Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2010–2011

Open-File Report 2012–1102

U.S. Department of the Interior
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Cover:
Photograph of windmill and well 8K-443 near Chilchinbito, AZ. (USGS photograph taken by Curtis Crouch.)

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By Jamie P. Macy, Christopher R. Brown, and Jessica R. Anderson

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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: °F=(1.8×°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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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 to 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 2010 to September 2011. The monitoring program includes measurements of (1) groundwater withdrawals, (2) groundwater levels, (3) spring discharge, (4) surface-water discharge, and (5) groundwater chemistry.

In 2010, total groundwater withdrawals were 4,040 acre-ft, industrial withdrawals were 1,170 acre-ft, and municipal withdrawals were 2,870 acre-ft. Total withdrawals during 2010 were about 42 percent less than total withdrawals in 2005 because of Peabody Western Coal Company's discontinued use of water to transport coal in a slurry. From 2009 to 2010 total withdrawals decreased by 5 percent; industrial withdrawals decreased by approximately 16 percent, and total municipal withdrawals increased by 1 percent.

From 2010 to 2011, annually measured water levels in the Black Mesa area declined in 7 of 15 wells that were available for comparison in the unconfined areas of the N aquifer, and the median change was 0.0 foot. Water levels declined in 11 of 18 wells measured in the confined area of the aquifer. The median change for the confined area of the aquifer was -0.7 foot. From the prestress period (prior to 1965) to 2011, the median water-level change for 33 wells in both the confined and unconfined areas was -15.0 feet. Also, from the prestress period to 2011, the median water-level changes were -1.2 foot for 15 wells measured in the unconfined areas and -41.2 feet for 18 wells measured in the confined area.

Spring flow was measured at three springs in 2011. 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 has remained relatively constant since it was 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 2010), Dinnebito Wash near Sand Springs 09401110 (1993 to 2010), Polacca Wash near Second Mesa 09400568 (1994 to 2010), and Pasture Canyon Springs 09401265 (2004 to 2010). 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 2011, 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-mi^2 Black Mesa study area in northeastern Arizona contains diverse topography that includes flat plains, mesas, and incised drainages (fig. 1). Black Mesa, a topographic high at the center of the study area, encompasses about 2,000 mi^2. It has 2,000-foot-high cliffs on its northern and northeastern sides, but it slopes gradually down to the south and southwest. Availability of water is an important issue in the study area because of continued groundwater withdrawals, the growing population, and an arid to semiarid climate with average annual precipitation ranging 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).

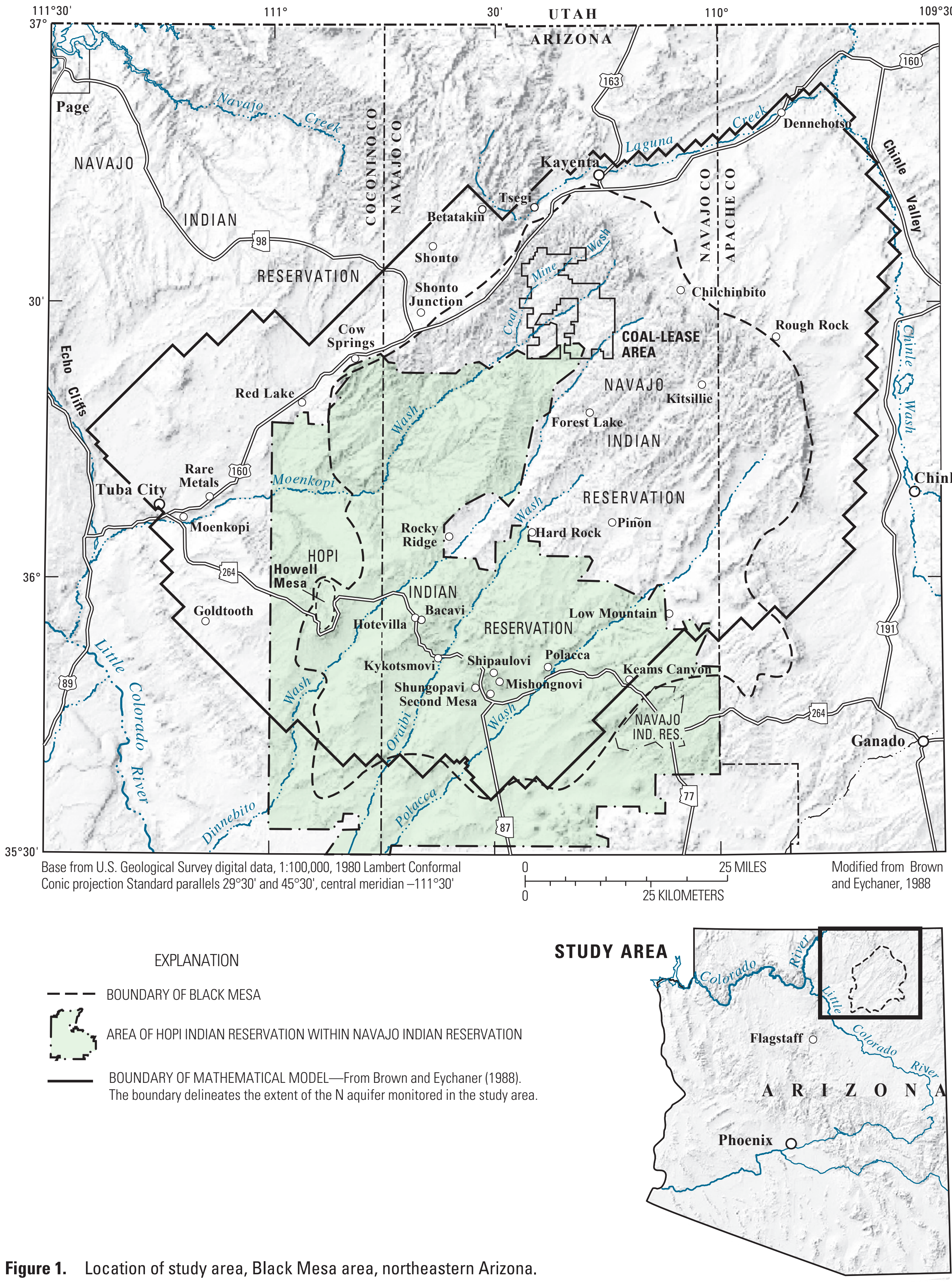
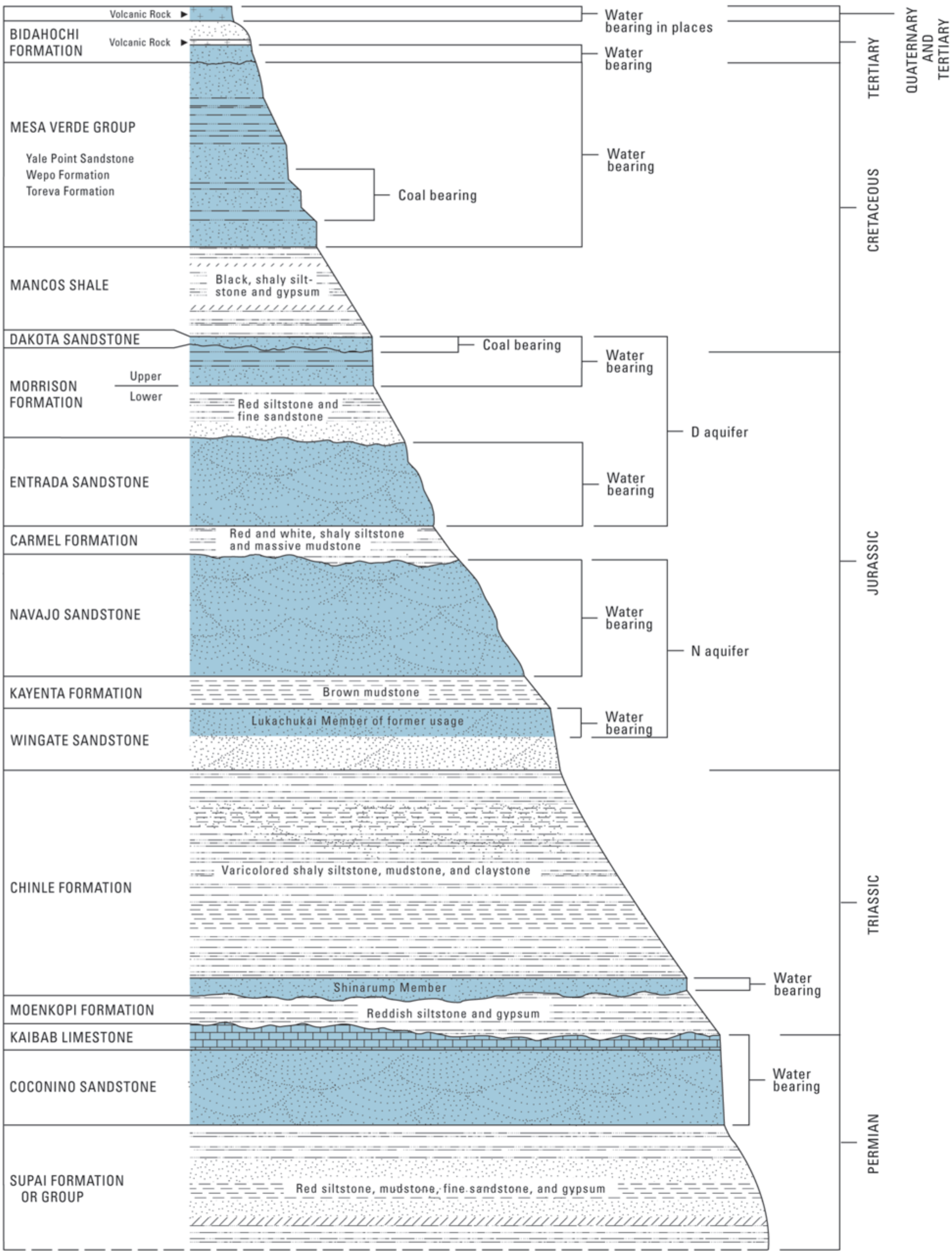


Figure 1. Location of study area, Black Mesa area, northeastern Arizona.



Modified from Harshbarger and others, 1966

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.

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). PWCC's mining operation consisted of two mines on Black Mesa, the Kayenta mine which transported coal to the Navajo Generating Station by train and the Black Mesa mine which transported coal to the Mohave generating station by a coal slurry pipeline. 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 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.

PWCC operated two mines on Black Mesa from the 1970s until about 2005 when the Mohave Generating Station ceased operations. On December 31, 2005, PWCC reduced pumping of the N aquifer by approximately 70 percent as a result of discontinued use of a coal slurry pipeline that delivered water to the Mohave Generating Station. The two mines at PWCC have since been combined into the Black Mesa complex which still delivers coal to the Navajo Generating Station via an electric train. 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 2010 to September 2011. 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 2009 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-six 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/wy2010/search.jsp) in the 2010 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, HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering (1999) developed a three-dimensional numerical model of the N aquifer and the overlying Dakota (D) aquifer.

Table 1. Withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2010.

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

Calendar Year	Industrial[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	[5,6]1,430	[5]1,560	[6]4,200
2009	1,390	1,440	1,400	4,230
2010	1,170	[4]1,450	1,420	[4]4,040

[1]Metered pumpage from the confined part of the aquifer by Peabody Western Coal Company.
[2]Does not include withdrawals from the wells equipped with windmills.
[3]Includes estimated pumpage 1965–73 and metered pumpage 1974–79 at Tuba City; metered pumpage at Kayenta and estimated pumpage at Chilchinbito, Rough Rock, Piñon, Keams Canyon, and Kykotsmovi before 1980; metered and estimated pumpage furnished by the Navajo Tribal Utility Authority and the Bureau of Indian Affairs and collected by the U.S. Geological Survey, 1980–85; and metered pumpage furnished by the Navajo Tribal Utility Authority, the Bureau of Indian Affairs, various Hopi Village Administrations, and the U.S. Geological Survey, 1986–2010.
[4]NTUA meter data were not available for 2006 and 2010; therefore, municipal withdrawals are estmated, and total withdrawal uses an estimation in the calculation.
[5]Confined and unconfined totals were reversed in previous reports
[6]Confined withdrawals are about 90 acre-ft greater than previously reported.

Table 2. Tabulated list of progress reports for the Black Mesa monitoring program 1978–2011.

Year Published	Author(s)	Title	USGS Report Type and Number
1978	U.S. Geological Survey	Progress report on Black Mesa monitoring program—1977	Open-File Report 78–459
1985	Hill, G.W.	Progress report on Black Mesa monitoring program—1984	Open-File Report 85-483
1986	Hill, G.W., and Whetten, M.I.	Progress report on Black Mesa monitoring program—1985–86	Open-File Report 86-414
1987	Hill, G.W., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987	Open-File Report 87–458
1988	Hart, R.J., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987–88	Open-File Report 88–467
1989	Hart, R.J., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1988–89	Open-File Report 89–383
1992	Sottilare, J.P.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1989–90	Water-Resources Investigations Report 92–4008
1992	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1990–91	Water-Resources Investigations Report 92–4045
1993	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1991–92	Water-Resources Investigations Report 93–4111
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1992–93	Water-Resources Investigations Report 95–4156
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-chemistry monitoring, Black Mesa area, northeastern Arizona—1994	Water-Resources Investigations Report 95–4238
1996	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1995	Open-File Report 96–616
1997	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1996	Open-File Report 97–566
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
2011	Macy, Jamie P., and Brown, C.R.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2009–2010	Open-File Report 2011-1198

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water collected from wells and springs in the Black Mesa area. HSIGeoTrans, Inc. (1993) evaluated the major-ion and isotopic chemistry of the D and N aquifers. Lopes and Hoffmann (1997) analyzed groundwater ages, recharge, and hydraulic conductivity of the N aquifer by using geochemical techniques. Zhu and others (1998) estimated groundwater recharge in the Black Mesa area by using isotopic data and flow estimates from the N-aquifer model developed by GeoTrans, Inc. (1987). Zhu (2000) estimated recharge using advective transport modeling and the same isotopic data from the GeoTrans model. Truini and Longsworth (2003) described the hydrogeology of the D aquifer and the movement and ages of groundwater in the Black Mesa area by using data from geochemical and isotopic analyses. Truini and Macy (2005) 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 2010–11, activities of the Black Mesa area monitoring program included metered groundwater withdrawals, measurements of groundwater levels, spring discharge measurements, streamflow gaging, and the collection of water-chemistry samples from wells and springs. All data were collected by the USGS except withdrawal data from NTUA wells, which were compiled by NTUA personnel. Linear regression and Kendall's tau trend analyses were applied to streamflow data, spring discharge measurements, and water-chemistry samples by using TIBCO Spotfire S+ statistical software (TIBCO Software, Inc.; Sommerville, MA). Annual discharge measurements were made at 4 springs, and annual groundwater-level measurements were made at 33 wells. Of those 33 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 March 2011. 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 February to June 2011. Groundwater samples were collected from 11 wells and 4 springs in June 2011 and were analyzed for chemical constituents. Annual groundwater-withdrawal data are collected from 36 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, however streamflow data are reported in water years beginning October 1 and ending September 30 with the exception of tables 10-13 which are reported in calendar years.

