison Formation is missing. Cooley and others (1969) show the Morrison Formation present in a band along and to the north and northeast of Black Mesa. Where present, sandstone beds in the Morison Formation can be a water-bearing part of the D aquifer in the Black Mesa area (Cooley and others, 1969).

Dakota Sandstone

According to Aubrey (1992), the Dakota Sandstone (fig. 2) represents a complex variety of continental, marginal-marine, and marine environments, and was deposited during the Late Cretaceous in response to the westward transgression of the Cretaceous Interior Seaway. Blakey and Ranney (2008) described the Dakota Sandstone as being made up of beach and coastal plain deposits. The lithology of the unit is described as "medium-to light-gray, slope-forming, laminated to thin-bedded mudstone, siltstone, and sandstone" by Billingsley and others (2012). Cooley and others (1969) reported that the Dakota Sandstone was the chief unit of the D aquifer system.

Mancos Shale

Kirkland (1991) reported that exposures of Mancos Shale (fig. 2) around Black Mesa represent an open marine environment of the Cretaceous Interior Seaway. According to Blakey and Ranney (2008), the Mancos Shale is drab gray and can form odd, moonlike badlands. A good example of badlands weathering of the Mancos Shale can be seen in Blue Canyon along Moenkopi Wash on the Hopi Reservation. Presumably the canyon takes its name from the blueish-gray hue of the Mancos Shale in this location. The Mancos Shale is a thick aquiclude that separates groundwater in the underlying Dakota Sandstone from that in the overlying sandstone aquifers of the Mesaverde Group (Cooley and others, 1969).

Geologic Units of the T Aquifer

Mesaverde Group

According to Franczyk (1988), geologic units of the Mesaverde Group (fig. 2) in the Black Mesa area (Toreva Formation, Wepo Formation, and Yale Point Sandstone) were deposited during the Late Cretaceous by further transgressions and regressions of the Cretaceous Interior Seaway. The Toreva Formation is likely a fluvial and deltaic deposit laid down as the Cretaceous sea regressed after depositing the Mancos Shale (Franczyk, 1988). The formation has multiple members that represent the different depositional environments associated with coastal deposition. The lithology of the Toreva Formation is varied. Franczyk (1988) reported the formation includes sandstone, siltstone, mudstone, and shale, with some beds being carbonaceous.

Page and Repenning (1958) reported the Wepo Formation is of mostly continental origin and consists of a thick series of intercalated siltstone, mudstone, sandstone, and coal. According to Franczyk (1988), the Wepo Formation was deposited while the Cretaceous Interior Seaway was located to the northeast of Black Mesa. Coal beds mined at the Black Mesa Mine Complex occur in the Wepo Formation.

Molenaar (1983) described the Yale Point Sandstone as a coastal-barrier sandstone deposited during one of the last transgressions of the Cretaceous Interior Seaway. According to O'Sullivan and others (1972), the Yale Point Sandstone is "yellowish gray, weathers grayish orange, and is composed of coarse- to fine grained subrounded to subangular clear quartz." Bedding in the formation is lenticular, and individual units are crossbedded (O'Sullivan and others, 1972).

Sandstone units in the Mesaverde Group can be water-bearing units of the T aquifer. Many small contact springs issue from Mesaverde sandstones around the perimeter of Black Mesa and in canyons where the sandstones have been truncated.

Bidahochi Formation

According to a distribution map of the Bidahochi Formation by Repenning and Irwin (1954), the only place the formation is present in the Black Mesa area is around the Hopi Buttes. They described it as consisting of fluvial and lacustrine deposits and basaltic volcanic rock (Repenning and Irwin, 1954). According to Blakey and Ranney (2008), the depositional environment of the Bidahochi Formation is still unresolved; they suggested the formation could have been deposited in a Neogene lake, but the evidence for this deposition is unclear. Harshbarger and others (1966) reported that the lower part of the Bidahochi Formation can be water bearing.

Hydrologic Data

Groundwater data collected for this report are exclusively from the N aquifer. Water from the T and D aquifers are not used in significant quantities in the Black Mesa area. Water from the T aquifer is used locally for livestock watering and to irrigate small plots of land, but it probably cannot produce enough water for municipal or industrial use. Water from the D aquifer is used locally for livestock watering and in the past contributed to some wells at the PWCC well field, but water from the aquifer generally has total-dissolved solids concentrations that make it unsuitable for municipal use.

In 2016–18, activities of the Black Mesa area monitoring program included metered groundwater withdrawals, measurements of groundwater levels, spring-discharge measurements, streamflow gaging, and the collection of water-chemistry samples from wells, springs, and streams. All data were collected by the USGS except withdrawal data from NTUA wells, which were compiled by NTUA personnel. Linear regression trend analysis was applied to streamflow data, spring-discharge measurements, and water-chemistry samples by using R package stats and R Project for Statistical Computing (R Development Core Team, 2019). Annual discharge measurements were made at 4 springs, and annual groundwater-level measurements were attempted at 34 wells. Of the 34 wells, 6 are continuous-recording observation wells that have been outfitted for real-time data telemetry (referred to as "BM observation well" in table 3 and BM in text). The water-level data from these six continuous-recording observation wells are available on the NWIS website (https://waterdata.usgs.gov/nwis/gw).

Groundwater-withdrawal data were compiled during spring 2019. Spring discharges were measured between June and July in 2017 and 2018. Most groundwater levels were measured during the spring in 2017 and 2018, although some were measured during other times of the year. Groundwater samples were collected from three springs in July 2017 and from four springs in June or July 2018. Spring samples were analyzed for chemical constituents. Additionally, two wells were sampled in August 2017 and were analyzed for chemical constituents. Annual groundwater-withdrawal data are collected from 36 well systems within the NTUA, BIA, and Hopi municipal systems, as well as the PWCC industrial well field. Water-level measurements are attempted from 34 wells and well identification information is shown in table 3. Streamflow data are collected at four USGS gaging stations (table 10) and are available online (https://waterdata.usgs.gov/nwis/sw). In October 2017, water chemistry samples were collected at three of these stream gages and analyzed for chemical constituents. All annual data reported in this document are for calendar years beginning January 1 and ending December 31. Median winter streamflow is reported for water years which begin October 1 and end September 30 of the following year. The period before appreciable groundwater withdrawals began for mining or municipal purposes (about 1965) is referred to in this report as the prestress period.

Withdrawals from the N Aquifer

Total annual withdrawals from the N aquifer are monitored on a continuing basis to help determine the effects from industrial and municipal pumping. Withdrawals from the N aquifer are separated into three categories: (1) industrial withdrawals from the confined area, (2) municipal withdrawals from the confined area, and (3) municipal withdrawals from the unconfined areas. Within the study area there are no industrial withdrawals from the unconfined area. The industrial category includes eight wells in the PWCC well field in the northern Black Mesa area. The BIA, NTUA, and Hopi Tribe operate about 70 municipal wells that are combined into 36 well systems. Information about withdrawals from the N aquifer is compiled primarily based on metered data from individual wells operated by the BIA, NTUA, and Hopi Tribe (table 4).

Table 3. Identification numbers and names of monitoring program study wells, 2017–18, Black Mesa area, northeastern Arizona.

[---, no data]

U.S. Geological Survey identification number	Common name or location	Bureau of Indian Affairs site number
355023110182701	Keams Canyon PM2	---
355215110375001	Kykotsmovi PM2	---
355230110365801	Kykotsmovi PM1	---
355236110364501	Kykotsmovi PM3	---
355428111084601	Goldtooth	3A-28
355924110485001	Howell Mesa	3K-311
360055110304001	BM observation well 5[a]	4T-519
360217111122601	Tuba City	3K-325
360614110130801	Piñon PM6	---
360734111144801	Tuba City	3T-333
360904111140201	Tuba City NTUA 1	3T-508
360918111080701	Tuba City Rare Metals 2	---
360924111142201	Tuba City NTUA 3	---
360953111142401	Tuba City NTUA 4	3T-546
361225110240701	BM observation well 6[a]	---
361737110180301	Forest Lake NTUA 1	4T-523
361832109462701	Rough Rock	10T-258
362043110030501	Kits'iili NTUA 2	---
362149109463301	Rough Rock	10R-111
362406110563201	White Mesa Arch	1K-214
362823109463101	Rough Rock	10R-119
362936109564101	BM observation well 1[a]	8T-537
363005110250901	Peabody 2	---
363013109584901	Sweetwater Mesa	8K-443
363103109445201	Rough Rock	9Y-95
363143110355001	BM observation well 4[a]	2T-514
363213110342001	Shonto Southeast	2K-301
363232109465601	Rough Rock	9Y-92
363309110420501	Shonto	2K-300
363423110305501	Shonto Southeast	2T-502
363727110274501	Long House Valley	8T-510
363850110100801	BM observation well 2[a]	8T-538
364034110240001	Marsh Pass	8T-522
364226110171701	Kayenta West	8T-541
364248109514601	Northeast Rough Rock	8A-180
364338110154601	BM observation well 3[a]	8T-500

[a]Well with continuous water-level recorder.

Table 4. Withdrawals from the N aquifer by well system, Black Mesa area, northeastern Arizona, calendar years 2017 and 2018.

[---, no data]

Well system (one or more wells)	Owner	Source of data	2017 Withdrawals		2018 Withdrawals	
			Confined aquifer	Unconfined aquifer	Confined aquifer	Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	3.5	---	8.6	---
Dennehotso	BIA	USGS/BIA	---	3.6	---	3.7
Hopi High School	BIA	USGS/BIA	13.7	---	16.4	---
Hotevilla	BIA	USGS/BIA	21.8	---	22.3	---
Kayenta	BIA	USGS/BIA	20.3	---	17.1	---
Keams Canyon	BIA	USGS/BIA	44.2	---	47.5	---
Low Mountain	BIA	USGS/BIA	[1]0	---	[1]0	---
Piñon	BIA	USGS/BIA	[1]0	---	[1]0	---
Red Lake	BIA	USGS/BIA	---	3.3	---	4.4
Rocky Ridge	BIA	USGS/BIA	4.2	---	3.3	---
Rough Rock	BIA	USGS/BIA	13.7	---	[2]14.3	---
Second Mesa	BIA	USGS/BIA	4.7	---	3.8	---
Shonto	BIA	USGS/BIA	---	124.6	---	136.1
Tuba City	BIA	USGS/BIA	---	71.1	---	74.4
Chilchinbito	NTUA	USGS/NTUA	52.6	---	[2]62.7	---
Dennehotso	NTUA	USGS/NTUA	---	39.2	---	37.9
Forest Lake	NTUA	USGS/NTUA	13.0	---	14.5	---
Hard Rock	NTUA	USGS/NTUA	47.7	---	76.5	---
Kayenta	NTUA	USGS/NTUA	347.6	---	[2]360.1	---
Kits'iili	NTUA	USGS/NTUA	15.9	---	[2]16.1	---
Piñon	NTUA	USGS/NTUA	365.9	---	358.7	---
Red Lake	NTUA	USGS/NTUA	---	36.1	---	33.8
Rough Rock	NTUA	USGS/NTUA	52.0	---	46.8	---
Shonto	NTUA	USGS/NTUA	---	[2]24.1	---	25.9
Shonto Junction	NTUA	USGS/NTUA	---	68.3	---	65.5
Tuba City	NTUA	USGS/NTUA	---	822.8	---	687.2
Mine Well Field	PWCC	PWCC	1,110	---	1,170	---
Bacavi	Hopi	USGS/Hopi	18.4	---	18.0	---
Hopi Civic Center	Hopi	USGS/Hopi	0.9	---	1.2	---
Hopi Cultural Center	Hopi	USGS/Hopi	5.1	---	5.7	---
Kykotsmovi	Hopi	USGS/Hopi	60.6	---	60.1	---
Mishongnovi	Hopi	USGS/Hopi	5.1	---	5.2	---
Moenkopi	Hopi	USGS/Hopi	---	72.6	---	66.7
Polacca	Hopi	USGS/Hopi	169.3	---	157.9	---
Shipaulovi	Hopi	USGS/Hopi	24.3	---	20.2	---
Shungopovi	Hopi	USGS/Hopi	30.6	---	[2]30.7	---

[1]Well taken out of service.

[2]Estimated value due to partial record.

Withdrawals from wells equipped with windmills are not measured in this monitoring program and are not included in total withdrawal values reported here. About 270 windmills in the Black Mesa area withdraw water from the N, D, T, and alluvial aquifers, primarily for livestock. The estimated total withdrawal by the windmills from the N aquifer is about 65 acre-ft/yr (HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc., 1999). The total withdrawal by the windmills is less than 1 percent of the total annual withdrawal from the N aquifer.

Withdrawals in Calendar Years 2017 and 2018 Compared to Previous Years

In 2017 and 2018 total groundwater withdrawal from the N aquifer was about 3,710 and 3,670 acre-ft respectively (table 1). Total withdrawals for municipal use in 2017 and 2018 were about 2,600 and 2,500 acre-ft respectively; municipal withdrawals from the confined area averaged about 1,350 acre-ft per year, while withdrawals from the unconfined areas averaged about 1,200 acre-ft. Withdrawals for industrial use averaged about 1,140 acre-ft per year (tables 1 and 5).

Withdrawals from the N aquifer have varied annually from 1965 to the present but generally increased from 1965 to 2005 and decreased from 2006 to 2018. Beginning in 2006, the Peabody Western Coal Company reduced their pumping by about 70 percent, a reduction that is reflected by a decrease in total annual withdrawals between 2005 and 2006 of about 44 percent (tables 1 and 5, fig. 6). Total withdrawal for the period of record (1965–2018) totaled 270,700 acre-ft; industrial withdrawals were 57 percent and municipal withdrawals were 43 percent of total withdrawals (table 5). Total withdrawals in 2018 were 3,670 acre-ft, with 32 percent from industrial withdrawals and 68 percent from municipal withdrawals (table 5).

Groundwater Levels in the N Aquifer

Groundwater levels are monitored at wells that are screened in the N aquifer to help understand the effects of withdrawals on the potentiometric surface of the aquifer. Groundwater in the N aquifer is under confined conditions in the central part of the study area and under unconfined or water-table conditions around the periphery (fig. 7).

Groundwater levels are measured once a year at around the same time of year to limit the effect of seasonal variability. Groundwater levels are compared to prestress water levels to identify long-term changes. Only water levels from municipal and stock wells that are not considered to have been recently pumped, affected by nearby pumping, or blocked or obstructed are compared. In 2017 and 2018 most water levels were

Table 5. Total, industrial, and municipal withdrawals from the N aquifer for discrete time periods from 1965 to 2018, Black Mesa area, northeastern Arizona.

