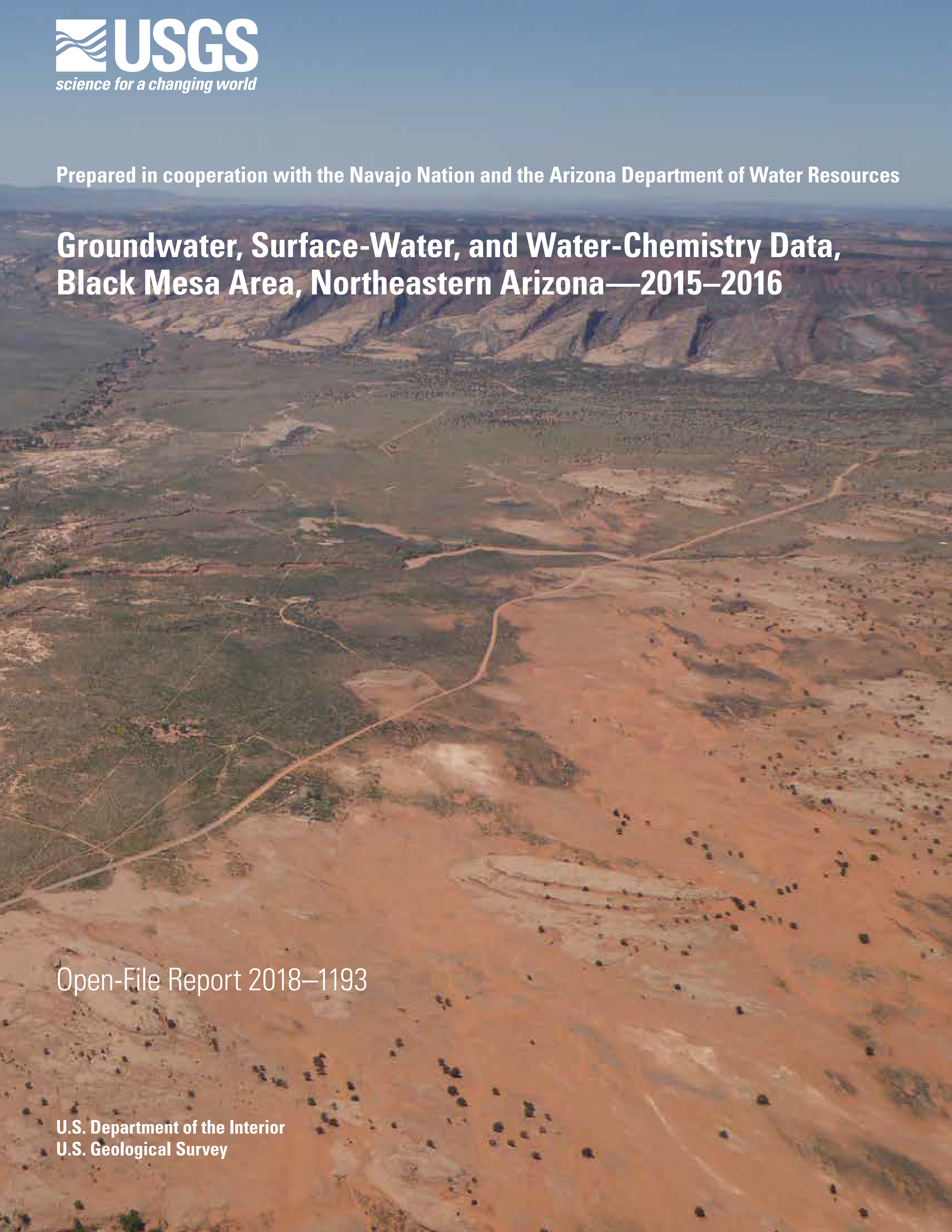

Prepared in cooperation with the Navajo Nation and the Arizona Department of Water Resources

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2015–2016

Open-File Report 2018–1193

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

Oblique aerial photograph looking southwest down the axis of Long House Valley. The southeast side of the valley is flanked by flat lying rocks of Cretaceous age (Black Mesa), whereas the northwest side of the valley is composed of steeply dipping Jurassic age rocks (Organ Rock monocline). Photograph by J.P. Mason, U.S. Geological Survey.

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2015–2016

By Jon P. Mason and Jamie P. Macy

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

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2018

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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)

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

Datum

Vertical coordinate information is referenced to the [insert datum name (and abbreviation) here; for example, North American Vertical Datum of 1988 (NAVD 88)].

Horizontal coordinate information is referenced to the [insert datum name (and abbreviation) here; for example, North American Datum of 1983 (NAD 83)].

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

Supplemental Information

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

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

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

Results for measurements of stable isotopes of an element (with symbol E) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope (^{i}E) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Note to USGS users: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter.

Abbreviations

ADWR	Arizona Department of Water Resources
BIA	Bureau of Indian Affairs
C aquifer	Coconino 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	U.S. Geological Survey

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2015–2016

By Jon P. Mason and Jamie P. Macy

Abstract

The Navajo (N) aquifer is an extensive aquifer and 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 the 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 2015 to December 2016. The monitoring program includes measurements of (1) groundwater withdrawals (pumping), (2) groundwater levels, (3) spring discharge, (4) surface-water discharge, and (5) groundwater chemistry.

In calendar year 2016, total groundwater withdrawals were 3,540 acre-ft, industrial withdrawals were 1,090 acre-ft, and municipal withdrawals were 2,450 acre-ft. Total withdrawals during 2016 were about 52 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 2015 to 2016, annually measured water levels available for comparison in wells completed in the unconfined areas of the N aquifer within the Black Mesa area declined in 9 of 16 wells, and the median change was -0.1 feet. Water levels also declined in 8 of 16 wells measured in the confined area of the aquifer. The median change for the confined area of the aquifer was 0.0 feet. From the prestress period (prior to 1965) to 2016, the median water-level change for all 32 wells in both the confined and unconfined areas was -10.2 feet; the median water-level changes were -1.6 feet for the 16 wells measured in the unconfined areas and -36.1 feet for the 16 wells measured in the confined area.

Spring flow was measured at four springs in 2016. 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 2016), Dinnebito Wash near Sand Springs 09401110 (1993 to 2016), Polacca Wash near Second Mesa 09400568 (1994 to 2016), and Pasture Canyon Springs 09401265 (2004 to 2016). 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 2016, water samples collected from three wells and four springs in the Black Mesa area were analyzed for selected chemical constituents, and the results were compared with previous analyses from the same wells and springs. Concentrations of dissolved solids, chloride, and sulfate have varied at all three wells for the period of record, but neither increasing nor decreasing trends over time were found. Dissolved solids, chloride, and sulfate concentrations increased at Moenkopi School Spring during the more than 25 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.

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 that includes flat plains, mesas, and incised drainages (fig. 1).

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.

Recognized 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 also 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 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 contributes 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, the Kayenta Formation, and the 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 to the southwest toward Tuba City, to the south toward the Hopi Reservation, and to the 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 (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 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 2015 to December 2016. 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. Together, these data are compared with groundwater and surface-water data from 1965 to 2016 to describe the overall status of and change over time of

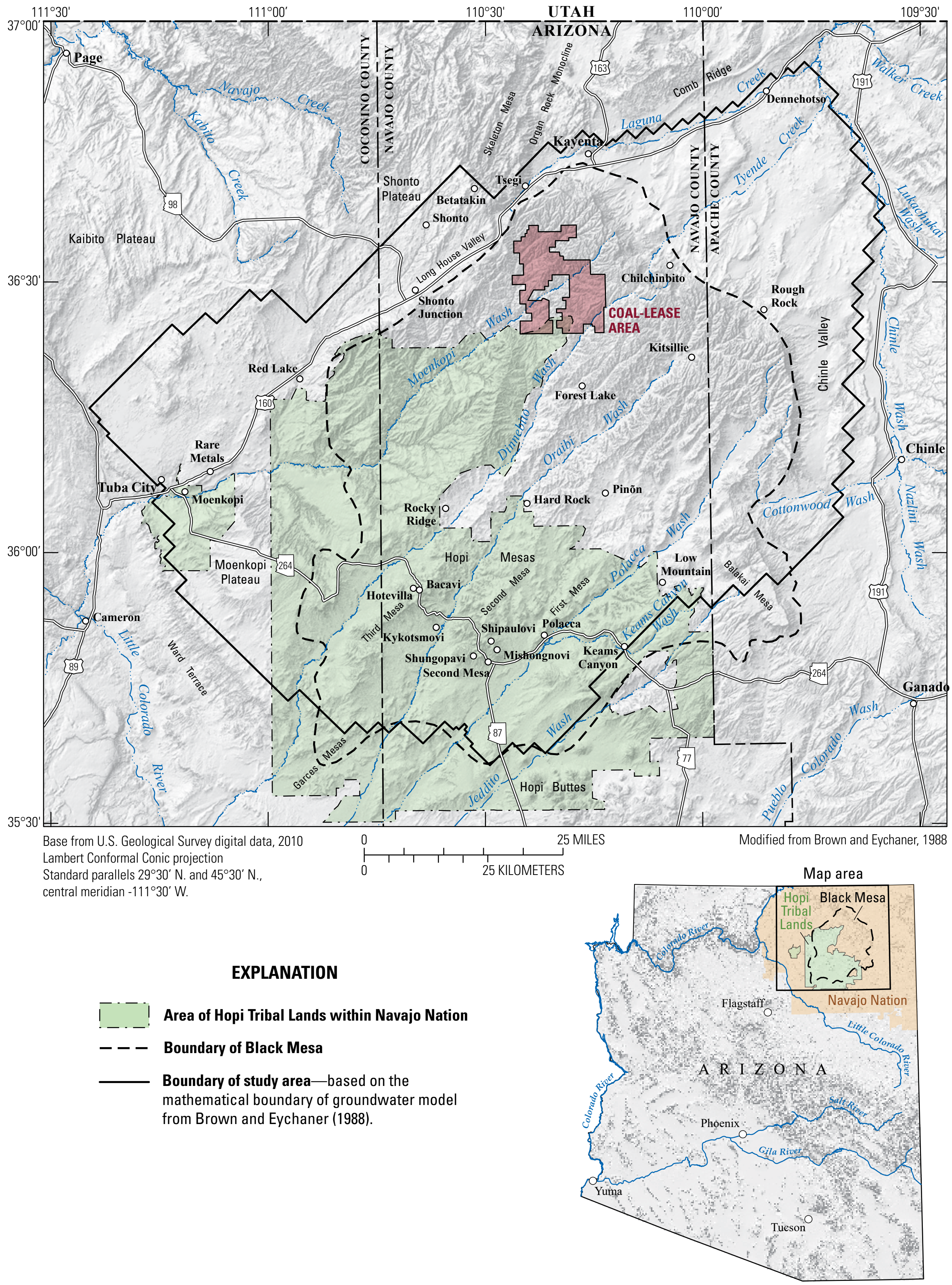
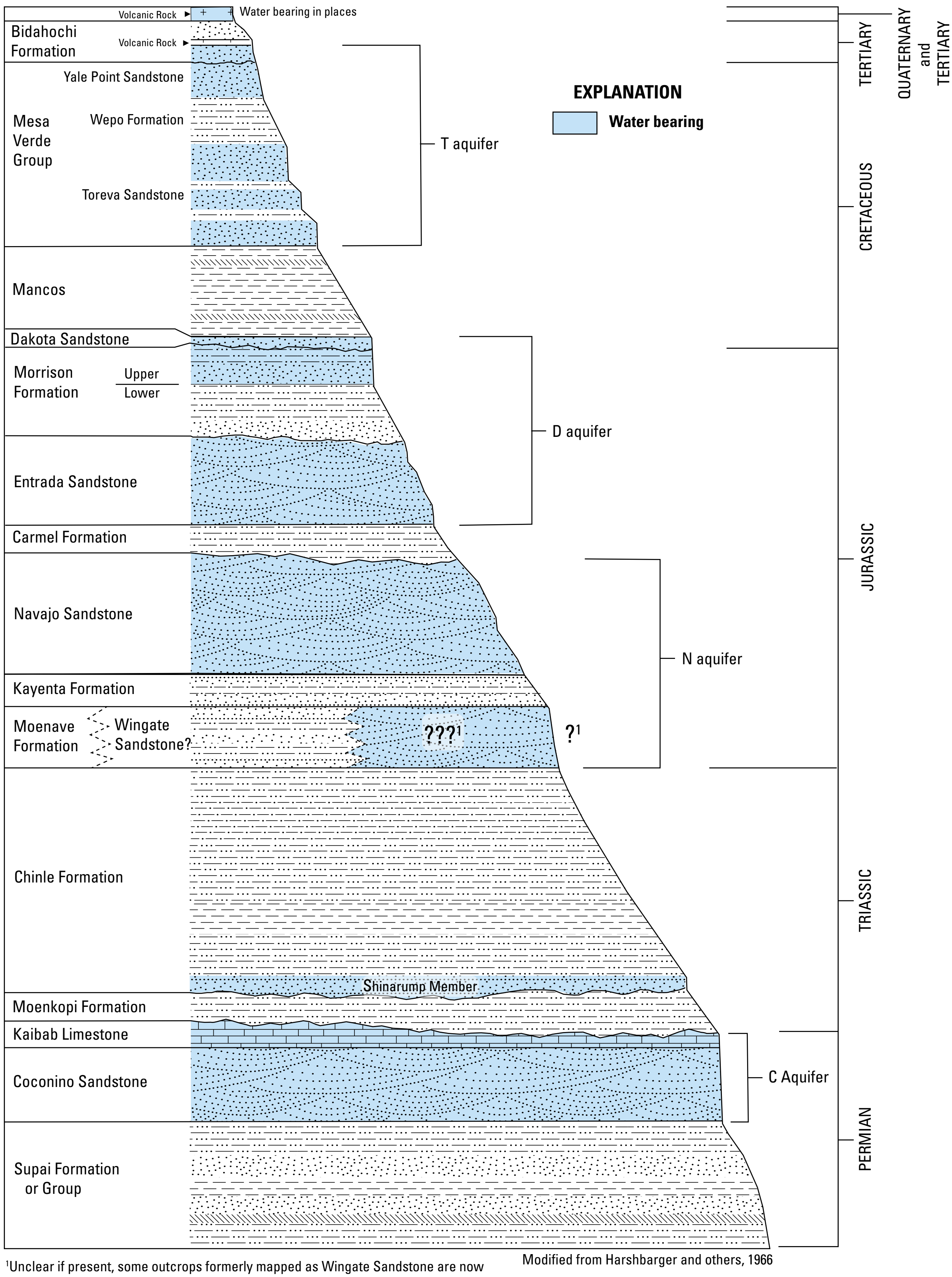


Figure 1. Map showing location of study area, Black Mesa area, northeastern Arizona. Boundary of study area is based on boundary of groundwater model from Eychaner (1983).



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

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. Withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2016.

[Values are rounded to nearest 10 acre-feet. Data for 1965–79 from Eychaner (1983). Total withdrawals in Littin and Monroe (1996) were for the confined area of the aquifer]

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
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

Table 1. Withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2016.—Continued.

Calendar year	Industrial[a]	Municipal[b,c]		Total withdrawals
		Confined	Unconfined	
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

[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, 1986–2011.

[d]Meter data were incomplete; therefore, municipal withdrawals are estimated, 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-feet greater than previously reported.

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 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

Table 2. Tabulated list of progress reports for the Black Mesa monitoring program 1978–2017.

Year published	Author(s)	Title	U.S. Geological Survey 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
1995a	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
1995b	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
1999	Littin, G.R., Baum, B.M., and Truini, M.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1997	Open-File Report 98–653
2000	Truini, M., Baum, B.M., Littin, G.R., and Shingoitewa-Honanie, G.	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, M.	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

Table 2. Tabulated list of progress reports for the Black Mesa monitoring program 1978–2017.—Continued.

