

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2009–10



Prepared in cooperation with the BUREAU OF INDIAN AFFAIRS
and the ARIZONA DEPARTMENT OF WATER RESOURCES

Open-File Report 2011–1198

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

COVER:

Photograph of the northern cliffs of Black Mesa near Black Mesa observation well #2, Arizona. (USGS photograph taken by Geoff DeBenedetto.)

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By Jamie P. Macy and Christopher R. Brown

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

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Suggested citation:
Macy, J.P., and Brown, C.R., 2011, Groundwater, surface-water, and water-chemistry data,
Black Mesa area, northeastern Arizona—2009–10: U.S. Geological Survey
Open-File Report 2011–1198, 42 p.

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Conversion Factors and Datums

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 (gal/yr)	3.785	liter per year (L/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
 $^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Altitude, as used in this report, refers to distance above the vertical datum.

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27). Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

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

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Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2009–10

By Jamie P. Macy and Christopher R. Brown

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 northeastern Arizona because of continued water requirements for industrial and municipal use by a growing population and because of low precipitation in the arid climate of the Black Mesa area. Precipitation in the area is typically between 6 and 14 inches per year.

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 January 2009 to September 2010. The monitoring program includes measurements of (1) groundwater withdrawals, (2) groundwater levels, (3) spring discharge, (4) surface-water discharge, and (5) groundwater chemistry.

In 2009, total groundwater withdrawals were 4,230 acre-ft, industrial withdrawals were 1,390 acre-ft, and municipal withdrawals were 2,840 acre-ft. Total withdrawals during 2009 were about 42 percent less than total withdrawals in 2005 because of Peabody Western Coal Company's discontinued use of water in a coal slurry used for transporting coal. From 2008 to 2009 total withdrawals increased by 3 percent and industrial withdrawals increased by approximately 15 percent, but total municipal withdrawals decreased by 2 percent.

From 2009 to 2010, annually measured water levels in the Black Mesa area declined in 7 of 16 wells that were available for comparison in the unconfined areas of the N aquifer, and the median change was 0.1 foot. Water levels declined in 12 of 18 wells measured in the confined area of the aquifer. The median change for the confined area of the aquifer was -0.3 foot. From the prestress period (prior to 1965) to 2010, the median water-level change for 34 wells in both the confined and unconfined area was -13.9 feet. Also, from the prestress period to 2009, the median water-level changes were -0.8 foot for 16 wells measured in the unconfined areas and -38.7 feet for 18 wells measured in the confined area.

Spring flow was measured at four springs in 2010. Flow fluctuated during the period of record, but a decreasing trend

was apparent at Moenkopi School Spring and Pasture Canyon Spring. Discharge at Burro Spring and Unnamed Spring near Dennehotso has remained relatively constant since they were first measured in the 1980s.

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 2009), Dinnebito Wash near Sand Springs 09401110 (1993 to 2009), Polacca Wash near Second Mesa 09400568 (1994 to 2009), and Pasture Canyon Springs 09401265 (2004 to 2009). 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 of each streamflow-gaging station, the median winter flows have generally remained constant, which suggests no change in groundwater discharge.

In 2010, water samples collected from 11 wells and 4 springs in the Black Mesa area were analyzed for selected chemical constituents, and the results were compared with previous analyses. Concentrations of dissolved solids, chloride, and sulfate have varied at all 11 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 12 years of record at that site. Concentrations of dissolved solids, chloride, and sulfate at Pasture Canyon Spring have not varied much 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 increasing or decreasing trend in the data.

Introduction

The 5,400-mi² Black Mesa study area in northeastern Arizona contains a diverse topography that includes flat plains, mesas, and incised drainages (fig. 1). Black Mesa is a topographic high at the center of the study area that covers about 2,000 mi². 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 average annual precipitation in the arid to semiarid climate that ranges between 6 and 14 in. (U.S. Department of Agriculture, 1999). The Navajo (N) aquifer is the major source of water for industrial and municipal uses in the Black Mesa area. The N aquifer is composed of three hydraulically connected formations—the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member of the Wingate Sandstone—that function as a single aquifer (fig. 2).

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).

Within the Black Mesa study area, the Navajo Nation and Hopi Tribe are the principal municipal water users, and Peabody Western Coal Company (PWCC) is the principal industrial water user. Withdrawals from the N aquifer in the Black Mesa area increased fairly consistently from 1965 through 2002 (table 1). PWCC began operating a strip mine in the northern part of the study area in 1968 (fig. 1). In 1982, PWCC sold the largest amount of moisture-adjusted tons of coal to the Mohave generating station and the quantity of water pumped by PWCC increased from about 100 acre-ft in 1968 to a maximum of 4,740 acre-ft in 1982 (John Cochran, Manager of Environmental Hydrology, Peabody Investments Corporation, written commun., 2010). During the same time period, municipal withdrawals grew from about 250 acre-ft in 1968 to 1,830 acre-ft in 1982.

On December 31, 2005, PWCC reduced pumping of the N aquifer by approximately 70 percent as a result of discontinued use of a coal slurry pipeline. PWCC planned to continue to pump approximately 1,000 to 1,500 acre-ft per year after 2005, primarily for dust control (table 1).

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), 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 January 2009 to September 2010. Continuous and periodic groundwater and surface-water data are collected to

determine the effects of industrial and municipal withdrawals from the N aquifer on groundwater levels, stream and spring discharge, and groundwater chemistry. Groundwater data include 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 data from 1965 to 2008 to describe the overall status of and change over time of groundwater conditions in the N aquifer, as well as 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 identify groundwater conditions in the N aquifer.

Previous Investigations

Twenty-five progress reports on the Black Mesa area monitoring program have been prepared by the USGS, and they are summarized in table 2. Most of the 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/>).

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 2009 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, 2007, 2008, 2009, 2010), and online at (<http://wdr.water.usgs.gov/wy2009/search.jsp>) in the 2009 annual data report. 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, HSI GeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering (1999) developed a three-dimensional numerical model of the N aquifer and the overlying Dakota (D) aquifer.

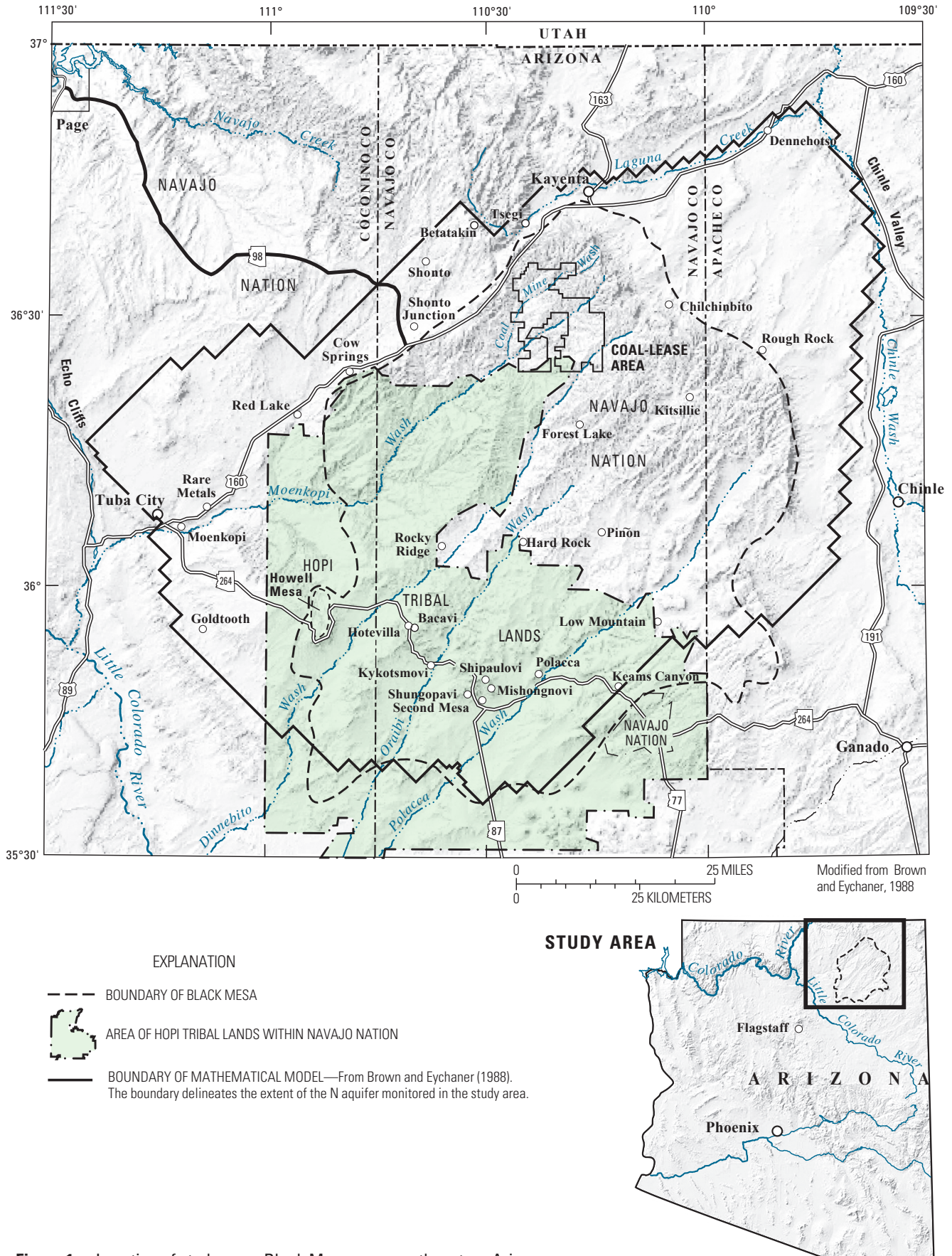


Figure 1. Location of study area, Black Mesa area, northeastern Arizona.

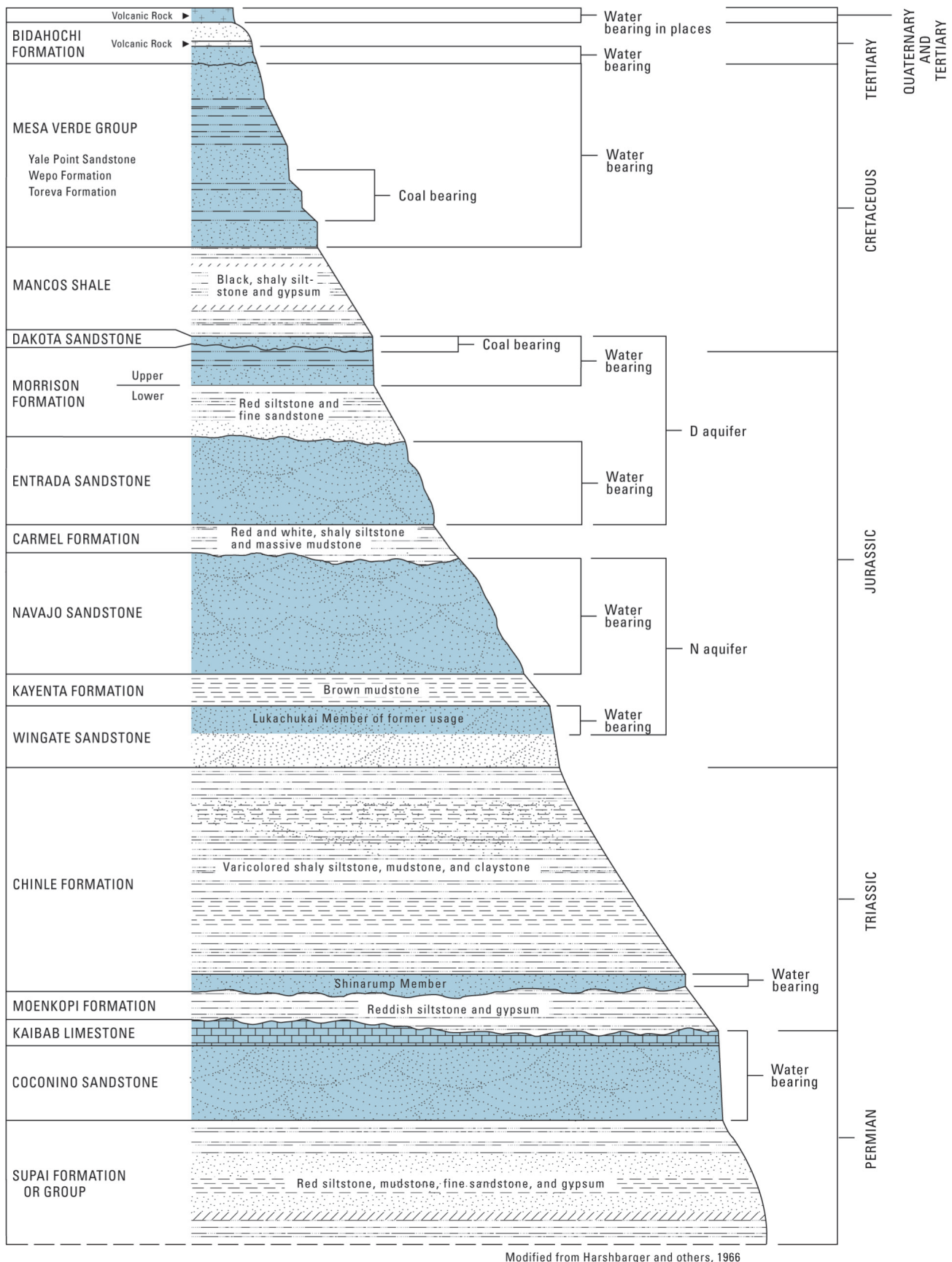


Figure 2. Rock formations and hydrogeologic units of the Black Mesa area, northeastern Arizona (not to scale). The N aquifer is approximately 1,000 feet thick.

Table 1. Withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2009.

[Values are rounded to nearest 10 acre-feet. Data for 1965–79 from Eychaner (1983).

Total withdrawals in Litten and Monroe (1996) were for the confined area of the aquifer]

Calendar Year	Industrial ¹	Municipal ^{2,3}		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
2006	1,200	⁴ 1,300	⁴ 1,600	⁴ 4,100
2007	1,170	1,460	1,640	4,270
2008	1,210	1,560	1,340	4,110
2009	1,390	1,440	1,400	4,230

¹Metered pumpage from the confined part of the aquifer by Peabody Western Coal Company.²Does not include withdrawals from the wells equipped with windmills.³Includes 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 Kykotsmóvi 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, 1986–2009.⁴NTUA meter data were not available for 2006; therefore, municipal withdrawals are estimated, and total withdrawal uses an estimation in the calculation.

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water collected from wells and springs in the Black Mesa area. HSI GeoTrans, 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 Longworth (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) addressed leakage through the confining unit between the D aquifer and the N aquifer as part of an investigation of the Carmel Formation.

Hydrologic Data

In 2009–10, 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 U.S. Geological Survey 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 TIBCO Spotfire S+ statistical software. Annual discharge measurements were made at 4 springs, and annual groundwater-level measurements were made at 34 wells. Of those 34 wells, 6 are continuous-recording observation wells that have been upgraded 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 online (<http://waterdata.usgs.gov/az/nwis/gw>). Groundwater withdrawal data were compiled during February 2010. The period before appreciable groundwater withdrawals began for mining or municipal purposes (about 1965) is referred to in this report as the "prestress period." Spring discharges and groundwater levels were measured from January to June 2010. Groundwater samples were collected from 11 wells and 4 springs in June 2010 and were analyzed for chemical constituents. Annual groundwater-withdrawal data are collected from 28 well systems within the NTUA, BIA, and Hopi municipal systems and the PWCC industrial well field. Identification information for the 34 wells used for water-level measurements and water-quality sampling 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, except for streamflow data which are reported in water years beginning October 1 and ending September 30.

Withdrawals from the N Aquifer

Total annual withdrawals from the N aquifer are monitored on a continuing basis to 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. 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 28 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 D and N aquifers primarily for feeding livestock, and the estimated total withdrawal by the windmills is about 65 acre-ft/yr (HSI GeoTrans, 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 2009 Compared to Previous Years

In 2009, the total groundwater withdrawal from the N aquifer was about 4,230 acre-ft (table 1). Withdrawals for municipal use from the confined area totaled 1,440 acre-ft. Withdrawals for municipal use from the unconfined areas totaled 1,400 acre-ft. Withdrawals for industrial use totaled 1,390 acre-ft, a 15-percent increase from 2008, and withdrawals for municipal use totaled 2,840 acre-ft, a 2-percent decrease from 2008 (table 5).

Withdrawals from the N aquifer have varied from 1965 to the present but generally increased from 1965 to 2005 and decreased from 2006 to 2009. Beginning in 2006, Peabody Western Coal Company reduced their pumping by 70 percent, a reduction that is reflected by a decrease in total annual withdrawals from 2005 by about 42 percent (tables 1 and 5, fig. 3). Total withdrawal for the period of record 1965–2009 totaled 235,000 acre-ft; industrial withdrawals were 61 percent and municipal withdrawals were 39 percent of total withdrawals (table 5). During 1965 to 2005, total annual withdrawals increased from 70 to 4,300 acre-ft (table 1); industrial withdrawals were 63 percent and municipal withdrawals were 37 percent of total withdrawals (table 5). A change in the amount of water being pumped from the N aquifer occurred in 2006; industrial withdrawals accounted for only about 30 percent of the total withdrawals compared to 61 percent the previous year (table 5). From 2006 to 2009, withdrawals totaled 16,710 acre-ft;

Table 2. Tabulated list of progress reports for the Black Mesa monitoring program 1978–2010.

Year Published	Author(s)	Title	USGS Report Type and Number
1978	U.S. Geological Survey	Progress report on Black Mesa monitoring program—1977	Open-File Report 78–459
1985	Hill, G.W.	Progress report on Black Mesa monitoring program—1984	Open-File Report 85–483
1986	Hill, G.W., and Whetten, M.I.	Progress report on Black Mesa monitoring program—1985–86	Open-File Report 86–414
1987	Hill, G.W., and Sottolare, 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 Sottolare, 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 Sottolare, 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	Sottolare, J.P.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1989–90	Water-Resources Investigations Report 92–4008
1992	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1990–91	Water-Resources Investigations Report 92–4045
1993	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1991–92	Water-Resources Investigations Report 93–4111
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1992–93	Water-Resources Investigations Report 95–4156
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-chemistry monitoring, Black Mesa area, northeastern Arizona—1994	Water-Resources Investigations Report 95–4238
1996	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1995	Open-File Report 96–616
1997	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1996	Open-File Report 97–566
1999	Littin, G.R., Baum, B.M., and Truini, Margot	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1997	Open-File Report 98–653
2000	Truini, Margot, Baum, B.M., Littin, G.R., and Shingoitewa-Honanie, Gayl	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1998	Open-File Report 00–66
2000	Thomas, B.E., and Truini, Margot	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1999	Open-File Report 00–453
2002	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
2002	Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2001–02	Open-File Report 02–485
2004	Truini, Margot, and Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2002–03	Open-File Report 03–503
2005	Truini, Margot, Macy, J.P., and Porter T.J.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2003–04	Open-File Report 2005–1080
2006	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2004–05	Open-File Report 2006–1058
2007	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2005–06	Open-File Report 2007–1041
2008	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2006–07	Open-File Report 2008–1324
2009	Macy, Jamie P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2007–2008	Open-File Report 2009–1148
2010	Macy, Jamie P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2008–2009	Open-File Report 2010–1038

Table 3. Identification numbers and names of monitoring program study wells, 2009–10, Black Mesa area, northeastern Arizona.

[Dashes indicate 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	4T-519
360217111122601	Tuba City	3K-325
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	---
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	8T-537
363005110250901	Peabody 2	---
363007110221201	Peabody 6	---
363013109584901	Sweetwater Mesa	8K-443
363103109445201	Rough Rock	9Y-95
363143110355001	BM observation well 4	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	8T-538
364034110240001	Marsh Pass	8T-522
364226110171701	Kayenta West	8T-541
364248109514601	Northeast Rough Rock	8A-180
364338110154601	BM observation well 3	8T-500
364344110151201	Kayenta PM2	8A-295
365045109504001	Dennehotso PM2	---

Table 4. Withdrawals from the N aquifer by well system, Black Mesa area, northeastern Arizona, calendar year 2009.