Period	Total withdrawals (acre-feet)	Industrial withdrawals (acre-feet)	Municipal withdrawals (acre-feet)	Percent industrial	Percent municipal
1965–2018	270,700	154,800	115,900	57	43
1965–2005	218,300	138,100	80,200	63	37
2006–2018	52,400	16,600	35,800	32	68
2018	3,670	1,170	2,500	32	68

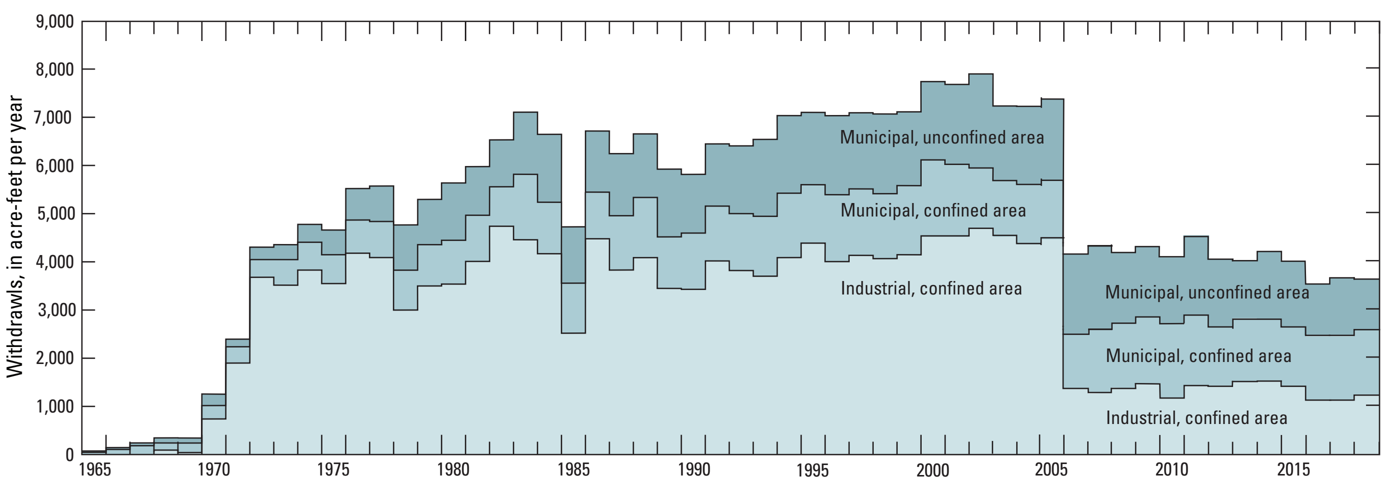


Figure 6. Annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2018.

measured during the spring. There are 34 wells used for water-level measurements in the Black Mesa Monitoring Program. It is not always possible to obtain a water level from all 34 wells. In 2017 and 2018, Tuba City NTUA 1 and NTUA 3 wells were in the process of being replaced. During that time, the wells were unavailable for measurements. New wells have since been installed near the original wells. The new wells will be incorporated into the water-level network in the future. Water-levels were measured in 31 wells in 2017, and 32 wells in 2018. Of the 34 wells in the network, 6 are continuous-recording

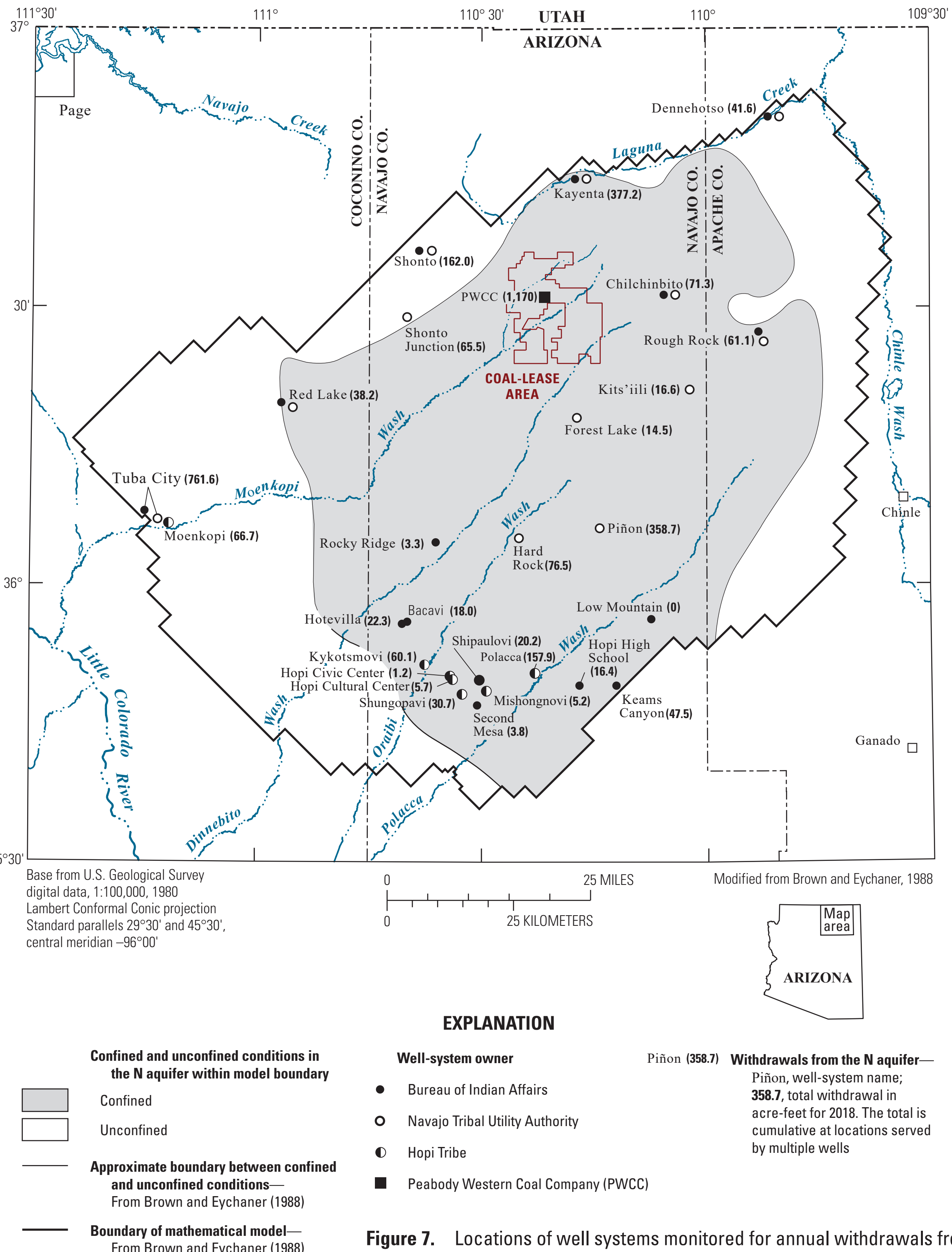


Figure 7. Locations of well systems monitored for annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, calendar year 2018, and confined/unconfined zones of the N aquifer.

observation wells. Water levels were measured quarterly using an electric tape in these six wells during 2017 and 2018 to verify or update instrument calibration.

The wells used for water-level measurements are distributed throughout the study area (fig. 8). The wells were constructed between 1934 and 1993 and the total well depths range from 107 ft near Rough Rock (8A-180) to 2,674 ft (Forest Lake NTUA 1). Depths to the top of the N aquifer range from 0 ft near Tuba City to 2,205 ft at the Kits'iilie NTUA 2 well (table 7).

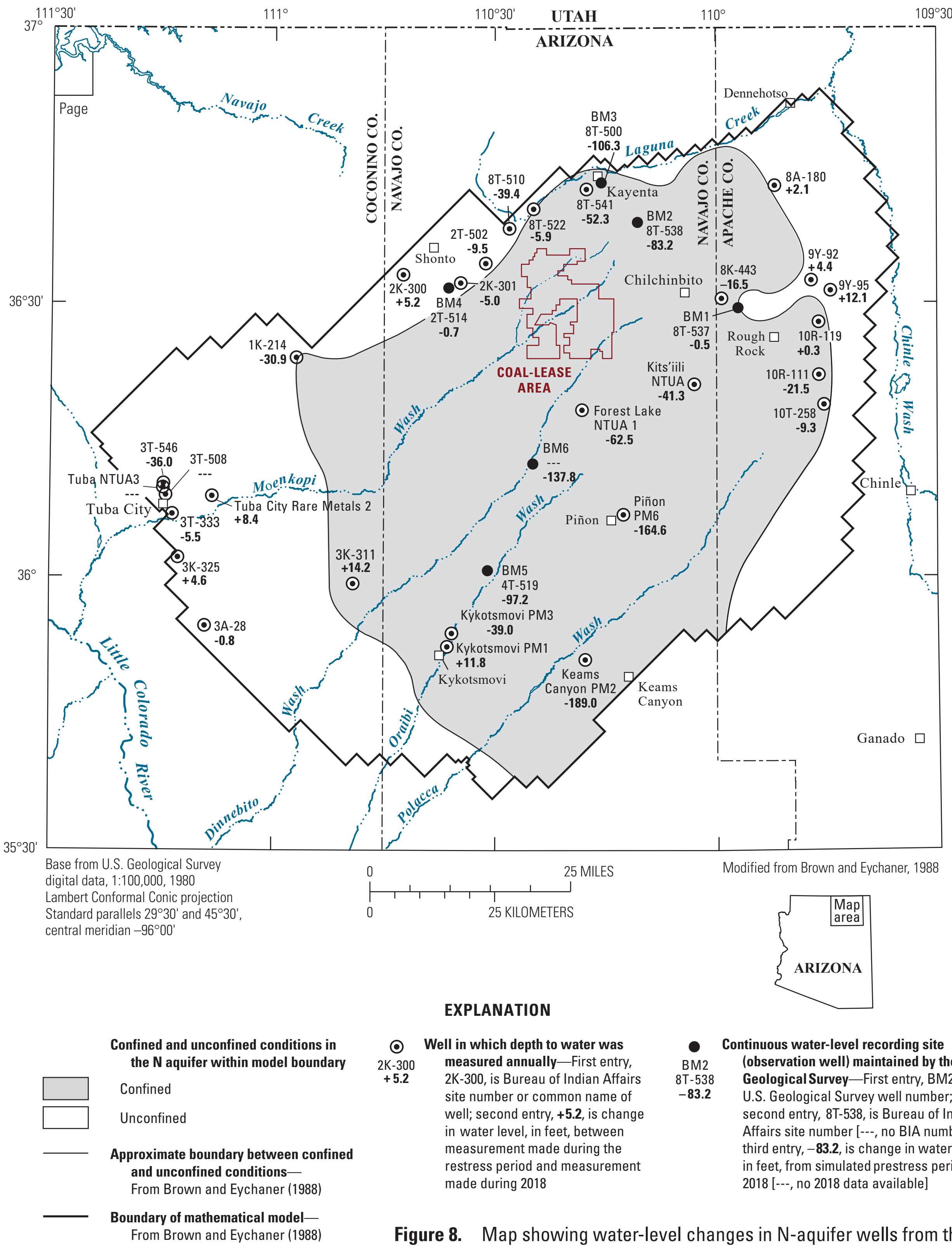


Figure 8. Map showing water-level changes in N-aquifer wells from the prestress period (prior to 1965) to 2018, Black Mesa area, northeastern Arizona.

Table 6. Water-levels measured in monitoring program wells completed in the N aquifer during calendar years 2017 and 2018, and water level changes from the prestress period to calendar year 2018, Black Mesa area, northeastern Arizona.

[---, no data; R, reported from driller's log]

Common name or location	Bureau of Indian Affairs site number	Water level (feet below land surface), 2017	Water level (feet below land surface), 2018	Prestress period water level		Change in water level from prestress period to 2018 (feet)
				Feet below land surface	Date	
Unconfined areas						
BM observation well 1[a]	8T-537	374.3	374.5	374.0	([a])	−0.5
BM observation well 4[a]	2T-514	216.8	216.7	216.0	([a])	−0.7
Goldtooth	3A-28	234.0	230.8	230.0	10/29/53	−0.8
Long House Valley	8T-510	138.2	138.8	99.4	08/22/67	−39.4
Northeast Rough Rock	8A-180	44.7	44.8	46.9	11/13/53	2.1
Rough Rock	9Y-95	105.8	107.4	119.5	08/03/49	12.1
Rough Rock	9Y-92	165.3	164.4	168.8	12/13/52	4.4
Shonto	2K-300	171.7	171.3	176.5	06/13/50	5.2
Shonto Southeast	2K-301	292.7	288.9	283.9	12/10/52	−5.0
Shonto Southeast	2T-502	418.6	415.3	405.8	08/22/67	−9.5
Tuba City	3T-333	29.0	28.5	23.0	12/02/55	−5.5
Tuba City	3K-325	202.6	203.4	208.0	06/30/55	4.6
Tuba City Rare Metals 2	---	48.7	48.6	57.0	09/24/55	8.4
Tuba City NTUA 1	3T-508	([b])	([b])	29.0	02/12/69	([b])
Tuba City NTUA 3	---	([b])	([b])	34.2	11/08/71	([b])
Tuba City NTUA 4	3T-546	70.2	69.7	33.7	08/06/71	−36.0
Confined areas						
BM observation well 2[a]	8T-538	208.8	208.2	125.0	([a])	−83.2
BM observation well 3[a]	8T-500	163.7	161.3	55.0	04/29/63	−106.3
BM observation well 5[a]	4T-519	422.0	421.2	324.0	([a])	−97.2
BM observation well 6[a]	---	836.6	834.8	697.0	([a])	−137.8
Forest Lake NTUA 1	4T-523	1,160.7	1,158.5	1,096R	05/21/82	−62.5
Howell Mesa	3K-311	---	448.8	463.0	11/03/53	14.2
Kayenta West	8T-541	291.3	282.3	230.0	03/17/76	−52.3
Keams Canyon PM2	---	483.8	481.5	292.5	06/10/70	−189.0
Kits'iili NTUA 2	---	1,340.1	1,339.2	[c]1,297.9	01/14/99	−41.3
Kykotsmovi PM1	---	208.7	208.2	220.0	05/20/67	11.8
Kykotsmovi PM3	---	248.4	249.0	210.0	08/28/68	−39.0
Marsh Pass	8T-522	131.2	131.4	125.5	02/07/72	−5.9
Piñon PM6	---	908.1	908.2	743.6	05/28/70	−164.6
Rough Rock	10R-119	261.8	256.3	256.6	12/02/53	0.3
Rough Rock	10T-258	310.6	310.3	301.0	04/14/60	−9.3
Rough Rock	10R-111	191.6	191.5	170.0	08/04/54	−21.5
Sweetwater Mesa	8K-443	547.7	545.9	529.4	09/26/67	−16.5
White Mesa Arch	1K-214	218.6	218.9	188.0	06/04/53	−30.9

Table 7. Well-construction characteristics, depth to top of N aquifer, and 2018 static water level for wells used in annual water-level measurements and for continuous-record observation wells, 2017–18, Black Mesa area, northeastern Arizona.