Year published	Author(s)	Title	U.S. Geological Survey report type and number
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, M., 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, M., 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, M., 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, M., 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, M., 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
2016	Macy, J.P. and Truini, M.	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

(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 also influences the movement and chemistry of surface water and groundwater.

Physiography

The Black Mesa area is located 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 significant tectonic deformation and uplift during the past 70 million years. Parts of Black Mesa which were once below sea level now rise over 6,000 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.

Figure 3. Aerial photograph looking north at 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.

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 evaporates before it can infiltrate to groundwater. As a result, the vegetation cover consists mostly of 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 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, 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).

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 to remember 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 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

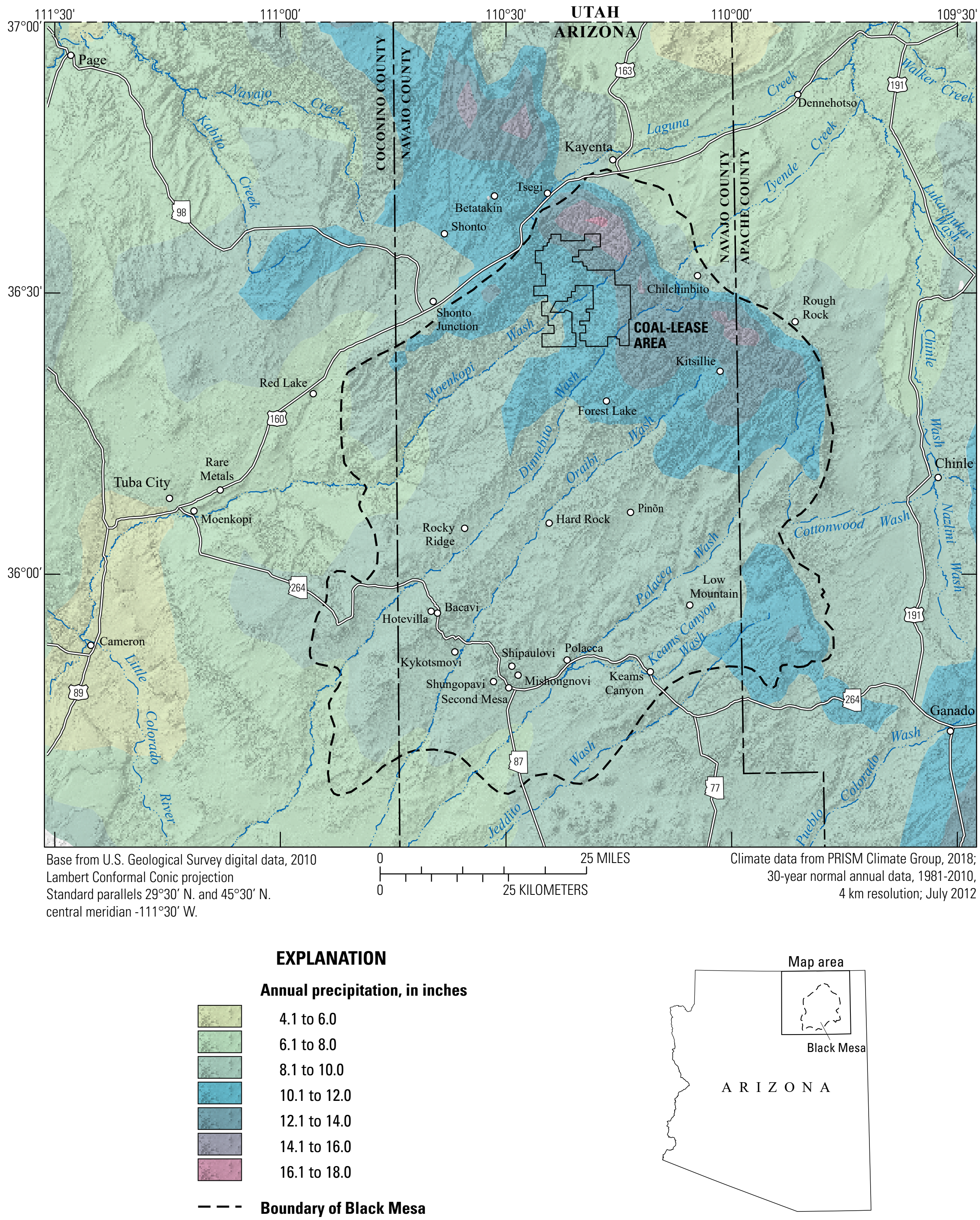


Figure 4. Map showing mean annual precipitation, 1981–2010, Black Mesa area, Arizona.

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 at the same time 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.

Wingate Sandstone

It is uncertain if the Wingate Sandstone is present in the Black Mesa area. Billingsley and others (2012, 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

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, U.S. Geological Survey.

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 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 bleach to a lighter color (Beitler and others, 2003). Bedding features in the Navajo 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 spheroidally weathered 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), 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 was 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 contributes 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 2015–16, 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 and springs. All data were collected by the USGS except withdrawal data from NTUA wells, which were compiled by NTUA personnel. Linear regression and Kendall's tau trend analyses were applied to streamflow data, spring-discharge measurements, and water-chemistry samples by using R Project for Statistical Computing (R Development Core Team, 2018). 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). The water-level data from these six continuous-recording observation wells are available on the NWIS website (http://waterdata.usgs.gov/az/nwis/gw).

Groundwater-withdrawal data were compiled during spring 2017. Spring discharges and groundwater levels were measured between March and October 2016. Groundwater samples were collected from four springs and three wells from June to October 2016 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 and are available online (http://waterdata.usgs.gov/az/nwis/rt). All annual data reported in this document are for calendar years beginning January 1 and ending December 31. 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 on the basis of metered data from individual wells operated by the BIA, NTUA, and Hopi Tribe (table 4).

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 Year 2016 Compared to Previous Years

In 2016 total groundwater withdrawal from the N aquifer was about 3,540 acre-ft (table 1). Total withdrawals for municipal use from 2016 was about 2,450 acre-ft per year; municipal withdrawals from the confined area totaled about 1,380 acre-ft per year, while withdrawals from the unconfined areas totaled about 1,070 acre-ft. Withdrawals for industrial use totaled about 1,090 acre-ft (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 2016. 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 from 2005 by about 44 percent (tables 1 and 5, fig. 6). Total withdrawal for the period of record (1965–2016) totaled 263,300 acre-ft; industrial withdrawals were 58 percent and municipal withdrawals were 42 percent of total withdrawals (table 5). Total withdrawals in 2016 were 3,540 acre-ft, with 31 percent from industrial withdrawals and 69 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 the same time of year to limit the effect of seasonal variability.

Table 3. Identification numbers and names of monitoring program study wells, 2015–16, Black Mesa area, northeastern Arizona.

[---, no data]

U.S. Geological Survey identification number	Common name or location	Bureau of Indian Affairs site number
354749110300101	Second Mesa PM2	---
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
360422110353501	Rocky Ridge PM3	---
360527110122501	Piñon NTUA 1	---
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
362418109514601	Rough Rock PM5	---
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
363558110392501	Shonto PM2	---
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
364344110151201	Kayenta PM2	8A-295
365045109504001	Dennehotso PM2	---

[a]Well with continuous water-level recorder.

Table 4. Withdrawals from the N aquifer by well system, Black Mesa area, northeastern Arizona, calendar year 2016.

[Withdrawals, in acre-feet, are from flowmeter measurements. BIA, Bureau of Indian Affairs; NTUA, Navajo Tribal Utility Authority; USGS, U.S. Geological Survey; Peabody, Peabody Western Coal Company; Hopi, Hopi Village Administrations]

Well system (one or more wells)	Owner	Source of data	2016 Withdrawals	
			Confined aquifer	Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	4.6	
Dennehotso	BIA	USGS/BIA		[b]11.2
Hopi High School	BIA	USGS/BIA	18.0	
Hotevilla	BIA	USGS/BIA	22.7	
Kayenta	BIA	USGS/BIA	19.4	
Keams Canyon	BIA	USGS/BIA	56.0	
Low Mountain	BIA	USGS/BIA	[a]0	
Piñon	BIA	USGS/BIA	[a]0	
Red Lake	BIA	USGS/BIA		3.4
Rocky Ridge	BIA	USGS/BIA	3.4	
Rough Rock	BIA	USGS/BIA	[b]14.9	
Second Mesa	BIA	USGS/BIA	6.4	
Shonto	BIA	USGS/BIA		98.1
Tuba City	BIA	USGS/BIA		76.4
Chilchinbito	NTUA	USGS/NTUA	67.7	
Dennehotso	NTUA	USGS/NTUA		40.4
Forest Lake	NTUA	USGS/NTUA	12.6	
Hard Rock	NTUA	USGS/NTUA	67.0	
Kayenta	NTUA	USGS/NTUA	372.0	
Kits'iili	NTUA	USGS/NTUA	18.2	
Piñon	NTUA	USGS/NTUA	341.9	
Red Lake	NTUA	USGS/NTUA		37.9
Rough Rock	NTUA	USGS/NTUA	39.7	
Shonto	NTUA	USGS/NTUA		48.2
Shonto Junction	NTUA	USGS/NTUA		75.7
Tuba City	NTUA	USGS/NTUA		591.6
Mine Well Field	Peabody	Peabody	1,090	
Bacavi	Hopi	USGS/Hopi	18.5	
Hopi Civic Center	Hopi	USGS/Hopi	1.5	
Hopi Cultural Center	Hopi	USGS/Hopi	6.5	
Kykotsmovi	Hopi	USGS/Hopi	63.6	
Mishongnovi	Hopi	USGS/Hopi	4.1	
Moenkopi	Hopi	USGS/Hopi		92.0
Polacca	Hopi	USGS/Hopi	167.6	
Shipaulovi	Hopi	USGS/Hopi	23.4	
Shungopovi	Hopi	USGS/Hopi	24.9	

[a]Well taken out of service.

[b]Estimated value due to partial record.

Table 5. Total, industrial, and municipal withdrawals from the N aquifer for discrete time periods during 1965 to 2016, Black Mesa area, northeastern Arizona.

Period	Total withdrawals (acre-feet)	Industrial withdrawals (acre-feet)	Municipal withdrawals (acre-feet)	Percent industrial	Percent municipal
1965–2016	263,300	152,500	110,800	58	42
1965–2005	218,300	138,100	80,200	63	37
2006–2016	45,000	14,400	30,600	32	68
2016	3,540	1,090	2,450	31	69

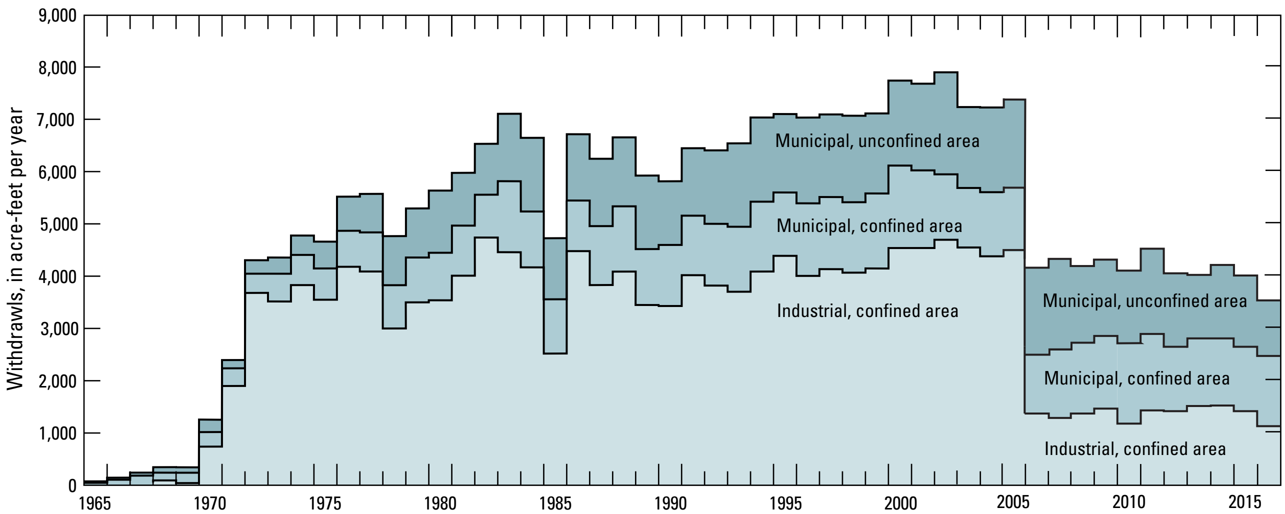


Figure 6. Annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2016.

Groundwater levels are compared with levels from previous years to determine short-term changes and are compared to prestress water levels to identify long-term changes. Only water levels from municipal and stock wells that were not considered to have been recently pumped, affected by nearby pumping, or blocked or obstructed are compared. Between March and October 2016, water-levels were measured in 32 wells and water-level comparisons were made between years (table 6). Of the 32 wells, 6 are continuous-recording observation wells. Water levels were measured quarterly using electric tape in these six wells during water year 2016 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 Kits'iilie NTUA 2 (table 7).

Changes in water levels from 2015 to 2016 and from the prestress period to 2016 are shown in table 6. From 2015 to 2016 water levels decreased in 17 of the 32 wells for which comparisons could be made (table 6). The median water-level change in the 32 wells was -0.1 ft (table 8). In the unconfined parts of the aquifer, water levels declined in 9 of the 16 wells measured (table 6), and the median water-level change was -0.1 ft (table 8). In the confined parts of the aquifer, water levels declined from 2015 to 2016 in 8 of 16 wells measured. The median water-level change was 0.0 ft (table 8).