Table 3. Identification numbers and names of monitoring program study wells, 2010–11, 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
362901110234101	Peabody 5	---
362936109564101	BM observation well 1	8T-537
363005110250901	Peabody 2	---
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	---

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 36 well systems. Information about withdrawals from 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, N, Toreva (T), and alluvial aquifers primarily for feeding livestock. The estimated total withdrawal by the windmills is about 65 acre-ft/yr (HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., 1999). The total withdrawal by the windmills is less than 1 percent of the total annual withdrawal from the N aquifer.

Withdrawals in Calendar Year 2010 Compared to Previous Years

In 2010, the total groundwater withdrawal from the N aquifer was about 4,040 acre-ft (table 1). Total withdrawals for municipal use in 2010 was about 2,870 acre-ft; withdrawals from the confined area totaled about1,450 acre-ft, while withdrawals from the unconfined areas totaled about 1,420 acre-ft. Withdrawals for industrial use totaled about 1,170 acre-ft, a 16-percent decrease from 2009 (table 5). Total withdrawals in 2010 for municipal use increased by about 1 percent from the previous year; this equates to a 1-percent increase in withdrawals from the confined areas of the aquifer, and a 1-percent increase in withdrawals from the unconfined areas.

Withdrawals from the N aquifer have varied from 1965 to the present but generally increased from 1965 to 2005 and decreased from 2006 to 2010. Beginning in 2006, the 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 (1965–2010) totaled 239,140 acre-ft; industrial withdrawals were 60 percent and municipal withdrawals were 40 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

Table 4. Withdrawals from the N aquifer by well system, Black Mesa area, northeastern Arizona, calendar year 2010.

[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	2.1	
Dennehotso	BIA	USGS/BIA		11.7
Hopi High School	BIA	USGS/BIA	17.0	
Hotevilla	BIA	USGS/BIA	22.4	
Kayenta	BIA	USGS/BIA	31.3	
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		5.0
Rocky Ridge	BIA	USGS/BIA	5.3	
Rough Rock	BIA	USGS/BIA	20.5	
Second Mesa	BIA	USGS/BIA	5.4	
Shonto	BIA	USGS/BIA		127.8
Tuba City	BIA	USGS/BIA		81.6
Chilchinbito	NTUA	USGS/NTUA	63.4	
Dennehotso	NTUA	USGS/NTUA		46.5
Forest Lake	NTUA	USGS/NTUA	20.4	
Hard Rock	NTUA	USGS/NTUA	47.1	
Kayenta	NTUA	USGS/NTUA	453.0	
Kits'iili	NTUA	USGS/NTUA	21.1	
Piñon	NTUA	USGS/NTUA	303.1	
Red Lake	NTUA	USGS/NTUA		56.1
Rough Rock	NTUA	USGS/NTUA	35.8	
Shonto	NTUA	USGS/NTUA		23.8
Shonto Junction	NTUA	USGS/NTUA		91.4
Tuba City	NTUA	USGS/NTUA		890.8
Mine Well Field	Peabody	Peabody	1,171	
Bacavi	Hopi	USGS/Hopi	24.5	
Hopi Civic Center	Hopi	USGS/Hopi	3.0	
Hopi Cultural Center	Hopi	USGS/Hopi	6.5	
Kykotsmovi	Hopi	USGS/Hopi	64.5	
Mishongnovi	Hopi	USGS/Hopi	6.0	
Moenkopi	Hopi	USGS/Hopi		81.9
Polacca	Hopi	USGS/Hopi	161.3	
Shipaulovi	Hopi	USGS/Hopi	21.2	
Shungopovi	Hopi	USGS/Hopi	62.1	

[1]Well taken out of service.

[2]Estimated value due to partial record.

Table 5. Total, industrial, and municipal withdrawals from the N aquifer for discrete time periods during 1965 to 2010, Black Mesa area, northeastern Arizona.

Period	Withdrawals (acre-feet)			Percent	
	Total	Industrial	Municipal	Industrial	Municipal
1965–2010	239,140	144,240	94,900	60	40
1965–2005	218,300	138,100	80,200	63	37
2006–2010	20,840	6,140	14,700	30	70
2010	4,040	1,170	2,870	29	71

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 2010, withdrawals totaled 20,840 acre-ft; industrial withdrawals were 30 percent and municipal withdrawals were 70 percent of total withdrawals (table 5). Total withdrawals in 2010 were 4,040 acre-ft, with 29 percent from industrial withdrawals and 71 percent from municipal withdrawals (table 5).

Withdrawal data from Kayenta NTUA wells in 2008 were reported incorrectly in "Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2008–2009." The value reported in the 2008–2009 Black Mesa report for Kayenta NTUA wells was 342.2 acre-ft; however, it should have been 429.5 acre-ft. Total pumping from the confined part of the N aquifer in 2008 was actually about 90 acre-ft more than was previously reported.

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 February 2011 to March 2011, water levels in 33 of the 34 wells having annual measurements met these criteria (table 6). Of the 33 wells, 6 are continuous-recording observation wells. Water levels were measured by electric tape in these 6 wells 3 times between June 2010 and June 2011 to verify or update instrument calibration

The wells used for water-level measurements are distributed throughout the study area (fig. 5). The wells were constructed between 1934 and 1993, the total well depths range from 107 ft near Northeast Rough Rock (8A-180) to 3,737 ft near PWCC, and depths to the top of the N aquifer range from 0 ft near Tuba City to 3,140 ft at PWCC (table 7).

From 2010 to 2011, water levels decreased in 18 of the 33 wells for which comparisons could be made (table 6). The median water-level change in the 33 wells was -0.2 ft (table 8). From 2010 to 2011, water levels declined in 7 of the 15 wells measured in the unconfined parts of the aquifer (table 6), and the median water-level change was 0.0 ft (table 8). Water-level changes in the unconfined part of the aquifer ranged from -0.8 ft at Tuba City (3K-325) and Long House Valley (8T-510) to +9.3 ft at Tuba City NTUA 4 (3T-546) (table 6). In the confined area, water levels declined in 11 of 18 wells measured from 2010 to 2011. The median water-level change was -0.7 ft (table 8). Water-level changes in the confined part of the aquifer ranged from -4.2 ft at Piñon PM6 to +9.7 ft at Kayenta West (8T-541) (table 6).

From the prestress period (before 1965) to 2011, the median water-level change in 33 wells was -15.0 ft (table 8). Water levels in 15 unconfined wells had a median change of -1.2 ft (table 8).

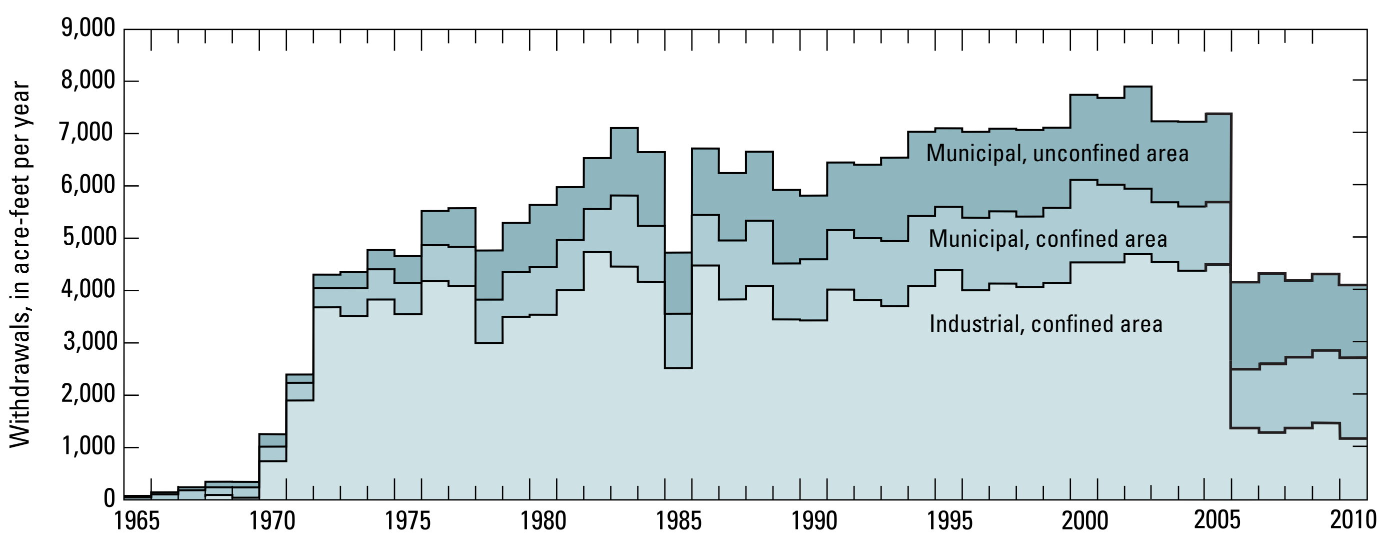


Figure 3. Annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2010.

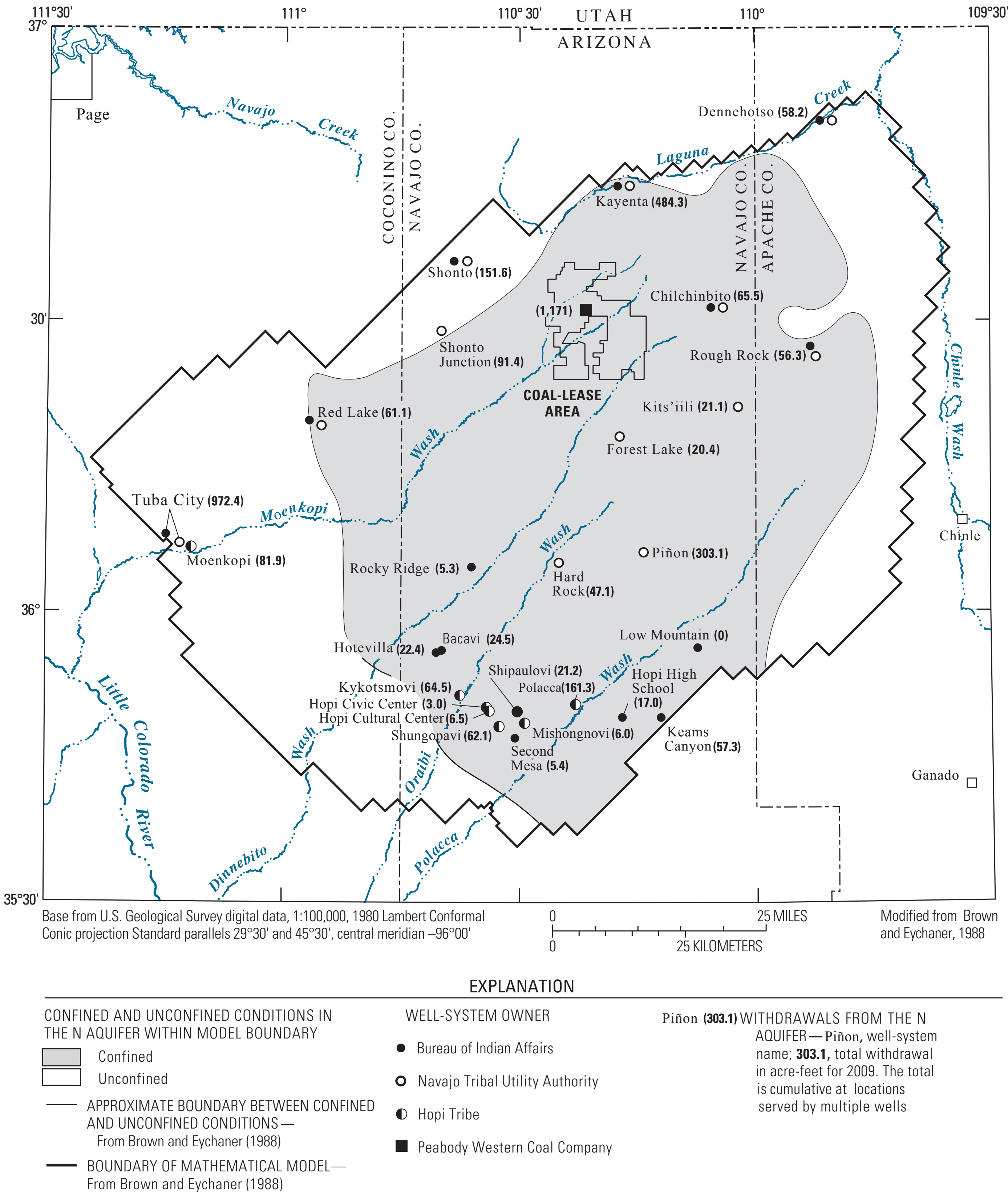


Figure 4. Locations of well systems monitored for annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, calendar year 2010.

Table 6. Water-level changes in monitoring program wells completed in the N aquifer, Black Mesa area, northeastern Arizona, prestress period to 2011 (calendar year).