[---, no data]

Bureau of Indian Affairs site number, and (or) common name	Date well was completed	Land-surface elevation (feet)	Well depth (feet below land surface	Screened/open interval(s) (feet below land surface)	Depth to top of N aquifer (feet below land surfacea)	2018 static water level (feet below land surface)
8T-537 (BM observation well 1)	02/01/72	5,864	851	300–360; 400–420; 500–520; 600–620; 730–780	90	374.5
8T-538 (BM observation well 2)	01/29/72	5,656	1,338	470–1,338	52	208.2
8T-500 (BM observation well 3)	07/29/59	5,724	868	712–868	5	161.3
2T-514 (BM observation well 4)	02/15/72	6,320	400	250–400	60	216.7
4T-519 (BM observation well 5)	02/25/72	5,869	1,683	1,521–1,683	1,520	421.2
BM observation well 6	01/31/77	6,332	2,507	1,954–2,506	1,950	834.8
1K-214	05/26/50	5,771	356	168–356	250	218.9
2K-300	[b]06/00/50	6,264	300	260–300	0	171.3
2K-301	06/12/50	6,435	500	318–328; 378–500	[c]30	288.9
2T-502	08/10/59	6,670	523	12–523	25	415.3
3A-28	04/19/35	5,381	358	([d])	60	230.8
3K-311	[b]11/00/34	5,855	745	380–395 605–745	615	448.8
3K-325	06/01/55	5,250	450	75–450	[c]30	203.4
3T-333	12/02/55	4,940	229	63–229	24	28.5
3T-508 (Tuba City NTUA 1)	08/25/59	5,119	475	([d])	---	([e])
3T-546 (Tuba City NTUA 4)	[b]08/00/71	5,206	612	256–556	---	69.7
4T-523 (Forest Lake NTUA 1)	10/01/80	6,654	2,674	1,870–1,910; 2,070–2,210; 2,250–2,674	([f])	1,158.5
8A-180	01/20/39	5,200	107	60–107	[c]40	44.8
8K-443	08/15/57	6,024	720	619–720	590	545.9
8T-510	02/11/63	6,262	314	130–314	[c]125	138.8
8T-522	[b]07/00/63	6,040	933	180–933	480	131.4
8T-541	03/17/76	5,885	890	740–890	700	282.3
9Y-92	01/02/39	5,615	300	154–300	[c]50	164.4
9Y-95	11/05/37	5,633	300	145–300	[c]68	107.4
10R-111	04/11/35	5,757	360	267–360	210	191.5
10R-119	01/09/35	5,775	360	([d])	310	256.3
10T-258	04/12/60	5,903	670	465–670	460	310.3
Keams Canyon PM2	[b]05/00/70	5,809	1,106	906–1,106	900	481.5

Table 7.—Continued

Bureau of Indian Affairs site number, and (or) common name	Date well was completed	Land-surface elevation (feet)	Well depth (feet below land surface	Screened/open interval(s) (feet below land surface)	Depth to top of N aquifer (feet below land surfacea)	2018 static water level (feet below land surface)
Kits'iili NTUA 2	10/30/93	6,780	2,549	2,217–2,223	2,205	1,339.2
				2,240–2,256		
				2,314–2,324		
				2,344–2,394		
				2,472–2,527		
Kykotsmovi PM1	02/20/67	5,657	995	655–675	880	208.2
				890–990		
Kykotsmovi PM3	08/07/68	5,618	1,220	850–1,220	840	249.0
Piñon PM6	[b]02/00/70	6,397	2,248	1,895–2,243	1,870	908.2
				514–539		
Tuba City NTUA 3	[b]10/00/71	5,176	442	142–442	34	([e])
Tuba City Rare Metals 2	[b]09/00/55	5,108	705	100–705	255	48.6

[a]Depth to top of N aquifer from Eychaner (1983) and Brown and Eychaner (1988).

[b]00, indicates day is unknown.

[c]All material between land surface and top of the N aquifer is unconsolidated —soil, alluvium, or dune sand.

[d]Screened and (or) open intervals are unknown.

[e]No water level collected in 2018, well has been plugged and is in the process of being replaced.

[f]Depth to top of N aquifer was not estimated.

Table 8. Median changes in water levels in monitoring-program wells from prestress period (prior to 1965) to 2018, N aquifer, Black Mesa area, northeastern Arizona.

Years	Aquifer conditions	Number of wells	Median change in water level (feet)
Prestress–2018	All	32	−9.4
	Unconfined	14	−0.6
	Confined	18	−40.2

Water levels measured in 2017 and 2018, and changes in water levels from the prestress period to 2018, are shown in table 6. From the prestress period (before 1965) to 2018, the median water-level change in 32 wells measured in 2018 was −9.4 ft, which is an increase in the depth to water from the surface (table 8). Water levels in 14 unconfined wells had a median change of -0.6 ft (table 8), and water-level changes ranged from -39.4 ft at Long House Valley (8T-510) to +12.1 ft at Rough Rock (9Y-95) (fig. 8 and table 6). Water levels in 18 wells in the confined part of the aquifer had a median change of −40.2 ft (table 8), and water-level changes ranged from −189.0 ft at Keams Canyon PM2 to +14.2 ft at Howell Mesa (3K-311) (fig. 8 and table 6).

Hydrographs of groundwater levels in the network of wells observed annually show the temporal changes from the 1950s to present (fig. 9). In most of the unconfined area, water levels have changed only slightly, generally less than 10 ft. Near the Shonto area, however, the water level in Longhouse Valley well 8T-510, has declined 39.4 ft (fig. 8; table 6). Water levels have declined in most of the confined area, but the magnitudes of declines are varied. Larger declines have occurred near the municipal pumping centers (wells Piñon PM6 and Keams Canyon PM2) and near the well field for PWCC (BM6). Smaller declines occurred away from the pumping centers found in or near towns in the study area (wells 10T-258, 10R-119, 8T-522; figs. 8 and 9).

Hydrographs for the Black Mesa continuous-record observation wells (fig. 10) show water levels since the early 1970s. The two wells in the unconfined areas (BM1 and BM4) have shown small seasonal or year-to-year variation since 1972 but no apparent long-term decline. In the confined area, water levels (not corrected for barometric pressure effects or seasonal effects) in wells BM2, BM3, BM5, and BM6 consistently declined from the 1970s to the mid-2000s (fig. 10). After the mid-2000s, water levels in BM2, BM5, and BM6 began to level off and then rose. The water-level recoveries in BM2, BM5, and BM6 since the mid-2000s has been 10.2 ft, 7.0 ft, and 27.0 ft respectively. Water levels in BM3 are more variable because of nearby municipal pumping. After the mid-2000s, water levels in BM3 continued to vary, but the overall trend flattened out (fig. 10).

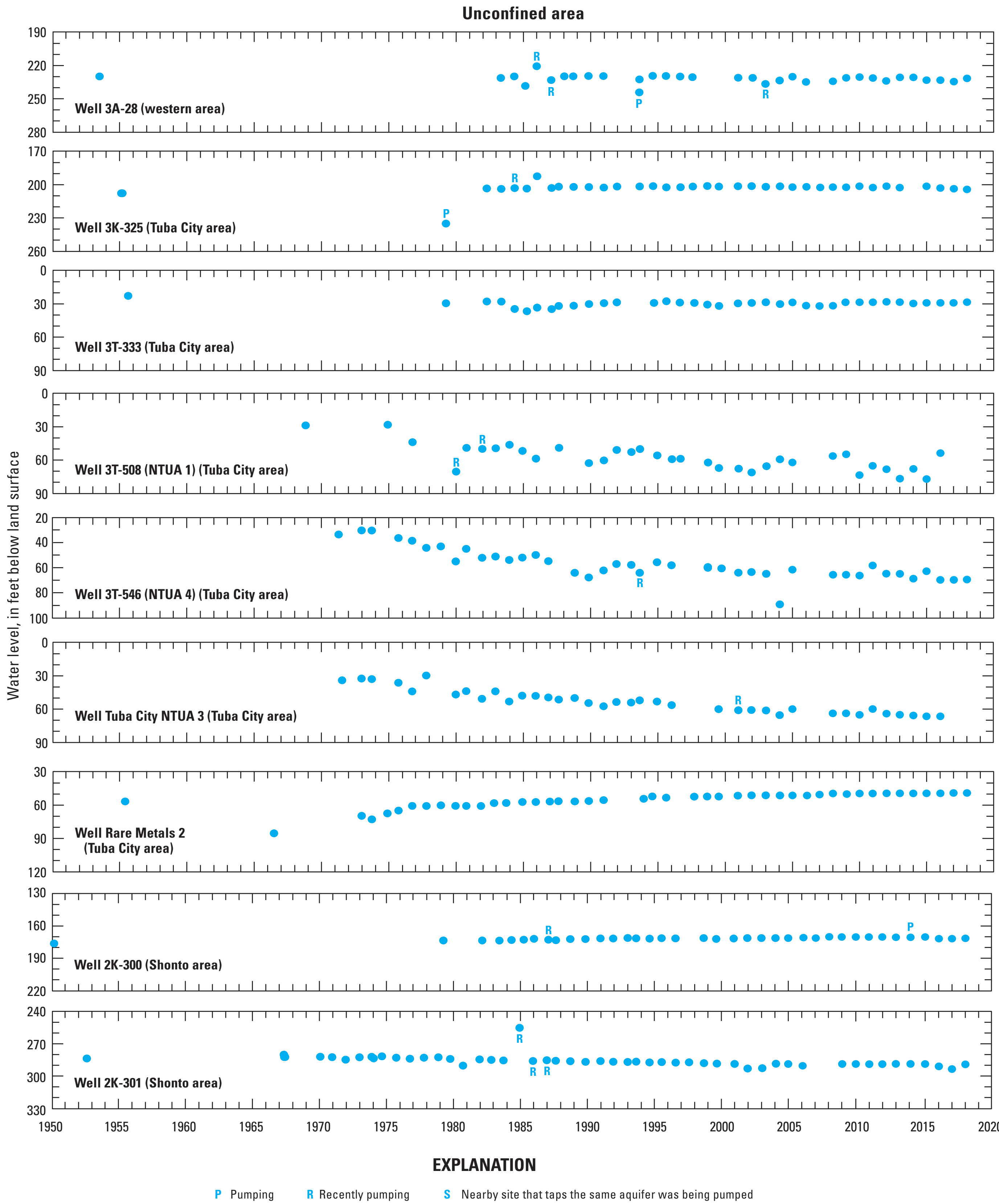


Figure 9 (pages 23–26). Plots of observed water levels (1950–2018) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.

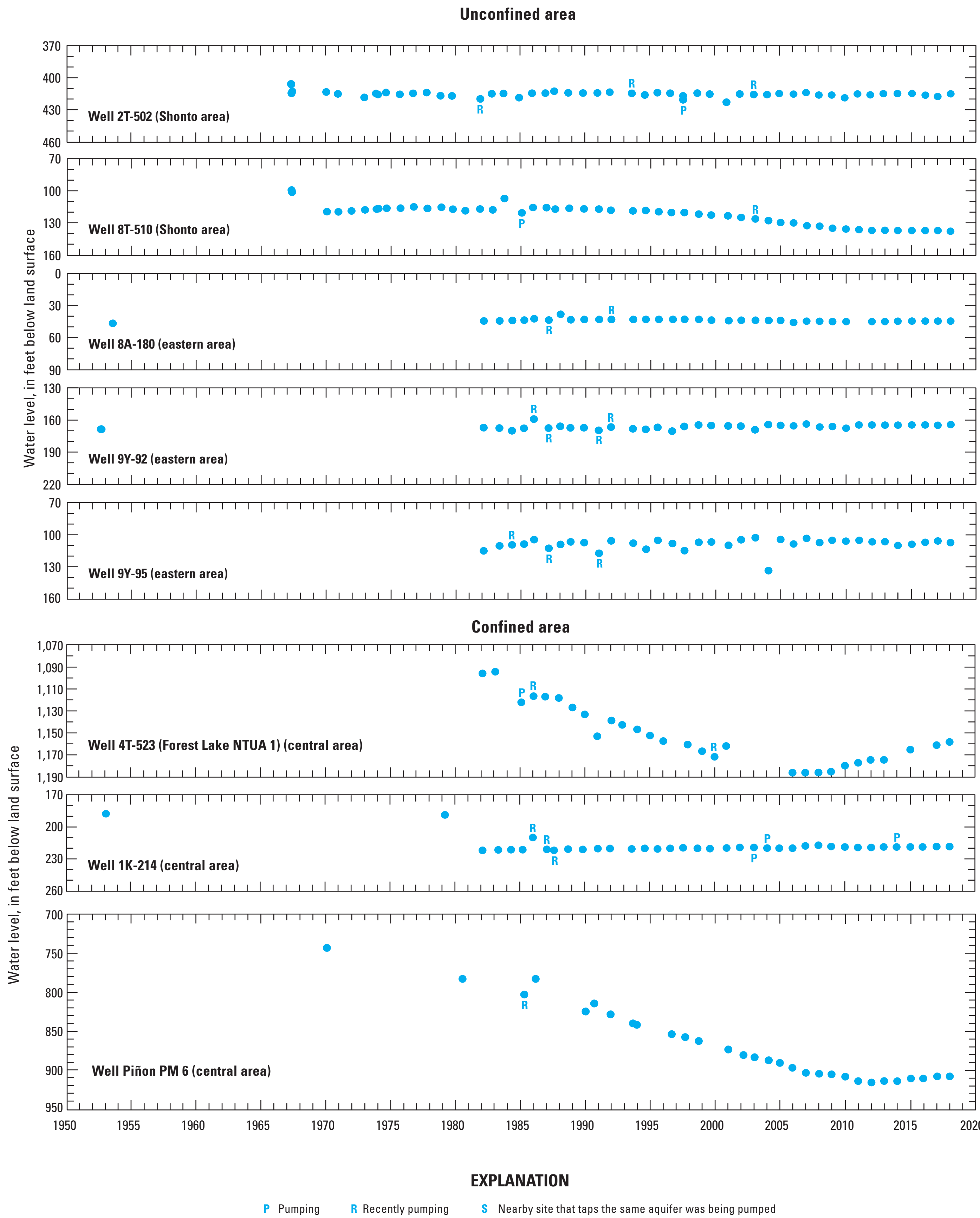


Figure 9 (pages 23–26).—Continued

Figure 9 (pages 23–26).—Continued

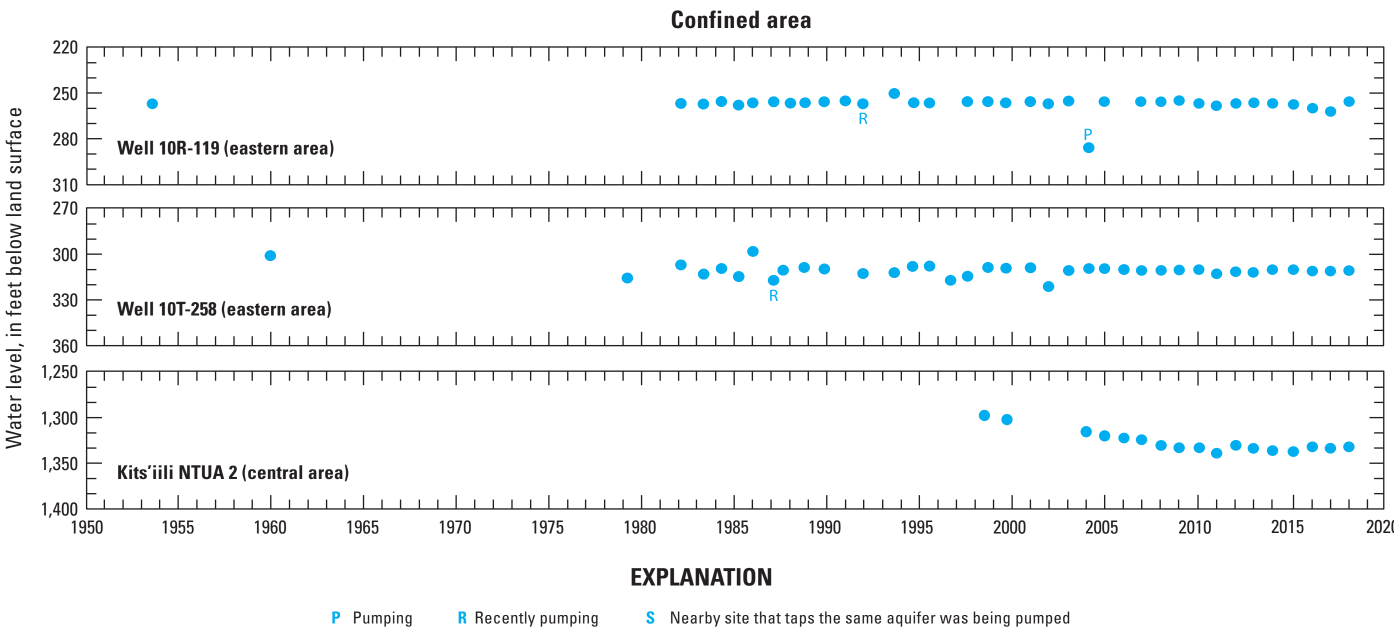


Figure 9 (pages 23–26).—Continued

Spring Discharge from the N Aquifer

Groundwater in the N aquifer discharges from many springs around the margins of Black Mesa. Changes to the discharge from those springs could indicate effects of withdrawals from the N aquifer. Discharge at Moenkopi School Spring (360632111131101), Pasture Canyon Spring (361021111115901), Burro Spring (354156110413701), and Unnamed Spring near Dennehotso (364656109425400), has been measured intermittently since the late 1980s. Discharge at three springs was measured in 2017, while all four springs were measured for discharge in 2018. Additionally, trend analyses were performed on the flow data from the four springs.