From the prestress period (before 1965) to 2016, the median water-level change in 32 wells measured in 2016 was -10.2 ft (table 8). Water levels in 16 unconfined wells had a median change of -1.6 ft (table 8), and water-level changes ranged from -38.9 ft at Long House Valley (8T-510) to +12.5 ft at Rough Rock (9Y-95) (fig. 8 and table 6). Water levels in 16 wells in the confined part of the aquifer had a median change of -36.1 ft (table 8), and water-level changes ranged from -197.6 ft at Keams Canyon PM2 to +10.9 ft at Howell Mesa (3K-311) and Kykotsmovi PM1 (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 well 8T-510 (Longhouse Valley) has declined 38.9 ft (figs. 8 and 9; 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

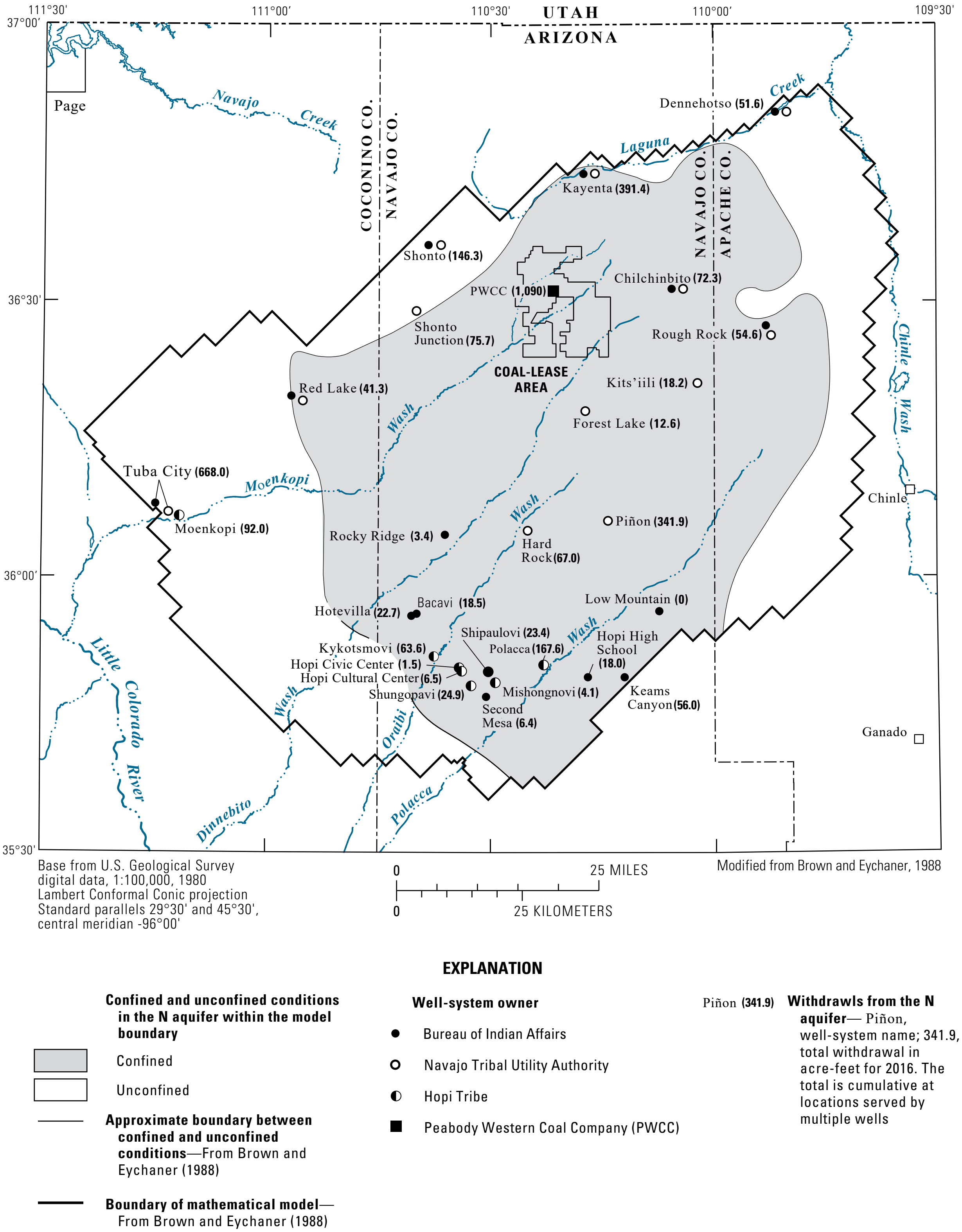


Figure 7. Locations of well systems monitored for annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, calendar year 2016, and confined/unconfined zones of the N aquifer.

Table 6. Water-level changes in monitoring program wells completed in the N aquifer, Black Mesa area, northeastern Arizona, prestress period to calendar year 2016.

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

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year (feet)		Water level (feet below land surface 2016)	Prestress period water level		Change in water level from pre-stress period to 2016 (feet)
		2015	2016		Feet below land surface	Date	
Unconfined areas							
BM observation well 1[a]	8T-537	-0.1	0.0	374.5	374.0	([a])	-0.5
BM observation well 4[a]	2T-514	-0.1	0.2	216.8	216.0	([a])	-0.8
Goldtooth	3A-28	-1.6	0.1	232.4	230.0	10–29–53	-2.4
Long House Valley	8T-510	-1.1	-0.7	138.3	99.4	08–22–67	-38.9
Northeast Rough Rock	8A-180	0.0	0.2	44.7	46.9	11–13–53	2.2
Rough Rock	9Y-95	0.8	2.4	107.0	119.5	08–03–49	12.5
Rough Rock	9Y-92	1.1	-0.2	164.7	168.8	12–13–52	4.1
Shonto	2K-300	1.3	-0.6	171.8	176.5	06–13–50	4.7
Shonto Southeast	2K-301	0.4	-2.8	291.5	283.9	12–10–52	-7.6
Shonto Southeast	2T-502	0.1	-1.0	416.6	405.8	08–22–67	-10.8
Tuba City	3T-333	0.8	0.2	28.8	23.0	12–02–55	-5.8
Tuba City	3K-325	([b])	-0.6	202.2	208.0	06–30–55	5.8
Tuba City Rare Metals 2	---	0.1	-0.1	49.0	57.0	09–24–55	8.0
Tuba City NTUA 1	3T-508	-17.3	26.1	52.4	29.0	02–12–69	-23.4
Tuba City NTUA 3	---	-0.9	-0.4	66.9	34.2	11–08–71	-32.7
Tuba City NTUA 4	3T-546	7.1	-7.9	70.1	33.7	08–06–71	-36.4

Table 6. Water-level changes in monitoring program wells completed in the N aquifer, Black Mesa area, northeastern Arizona, prestress period to calendar year 2016.—Continued.

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year (feet)		Water level (feet below land surface 2016)	Prestress period water level		Change in water level from prestress period to 2016 (feet)
		2015	2016		Feet below land surface	Date	
				Confined area			
BM observation well 2[a]	8T-538	1.1	1.5	211.2	125.0	([a])	-86.2
BM observation well 3[a]	8T-500	0.6	-0.4	162.5	55.0	04–29–63	-107.5
BM observation well 5[a]	4T-519	1.0	1.4	423.4	324.0	([a])	-99.4
BM observation well 6[a]	---	1.1	1.8	839.7	697.0	([a])	-142.7
Forest Lake NTUA 1	4T-523	([b])	([b])	---	1,096R	05–21–82	([b])
Howell Mesa	3K-311	3.9	-7.1	452.1	463.0	11–03–53	10.9
Kayenta West	8T-541	0.9	3.2	289.9	230.0	03–17–76	-59.9
Keams Canyon PM2	---	([b])	1.5	490.1	292.5	06–10–70	-197.6
Kits'iili NTUA 2	---	-0.6	2.8	1,339.0	[c]1,297.9	01–14–99	-41.1
Kykotsmovi PM1	---	0.2	0.6	209.1	220.0	05–20–67	10.9
Kykotsmovi PM3	---	0.2	([b])	---	210.0	08–28–68	([b])
Marsh Pass	8T-522	-1.1	0.2	130.7	125.5	02–07–72	-5.2
Piñon PM6	---	3.1	-0.5	911.1	743.6	05–28–70	-167.5
Rough Rock	10R-119	1.3	-3.2	260.2	256.6	12–02–53	-3.6
Rough Rock	10T-258	0.1	-0.3	310.5	301.0	04–14–60	-9.5
Rough Rock	10R-111	0.0	-0.4	192.0	170.0	08–04–54	-22.0
Sweetwater Mesa	8K-443	-0.7	-0.8	546.8	529.4	09–26–67	-17.4
White Mesa Arch	1K-214	0.6	-0.3	219.2	188.0	06–04–53	-31.2

[a]Continuous recorder. Prestress water levels were estimated from a ground-water model, except for well BM3 (Brown and Eychaner, 1988).

[b]Cannot be determined because at least one of the water-level measurements is not available.

[c]Water level is the first water level measured after completion of well.

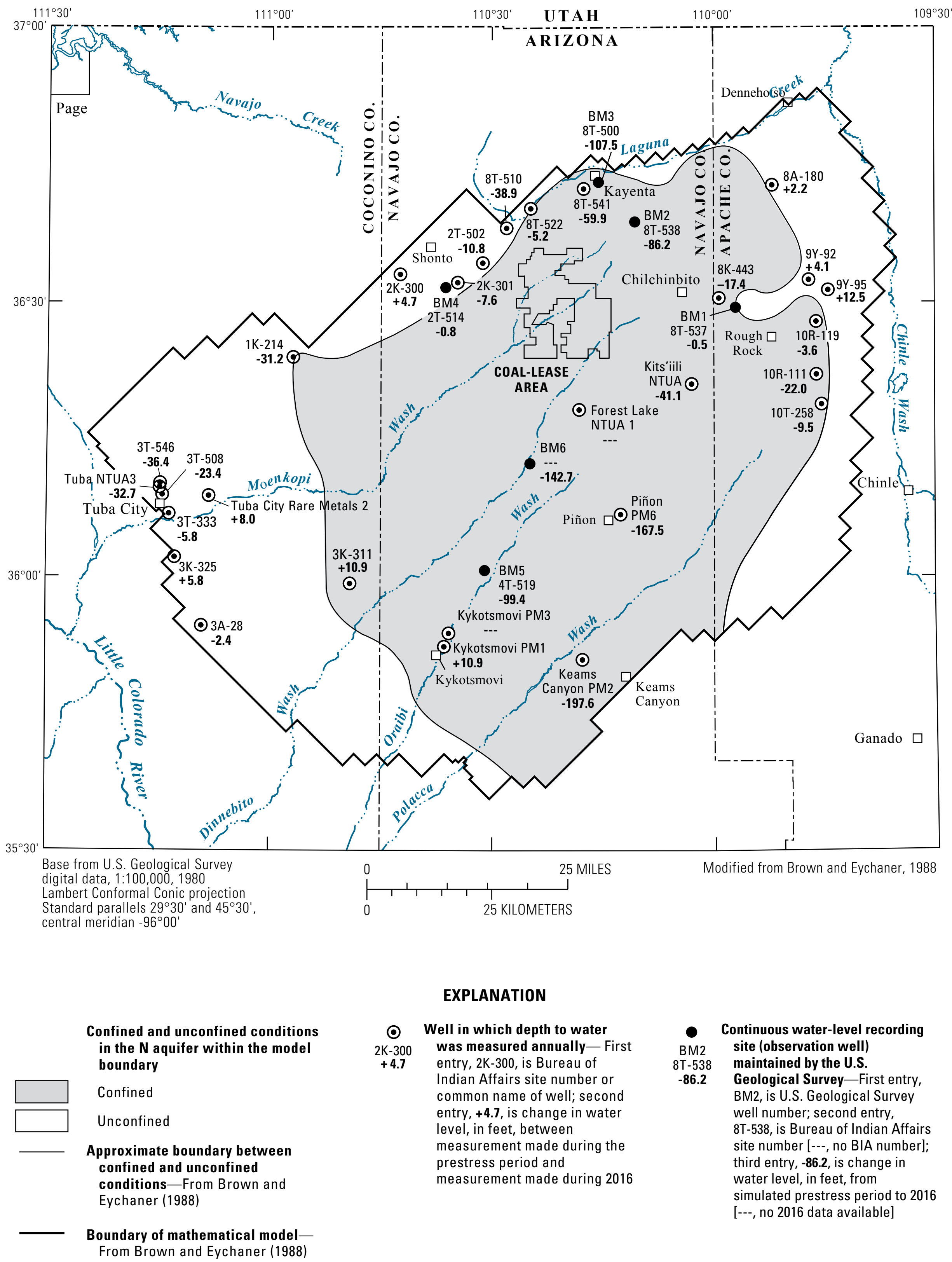


Figure 8. Map showing water-level changes in N-aquifer wells from the prestress period (prior to 1965) to 2016, Black Mesa area, northeastern Arizona.

Table 7. Well-construction characteristics, depth to top of N aquifer, and 2016 static water level for wells used in annual water-level measurements and for continuous-record observation wells, 2015–16, Black Mesa area, northeastern Arizona.

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-surface[a])	2016 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	290	374.5
8T-538 (BM observation well 2)	01–29–72	5,656	1,338	470–1,338	452	211.2
8T-500 (BM observation well 3)	07–29–59	5,724	868	712–868	155	162.5
2T-514 (BM observation well 4)	02–15–72	6,320	400	250–400	160	216.8
4T-519 (BM observation well 5)	02–25–72	5,869	1,683	1,521–1,683	1,520	423.4
BM observation well 6	01–31–77	6,332	2,507	1,954–2,506	1,950	839.7
1K-214	05–26–50	5,771	356	168–356	250	219.2
2K-300	[c]06–00–50	6,264	300	260–300	0	171.8
2K-301	06–12–50	6,435	500	318–328; 378–500	[b]30	291.5
2T-502	08–10–59	6,670	523	12–523	25	416.6
3A-28	04–19–35	5,381	358	([d])	60	232.4
3K-311	[c]11–00–34	5,855	745	380–395 605–745	615	452.1
3K-325	06–01–55	5,250	450	75–450	[b]30	202.2
3T-333	12–02–55	4,940	229	63–229	24	28.8
3T-508 (Tuba City NTUA 1)	08–25–59	5,119	475	([d])	0	52.4
3T-546 (Tuba City NTUA 4)	[c]08–00–71	5,206	612	256–556	0	70.1
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	([e])	([f])
8A-180	01–20–39	5,200	107	60–107	[b]40	44.7
8K-443	08–15–57	6,024	720	619–720	590	546.8
8T-510	02–11–63	6,262	314	130–314	[b]125	138.3
8T-522	[c]07–00–63	6,040	933	180–933	480	130.7
8T-541	03–17–76	5,885	890	740–890	700	289.9
9Y-92	01–02–39	5,615	300	154–300	[b]50	164.7
9Y-95	11–05–37	5,633	300	145–300	[b]68	107.0
10R-111	04–11–35	5,757	360	267–360	210	192.0
10R-119	01–09–35	5,775	360	([d])	310	260.2
10T-258	04–12–60	5,903	670	465–670	460	310.5
Keams Canyon PM2	[c]05–00–70	5,809	1,106	906–1,106	900	490.1

Table 7. Well-construction characteristics, depth to top of N aquifer, and 2016 static water level for wells used in annual water-level measurements and for continuous-record observation wells, 2015–16, Black Mesa area, northeastern Arizona.—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-surface[a])	2016 static water level (feet below land-surface)
Kits'iili NTUA 2	10–30–93	6,780	2,549	2,217–2,223 2,240–2,256 2,314–2,324 2,344–2,394 2,472–2,527	2,205	1,339.0
Kykotsmovi PM1	02–20–67	5,657	995	655–675 890–990	880	209.1
Kykotsmovi PM3	08–07–68	5,618	1,220	850–1,220	840	([f])
Piñon PM6	[c]02–00–70	6,397	2,248	1,895–2,243 514–539	1,870	911.1
Tuba City NTUA 3	[c]10–00–71	5,176	442	142–442	34	66.9
Tuba City Rare Metals 2	[c]09–00–55	5,108	705	100–705	255	49.0

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

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

[c]00, indicates day is unknown.

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

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

[f]No water level collected in 2016.

Table 8. Median changes in water levels in monitoring-program wells, 2015–16 and prestress period (prior to 1965) to 2016, N aquifer, Black Mesa area, northeastern Arizona.

Years	Aquifer conditions	Number of wells	Median change in water level (feet)
2015–2016	All	32	-0.1
	Unconfined	16	-0.1
	Confined	16	0.0
Prestress–2016	All	32	-10.2
	Unconfined	16	-1.6
	Confined	16	-36.1

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 found in figure 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 to rise. The water-level recoveries in BM2, BM5, and BM6 since the mid-2000s has been 8.0 ft, 5.4 ft, and 23.6 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).