[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	Withdrawals	
			Confined aquifer	Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	3.3	
Dennehotso	BIA	USGS/BIA		17.5
Hopi High School	BIA	USGS/BIA	18.5	
Hotevilla	BIA	USGS/BIA	19.4	
Kayenta	BIA	USGS/BIA	38.7	
Keams Canyon	BIA	USGS/BIA	² 57.3	
Low Mountain	BIA	USGS/BIA	¹ 0	
Piñon	BIA	USGS/BIA	¹ 0	
Red Lake	BIA	USGS/BIA		5.2
Rocky Ridge	BIA	USGS/BIA	6.4	
Rough Rock	BIA	USGS/BIA	24.3	
Second Mesa	BIA	USGS/BIA	4.3	
Shonto	BIA	USGS/BIA		158.0
Tuba City	BIA	USGS/BIA		81.0
Chilchinbito	NTUA	USGS/NTUA	65.4	
Dennehotso	NTUA	USGS/NTUA		44.3
Forest Lake	NTUA	USGS/NTUA	² 12.5	
Hard Rock	NTUA	USGS/NTUA	49.7	
Kayenta	NTUA	USGS/NTUA	441	
Kits'iili	NTUA	USGS/NTUA	² 20.8	
Piñon	NTUA	USGS/NTUA	² 347	
Red Lake	NTUA	USGS/NTUA		52.6
Rough Rock	NTUA	USGS/NTUA	² 31.8	
Shonto	NTUA	USGS/NTUA		25.7
Shonto Junction	NTUA	USGS/NTUA		55.8
Tuba City	NTUA	USGS/NTUA		881.2
Mine Well Field	Peabody	Peabody	1,390	
Bacavi	Hopi	USGS/Hopi	24.7	
Hopi Civic Center	Hopi	USGS/Hopi	2.1	
Hopi Cultural Center	Hopi	USGS/Hopi	6.8	
Kykotsmovi	Hopi	USGS/Hopi	41.5	
Mishongnovi	Hopi	USGS/Hopi	6.3	
Moenkopi	Hopi	USGS/Hopi		² 79.6
Polacca	Hopi	USGS/Hopi	188	
Shipaulovi	Hopi	USGS/Hopi	21.9	
Shungopovi	Hopi	USGS/Hopi	9.9	

¹Well taken out of service.²Estimated value due to partial record.

Table 5. Total, industrial, and municipal withdrawals from the N aquifer for discrete time periods during 1965 to 2009, Black Mesa area, northeastern Arizona.

Period	Withdrawals (acre-feet)			Percent	
	Total	Industrial	Municipal	Industrial	Municipal
1965–2009	235,010	143,070	91,940	61	39
1965–2005	218,300	138,100	80,200	63	37
2006–2009	16,710	4,970	11,740	30	70
2009	4,230	1,390	2,840	33	67

industrial withdrawals were 30 percent and municipal withdrawals were 70 percent of total withdrawals (table 5). Total withdrawals in 2009 were 4,230 acre-ft, with 33 percent from industrial withdrawals and 67 percent from municipal withdrawals (table 5).

Flowmeter Quality Assurance

In an effort to improve and ensure the accuracy of groundwater-withdrawal data, a quality-assurance program was begun in 1985 for withdrawal data from industrial and municipal wells completed in the N aquifer. Nearly all industrial and municipal wells in the study area are equipped with totalizing flowmeters to measure groundwater withdrawals. The flowmeters on the wells are tested about once every 5 years by measuring withdrawal with a calibrated mechanical flowmeter and comparing the measured withdrawal to the metered withdrawal. For the purpose of this study, the allowable difference between the discharge measured by the permanent totalizing flowmeter and the test meter is 10 percent. A flowmeter that tests outside the 10 percent limit is repaired where possible and is revisited the following year and tested again. Flowmeter testing was done at about 19 percent of the total wells (34 wells were visited and 14 wells were tested) during June and July 2010 (table 6). Testing for 2010 was limited to meters that previously were unable to be tested or had percent-

difference magnitudes larger than 10 percent in 2009. The median percent difference between pumping rates for the permanent meter and the test meter for all sites tested was -4.6 percent. Values ranged from -16.3 percent at Shonto Junction NTUA 1 to +7.0 percent at Bacavi Village. Three wells had greater than 10-percent-difference magnitudes: Hopi High 2 (-15.9 percent), Kayenta NTUA 7 (-12.1 percent), and Shonto Junction NTUA 1 (-16.3 percent). No corrections based on these results were applied to pumping data.

Groundwater Levels in the N Aquifer

Groundwater levels are monitored in the N aquifer to determine the effects that withdrawals have 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. 4). 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).

Groundwater levels are measured once a year at the same time of year to limit the effect of seasonal variability. Groundwater levels are compared with levels from previous years to determine short-term changes and also are compared to prestress water levels to determine 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. During March 2010 to May 2010, water levels in all 34 wells having annual measurements met these criteria (table 7). Of the 34 wells, 6 are continuous-recording observation wells, and water levels were measured by electric tape in these 6 wells 3 times between June 2009 and June 2010.

The wells used for water-level measurements are distributed throughout the study area (fig. 5). The wells were constructed

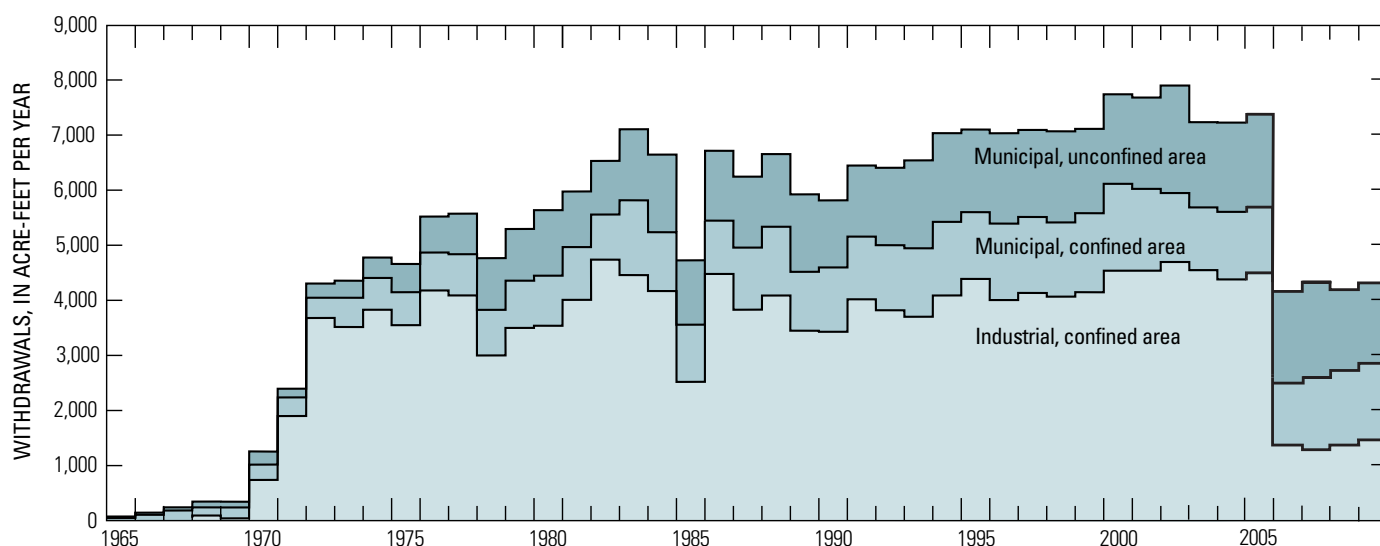
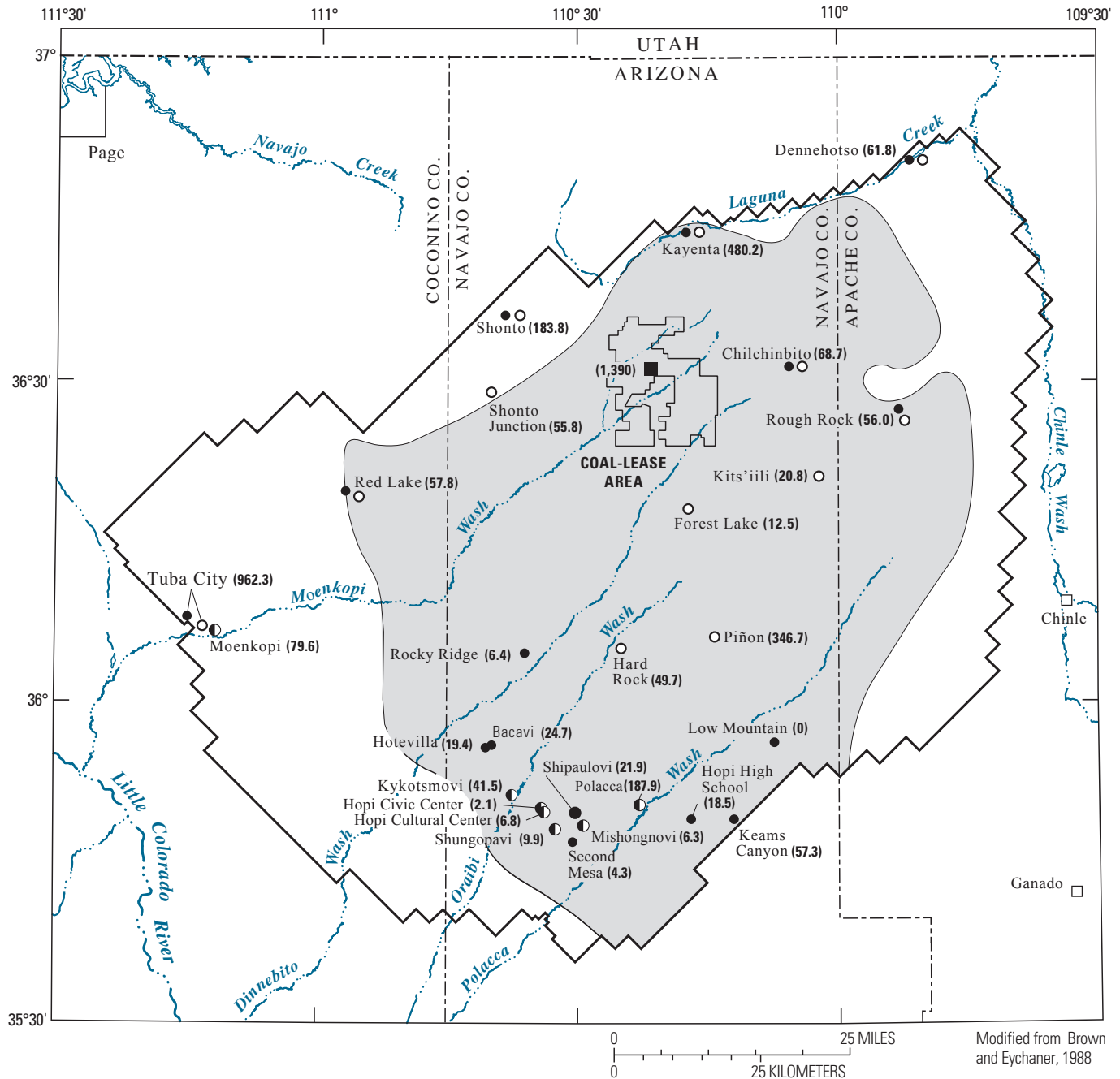


Figure 3. Annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2009.

Table 6. Flowmeter-test results for municipal wells that are completed in the N aquifer, Black Mesa area, northeastern Arizona, 2010.

Well name	Date visited	Permanent meter	Test meter	Percent difference	Manufacture	Serial or W number ⁷
Bureau of Indian Affairs						
Chilchinbito PM3	06-18-10	(⁶)	(⁶)	(⁶)	Unknown	Unknown
Red Lake PM1	06-10-10	60	60	0.0	Master Meter	1699087
Rocky Ridge PM2	06-15-10	(¹)	(¹)	(¹)	Rockwell	1331031
Rough Rock PM3	06-18-10	(⁶)	(⁶)	(⁶)	Rockwell	1323856
Tuba City PM5	06-10-10	55	56	-2.0	Sensus	61234907
Hopi Tribal Authority						
Bacavi	06-15-10	76	71	7.0	Sensus	1403844
Hopi High 1	06-09-10	(³)	(³)	(³)	(³)	(³)
Hopi High 2	06-09-10	90	107	-15.9	Neptune	31625415
Hopi High 3	06-09-10	(³)	(³)	(³)	(³)	(³)
Hotevilla Community 2	06-09-10	(¹)	(¹)	(¹)	Sensus	62062728
Keams Canyon #2	06-09-10	(⁴)	(⁴)	(⁴)	Neptune	60070618
Keams Canyon #3	06-09-10	(⁴)	(⁴)	(⁴)	Precision	E569880
Kykosmovi 2	06-09-10	(⁶)	(⁶)	(⁶)	Master Meter	Unknown
Kykosmovi 3	06-09-10	152	156	-2.6	Rockwell	W#454868
Moenkopi 1 and 2	06-10-10	48	48	0.0	Rockwell	1231000
Polacca 5	06-09-10	(³)	(³)	(³)	(³)	(³)
Polacca 6	06-09-10	(¹)	(¹)	(¹)	McCrometer	9261586
Second Mesa Day School 2	06-29-09	(⁴)	(⁴)	(⁴)	Amco	05337645
Navajo Tribal Utility Authority (NTUA)						
Kayenta NTUA 1	06-18-10	(⁶)	(⁶)	(⁶)	Sensus	60645246
Kayenta NTUA 2	06-18-10	(¹)	(¹)	(¹)	Sensus	60645245
Kayenta NTUA 4	06-18-10	(¹)	(¹)	(¹)	Unknown	Unknown
Kayenta NTUA 5	06-18-10	(²)	(²)	(²)	Rockwell	1276730
Kayenta NTUA 7	06-18-10	94	107	-12.1	Sensus	1436356
Kitsillie NTUA 1	06-15-10	(¹)	(¹)	(¹)	Rockwell	53189191
Pinon NTUA 3	06-15-10	(³)	(³)	(³)	Rockwell	1303039
Pinon NTUA 4	06-15-10	129	138	-6.5	Sensus	1552341
Red Lake NTUA	06-10-10	67	69	-2.9	Sensus	1550832
Rough Rock NTUA 1	06-18-10	(³)	(³)	(³)	(³)	(³)
Shonto NTUA 1	05-26-09	53	57	-7.0	Rockwell	28945149
Shonto Junction NTUA 1	06-18-10	87	104	-16.3	Sensus	62532598
Tuba City NTUA 1	06-10-10	(¹)	(¹)	(¹)	Unknown	Unknown
Tuba City NTUA 2	06-10-10	152	148	2.7	Sparkling	125709
Tuba City NTUA 3	06-18-10	157	160	-1.9	Sensus	46571
Tuba City NTUA 6	06-10-10	(⁵)	(⁵)	(⁵)	Rockwell	1153829

¹Well inactive.²Meter broken.³Well not in service.⁴Unable to test.⁵Flow too high for test meter.⁶Factory calibrated meter recently installed.⁷W number is a U.S. Geological Survey equipment identification number.



EXPLANATION

CONFINED AND UNCONFINED CONDITIONS IN THE N AQUIFER WITHIN MODEL BOUNDARY

- Confined
- Unconfined

— APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS —
From Brown and Eychaner (1988)

— BOUNDARY OF MATHEMATICAL MODEL —
From Brown and Eychaner (1988)

WELL-SYSTEM OWNER

- Bureau of Indian Affairs
- Navajo Tribal Utility Authority
- ◐ Hopi Tribe
- Peabody Western Coal Company

Piñon (346.7) WITHDRAWALS FROM THE N AQUIFER — Piñon, well-system name; 346.7, total withdrawal in acre-feet for 2009. The total is cumulative at locations served by multiple wells

Figure 4. Locations of well systems monitored for annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, calendar year 2009.

12 Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona, 2009–10

between 1934 and 1993, the total well depths range from 107 ft near Dennehotso (8A-180) to 3,636 ft near PWCC, and depths to the top of the N aquifer range from 0 ft near Tuba City to 2,205 ft at Kits'illi NTUA 2 (table 8).

From 2009 to 2010, water levels decreased in 19 of the 34 wells for which comparisons could be made (table 7). The median water-level change in the 34 wells was -0.2 ft (table 9).

From 2009 to 2010, water levels declined in 7 of the 16 wells measured in the unconfined parts of the aquifer (table 7), and the median water-level change was 0.1 ft (table 9). Water-level changes in the unconfined part of the aquifer ranged from -18.5 ft at Tuba City NTUA 1 (3T-508) to +1.5 ft at Goldtooth (3A-28) (table 7). In the confined area, water levels declined in 12 of 18 wells measured from 2009 to 2010. The median water-level

Table 7. Water-level changes in monitoring program wells completed in the N aquifer, Black Mesa area, northeastern Arizona, prestress period to 2010 (calendar year).