Moenkopi School Spring, also called Susunova Spring by the Hopi Tribe, is in the western part of the Black Mesa area (fig. 11). Discharge from Moenkopi School Spring was measured in July 2017 and June 2018 using the volumetric method and compared to discharge data from previous years to determine changes over time (fig. 12*A*). The trend for discharge measurements at this spring is not corrected for seasonal variability, but discharge measurements are generally made annually at or close to the same time of year. In 2017 and 2018, the measured discharge from Moenkopi School Spring was 6.8 and 6.4 gallons per minute (gal/min) respectively (table 9). A linear regression analysis indicated a decreasing trend ($p<0.05$) of about 0.3 gal/min per year during the period of record (fig. 12*A*).

Burro Spring is in the southwestern part of the study area and discharges from the Navajo Sandstone and alluvium (fig. 11). Burro Spring discharges from the aquifer through a metal pipe and into a cement trough for livestock. As in previous years, the 2017 and 2018 discharge measurement and water-quality sampling point was from the end of the metal pipe before the livestock trough. Discharge at Burro Spring has fluctuated between 0.2 and 0.4 gal/min since 1989, but there is no significant ($p>0.05$) trend from linear regression analysis (fig. 12*B*). In both 2017 and 2018, the measured discharge was 0.3 gal/min (table 9).

Pasture Canyon Spring is in the western part of the study area and discharges from the Navajo Sandstone and alluvium (fig. 11). Discharge is measured at two locations: where the spring issues from the Navajo Sandstone (also the water-quality sampling point), and farther down the canyon at the USGS gaging station. The USGS gaging station at Pasture Canyon measures the discharge from Pasture Canyon Spring as well as additional discharge from seeps in Pasture Canyon. As in previous years, discharge was measured at Pasture Canyon Spring at its emergence point in July 2017 and June 2018 using the volumetric method. The measured discharge was 43.0 and 42.0 gal/min respectively (table 9). The discharges measured in 2017 and 2018 are the highest two discharges recorded at the spring emergence point. Discharge at Pasture Canyon Spring has fluctuated between 26.5 and 43.0 gal/min since 1995, but there is no significant ($p>0.05$) trend from linear regression analysis (fig. 12*C*).

Unnamed Spring near Dennehotso is the only spring located in the northeastern part of the study area (fig. 11), and it discharges from the Navajo Sandstone. As in previous years, measurements at this spring are made using a flume. There have been marked decreases in discharge at Unnamed Spring

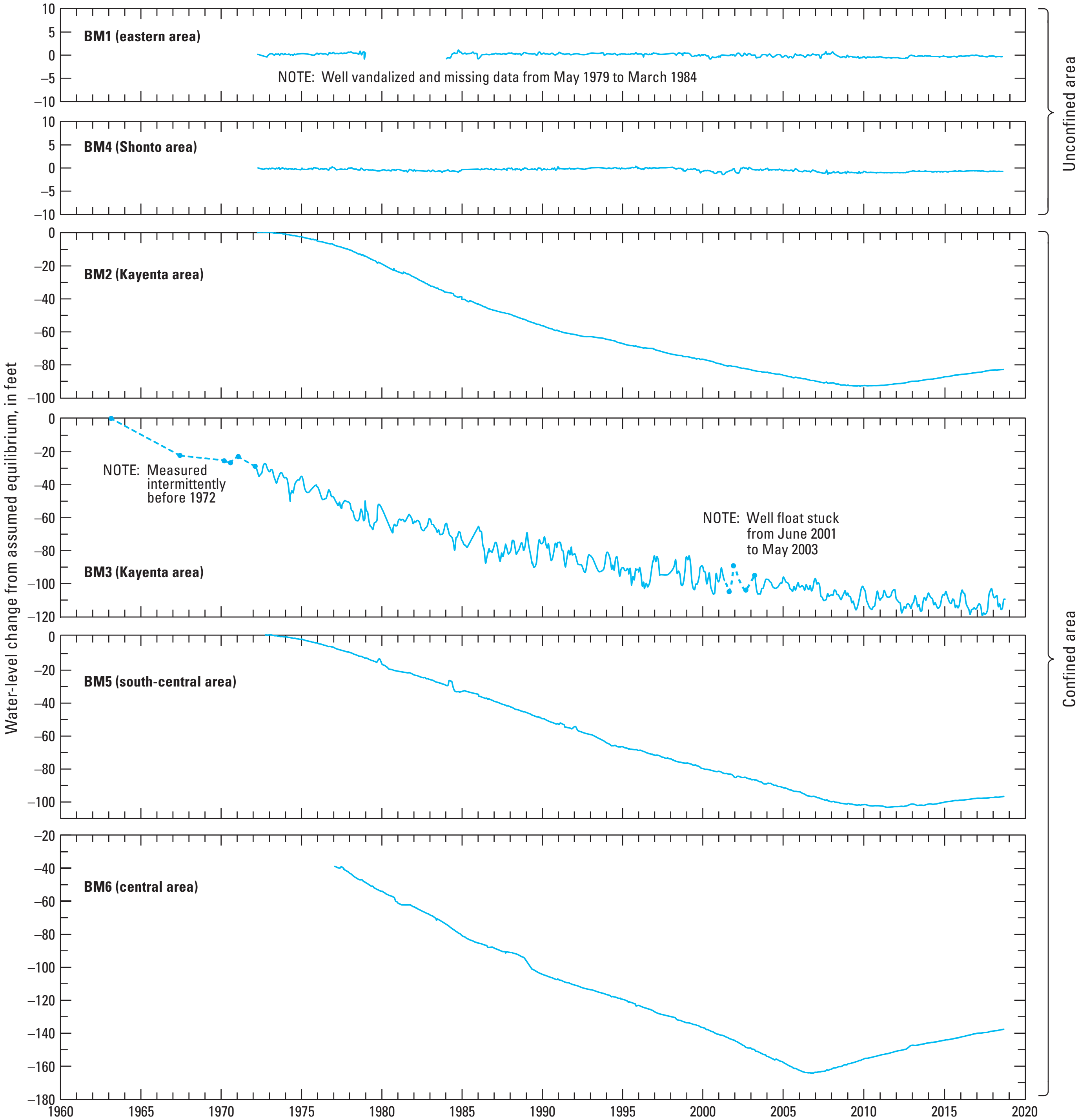


Figure 10. Plots of observed groundwater water-levels in continuous-record observation wells BM1–BM6 from 1963 to 2018 in the N aquifer, Black Mesa area, northeastern Arizona.

near Dennehotso since 2005. In 2005, the discharge at the spring was 21.5 gal/min. The discharge wasn't measured again until 2010 when it was 9.0 gal/min, in 2018 it was 3.0 gal/min (discharge was not measured at the spring in 2017) (table 9). For the period of record, which includes a gap in data from 2005 to 2010, a decreasing trend ($p<0.05$) is evident from linear regression analysis (fig. 12*D*). The discharge data measured at this spring is not corrected for seasonal variability.

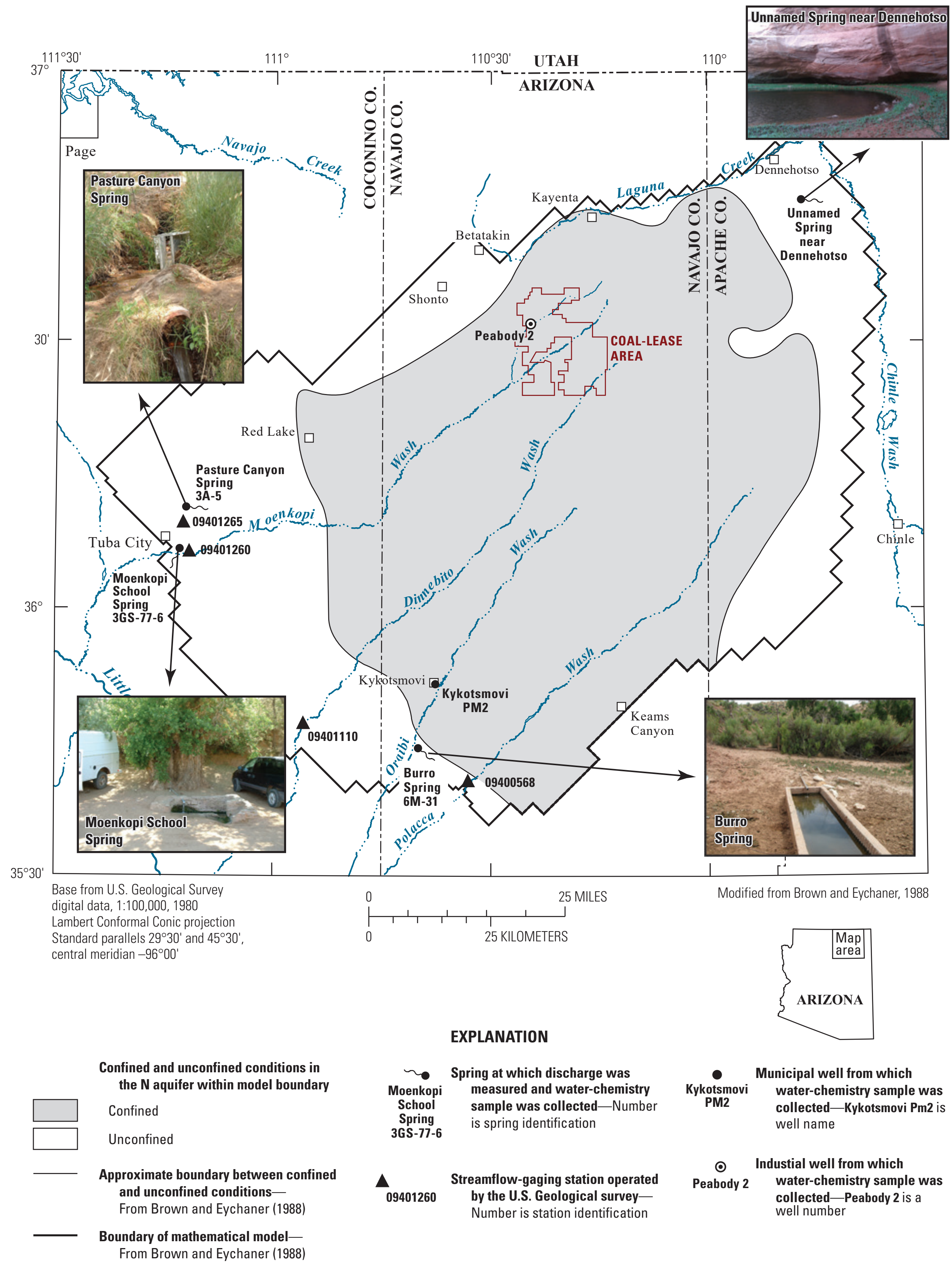


Figure 11. Map of surface-water and water-chemistry data-collection sites, N aquifer, Black Mesa area, northeastern Arizona, 2017–18.

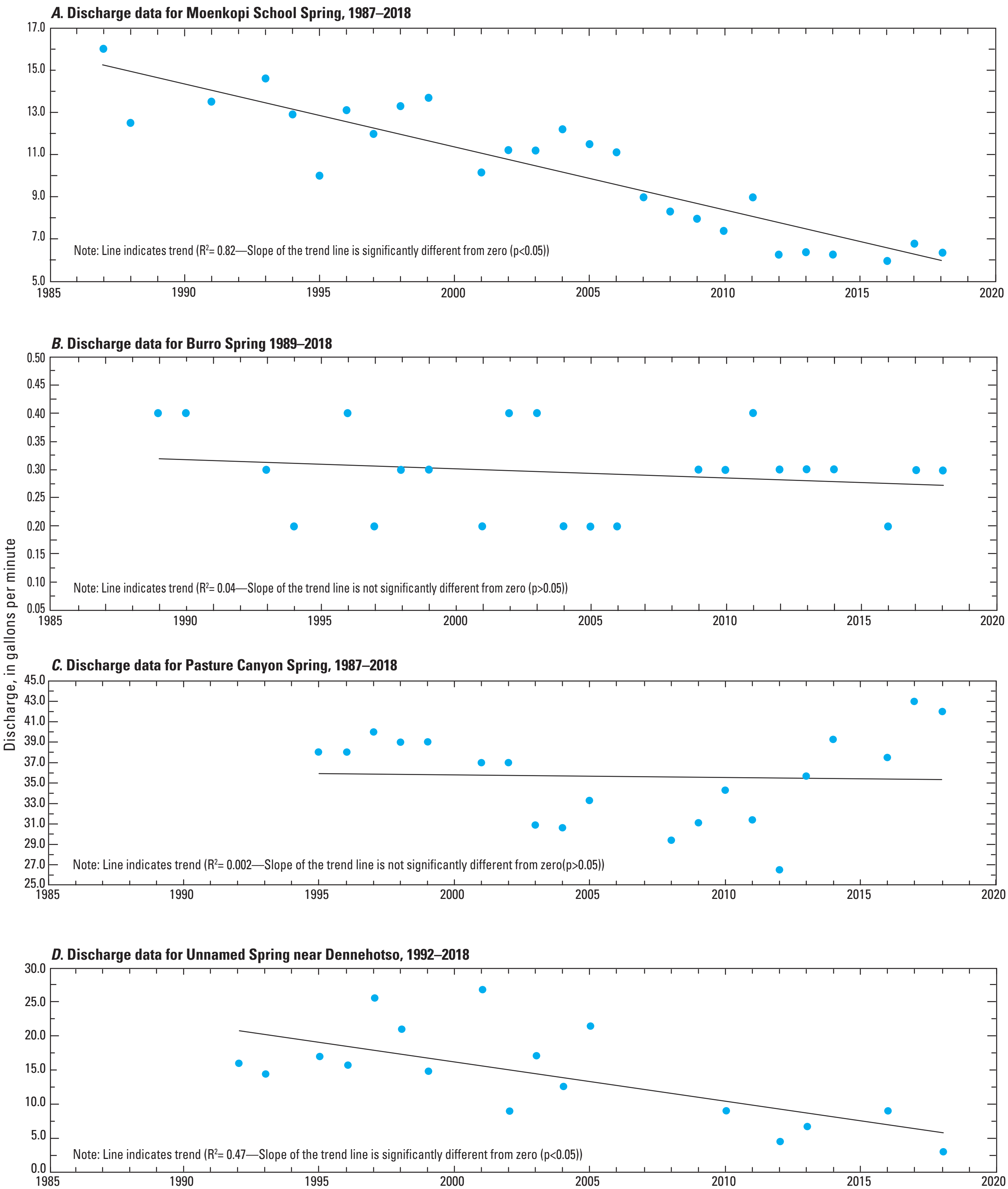


Figure 12. Plots of discharge from *A*, Moenkopi School Spring; *B*, Burro Spring; *C*, Pasture Canyon Spring; and *D*, Unnamed Spring near Dennehotso, N Aquifer, Black Mesa area, northeastern Arizona, 1987–2018. Data from 1952 measurement at Moenkopi School Spring are not shown because measurement was from a different measuring location. Data from 1988 to 1993 measurements at Pasture Canyon Spring are not shown because they were taken from a different measuring location. Trend lines were generated using method of least squares.