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

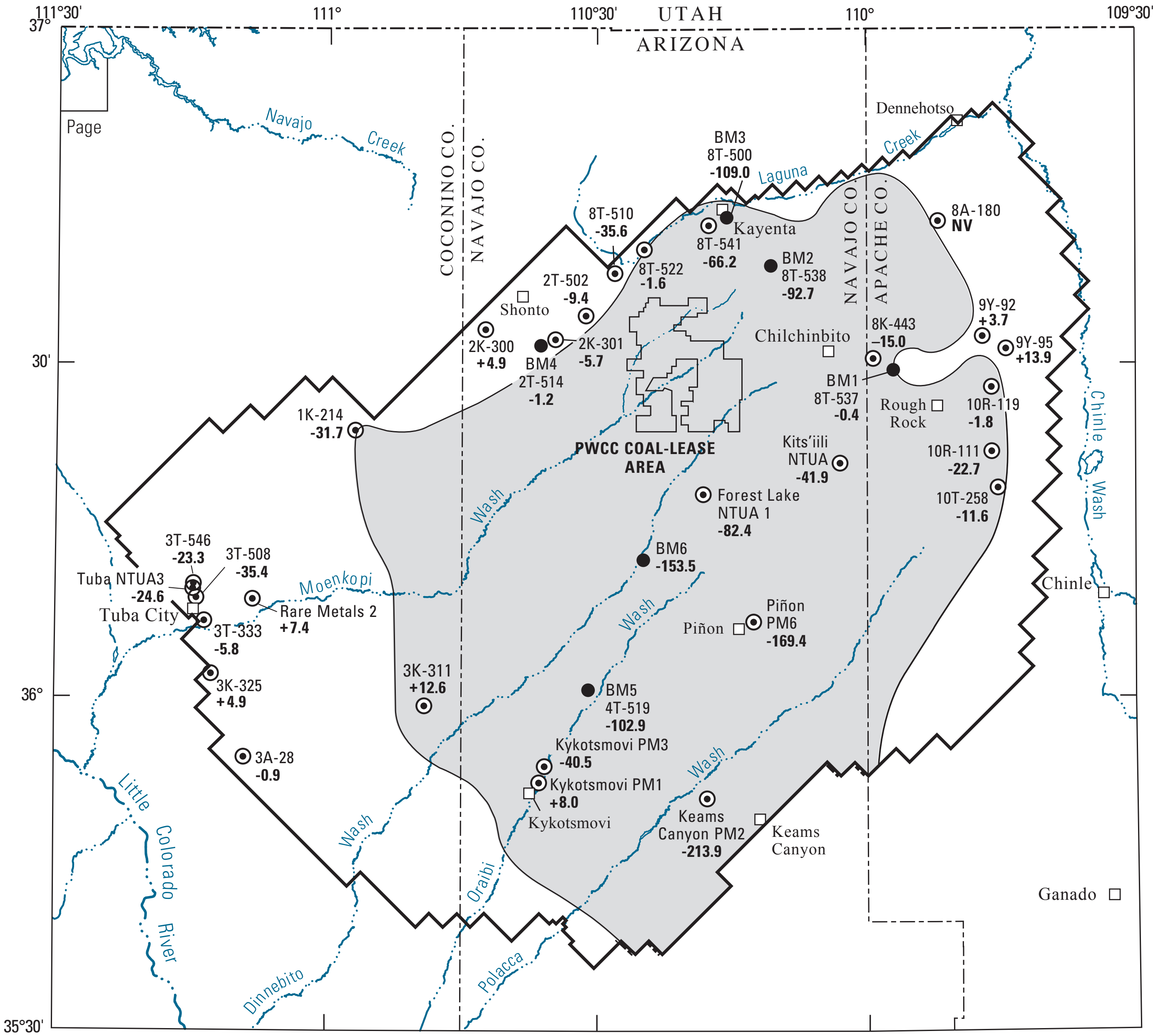
Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year (feet)		Water level (feet below and surface) 2011	Prestress period water level		Change in water level from prestress period to 2011 (feet)
		2010	2011		Feet below land surface	Date	
Unconfined areas							
BM observation well 1[1]	8T-537	0.2	0.0	374.4	374.0	([1])	-0.4
BM observation well 4[1]	2T-514	0.2	-0.2	217.2	216.0	([1])	-1.2
Goldtooth	3A-28	1.5	-0.4	230.9	230.0	10–29–53	-0.9
Long House Valley	8T-510	-1.0	-0.8	135.0	99.4	08–22–67	-35.6
Northeast Rough Rock	8A-180	0.2	([2])	---	46.9	11–13–53	[4]2.4
Rough Rock	9Y-95	-1.3	1.0	105.6	119.5	08–03–49	13.9
Do.	9Y-92	-2.2	3.1	165.1	168.8	12–13–52	3.7
Shonto	2K-300	0.0	-0.2	171.6	176.5	06–13–50	4.9
Shonto Southeast	2K-301	0.2	-0.4	289.6	283.9	12–10–52	-5.7
Do.	2T-502	-2.4	4.0	415.2	405.8	08–22–67	-9.4
Tuba City	3T-333	0.3	-0.2	28.8	23.0	12–02–55	-5.8
Do.	3K-325	0.9	-0.8	203.1	208.0	06–30–55	4.9
Tuba City Rare Metals 2	---	0.6	0.2	49.6	57.0	09–24–55	7.4
Tuba City NTUA 1	3T-508	-18.5	8.5	64.4	29.0	02–12–69	-35.4
Tuba City NTUA 3	---	-2.3	5.4	58.8	34.2	11–08–71	-24.6
Tuba City NTUA 4	3T-546	-1.3	9.3	57.0	33.7	08–06–71	-23.3
Confined area							
BM observation well 2[1]	8T-538	-0.2	0.1	217.7	125.0	([1])	-92.7
BM observation well 3[1]	8T-500	-0.1	-2.0	164.0	55.0	04–29–63	-109.0
BM observation well 5[1]	4T-519	-0.4	-0.8	426.9	324.0	([1])	-102.9
BM observation well 6[1]	---	3.8	2.1	850.5	697.0	([1])	-153.5
Forest Lake NTUA 1	4T-523	5.6	2.4	1,178.4	1,096R	05–21–82	-82.4
Howell Mesa	3K-311	-3.1	-2.0	450.4	463.0	11–03–53	12.6
Kayenta West	8T-541	-6.3	9.7	296.2	230.0	03–17–76	-66.2
Keams Canyon PM2	---	-6.6	-1.4	506.4	292.5	06–10–70	-213.9
Kits'iili NTUA 2	---	-3.8	-3.6	1,339.8	[3]1,297.9	01–14–99	-41.9
Kykotsmovi PM1	---	-0.7	0.5	212.0	220.0	05–20–67	8.0
Kykotsmovi PM3	---	-0.2	-1.4	250.5	210.0	08–28–68	-40.5
Marsh Pass	8T-522	0.0	0.5	127.1	125.5	02–07–72	-1.6
Piñon PM6	---	-3.9	-4.2	913.0	743.6	05–28–70	-169.4
Rough Rock	10R-119	0.1	-1.7	258.4	256.6	12–02–53	-1.8
Do.	10T-258	0.1	-2.8	312.6	301.0	04–14–60	-11.6
Do.	10R-111	-5.4	6.0	192.7	170.0	08–04–54	-22.7
Sweetwater Mesa	8K-443	-1.9	-0.6	544.4	529.4	09–26–67	-15.0
White Mesa Arch	1K-214	0.3	-0.1	219.7	188.0	06–04–53	-31.7

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

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

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

[4]Change in water level from prestress period to 2010.



Base from U.S. Geological Survey digital data, 1:100,000, 1980 Lambert Conformal Conic projection Standard parallels 29°30' and 45°30', central meridian –96°00'

0 25 MILES
0 25 KILOMETERS

Modified from Brown and Eychaner, 1988

EXPLANATION

CONFINED AND UNCONFINED CONDITIONS IN THE N AQUIFER

Confined area within the boundary of the mathmatical boundary

Unconfined area within the boundary of the mathematcal boundary

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

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

2K-300 **+4.90** WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry,2K-300, is Bureau of Indian Affairs site number; second entry, **+4.9**, is change in water level, in feet, between measurement made during the prestress period and measurement made during 2010. **NV**, site not visited

BM2 8T-538 **–92.7** 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, **–92.7**, is change in water level, in feet, from simulated prestress period to 2010

Figure 5. Water-level changes in N-aquifer wells from the prestress period (prior to 1965) to 2011, Black Mesa area, northeastern Arizona.

Table 7. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, northeastern Arizona, 2010–11.

Bureau of Indian Affairs site number, and (or) common name	Date well was completed	Land-surface elevation (feet)	Well depth (feet below landsurface)	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	[2]30	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	[2]30	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	[2]40	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	90	Water level
8T-510	02–11–63	6,262	314	130–314	[2]125	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	[2]50	Water level
9Y-95	11–05–37	5,633	300	145–300	[2]68	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

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

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

[3]00, indicates day is unknown.

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

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

Table 8. Median changes in water levels in monitoring-program wells, 2010–2011 and prestress period (prior to 1965) to 2011, N aquifer, Black Mesa area, northeastern Arizona.

Years	Aquifer conditions	Number of wells	Median change in water level (feet)
2010–2011	All	33	-0.2
	Unconfined	15	0.0
	Confined	18	-0.7
Prestress–2011	All	33	-15.0
	Unconfined	15	-1.2
	Confined	18	-41.2

Water-level changes in the unconfined part of the aquifer ranged from -35.6 ft at Long House Valley (8T-510) to +13.9 ft at Rough Rock (9Y-95) (fig. 5 and table 6). Water levels in 18 wells in the confined part of the aquifer had a median change of -41.2 ft (table 8). Water-level changes in the confined part of the aquifer ranged from -213.9 ft at Keams Canyon PM2 to +12.6 ft at Howell Mesa 3K-311 (fig. 5 and table 6).

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

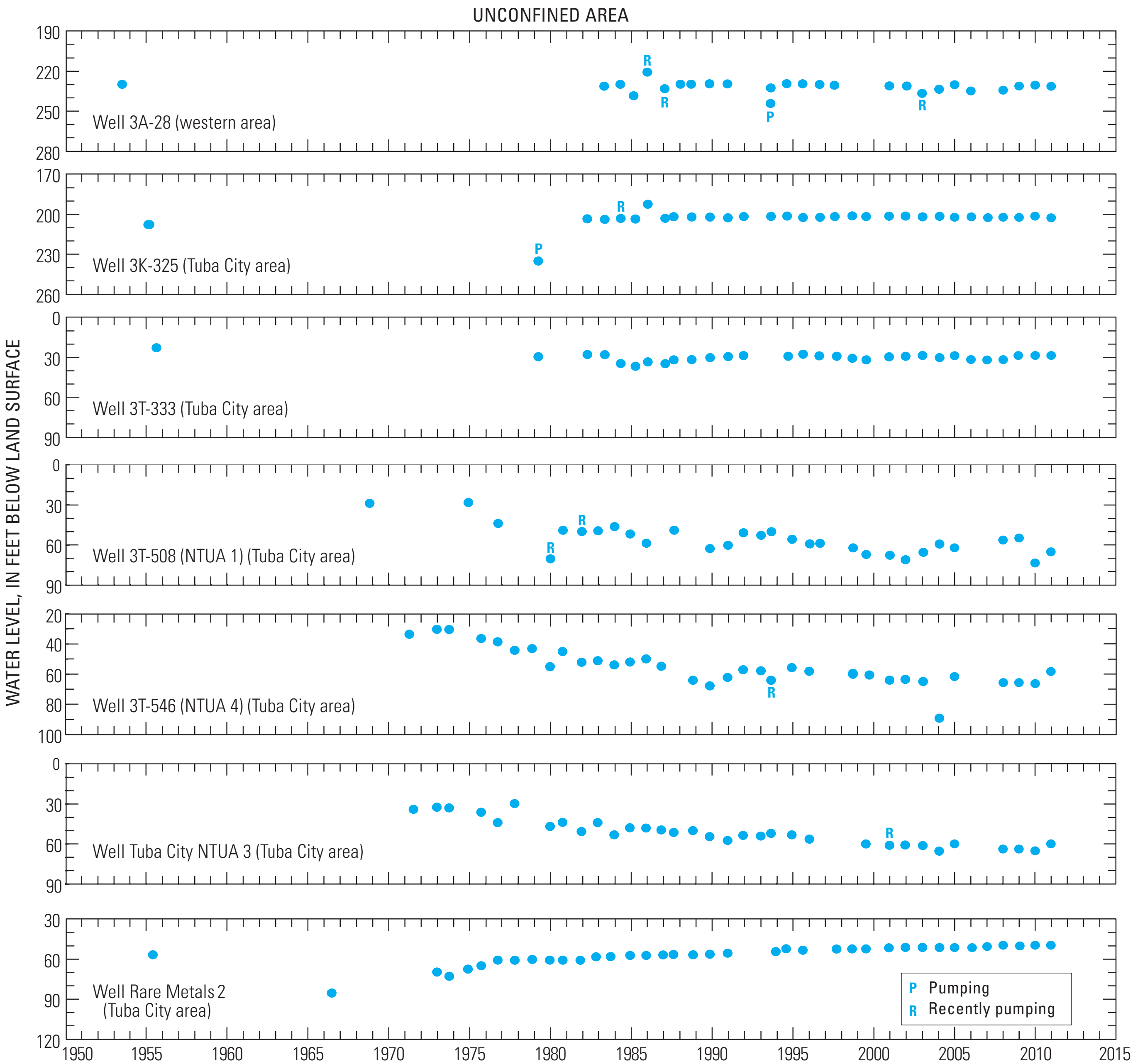


Figure 6. Observed water levels (1950–2011) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona..

Valley, however, the water level in well 8T-510 has declined about 36 ft (figs. 5 and 6 and table 6). 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; figs. 5 and 6).

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 (that 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 1960s and 1970s (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 849.6 ft below land surface on August 25, 2011, about 12 feet of total recovery to date.

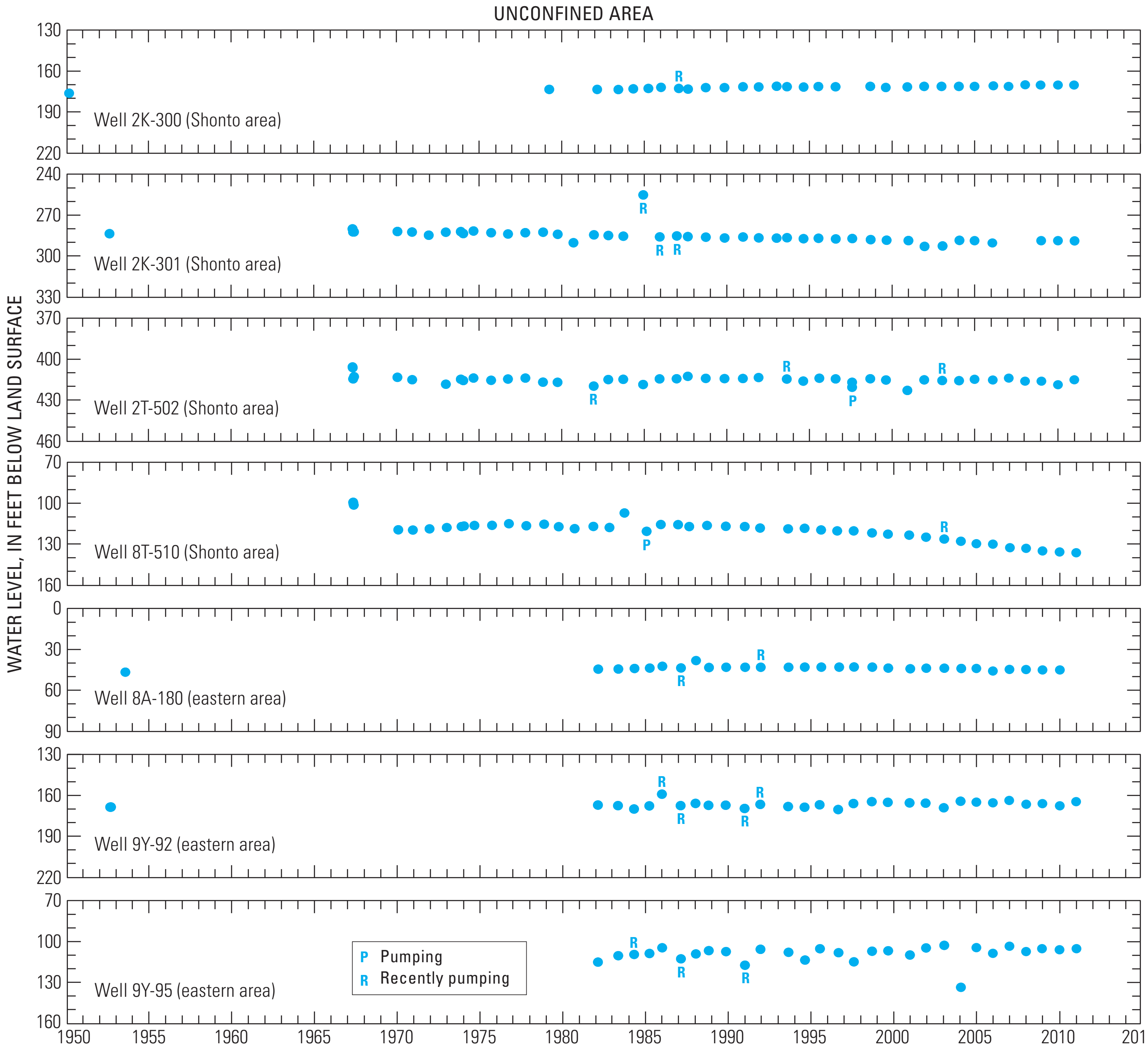


Figure 6. Observed water levels (1950–2011) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.—Continued.