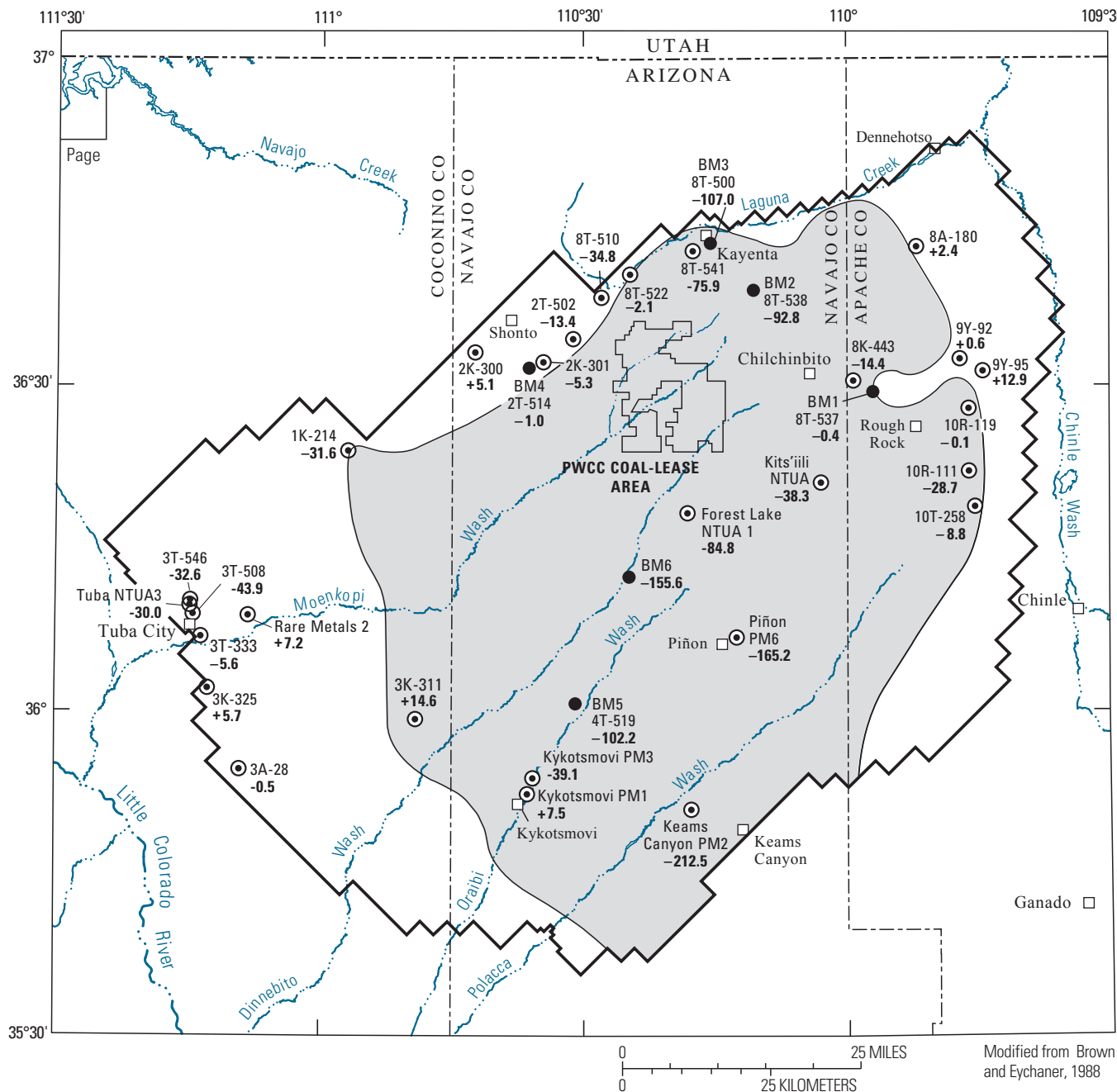
[Dashes indicate no data. Do., ditto; R, reported from driller's log]

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year (feet)		Water level (feet below land surface), 2010	Prestress period water level		Change in water level from prestress period to 2010 (feet)
		2009	2010		Feet below land surface	Date	
Unconfined areas							
BM observation well 1 ¹	8T-537	-0.4	0.2	374.4	374.0	(¹)	-0.4
BM observation well 4 ¹	2T-514	-0.2	0.2	217.0	216.0	(¹)	-1.0
Goldtooth	3A-28	2.7	1.5	230.5	230.0	10–29–53	-0.5
Long House Valley	8T-510	-0.7	-1.0	134.2	99.4	08–22–67	-34.8
Northeast Rough Rock	8A-180	-0.5	0.2	44.5	46.9	11–13–53	2.4
Rough Rock	9Y-95	2.4	-1.3	106.6	119.5	08–03–49	12.9
Do.	9Y-92	0.7	-2.2	168.2	168.8	12–13–52	0.6
Shonto	2K-300	-0.2	0.0	171.4	176.5	06–13–50	5.1
Shonto Southeast	2K-301	(²)	0.2	289.2	283.9	12–10–52	-5.3
Do.	2T-502	1.7	-2.4	419.2	405.8	08–22–67	-13.4
Tuba City	3T-333	0.4	0.3	28.6	23.0	12–02–55	-5.6
Do.	3K-325	-0.2	0.9	202.3	208.0	06–30–55	5.7
Tuba City Rare Metals 2	---	-0.1	0.6	49.8	57.0	09–24–55	7.2
Tuba City NTUA 1	3T-508	2.0	-18.5	72.9	29.0	02–12–69	-43.9
Tuba City NTUA 3	---	0.0	-2.3	64.2	34.2	11–08–71	-30.0
Tuba City NTUA 4	3T-546	-0.3	-1.3	66.3	33.7	08–06–71	-32.6
Confined area							
BM observation well 2 ¹	8T-538	-1.2	-0.2	217.8	125.0	(¹)	-92.8
BM observation well 3 ¹	8T-500	-0.2	-0.1	162.0	55.0	04–29–63	-107.0
BM observation well 5 ¹	4T-519	-1.4	-0.4	426.2	324.0	(¹)	-102.2
BM observation well 6 ¹	---	2.2	3.8	852.6	697.0	(¹)	-155.6
Forest Lake NTUA 1	4T-523	3.3	5.6	1180.8	1,096R	05–21–82	-84.8
Howell Mesa	3K-311	4.3	-3.1	448.4	463.0	11–03–53	14.6
Kayenta West	8T-541	-2.6	-6.3	305.9	230.0	03–17–76	-75.9
Keams Canyon PM2	---	-7.2	-6.6	505.0	292.5	06–10–70	-212.5
Kits'iili NTUA 2	---	-1.7	-3.8	1336.2	³ 1,297.9	01–14–99	-38.3
Kykotsmovi PM1	---	-0.1	-0.7	212.5	220.0	05–20–67	7.5
Kykotsmovi PM3	---	-5.3	-0.2	249.1	210.0	08–28–68	-39.1
Marsh Pass	8T-522	0.1	0.0	127.6	125.5	02–07–72	-2.1
Piñon PM6	---	0.0	-3.9	908.8	743.6	05–28–70	-165.2
Rough Rock	10R-119	-0.2	0.1	256.7	256.6	12–02–53	-1.1
Do.	10T-258	-0.4	0.1	309.8	301.0	04–14–60	-8.8
Do.	10R-111	0.2	-5.4	198.7	170.0	08–04–54	-28.7
Sweetwater Mesa	8K-443	0.4	-1.9	543.8	529.4	09–26–67	-14.4
White Mesa Arch	1K-214	-0.3	0.3	219.6	188.0	06–04–53	-31.6

¹Continuous recorder. Prestress water levels were estimated from a ground-water model, except for well BM3 (Brown and Eychaner, 1988).

²Cannot be determined because at least one of the water-level measurements is not available.

³Water level is the first water level measured after completion of well.



EXPLANATION

CONFINED AND UNCONFINED CONDITIONS
IN THE N AQUIFER

- Confined area within the boundary of the mathematical boundary
- Unconfined area within the boundary of the mathematical boundary

— APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS —
From Brown and Eychaner (1988)

— BOUNDARY OF MATHEMATICAL MODEL —
From Brown and Eychaner (1988)

WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 2K-300, is Bureau of Indian Affairs site number; second entry, **+5.1**, is change in water level, in feet, between measurement made during the prestress period and measurement made during 2010. **NV**, site not visited

CONTINUOUS WATER-LEVEL RECORDING SITE (OBSERVATION WELL) MAINTAINED BY THE U.S. GEOLOGICAL SURVEY—First entry, BM2, is U.S. Geological Survey well number; second entry, 8T-538, is Bureau of Indian Affairs site number; third entry, **-92.8**, is change in water level, in feet, from simulated prestress period to 2010

Figure 5. Water-level changes in monitoring program wells completed in the N aquifer, Black Mesa area, northeastern Arizona, prestress period to 2010 (calendar year).

14 Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona, 2009–10

Table 8. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, northeastern Arizona, 2009–10.

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 ¹)	Type of data collected
8T-537 (BM observation well 1)	02-01-72	5,864	851	300-360; 400-420; 500-520; 600-620; 730-780	290	Water level
8T-538 (BM observation well 2)	01-29-72	5,656	1,338	470-1,338	452	Water level
8T-500 (BM observation well 3)	07-29-59	5,724	868	712-868	155	Water level
2T-514 (BM observation well 4)	02-15-72	6,320	400	250-400	160	Water level
4T-519 (BM observation well 5)	02-25-72	5,869	1,683	1,521-1,683	1,520	Water level
BM observation well 6	01-31-77	6,332	2,507	1,954-2,506	1,950	Water level
1K-214	05-26-50	5,771	356	168-356	250	Water level
2K-300	³ 06-00-50	6,264	300	260-300	0	Water level
2K-301	06-12-50	6,435	500	318-328; 378-500	230	Water level
2T-502	08-10-59	6,670	523	12-523	25	Water level
3A-28	04-19-35	5,381	358	⁽⁴⁾	60	Water level
3K-311	³ 11-00-34	5,855	745	380-395 605-745	615	Water level
3K-325	06-01-55	5,250	450	75-450	230	Water level
3T-333	12-02-55	4,940	229	63-229	24	Water level
3T-508 (Tuba City NTUA 1)	08-25-59	5,119	475	⁽⁴⁾	0	Water level, withdrawals
3T-546 (Tuba City NTUA 4)	³ 08-00-71	5,206	612	256-556	0	Water level, withdrawals
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	⁽⁵⁾	Water level, water chemistry, withdrawals
8A-180	01-20-39	5,200	107	60-107	240	Water level
8A-295 (Kayenta PM2)	³ 00-00-36	5,623	840	268-280; 691-788	95	Water chemistry
8K-443	08-15-57	6,024	720	619-720	590	Water level
8T-510	02-11-63	6,262	314	130-314	2125	Water level
8T-522	³ 07-00-63	6,040	933	180-933	480	Water level
8T-541	03-17-76	5,885	890	740-890	700	Water level
9Y-92	01-02-39	5,615	300	154-300	250	Water level
9Y-95	11-05-37	5,633	300	145-300	268	Water level
10R-111	04-11-35	5,757	360	267-360	210	Water level
10R-119	01-09-35	5,775	360	⁽⁴⁾	310	Water level
10T-258	04-12-60	5,903	670	465-670	460	Water level
Dennehotso PM2	06-05-64	5,005	675	475-675	8	Water chemistry
Keams Canyon PM2	³ 05-00-70	5,809	1,106	906-1,106	900	Water level, withdrawals, Water chemistry
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	Water level, withdrawals
Kykotsmovi PM1	02-20-67	5,657	995	655-675 890-990	880	Water level, withdrawals
Kykotsmovi PM2	10-14-77	5,760	1,155	950-1,155	890	Water chemistry, withdrawals
Kykotsmovi PM3	08-07-68	5,618	1,220	850-1,220	840	Water level, withdrawals
Low Mountain PM2	³ 04-00-72	6,123	1,343	1,181-1,262	1,153	Withdrawals
Peabody 2	³ 06-00-67	6,530	3,636	1,816-3,603	728	Water chemistry, withdrawals
Peabody 6	06-00-65	6,645	3,559	2,047-3,494	894	Water chemistry, withdrawals
Piñon NTUA 1	02-25-80	6,336	2,350	1,860-2,350	1,850	Water chemistry, withdrawals
Rough Rock PM5	06-27-64	6,299	1,425	1,175-1,425	1,156	Water chemistry, withdrawals
Second Mesa PM2	³ 10-00-68	5,777	1,090	740-1,090	720	Water chemistry, withdrawals
Piñon PM6	³ 02-00-70	6,397	2,248	1,895-2,243	1,870	Water level, withdrawals
Shonto PM2	05-05-61	6,465	554	485-510; 514-539	0	Water chemistry
Tuba City NTUA 3	³ 10-00-71	5,176	442	142-442	34	Water level, withdrawals
Tuba City Rare Metals 2	³ 09-00-55	5,108	705	100-705	255	Water level

¹Depth to top of N aquifer from Eychaner (1983) and Brown and Eychaner (1988).

²All material between land surface and top of the N aquifer is unconsolidated—soil, alluvium, or dune sand.

³00, indicates day is unknown.

⁴Screened and (or) open intervals are unknown.

⁵Depth to top of N aquifer was not estimated

Table 9. Median changes in water levels in monitoring-program wells, 2009–10 and prestress period (prior to 1965) to 2010, N aquifer, Black Mesa area, northeastern Arizona

Years	Aquifer conditions	Number of wells	Median change in water level (feet)
2009–10	All	34	-0.2
	Unconfined	16	0.1
	Confined	18	-0.3
Prestress–2010	All	34	-13.9
	Unconfined	16	-0.8
	Confined	18	-38.7

change was -0.3 ft (table 9). Water-level changes in the confined part of the aquifer ranged from -6.6 ft at Keams Canyon PM2 to +5.6 ft at Forest Lake NTUA 1 (4T-523) (table 7).

From the prestress period (before 1965) to 2010, the median water-level change in 34 wells was -13.9 ft (table 9). Water levels in 16 unconfined wells had a median change of -0.8 ft. Water-level changes in the unconfined part of the aquifer ranged from -43.9 ft at Tuba City NTUA 1 (3T-508) to +12.9 ft at 9Y-95 in Rough Rock (fig. 5 and table 7). Water levels in 18 wells in the confined part of the aquifer had a median change of -38.7 ft (table 9). Water-level changes in the confined part of the aquifer ranged from -212.5 ft at Keams Canyon PM2 to +14.6 ft at Howell Mesa 3K-311 (fig. 5 and table 7).

Hydrographs of groundwater levels in the network of wells observed annually show the temporal changes since the 1950s, 1960s, or 1970s (fig. 6). In most of the unconfined area, water levels have changed only slightly (generally less than 10 ft). Near Long House Valley, however, the water level in well 8T-510 has declined about 35 ft (fig. 5 and table 7). Water levels have declined in most of the confined area; however, the magnitudes of declines are varied. Larger declines have occurred near the municipal pumping centers (wells Piñon PM6, Keams Canyon PM2) and near the wells for PWCC (BM6). Smaller declines occurred away from pumping centers in or near towns in the study area (wells 10T-258, 8K-443, 10R-111, 8T-522; fig. 5).

Hydrographs for the Black Mesa continuous-record observation wells show continuous water levels since the early 1970s (fig. 7). Water levels in 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 declines. Water levels (which have not been corrected for barometric pressure effects or seasonal effects) in wells BM2, BM3, and BM5 in the confined area have consistently declined since the early to mid 1960s (fig. 7). Since October 2009, water levels in BM2 have flattened. Water levels in BM6 in the confined area had consistently declined since the mid 1970s until the year 2007, when a distinct change occurred in the trend of the water level from decreasing to increasing. BM6 reached a maximum depth to water of 861.2 ft below land surface on December 4, 2006, and recovered to a water level of 852.1 ft below land surface on July 1, 2010, about 9 feet of total recovery to date.

Spring Discharge from the N Aquifer

The effect of withdrawals from the N aquifer on the water quality and discharge of springs around Black Mesa is a concern of the cooperators of this program. 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. In 2010, Moenkopi School Spring, Burro Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso were measured for discharge.

Moenkopi School Spring is in the western part of the Black Mesa area and is also called Susunova Spring by the Hopi Tribe (fig. 8). Discharge from Moenkopi School Spring was measured in June 2010 by the volumetric method and compared to discharge data from previous years to determine changes over time (fig. 9). The trend for discharge measurements at this spring is not corrected for seasonal variability, but discharge measurements are made annually at the same time or as close to the same time of year. In 2010, the measured discharge was 7.4 gal/min from Moenkopi School Spring (table 10). From 2009 to 2010, discharge decreased by 7.5 percent; for the period of record, discharge measurements have a significant ($p < 0.05$) decreasing trend, and linear regression analysis indicates that spring discharge decreases an average of about 0.3 gal/yr (fig. 9 and table 10).

Burro Spring is in the southwestern part of the study area and discharges from the Navajo Sandstone and alluvium (fig. 8). Burro Spring discharges from the aquifer through a metal pipe and into a cement trough for livestock. The 2010 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. 9). In 2010 the measured discharge was 0.3 gal/min, the same measured discharge as the previous year (fig. 9 and table 10).

A third spring measured in 2010 was Pasture Canyon Spring. Pasture Canyon Spring is in the western part of the study area and discharges from the Navajo Sandstone and alluvium (fig. 8). Discharge of Pasture Canyon Spring is measured at two locations. The first location is where the spring issues from the Navajo Sandstone, which is also the water-quality sampling point, and the second location is further down-canyon at the USGS gaging station. The USGS gaging station at Pasture Canyon measures the discharge from Pasture Canyon Spring and the additional discharge from seeps along Pasture Canyon. Discharge was measured at Pasture Canyon Spring in June 2010 by the volumetric method; when compared to discharge in previous years, a decreasing trend ($p < 0.05$) is evident from both linear regression and Kendall's tau analyses, a decrease in discharge of about 0.5 gal/yr (fig. 9 and table 10). The trend in discharge data measured at this spring, however, is not corrected for seasonal variability, but discharge measurements are made annually at the same time or as close to the same time of year. In 2010 the measured discharge was 34.3 gal/min, a 10-percent increase from 2009 (table 10).

The fourth spring measured in 2010 was Unnamed Spring near Dennehotso (fig. 8). This spring is the only spring in the northeastern part of the study area, and it discharges from the Navajo Sandstone. Discharge measurements at Unnamed Spring near Dennehotso are made by using a flume. Discharge had not been measured at Unnamed Spring near Dennehotso since 2005, however, the measurement made in 2010 shows that there has been a substantial decrease in flow since the last measurement in 2005. In 2005 the discharge at the spring was 21.5 gal/min, and in 2010 the measured discharge was only 9.0 gal/min (table 10). For the period of record, there

is no appreciable trend in the data based on linear regression ($p>0.05$) and Kendall's tau analyses.

Surface-Water Discharge, 2009 Water Year

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 and as surface runoff from rainfall or snowmelt. Groundwater discharges to some stream reaches at a fairly constant rate throughout the year; however, the

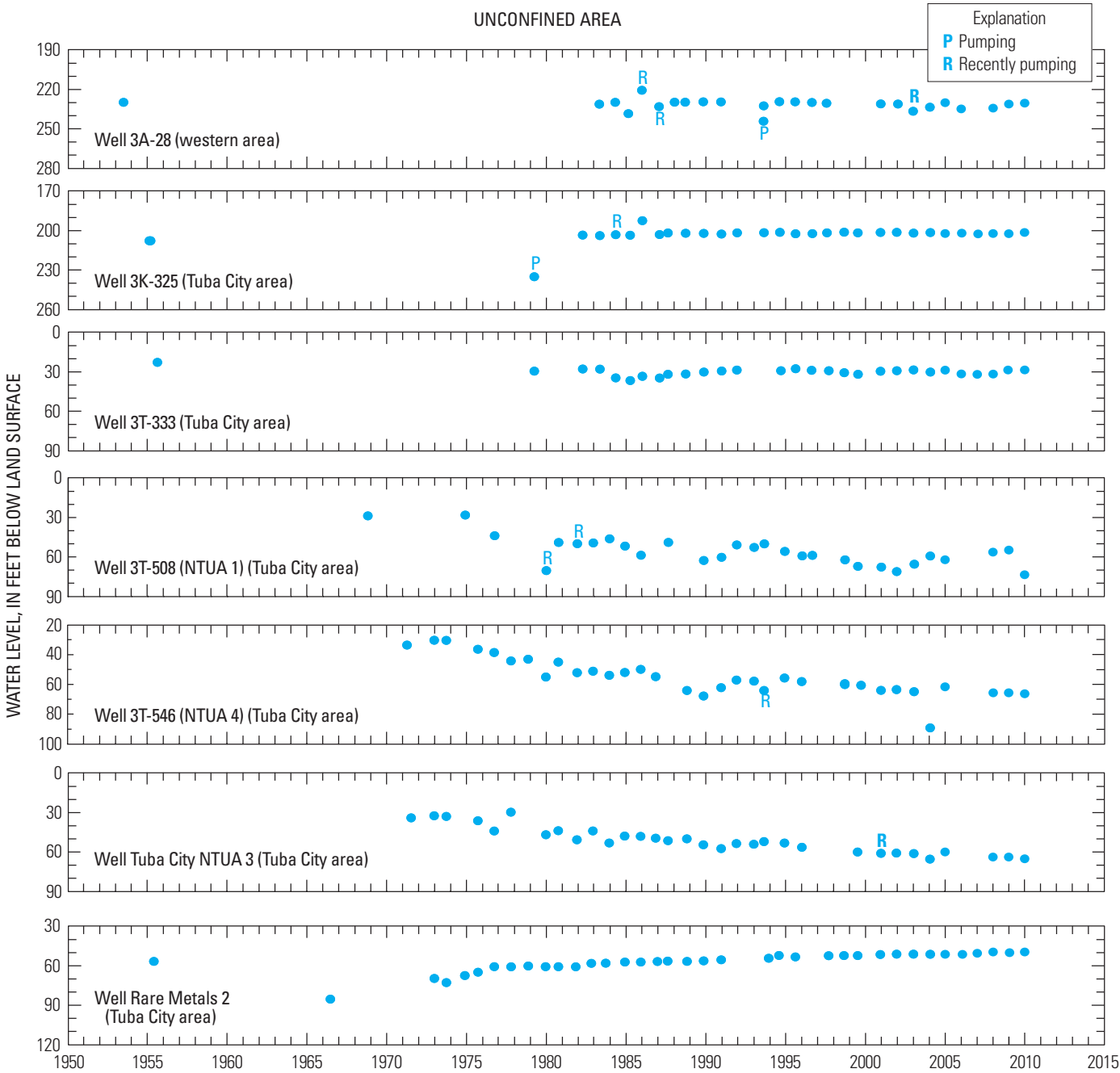


Figure 6. Water-level changes in N aquifer wells from the prestress period (prior to 1965) to 2010, Black Mesa area, northeastern Arizona.