Table 9. Discharge from Moenkopi School Spring, Burro Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso, N Aquifer, Black Mesa area, northeastern Arizona, 1952–2018.

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Moenkopi School Spring[a]			
3GS-77-6	Navajo Sandstone[b]	05/16/52	40.0
		04/22/87	[c]16.0
		11/29/88	[c]12.5
		02/21/91	[c]13.5
		04/07/93	[c]14.6
		12/07/94	[c]12.9
		12/04/95	[c]10.0
		12/16/96	[c]13.1
		12/17/97	[c]12.0
		12/08/98	[c]13.3
		12/13/99	[c]13.7
		03/12/01	[c]10.2
		06/19/02	[c]11.2
		05/01/03	[c]11.2
		03/29/04	[c]12.2
		04/04/05	[c]11.5
		03/13/06	[c]11.1
		05/31/07	[c]9.0
		06/03/08	[c]8.3
		06/03/09	[c]8.0
		06/14/10	[c]7.4
		06/10/11	[c]9.0
		06/07/12	[c]6.3
		07/29/13	[c]6.4
		08/27/14	[c]6.3
		06/21/16	[c]6.0
		07/11/17	[c]6.8
		06/06/18	[c]6.4
Burro Spring[a]			
6M-31	Navajo Sandstone	12/15/89	0.4
		12/13/90	0.4
		03/18/93	0.3
		12/08/94	0.2
		12/17/96	0.4
		12/30/97	0.2
		12/08/98	0.3
		12/07/99	0.3
		04/02/01	0.2
		04/04/02	0.4
		04/30/03	0.4

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Burro Spring[a]—Continued			
6M-31—Continued	Navajo Sandstone—Continued	04/06/04	[f]0.2
		03/28/05	0.2
		03/28/06	0.2
		06/04/09	0.3
		06/07/10	0.3
		06/08/11	0.4
		06/14/12	0.3
		07/30/13	0.3
		09/02/14	0.3
		06/23/16	0.2
		07/18/17	0.3
		06/06/18	0.3
Pasture Canyon Spring[a]			
3A-5	Navajo Sandstone, alluvium	11/18/88	[d]211
		03/24/92	[d]233
		10/12/93	[d]211
		12/04/95	[e]38.0
		12/16/96	[e]38.0
		12/17/97	[e]40.0
		12/10/98	[e]39.0
		12/21/99	[e]39.0
		06/12/01	[e]37.0
		04/04/02	[e]37.0
		05/01/03	[e]30.9
		04/26/04	[e]30.6
		04/27/05	[e]33.3
		06/03/08	[e]29.4
		06/03/09	[e]31.1
		06/14/10	[e]34.3
		06/09/11	[e]31.4
		06/07/12	[e]26.5
		07/29/13	[e]35.7
		08/27/14	[e]39.3
		06/21/16	[e]37.5
		07/11/17	[e]43.0
		06/06/18	[e]42.0
Unnamed Spring near Dennehotso[d]			
8A-224	Navajo Sandstone	10/06/54	[g]1
		06/27/84	[g]2
		11/17/87	[g]5

Table 9.—Continued

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Unnamed Spring near Dennehotsod—Continued			
8A-224—Continued	Navajo Sandstone—Continued	03/26/92	16.0
		10/22/93	14.4
		12/05/95	17.0
		12/19/96	15.7
		12/30/97	25.6
		12/14/98	21.0
		12/15/99	14.8
		03/14/01	26.8
		04/03/02	5.8
		07/15/02	9.0
		05/01/03	17.1
		04/01/04	12.6
		04/06/05	21.5
		06/17/10	9.0
		06/04/12	4.5
		08/06/13	6.7
		09/03/14	8.1
		10/26/16	9.0
		07/03/18	3.0

[a]Volumetric discharge measurement.

[b]Interfingering with the Kayenta Formation at this site.

[c]Discharge measured at water-quality sampling site and at a different point than the measurement in 1952.

[d]Discharge measured in channel below water-quality sampling point

[e]Discharge measured at water-quality sampling point about 20 feet below upper spring on west side of canyon

[f]Discharge is approximate because the container used for the volumetric measurement was not calibrated.

[g]Discharge measured at a different point than later measurements.

Surface-Water Discharge, Calendar Years 2017–18

Continuous surface-water discharge data have been collected at selected streams since the monitoring program began in 1971. Surface-water discharge in the study area generally originates as groundwater that discharges to streams or as surface runoff from rainfall or snowmelt. Groundwater discharges to some stream reaches at a fairly constant rate throughout the year; however, the amount of groundwater discharge that results in surface flow is affected by seasonal fluctuations in evapotranspiration (Thomas, 2002a). In contrast, the amount of rainfall or snowmelt runoff varies widely throughout the year. In the winter and spring, the amount and timing of snowmelt runoff are a result of the temporal variation in factors such as snow accumulation, air temperatures, and rate of snowmelt. Rainfall can occur throughout the year, but predominates in the summer. The amount and timing of rainfall depends on the intensity and duration of thunderstorms during the summer and cyclonic storms during the fall, winter, and spring.

In 2017 and 2018, discharge data were collected at four continuous-recording streamflow-gaging stations (fig. 13). Data collection at these stations began in July 1976 (Moenkopi Wash at Moenkopi, 09401260), June 1993 (Dinnebito Wash near Sand Springs, 09401110), April 1994 (Polacca Wash near Second Mesa, 09400568), and August 2004 (Pasture Canyon Springs, 09401265) (table 10). Most of the daily mean discharge values highlighted as estimated in figure 13 were either estimated because the streamflow record was affected by ice during the winter months or because the stage recorder was damaged during high flow conditions. Estimated daily values are based on adjacent good record, records from comparison stations, and discrete discharge measurements. The geologic and hydrologic settings along with trend analyses of base flow at the four streamflow sites are described briefly in the following sections.

Moenkopi Wash

Moenkopi Wash has a drainage area of 1,629 mi^2 and drains a large portion of the western part of Black Mesa (fig. 1). The streamflow gage is located near the Village of Moenkopi in a portion of the wash that is cut down into interbedded Navajo Sandstone and Kayenta Formation. During the period of streamflow gage operation, there has generally been continuous flow at the gage except for the summer months, when the stream is often dry at the gage (fig. 13). Monsoon rain events occurring between July and September can result in large sediment laden flows in Moenkopi Wash. The maximum instantaneous discharge recorded at the gage was 10,100 cubic feet per second (ft^3/s) on September 30, 1983. Snowmelt usually does not lead to large runoff events on Moenkopi Wash.

There are no obvious N aquifer springs issuing directly from the Navajo Sandstone near the streamflow gage. During base flow conditions flow seems to initiate from Moenkopi Wash alluvium, but it is assumed this flow is supplied by the N aquifer from below and through the alluvium.

Dinnebito Wash

Dinnebito Wash has a drainage area of 473 mi^2 and drains part of the middle portion of Black Mesa (fig. 1). The streamflow gage is in a part of the wash that is cut down into the Navajo Sandstone. Dinnebito Wash is an intermittent stream with small sections that flow year-round, though most of the stream is dry much of the year. The streamflow gaging station is in a perennial reach (fig. 13). From July through September monsoon rain events can result in large sediment laden flows in Dinnebito Wash. The maximum instantaneous discharge recorded at the gage was 3,970 ft^3/s on September 20, 2004. The minimum daily mean discharge recorded at the

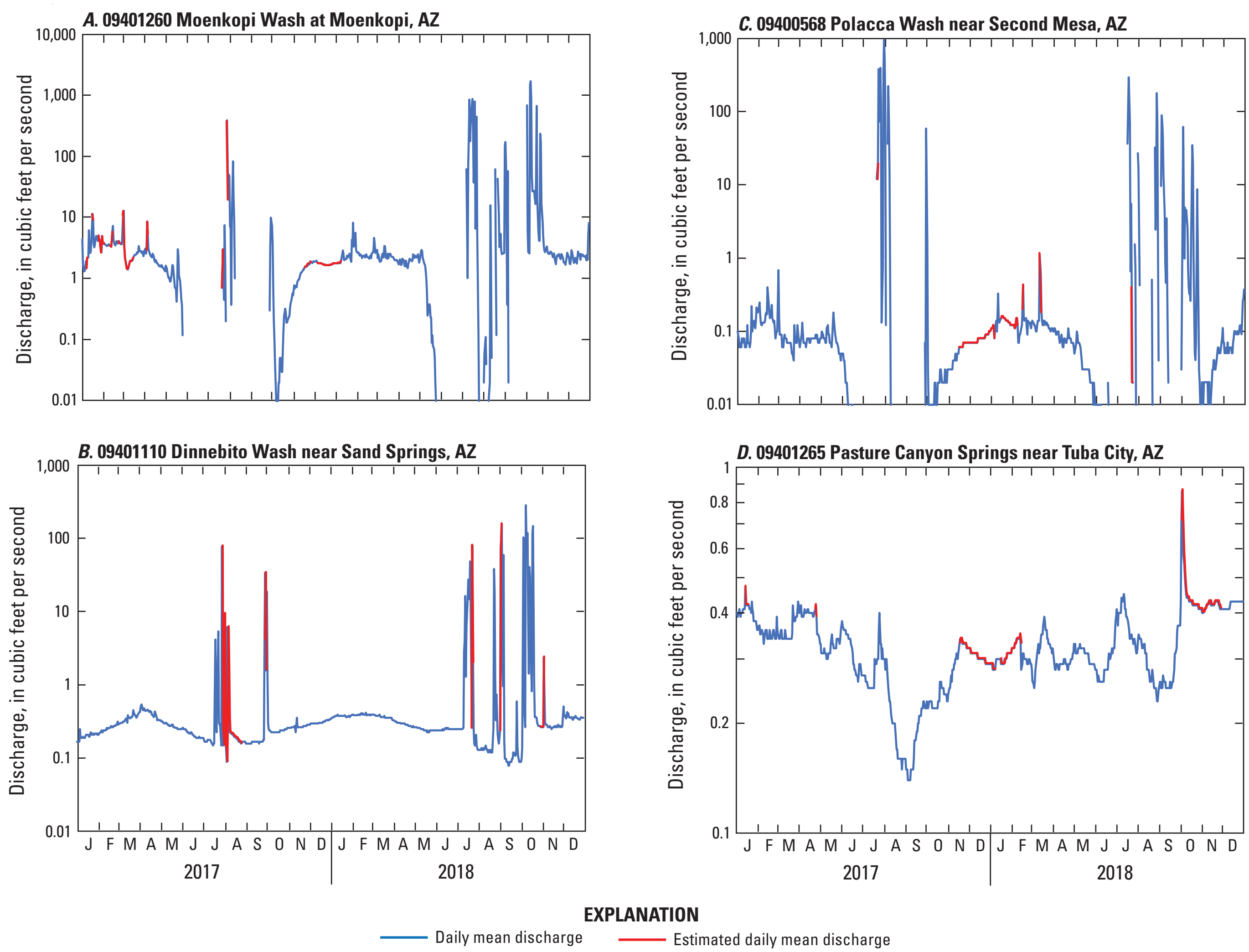


Figure 13. Plots of daily mean discharge, calendar years 2017–2018 for *A*, Moenkopi Wash at Moenkopi (09401260); *B*, Dinnebito Wash near Sand Springs (09401110); *C*, Polacca Wash near Second Mesa (09400568); and *D*, Pasture Canyon Springs (09401265), Black Mesa area, northeastern Arizona.

Table 10. Streamflow-gaging stations used in the Black Mesa monitoring program, their periods of record, and drainage areas.

[---, no data]

Station name	Station number	Date data collection began	Drainage area (square miles)
Moenkopi Wash at Moenkopi	09401260	July 1976	1,629
Dinnebito Wash near Sand Springs	09401110	June 1993	473
Polacca Wash near Second Mesa	09400568	April 1994	905
Pasture Canyon Springs	09401265	August 2004	---

gage was 0.05 ft^3/s on August 16, 23, and October 1–6, 2002. Winter snowmelt usually does not lead to large runoff events on Dinnebito Wash.

There are no observed N aquifer springs issuing directly from the Navajo Sandstone near the streamflow gage. During base flow conditions flow seems to initiate from Dinnebito Wash alluvium, but it is assumed this flow is supplied by the N aquifer from below and through the alluvium.

Polacca Wash

Polacca Wash has a drainage area of 905 mi^2 and drains a large section of the eastern part of Black Mesa (fig. 1). The streamflow gage is in a portion of the wash that is cut down into the Kayenta Formation. Much of Polacca Wash is ephemeral, remaining dry except during and after precipitation runoff events. However, the streamflow gage is in a stream reach that does often have flow. During the period of streamflow gage operation, there has been continuous flow at the gage for most months of the year except for the summer months, when the stream is often dry at the gage (fig. 13). From July through September, monsoon rain events can result in large sediment-laden flows in Polacca Wash. The maximum instantaneous discharge recorded at the gage was 2,140 ft^3/s on July 30, 2017. Winter snowmelt usually does not lead to large runoff events on Polacca Wash. Most of the base flow at the Polacca Wash streamflow gage is likely provided by a spring issuing from the base of the Navajo Sandstone located about one mile upstream of the gage.