Figure 6. Observed water levels (1950–2011) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.—Continued.

Figure 6. Observed water levels (1950–2011) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.—Continued.

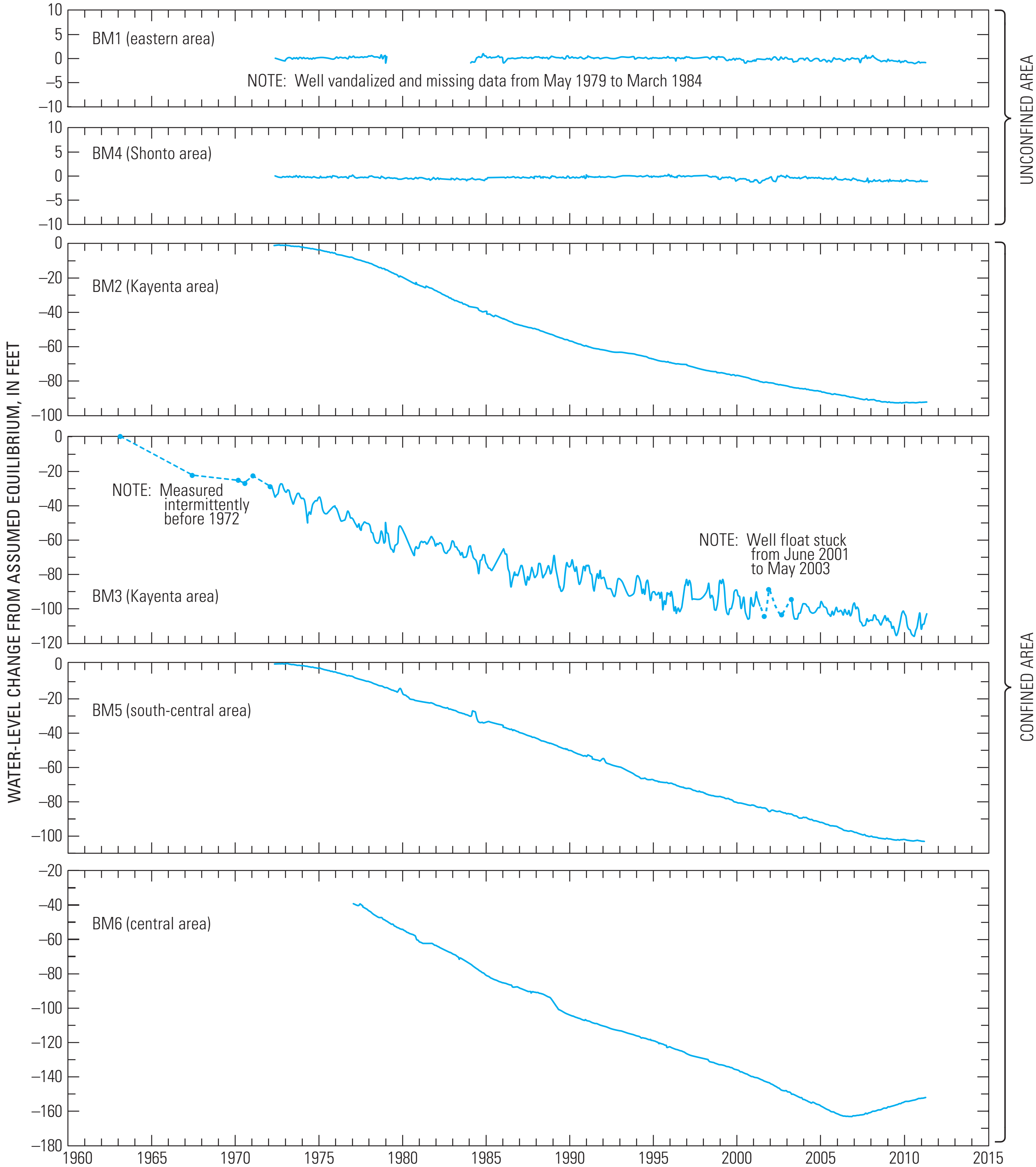


Figure 7. Observed water-level changes in continuous-record observation wells, BM1-BM6, 1963-2011, N aquifer, Black Mesa area, northeastern Arizona.

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 2011, Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring 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 2011 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 or close to the same time of year. In 2011, the measured discharge was 9.0 gal/min from Moenkopi School Spring (table 9). From 2010 to 2011, discharge increased by 21 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 9).

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 2011 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 2011 the measured discharge was 0.4 gal/min, an increase of 33 percent from the previous year (fig. 9 and table 9).

A third spring measured in 2011 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 farther down-canyon at the USGS gaging station. The USGS gaging station at Pasture Canyon measures the discharge from Pasture Canyon Spring as well as additional discharge from seeps along Pasture Canyon. Discharge was measured at Pasture Canyon Spring in June 2011 by the volumetric method and showed a decrease in discharge of about 0.5 gal/yr (fig. 9 and table 9). When compared to discharge in previous years, a decreasing trend ($p<0.05$) is evident from both linear regression and Kendall's tau analyses. 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 or close to the same time of year. In 2011 the measured discharge was 31.4 gal/min, an 8-percent decrease from 2010 (table 9).

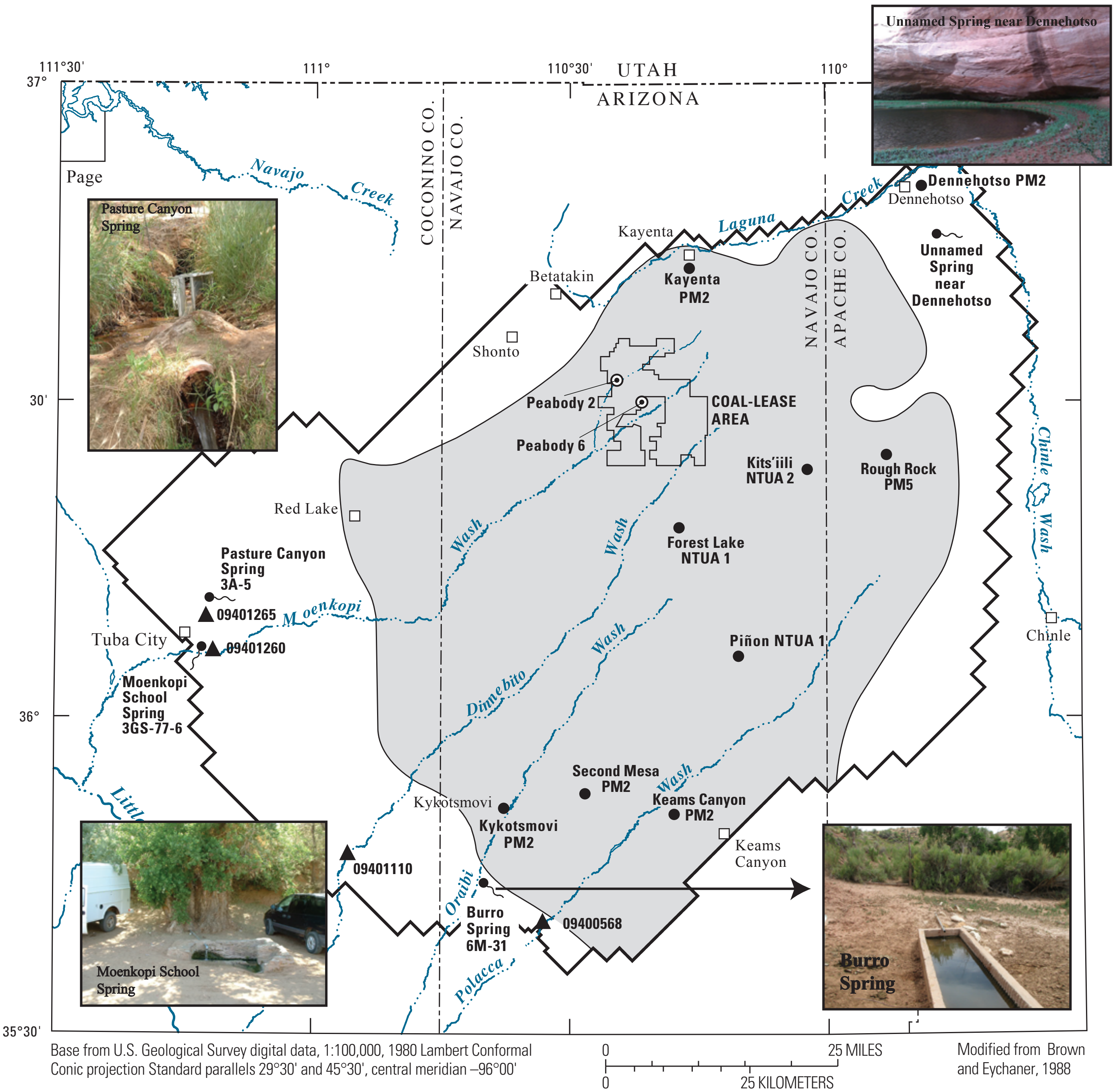
Surface-Water Discharge, 2010 Water Year

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 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 2010, discharge data were collected at four continuous-recording streamflow-gaging stations (tables 10–13). Data collection at these stations began in July 1976 (Moenkopi Wash at Moenkopi, 09401260), June 1993 (Dinnebito Wash near Sand Springs, 09401110), April 1994 (Polacca Wash near Second Mesa, 09400568), and August 2004 (Pasture Canyon Springs, 09401265; fig. 10*A*; table 14). The annual average discharges at the four streamflow-gaging stations vary during the periods of record (fig. 10*A*), and there are no significant trends in annual average discharge for Moenkopi Wash, Polacca Wash, Dinnebito Wash, and Pasture Canyon Springs.

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 annual precipitation measured at Navajo National Monument (Betatakin; fig. 1) from 1976 to 2010 has varied and the average annual precipitation is 12.6 in. (fig. 10*B*). In 2010 the annual precipitation was near average (12.82 in.; fig 10*B*; National Climatic Data Center, 2011).

Trends in the groundwater-discharge component of total flow at the three streamflow-gaging stations were evaluated on the basis of the median of 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



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)

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

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

Moenkopi School Spring 3GS-77-6 SPRING AT WHICH DISCHARGE WAS MEASURED AND WATER-CHEMISTRY SAMPLE WAS COLLECTED—Number is spring identification

09401260 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, 2010–11.

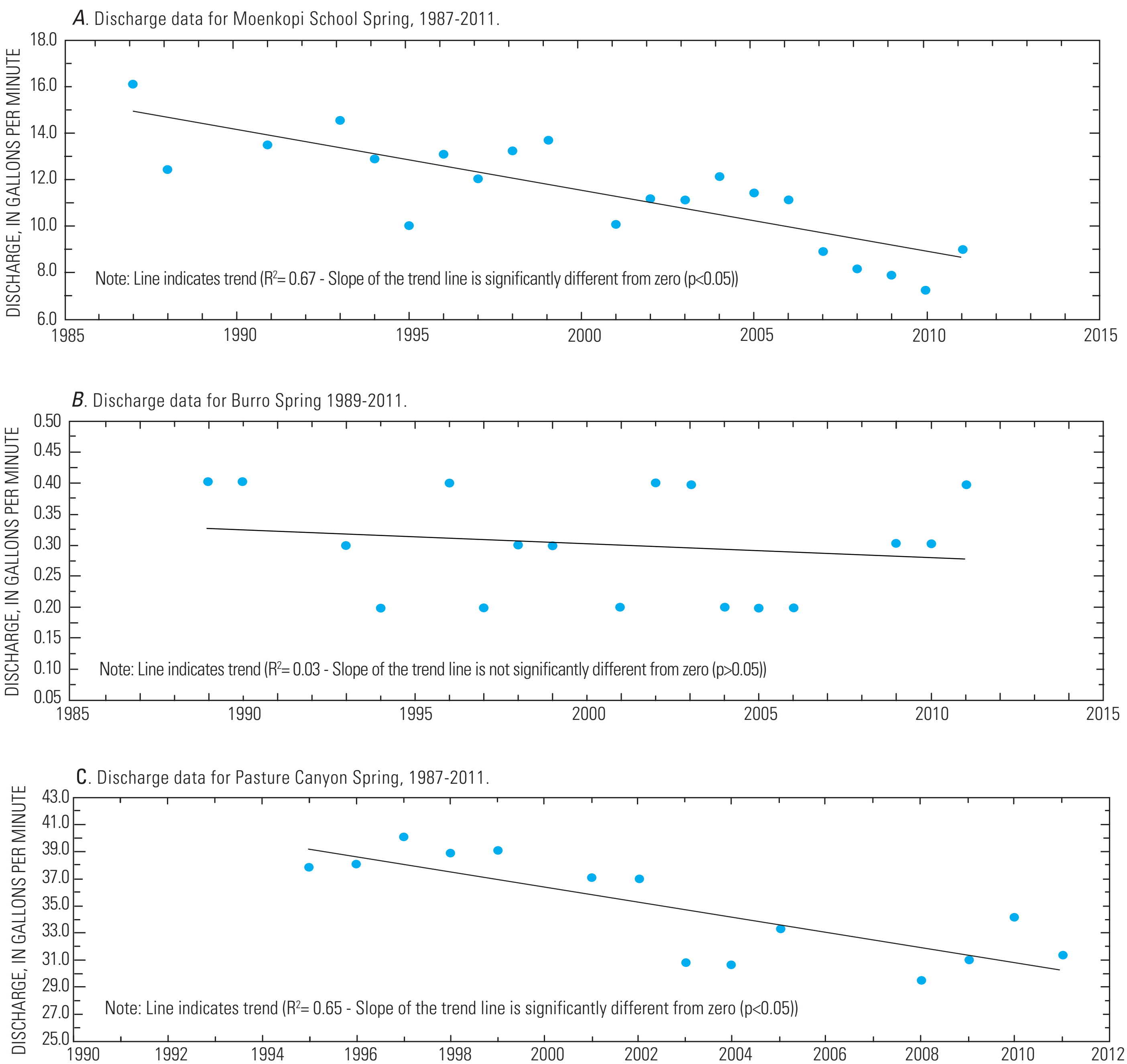


Figure 9. Discharge from *A*, Moenkopi School Spring, *B*, Burro Spring, and *C*, Pasture Canyon Spring, N Aquifer, Black Mesa area, northeastern Arizona, 1987–2011. Data from 1952 measurement at Moenkopi School Spring are not shown because measurement was from a different measuring location. Data from 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 9. Discharge measurements from three springs in the Black Mesa area, northeastern Arizona, 1952–2011.