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 snow accumulation, air temperatures, and rate of snowmelt. Although rainfall can occur throughout the year, most rainfall runoff occurs during the summer months. The amount and timing of rainfall runoff depend on the intensity and duration of thunderstorms during the summer and cyclonic storms during the fall, winter, and spring.

In 2009, discharge data were collected at four continuous-recording streamflow-gaging stations (tables 11–14). 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, near Tuba City, 09401265; fig. 10A; table 15). The annual average discharges at the four streamflow-gaging stations vary during the periods of record (fig. 10A), and there are no significant trends in annual average discharge for Moenkopi Wash, Polacca Wash, Dinnebito Wash, and Pasture Canyon Springs.

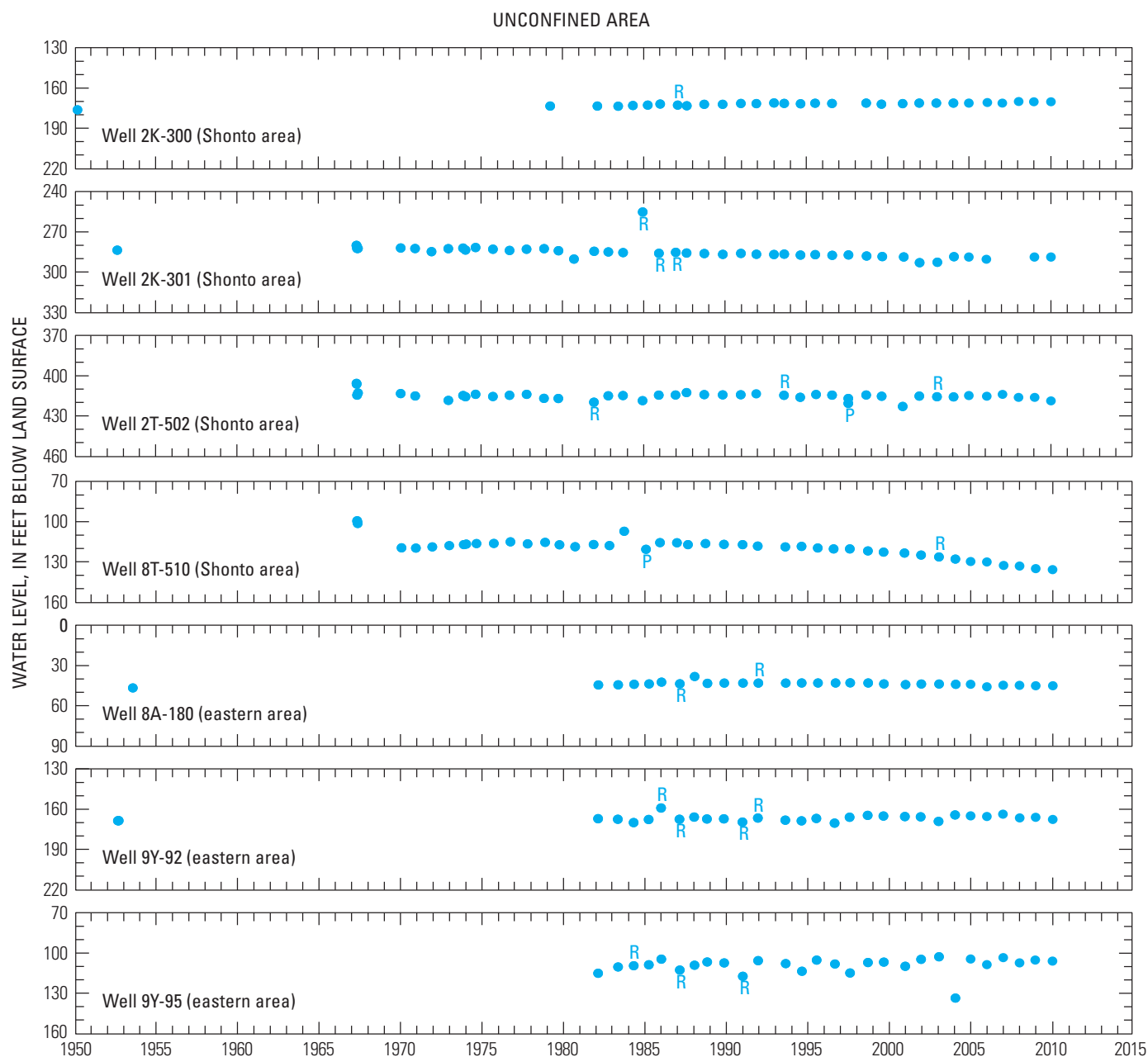


Figure 6. Water-level changes in N aquifer wells from the prestress period (prior to 1965) to 2010, Black Mesa area, northeastern Arizona.—Continued

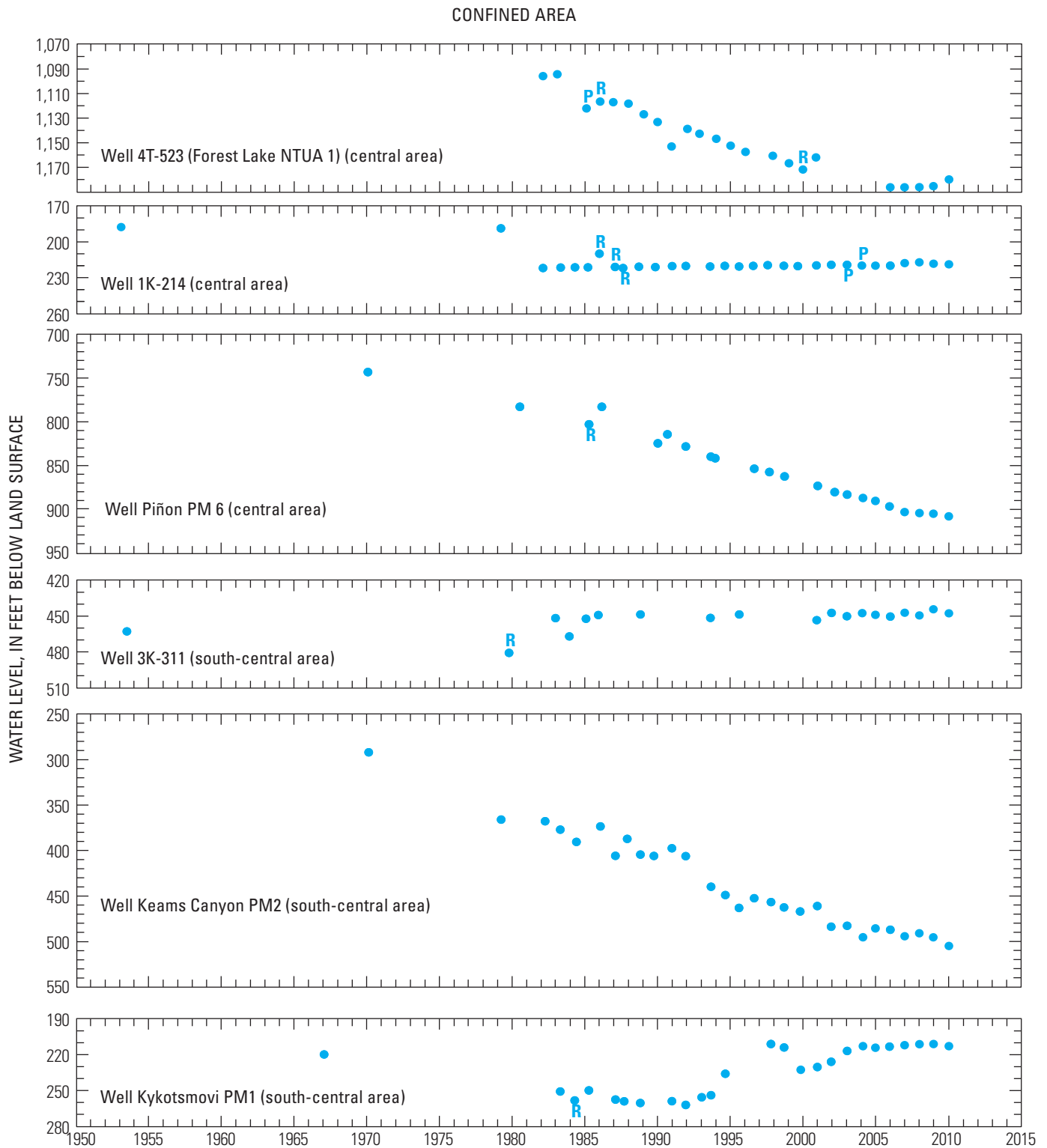


Figure 6. Water-level changes in N aquifer wells from the prestress period (prior to 1965) to 2010, Black Mesa area, northeastern Arizona. —Continued

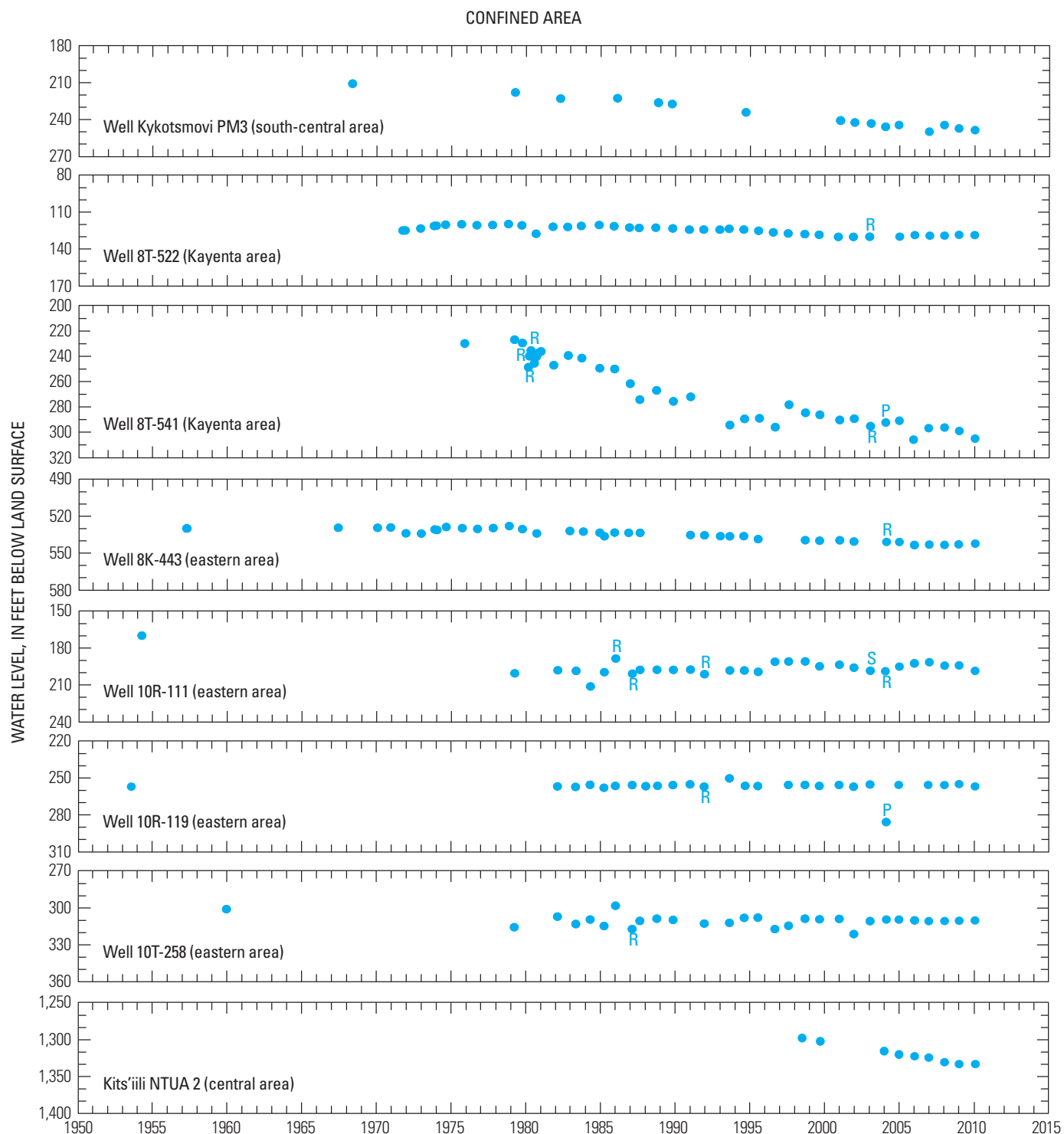


Figure 6. Water-level changes in N aquifer wells from the prestress period (prior to 1965) to 2010, Black Mesa area, northeastern Arizona. —Continued

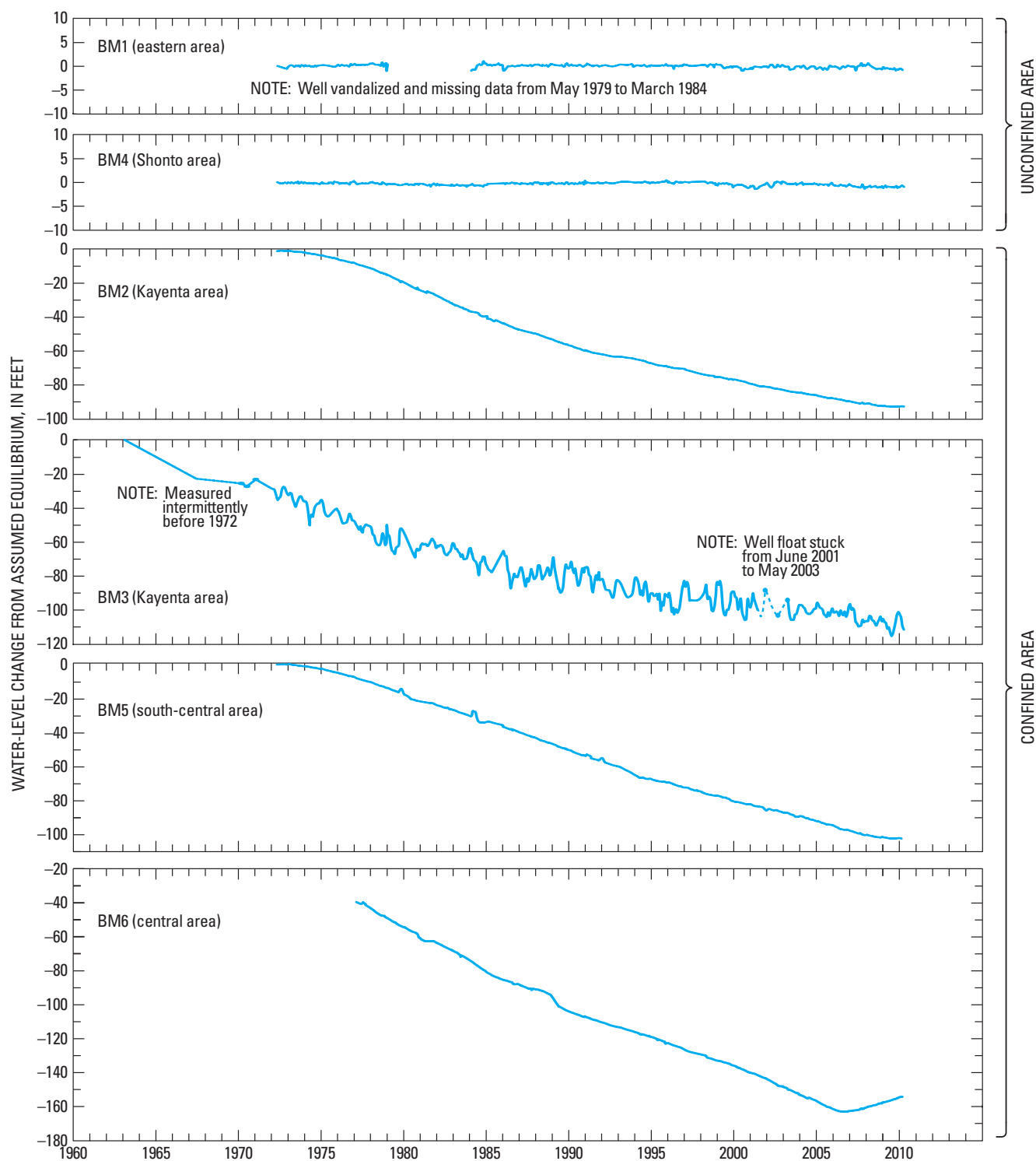
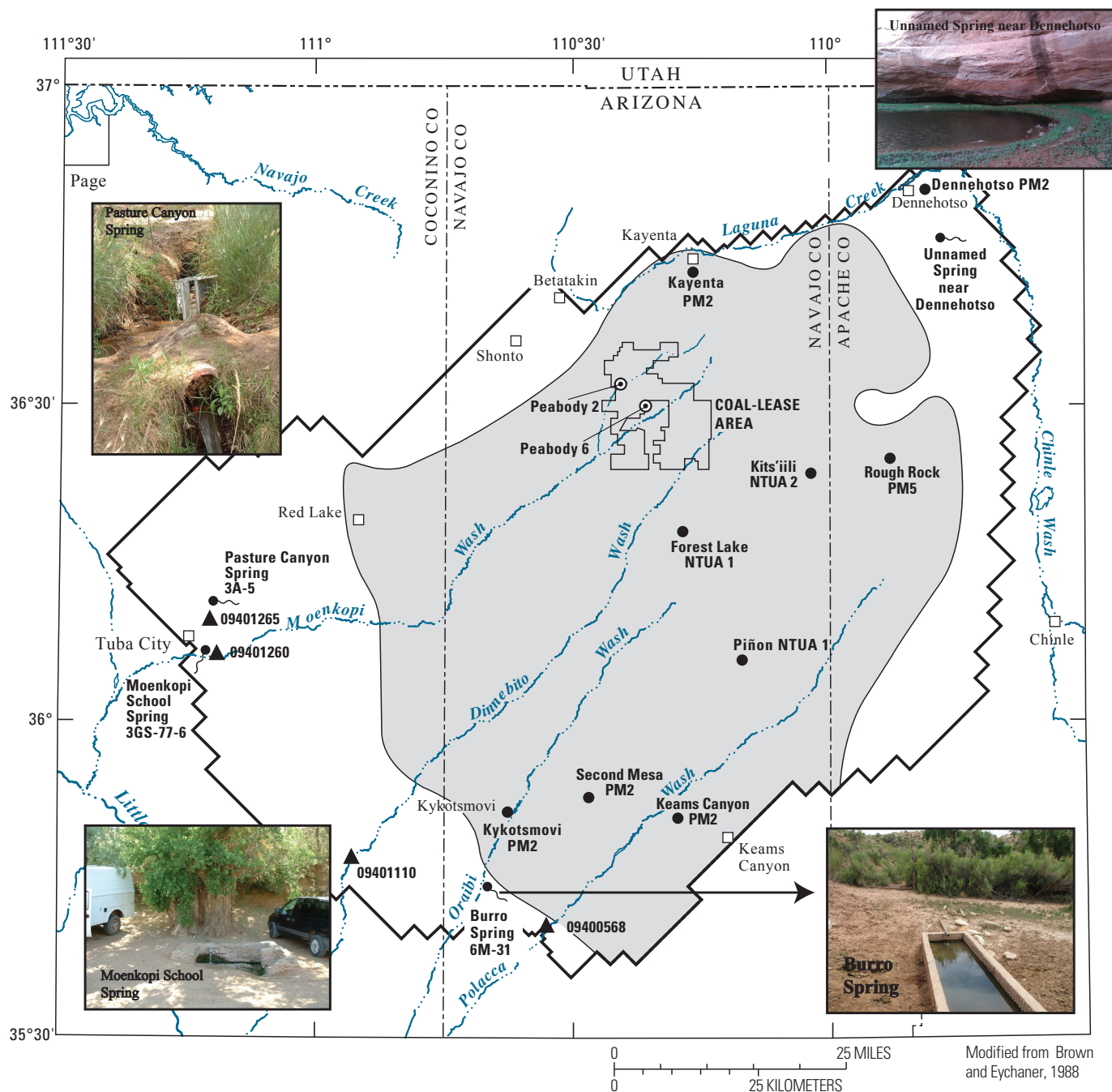


Figure 7. Observed water-level changes in continuous-record observation wells, BM1–BM6, 1963–2010, N aquifer, Black Mesa area, northeastern Arizona.