Pasture Canyon Springs

Pasture Canyon Springs discharges to a small perennial stream that begins near the head of Pasture Canyon (fig. 1), a narrow box canyon carved into the Navajo Sandstone. Base flow begins near the head of the canyon from a piped spring. Discharge from that spring accounts for around 20 percent of the total flow measured at the streamflow gage, which is located approximately 370 meters downstream from the spring. The remaining base flow measured at the streamflow gage comes from additional springs issuing through the alluvium between the head of the canyon and the gage. Because the drainage area is small, very little surface runoff from rainstorms or snowmelt occurs above the Pasture Canyon Springs streamflow gage (fig. 13). In addition, most of the alluvium in the wash is composed of reworked dune sand, so precipitation tends to infiltrate rather than run off. During the operational period of record for the gage, the minimum daily mean discharge recorded was 0.14 ft^3/s on September 5-8, 2017, and the maximum instantaneous discharge was 4.96 ft^3/s on October 3, 2018.

Surface-Water Base Flow

Trends in the groundwater-discharge component of total flow at the four streamflow-gaging stations were evaluated based on the median of 120 consecutive daily mean flows of four winter months, November through February, as a surrogate measure for base flow (fig. 14). Groundwater discharge was assumed to be constant throughout the year, and the median winter flow was assumed to represent constant annual groundwater discharge. Most flow that occurs during the winter is groundwater discharge; rainfall and snowmelt runoff are infrequent, and evapotranspiration is at a minimum during the winter. Rather than the average flow, the median flow for November through February is used to estimate groundwater discharge because the median is less affected by occasional winter runoff. Nonetheless, the median flow for November through February is an index of groundwater discharge rather than a calculation of base-flow groundwater discharge. A more rigorous and accurate calculation of base-flow would involve detailed evaluations of streamflow hydrographs, flows into and out of bank storage, gain and loss of streamflow as it moves down the stream channel, and interaction of groundwater in the N aquifer with groundwater in the shallow alluvial aquifers in the stream valleys. The median winter flow, however, is useful as a consistent index for evaluating possible temporal trends in groundwater discharge.

Median winter flows calculated for the 2017 winter season (November 2017 – February 2018) were 1.8 ft^3/s for Moenkopi Wash at Moenkopi, 0.35 ft^3/s for Dinnebito Wash near Sand Springs, 0.09 ft^3/s for Polacca Wash near Second Mesa, and 0.30 ft^3/s for Pasture Canyon Springs (fig. 14*A–D*). A significant decreasing trend in median winter flows, calculated using the method of least squares ($p<0.05$), is indicated at both the Moenkopi Wash and Pasture Canyon Springs streamflow-gaging stations, but no significant trends are indicated at the Dinnebito Wash and Polacca Wash streamflow-gaging stations (fig. 14*A, B, C, D*).

Water Chemistry

Water samples for water-chemistry analyses were collected in 2017 and 2018 from selected wells, springs, and streams as part of the Black Mesa monitoring program. Field measurements were taken, and water samples were analyzed for major ions, trace elements, nutrients, and arsenic. Field measurements were taken in accordance with standard USGS protocols documented in the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). Field measurements include pH, specific conductance, temperature, dissolved oxygen, alkalinity, and discharge rates at springs. Field alkalinities were determined using incremental equivalence. Dissolved constituent samples were filtered through a 0.45-micron pore size filter and preserved according to sampling and analytical protocols. Laboratory analyses for samples were done at the USGS National Water Quality Laboratory (NWQL) according to techniques described in Fishman and Friedman (1989), Fishman (1993), Struzeski and others (1996), and Garbarino and others (2006).

Quality assurance for this study was maintained by standard USGS training of field personnel, use of standard USGS field protocols (U.S. Geological Survey, variously dated), collection of quality control (QC) samples, and thorough review of the analytical results. All USGS scientists involved with this study have participated in the USGS National Field Quality Assurance Program.

A sequential replicate QC sample was collected at Burro Spring to better understand potential variability associated with field conditions, and field and laboratory procedures (table 11). Besides iron, the relative percent differences ranged from 0 to 7.1 percent. Only iron had a relative percent differences greater than 10 percent. Iron values from the environmental and replicate samples differed by 137 percent. The environmental sample result of 11.8 micrograms per liter (µg/L) is like iron concentrations from samples collected in previous years (period of record median = 11.4 µg/L). The replicate iron value may have been affected by contamination or a laboratory error.

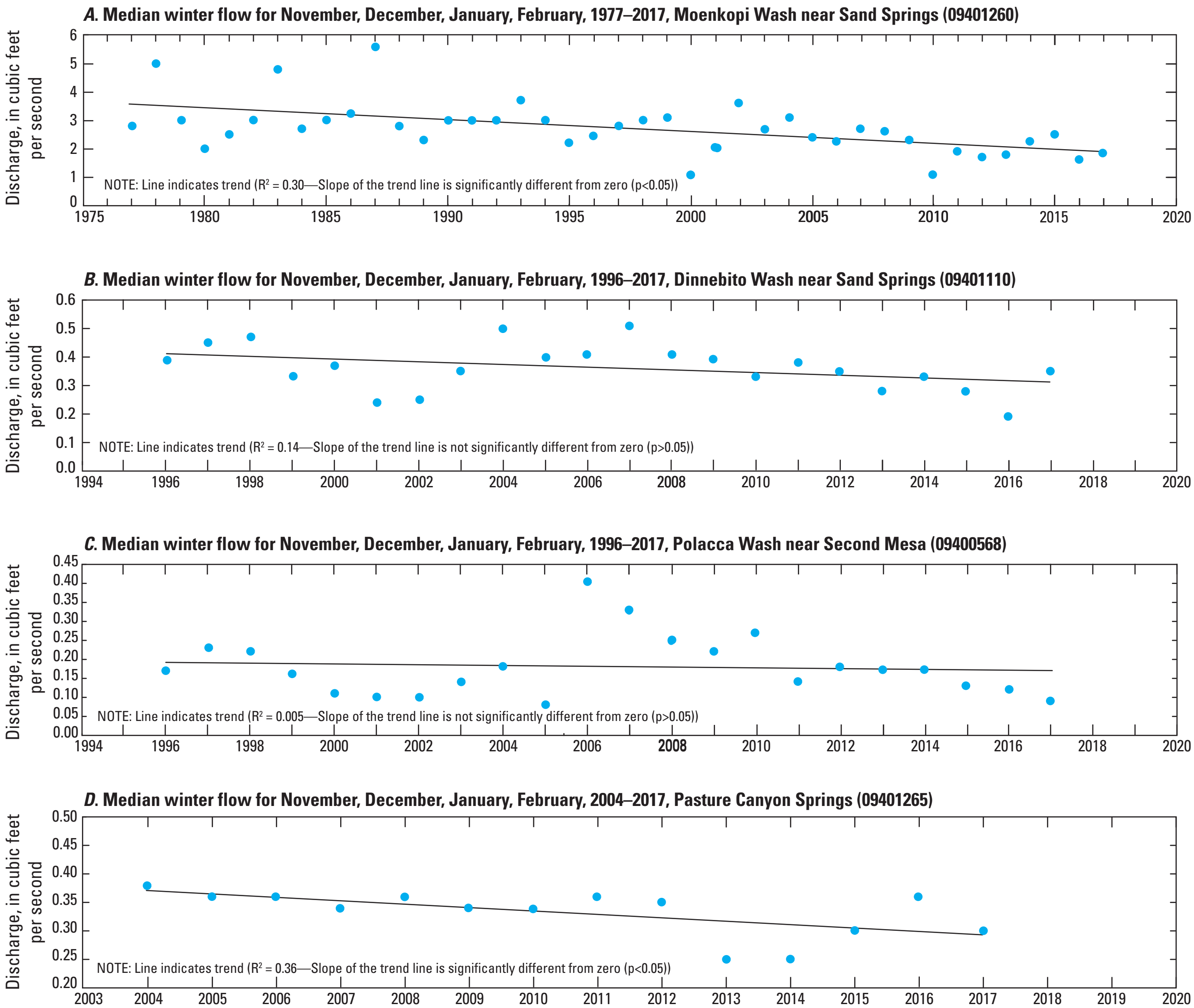


Figure 14. Plots of median winter flow for November, December, January, and February for water years 1977–2017 for *A*, Moenkopi Wash at Moenkopi (09401260); *B*, Dinnebito Wash near Sand Springs (09401110); *C*, Polacca Wash near Second Mesa (09400568); and *D*, Pasture Canyon Springs (09401265), Black Mesa area, northeastern Arizona. Median winter flow is calculated by computing the median flow for 120 consecutive daily mean flows for the winter months of November through February. Trend lines were generated by using the method of least squares.

The one replicate sample suggests that, except for iron, there is an acceptably low level of variability affecting the data; no QC data was collected to assess potential bias affecting the data. A field blank was collected at Unnamed Spring near Dennehotso during the collection of an environmental sample. Concentrations of analytes in the field blank were below the NWQL method detection limit (table 12).

In past years water-chemistry samples were systematically collected from as many as 12 different wells as part of the Black Mesa monitoring program. The number of wells sampled has been reduced owing to budgetary constraints. Two wells were sampled in 2017, Peabody 2 and Kykotsmovi PM2, and no wells were sampled in 2018. Since 1989, samples have been collected from the same four springs—Moenkopi School Spring, Pasture Canyon Spring, Unnamed Spring near Dennehotso, and Burro Spring. Three of the springs were sampled in 2017 and all four were sampled in 2018. Long-term data for specific conductance, dissolved solids, chloride, and sulfate for the wells and springs sampled each year are shown in the annual reports (table 2). These constituents are monitored on an annual basis because increased concentrations in the N aquifer could indicate leakage from the overlying D aquifer. On

Table 11. Comparison of chemical analyses of replicate and environmental water samples taken from Burro Spring, Black Mesa area, northeastern Arizona, 2017.

[°C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; ---, no data]

Physical property or chemical analysis	Environmental	Replicate	Relative percent difference
Common well name	Burro Spring	Burro Spring	---
U.S. Geological Survey identification number	354156110413701	354156110413701	---
Date of samples	7/18/2017	7/18/2017	---
Alkalinity, field, dissolved (mg/L as $CaCO_3$)	185	187	-1.1
Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	<0.04	<0.04	---
Ortho- Phosphate, dissolved (mg/L as P)	0.009	0.009	0
Calcium, dissolved (mg/L as Ca)	55.3	55.3	0
Magnesium, dissolved (mg/L as Mg)	3.90	3.90	0
Potassium, dissolved (mg/L as K)	0.41	0.44	-7.1
Sodium, dissolved (mg/L as Na)	57.5	57.5	0
Chloride, dissolved (mg/L as Cl)	22.0	21.9	0
Flouride, dissolved (mg/L as F)	0.37	0.37	0
Silica, dissolved (mg/L as SiO2)	17.6	17.4	-1.1
Sulfate, dissolved (mg/L as SO4)	59.5	59.4	0.2
Arsenic, dissolved (µg/L as As)	2.4	2.4	0
Boron, dissolved (µg/L as B)	90	90	0
Iron, dissolved (µg/L as Fe)	11.8	63.6	-137
Dissolved solids, residue at 180 °C (mg/L)	329	326	0.9

Table 12. Chemical analyses of a field blank water sample processed at Unnamed Spring near Dennehotso, Black Mesa area, northeastern Arizona, 2018.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; E, estimated; µg/L, micrograms per liter; <, less than; --, no data]

Common spring name	U.S. Geological Survey identification number	Date of samples	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	Chloride, dissolved (mg/L as Cl)	Flouride, dissolved (mg/L as F)
Unnamed Spring near Dennehotso	364656109425400	7/3/2018	<0.022	<0.011	<0.30	<0.40	<0.02	<0.01

Common spring name	U.S. Geological Survey identification number	Date of samples	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Unnamed Spring near Dennehotso	364656109425400	7/3/2018	<0.06	<0.02	<0.10	<2.0	<10.0	<20

average, the concentrations of dissolved solids in water from the D aquifer is about 7 times greater than that of water from the N aquifer; concentration of chloride ions is about 11 times greater, and concentration of sulfate ions is about 30 times greater (Eychaner, 1983). Historical data for other constituents for all the wells and springs in the Black Mesa study area are available from the USGS water-quality database (https://waterdata.usgs.gov/nwis/qw), and they can be found in monitoring reports cited in the "Previous Investigations" section of this report and listed in table 2. In 2017 water-quality samples also were collected at three of the streamflow gaging stations to determine the water chemistry of the streams at baseflow, when discharge in the streams is thought to be primarily derived directly from the N aquifer.

Water-Chemistry Data for Wells Completed in the N Aquifer

Previous monitoring (table 2) has found that the primary types of water in the N aquifer in the Black Mesa study area are calcium-bicarbonate water and sodium-bicarbonate water. Calcium-bicarbonate water is mostly found in the recharge, and unconfined areas of the northern and northwestern parts of the Black Mesa study area (Lopes and Hoffmann, 1997). Sodium-bicarbonate water is mostly found in the area that is confined and downgradient to the south and east (Lopes and Hoffmann, 1997). Water-chemistry results from well samples in 2017 are like results from previous years and are presented in figures 15 and 16 and in tables 13 and 14.

Chemical constituents analyzed from the two wells were compared to the U.S. Environmental Protection Agency (EPA) primary and secondary drinking water standards (U.S. Environmental Protection Agency, 2003). Maximum Contaminant Levels (MCLs), which are the primary regulations, are legally enforceable standards that apply to public water systems. They 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 EPA recommends compliance with SMCLs for public water systems; however, compliance is not enforced.

In 2017, all the analyzed constituents from the two wells were below the EPA MCL for drinking water. However, both wells had pH values that were higher than the SMCL pH range (6.5–8.5) (table 13). The SMCL for pH is a guideline, waters with a pH higher than the SMCL may have a slippery feel, soda taste, and cause water deposits (U.S. Environmental Protection Agency, 2003). All other analyzed constituents were below the SMCL for drinking water (table 13).

Water-Chemistry Data for Springs that Discharge from the N Aquifer

In 2017, water samples were collected from Burro Spring, Moenkopi School Spring, and Pasture Canyon Spring, while in 2018, water samples were collected from these three springs and Unnamed Spring near Dennehotso (figs. 11 and 15). Geologic maps and field observations indicate that these four springs discharge water from the unconfined part of the N aquifer. At Moenkopi School Spring, samples were collected from a horizontal metal pipe built into the hillside to collect water from the spring. At Pasture Canyon Spring, samples were collected from a pipe at the end of a channel that is approximately 50 ft away from the spring. At Burro Spring, samples were collected from the end of a pipe that fills a trough for cattle. At Unnamed Spring near Dennehotso, samples were collected from a pool along the bedrock wall from which the spring discharges.