[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			06–08–11	0.4
		05–31–07	[3]9.0				
		06–03–08	[3]8.3				
		06–03–09	[3]8.0				
		06–14–10	[3]7.4				
		06–10–11	[3]9.0				
Pasture Canyon Spring[1]							
3A-5	Navajo Sandstone, alluvium	11–18–88	[4]211				
		03–24–92	[4]233				
		10–12–93	[4]211				
		12–04–95	[5]38.0				
		12–16–96	[5]38.0				
		12–17–97	[5]40.0				
		12–10–98	[5]39.0				
		12–21–99	[5]39.0				
		06–12–01	[5]37.0				
		04–04–02	[5]37.0				
		05–01–03	[5]30.9				
		04–26–04	[5]30.6				
		04–27–05	[5]33.3				
		06–03–08	[5]29.4				
		06–03–09	[5]31.1				
		06–14–10	[5]34.3				
		06–09–11	[5]31.4				

[1]Volumetric discharge measurement.

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

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

[4]Discharge measured in an irrigation ditch about 0.25 mile below water-quality sampling point.

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

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

was assumed to represent constant annual groundwater discharge. Most flow that occurs during the winter is groundwater discharge; rainfall and snowmelt runoff are infrequent. Most 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 a calculation of base-flow groundwater discharge. A more rigorous and accurate calculation of base-flow would involve detailed evaluations of streamflow hydrographs, flows into and out of bank storage, gain and loss of streamflow as it moves down the stream channel, and interaction of groundwater in the N aquifer with groundwater in the shallow alluvial aquifers in the stream valleys. The median winter flow, however, is useful as a consistent index for evaluating possible time trends in groundwater discharge.

Median winter flows calculated for the 2010 water year were 1.1 ft^3/s for Moenkopi Wash at Moenkopi, 0.33 ft^3/s for Dinnebito Wash near Sand Springs, 0.27 ft^3/s for

Table 10. Discharge data (daily mean values), Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2010.

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

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2010—DAILY MEAN VALUES												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	e1.8	2.9	e2.7	2	1.4	0.03	0	e13	0	0	e0.06	1
2	1.7	3.2	e2.5	2.2	1	0.02	0	e225	0	0	0	e1.1
3	1.2	3.2	e2.3	2	1.4	0	0	e27	0	0	0.01	e1.2
4	e2.0	2.8	e2.3	1.9	1.2	0.01	0	e9.1	0	0	0.02	e1.1
5	2.2	e3.4	2.2	1.7	0.96	0	0	e13	0	1.7	0.04	0.79
6	1.8	e4.0	2	1.5	0.71	0	0	e125	0	164	e0.17	0.38
7	2.3	9.9	2.6	1.6	0.52	0	0	17	0	47	e0.18	e0.43
8	2.5	12	2.6	1.6	0.57	0	0	59	0	18	e0.19	e0.34
9	2.6	4.1	2.5	1.6	0.46	0	0	16	0	e14	0.26	e0.40
10	2.8	3	2.7	1.6	0.56	0	0	3.1	0	e11	0.21	e0.48
11	2.6	2.4	2.3	1.4	0.63	0	0	1.1	0	e7.2	0.51	e0.45
12	2	2.2	2	1.3	0.72	0	0	0.27	0	5.1	0.41	e0.37
13	2.4	2.3	2.2	1.4	1	0	0	0	0	e5.2	1.3	e0.43
14	2.4	2.2	2.6	1.4	1.1	0	0	0	0	1.8	0.47	e0.34
15	2.6	2.2	2.4	1.4	0.88	0	0	0	0	e2.1	0.9	e0.37
16	e2.6	2.2	2.1	1.4	0.88	0	0	0	0	e3.6	1.3	0.42
17	e2.7	2.2	2	1.4	0.81	e0.00	0	0	0	e1.9	0.99	0.64
18	2.1	2.4	2.3	1.3	0.68	e0.00	0	0	0	1.4	0.84	0.57
19	1.9	2.5	2.4	1.3	0.63	0	0	0	0	0.31	0.74	0.49
20	2.8	2.5	2	1.4	0.66	0	0	23	0	0.04	0.48	0.38
21	6.8	2.6	1.9	1.3	0.55	0	0	4.5	0	14	0.48	0.35
22	169	3.7	2	1.4	0.23	0	0	0.99	0	e4.7	0.38	0.43
23	47	2.7	2	1.5	0.15	0	0	0.47	0.19	1.8	0.62	0.47
24	e18	2.7	1.8	1.3	0.12	0	0	0	0	e0.82	0.45	0.27
25	e11	3	1.8	1.1	0.27	0	0	0	0	0.14	0.51	0.19
26	e9.9	2.9	1.8	1.1	0.32	0	e0.00	0	0.1	e0.14	1.3	0.17
27	e8.6	2.8	1.7	1	0.21	0	e111	0	0	e0.11	0.58	0.25
28	e9.7	2.9	1.6	1	0.08	0	e54	0	0	e0.11	1.2	0.28
29	e10	---	1.7	1.1	0.02	0	e37	0	0	0.05	e1.5	0.33
30	e6.3	---	1.9	1.5	0.04	0	e33	0	0	0	e1.3	e0.20
31	4.6	---	1.9	---	0.03	---	e80	0	---	0	---	e0.20
TOTAL	345.9	94.9	66.8	43.7	18.79	0.06	315	537.53	0.29	306.22	17.4	14.82
MEAN	11.2	3.39	2.15	1.46	0.61	0	10.2	17.3	0.01	9.88	0.58	0.48
MAX	169	12	2.7	2.2	1.4	0.03	111	225	0.19	164	1.5	1.2
MIN	1.2	2.2	1.6	1	0.02	0	0	0	0	0	0	0.17
MED	2.6	2.8	2.1	1.4	0.63	0	0	0.27	0	1.7	0.48	0.4
AC-FT	686	188	132	87	37	0.1	625	1070	0.6	607	35	29
CFSM	0.01	0	0	0	0	0	0.01	0.01	0	0.01	0	0

Calendar year 2009	Total 1,761.4	Mean 4.82	Max 225	Min 0.00	Median 0.72	Acre-ft 3,497	CFSM 0.003

Table 11. Discharge data (daily mean values), Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2010.

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

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2010—DAILY MEAN VALUES												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.48	0.35	0.32	0.39	0.27	0.25	0.18	62	0.18	0.18	0.32	0.09
2	e0.53	0.35	0.32	0.31	0.31	0.25	0.17	195	0.18	0.18	0.33	0.61
3	0.52	0.35	0.32	0.31	0.28	0.25	0.16	67	0.18	0.19	0.33	0.37
4	0.5	0.34	0.31	0.3	0.27	0.25	0.17	35	0.18	0.2	0.34	0.35
5	0.49	0.35	0.32	0.26	0.27	0.24	0.17	55	0.18	0.69	0.35	0.36
6	0.42	0.38	0.32	0.27	0.27	0.24	0.16	145	0.17	70	0.33	0.35
7	0.4	0.49	0.4	0.26	0.28	0.22	0.16	76	0.19	2.4	0.33	0.33
8	e0.39	0.29	0.35	0.26	0.28	0.22	0.16	8.8	0.19	0.32	0.33	0.33
9	0.36	0.29	0.38	0.26	0.26	0.22	0.16	1.8	0.18	0.28	0.33	0.34
10	0.37	0.29	0.38	0.27	e0.28	0.2	0.16	0.31	0.18	0.27	0.32	0.34
11	0.38	0.28	0.33	0.28	e0.28	0.22	0.16	0.2	0.19	0.27	0.34	0.33
12	0.39	0.28	0.33	0.28	e0.25	0.22	0.15	0.19	0.19	0.27	0.33	0.33
13	0.43	0.28	0.33	0.29	e0.27	0.23	0.14	0.17	0.19	0.27	0.35	0.32
14	0.45	0.28	0.32	0.28	0.28	0.21	0.14	0.18	0.18	0.27	0.37	0.34
15	0.42	0.28	0.3	0.28	0.28	0.21	0.15	0.17	0.19	0.27	0.36	0.35
16	0.42	0.28	0.3	0.28	0.28	0.2	0.14	0.18	0.19	0.27	0.35	0.59
17	0.43	0.34	0.3	0.28	0.27	0.2	0.15	0.18	0.18	0.27	0.33	0.43
18	0.46	0.46	0.3	0.28	0.27	0.19	0.16	0.19	0.18	0.28	0.31	0.4
19	0.6	0.33	0.3	0.26	0.27	0.18	0.15	0.19	0.18	0.28	0.31	0.37
20	0.88	0.34	0.29	0.26	0.27	0.19	0.16	27	0.18	0.29	0.31	0.35
21	5.9	0.33	0.3	0.25	0.26	0.18	0.17	12	0.17	15	0.31	0.35
22	6.9	0.39	0.3	0.27	0.24	0.18	0.22	0.83	17	4.2	0.3	0.36
23	0.42	0.33	0.3	0.26	0.24	0.18	2.2	0.26	54	0.6	0.3	0.45
24	0.34	0.33	0.3	0.26	0.26	0.17	16	0.22	4.9	0.31	0.32	0.36
25	0.36	0.33	0.3	0.25	0.27	0.19	10	0.2	0.4	0.33	0.28	0.36
26	0.36	0.32	0.3	0.26	0.26	0.18	1.1	0.21	0.21	0.32	0.28	0.36
27	0.43	0.32	0.29	0.26	0.24	0.17	e134	0.2	0.19	0.3	0.29	0.36
28	0.45	0.33	0.29	0.25	0.24	0.17	e37	0.2	0.18	0.31	0.31	0.35
29	0.37	---	0.3	0.27	0.24	0.16	75	0.18	0.18	0.32	0.31	0.41
30	0.36	---	0.29	0.28	0.25	0.16	124	0.18	0.18	0.31	0.09	0.4
31	0.36	---	0.29	---	0.25	---	e186	0.19	---	0.32	---	0.3
TOTAL	25.57	9.31	9.78	8.27	8.24	6.13	588.84	689.23	81.07	99.77	9.46	11.34
MEAN	0.82	0.33	0.32	0.28	0.27	0.2	19	22.2	2.7	3.22	0.32	0.37
MAX	6.9	0.49	0.4	0.39	0.31	0.25	186	195	54	70	0.37	0.61
MIN	0.34	0.28	0.29	0.25	0.24	0.16	0.14	0.17	0.17	0.18	0.09	0.09
MED	0.42	0.33	0.3	0.27	0.27	0.2	0.16	0.21	0.18	0.29	0.33	0.35
AC-FT	51	18	19	16	16	12	1170	1370	161	198	19	22
CFSM	0	0	0	0	0	0	0.04	0.05	0.01	0.01	0	0

Calendar year 2010	Total	Mean	Max	Min	Median	Acre-ft	CFSM
	1,547.0	4.2	195	0.09	0.29	3072	0.009

Table 12. Discharge data (daily mean values), Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2010.

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

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2010—DAILY MEAN VALUES												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	e0.24	0.21	0.27	0.25	0.26	0.17	0.01	1180	0.12	0.16	0.15	e0.24
2	e0.20	0.25	0.25	0.22	0.26	0.15	0.02	1130	0.52	0.11	0.15	e0.24
3	e0.20	e0.26	0.25	0.24	0.17	0.13	0.01	849	2.1	0.11	0.15	0.27
4	e0.24	e0.26	0.27	0.26	0.14	0.14	0.01	137	0.8	0.11	0.16	0.28
5	e0.23	e0.21	0.25	0.34	0.16	e0.15	0.01	125	0.25	0.16	0.15	0.24
6	e0.25	e0.23	0.23	0.27	0.14	e0.15	0.01	18	0.13	0.16	0.17	0.26
7	e0.24	e0.26	0.27	0.24	0.12	e0.15	0.01	25	0.18	0.13	0.16	e0.27
8	e0.25	e0.26	0.25	0.19	0.12	e0.15	0.01	28	0.12	0.13	0.17	e0.28
9	e0.27	e0.26	e0.25	0.2	0.17	0.15	0.01	2.3	0.11	0.12	0.16	e0.28
10	e0.24	e0.26	e0.26	0.18	e0.18	0.15	0.02	0.36	0.11	0.12	0.18	e0.28
11	e0.22	e0.28	e0.23	0.17	e0.15	0.14	0.02	0.23	0.11	0.12	0.18	e0.29
12	e0.31	e0.28	e0.23	0.2	e0.15	0.11	0.02	0.22	0.11	0.11	0.19	e0.29
13	e0.25	e0.24	e0.23	0.19	e0.15	0.09	0.01	0.19	0.11	0.12	0.18	e0.30
14	e0.28	e0.24	e0.25	0.19	0.14	0.09	0.02	0.18	0.11	0.12	0.17	e0.28
15	0.27	e0.26	e0.24	0.19	0.12	0.08	0.01	0.17	0.11	0.11	0.19	0.27
16	0.2	e0.22	e0.21	0.15	0.12	0.07	0.01	0.17	0.11	0.11	0.21	0.41
17	e0.16	e0.25	0.19	0.16	0.13	0.06	0.01	0.18	0.11	0.11	0.17	0.29
18	0.19	e0.24	0.2	0.2	0.15	0.06	0.01	0.17	0.11	0.11	0.22	0.23
19	0.15	0.24	0.19	0.24	0.16	0.05	0.01	181	0.11	0.1	0.24	0.24
20	0.17	0.22	0.18	0.25	0.14	0.04	0.02	85	0.11	0.11	0.19	0.21
21	0.22	0.23	0.21	0.27	0.14	0.04	0.02	10	0.11	0.19	0.23	0.21
22	e0.19	0.27	0.18	0.2	0.17	0.04	0.02	1.3	0.15	0.16	0.18	0.25
23	e0.21	e0.27	0.2	0.22	0.18	0.04	0.05	1.4	18	0.15	e0.20	0.29
24	e0.21	e0.26	0.21	0.2	0.18	0.03	0.07	0.21	20	0.15	e0.20	0.24
25	e0.23	0.22	0.22	0.2	0.17	0.03	0.07	0.28	0.53	0.16	e0.20	0.26
26	e0.25	e0.25	0.22	0.21	0.17	0.03	e28	0.15	0.36	e0.12	e0.18	0.24
27	e0.25	0.24	0.21	0.33	0.2	0.03	34	0.14	0.18	e0.14	e0.20	0.23
28	e0.25	0.29	0.24	0.46	0.2	0.03	102	0.34	0.16	0.15	e0.19	e0.26
29	e0.26	---	0.23	0.29	0.17	0.02	211	0.19	0.14	0.15	e0.23	e0.25
30	e0.23	---	0.24	0.25	0.16	0.02	225	0.15	0.14	0.16	e0.24	e0.26
31	e0.23	---	0.27	---	0.16	---	422	0.13	---	0.15	---	e0.27
TOTAL	7.09	6.96	7.13	6.96	5.03	2.59	1022.49	3776.46	45.31	4.11	5.59	8.21
MEAN	0.23	0.25	0.23	0.23	0.16	0.09	33	122	1.51	0.13	0.19	0.26
MAX	0.31	0.29	0.27	0.46	0.26	0.17	422	1180	20	0.19	0.24	0.41
MIN	0.15	0.21	0.18	0.15	0.12	0.02	0.01	0.13	0.11	0.1	0.15	0.21
MED	0.23	0.25	0.23	0.22	0.16	0.08	0.02	0.34	0.13	0.12	0.18	0.26
AC-FT	14	14	14	14	10	5.1	2030	7490	90	8.2	11	16
CFSM	0	0	0	0	0	0	0.04	0.13	0	0	0	0

Calendar year 2010	Total 4,898	Mean 13.4	Max 1,180	Min 0.01	Median 0.19	Acre-ft 9,716	CFSM 0.01

Table 13. Discharge data (daily mean values), Pasture Canyon Springs near Tuba City, Arizona (09401265), calendar year 2010.