Spring Discharge from the N Aquifer

Groundwater in the N aquifer discharges from many springs around the margins of Black Mesa, and changes to the discharge from those springs, could indicate effects of withdrawals from the N aquifer. Moenkopi School Spring, Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso have been measured intermittently since the late 1980s and all four springs were measured for discharge in 2016. 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 located in the western part of the Black Mesa area (fig. 11). Discharge from Moenkopi School Spring was measured in June 2016 by the volumetric method and compared to discharge data from previous years to determine changes over time (fig. 12*A*). The trend for discharge

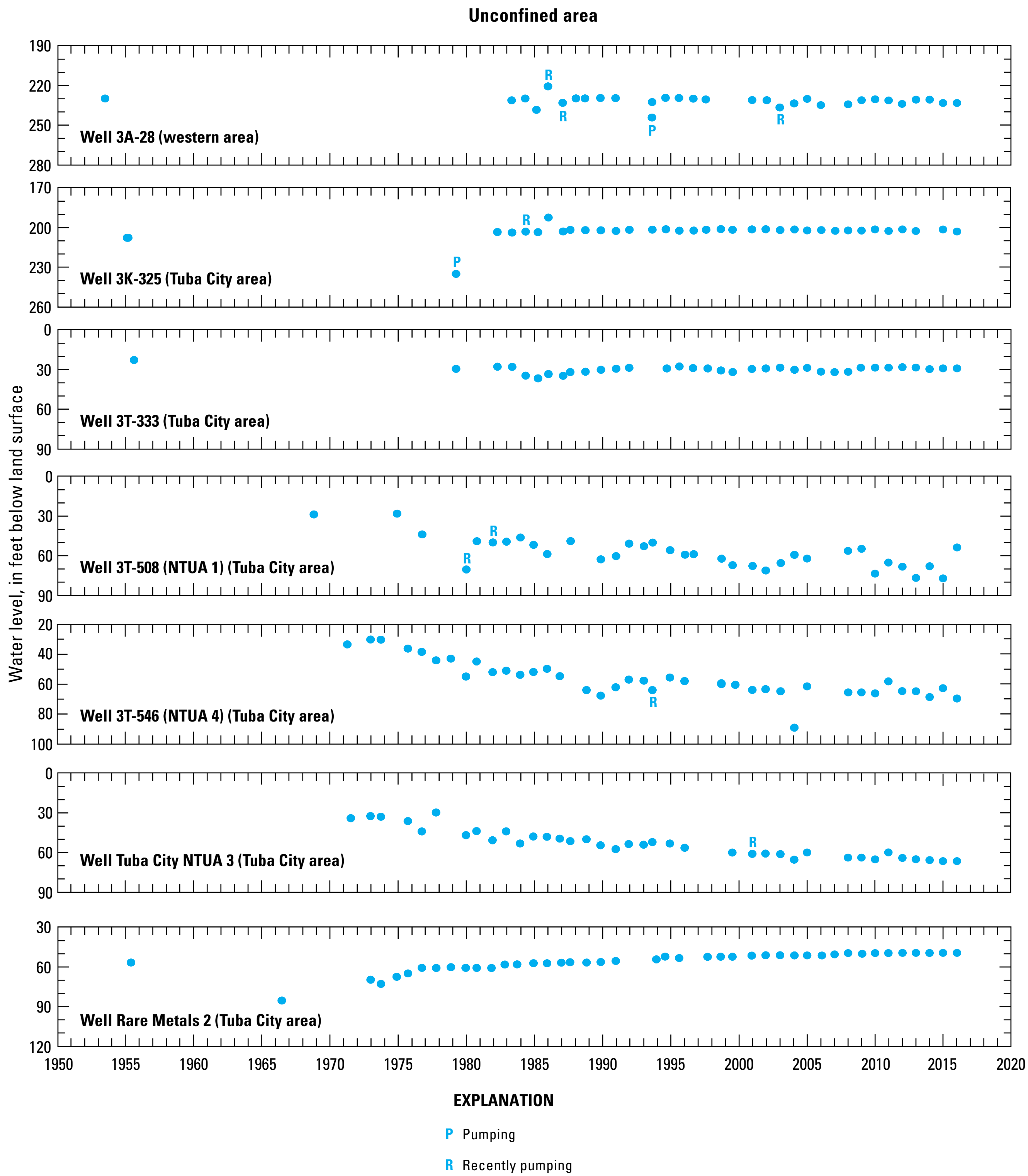
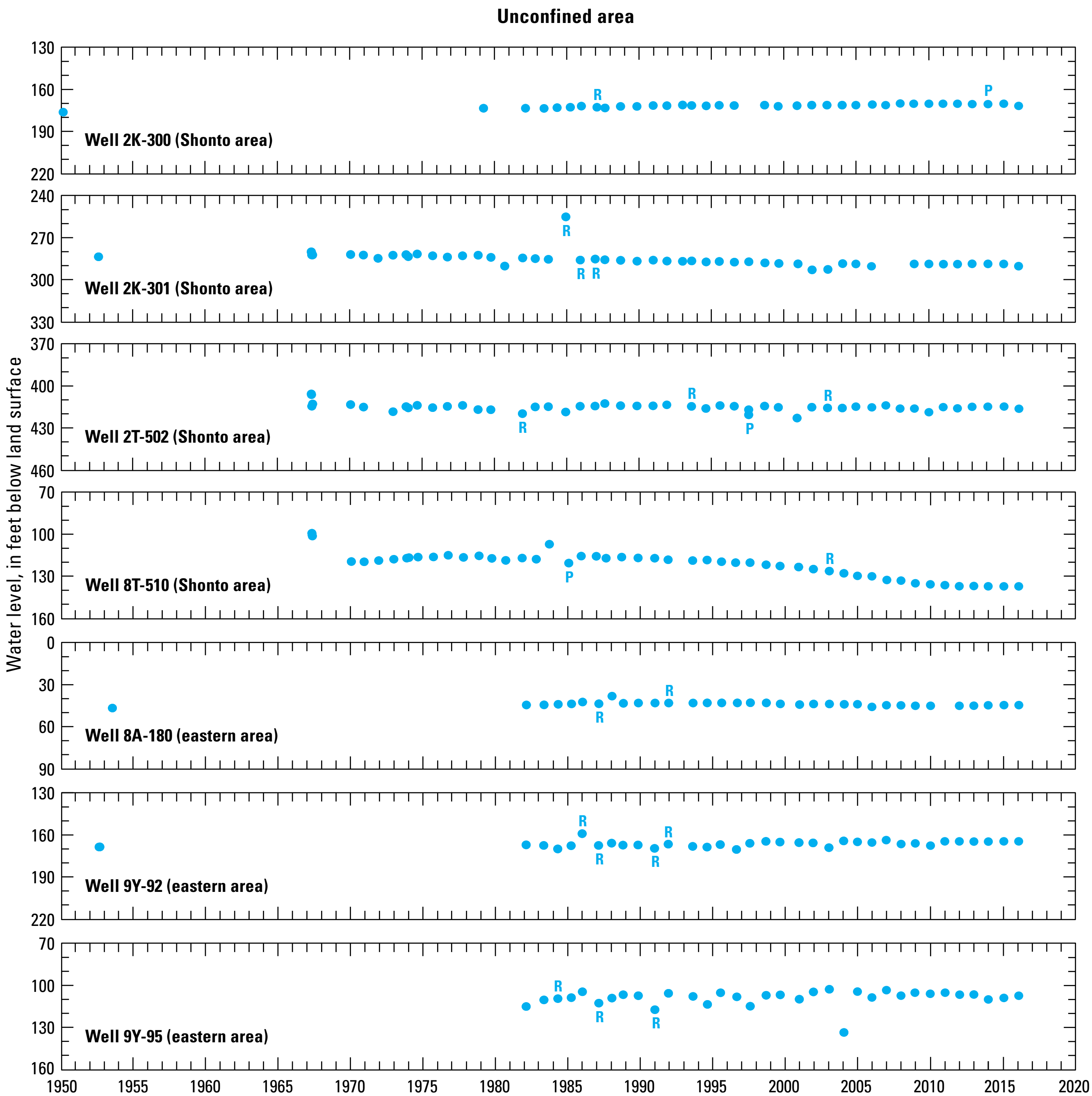


Figure 9. Plots of observed water levels (1950–2016) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.



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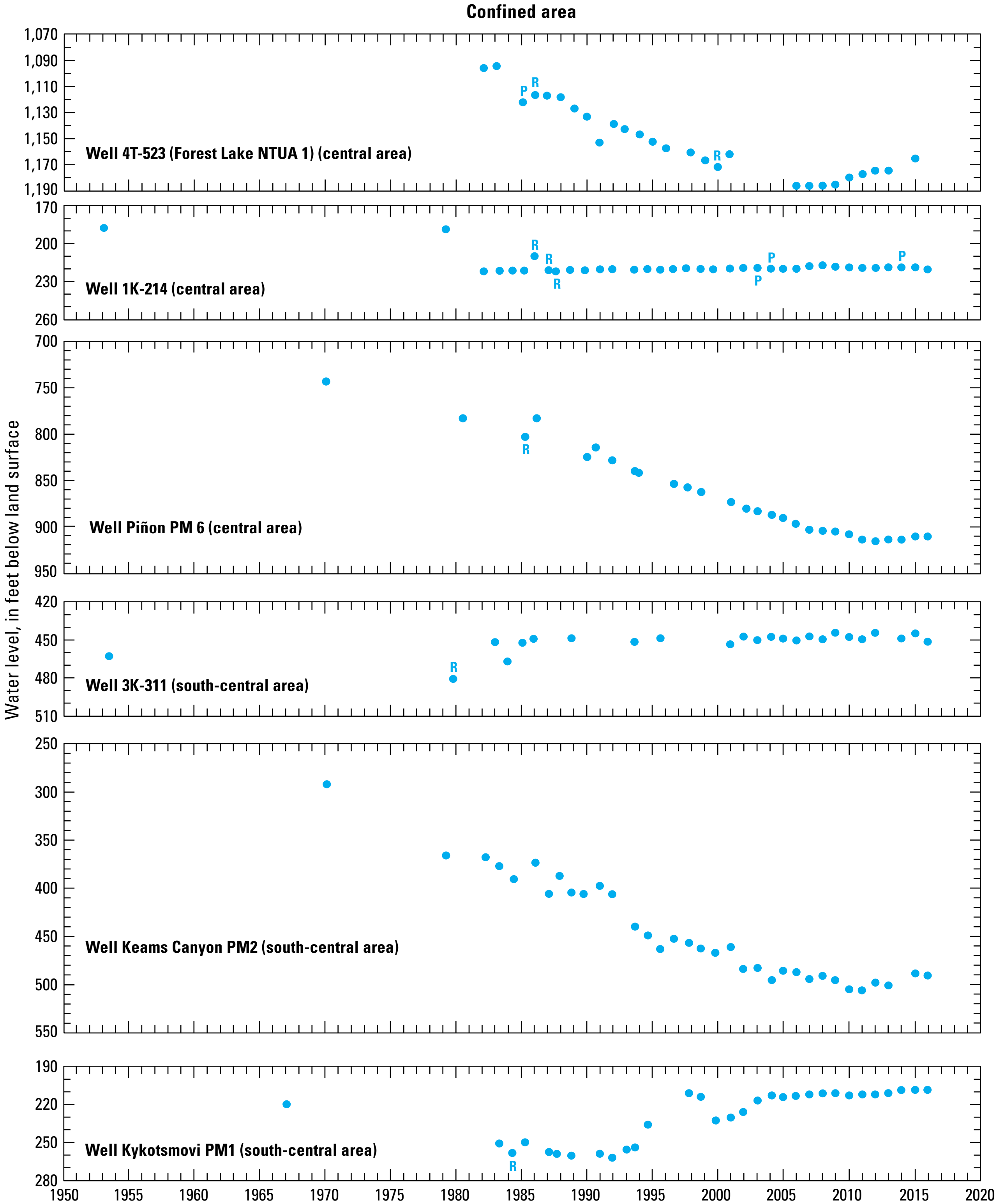

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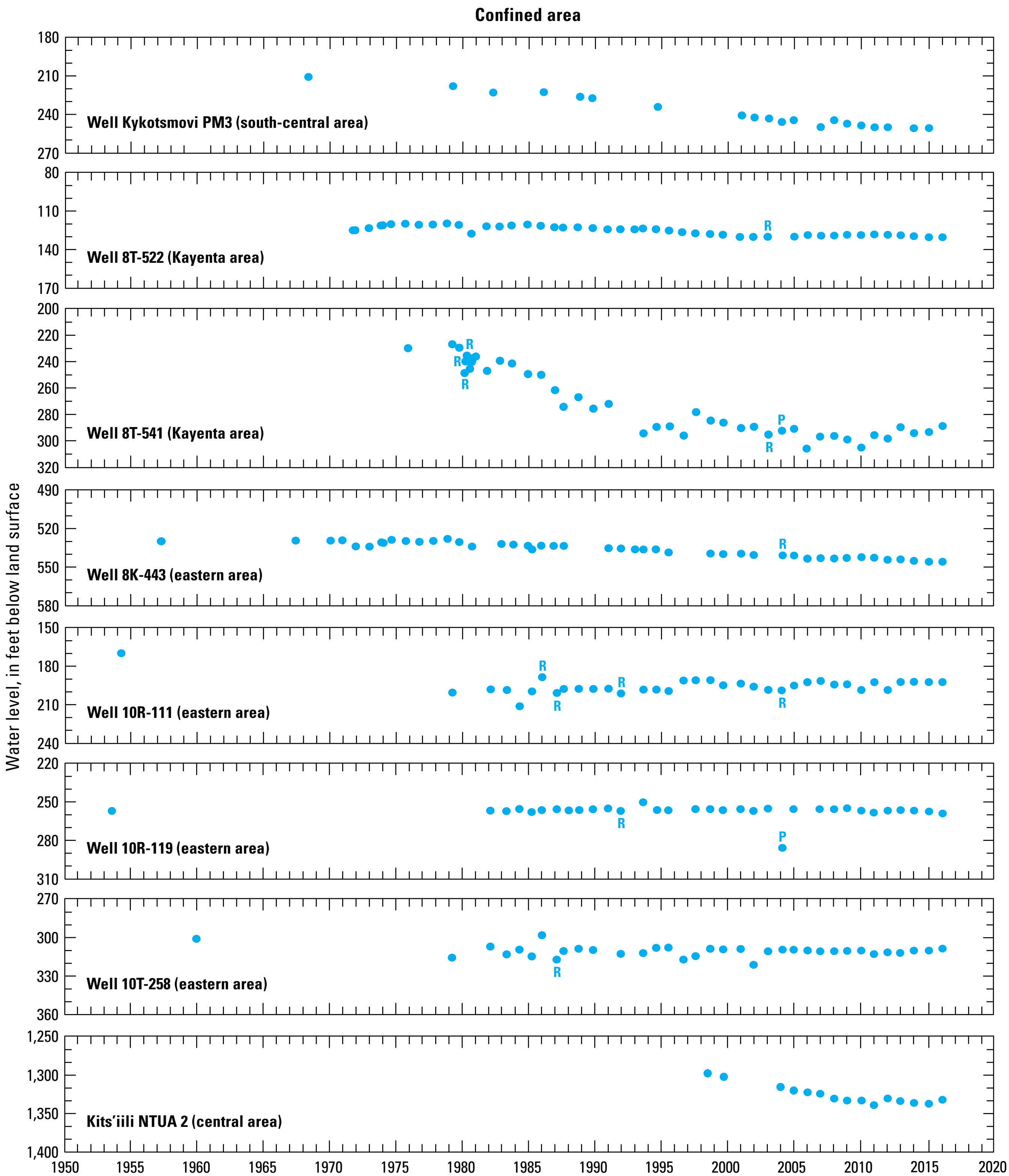