EXPLANATION

CONFINED AND UNCONFINED CONDITIONS
IN THE N AQUIFER WITHIN MODEL BOUNDARY

Confined

Unconfined

APPROXIMATE BOUNDARY BETWEEN CONFINED
AND UNCONFINED CONDITIONS —
From Brown and Eychaner (1988)

BOUNDARY OF MATHEMATICAL MODEL —
From Brown and Eychaner (1988)

MUNICIPAL WELL FROM WHICH
WATER-CHEMISTRY SAMPLE
WAS COLLECTED—Kykotsmovi
PM2 is well name

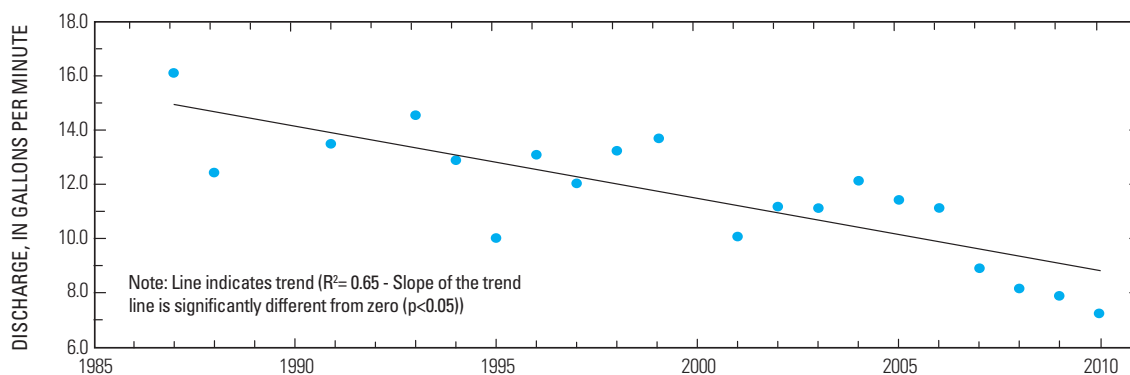
INDUSTIAL WELL FROM WHICH
WATER-CHEMISTRY SAMPLE WAS
COLLECTED—Peabody 2 is a well
number

SPRING AT WHICH DISCHARGE WAS
MEASURED AND
WATER-CHEMISTRY SAMPLE WAS
COLLECTED—Number is spring
identification

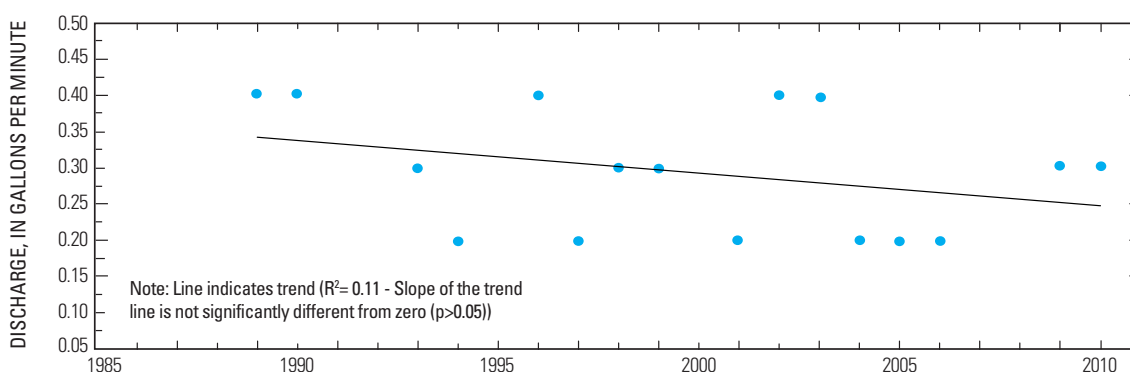
STREAMFLOW-GAGING STATION
OPERATED BY THE U.S. GEOLOGICAL
SURVEY—Number is station
identification

Figure 8. Surface-water and water-chemistry data-collection sites, N aquifer, Black Mesa area, northeastern Arizona, 2009–10.

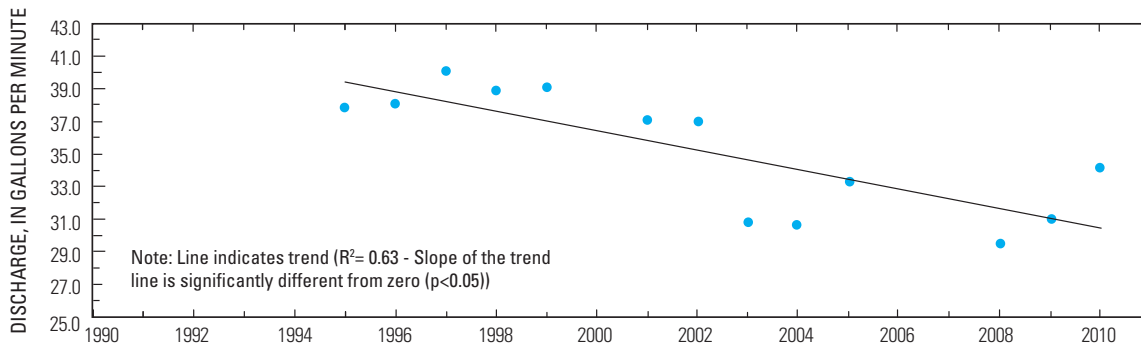
A. Discharge data for Moenkopi School Spring, 1987–2010.



B. Discharge data for Burro Spring 1989–2010.



C. Discharge data for Pasture Canyon Spring, 1987–2010.



D. Discharge data for Unnamed Spring near Dennehotso, 1992–2010.

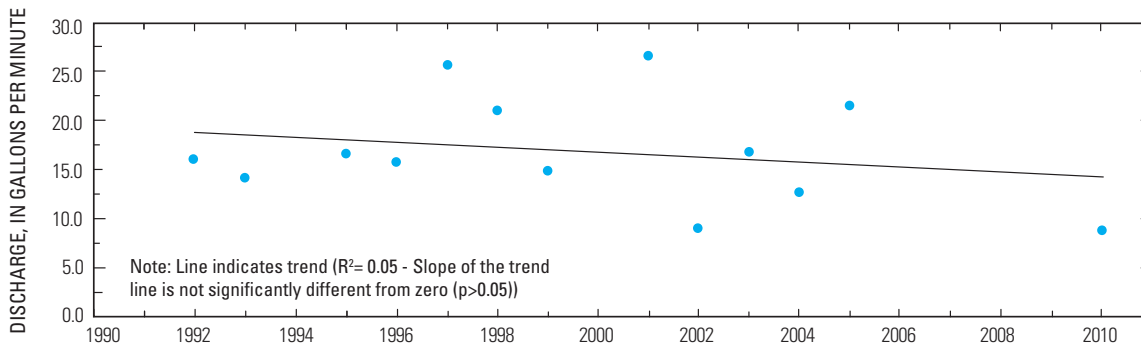


Figure 9. Discharge from A, Moenkopi School Spring, B, Burro Spring, C, Pasture Canyon Spring, and D, Unnamed Spring near Dennehotso, N aquifer, Black Mesa area, northeastern Arizona, 1987–2010. Data from 1952 measurement at Moenkopi School Spring are not shown because measurement was from a different measuring location. Data from 1988 to 1993 measurements at Pasture Canyon Spring are not shown because they were from a different measuring location. Trend lines were generated by using method of least squares.

Table 10. Discharge measurements from Moenkopi School Spring, Burro Spring, Pasture Canyon Spring, and Unnamed spring near Dennehotso in the Black Mesa area, northeastern Arizona, 1952–2010.

[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	Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Moenkopi School Spring ¹				Burro Spring ¹			
3GS-77-6	Navajo Sandstone ²	05-16-52	40.0	6M-31	Navajo Sandstone	12-15-89	0.4
		04-22-87	³ 16.0			12-13-90	0.4
		11-29-88	³ 12.5			03-18-93	0.3
		02-21-91	³ 13.5			12-08-94	0.2
		04-07-93	³ 14.6			12-17-96	0.4
		12-07-94	³ 12.9			12-30-97	0.2
		12-04-95	³ 10.0			12-08-98	0.3
		12-16-96	³ 13.1			12-07-99	0.3
		12-17-97	³ 12.0			04-02-01	0.2
		12-08-98	³ 13.3			04-04-02	0.4
		12-13-99	³ 13.7			04-30-03	0.4
		03-12-01	³ 10.2			04-06-04	⁶ 0.2
		06-19-02	³ 11.2			03-28-05	0.2
		05-01-03	³ 11.2			03-28-06	0.2
		03-29-04	³ 12.2			06-04-09	0.3
		04-04-05	³ 11.5			06-07-10	0.3
		03-13-06	³ 11.1				
		05-31-07	³ 9.0				
		06-03-08	³ 8.3				
		06-03-09	³ 8.0				
		06-14-10	37.4				
Pasture Canyon Spring ¹				Unnamed spring near Dennehotso ⁴			
3A-5	Navajo Sandstone, alluvium	11-18-88	⁴ 211	8A-224	Navajo Sandstone	10-06-54	71
		03-24-92	⁴ 233			06-27-84	72
		10-12-93	⁴ 211			11-17-87	75
		12-04-95	⁵ 38.0			03-26-92	16.
		12-16-96	⁵ 38.0			10-22-93	14.4
		12-17-97	⁵ 40.0			12-05-95	17.
		12-10-98	⁵ 39.0			12-19-96	15.7
		12-21-99	⁵ 39.0			12-30-97	25.6
		06-12-01	⁵ 37.0			12-14-98	21.
		04-04-02	⁵ 37.0			12-15-99	14.8
		05-01-03	⁵ 30.9			03-14-01	26.8
		04-26-04	⁵ 30.6			04-03-02	9.
		04-27-05	⁵ 33.3			05-01-03	17.1
		06-03-08	⁵ 29.4			04-01-04	12.6
		06-03-09	⁵ 31.1			04-06-05	21.5
		06-14-10	⁵ 34.3			06-17-10	9.0

¹Volumetric discharge measurement.²Interfingering with the Kayenta Formation at this site.³Discharge measured at water-quality sampling site and at a different point than the measurement in 1952.⁴Discharge measured in an irrigation ditch about 0.25 mile below water-quality sampling point.⁵Discharge measured at water-quality sampling point about 20 feet below upper spring on west side of canyon.⁶Discharge is approximate because the container used for the volumetric measurement was not calibrated.⁷Discharge measured at a different point than later measurements.

Table 11. Discharge data (daily mean values), Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2009.

[e, estimated; CFSM, cubic feet per square mile; dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2009—DAILY MEAN VALUES												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	e3.1	e2.6	2.4	1.7	0.71	0.72	0.00	15	0.00	0.00	0.00	0.90
2	e3.0	e2.6	2.5	1.7	0.62	0.71	0.00	1.4	0.00	0.00	0.00	1.6
3	e2.9	e2.6	2.5	1.6	0.61	0.60	0.00	0.03	0.00	0.00	0.00	3.3
4	e2.9	e2.7	2.3	1.8	0.57	0.43	0.00	0.00	0.00	0.00	0.00	1.0
5	e2.9	e2.6	2.0	1.8	0.55	0.16	0.00	0.00	0.00	0.00	0.00	1.4
6	e2.8	e2.7	2.0	1.6	0.48	0.00	0.00	0.00	0.00	0.00	0.00	5.2
7	e2.6	2.6	2.0	1.4	0.41	0.00	0.00	0.00	0.00	0.00	0.00	e5.5
8	e2.7	2.9	2.2	1.5	0.39	0.00	0.00	0.00	0.00	0.00	0.00	e5.3
9	e2.6	3.3	2.2	1.5	0.27	0.00	0.00	0.00	0.00	0.00	0.00	e5.3
10	e2.4	3.8	2.2	1.6	0.10	0.00	0.00	0.00	0.00	0.00	0.00	e5.0
11	e2.3	3.2	2.4	1.7	0.10	0.00	0.00	0.00	0.00	0.00	0.00	e4.9
12	e2.0	3.0	2.4	1.9	0.03	0.00	0.00	0.00	0.00	0.00	0.00	e3.7
13	e2.3	3.4	2.7	1.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	e2.7
14	e2.5	3.6	2.7	1.4	0.01	0.00	0.00	0.00	0.00	0.00	0.06	e2.5
15	e2.4	2.9	2.6	1.4	0.01	0.00	0.00	0.00	0.00	0.00	0.11	e3.1
16	e2.3	3.3	2.5	1.3	0.02	0.00	0.00	0.00	0.00	0.00	0.20	e3.2
17	e2.1	2.9	2.3	1.2	0.00	0.00	0.00	0.00	0.00	0.00	0.57	e1.4
18	e2.5	2.7	2.4	1.3	0.00	0.00	0.00	0.00	0.00	0.00	1.4	e0.89
19	e3.0	2.6	2.2	1.2	0.00	0.00	0.00	0.00	0.00	0.00	1.4	0.85
20	e3.3	2.7	2.0	1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.91	0.93
21	e3.3	2.9	1.8	1.1	0.00	0.00	0.00	0.00	0.00	0.00	2.2	1.6
22	4.0	2.8	1.7	0.96	28	0.00	162	0.00	0.00	0.00	2.2	1.2
23	e4.1	2.7	1.8	0.84	271	0.00	e65	0.00	0.00	0.00	0.51	1.1
24	4.5	2.7	1.9	0.78	e268	0.00	e0.00	0.00	0.00	0.00	0.50	0.78
25	4.1	2.6	1.9	0.77	e48	e0.00	0.00	0.00	0.00	0.00	0.15	e1.2
26	3.3	2.5	1.9	0.83	e15	e0.00	0.00	0.00	0.00	0.00	e0.51	e2.4
27	2.8	2.5	2.0	0.86	e6.9	e0.00	0.00	0.00	0.00	0.00	e0.85	e2.0
28	2.7	2.5	2.0	0.83	e1.5	e0.00	0.00	0.00	0.00	0.00	e1.5	1.2
29	2.6	---	1.9	0.82	1.0	e0.00	0.00	0.00	0.00	0.00	1.1	2.3
30	e2.3	---	2.1	0.79	0.90	0.00	0.00	0.00	0.00	0.00	1.7	2.7
31	e2.5	---	2.0	---	0.80	---	0.00	0.00	---	0.00	---	e2.3
TOTAL	88.8	79.9	67.5	38.88	645.98	2.62	227	16.43	0.00	0.00	15.87	77.45
MEAN	2.86	2.85	2.18	1.3	20.8	0.09	7.32	0.53	0.00	0.00	0.53	2.5
MAX	4.5	3.8	2.7	1.9	271	0.72	162	15	0.00	0.00	2.2	5.5
MIN	2.0	2.5	1.7	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.78
MED	2.7	2.7	2.2	1.3	0.48	0.00	0.00	0.00	0.00	0.00	0.13	2.3
AC-FT	176	158	134	77	1280	5.2	450	33	0.00	0.00	31	154
CFSM	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Calendar year 2009	Total 1,260.4		Mean 3.45		Max 271	Min 0.00	Median 0.55		Acre-ft 2,498		CFSM 0.002	

Table 12. Discharge data (daily mean values), Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2009.

[e, estimated; CFSM, cubic feet per square mile; dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2009—DAILY MEAN VALUES												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.54	0.35	0.35	0.29	0.3	0.44	0.19	32	0.15	0.19	0.29	0.46
2	e0.62	0.36	0.35	0.29	0.33	0.42	0.21	4.7	0.15	0.20	0.30	0.44
3	0.52	0.36	0.33	0.32	0.33	0.39	0.20	0.20	0.16	0.21	0.27	0.41
4	0.50	0.37	0.32	0.3	0.37	0.37	0.17	0.15	0.16	0.20	0.24	0.35
5	0.48	0.37	0.32	0.29	0.47	0.34	0.16	0.14	0.18	0.19	0.24	0.42
6	0.48	0.37	0.32	0.28	0.47	0.33	0.14	0.13	0.20	0.20	0.25	0.50
7	0.46	0.37	0.32	0.28	0.44	0.34	0.14	0.12	0.20	0.21	0.24	0.61
8	0.48	0.40	0.32	0.27	0.45	0.35	0.15	0.13	0.21	0.21	0.25	7.6
9	0.46	0.39	0.31	0.28	0.42	0.31	0.16	0.14	0.22	0.20	0.24	1.4
10	0.44	0.60	0.33	0.29	0.43	0.30	0.15	0.14	0.25	0.20	e2.1	0.67
11	0.45	0.39	0.32	0.30	0.41	0.31	0.15	0.14	0.23	0.20	e0.44	0.44
12	e0.47	0.41	0.34	0.29	0.37	0.29	0.15	0.13	0.22	0.20	e0.39	0.59
13	0.47	0.41	0.32	0.28	0.36	0.27	0.14	0.14	0.23	0.21	0.39	0.69
14	0.47	0.40	0.32	0.27	0.38	0.27	0.14	0.14	0.23	0.21	0.41	0.52
15	0.52	0.41	0.31	0.26	0.43	0.27	0.14	0.13	0.23	0.21	0.35	0.47
16	0.49	0.42	0.30	0.25	0.42	0.27	0.14	0.13	e1.5	0.21	0.35	0.48
17	0.50	0.40	0.30	0.25	0.39	0.27	0.13	0.13	e0.26	0.22	0.37	0.45
18	0.49	0.40	0.30	0.26	0.42	0.27	0.13	0.13	e0.22	0.24	0.38	0.48
19	0.52	0.41	0.31	0.26	0.36	0.26	0.12	0.13	0.21	0.24	0.37	0.45
20	0.52	0.41	0.31	0.25	0.35	0.28	0.13	0.13	0.20	0.24	0.38	0.46
21	0.55	0.40	0.30	0.26	0.44	0.23	1.8	0.13	e0.23	0.25	0.38	0.50
22	0.58	0.39	0.30	0.26	26	0.22	1.2	0.16	e0.22	0.25	0.38	e0.55
23	0.65	0.38	0.31	0.25	11	0.22	0.33	0.24	e0.19	0.26	0.38	e0.59
24	0.65	0.39	0.31	0.25	9.4	0.22	0.14	0.79	0.19	0.26	0.35	0.42
25	0.51	0.35	0.31	0.24	1.3	0.22	0.13	0.16	0.19	0.26	0.36	0.38
26	0.96	0.34	0.31	0.25	0.64	0.25	0.46	0.16	0.19	0.26	0.38	0.39
27	0.50	0.34	0.30	0.26	0.54	0.22	0.69	0.15	0.19	0.31	0.41	0.38
28	0.35	0.34	0.31	0.26	0.41	0.21	0.69	0.15	0.19	0.48	0.46	0.40
29	0.35	---	0.30	0.28	1.0	0.23	0.14	0.15	0.18	0.29	0.52	0.50
30	0.35	---	0.31	0.29	0.76	0.23	e0.22	0.15	0.18	0.28	0.48	0.50
31	0.36	---	0.30	---	0.48	---	e0.32	0.15	---	0.29	---	0.54
TOTAL	15.69	10.93	9.76	8.16	59.87	8.6	9.16	41.57	7.36	7.38	12.35	23.04
MEAN	0.51	0.39	0.31	0.27	1.93	0.29	0.3	1.34	0.25	0.24	0.41	0.74
MAX	0.96	0.60	0.35	0.32	26	0.44	1.8	32	1.5	0.48	2.1	7.6
MIN	0.35	0.34	0.30	0.24	0.30	0.21	0.12	0.12	0.15	0.19	0.24	0.35
MED	0.49	0.39	0.31	0.27	0.43	0.27	0.15	0.14	0.20	0.21	0.38	0.48
AC-FT	31	22	19	16	119	17	18	82	15	15	24	46
CFSM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Calendar year 2009	Total 213.9		Mean 0.58		Max 32	Min 0.12	Median 0.31		Acre-ft 424		CFSM 0.001	

Table 13. Discharge data (daily mean values), Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2009.