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

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2010—DAILY MEAN VALUES												
DAY	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
1	0.34	0.3	0.28	0.32	0.32	0.31	0.25	0.22	0.23	0.3	0.34	0.34
2	0.35	0.3	0.3	0.32	0.32	0.31	0.25	0.23	0.23	0.31	0.34	0.34
3	0.36	0.3	0.3	0.34	0.34	0.31	0.25	0.23	0.23	0.31	0.34	0.34
4	0.36	0.3	0.3	0.34	0.34	0.31	0.25	0.21	0.23	0.31	0.34	0.32
5	0.36	0.3	0.29	0.32	0.34	0.31	0.24	0.21	0.23	0.33	0.34	0.32
6	0.36	0.33	0.28	0.3	0.34	0.3	0.23	0.2	0.23	0.34	0.34	0.32
7	0.34	0.34	0.31	0.3	0.34	0.3	0.23	0.22	0.24	0.33	0.34	0.32
8	0.34	0.32	0.31	0.32	0.36	0.3	0.23	0.23	0.25	0.32	0.34	0.32
9	0.34	0.3	0.31	0.32	0.36	0.3	0.23	0.22	0.25	0.32	0.34	0.32
10	0.34	0.28	0.32	0.32	0.35	0.28	0.23	0.21	0.25	0.32	0.34	0.32
11	0.34	0.28	0.31	0.32	0.32	0.28	0.23	0.2	0.25	0.32	0.34	0.32
12	0.33	0.28	0.3	0.32	0.33	0.28	0.23	0.2	0.25	0.32	0.34	0.32
13	0.32	0.28	0.3	0.3	0.33	0.28	0.23	e0.20	0.27	0.32	0.34	0.33
14	0.32	0.28	0.3	e0.31	0.32	0.28	0.23	e0.19	0.27	0.32	0.34	0.34
15	0.32	0.28	0.3	0.32	0.32	0.28	0.22	e0.18	0.28	0.32	0.34	0.34
16	0.32	0.28	0.3	0.32	0.32	0.28	0.21	0.18	0.29	0.32	0.34	0.33
17	0.32	0.28	0.3	0.33	0.32	0.27	0.21	0.18	0.3	0.32	0.34	0.34
18	0.32	0.28	0.32	0.33	0.32	0.27	0.21	e0.19	0.3	0.32	0.34	0.34
19	0.32	0.29	0.31	0.32	0.32	0.25	0.21	0.2	0.3	0.32	0.34	0.34
20	0.34	0.3	0.3	0.32	0.32	0.25	0.22	0.2	0.3	0.32	0.35	0.34
21	0.43	0.3	0.3	0.32	0.32	0.25	0.22	0.2	0.3	0.32	0.36	0.34
22	0.4	0.3	0.3	0.33	0.32	0.25	0.22	0.21	0.31	0.32	0.34	0.34
23	0.32	0.3	0.31	0.32	0.32	0.26	0.22	0.22	0.32	0.32	0.34	0.36
24	0.32	0.3	0.32	0.32	0.32	0.26	0.22	0.22	0.34	0.32	0.34	0.36
25	0.32	0.3	0.32	0.32	0.32	0.27	0.21	0.22	0.34	0.32	0.34	0.35
26	0.32	0.3	0.32	0.32	0.31	0.27	0.2	0.22	e0.33	0.34	0.34	0.34
27	0.3	0.28	0.32	0.33	0.31	0.27	0.2	0.22	e0.31	0.34	0.34	0.34
28	0.3	0.28	0.32	0.33	0.31	0.25	0.2	0.21	e0.31	0.34	0.34	0.33
29	0.3	---	0.32	0.32	0.31	0.25	0.2	0.21	e0.30	0.34	0.34	0.32
30	0.3	---	0.32	0.33	0.31	0.25	e0.21	0.22	0.29	0.34	0.34	0.34
31	0.3	---	0.32	---	0.31	---	0.23	0.23	---	0.34	---	0.34
TOTAL	10.35	8.26	9.51	9.63	10.09	8.33	6.92	6.48	8.33	10.03	10.23	10.36
MEAN	0.33	0.29	0.31	0.32	0.33	0.28	0.22	0.21	0.28	0.32	0.34	0.33
MAX	0.43	0.34	0.32	0.34	0.36	0.31	0.25	0.23	0.34	0.34	0.36	0.36
MIN	0.3	0.28	0.28	0.3	0.31	0.25	0.2	0.18	0.23	0.3	0.34	0.32
MED	0.32	0.3	0.31	0.32	0.32	0.28	0.22	0.21	0.28	0.32	0.34	0.34
AC-FT	21	16	19	19	20	17	14	13	17	20	20	21
Calendar year 2010	**Total 108.5**		**Mean 0.30**		**Max 0.43**	**Min 0.18**	**Median 0.31**		**Acre-ft 217**			

Polacca Wash near Second Mesa, and 0.34 ft^3/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 and others, 1998a, b, c; Wilde and Radtke, 1998; and Wilde and others, 1999). Field measurements include pH, specific conductance, temperature, dissolved oxygen, alkalinity, and discharge rates at springs. Field alkalinities were determined using incremental equivalence (Wilde, 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 protocols. Laboratory analyses for samples were done at the USGS National Water Quality Laboratory (NWQL) according to techniques described in Fishman and Friedman (1989), Fishman (1993), Struzeski and others (1996), and Garbarino and others (2006).

Quality assurance for this study was maintained through the use of proper training of field personnel, use of standard USGS field and laboratory protocols, collection of quality control samples, 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 during the past 10 years of the project; 4 of the wells have been sampled every year, and the other 8 wells have

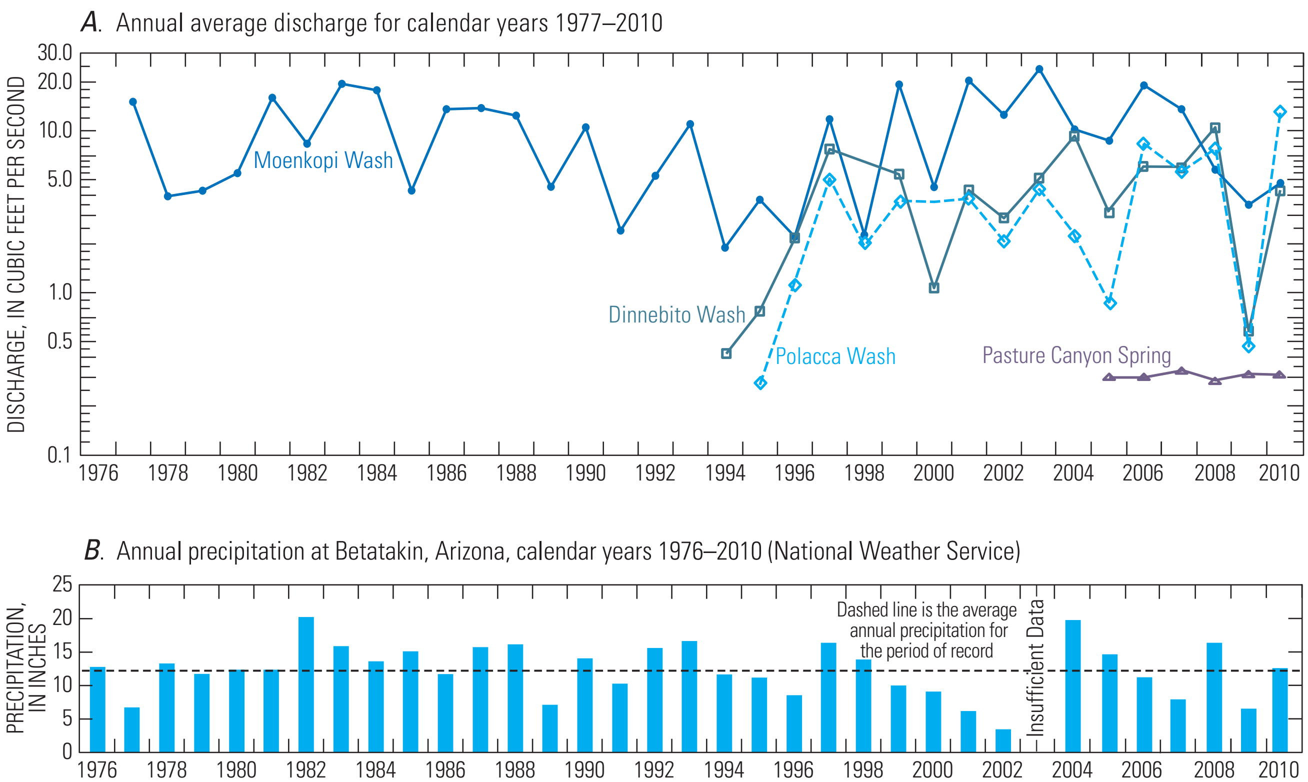


Figure 10. Annual average discharge at Moenkopi Wash at Moenkopi (09401260), Pasture Canyon Springs (09401265), Dinnebito Wash near Sand Springs (09401110), and Polacca Wash near Second Mesa (09400568), and annual precipitation at Betatakin, Arizona, Black Mesa area, northeastern Arizona. *A*, Annual average discharge for calendar years 1977–2010; *B*, Annual precipitation at Betatakin, northeastern Arizona, calendar years 1976–2010 (NCDC, 2011).

Table 14. 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	---

been selected on the basis of a sampling rotation. In 2011, water samples were collected at 11 well sites: Second Mesa PM2, Keams Canyon PM2, Kykotsmovi PM2, Piñon NTUA 1, Forest Lake NTUA 1, Kits'iili NTUA 2, Rough Rock PM5, Peabody 2, Peabody 5, 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 2011 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

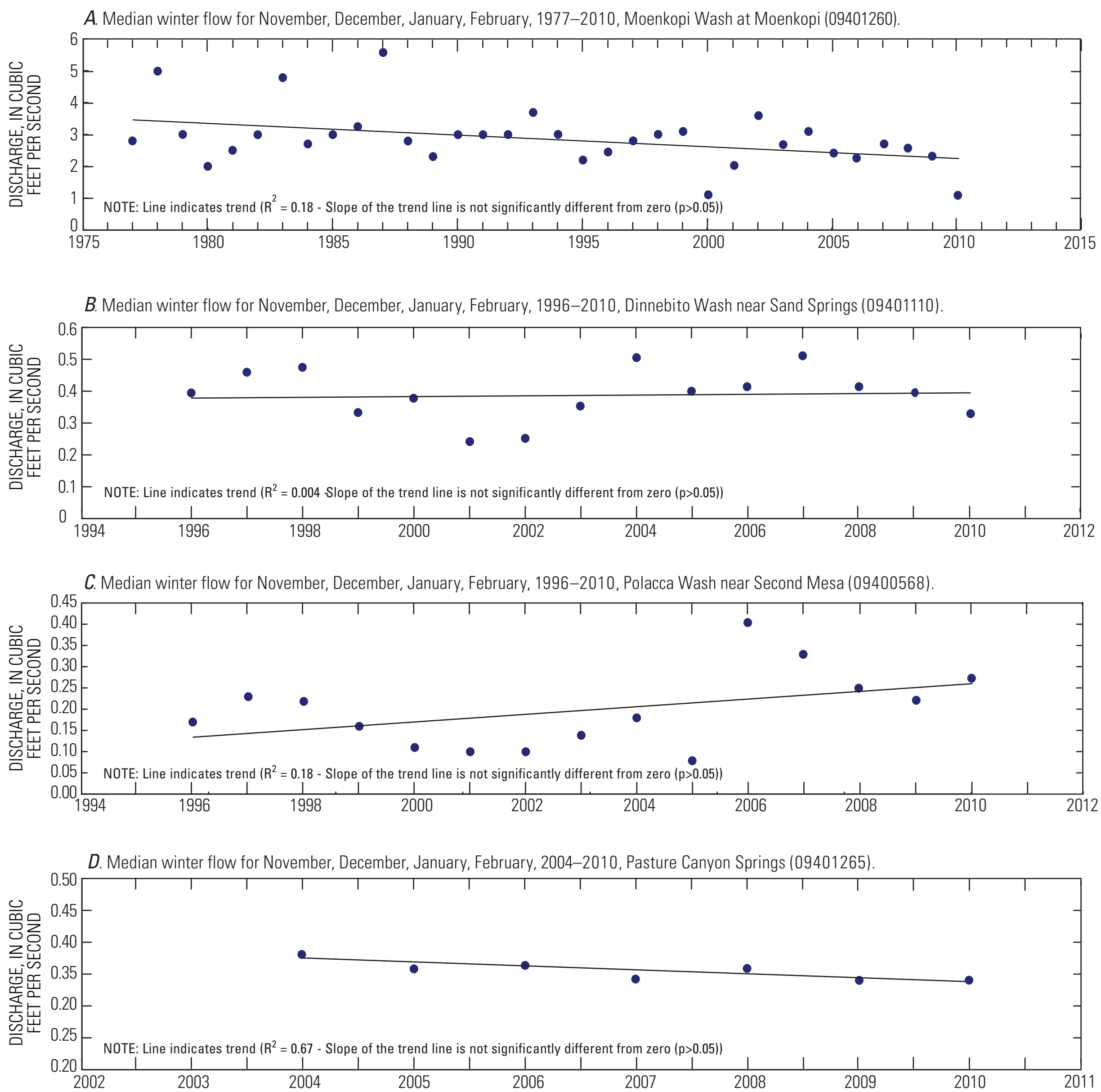


Figure 11. Median winter flow for November, December, January, and February for water years 1977–2010 for *A*, Moenkopi Wash at Moenkopi (09401260), *B*, Dinnebito Wash near Sand Springs (09401110), *C*, Polacca Wash near Second Mesa (09400568), and *D*, Pasture Canyon Springs (09401265), Black Mesa 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.