Samples from all springs except Burro Spring, yielded calcium-bicarbonate-type water. The sample from Burro Spring yielded a sodium, calcium- bicarbonate-type water (fig. 15 and table 15). Dissolved-solids concentrations measured 329 and 330 mg/L in 2017 and 2018 respectively, at Burro Spring, 266 and 260 mg/L in 2017 and 2018 respectively, at Moenkopi School Spring, 151 and 145 mg/L in 2017 and 2018 respectively, at Pasture Canyon Spring, and 108 mg/L at Unnamed Spring near Dennehotso in 2018 (tables 15 and 16). Chloride concentrations were highest at Moenkopi School Spring (36.9 mg/L (2018); tables 15 and 16). Concentrations of sulfate was highest at Burro Spring (59.5 mg/L (2017); tables 15 and 16). Concentrations of all the analyzed constituents in samples from all four springs were less than current EPA MCLs and SMCLs (U.S. Environmental Protection Agency, 2003).

There are significant increasing trends in concentrations of dissolved solids, chloride, and sulfate in water from Moenkopi School Spring ($p<0.05$; table 16 and fig. 17). Concentrations of the same constituents from Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso did not show any significant trends (table 16 and fig. 17). However, in 2010, 2011, and 2012, Unnamed Spring near Dennehotso showed an increase in dissolved-solids concentrations which may be a result of sampling from an alternate sample location. Since then, Unnamed Spring near Dennehotso has been sampled from the same location that was used prior to 2010 and the results for dissolved-solids analysis returned to levels observed prior to 2010 (fig. 17).

Water-Chemistry Data for Streams that Receive Flow from the N Aquifer

Water chemistry samples are not systematically collected at the four-streamflow gaging-stations described in the surface-water discharge portion of this report. However, samples were collected at three of the gaging stations in 2017 to determine the water chemistry of the streams at baseflow, when discharge in the streams is thought to be primarily derived directly from the N aquifer. A chemistry sample was not collected at the Pasture Canyon Springs streamflow-gaging station since it is located about a quarter mile downstream from Pasture Canyon Spring which is sampled annually. The water chemistry results from Pasture Canyon Spring are described in the previous section.

Moenkopi Wash at Moenkopi (09401260), Dinnebito Wash near Sand Springs (09401110), and Polacca Wash near Second Mesa (09400568) were sampled on October 18, 2017. Discharge recorded at all three gaging stations indicated that baseflow conditions persisted for at least two weeks prior to October 18, 2017. Further, a recording precipitation gage located at the Polacca Wash streamflow gaging-station showed no precipitation had fallen at the gage in the two-week period prior to October 18, 2017. The samples from all three streams yielded sodium-sulfate-type water (fig. 15 and

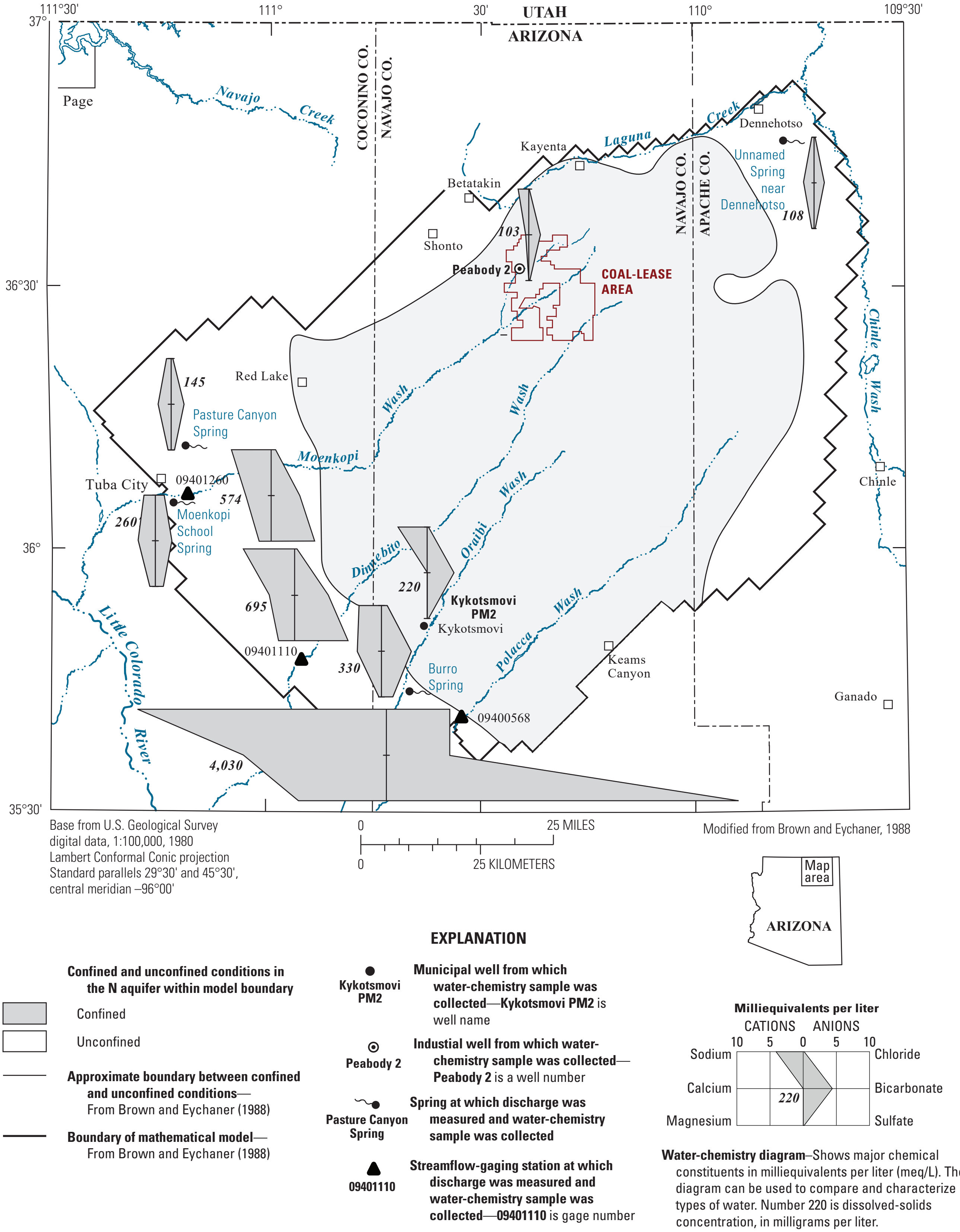


Figure 15. Map showing water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, northeastern Arizona, 2017–2018.

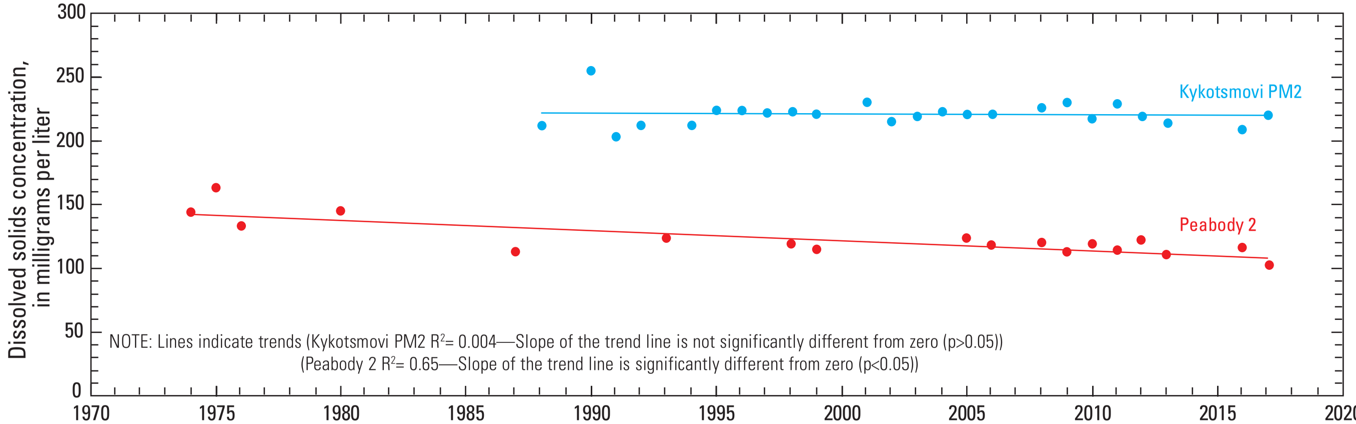


Figure 16. Plots of dissolved-solids concentrations for water samples from selected wells, N aquifer, Black Mesa area, northeastern Arizona: Kykotsmovi PM2, 1988–2017; and Peabody 2, 1974–2017.

Table 13. Physical properties and chemical analyses of water samples from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, 2017.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Common well name	U.S. Geological Survey identification number	Date of samples	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	Ortho-Phosphate, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)
Kykotsmovi PM2	355215110375001	8/30/2017	22.9	367	9.8	161	1.20	0.035	0.478	0.015	0.42
Peabody 2	363005110250901	8/29/2017	31.2	164	8.8	67.3	0.964	0.008	8.12	0.127	0.73

Common well name	U.S. Geological Survey identification number	Date of samples	Sodium, dissolved (mg/L as Na)	Chloride, dissolved (mg/L as Cl)	Flouride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Kykotsmovi PM2	355215110375001	8/30/2017	80.5	2.99	0.15	24.5	7.93	5.7	29	<10.0	220
Peabody 2	363005110250901	8/29/2017	25.7	1.97	0.11	22.0	6.85	2.9	16	<10.0	103

Table 14. Specific conductance and concentrations of selected chemical constituents in water samples from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, during 1967–2017.

[µS/cm, microsiemens per centimeter at 25 °C; °C, degrees Celsius; mg/L, milligram per liter; ---, no data]

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180 °C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Kykotsmovi PM2				
1988	368	212	3.2	8.6
1990	355	255	3.2	9.0
1991	[a]374	203	4.4	7.9
1992	363	212	3.3	8.4
1994	[a]365	212	3.6	8.5
1995	368	224	3.1	6.2
1996	365	224	3.3	8.5
1997	[a]379	222	3.02	7.97
1998	348	223	3.33	7.33
1999	317	221	3.50	7.94
2001	339	230	3.48	8.18
2002	350	215	3.39	7.86
2003	364	219	3.49	7.76
2004	261	223	3.46	8.32
2005	316	221	3.08	6.93
2006	367	221	3.25	7.69
2008	373	226	3.04	8.22
2009	369	230	3.13	8.11
2010	382	217	3.17	8.38
2011	367	229	3.10	8.35
2012	367	219	3.07	7.75
2013	369	214	3.05	8.01
2016	364	209	3.27	7.86
2017	367	220	2.99	7.93
Peabody 2				
1967	221	---	5.0	21
1971	211	---	2.8	18
1974	210	144	2.8	17
1975	230	163	5.0	20
1976	260	133	3.6	16
1979	220	---	3.4	24
1980	225	145	11.0	20
1986	172	---	2.6	8.1
1987	149	113	5.0	9.1
1993	163	124	1.7	8.9
1998	[b]167	119	2.22	7.87
1999	167	115	2.31	8.14
2005	134	124	2.09	8.22
2006	167	118	2.16	8.23
2008	160	120	2.04	7.47
2009	[a]163	113	2.08	7.16
2010	168	119	2.08	7.37
2011	162	114	2.13	8.12
2012	155	122	2.04	7.25
2013	162	111	2.03	6.86
2016	163	116	2.01	7.28
2017	164	103	1.97	6.85

[a]Value is different in Black Mesa monitoring reports. Some earlier reports showed values determined by laboratory analysis.

[b]Value is from laboratory analysis.

table 17). Dissolved-solids concentrations measured 574 mg/L at Moenkopi Wash, 695 mg/L at Dinnebito Wash, and 4,030 mg/L at Polacca Wash (tables 17 and 18).

Both the water type and dissolved-solids concentrations from the stream water-quality samples are not characteristic of N aquifer water. A review of dissolved-solids concentrations from previous water-quality samples collected during baseflow conditions indicate that water chemistry of the streams is variable even during baseflow conditions (table 18). Baseflow conditions for table 18 were estimated by using the maximum median winter flow calculated as described in figure 14. Results in table 18 show that the highest dissolved-solids concentrations measured during baseflow conditions at Moenkopi Wash occurred after precipitation runoff events. This is not surprising given that salts tend to accumulate in the soils of arid lands and can be mobilized by overland flow during heavy precipitation events. It is less clear why stream water type and dissolved-solids concentrations are different from N aquifer water after longer periods of stable baseflow. Two possible reasons for this could be evapoconcentration and salts stored in stream alluvium.

Evapoconcentration was likely occurring when the Polacca Wash water chemistry sample was collected on October 18, 2017. The streamflow-gaging station is located a mile downstream of the spring that provides baseflow in that stream reach. On October 18, 2017 the discharge measured at the streamflow-gaging station was less than half of the discharge measured during the collection of all other previous water chemistry samples collected at baseflow. The dissolved solids concentration of the October 18, 2017 water chemistry sample was about 60-percent higher than the average dissolved-solids concentration from previous baseflow samples (table 18).

Salts deposited along with stream alluvium and released slowly during baseflow conditions may be another source of

Table 15. Physical properties and chemical analyses of water samples from four springs in the Black Mesa area, northeastern Arizona, in 2017–2018.

[°C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Ortho-Phosphate, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)
354156110413701	6M-31	Burro Spring	7/18/2017	22.6	536	7.4	185	<0.040	0.009	55.3	3.90	0.41
			6/6/2018	19.1	532	7.5	178	<0.040	0.007	53.6	3.85	0.15
360632111131101	3GS-77-6	Moenkopi School Spring	7/11/2017	18.5	424	7.2	98.5	2.47	0.007	41.1	8.67	1.42
			6/6/2018	18.2	434	7.2	98.3	2.31	0.005	41.6	8.63	1.28
361021111115901	3A-5	Pasture Canyon Spring	7/11/2017	17.0	236	7.5	78.0	4.44	0.013	30.7	4.65	1.21
			6/6/2018	16.8	238	7.8	78.4	4.50	0.017	29.6	4.33	1.42
364656109425400	8A-224	Unnamed Spring near Dennehotso	7/3/2018	15.0	157	7.8	64.9	1.38	0.023	24.0	3.86	1.15

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Sodium, dissolved (mg/L as Na)	Chloride, dissolved (mg/L as Cl)	Flouride, dissolved (mg/L as F)	Silica dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
354156110413701	6M-31	Burro Spring	7/18/2017	57.5	22.0	0.37	17.6	59.5	2.4	90	11.8	329
			6/6/2018	59.7	21.6	0.35	16.8	58.7	0.86	84	13.0	330
360632111131101	3GS-77-6	Moenkopi School Spring	7/11/2017	31.4	35.5	0.15	13.3	44.7	2.1	47	<10.0	266
			6/6/2018	32.8	36.9	0.15	13.5	45.9	2.2	48	<10.0	260
361021111115901	3A-5	Pasture Canyon Spring	7/11/2017	12.7	5.07	0.15	9.97	17.1	1.7	35	<10.0	151
			6/6/2018	12.6	5.04	0.16	10.3	16.9	1.7	36	<10.0	145
364656109425400	8A-224	Unnamed Spring near Dennehotso	7/3/2018	5.16	2.33	0.15	13.8	5.39	3.1	17	<10.0	108

dissolved solids in stream water. Rocks of Cretaceous and Jurassic age in the drainage basins above the three streamflow-gaging stations likely contain evaporite minerals like gypsum that readily dissolve in water and may be a source of salts in stream alluvium. Billingsley and others (2012) describe Holocene alluvial and flood-plain deposits in the Tuba City area as partially cemented by gypsum.