[e, estimated; CFSM, cubic feet per square mile; dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2009—DAILY MEAN VALUES												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.29	e0.36	e0.26	e0.24	e0.21	0.15	e0.09	0.01	0.02	0.05	0.06	0.10
2	0.28	e0.36	0.22	0.25	e0.21	0.16	0.07	0.01	0.03	0.05	0.06	0.11
3	0.30	e0.38	0.28	0.27	e0.22	0.17	e0.08	0.01	0.04	0.05	0.06	0.13
4	e0.33	e0.37	0.32	0.26	e0.20	e0.17	e0.09	0.01	0.04	0.06	0.07	e0.16
5	e0.35	e0.37	0.27	0.22	e0.20	0.16	e0.09	0.01	0.04	0.05	0.07	e0.37
6	e0.35	e0.35	0.24	0.23	e0.19	e0.15	e0.08	0.01	0.05	0.05	0.06	e0.39
7	0.32	0.33	e0.25	0.23	0.17	e0.15	e0.08	0.01	0.05	0.06	0.06	e0.29
8	0.29	0.30	e0.26	0.25	0.16	e0.14	e0.07	0.00	0.05	0.06	0.07	e0.22
9	0.33	e0.33	e0.23	0.22	0.16	e0.12	e0.06	0.01	0.05	0.08	0.07	e0.22
10	0.39	e0.26	e0.21	0.21	0.15	0.13	0.06	0.02	0.05	0.09	0.07	e0.27
11	0.42	e0.24	e0.21	0.24	0.15	0.13	0.06	0.01	0.05	0.05	0.07	e0.26
12	0.41	e0.24	e0.22	e0.23	0.13	e0.12	0.05	0.01	0.04	0.05	0.08	e0.16
13	e0.37	e0.24	e0.22	e0.21	0.16	e0.12	0.05	0.02	0.05	0.05	0.08	e0.14
14	e0.35	e0.25	e0.21	e0.20	0.18	e0.12	0.04	e0.02	0.05	0.05	0.08	0.13
15	e0.35	e0.25	e0.21	e0.21	0.17	e0.11	0.04	e0.02	0.05	0.05	0.08	0.16
16	e0.31	e0.27	e0.24	e0.21	0.16	e0.11	0.04	e0.02	0.05	0.06	0.08	e0.17
17	e0.30	0.27	0.25	e0.23	0.16	0.11	0.04	e0.02	0.05	0.06	0.08	0.16
18	e0.30	0.26	0.31	e0.25	0.18	0.11	0.04	e0.02	0.05	0.06	0.08	0.14
19	e0.28	0.27	0.33	e0.28	0.17	0.09	0.04	0.02	0.05	0.07	0.08	0.16
20	e0.28	0.29	0.32	e0.25	0.15	0.12	0.04	0.02	0.05	0.07	0.09	0.18
21	e0.30	e0.28	0.28	e0.22	0.11	0.11	0.03	0.02	0.04	0.07	0.09	e0.14
22	0.29	e0.28	0.25	e0.19	44	0.09	0.03	0.02	0.04	0.07	0.08	0.10
23	0.31	e0.26	0.26	0.23	8.3	0.09	0.02	0.04	0.05	0.07	0.09	0.19
24	0.34	e0.24	0.27	0.23	47	0.10	0.02	0.04	0.05	0.07	0.11	0.17
25	0.35	0.24	e0.29	0.19	e12	0.09	0.02	0.03	0.05	0.07	0.13	e0.26
26	0.37	e0.26	e0.33	e0.20	e0.74	0.09	0.01	0.03	0.05	0.07	0.14	e0.36
27	0.41	e0.25	e0.31	e0.19	e0.26	0.10	0.02	0.03	0.05	0.08	0.11	e0.31
28	e0.37	e0.25	e0.27	e0.20	e0.21	e0.10	e0.02	0.02	0.05	0.08	0.08	e0.26
29	e0.38	---	e0.24	e0.19	e0.18	0.13	e0.02	0.03	0.05	0.07	0.08	e0.21
30	e0.40	---	e0.23	e0.21	0.37	e0.10	0.01	0.02	0.05	0.07	0.08	e0.23
31	e0.39	---	e0.24	---	0.18	---	0.01	0.02	---	0.07	---	e0.25
TOTAL	10.51	8.05	8.03	6.74	116.83	3.64	1.42	0.58	1.39	1.96	2.44	6.4
MEAN	0.34	0.29	0.26	0.22	3.77	0.12	0.05	0.02	0.05	0.06	0.08	0.21
MAX	0.42	0.38	0.33	0.28	47	0.17	0.09	0.04	0.05	0.09	0.14	0.39
MIN	0.28	0.24	0.21	0.19	0.11	0.09	0.01	0.00	0.02	0.05	0.06	0.10
MED	0.34	0.27	0.25	0.23	0.18	0.12	0.04	0.02	0.05	0.06	0.08	0.18
AC-FT	21	16	16	13	232	7.2	2.8	1.2	2.8	3.9	4.8	13
CFSM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Calendar year 2009	Total 168.00		Mean 0.46		Max 47	Min 0.0	Median 0.14		Acre-ft 333.7		CFSM 0.0005	

Table 14. Discharge data (daily mean values), Pasture Canyon Springs near Tuba City, Arizona (09401265), calendar year 2009.

[e, estimated; CFSM, cubic feet per square mile; dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2009—DAILY MEAN VALUES												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.41	0.36	0.32	0.32	0.32	0.28	0.27	0.27	0.24	0.26	0.35	0.33
2	0.41	0.36	0.32	0.29	0.32	0.27	0.27	0.25	0.24	0.25	0.37	0.32
3	0.42	0.36	0.32	0.33	0.32	0.27	e0.40	0.25	0.25	0.24	0.36	0.32
4	0.43	0.35	0.33	0.34	0.32	0.28	0.30	0.25	0.24	0.26	0.36	0.32
5	0.43	0.34	0.33	0.35	0.32	0.28	0.28	0.25	0.24	0.25	0.35	0.32
6	0.43	0.34	0.34	0.35	0.32	0.28	0.28	0.26	0.24	0.26	0.34	0.32
7	0.43	0.34	0.34	0.36	0.31	0.28	0.27	0.26	0.25	0.25	0.33	0.34
8	0.43	0.40	0.34	0.35	0.30	0.28	0.24	0.26	0.24	0.26	0.33	0.43
9	0.43	0.38	0.34	0.34	0.30	0.28	0.22	0.25	0.24	0.26	0.34	0.41
10	0.43	0.37	0.34	0.35	0.30	0.28	0.23	0.25	0.25	0.26	e0.35	0.41
11	0.43	0.36	0.36	0.36	0.30	0.28	0.23	0.25	0.23	0.24	0.34	0.41
12	0.42	0.36	0.34	0.34	0.30	0.28	0.22	0.24	0.26	0.22	0.34	0.42
13	0.41	0.36	0.34	0.33	0.30	0.29	0.23	0.26	0.27	0.21	0.34	0.44
14	0.41	0.36	0.33	0.32	0.30	0.30	0.23	0.27	0.28	0.23	0.34	0.37
15	0.39	0.36	0.31	0.34	0.30	0.30	0.23	0.27	0.28	0.24	0.34	0.33
16	0.38	0.35	0.31	0.34	0.30	0.30	0.24	0.25	0.29	0.26	0.34	0.35
17	0.38	0.36	0.31	0.34	0.30	0.31	0.25	0.25	0.28	0.25	0.34	0.36
18	0.39	0.36	0.33	0.33	0.31	0.29	0.25	0.26	0.28	0.23	0.34	0.36
19	0.42	0.36	0.34	0.33	0.32	0.27	0.26	0.26	0.27	0.24	0.34	0.36
20	0.43	0.36	0.34	0.33	0.26	0.27	0.27	0.25	0.26	0.25	0.36	0.34
21	0.41	0.36	0.34	0.32	0.25	0.26	0.27	0.25	0.26	0.27	0.38	0.36
22	0.41	0.35	0.32	0.32	0.29	0.25	0.27	0.26	0.25	0.28	0.37	0.39
23	0.41	0.34	0.32	0.32	0.35	0.25	0.28	0.24	0.25	0.27	0.36	0.35
24	0.41	0.35	0.32	0.32	0.31	0.25	0.26	0.25	0.26	0.28	0.36	0.32
25	0.41	0.34	0.33	0.32	0.28	0.27	0.24	0.25	0.27	0.25	0.36	0.32
26	0.39	0.32	0.34	0.32	0.27	0.27	0.25	0.25	0.26	0.24	0.36	0.32
27	0.38	0.32	0.34	0.32	0.28	0.29	0.27	0.31	0.25	0.25	0.35	0.33
28	0.38	0.32	0.33	0.32	0.29	0.29	0.28	0.30	0.26	0.25	0.36	0.34
29	0.38	---	0.34	0.32	0.29	0.29	0.28	0.28	0.26	0.29	0.35	0.34
30	0.38	---	0.36	0.32	0.28	0.28	0.27	0.27	0.27	0.31	0.34	0.34
31	0.38	---	0.36	---	0.28	---	0.27	0.25	---	0.33	---	0.34
TOTAL	12.65	9.89	10.33	9.94	9.29	8.37	8.11	8.02	7.72	7.94	10.49	11.01
MEAN	0.41	0.35	0.33	0.33	0.30	0.28	0.26	0.26	0.26	0.26	0.35	0.36
MAX	0.43	0.40	0.36	0.36	0.35	0.31	0.40	0.31	0.29	0.33	0.38	0.44
MIN	0.38	0.32	0.31	0.29	0.25	0.25	0.22	0.24	0.23	0.21	0.33	0.32
MED	0.41	0.36	0.34	0.33	0.30	0.28	0.27	0.25	0.26	0.25	0.35	0.34
AC-FT	25	20	20	20	18	17	16	16	15	16	21	22
Calendar year 2009	Total 113.8		Mean 0.31		Max 0.44	Min 0.21	Median 0.32		Acre-ft 226			

Table 15. Period of record for monitoring program streamflow-gaging stations and drainage areas for streamflow-gaging stations, Black Mesa area, northeastern Arizona.

[Dashes indicate 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	---

Precipitation is another variable to consider when evaluating for trends in annual discharge. Higher precipitation would generally lead to greater annual discharge at a streamflow-gaging station. The average annual precipitation measured at Navajo National Monument (Betatakin; fig. 1) from 1976 to 2009 was 12.6 in. (fig. 10*B*). Annual precipitation at Betatakin was mostly less than that average from 1995 through 2002 (11.4 in.); precipitation data were incomplete for 2003, above average for calendar year 2004 and 2005 (17.4 in.), below average for calendar years 2006 (11.24 in.) and 2007 (8.26 in.; fig. 10*B*), above average for 2008 (16.63 in.; fig. 10*B*), and well below average for 2009 (6.58 in.; fig. 10*B*).

Trends in the groundwater-discharge component of total flow at the three streamflow-gaging stations were evaluated on the basis of the median flow for 120 consecutive daily mean flows for 4 winter months (November, December, January, and February) as a surrogate measure for base flow (fig. 11). Groundwater discharge was assumed to be constant throughout the year, and the median winter flow was assumed to represent the constant annual groundwater discharge. Most flow that occurs during the winter is groundwater discharge; rainfall and snowmelt runoff are infrequent. Most of the precipitation in the winter falls as snow, and the cold temperatures prevent appreciable snowmelt. 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 an absolute estimate of groundwater discharge. A more rigorous and accurate estimate 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 time trends in groundwater discharge.

Median winter flows calculated for the 2009 water year were 2.3 ft³/s for Moenkopi Wash at Moenkopi, 0.39 ft³/s for Dinnebito Wash near Sand Springs, 0.22 ft³/s for Polacca Wash near Second Mesa, and 0.34 ft³/s for Pasture Canyon Springs (fig. 11*A–D*). For the period of record at each streamflow-gaging station, there have been no significant trends in median winter flows, as indicated by trends calculated by using the method of least squares and Kendall's tau ($p > 0.05$; fig. 11*A–D*).

Water Chemistry

Water samples for water-chemistry analyses are collected each year from selected wells and springs as part of the Black Mesa monitoring program. Field measurements are made and water samples are analyzed for major ions, trace elements, nutrients, iron, boron, and arsenic. Field measurements are made in accordance with standard USGS protocols documented in the USGS National Field Manual for the Collection of Water-Quality Data and in several USGS Techniques of Water-Resources Investigations Reports (Friedman and Erdmann, 1982; Koterba and others, 1995; Wilde, 2005; Lane and others, 2003; Wilde, 2004; Wilde and Radtke, 1998; and U.S. Geological Survey, 2006). Field measurements include pH, specific conductance, temperature, dissolved oxygen, alkalinity, and discharge rates at springs. Field alkalinities were determined using incremental equivalence (Wilde and Radtke, 1998). Major ion, nutrient, trace element, iron, boron, arsenic and alkalinity samples were filtered through a 0.45-micron pore size filter and preserved according to sampling and analytical protocol. 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 control for this study was maintained through the use of proper training of field personnel, use of standard USGS field and lab protocols, collection of an equipment sample blank, collection of a field sample blank, and a thorough review of the analytical results. All USGS scientists involved with this study have participated in the USGS National Field Quality Assurance Program, which requires participants to successfully determine pH, specific conductance and alkalinity of reference samples supplied by the USGS Branch of Quality Systems. Field personnel were trained in water-quality field methods by USGS personnel or through formal instruction at the USGS water-quality field-methods class.

Water-chemistry samples have been collected from 12 wells; 4 of the wells have been sampled every year, and the other 8 wells have been selected on the basis of a sampling

rotation. In 2010, water samples were collected at 11 well sites: Second Mesa PM2, Keams Canyon PM2, Kykots-movi PM2, Piñon NTUA 1, Forest Lake NTUA 1, Kits'iili NTUA 2, Rough Rock PM5, Peabody 2, Peabody 6, Kayenta PM2, and Dennehotso 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 2010 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 reports published each year. 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 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

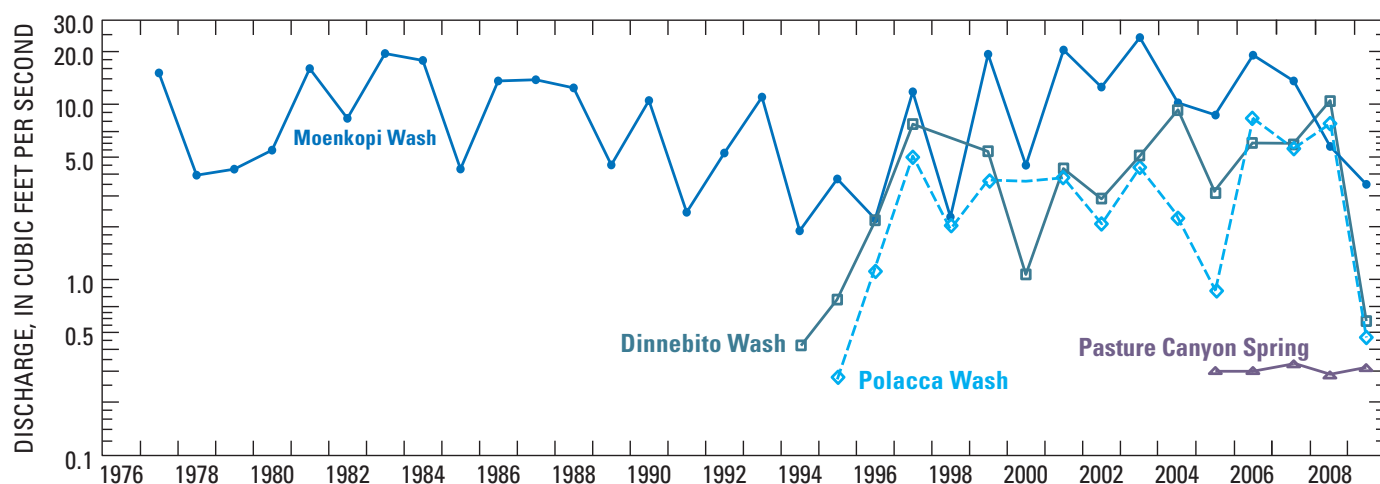
(<http://waterdata.usgs.gov/az/nwis/qw>), and they can be found in the past monitoring reports cited in the “Previous Investigations” section of this report.

Water-Chemistry Data for Wells Completed in the N Aquifer

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 generally is in the recharge and unconfined areas of the northern and northwestern parts of the Black Mesa study area, and sodium bicarbonate water is generally in the area that is confined and downgradient to the south and east (Lopes and Hoffmann, 1997). Results from the 2010 sampling are presented in figures 8 and 12 and in table 16.

Rough Rock PM5 yielded the highest dissolved-solids concentration (635 mg/L) as well as the highest chloride concentration (129 mg/L) of the 11 wells sampled (table 16 and fig. 13). Dissolved-solids concentrations in the other 10 wells

A. Annual average discharge for calendar years 1977–2009



B. Annual precipitation at Betatakin, Arizona, calendar years 1976–2009 (National Weather Service)

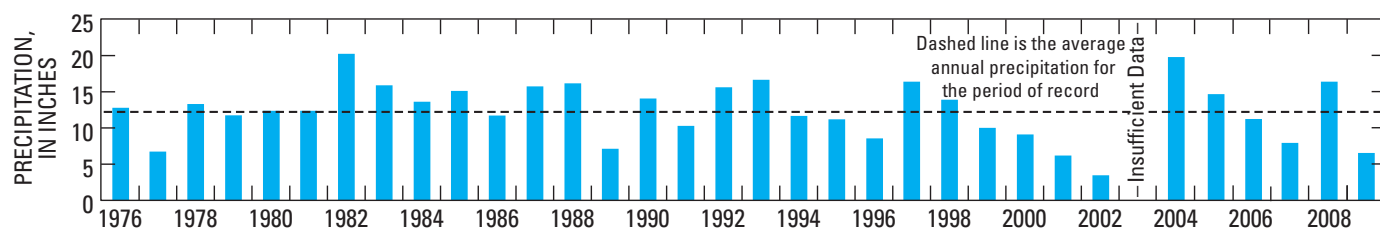


Figure 10. Annual average discharge at Moenkopi Wash at Moenkopi (09401260), Pasture Canyon Springs near Tuba City (09401265), Dinnebito Wash near Sand Springs (09401110), and Polacca Wash near Second Mesa (09400568), and annual precipitation at Betatakin, Arizona, Black Mesa area, northeastern Arizona. A, Annual average discharge for calendar years 1977–2009; B, Annual precipitation at Betatakin, northeastern Arizona, calendar years 1976–2009 (National Park Service, Betatakin National Monument, written commun., 2010).

ranged from 119 mg/L at Peabody 2 to 607 mg/L at Keams Canyon PM2, and their chloride concentrations ranged from 1.7 mg/L at Peabody 6 to 104 mg/L at Keams Canyon PM2 (table 16 and fig. 13). Forest Lake NTUA 1 had the highest sulfate concentration (125 mg/L) of the 11 wells, and the concentrations at the other wells ranged from 4.7 mg/L at Kits'iili NTUA 2 to 114 mg/L at Rough Rock PM5 (table 16 and fig. 13).