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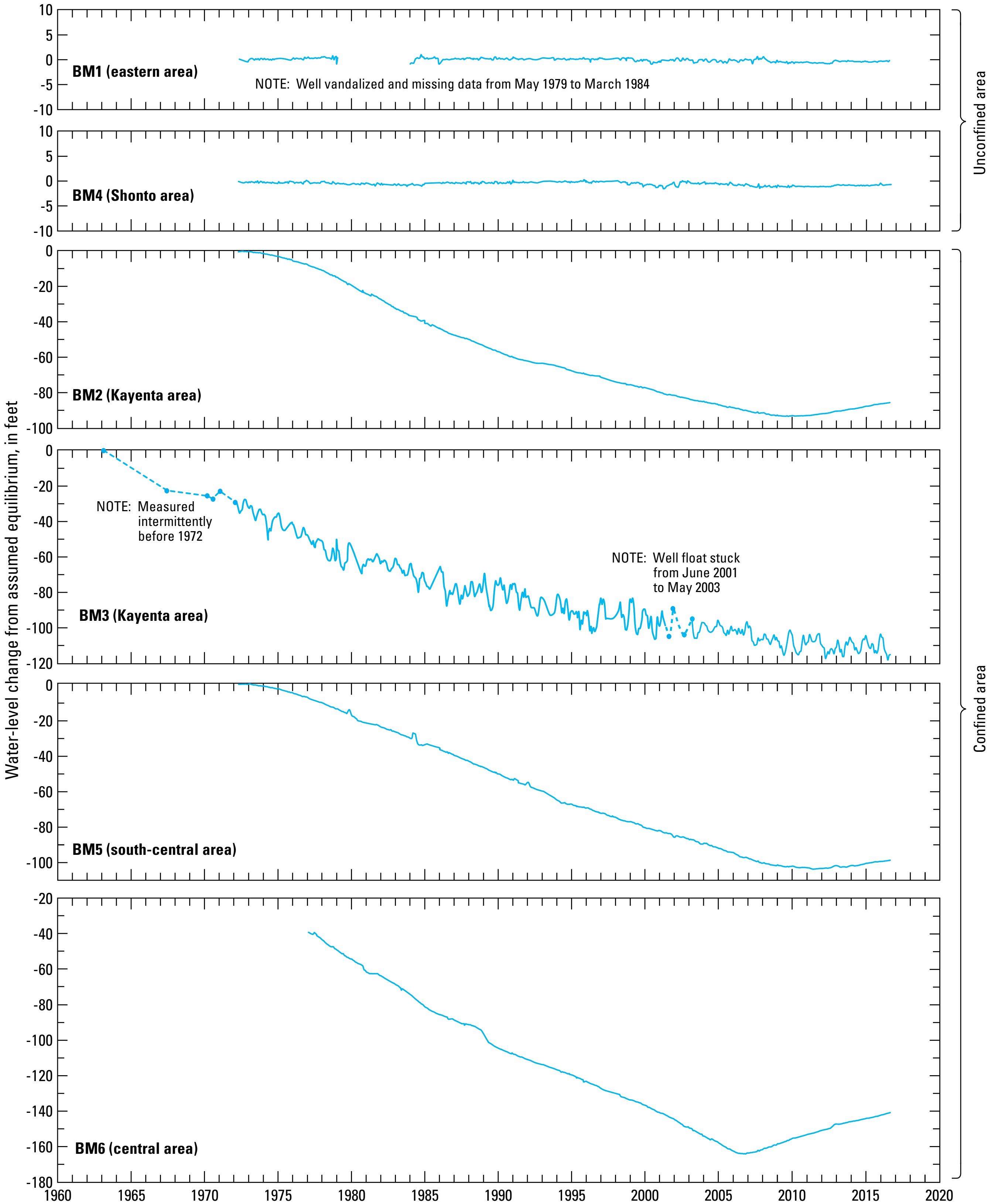

Figure 10. Plots of observed groundwater water-levels in continuous-record observation wells BM1–BM6 from 1963 to 2016 in the N aquifer, Black Mesa area, northeastern Arizona.

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 2016, the measured discharge from Moenkopi School Spring was 6.0 gallons per minute (gal/min) (table 9). No discharge measurement was collected at the spring in 2015, but the 2014 and 2016 discharges are about the same. A combined linear regression and Kendall's tau analysis indicated a decreasing trend ($p<0.05$) of about 0.3 gal/yr 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 2016 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 since 1989 between 0.2 and 0.4 gal/min, but there is no significant ($p>0.05$) trend from linear regression and Kendall's tau analyses (fig. 12*B*). In 2016, the measured discharge was 0.2 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 June 2016 using the volumetric method. The measured discharge was 37.5 gal/min (table 9), indicating a decrease in discharge of about 1.8 gal/min from the 2014 measurement (discharge was not measured in 2015). Discharge at Pasture Canyon Spring has fluctuated since 1995 between 26.5 and 40.0 gal/min, but there is no significant ($p>0.05$) trend from linear regression and Kendall's tau analyses (fig. 12*C*). The discharge data measured at this spring is not corrected for seasonal variability, but annual discharge measurements are generally made close to the same time of year.

Unnamed Spring near Dennehotso is the only spring in the northeastern part of the study area (fig. 11), and it discharges from the Navajo Sandstone. As in previous years, measurements at Unnamed Spring near Dennehotso are made using a flume. There have been marked decreases in discharge at Unnamed Spring near Dennehotso since 2005. That year, 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 2016 it was again 9.0 gal/min after several years of being lower (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 both linear regression and Kendall's tau analyses (fig. 12*D*).

Surface-Water Discharge, Calendar Year 2016

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 more usually occurs during the summer months than during other part of the year. The amount and timing of rainfall runoff depends on the intensity and duration of thunderstorms during the summer and cyclonic storms during the fall, winter, and spring.

In 2016, discharge data were collected at four continuous-recording streamflow-gaging stations (tables 10–13). 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 14). Most of the daily mean discharge values flagged as estimated in tables 10–13 were estimated because the streamflow record was affected by ice during the winter months or because the stage recorder became isolated from flow during low 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 below.

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. 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 (table 10). 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

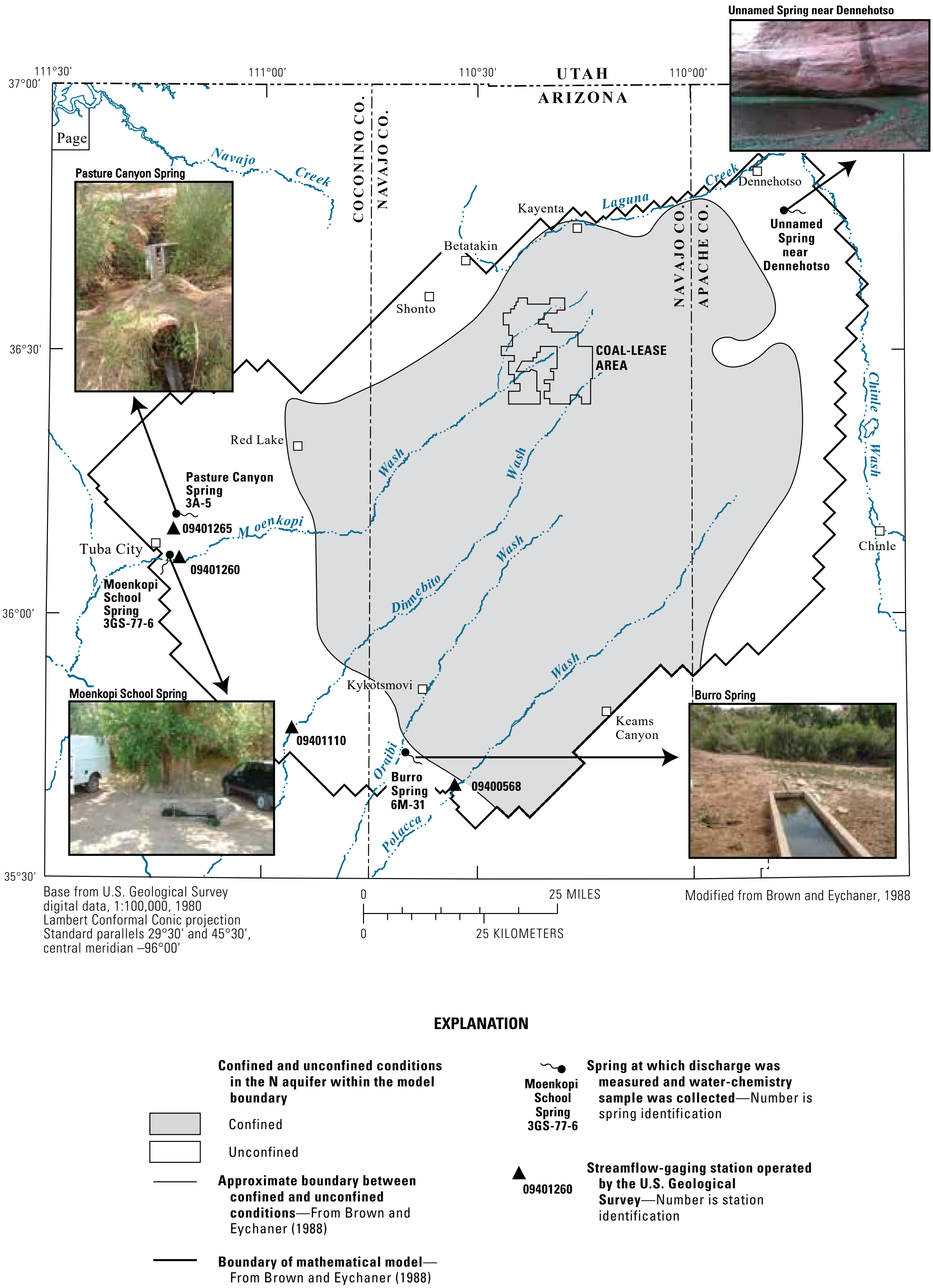

Figure 11. Map of surface-water and water-chemistry data-collection sites, N aquifer, Black Mesa area, northeastern Arizona, 2016.

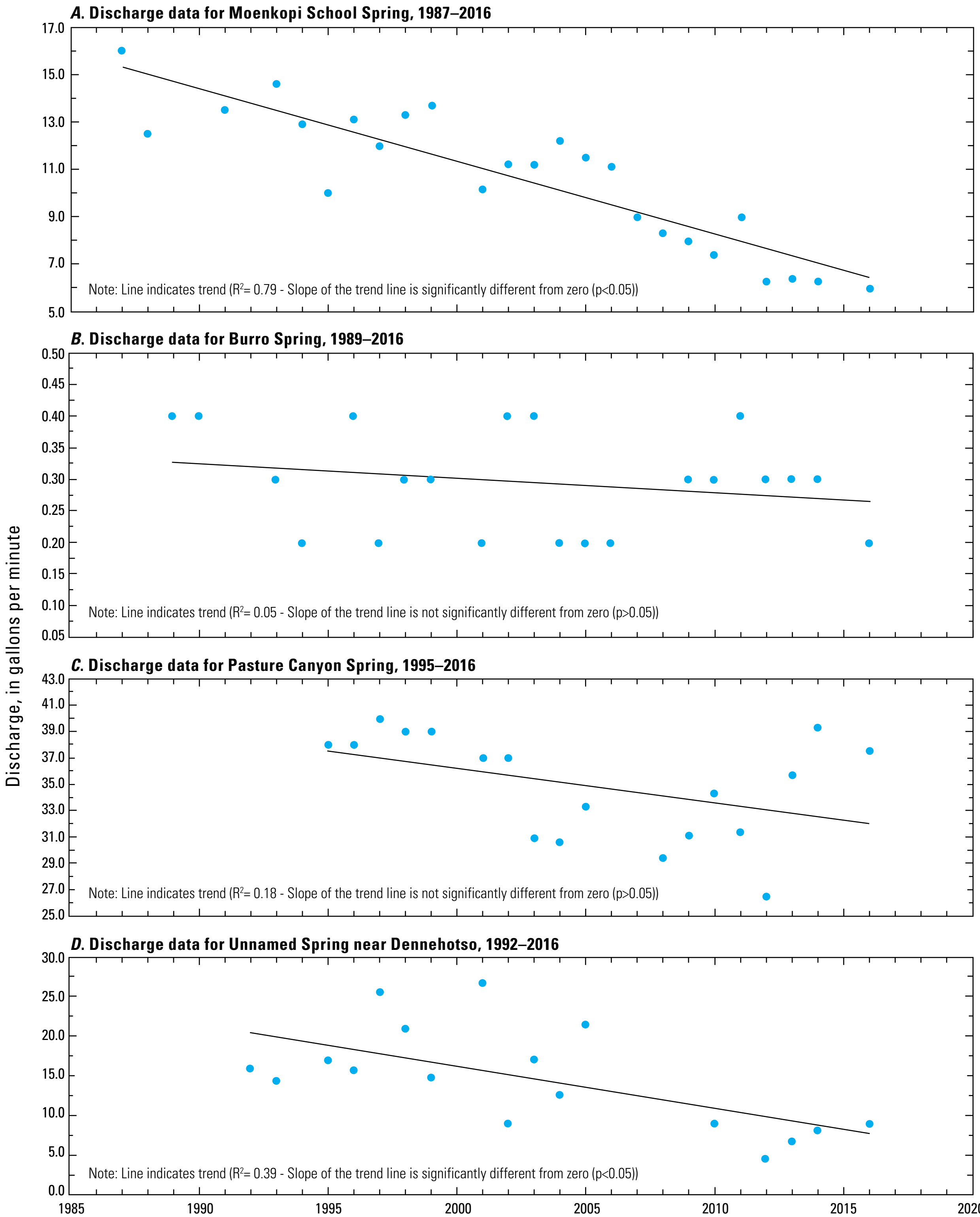

Figure 12. Plots of discharge from *A*, Moenkopi School Spring; *B*, Burro Spring; *C*, Pasture Canyon Spring; and *D*, Unnamed Spring near Dennehotso, N Aquifer, Black Mesa area, northeastern Arizona, 1987–2016. Data from 1952 measurement at Moenkopi School Spring are not shown because measurement was 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, 1952–2016.

[Measured discharges do not represent the total discharge from the springs]

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
		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

Table 9. Discharge from Moenkopi School Spring, Burro Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso, N Aquifer, Black Mesa area, northeastern Arizona, 1952–2016.—Continued.

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
		Pasture Canyon Spring[a]	
3A-5	Navajo Sandstone, alluvium	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
		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
		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

Table 9. Discharge from Moenkopi School Spring, Burro Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso, N Aquifer, Black Mesa area, northeastern Arizona, 1952–2016.—Continued.

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
		Burro Spring[a]	
6M-31	Navajo Sandstone	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
		Unnamed Spring near Dennehotso[d]	
8A-224	Navajo Sandstone	10–06–54	[g]1
		06–27–84	[g]2
		11–17–87	[g]5
		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

[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.

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. The streamflow gage is located 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 (table 11). 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 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 obvious 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. The streamflow gage is located 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 located in a stream reach that does often have flow (table 12). During the period of streamflow gage operation, there has been continuous flow at the gage for most months of the year with the exception of the summer months, when the stream is often dry at the gage. 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 1,880 ft^3/s on August 12, 2004. 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, 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 (table 13). 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. 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 0.18 ft^3/s on September 5-6, 2008, and August 15–17, 2010, and the maximum instantaneous discharge was estimated to be 2.6 ft^3/s on September 11, 2012.

Surface-water Base Flow

Trends in the groundwater-discharge component of total flow at the four streamflow-gaging stations were evaluated on the basis of the median of 121 (2016 is a leap year) consecutive daily mean flows for four winter months (November, December, January, and February) as a surrogate measure for base flow (fig. 13). 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. Evapotranspiration is at a minimum during the winter. Rather than the average flow, the median flow for November, December, January, and February is used to estimate groundwater discharge because the median is less affected by occasional winter runoff. Nonetheless, the median flow for November, December, January, and 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 2016 water year were 1.6 ft^3/s for Moenkopi Wash at Moenkopi, 0.19 ft^3/s for Dinnebito Wash near Sand Springs, 0.12 ft^3/s for Polacca Wash near Second Mesa, and 0.36 ft^3/s for Pasture Canyon Springs (fig. 13*A–D*). A significant decreasing trend in median winter flows is indicated at both the Moenkopi Wash and Pasture Canyon Springs streamflow-gaging stations calculated using the methods of least squares and Kendall's tau ($p<0.05$; fig. 13*A,D*), but no significant trends in median winter flows are indicated at the Dinnebito Wash and Polacca Wash streamflow-gaging stations using the methods of least squares and Kendall's tau ($p>0.05$; fig. 13*B*,*C*).