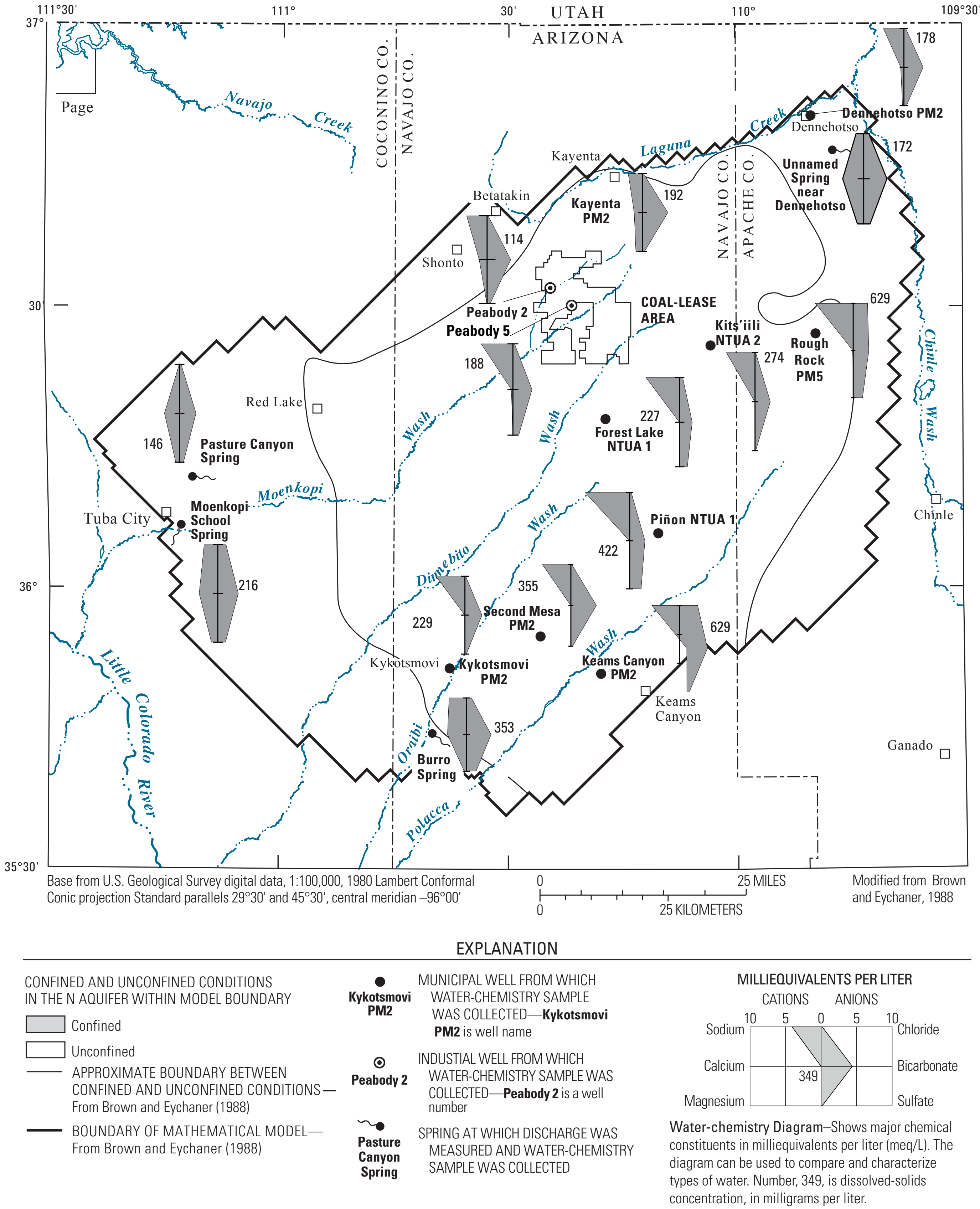


Figure 12. Water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, northeastern Arizona, 2011.

Table 15. Physical properties and chemical analyses of water samples from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, 2011.

[°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	Tempera-ture, field (°C)	Specific conduc-tance, field (µS/cm)	pH, field (units)	Dissolved (mg/L)					
						Alkalinity, field, ($CaCO^3$)	Nitrogen, $NO^2 + NO^3$	Ortho-Phosphate	Calcium	Magne-sium	Potas-sium
Second Mesa PM2	354749110300101	06–09–11	19.7	550	6.4	277	.02	.055	.49	.031	.44
Keams Canyon PM2	355023110182701	06–08–11	20.2	1080	8.7	343	<.02	<.004	.92	.179	.79
Kykotsmovi PM2	355215110375001	04–13–11	22.8	367	9.8	163	1.16	.041	.49	.015	.39
Piñon NTUA 1	360527110122501	06–07–11	27.0	629	9.4	234	1.28	.005	1.04	.148	.48
Forest Lake NTUA 1	361737110180301	06–06–11	29.8	369	8.9	94.6	.61	.005	.92	.082	.56
Kitsillie	362043110030501	06–07–11	29.8	449	9.3	166	1.37	<.004	.56	.015	.49
Rough Rock PM5	362418109514601	06–16–11	21.6	1090	8.4	219	1.04	.13	2.07	.29	1.34
Peabody 2	363005110250901	06–14–11	31.7	162	8.9	65.3	.97	.015	8.55	.139	.75
Peabody 5	362901110234101	06–14–11	31.9	311	8.8	113	1.00	.016	2.79	.045	.79
Kayenta PM2	364344110151201	06–16–11	17.4	302	7.5	143	.62	.013	18.4	8.84	1.33
Denehotso PM2	365045109504001	06–15–11	16.5	279	8.5	119	1.42	.010	7.38	1.94	.73

Common well name	U.S. Geological Survey identification number	Date of samples	Dissolved (mg/L)					Dissolved (µg/L)			Solids, residue at 180°C
			Sodium	Chloride	Flouride	Silica	Sulfate	Arsenic	Boron	Iron	
Second Mesa PM2	354749110300101	06–09–11	142	7.71	.32	19.5	16.3	19.7	91	5	355
Keams Canyon PM2	355023110182701	06–08–11	247	117	1.52	12.4	39.6	42.4	651	31	629
Kykotsmovi PM2	355215110375001	04–13–11	80.8	3.10	.21	23.9	8.35	5.0	30	5	229
Piñon NTUA 1	360527110122501	06–07–11	145	7.78	.31	26.1	77.8	4.6	74	6	422
Forest Lake NTUA 1	361737110180301	06–06–11	81.1	10.9	0.31	21.0	38	3.3	78	14	227
Kitsillie	362043110030501	06–07–11	104	3.88	.19	25.9	4.85	4.1	48	<3	274
Rough Rock PM5	362418109514601	06–16–11	231	135	1.74	12.4	119	51.6	382	18	629
Peabody 2	363005110250901	06–14–11	25.5	2.13	.14	22.0	8.12	3.0	16	6	114
Peabody 5	362901110234101	06–14–11	63.9	5.11	.25	20.7	24.30	3.0	35	6	188
Kayenta PM2	364344110151201	06–16–11	36.4	4.82	.27	19.5	11.1	4.1	43	5	192
Denehotso PM2	365045109504001	06–15–11	53.5	7.63	.21	12.0	13.9	6.3	36	<3	178

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 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 is generally in the recharge and unconfined areas of the northern and northwestern parts of the Black Mesa study area. Sodium bicarbonate water is generally in the area that is confined and downgradient to the south and east (Lopes and Hoffmann, 1997). Water-chemistry results from well samples for 2011 are presented in figures 12 and 13 and in table 15.

Rough Rock PM5 and Keams Canyon PM2 yield the highest dissolved-solids concentrations as well as the highest chloride concentrations of the 11 wells sampled. Rough Rock PM5 and Keams Canyon PM2 both had a dissolved-solids concentration of 629 mg/L (fig. 13 and table 15). Chloride concentrations were 135 mg/L at Rough Rock PM5 and 117 mg/L at Keams Canyon PM2 (table 15). Dissolved-solids concentrations in the other 9 wells ranged from 114 mg/L at Peabody 2 to 422 mg/L at Pinon NTUA 1, and their chloride concentrations ranged from 2.13 mg/L at Peabody 2 to 10.9 mg/L at Forest Lake NTUA 1 (table 15). Rough Rock PM5 had the highest sulfate concentration (119 mg/L) of the 11 wells, and the concentrations at the other wells ranged from 4.85 mg/L at Kits'iili NTUA 2 to 77.8 mg/L at Pinon NTUA 1 (table 15).

Samples from 1998 to present at Piñon NTUA 1 have shown varying sulfate, chloride and dissolved-solids concentrations (table 16). Purge times greater than 12 hours from Piñon NTUA 1 appear to induce leakage from the overlying D aquifer and result in higher 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 isotopic ratios of 87Sr/86Sr and major-ion data for groundwater indicate that D aquifer water has mixed with N aquifer water as a result of leakage (Truini and Longsworth, 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 2011, 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 µg/L): Second Mesa PM2 with a concentration of 19.7µg/L, Rough Rock PM5 with a concentration of 51.6 µg/L, and Keams Canyon PM2 with a concentration of 42.4 µg/L (table 15). The USEPA SMCL for concentration of dissolved solids (500 mg/L) was exceeded at Keams Canyon PM2 (629 mg/L), and Rough Rock MP5 (629 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, Peabody 2, and Peabody 5 (U.S. Environmental Protection Agency, 2003; table 15). The pH at Second Mesa PM2 (6.4) was below the USEPA SMCL for pH (U.S. Environmental Protection Agency, 2003; table 15).

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

In 2011, water samples were collected from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso (figs. 8 and 12). 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 to collect water from the spring. At Pasture Canyon Spring, samples were collected from a pipe at the end of a channel that is approximately 50 ft away from the spring. At Burro Spring, samples were collected from the end of a pipe that fills a trough for cattle. At Unnamed Spring near Dennehotso samples were collected from a pool along the bedrock wall from which the spring discharges.

The samples from all four springs yielded a calcium bicarbonate-type water (fig. 12 and table 17). Samples from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso had dissolved solid concentrations of 353 mg/L, 216 mg/L, 146 mg/L, and 172 mg/L, respectively (tables 17 and 18). Concentration of chloride was highest at Moenkopi School Spring (28.5 mg/L; tables 17 and 18). Concentration of sulfate was highest at Burro Spring (69.5 mg/L; tables 17 and 18). 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 18 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 (table 18 and fig. 14). However, in the last two years, Unnamed Spring near Dennehotso has shown an increase in dissolved solid concentrations (fig. 14).

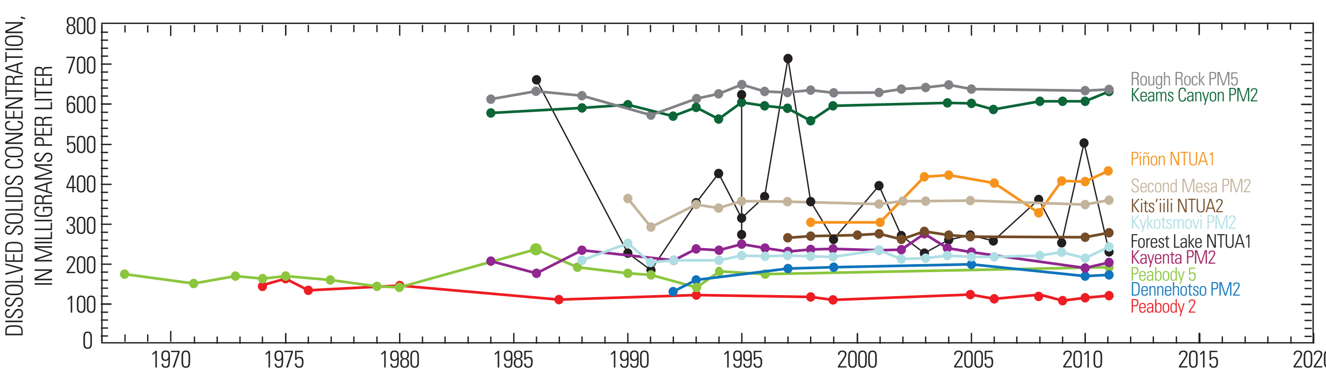


Figure 13. Dissolved-solids concentrations for water samples from selected wells, N aquifer, Black Mesa area, northeastern Arizona, 1974-2011: Rough Rock PM5, 1984–2011; Keams Canyon PM2, 1984–2011; Forest Lake NTUA 1, 1986–2011; Piñon NTUA 1, 1998–2011; Second Mesa PM2, 1990–2011; Kits'iili NTUA 2, 1997–2011; Kykotsmovi, 1988–2011; Kayenta PM2, 1984–2011; Dennehotso PM2, 1992–2011; Peabody 5, 1968–2011; and Peabody 2, 1974–2011.

Table 16. 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, 1974–2011.