Samples from 1998 to present at Piñon NTUA 1 have shown varying sulfate concentrations, from 4.7 to 83 mg/L (table 17). Purge times greater than 12 hours from Piñon NTUA 1 appear to induce leakage from the overlying D aquifer and result in higher sulfate concentrations in samples. The confining layer, Carmel Formation, in the area of Piñon is about 120 ft thick and composed of a more sandy siltstone rather than the clayey siltstone observed in the northern part of the study area, where leakage has not been detected (Truini and Macy, 2005). Areas where the Carmel Formation is 120 ft thick or less coincide with areas where $^{87}\text{Sr}/^{86}\text{Sr}$ values and major-ion data for groundwater indicate that D aquifer water has mixed with N aquifer water as a result of leakage (Truini and Longworth, 2003). Both the lithologic difference in the Carmel Formation near Piñon and the thickness of the Carmel Formation near Piñon indicate that leakage could be possible. Purge times may have an effect on samples taken from Piñon NTUA 1 and will be more closely monitored during future sampling.

Chemical constituents analyzed from the 11 wells were compared to the U.S. Environmental Protection Agency (USEPA) 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. MCLs protect drinking-water quality by limiting the levels of specific contaminants that can adversely affect public health. Secondary Maximum Contaminant Levels (SMCLs) provide guidelines for the control of contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. The USEPA recommends compliance with SMCLs for public water systems, however, compliance is not enforced.

In 2010, most of the analyzed constituents from the 11 wells were below the USEPA MCL or SMCL for drinking water. Three of the 11 wells sampled exceeded the USEPA MCL for arsenic (10.0 $\mu\text{g/L}$): Second Mesa PM2 with a concentration of 19.1 $\mu\text{g/L}$, Rough Rock PM5 with a concentration of 48.5 $\mu\text{g/L}$, and Keams Canyon PM2 with a concentration of 47.6 $\mu\text{g/L}$. The USEPA SMCL for concentration of dissolved solids (500 mg/L) was exceeded at Keams Canyon PM2 (607 mg/L), Forest Lake NTUA 1 (503 mg/L), and Rough Rock PM5 (635 mg/L). In addition, the USEPA SMCL for pH (6.5 to 8.5) was exceeded at Keams Canyon PM2, Kykotsmovi PM2, Piñon NTUA 1, Forest Lake NTUA 1, Kits'iili NTUA 2, Rough Rock PM5, Peabody 2, Peabody 6, and Dennehotso PM2 (U.S. Environmental Protection Agency, 2003; table 16).

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

In 2010, water samples were collected from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso (fig. 8). 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 that is developed into the hillside. 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 a calcium bicarbonate-type water (fig. 12 and table 18). Samples from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso had dissolved solid concentrations of 355 mg/L, 217 mg/L, 157 mg/L, and 155 mg/L, respectively (tables 18 and 19). Concentration of chloride was highest at Moenkopi School Spring (26 mg/L; tables 18 and 19). Concentration of sulfate was highest at Burro Spring (71.5 mg/L; tables 18 and 19). Concentrations of all the analyzed constituents in samples from all four springs were less than current USEPA MCLs and SMCLs (U.S. Environmental Protection Agency, 2003).

There are significant increasing trends in concentrations of dissolved solids, chloride, and sulfate in water from Moenkopi School Spring ($p < 0.05$; table 19 and fig. 14). Concentrations of the same constituents in Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso did not show any significant trends ($p > 0.05$; table 19 and fig. 14).

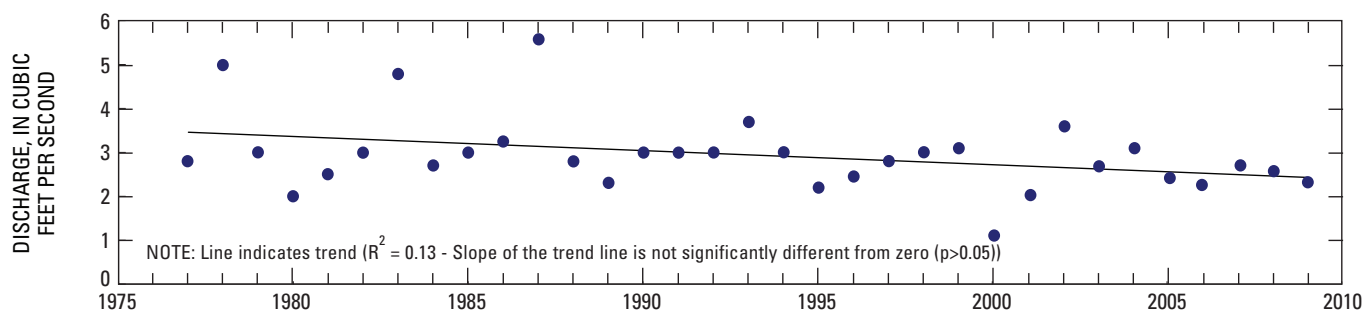
Summary

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 water is an important issue in the Black Mesa area because of continued industrial and municipal use, a growing population, and limited precipitation of about 6 to 14 inches per year.

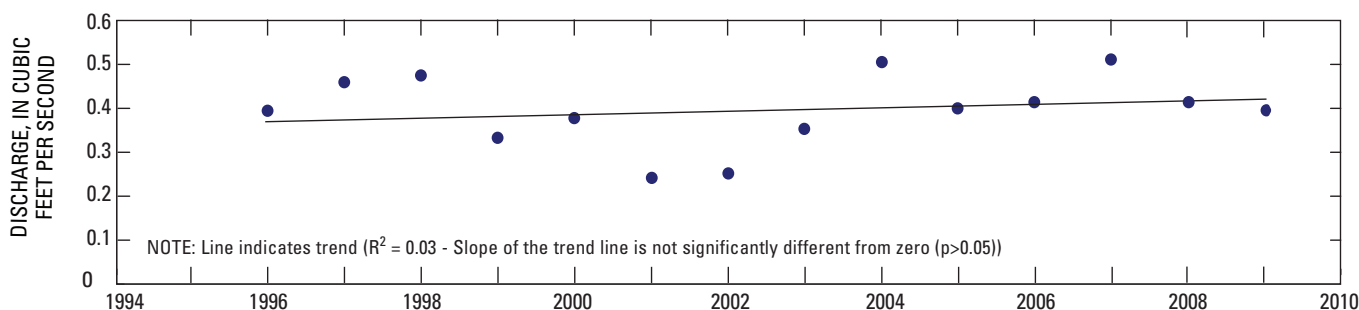
This report presents results of groundwater, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2009 to September 2010. The monitoring data for 2009–10 are compared to data for 2008–09 and to historical data from the 1950s to September 2010.

In 2009, total groundwater withdrawals were 4,230 acre-ft, industrial withdrawals were 1,390 acre-ft, and municipal withdrawals were 2,840 acre-ft. From 2008 to 2009, total withdrawals from the N aquifer increased by 3 percent, industrial withdrawals increased by approximately 15 percent, and total municipal withdrawals decreased by 2 percent.

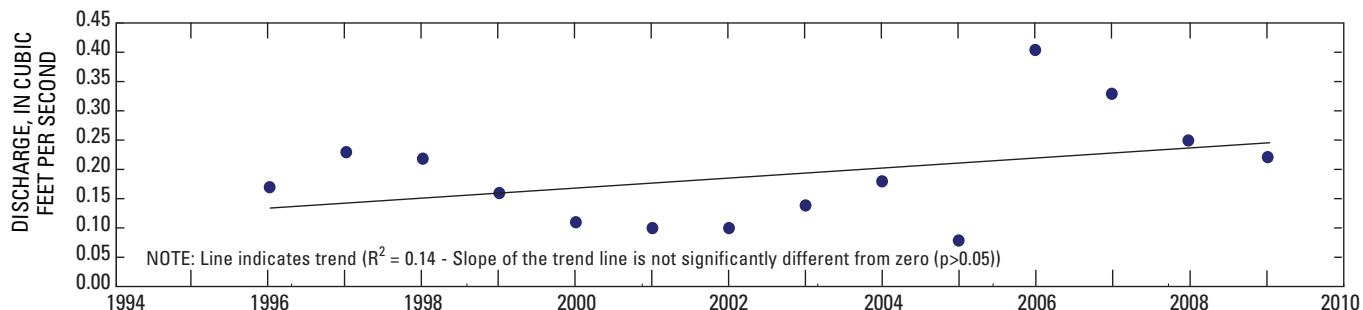
A. Median winter flow for November, December, January, February, 1977–2009, Moenkopi Wash at Moenkopi (09401260).



B. Median winter flow for November, December, January, February, 1996–2009, Dinnebito Wash near Sand Springs (09401110).



C. Median winter flow for November, December, January, February, 1996–2009, Polacca Wash near Second Mesa (09400568).



D. Median winter flow for November, December, January, February, 2004–09, Pasture Canyon Springs (09401265).

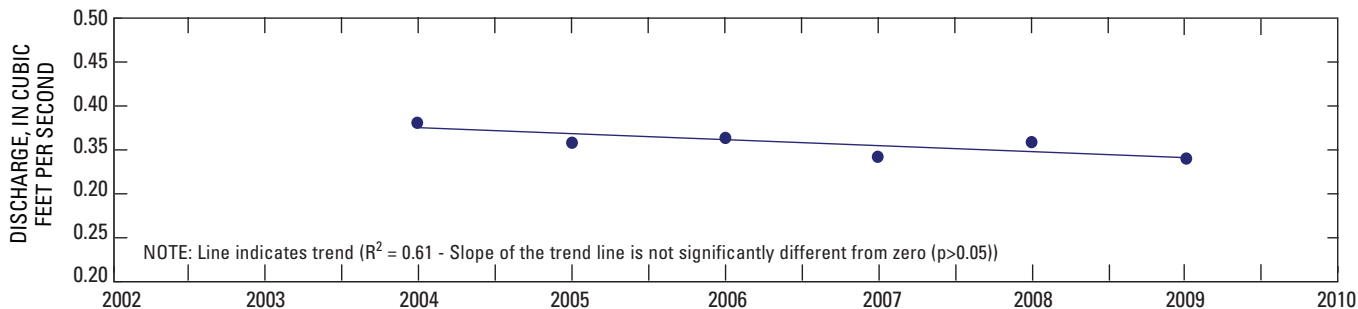


Figure 11. Median winter flow for November, December, January, and February for water years 1977–2009 for A, Moenkopi Wash at Moenkopi (09401260), B, Dinnebito Wash near Sand Springs (09401110), C, Polacca Wash near Second Mesa (09400568), and D, Pasture Canyon Springs (09401265), Black Mesa area, northeastern Arizona. Median winter flow is calculated by computing the median flow for 120 consecutive daily mean flows for winter months—November, December, January, and February. Note: Trend lines were generated by using the method of least squares.

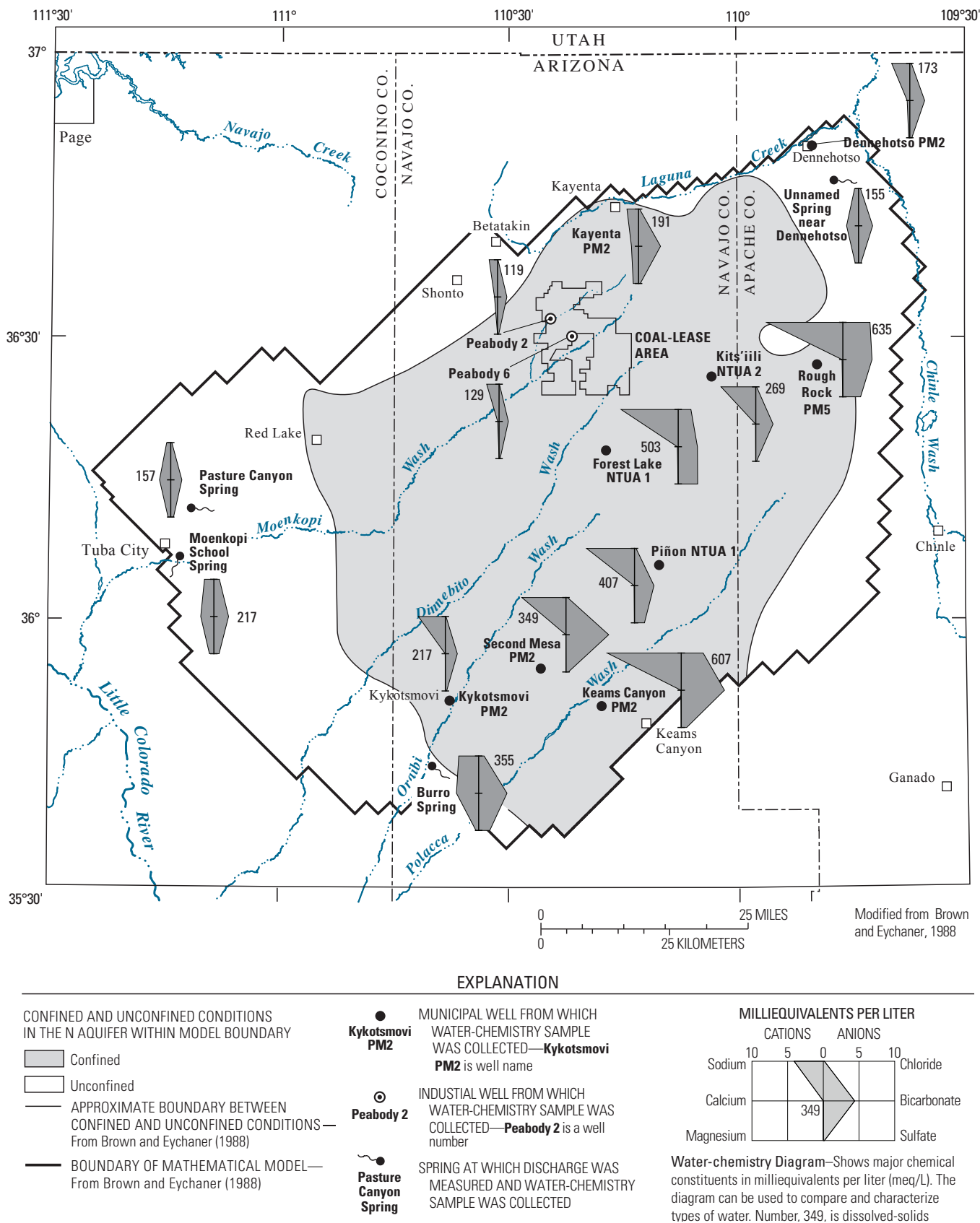


Figure 12. Water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, northeastern Arizona, 2010.

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, 2010.

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

Common well name	U.S. Geological Survey identification number	Date of samples	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)	Alkalinity, field, dissolved (mg/L as CaCO ₃)	Nitrogen, NO ₂ + NO ₃ , dissolved (mg/L as N)	Ortho-Phosphate, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)
Second Mesa PM2	354749110300101	06-08-10	19.5	553	6.9	286	<.04	.020	.50	.035	.39
Keams Canyon PM2	355023110182701	06-08-10	20.0	965	9.2	351	<.04	.014	.81	.161	.76
Kykotsmovi PM2	355215110375001	06-14-10	36.0	382	9.4	159	1.16	.036	.48	E.008	.39
Pinon NTUA 1	360527110122501	06-15-10	26.6	675	9.9	237	1.27	.020	1.08	.159	.51
Forest Lake NTUA 1	361737110180301	07-01-10	29.6	524	9.4	168	.39	.014	2.23	.226	.97
Kitsillie	362043110030501	06-15-10	16.9	457	9.8	213	1.36	.019	.58	.016	.56
Rough Rock PM5	362418109514601	07-01-10	22.0	1100	8.9	215	1.03	.018	2.19	.301	1.39
Peabody 2	363005110250901	06-09-10	31.1	168	8.6	69.3	.97	.014	8.34	.143	.70
Peabody 6	363007110221201	06-09-10	33.6	188	8.9	79.5	.66	.013	3.77	.022	.72
Kayenta PM2	364344110151201	06-10-10	17.0	308	8.1	147	.63	.013	19.1	8.59	1.41
Denehotso PM2	365045109504001	06-11-10	16.9	279	8.9	121	1.44	.011	6.97	1.82	.72
Common well name	U.S. Geological Survey identification number	Date of samples	Sodium, dissolved (mg/L as Na)	Chloride, dissolved (mg/L as Cl)	Flouride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO ₂)	Sulfate, dissolved (mg/L as SO ₄)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Second Mesa PM2	354749110300101	06-08-10	136	7.02	.38	18.7	15.3	19.1	99	8	349
Keams Canyon PM2	355023110182701	06-08-10	228	104	1.47	11.8	34.9	47.6	663	6	607
Kykotsmovi PM2	355215110375001	06-14-10	83.1	3.17	.19	24.1	8.38	5.2	30	<6	217
Pinon NTUA 1	360527110122501	06-15-10	148	7.06	.33	26.5	63.8	4.4	79	15	407
Forest Lake NTUA 1	361737110180301	07-01-10	176	60.3	1.18	17.4	125	2.0	376	18	503
Kitsillie	362043110030501	06-15-10	107	3.81	.22	25.6	4.65	3.8	49	<6	269
Rough Rock PM5	362418109514601	07-01-10	235	129	1.63	12.0	114	48.5	412	17	635
Peabody 2	363005110250901	06-09-10	26.0	2.08	.13	22.0	7.37	3.1	17	<6	119
Peabody 6	363007110221201	06-09-10	38.2	1.67	.17	21.8	6.36	3.9	20	<6	129
Kayenta PM2	364344110151201	06-10-10	35.8	4.71	.30	19.1	11.1	4.2	47	7	191
Denehotso PM2	365045109504001	06-11-10	55.9	7.41	.28	11.9	13.2	6.3	40	<6	173

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, 1974–2010.