Table 10. Discharge data (daily mean values) in cubic feet per second, Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2016.

[e, estimated; ac-ft, acre feet; ---, no data]

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	e2.5	e4.8	2.3	e2.4	e2.2	e0.05	2.7	3.7	0.00	7.3	0.39	e0.41
2	e3.2	e3.3	2.3	e2.2	e2.5	0.00	15	1.7	0.00	2.3	0.36	e0.65
3	e2.3	e1.9	2.3	e2.2	e2.0	0.00	3.9	68	0.00	0.84	0.34	e0.74
4	e3.5	e3.2	2.3	e2.3	e1.6	0.00	0.89	793	0.00	1.0	0.13	e0.81
5	e3.8	e3.3	2.3	e2.3	e1.5	0.00	0.15	228	0.00	1.1	454	e0.75
6	e3.3	e2.4	2.4	e2.2	e1.2	0.00	0.00	8.2	0.00	1.2	1.0	0.63
7	e2.3	e2.3	2.4	e2.1	e1.2	0.00	0.00	1.1	0.00	1.1	0.44	0.46
8	e1.7	e2.2	2.2	e2.4	e1.4	0.00	0.00	0.43	0.00	1.2	0.27	e0.58
9	e1.4	e2.1	2.1	e2.4	e1.3	0.00	0.00	0.16	0.00	1.1	0.24	e0.53
10	e1.3	e2.1	2.3	e2.3	e1.4	0.00	0.00	0.00	0.00	0.78	0.19	e0.74
11	e1.6	e2.0	2.8	e2.3	e1.1	0.00	0.00	0.04	0.00	0.75	0.18	0.57
12	e1.5	e2.0	3.0	e2.3	e1.1	0.00	0.00	0.00	0.00	0.88	0.15	0.54
13	e2.1	2.1	2.9	e2.1	e1.1	0.00	0.00	0.00	0.00	0.95	e0.15	0.47
14	e3.3	2.0	2.8	e2.0	e0.88	0.00	0.00	0.00	0.00	0.90	0.15	0.44
15	e2.7	e2.0	e2.5	e2.0	e0.89	0.03	0.00	0.01	0.00	0.76	0.18	0.41
16	e3.6	e1.6	e2.3	e2.4	e0.93	0.23	0.00	0.00	0.00	1.3	0.18	0.40
17	e3.4	2.1	e2.3	e2.1	e1.0	0.75	0.00	0.00	0.00	1.6	0.14	0.55
18	e3.0	2.1	e2.3	e1.9	e1.2	0.00	0.00	3.6	0.00	1.4	0.14	e0.53
19	e1.8	1.9	e2.4	e2.1	e1.3	0.00	0.01	1.6	0.00	1.3	0.14	e0.41
20	e1.7	1.9	e2.4	e2.1	e1.1	0.00	13	0.89	0.00	0.16	0.16	e0.43
21	e1.2	2.1	e2.2	e2.2	e0.84	0.00	120	0.33	0.00	0.25	0.37	e1.1
22	e1.6	2.0	e2.1	e2.1	e0.49	0.00	6.9	0.20	0.00	0.33	1.1	e1.5
23	e2.1	2.2	e2.1	e1.9	e0.53	0.00	72	1.0	0.00	0.45	1.2	e4.3
24	e1.8	2.3	e2.2	e1.9	e0.53	0.00	4.9	21	0.00	0.40	0.39	e1.4
25	e1.4	2.0	e2.3	e1.7	e0.45	0.00	1.5	0.80	0.00	4.4	0.28	e1.0
26	e2.0	1.9	e2.3	e1.8	e0.42	0.00	0.96	22	0.00	1.5	0.38	e0.81
27	e2.3	1.9	e2.3	e1.9	e0.42	0.00	1.2	1.4	0.00	0.27	0.34	e1.1

Table 10. Discharge data (daily mean values) in cubic feet per second, Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2016.—Continued.

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
28	e2.1	2.0	e2.4	e2.0	e0.49	0.00	0.22	6.2	0.00	0.27	0.34	e1.9
29	e2.4	2.2	e2.3	e2.0	e0.40	0.00	0.30	92	0.16	0.24	0.44	e1.6
30	e2.1	---	e2.5	e2.0	e0.19	27	0.79	0.32	570	0.28	e0.59	e1.6
31	e1.6	---	e2.4	---	e0.08	---	5.0	0.00	---	0.32	---	e3.1
Total	70.6	65.9	73.7	63.6	31.74	28.06	249.42	1255.68	570.16	36.63	464.36	30.46
Mean	2.28	2.27	2.38	2.12	1.02	0.94	8.05	40.5	19	1.18	15.5	0.98
Maximum	3.8	4.8	3	2.4	2.5	27.00	120	793	570	7.3	454	4.3
Minimum	1.2	1.6	2.1	1.7	0.08	0.00	0.00	0.00	0.0	0.16	0.13	0.4
Median	2.1	2.1	2.3	2.1	1.1	0.00	0.22	0.89	0	0.9	0.31	0.65
Acre-ft	140	131	146	126	63	56.00	495	2490	1130	73	921	60
Calendar year 2016		Total 2,940.31		Mean 8.03		Max 793		Min 0.00		Median 1.1		Acre-ft 5,830

Table 11. Discharge data (daily mean values) in cubic feet per second, Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2016.

[e, estimated; ac-ft, acre feet; ---, no data]

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.29	e0.72	0.25	0.20	0.20	e0.16	e0.18	e0.16	e0.26	1.2	0.16	0.14
2	0.32	e1.2	0.25	0.21	0.19	e0.16	37	29	18	0.21	0.14	0.14
3	0.42	e0.46	0.24	0.20	0.19	e0.15	e8.0	35	10	0.15	0.15	0.15
4	0.43	e0.38	0.24	0.19	0.18	e0.15	e4.0	121	1.7	0.14	0.17	0.14
5	0.55	e0.34	0.24	0.19	0.18	e0.15	e2.0	10	e0.44	0.11	4.6	0.15
6	0.53	e0.33	0.32	0.19	0.18	e0.15	e1.0	2.1	e0.26	0.11	0.28	0.14
7	0.45	e0.33	0.25	0.20	0.18	e0.15	e0.50	18	e0.23	0.11	0.17	0.14
8	0.38	e0.32	0.24	0.21	0.18	e0.15	e0.25	e1.8	e0.21	0.11	0.14	0.14
9	0.42	e0.31	0.24	0.20	0.18	e0.14	e0.14	e0.35	e0.19	0.11	0.15	0.15
10	0.42	0.31	0.24	0.21	0.18	e0.14	e0.14	e0.25	e0.17	0.11	0.15	0.16
11	0.38	0.31	0.23	0.21	0.18	e0.13	e0.14	e0.19	e0.16	0.11	0.15	0.16
12	0.38	0.38	0.23	0.21	0.18	e0.10	e0.14	e0.18	e0.16	0.11	0.15	0.16
13	0.38	0.35	0.23	0.20	0.18	e0.11	e0.14	e0.17	e0.16	0.11	0.15	0.16
14	0.40	0.40	0.23	0.20	0.19	e0.12	e0.14	e0.16	e0.15	0.11	0.15	0.16
15	0.43	0.47	0.23	0.21	0.19	e0.12	e0.14	e0.16	e0.15	0.12	0.15	0.16
16	0.43	0.30	0.23	0.21	0.19	e0.11	e0.14	e0.15	e0.14	0.12	0.14	0.17
17	0.43	0.29	0.23	0.20	0.19	e0.09	e0.14	e0.14	e0.14	0.11	0.14	0.16
18	0.44	0.29	0.23	0.20	0.19	e0.12	e0.14	e0.15	e0.14	0.12	0.14	0.15

Table 11. Discharge data (daily mean values) in cubic feet per second, Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2016.—Continued.

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
19	0.42	0.28	0.21	0.20	0.19	e0.13	e0.14	e0.15	e0.14	0.13	0.14	0.16
20	0.49	0.29	0.22	0.20	e0.18	e0.11	e59	e0.14	e0.14	0.11	0.15	0.16
21	0.47	0.28	0.21	0.20	e0.17	e0.14	e0.14	e0.14	e0.12	0.11	0.22	0.17
22	0.47	0.28	0.21	0.19	e0.18	e0.15	e0.14	e0.14	0.11	0.12	19	0.21
23	0.48	0.27	0.20	0.19	e0.17	e0.17	e0.14	e0.13	0.12	0.13	0.58	0.17
24	0.48	0.27	0.20	0.18	e0.17	e0.17	e0.14	e0.15	0.11	0.13	0.22	0.18
25	e0.47	0.27	0.20	0.18	e0.16	e0.20	e0.14	e0.16	0.11	0.14	0.15	0.18
26	e0.45	0.27	0.20	0.19	e0.16	e0.21	e0.14	e0.14	0.12	0.13	0.15	0.17
27	e0.43	0.26	0.20	0.19	e0.17	e0.19	e0.14	e0.14	0.12	0.14	0.15	0.17
28	e0.41	0.25	0.20	0.18	e0.17	e0.19	e0.14	e0.15	0.43	0.14	0.15	0.17
29	e0.39	0.25	0.21	0.18	e0.16	e0.20	e0.14	e0.15	0.17	0.14	0.14	0.17
30	0.37	---	0.19	0.19	e0.17	e0.18	e0.14	e0.16	4.8	0.14	0.14	0.18
31	0.36	---	0.19	---	e0.17	---	e0.14	e0.17	---	0.14	---	0.19
Total	13.17	10.46	6.99	5.91	5.55	4.44	115.01	220.88	39.15	4.97	28.47	5.01
Mean	0.42	0.36	0.23	0.20	0.18	0.15	3.71	7.13	1.3	0.16	0.95	0.16
Maximum	0.55	1.2	0.32	0.21	0.20	0.21	59	121	18	1.2	19	0.21
Minimum	0.29	0.25	0.19	0.18	0.16	0.09	0.14	0.13	0.11	0.11	0.14	0.14
Median	0.43	0.31	0.23	0.20	0.18	0.15	0.14	0.16	0.16	0.12	0.15	0.16
Acre-ft	26	21	14	12	11	8.8	228	438	78	9.9	56	9.9
Calendar year 2016	Total 460.01		Mean 1.26			Max 121		Min 0.09		Median 0.18		Acre-ft 912

Table 12. Discharge data (daily mean values) in cubic feet per second, Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2016.

[e, estimated; ac-ft, acre feet; ---, no data]

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	e0.14	0.52	0.16	0.11	1.0	0.03	0.00	0.00	0.00	0.04	0.07	0.14
2	e0.36	0.16	0.16	0.10	0.56	0.02	0.00	0.00	0.00	0.04	0.07	0.15
3	0.43	0.13	0.15	0.11	0.38	0.02	0.00	0.00	0.00	0.03	0.07	0.18
4	0.32	0.16	0.16	0.11	0.27	0.01	0.00	3.2	0.00	0.03	0.22	0.20
5	0.69	0.16	0.15	0.12	0.21	0.01	0.00	8.3	0.00	0.03	0.09	0.15
6	0.93	0.15	0.16	0.13	0.21	0.01	0.00	2.7	0.00	0.04	0.07	0.15
7	0.32	0.15	0.24	0.15	0.22	0.00	0.00	e1.1	0.00	0.04	0.07	0.12
8	0.28	0.14	0.20	0.23	0.25	0.00	0.00	e0.57	0.00	0.04	0.08	0.18
9	0.12	0.13	0.14	0.23	0.24	0.00	0.00	0.00	0.00	0.04	0.07	0.18

Table 12. Discharge data (daily mean values) in cubic feet per second, Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2016.—Continued.

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10	0.08	0.13	0.18	0.16	0.22	0.00	0.00	0.00	0.00	0.05	0.07	0.17
11	0.09	0.14	0.12	0.16	0.21	0.00	0.00	0.00	0.00	0.05	0.08	0.14
12	0.08	0.15	0.12	0.13	0.21	0.00	0.00	0.00	0.00	0.05	0.08	0.14
13	0.11	0.15	0.10	0.15	0.19	0.00	0.00	0.00	0.00	0.05	0.08	0.14
14	0.14	0.16	0.09	0.13	0.14	0.00	0.00	e0.00	0.00	0.06	0.07	0.15
15	0.09	0.15	0.08	0.15	0.13	0.00	0.00	e0.00	0.00	0.06	0.07	0.15
16	0.14	0.16	0.08	0.24	0.11	0.00	0.00	0.00	0.00	0.06	0.08	0.20
17	0.12	0.17	0.09	0.17	0.15	0.00	0.00	0.00	0.01	0.06	0.09	0.15
18	0.11	0.17	0.09	0.13	0.19	0.00	0.00	0.00	0.01	0.06	0.07	0.17
19	0.11	0.17	0.09	0.11	0.21	0.00	0.00	0.00	0.01	0.07	0.06	0.35
20	0.12	0.17	0.09	0.10	0.12	0.00	0.00	0.00	0.01	0.08	0.07	0.36
21	0.08	0.16	0.10	0.10	0.06	0.00	0.00	0.00	0.02	0.08	0.17	0.20
22	0.08	0.16	0.09	0.11	0.05	0.00	0.00	0.00	0.02	0.09	0.15	1.4
23	0.10	0.13	0.07	0.10	0.05	0.00	0.00	0.00	0.02	0.09	0.07	0.17
24	0.09	0.13	0.08	0.10	0.05	0.00	0.00	0.00	0.02	0.07	0.06	0.08
25	0.07	0.14	0.10	0.12	0.04	0.00	0.00	e0.00	0.02	0.11	0.05	0.06
26	0.07	0.16	0.10	0.12	0.05	0.00	0.00	e0.00	0.02	0.09	0.07	0.08
27	0.09	0.17	0.09	0.16	0.06	0.00	0.00	e0.00	0.02	0.08	0.07	0.07
28	0.09	0.16	0.13	0.19	0.05	0.00	0.00	e0.00	0.02	0.09	0.09	0.07
29	0.09	0.16	0.12	0.21	0.04	0.00	0.00	e0.00	0.55	0.08	0.09	0.08
30	0.11	---	0.12	0.35	0.04	0.00	0.00	e0.00	0.13	0.08	0.13	0.09
31	0.15	---	0.11	---	0.03	---	0.00	0.00	---	0.07	---	0.13
Total	5.8	4.79	3.76	4.48	5.74	0.1	0.00	15.87	0.88	1.91	2.58	6
Mean	0.19	0.17	0.12	0.15	0.19	0	0.00	0.51	0.03	0.06	0.09	0.19
Maximum	0.93	0.52	0.24	0.35	1	0.03	0.00	8.3	0.55	0.11	0.22	1.4
Minimum	0.07	0.13	0.07	0.1	0.03	0	0.00	0.00	0.00	0.03	0.05	0.06
Median	0.11	0.16	0.11	0.13	0.15	0.00	0.00	0.00	0.00	0.06	0.07	0.15
Acre-ft	12	9.5	7.5	8.9	11	0.2	0.00	31	1.7	3.8	5.1	12
Calendar year 2016		Total 51.91		Mean 0.14		Max 8.3		Min 0.00		Median 0.08		Acre-ft 103

Table 13. Discharge data (daily mean values) in cubic feet per second, Pasture Canyon Springs near Tuba City, Arizona (09401265), calendar year 2016.