Summary

The N aquifer is an extensive aquifer and the primary source of groundwater for industrial and municipal users in the Black Mesa area of northeastern Arizona. Availability of quality water is an important issue in the Black Mesa area because of continued industrial and municipal use, a growing population, and limited precipitation. This report presents results of groundwater, surface-water, and water-chemistry monitoring in the Black Mesa area from November 2016 to December 2018. The monitoring data for 2016–18 are compared to historical data from the 1950s to December 2018.

In 2017, total groundwater withdrawals were about 3,710 acre-ft; industrial withdrawals were about 1,110 acre-ft, and municipal withdrawals were about 2,600 acre-ft. In 2018, total groundwater withdrawals were about 3,670 acre-ft; industrial withdrawals were about 1,170 acre-ft, and municipal withdrawals were about 2,500 acre-ft.

From the prestress period before 1965, to 2018, the median groundwater-level change in 32 wells was −9.4 ft. Water levels in the unconfined areas of the N aquifer had a median change of -0.6 ft, and the changes ranged from −39.4 ft to +12.1 ft. Water levels in the confined area of the N aquifer had a median change of −40.2 ft, and the changes ranged from −189.0 ft to +14.2 ft.

Table 16. Specific conductance and concentrations of selected chemical constituents in N aquifer water samples from four springs in the Black Mesa area, northeastern Arizona, 1948–2018.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; ---, no data]

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Burro Spring				
1989	485	308	22.0	59
1990	[a]545	347	23.0	65.0
1993	595	368	30.0	85.0
1994	[a]597	368	26.0	80.0
1996	525	324	23.0	62.0
1997	[a]511	332	26.0	75.0
1998	504	346	24.6	70.4
1999	545	346	24.8	69.2
2001	480	348	23.6	67.8
2002	591	374	30.6	77.0
2003	612	374	30.5	81.1
2004	558	337	24.9	63.6
2005	558	357	25.8	68.9
2006	576	359	25.0	68.2
2009	577	372	25.7	72.5
2010	583	355	25.9	71.5
2011	560	353	25.7	69.5
2012	553	330	23.1	64.7
2013	560	350	24.4	67.7
2014	549	360	22.8	64.6
2016	544	318	22.2	61.7
2017	536	329	22.0	59.5
2018	532	330	21.6	58.7

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Moenkopi School Spring				
1952	222	---	6	---
1987	270	161	12.0	19.0
1988	270	155	12.0	19.0
1991	297	157	14.0	20.0
1993	313	204	17.0	27.0
1994	305	182	17.0	23.0
1995	314	206	18.0	22.0
1996	332	196	19.0	26.0
1997	[a]305	185	17.8	23.8
1998	296	188	17.6	23.7
1999	305	192	18.7	25.6
2001	313	194	18.3	25.5
2002	316	191	18.3	23.1
2003	344	197	18.6	23.4
2004	349	196	19.1	21.3
2005	349	212	23.3	29.6
2006	387	232	27.2	34.2
2007	405	238	30.6	39.9
2008	390	230	28.3	37.6
2009	381	240	27.0	35.4
2010	480	217	26.2	33.4
2011	374	216	28.5	36.2
2012	382	218	27.5	33.3

Table 16.—Continued

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Moenkopi School Spring—Continued				
2013	370	220	27.2	33.3
2014	382	226	28.5	34.6
2016	427	244	34.6	43.8
2017	424	266	35.5	44.7
2018	434	260	36.9	45.9
Pasture Canyon Spring				
1948	[a]227	([b])	6.0	13
1982	240	---	5.1	18.0
1986	257	---	5.4	19.0
1988	232	146	5.3	18.0
1992	235	168	7.10	17.0
1993	242	134	5.3	17.0
1995	235	152	4.80	14.0
1996	238	130	4.70	15.0
1997	232	143	5.27	16.9
1998	232	147	5.12	16.2
1999	235	142	5.06	14.2
2001	236	140	5.06	17.0
2002	243	143	5.14	16.5
2003	236	151	5.09	16.1
2004	248	150	5.50	16.4
2005	250	149	5.07	16.3
2008	240	149	5.01	18.3
2009	241	160	5.10	18.6
2010	314	157	5.25	17.9
2011	236	146	5.47	18.5
2012	248	142	5.20	17.5
2013	245	145	5.16	17.7
2014	249	149	5.03	17.2

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Moenkopi School Spring—Continued				
2016	252	155	5.09	17.2
2017	236	151	5.07	17.1
2018	238	145	5.04	16.9
Unnamed Spring near Dennehotso				
1984	195	112	2.8	7.1
1987	178	[b]109	3.4	7.5
1992	178	108	3.60	7.30
1993	184	100	3.2	8.00
1995	184	124	2.60	5.70
1996	189	112	2.80	8.20
1997	[a]170	98	2.40	6.10
1998	179	116	2.43	5.36
1999	184	110	2.76	6.30
2001	176	116	2.61	5.96
2002	183	104	2.67	7.38
2003	180	118	2.95	7.16
2004	170	117	2.72	5.05
2005	194	114	2.65	8.67
2010	259	155	9.38	15.5
2011	292	172	14.5	24.1
2012	298	179	13.5	21.9
2013	196	127	3.06	8.24
2014	160	122	2.68	7.40
2016	197	116	3.21	9.46
2018	157	108	2.33	5.39

[a]Value is different in Black Mesa monitoring reports before 2000. Earlier reports showed values determined by laboratory analysis.

[b]Value is different in Black Mesa monitoring reports before 2000. Earlier reports showed values determined by the sum of constituents.

Discharge has been measured annually at Moenkopi School Spring and Pasture Canyon Spring and intermittently at Burro Spring and Unnamed Spring near Dennehotso. For the period of record, discharge at Moenkopi School Spring and Unnamed Spring near Dennehotso has fluctuated, and the data indicate a decreasing trend in discharge for both springs; however, no trend is apparent for either Burro Spring or Pasture Canyon Spring.

Streamflow was measured continuously at four streamflow-gaging stations—Moenkopi Wash, Dinnebito Wash, Pasture Canyon Springs, and Polacca Wash—and varied during the periods of record. Median flows for November, December, January, and February of each water year are used as an indicator of groundwater discharge to those streams. For the period of record at Moenkopi Wash and Pasture Canyon Springs, winter flows indicate a decreasing trend in discharge. Winter flows at Dinnebito Wash and Polacca Wash have generally remained constant, showing neither a significant increase nor decrease.

In 2017, water chemistry samples were collected from two wells, three springs, and three streams and analyzed for selected chemical constituents. In 2018, water chemistry samples were collected from four springs. A replicate quality assurance sample suggests that overall there is an acceptably

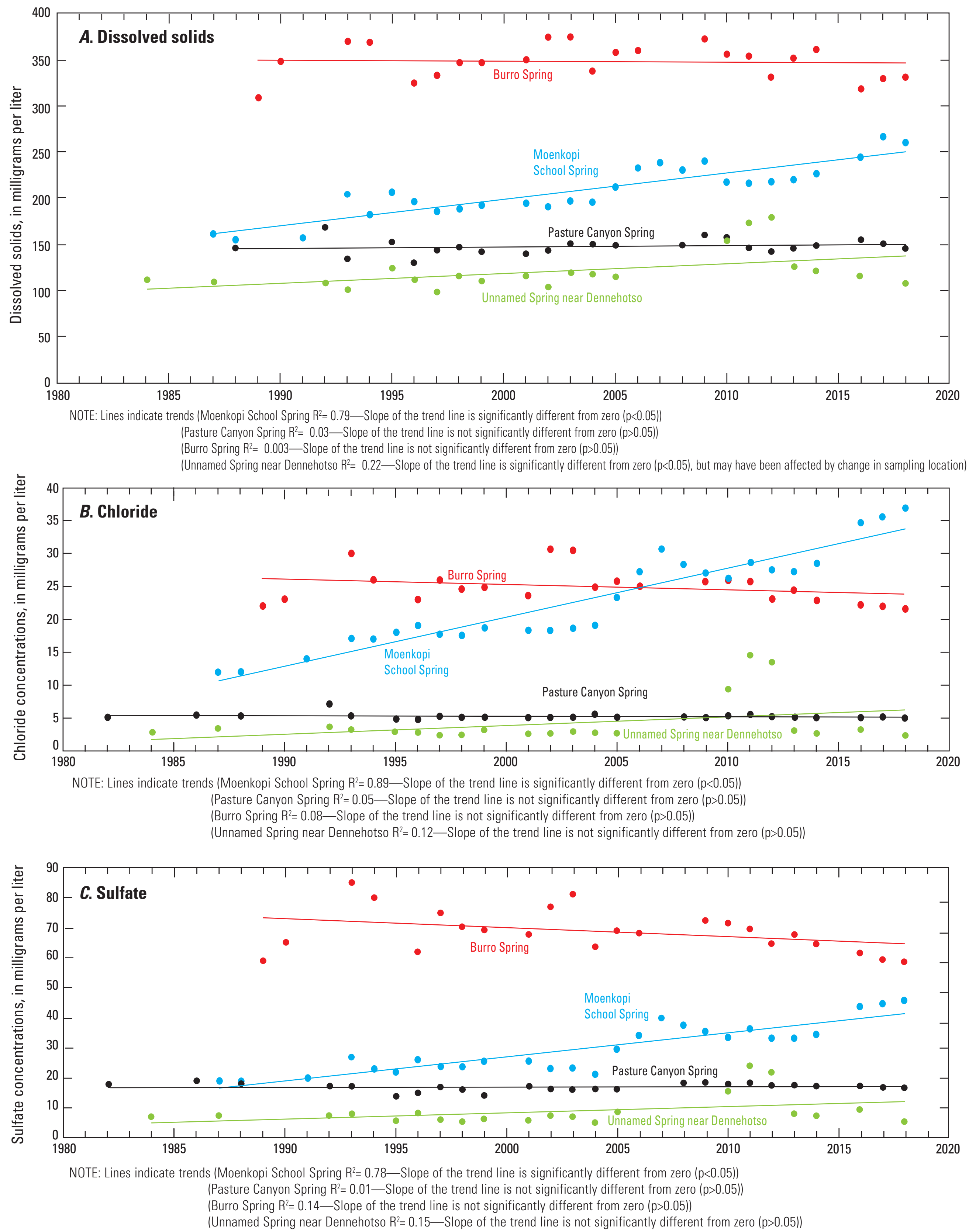


Figure 17. Plots of concentrations of dissolved solids, chloride, and sulfate for water samples from Moenkopi School Spring, Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso, which discharge from the N aquifer in Black Mesa area, northeastern Arizona, measured from 1982 to 2018. *A*, Dissolved solids; *B*, Chloride; and *C*, Sulfate. Trend lines were generated using the method of least squares.

Table 17. Physical properties and chemical analyses of water samples from selected surface-water sites, Black Mesa area, northeastern Arizona, 2017.

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Common surface-water site name	U.S. Geological Survey identification number	Date of samples	Instantaneous discharge (ft^3/s)	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	Ortho-Phosphate, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)
Moenkopi Wash at Moenkopi	09401260	10/18/2017	0.23	11.0	885	8.3	176	<0.040	<0.004	60.9	17.8	4.61
Dinnebito Wash near Sand Springs	09401110	10/18/2017	0.23	13.7	1,020	8.5	204	0.054	0.018	61.5	23.4	2.55
Polacca Wash near Second mesa	09400568	10/18/2017	0.02	11.1	5,030	7.3	412	<0.040	0.004	376	139	8.57

Common surface-water site name	U.S. Geological Survey identification number	Date of samples	Sodium, dissolved (mg/L as Na)	Chloride, dissolved (mg/L as Cl)	Flouride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Moenkopi Wash at Moenkopi	09401260	10/18/2017	108.0	16.3	0.57	5.33	247	1.0	87	<10.0	574
Dinnebito Wash near Sand Springs	09401110	10/18/2017	139	10.4	0.71	14.0	312	5.3	135	<10.0	695
Polacca Wash near Second mesa	09400568	10/18/2017	744	297	0.51	10.8	2,220	0.82	426	<30.0	4,030

Table 18. Total dissolved-solids concentrations at base flow from three stream in the Black Mesa area, northeastern Arizona, 1976–2017.

[ft^3/s, cubic feet per second; mg/L, milligrams per liter, ---, no data]

Date	Instantaneous discharge, ft^3/s	Dissolved solids, sum of constituents (mg/L)	Remarks
Moenkopi Wash at Moenkopi[a]			
7/30/1976	2.4	2,710	Sample collected near end of runoff event
11/11/1976	2.6	708	---
1/19/1977	3.4	588	---
3/15/1977	1.5	663	---
6/15/1977	0.04	826	---
7/13/1977	2.7	1,740	Sample collected near end of runoff event
7/29/1977	0.89	1,670	Sample collected near end of runoff event
9/8/1977	1.3	1,680	Sample collected near end of runoff event
11/21/1977	2.4	689	---
1/4/1978	2.8	624	---
2/17/1978	3.6	577	---
4/3/1978	1.8	642	---
5/16/1978	0.4	633	---
7/19/1978	2.8	1,020	Sample collected during runoff event
1/3/1979	2.6	734	---
11/14/1979	0.6	526	---
12/12/1979	3.7	468	---
1/15/1980	3.1	549	---
8/18/1980	0.42	2,310	Sample collected near end of runoff event
2/5/1981	2.5	521	---
4/2/1981	1.8	562	---
10/18/2017	0.23	565	---
Dinnebito Wash near Sand Springs[b]			
7/27/1994	0.38	849	---
10/18/2017	0.23	687	---
Polacca Wash near Second Mesa[c]			
9/23/1993	0.10	2,560	---
7/28/1994	0.05	2,620	---
1/13/1995	0.31	2,370	---
10/18/2017	0.02	4,040	---

[a]Base flow assumed to be discharge <5.6 ft^3/s

[b]Base flow assumed to be discharge <0.5 ft^3/s

[c]Base flow assumed to be discharge <0.4 ft^3/s

low level of variability affecting the data, although an anomaly occurred with the replicate value for iron. Concentrations of selected constituents from the two wells sampled in 2017 were like the concentrations measured from these wells in previous years. In 2018, dissolved-solids concentrations in water samples from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso were 330 mg/L, 260 mg/L, 145 mg/L, and 108 mg/L, respectively. From the mid-1980s to 2018, long-term data from Moenkopi School Spring indicate increasing concentrations of dissolved solids, chloride, and sulfate. Concentrations of dissolved solids, chloride, and sulfate from Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso do not indicate a trend for the period of record. Baseflow water chemistry samples were collected from Moenkopi, Dinnebito, and Polacca washes in 2017. Samples from all three streams had total-dissolved solids concentrations that were higher than is typically found in N aquifer water. It is unclear why the total-dissolved solids concentrations collected from these streams are so different from groundwater in the N aquifer, but possible causes include evapoconcentration in the stream reaches above the gages and the dissolution of salts from stream alluvium.

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