[μS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; mg/L, milligram per liter; <, less than. Dashes indicate no data]

Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO ₄)	Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO ₄)
Second Mesa PM2					Pinon NTUA 1				
1968	670	---	14	35	1998	460	304	4.6	4.7
1990	590	364	6.5	16	2001	473	304	4.9	5.5
1991	¹ 595	292	10	15	2002	512	---	5.0	5.5
1993	630	350	7.5	15	2003	716	421	6.7	83
1994	¹ 605	342	7.6	15	2004	691	421	7.0	76
1995	610	357	7.2	14	2006	709	399	6.6	67
1997	¹ 646	356	7.1	14	2008	565	328	6.2	8.7
2001	597	352	7.1	15	2009	646	409	7.1	68
2002	608	357	7.5	14	2010	675	407	7.1	64
2003	601	359	6.3	14	Forest Lake NTUA 1				
2005	615	361	6.8	13	1982	470	---	11	67
2010	553	349	7	15	1986	---	660	35	300
Keams Canyon PM2					1990	375	226	8.2	38
1982	1,010	---	94	35	1991	¹ 350	183	10	24
1983	1,120	---	120	42	1993	693	352	35	88
1984	1,060	578	96	36	1994	¹ 734	430	56	100
1988	1,040	591	97	34	1995	470	274	13	60
1990	1,020	600	94	34	1995	1,030	626	86	160
1992	1,010	570	93	36	1995	488	316	16	71
1993	1,040	590	92	36	1996	684	368	44	79
1994	975	562	86	32	1997	¹ 1,140	714	78	250
1995	1,010	606	99	32	1998	489	350	37	71
1996	1,020	596	96	34	1999	380	259	16	49
1997	1,070	590	96	33	2001	584	398	50	84
1998	908	558	78	29	2002	452	268	22	50
1999	1,040	595	97	35	2003	385	228	10	40
2004	945	³ 603	97	32	2004	222	263	16	40
2005	828	601	97	34	2005	402	272	18	44
2006	1,067	588	99	34	2006	445	258	14	49
2008	1,079	607	95	34	2008	424	362	36	73
2009	1,050	609	100	36	2009	384	250	12	44
2010	965	607	104	35	2010	524	503	60	125
Kykotsmovi PM2					Kits'iili NTUA 2				
1988	368	212	3.2	8.6	1997	¹ 524	269	3.6	4.3
1990	355	255	3.2	9.0	1998	379	270	3.8	4.1
1991	¹ 374	203	4.4	7.9	2000	454	274	4.0	4.1
1992	363	212	3.3	8.4	2001	409	276	5.0	4.5
1994	¹ 365	212	3.6	8.5	2002	439	264	4.5	4.4
1995	368	224	3.1	6.2	2003	445	275	4.2	4.4
1996	365	224	3.3	8.5	2004	367	273	4.0	4.6
1997	¹ 379	222	3.0	8.0	2005	424	271	3.7	3.7
1998	348	223	3.3	7.3	2010	457	269	3.8	4.7
1999	317	221	3.5	7.9	¹ Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports showed values determined by laboratory analysis. ² Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports showed values determined by the sum of constituents. ³ Value is different in Black Mesa monitoring report printed in 2004.				
2001	339	230	3.5	8.2					
2002	350	215	3.4	7.9					
2003	364	219	3.5	7.8					
2004	261	223	3.5	8.3					
2005	316	221	3.1	6.9					
2006	367	221	3.2	7.7					
2008	373	226	3.0	8.2					
2009	371	230	3.1	8.1					
2010	382	217	3.2	8.4					

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, 1974–2010.—Continued

[μS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; mg/L, milligram per liter; <, less than. Dashes indicate no data]

Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO ₄)	Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO ₄)
Rough Rock PM5					Peabody 6				
1964	1120	(²)	100	110	1968	201	--	3.0	13
1970	610	(²)	13	50	1974	500	333	11.0	40
1983	1,090	(²)	130	110	1977	240	--	3.2	13
1984	¹ 1,100	613	130	99	1979	260	--	3.2	19
1986	1,010	633	140	120	1980	260	160	3.5	15
1988	1,120	624	130	³ 110	1986	182	--	2.3	9.6
1991	¹ 1,210	574	130	110	1988	173	127	2.4	9.1
1993	1,040	614	130	110	1993	181	126	1.9	6.6
1994	¹ 1,180	626	130	110	1996	177	122	1.5	6
1995	1,110	648	140	110	2005	174	122	1.5	5.7
1996	1,100	634	130	110	2010	188	129	1.7	6.7
1997	¹ 1,060	628	130	112	Kayenta PM2				
1998	894	637	133	112	1982	360	(²)	4.5	58
1999	1,050	630	129	110	1983	375	(²)	5.9	60
2001	980	628	125	110	1984	¹ 370	209	4.2	51
2002	1,120	636	129	109	1986	300	181	8.2	30
2003	1,080	642	127	110	1988	358	235	3.8	74
2004	653	649	128	109	1992	383	210	5.6	78
2005	1053	639	128	113	1993	374	232	3.7	78
2010	1101	635	129	114	1994	¹ 371	236	4.2	77
Peabody 2					1995	371	250	4.2	72
1967	221	---	5.0	21	1996	370	238	3.8	76
1971	211	---	2.8	18	1997	379	230	3.9	77
1974	210	144	2.8	17	1998	349	236	3.7	71
1975	230	163	5.0	20	1999	364	236	4.0	72
1976	260	133	3.6	16	2001	331	234	5.0	73
1979	220	---	3.4	24	2002	363	237	5.1	67
1980	225	145	11.0	20	2003	378	273	5.9	88
1986	172	---	2.6	8.1	2004	303	241	4.0	72
1987	149	113	5.0	9.1	2005	374	231	3.7	76
1993	163	124	1.7	8.9	2010	308	191	4.7	11
1998	93	119	2.2	7.9	Dennehotso PM2				
1999	167	115	2.3	8.1	1964	350	---	12	31
2005	134	124	2.1	8.2	1992	226	131	9.8	19
2006	167	118	2.2	8.2	1993	298	164	8.2	16
2008	160	120	2.0	7.5	1997	¹ 305	190	11	14
2009	146	113	2.1	7.2	1999	314	196	14	15
2010	168	119	2.1	7.4	2005	339	205	10.5	14
					2010	279	173	7.4	13

¹Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports showed values determined by laboratory analysis.²Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports showed values determined by the sum of constituents.³Value is different in Black Mesa monitoring report printed in 2004.

Table 18. Physical properties and chemical analyses of water samples from four springs in the Black Mesa area, northeastern Arizona, 2010.

[°C, degree Celsius; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; $\mu\text{g}/\text{L}$, micrograms per liter; <, less than. Dashes indicate no data; e, estimated]

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Temperature, field (°C)	Specific conductance, field ($\mu\text{S}/\text{cm}$)	pH, field (units)	Alkalinity, field, dissolved (mg/L as CaCO_3)	Nitrogen, $\text{NO}_2 + \text{NO}_3$, dissolved (mg/L as N)	Ortho-Phosphate, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)
354156110413701	6M-31	Burro Spring	06-07-10	28.3	583	8.0	190	<.04	.012	59.7	4.42	.31
360632111131101	3GS-77-6	Moenkopi School Spring	06-14-10	17.9	480	7.4	98.7	2.19	.010	35.3	7.20	1.20
36102111115901	3A-5	Pasture Canyon Spring	06-14-10	16.8	636	7.6	74.4	4.34	.019	30.1	4.31	1.23
364656109425400	8A-224	Unnamed Spring near Dennehotso	06-10-10	16.8	259	7.6	94.6	1.00	.056	32.2	5.50	1.47
U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Sodium, dissolved (mg/L as Na)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Arsenic, dissolved ($\mu\text{g}/\text{L}$ as As)	Boron, dissolved ($\mu\text{g}/\text{L}$ as B)	Iron, dissolved ($\mu\text{g}/\text{L}$ as Fe)	Dissolved solids, residue at 180°C (mg/L)
354156110413701	6M-31	Burro Spring	06-07-10	61.3	25.9	.44	15.6	71.5	.93	83	18	355
360632111131101	3GS-77-6	Moenkopi School Spring	06-14-10	28.9	26.2	.18	13.4	33.4	2.4	43	E4	217
36102111115901	3A-5	Pasture Canyon Spring	06-14-10	12.5	5.25	.17	9.9	17.9	1.8	34	<6	157
364656109425400	8A-224	Unnamed Spring near Dennehotso	06-10-10	12.0	9.38	.53	12.8	15.5	2.4	43	13	155

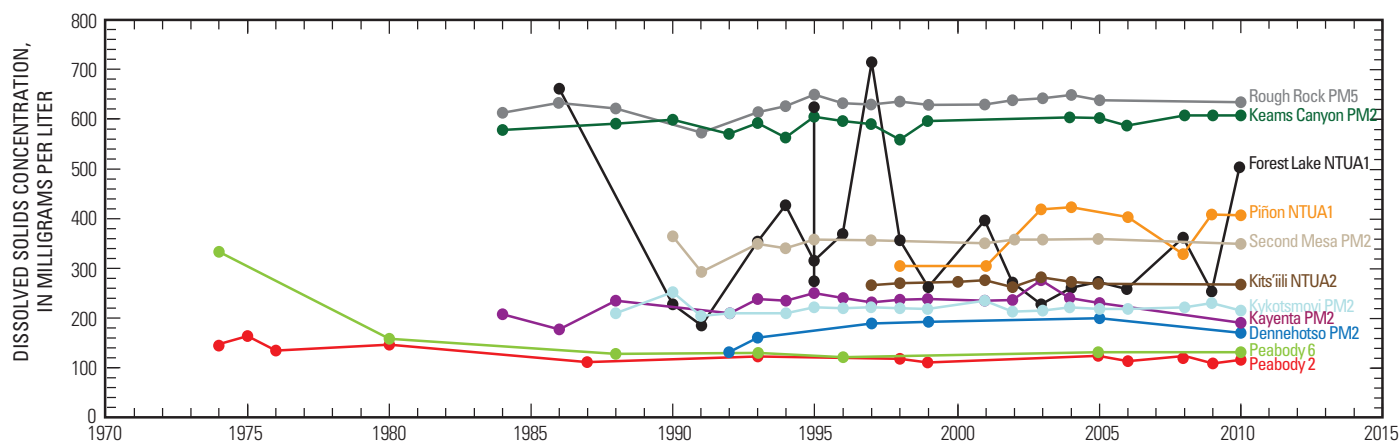


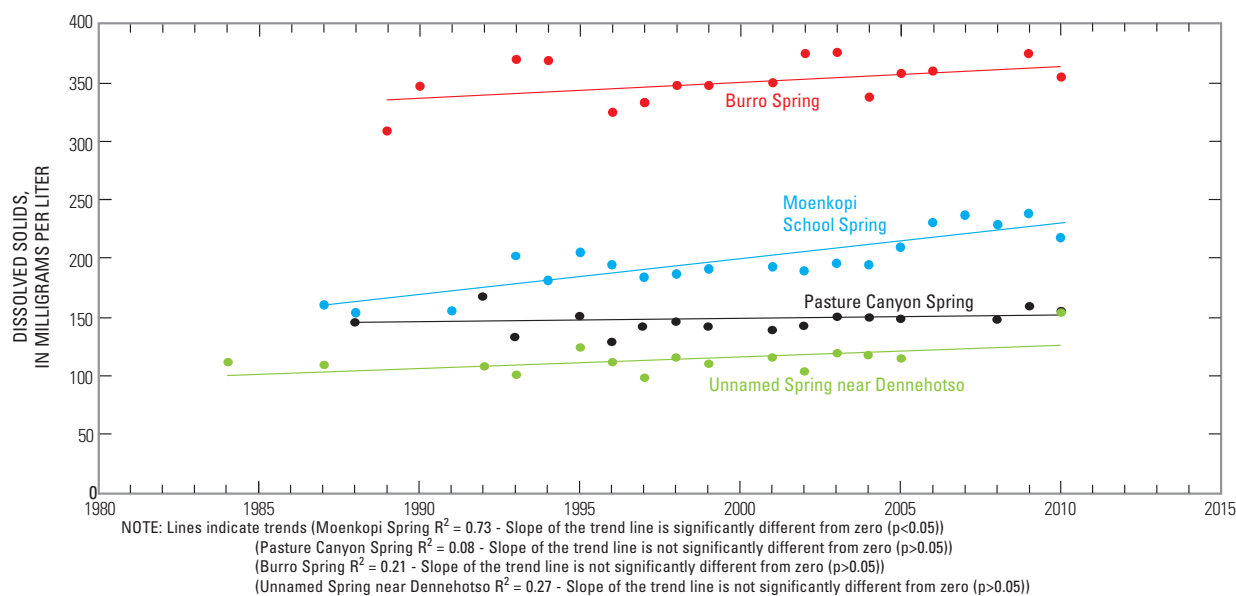
Figure 13. Dissolved-solids concentrations for water samples from selected wells, N aquifer, Black Mesa area, northeastern Arizona, 1974–2010: Rough Rock PM5, 1984–2010; Keams Canyon PM2, 1984–2010; Forest Lake NTUA 1, 1986–2010; Piñon NTUA 1, 1998–2010; Second Mesa PM2, 1990–2010; Kits'illi NTUA 2, 1997–2010; Kykotsmovi, 1988–2010; Kayenta PM2, 1984–2010; Dennehotso PM2, 1992–2010; Peabody 6, 1974–2010; and Peabody 2, 1974–2010.

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, 1948–2010.[$\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25°C; °C, degrees Celsius; mg/L, milligram per liter; <, less than. Dashes indicate no data]

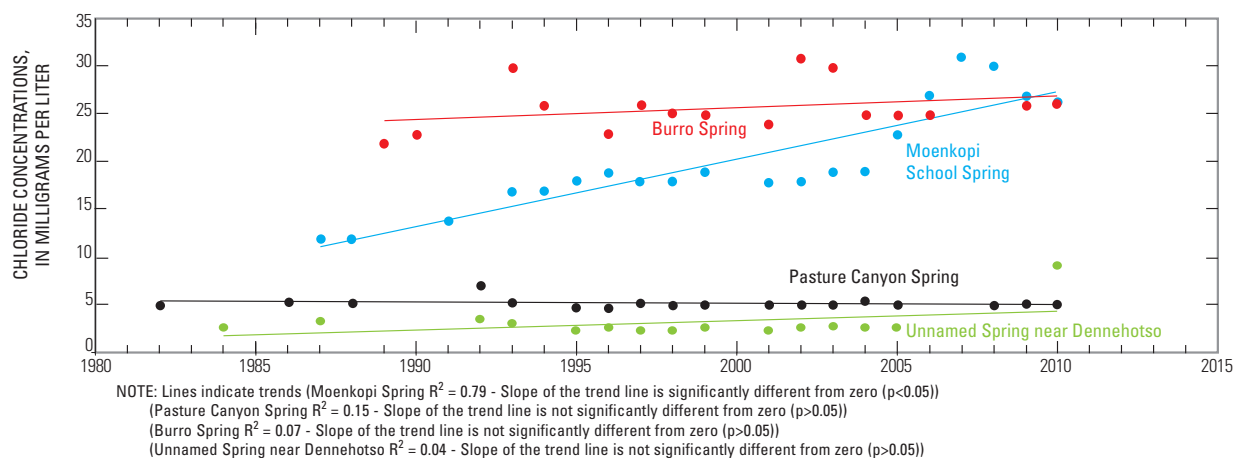
Year	Specific conductance, field ($\mu\text{S}/\text{cm}$)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Year	Specific conductance, field ($\mu\text{S}/\text{cm}$)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Burro Spring					Pasture Canyon Spring				
1989	485	308	22	59	1948	¹ 227	(²)	5.0	13
1990	¹ 545	347	23	65	1982	240	---	5.1	18
1993	595	368	30	85	1986	257	---	5.4	19
1994	¹ 597	368	26	80	1988	232	146	5.3	18
1996	525	324	23	62	1992	235	168	7.1	17
1997	¹ 511	332	26	75	1993	242	134	5.3	17
1998	504	346	25	70	1995	235	152	4.8	14
1999	545	346	25	69	1996	238	130	4.7	15
2001	480	348	24	68	1997	232	143	5.3	17
2002	591	374	31	77	1998	232	147	5.1	16
2003	612	374	30	81	1999	235	142	5.1	14
2004	558	337	25	64	2001	236	140	5.1	17
2005	558	357	25	69	2002	243	143	5.1	16
2006	576	359	25	68	2003	236	151	5.1	16
2009	577	372	26	73	2004	248	150	5.5	16
2010	583	355	26	72	2005	250	149	5.1	16
Moenkopi School Spring					2008	240	149	5.0	18
1952	222	---	6	---	2009	241	160	5.1	19
1987	270	161	12	19	2010	314	157	5.3	18
1988	270	155	12	19	Unnamed Spring near Dennehotso				
1991	297	157	14	20	1984	195	112	2.8	7.1
1993	313	204	17	27	1987	178	² 109	3.4	7.5
1994	305	182	17	23	1992	178	108	3.6	7.3
1995	314	206	18	22	1993	184	100	3.2	8.0
1996	332	196	19	26	1995	184	124	2.6	5.7
1997	¹ 305	185	18	24	1996	189	112	2.8	8.2
1998	296	188	18	24	1997	¹ 170	98	2.4	6.1
1999	305	192	19	26	1998	179	116	2.4	5.4
2001	313	194	18	26	1999	184	110	2.8	6.3
2002	316	191	18	23	2001	176	116	2.6	6.0
2003	344	197	19	23	2002	183	104	2.7	7.4
2004	349	196	19	21	2003	180	118	2.9	7.2
2005	349	212	23	30	2004	170	117	2.7	5.0
2006	387	232	27	34	2005	194	114	2.6	8.7
2007	405	238	31	40	2010	259	155	9.4	16
2008	390	230	30	38					
2009	381	240	27	36					
2010	480	217	26	33					

¹Value is different in Black Mesa monitoring reports before 2000. Earlier reports showed values determined by laboratory analysis.²Value is different in Black Mesa monitoring reports before 2000. Earlier reports showed values determined by the sum of constituents.

A. Dissolved Solids



B. Chloride



C. Sulfate

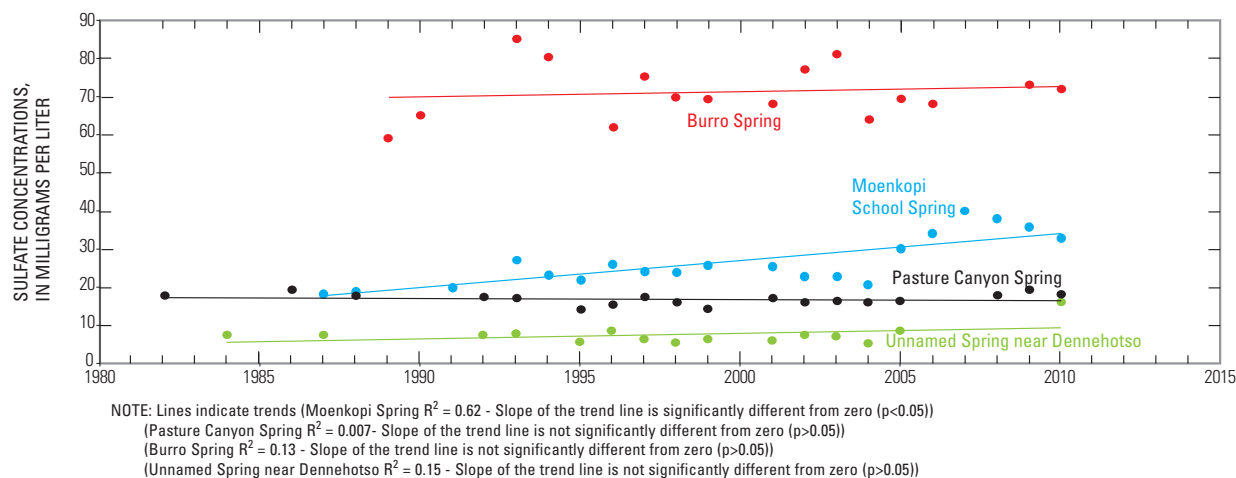


Figure 14. Concentrations of dissolved solids, chloride, and sulfate for water samples from Moenkopi School Spring, Pasture Canyon Spring, Burro Spring and Unnamed Spring near Dennehotso, N aquifer, Black Mesa area, northeastern Arizona, 1982–2010. A, Dissolved solids; B, Chloride; C, Sulfate. (Trend lines were generated by using the method of least squares).

From 2009 to 2010, annually measured groundwater levels declined in 19 of 34 wells available for comparison. The median water-level change for the 34 wells was -0.2 ft. In unconfined areas of the N aquifer, water levels declined in 7 of 16 annual wells available for comparison, and the median change was 0.1 ft. In the confined area of the N aquifer, water levels declined in 12 of 18 wells, and the median change was -0.3 ft. From the prestress period (before 1965) to 2010, the median groundwater level change in 34 wells was -13.9 ft. Water levels in the 16 wells in the unconfined areas of the N aquifer had a median change of -0.8 ft, and the changes ranged from -43.9 ft to +12.9 ft. Water levels in the 18 wells in the confined area of the N aquifer had a median change of -38.7 ft, and the changes ranged from -212.5 ft to +14.6 ft.

Discharge has been measured annually at Moenkopi School Spring and Pasture Canyon Spring and intermittently at Burro Spring and Unnamed Spring near Dennehotso. Between 2009 and 2010, spring flow decreased by 7.5 percent at Moenkopi School Spring, and spring flow increased by 10 percent at Pasture Canyon Spring. Discharge at Burro Spring and Unnamed Spring near Dennehotso has remained relatively constant since it was first measured. For the period of record, discharge at Moenkopi School Spring and Pasture Canyon Spring has fluctuated, and the data indicate a decreasing trend in discharge for both springs; however, no trend is apparent for either Burro Spring or Unnamed Spring near Dennehotso.

Annual average discharges at four streamflow-gaging stations—Moenkopi Wash, Dinnebito Wash, Pasture Canyon Springs, and Polacca Wash—vary during the periods of record. No trends are apparent in streamflow at the four streamflow-gaging stations. 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 each streamflow-gaging station, the median winter flows have generally remained constant, showing neither a significant increase nor decrease.

In 2010, water samples were collected from 11 wells and 4 springs and analyzed for selected chemical constituents. In the 11 wells, concentrations of dissolved solids, chloride, and sulfate have varied for the period of record, and the data do not indicate a trend.

Dissolved-solids concentrations in water samples from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso were 355 mg/L, 217 mg/L, 157 mg/L, and 155 mg/L, respectively. From the mid 1980s to 2010, long-term data from Moenkopi School Spring indicate increasing trends in 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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