[e, estimated; ac-ft, acre feet; ---, no data]

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	e0.30	e0.28	0.25	0.23	0.23	0.25	0.25	0.24	0.23	0.23	0.30	0.35
2	e0.30	e0.28	0.25	0.22	0.22	0.28	0.26	0.25	0.25	0.23	0.30	0.36
3	e0.30	e0.28	0.25	0.23	0.21	0.28	0.24	0.25	0.25	0.24	0.32	0.36
4	e0.30	0.27	0.25	0.23	0.20	0.29	0.24	0.26	0.24	0.23	0.34	0.36
5	e0.30	0.28	0.24	0.25	0.20	0.28	0.23	0.26	0.24	0.23	0.34	0.36
6	e0.30	0.29	0.24	0.25	0.19	0.29	0.23	0.26	0.24	0.23	0.32	0.36
7	e0.30	0.28	0.25	0.27	0.23	0.30	0.23	0.25	0.25	0.23	0.32	0.36
8	e0.30	0.28	0.25	0.27	0.25	0.30	0.23	0.25	0.24	0.22	0.32	0.36
9	e0.30	0.28	0.24	0.27	0.23	0.29	0.23	0.25	0.24	0.22	0.32	0.36
10	e0.30	0.28	0.23	0.27	0.22	0.28	0.23	0.25	0.24	0.23	0.32	0.36
11	e0.30	0.28	0.25	0.28	0.22	0.27	0.23	0.24	0.23	0.23	0.32	0.36
12	e0.30	0.28	0.25	0.28	0.21	0.27	0.23	0.22	0.23	0.22	0.32	0.37
13	e0.30	0.28	0.25	0.29	0.20	0.26	0.23	0.23	0.23	0.22	0.32	0.38
14	e0.30	0.26	0.25	0.30	0.22	0.26	0.23	0.23	0.24	0.22	0.32	0.38
15	e0.30	0.26	0.25	0.30	0.22	0.26	0.23	0.22	0.23	0.23	0.32	0.38
16	e0.30	0.27	0.25	0.29	0.22	0.26	0.21	0.21	0.23	0.23	0.32	0.39
17	e0.30	0.27	0.25	0.28	0.23	0.26	0.21	0.22	0.23	0.24	0.32	0.39
18	e0.30	0.28	0.25	0.29	0.23	0.26	0.22	0.23	0.23	0.25	0.32	0.38
19	e0.30	0.28	0.24	0.29	0.26	0.26	0.22	0.23	0.22	0.25	0.32	0.38
20	e0.30	0.28	0.23	0.26	0.27	0.26	e0.23	0.23	0.23	0.24	0.33	0.38
21	e0.30	0.26	0.24	0.24	0.25	0.25	e0.23	0.23	0.23	0.26	0.38	0.39

Table 13. Discharge data (daily mean values) in cubic feet per second, Pasture Canyon Springs near Tuba City, Arizona (09401265), calendar year 2016.—Continued.

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22	e0.28	0.26	0.25	0.24	0.24	0.24	0.23	0.23	0.25	0.28	0.34	0.45
23	e0.28	0.27	0.25	0.23	0.24	0.24	0.23	0.23	0.24	0.28	0.34	0.39
24	e0.29	0.27	0.25	0.23	e0.23	0.24	0.23	0.24	0.23	0.27	0.34	0.40
25	e0.29	0.26	0.25	0.23	0.24	0.24	0.23	0.25	0.23	0.34	0.34	0.40
26	e0.30	0.26	0.24	0.23	0.25	0.24	0.23	0.26	0.23	0.32	0.34	0.38
27	e0.30	0.26	0.23	0.22	0.26	0.24	0.23	0.24	0.22	0.32	0.34	0.38
28	e0.29	0.25	0.24	0.23	0.26	0.24	0.23	0.24	0.22	0.31	0.34	0.38
29	e0.29	0.25	0.25	0.22	0.23	0.24	0.23	0.24	0.26	0.29	0.34	0.38
30	e0.29	---	0.23	0.22	0.23	0.23	0.23	0.24	0.25	0.28	0.34	0.39
31	e0.29	---	0.23	---	0.23	---	0.26	0.23	---	0.29	---	0.44
Total	9.2	7.88	7.58	7.64	7.12	7.86	7.17	7.41	7.08	7.86	9.85	11.76
Mean	0.30	0.27	0.24	0.25	0.23	0.26	0.23	0.24	0.24	0.25	0.33	0.38
Maximum	0.30	0.29	0.25	0.30	0.27	0.30	0.26	0.26	0.26	0.34	0.38	0.45
Minimum	0.28	0.25	0.23	0.22	0.19	0.23	0.21	0.21	0.22	0.22	0.30	0.35
Median	0.30	0.28	0.25	0.25	0.23	0.26	0.23	0.24	0.23	0.24	0.32	0.38
Acre-ft	18	16	15	15	14	16	14	15	14	16	20	23
Calendar year 2016		Total 98.41		Mean 0.27		Max 0.45		Min 0.19		Median 0.25		Acre-ft 195

Table 14. Streamflow-gaging stations used in the Black Mesa monitoring program, their periods of record, and drainage areas.

[---, not determined]

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	---

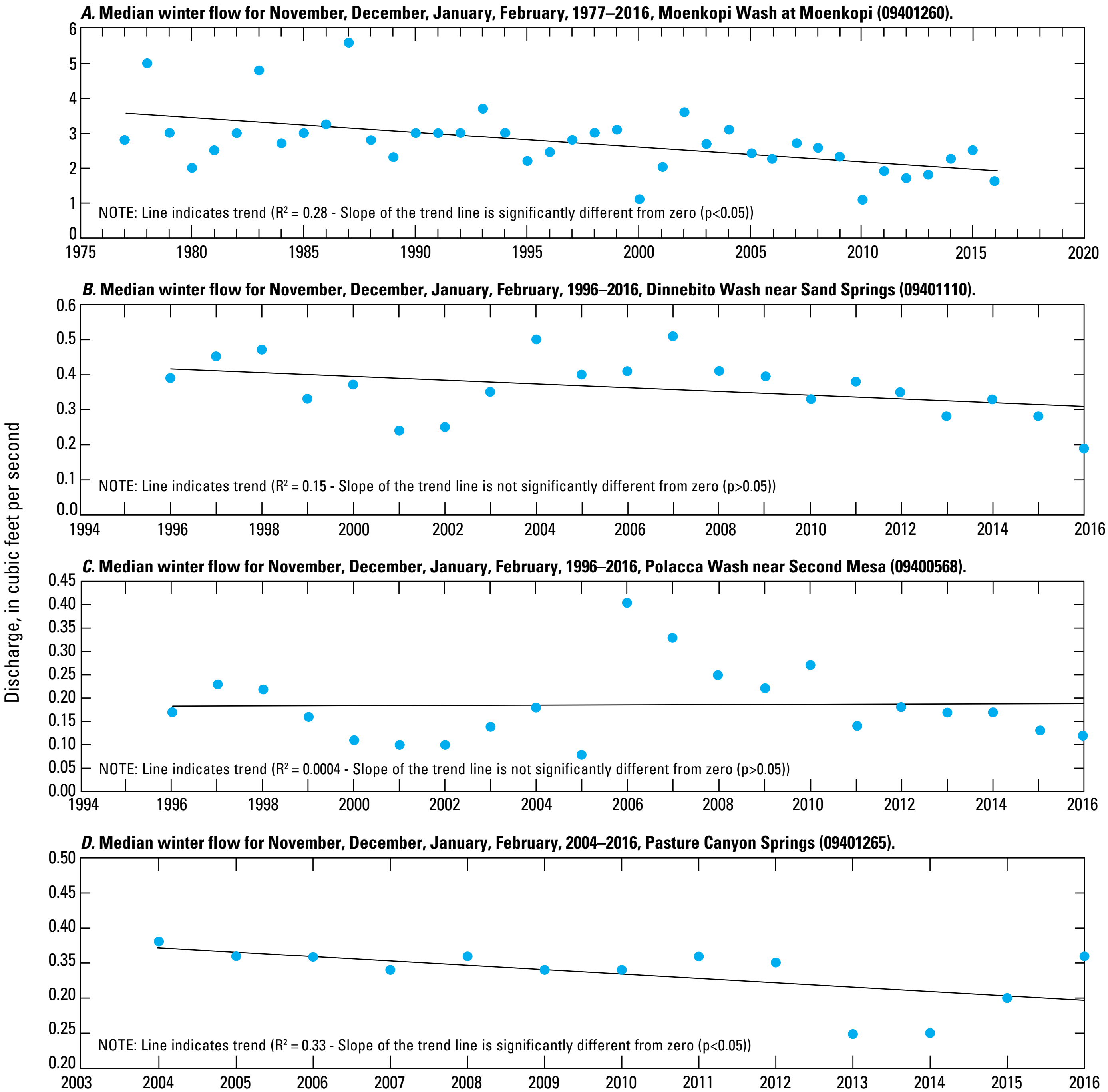

Figure 13. Plots of median winter flow for November, December, January, and February for water years 1977–2016 for A, Moenkopi Wash at Moenkopi (09401260); B, Dinnebito Wash near Sand Springs (09401110); C, Polacca Wash near Second Mesa (09400568); and D, Pasture Canyon Springs (09401265), Black Mesa area, northeastern Arizona. Median winter flow is calculated by computing the median flow for 121 consecutive daily mean flows for the winter months of November, December, January, and February. Trend lines were generated by using the method of least squares.

Water Chemistry

Water samples for water-chemistry analyses were collected in June, July, and October 2016 from selected wells and springs as part of the Black Mesa monitoring program. Field measurements were made and water samples were analyzed for major ions, trace elements, nutrients, and arsenic. Field measurements were made 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. Major ion, nutrient, trace element, iron, boron, and arsenic 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 through the use of standard USGS training of field personnel, use of standard USGS field protocols (U.S. Geological Survey, variously dated), collection of a quality control (QC) sample, 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 to better understand potential variability associated with field conditions and field and laboratory procedures (table 15). Relative percent differences ranged from 0 to 6.3 percent. Only alkalinity and potassium had relative percent differences greater than 5 percent. The one replicate sample suggests that there is an acceptably low level of variability affecting the data; no QC data was collected to assess potential bias affecting the data.

In past years water-chemistry samples were systematically collected from as many as 12 different wells as part of the Black Mesa monitoring program. In 2016, the number of wells sampled was reduced to three owing to budgetary constraints. The wells sampled in 2016 were Peabody 2, Rocky Ridge PM3, and Kykotsmovi PM2. Since 1989, samples have been collected from the same four springs—Moenkopi School Spring, Pasture Canyon Spring, Unnamed Spring near Dennehotso, and Burro Spring and in 2016 all four springs were sampled. 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 average, the concentrations of dissolved solids in water from the D aquifer is about 7 times

Table 15. Comparison of physical properties and chemical analyses of replicate and environmental water samples taken from well Peabody 2, Black Mesa area, northeastern Arizona, 2016.

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

Physical property or chemical analysis	Environmental	Replicate	Relative percent difference
U.S. Geological Survey identification number	363005110250901	363005110250901	
Date of samples	7/7/16	7/7/16	
Temperature, field (°C)	24.1	24.1	0
Specific conductance, field (µS/cm)	163	163	0
pH, field (units)	8.6	8.6	0
Alkalinity, field, dissolved (mg/L as $CaCO_3$)	68.3	64.5	5.7
Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	0.938	0.943	0.5
Ortho- Phosphate, dissolved (mg/L as P)	0.006	0.006	0
Calcium, dissolved (mg/L as Ca)	8.97	8.90	0.8
Magnesium, dissolved (mg/L as Mg)	0.143	0.143	0
Potassium, dissolved (mg/L as K)	0.82	0.77	6.3
Sodium, dissolved (mg/L as Na)	28.7	28.3	1.4
Chloride, dissolved (mg/L as Cl)	2.01	2.01	0
Flouride, dissolved (mg/L as F)	0.12	0.12	0
Silica, dissolved (mg/L as SiO_2)	21.9	22.1	0.9
Sulfate, dissolved (mg/L as SO_4)	7.28	7.27	0.1
Arsenic, dissolved (µg/L as As)	2.9	2.9	0
Boron, dissolved (µg/L as B)	16	16	0
Iron, dissolved (µg/L as Fe)	<4.0	<4.0	---
Dissolved solids, residue at 180 °C (mg/L)	116	114	1.7

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 (http://waterdata.usgs.gov/az/nwis/qw), and they can be found in monitoring reports cited in the "Previous Investigations" section of this report and listed in table 2.

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 2016 are similar to results from previous years and are presented in figures 14 and 15 and in tables 16 and 17.

Chemical constituents analyzed from the three 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 2016, all of the analyzed constituents from the three wells were below the EPA MCL for drinking water. However, all three wells had pH values that were higher than the SMCL pH range (6.5–8.5) (table 16). 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 16).

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

In 2016, water samples were collected from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso (figs. 11 and 14). 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.

The samples from all four springs yielded calcium bicarbonate-type water (fig. 14 and table 18). Dissolved solid concentrations measured 318 mg/L at Burro Spring, 244 mg/L at Moenkopi School Spring, 155 mg/L at Pasture Canyon Spring, and 116 mg/L at Unnamed Spring near Dennehotso (tables 18 and 19). Chloride concentration were highest at Moenkopi School Spring (34.6 mg/L; tables 18 and 19). Concentration of sulfate was highest at Burro Spring (61.7 mg/L; tables 18 and 19). Concentrations of all the analyzed constituents in samples from all four springs were less than current EPA maximum contaminant levels (MCLs) and secondary maximum contaminant levels (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 19 and fig. 16). Concentrations of the same constituents from Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso did not show any significant trends (table 19 and fig. 16). 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. In 2013, 2014, and 2016, Unnamed Spring near Dennehotso was 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. 16).

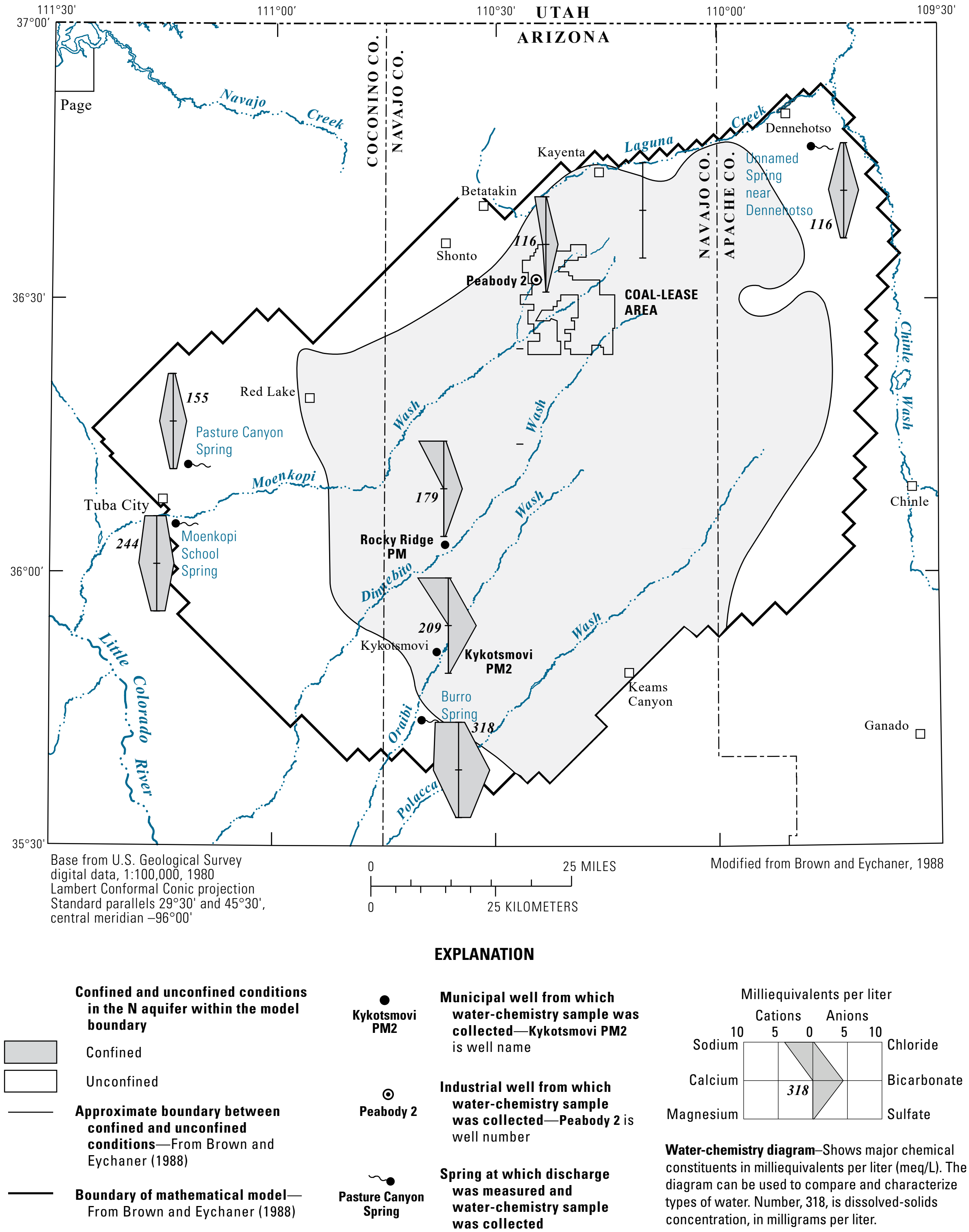

Figure 14. Map showing water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, northeastern Arizona, 2016.

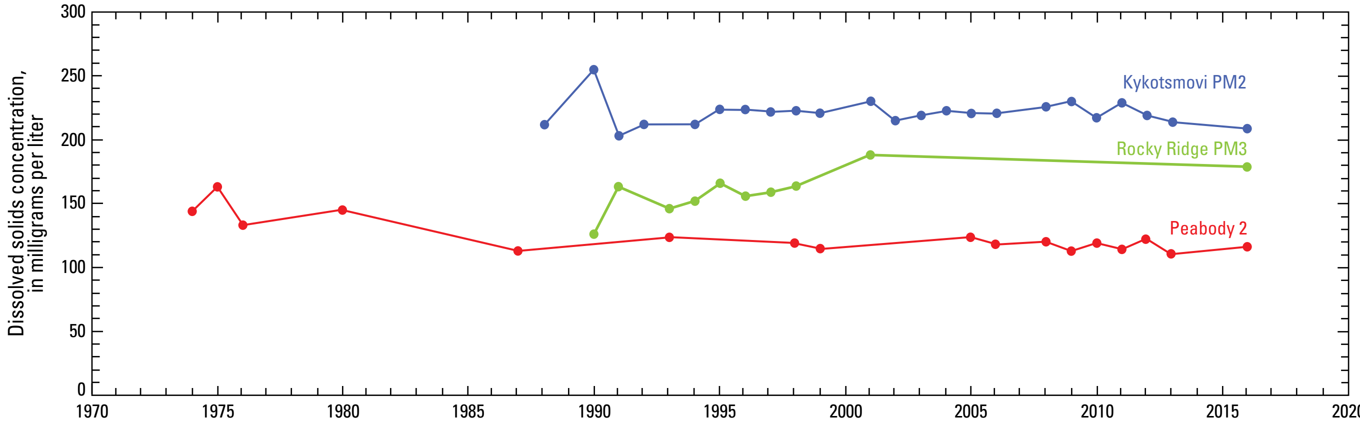

Figure 15. Dissolved-solids concentrations for water samples from selected wells, N aquifer, Black Mesa area, northeastern Arizona: Kykotsmovi, 1988–2016; Rocky Ridge PM3, 1990–2016; and Peabody 2, 1974–2016.

Table 16. Physical properties and chemical analyses of water samples from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, 2016.

Common well name	U.S. Geological Survey identification number	Date of samples	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)	Dissolved					
						Alkalinity, field (mg/L as $CaCO_3$)	Nitrogen, NO_2 + NO_3, (mg/L as N)	Orthophosphate, (mg/L as P)	Calcium (mg/L as Ca)	Magnesium, (mg/L as Mg)	Potassium, (mg/L as K)
Kykotsmovi PM2	355215110375001	10/6/16	19.1	364	10	164	1.05	0.033	0.470	0.014	0.41
Rocky Ridge PM3	360422110353501	7/21/16	26.5	280	9.6	108	1.23	0.023	0.504	0.016	0.44
Peabody 2	363005110250901	7/7/16	30.9	163	8.6	68.3	0.938	0.006	8.97	0.143	0.82

Common well name	U.S. Geological Survey identification number	Date of samples	Dissolved								
			Sodium (mg/L as Na)	Chloride (mg/L as Cl)	Fluoride (mg/L as F)	Silica (mg/L as SiO_2)	Sulfate (mg/L as SO_4)	Arsenic (µg/L as As)	Boron (µg/L as B)	Iron (µg/L as Fe)	Solids, residue at 180 °C (mg/L)
Kykotsmovi PM2	355215110375001	10/6/16	81.0	3.27	0.15	23.7	7.86	5.4	30	<5.0	209
Rocky Ridge PM3	360422110353501	7/21/16	65.8	7.80	0.09	19.7	8.00	2.9	21	<4.0	179
Peabody 2	363005110250901	7/7/16	28.7	2.01	0.12	21.9	7.28	2.9	16	<4.0	116

Table 17. 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, 1967–2016.

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

Year	Specific conductance, field (µS/cm)	Dissolved		
		Solid residue at 180 °C (mg/L)	Chloride (mg/L as Cl	Sulfate, (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
		Rocky Ridge PM3		
1976	270	---	5.3	3.8
1982	255	---	1.4	6.0
1990	222	126	1.5	6
1991	240	164	0.70	6.80
1993	254	146	1.30	5.50
1994	248	152	1.40	5.50
1995	242	166	1.30	4.00
1996	256	156	2.00	5.80
1997	238	159	2.47	5.00
1998	222	164	3.18	4.98
2001	160	188	1.31	5.42
2016	280	179	7.80	8.00

Table 17. 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, 1967–2016.—Continued.

Year	Specific conductance, field (µS/cm)	Dissolved		
		Solid residue at 180 °C (mg/L)	Chloride (mg/L as Cl	Sulfate, (mg/L as SO_4)
		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

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

[b]Value is from laboratory analysis.

Table 18. Physical properties and chemical analyses of water samples from four springs in the Black Mesa area, northeastern Arizona, in 2016.

[°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	Tempera-ture, field (°C)	Specific conduc-tance, field (µS/cm)	pH, field (units)	Dissolved					
							Alkalin-ity, field (mg/L as $CaCO_3$)	Nitrogen, $NO_2 + NO_3$ (mg/L as N)	Ortho-phosphate (mg/L as P)	Calcium (mg/L as Ca)	Mag-nesiu (mg/L as Mg)	Potas-sium, (mg/L as K)
354156110413701	6M-31	Burro Spring	6/23/16	21.6	544	7.4	173	<0.04	0.011	57.4	4.16	0.34
360632111131101	3GS-77-6	Moenkopi School Spring	6/21/16	18.3	427	7.2	94.2	2.30	0.005	41	8.54	1.15
361021111115901	3A-5	Pasture Canyon Spring	6/21/16	17.0	252	7.5	72.8	4.59	0.013	31.2	4.65	1.20
364656109425400	8A-224	Unnamed Spring near Denne-hotso	10/26/16	11.9	197	7.8	79.1	1.96	0.048	31.2	3.92	1.22

U.S Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Dissolved								
				Sodium (mg/L as Na)	Chloride (mg/L as Cl)	Fluoride (mg/L as F)	Silica (mg/L as SiO_2)	Sulfate (mg/L as SO_4)	Arsenic (µg/L as As)	Boron (µg/L as B)	Iron (µg/L as Fe)	solids, resi due at 180 °C (mg/L)
354156110413701	6M-31	Burro Spring	6/23/16	60.6	22.2	0.36	16.2	61.7	1.0	77	5.8	318
360632111131101	3GS-77-6	Moenkopi School Spring	6/21/16	30.5	34.6	0.15	10.2	43.8	2.3	42	<4.0	244
361021111115901	3A-5	Pasture Canyon Spring	6/21/16	12.5	5.09	0.16	3.59	17.2	1.7	32	<4.0	155
364656109425400	8A-224	Unnamed Spring near Denne-hotso	10/26/16	4.85	3.21	0.13	12.2	9.46	2.4	17	10.8	116

Table 19. Specific conductance and concentrations of selected chemical constituents in N-aquifer water samples from four springs in the Black Mesa area, northeastern Arizona, 1948–2016.

[°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 (mg/L as Cl)	Sulfate (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	64.47
2013	560	350	24.4	67.7
2014	549	360	22.8	64.4
2016	544	318	22.2	61.7
		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

Table 19. Specific conductance and concentrations of selected chemical constituents in N-aquifer water samples from four springs in the Black Mesa area, northeastern Arizona, 1948–2016.—Continued.

Year	Specific conductance, field (µS/cm)	Dissolved		
		Solids, residue at 180 °C (mg/L)	Chloride (mg/L as Cl)	Sulfate (mg/L as SO_4)
		Moenkopi School Spring		
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
2013	370	220	27.2	33.3
2014	382	226	28.5	34.6
2016	427	244	34.6	43.8
		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
2016	252	155	5.09	17.2
		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

Table 19. Specific conductance and concentrations of selected chemical constituents in N-aquifer water samples from four springs in the Black Mesa area, northeastern Arizona, 1948–2016.—Continued.

Year	Specific conductance, field (µS/cm)	Dissolved		
		Solids, residue at 180 °C (mg/L)	Chloride (mg/L as Cl)	Sulfate (mg/L as SO_4)
Unnamed Spring near Dennehotso				
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

[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.

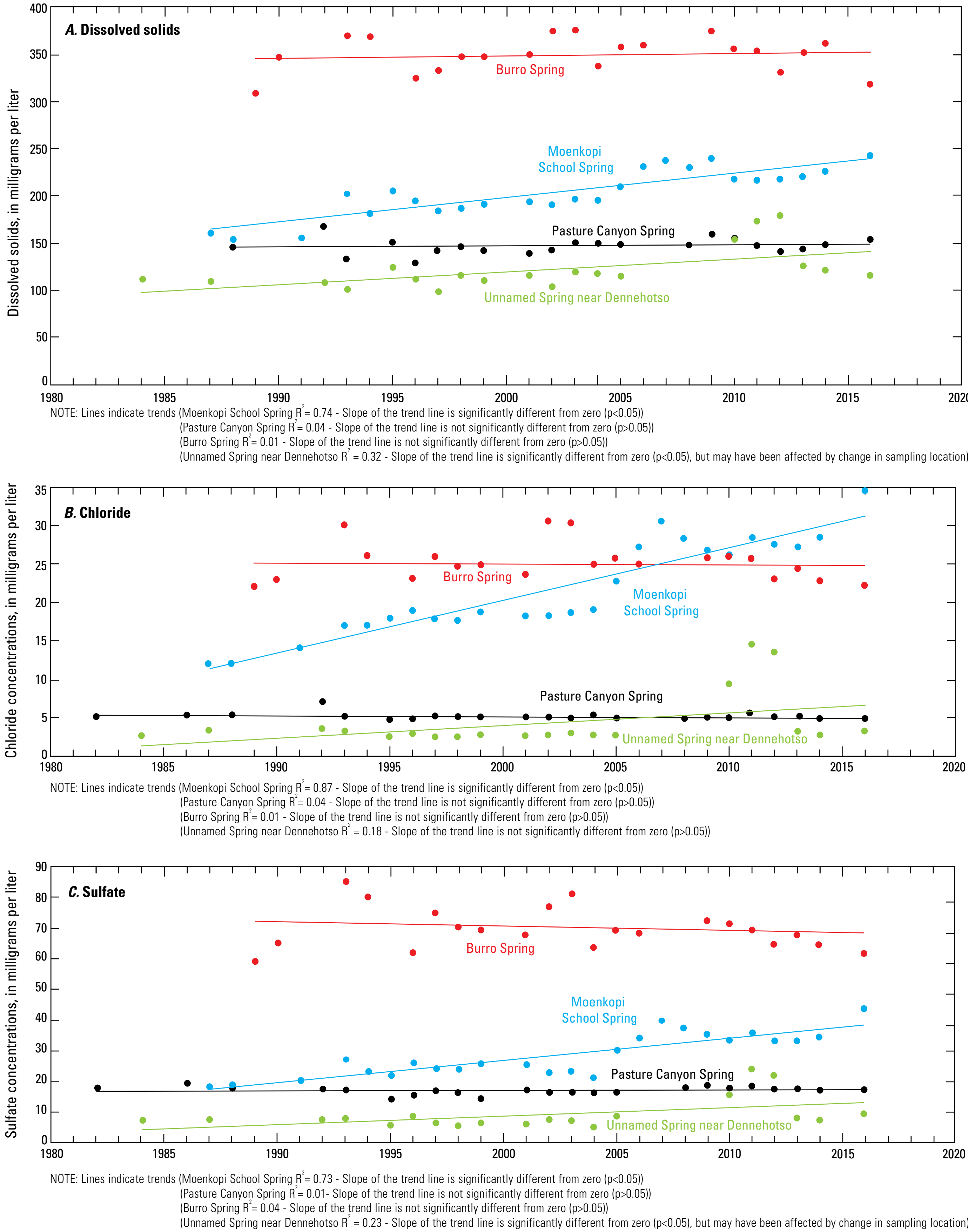

Figure 16. Plots of concentrations of dissolved solids, chloride, and sulfate for water samples from Moenkopi School Spring, Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso, which discharge from the N aquifer in Black Mesa area, northeastern Arizona, measured from 1982 to 2016. *A*, Dissolved solids; *B*, chloride; and *C*, sulfate. Trend lines were generated using the method of least squares.

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 2015 to December 2016. The monitoring data for 2015–16 are compared to historical data from the 1950s to December 2016.

In 2016, total groundwater withdrawals were about 3,540 acre-ft; industrial withdrawals were about 1,090 acre-ft, and municipal withdrawals were about 2,450 acre-ft. From 2015 to 2016, total withdrawals from the N aquifer decreased by about 11 percent, industrial withdrawals decreased by about 19 percent, and total municipal withdrawals decreased by about 7 percent.

From 2015 to 2016, annually measured groundwater levels declined in 17 of 32 wells available for comparison. The median water-level change for the 32 wells was -0.1 ft. In unconfined areas of the N aquifer the median change was also -0.1 ft. In the confined area of the N aquifer the median change was 0.0 ft. From the prestress period (before 1965) to 2016, the median groundwater-level change in 32 wells was -10.2 ft. Water levels in the unconfined areas of the N aquifer had a median change of -1.6 ft, and the changes ranged from -38.9 ft to +12.5 ft. Water levels in the confined area of the N aquifer had a median change of -36.1 ft, and the changes ranged from -197.6 ft to +10.9 ft.

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 2016, water samples were collected from three wells and four springs and analyzed for selected chemical constituents. A replicate quality assurance sample suggests that there is an acceptably low level of variability affecting the data. Dissolved-solids concentrations in water samples from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso were 318 mg/L, 244 mg/L, 155 mg/L, and 116 mg/L, respectively. From the mid-1980s to 2016, 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.

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