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

Year	Specific conductance, field (µS/cm)	Dissolved, in mg/L: Solids, residue at 180°C	Dissolved, in mg/L: Chloride	Dissolved, in mg/L: Sulfate
Second Mesa PM2				
1968	670	---	14	35
1990	590	364	6.5	16
1991	595	292	10	15
1993	630	350	7.5	15
1994	605	342	7.6	15
1995	610	357	7.2	14
1997	646	356	7.1	14
2001	597	352	7.1	15
2002	608	357	7.5	14
2003	601	359	6.3	14
2005	615	361	6.8	13
2010	553	349	7	15
2011	550	355	7.7	16
Keams Canyon PM2				
1982	1,010	---	94	35
1983	1,120	---	120	42
1984	1,060	578	96	36
1988	1,040	591	97	34
1990	1,020	600	94	34
1992	1,010	570	93	36
1993	1,040	590	92	36
1994	975	562	86	32
1995	1,010	606	99	32
1996	1,020	596	96	34
1997	1,070	590	96	33
1998	908	558	78	29
1999	1,040	595	97	35
2004	945	[3]603	97	32
2005	828	601	97	34
2006	1,067	588	99	34
2008	1,079	607	95	34
2009	1,050	609	100	36
2010	965	607	104	35
2011	1,080	629	117	40
Kykotsmovi PM2				
1988	368	212	3.2	8.6
1990	355	255	3.2	9.0
1991	[1]374	203	4.4	7.9
1992	363	212	3.3	8.4
1994	[1]365	212	3.6	8.5
1995	368	224	3.1	6.2
1996	365	224	3.3	8.5
1997	[1]379	222	3.0	8.0
1998	348	223	3.3	7.3
1999	317	221	3.5	7.9
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
2011	367	229	3.1	8.4

Year	Specific conductance, field (µS/cm)	Dissolved, in mg/L: Solids, residue at 180°C	Dissolved, in mg/L: Chloride	Dissolved, in mg/L: Sulfate
Piñon NTUA 1				
1998	460	304	4.6	4.7
2001	473	304	4.9	5.5
2002	512	---	5.0	5.5
2003	716	421	6.7	83
2004	691	421	7.0	76
2006	709	399	6.6	67
2008	565	328	6.2	8.7
2009	646	409	7.1	68
2010	675	407	7.1	64
2011	629	422	7.8	78
Forest Lake NTUA 1				
1982	470		11	67
1986	---	660	35	300
1990	375	226	8.2	38
1991	[1]350	183	10	24
1993	693	352	35	88
1994	[1]734	430	56	100
1995	470	274	13	60
1995	1,030	626	86	160
1995	488	316	16	71
1996	684	368	44	79
1997	[1]1,140	714	78	250
1998	489	350	37	71
1999	380	259	16	49
2001	584	398	50	84
2002	452	268	22	50
2003	385	228	10	40
2004	222	263	16	40
2005	402	272	18	44
2006	445	258	14	49
2008	424	362	36	73
2009	384	250	12	44
2010	524	503	60	125
2011	369	227	11	38
Kits'iili NTUA 2				
1997	[1]524	269	3.6	4.3
1998	379	270	3.8	4.1
2000	454	274	4.0	4.1
2001	409	276	5.0	4.5
2002	439	264	4.5	4.4
2003	445	275	4.2	4.4
2004	367	273	4.0	4.6
2005	424	271	3.7	3.7
2010	457	269	3.8	4.7
2011	449	274	3.9	4.8

[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.

Table 16. 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, 1974–2011.—Continued

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

Year	Specific conductance, field (µS/cm)	Dissolved, in mg/L		
		Solids, residue at 180°C	Chloride	Sulfate
Rough Rock PM5				
1964	1,120	([2])	100	110
1970	610	([2])	13	50
1983	1,090	([2])	130	110
1984	[1]1,100	613	130	99
1986	1,010	633	140	120
1988	1,120	624	130	[3]110
1991	[1]1,210	574	130	110
1993	1,040	614	130	110
1994	[1]1,180	626	130	110
1995	1,110	648	140	110
1996	1,100	634	130	110
1997	[1]1,060	628	130	112
1998	894	637	133	112
1999	1,050	630	129	110
2001	980	628	125	110
2002	1,120	636	129	109
2003	1,080	642	127	110
2004	653	649	128	109
2005	1,053	639	128	113
2010	1,101	635	129	114
2011	1,090	629	135	119
Peabody 2				
1967	221	---	5.0	21
1971	211	---	2.8	18
1974	210	144	2.8	17
1975	230	163	5.0	20
1976	260	133	3.6	16
1979	220	---	3.4	24
1980	225	145	11.0	20
1986	172	---	2.6	8.1
1987	149	113	5.0	9.1
1993	163	124	1.7	8.9
1998	93	119	2.2	7.9
1999	167	115	2.3	8.1
2005	134	124	2.1	8.2
2006	167	118	2.2	8.2
2008	160	120	2.0	7.5
2009	146	113	2.1	7.2
2010	168	119	2.1	7.4
2011	162	114	2.1	8.1
Dennehotso PM2				
1964	350	---	12	31
1992	226	131	9.8	19
1993	298	164	8.2	16
1997	[1]305	190	11	14
1999	314	196	14	15
2005	339	205	10.5	14
2010	279	173	7.4	13
2011	279	178	7.6	14
Kayenta PM2				
1982	360	([2])	4.5	58
1983	375	([2])	5.9	60
1984	[1]370	209	4.2	51
1986	300	181	8.2	30
1988	358	235	3.8	74
1992	383	210	5.6	78
1993	374	232	3.7	78
1994	[1]371	236	4.2	77
1995	371	250	4.2	72
1996	370	238	3.8	76
1997	379	230	3.9	77
1998	349	236	3.7	71
1999	364	236	4.0	72
2001	331	234	5.0	3
2002	363	237	5.1	67
2003	378	273	5.9	88
2004	303	241	4.0	72
2005	374	231	3.7	76
2010	308	191	4.7	11
2011	302	192	4.8	11
Peabody 5				
1968	224	168	3.5	16
1971	226	145	2.1	12
1973	---	162	---	---
1974	210	157	2.7	12
1975	240	162	4.0	18
1977	220	158	3.0	13
1977	220	155	3.0	12
1979	220	142	2.9	15
1980	210	135	2.9	9.5
1986	398	231	8.0	28
1987	270	---	4.6	21
1988	270	187	5.1	22
1988	263	183	4.1	26
1990	262	176	4.1	18
1991	260	168	3.0	18
1993	257	138	2.3	4.8
1994	279	175	4.7	20
1996	---	---	4.1	18
1996	274	169	4.1	19
2011	311	188	5.1	24

[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.

Table 17. Physical properties and chemical analyses of water samples from four springs in the Black Mesa area, northeastern Arizona, 2011.

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

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Temperature, field (°C)	Specific conductance field (µS/cm)	pH, field (units)	Dissolved, in mg/L					
							Alkalinity ($CaCO^3$)	Nitrogen, $NO^2 + NO^3$	Ortho-Phosphate	Calcium	Magnesium	Potassium
354156110413701	6M-31	Burro Spring	06–08–2011	20.3	560	7.2	188	.02	<.004	58.6	4.42	.29
360632111131101	3GS-77-6	Moenkopi School Spring	06–10–2011	18.2	374	6.6	101	2.28	.011	36.5	7.54	1.32
361021111115901	3A-5	Pasture Canyon Spring	06–09–2011	17.3	236	7.2	81.5	4.40	0.21	29.6	4.40	1.30
364656109425400	8A-224	Unnamed Spring near Dennehotso	06–15–2011	14.0	292	7.8	91.6	1.75	.041	33.0	6.02	1.63

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Dissolved, in mg/L					Dissolved, in µg/L			
				Sodium	Chloride	Flouride	Silica	Sulfate	Arsenic	Boron	Iron	Dissolved solids, residue at 180°C (mg/L)
354156110413701	6M-31	Burro Spring	06–08–2011	61.5	25.7	.37	17.1	69.5	.78	74	45	353
360632111131101	3GS-77-6	Moenkopi School Spring	06–10–2011	30.6	28.5	.15	14.0	36.2	2.4	42	<3	216
361021111115901	3A-5	Pasture Canyon Spring	06–09–2011	.59	5.47	.16	10.3	18.5	1.9	32	<3	146
364656109425400	8A-224	Unnamed Spring near Dennehotso	06–15–2011	13.8	14.50	.59	13.0	24.1	2.2	45	3	172

Table 18. Specific conductance and concentrations of selected chemical constituents in N-aquifer water samples from four springs in the Black Mesa area, northeastern Arizona, 1948–2011.

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

Year	Specific conductance, field (µS/cm)	Dissolved, in mg/L		
		Solids, residue at 180°C	Chloride	Sulfate
Burro Spring				
1989	485	308	22.0	59.0
1990	[1]545	347	23.0	65.0
1993	595	368	30.0	85.0
1994	[1]597	368	26.0	80.0
1996	525	324	23.0	62.0
1997	[1]511	332	26.0	75.0
1998	504	346	24.6	70.4
1999	545	346	24.8	69.2
2001	480	348	23.6	67.8
2002	591	374	30.6	77.0
2003	612	374	30.5	81.1
2004	558	337	24.9	63.6
2005	558	357	25.8	68.9
2006	576	359	25.0	68.2
2009	577	372	25.7	72.5
2010	583	355	25.9	71.5
2011	560	353	25.7	69.5
Moenkopi School Spring				
1952	222	---	6.0	---
1987	270	161	12.0	19.0
1988	270	155	12.0	19.0
1991	297	157	14.0	20.0
1993	313	204	17.0	27.0
1994	305	182	17.0	23.0
1995	314	206	18.0	22.0
1996	332	196	19.0	26.0
1997	[1]305	185	17.8	23.8
1998	296	188	17.6	23.7
1999	305	192	18.7	25.6
2001	313	194	18.3	25.5
2002	316	191	18.3	23.1
2003	344	197	18.6	23.4
2004	349	196	19.1	21.3
2005	349	212	23.3	29.6
2006	387	232	27.2	34.2
2007	405	238	30.6	39.9
2008	390	230	28.3	37.6
2009	381	240	27.0	35.4
2010	480	217	26.2	33.4
2011	374	216	28.5	36.2
Pasture Canyon Spring				
1948	[1]227	([2])	6.0	13.0
1982	240	---	5.1	18.0
1986	257	---	5.4	19.0
1988	232	146	5.3	18.0
1992	235	168	7.10	17.0
1993	242	134	5.3	17.0
1995	235	152	4.80	14.0
1996	238	130	4.70	15.0
1997	232	143	5.27	16.9
1998	232	147	5.12	16.2
1999	235	142	5.06	14.2
2001	236	140	5.06	17.0
2002	243	143	5.14	16.5
2003	236	151	5.09	16.1
2004	248	150	5.50	16.4
2005	250	149	5.07	16.3
2008	240	149	5.01	18.3
2009	241	160	5.10	18.6
2010	314	157	5.25	17.9
2011	236	146	5.47	18.5
Unnamed Spring near Dennehotso				
1984	195	112	2.8	7.1
1987	178	[2]109	3.4	7.5
1992	178	108	3.60	7.30
1993	184	100	3.2	8.00
1995	184	124	2.60	5.70
1996	189	112	2.80	8.20
1997	[1]170	98	2.40	6.10
1998	179	116	2.43	5.36
1999	184	110	2.76	6.30
2001	176	116	2.61	5.96
2002	183	104	2.67	7.38
2003	180	118	2.95	7.16
2004	170	117	2.72	5.05
2005	194	114	2.65	8.67
2010	259	155	9.38	15.5
2011	292	172	14.5	24.1

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

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

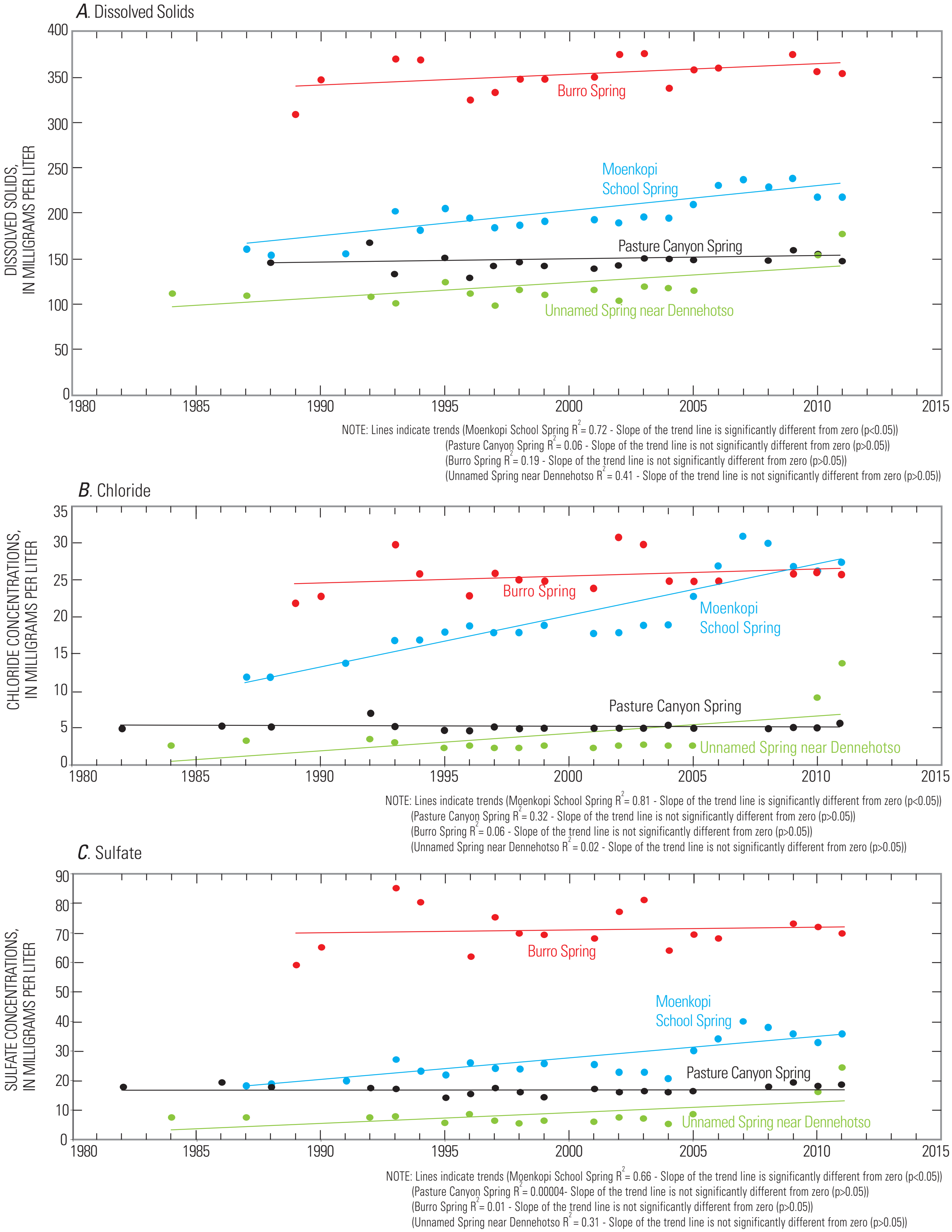


Figure 14. Concentrations of dissolved solids, chloride, and sulfate for water samples from Moenkopi School Spring, Pasture Canyon Spring, Burro Spring and Unnnamed Spring near Dennehotso, N aquifer, Black Mesa area, northeastern Arizona, 1982–2011. *A*, Dissolved solids; *B*, Chloride; *C*, Sulfate. (Trend lines were generated by using the method of least squares.)

Summary

The N aquifer is an extensive aquifer and the primary source of groundwater for industrial and municipal users in the Black Mesa area of northeastern Arizona. Availability of 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 2010 to September 2011. The monitoring data for 2010–11 are compared to data for 2009–10 and to historical data from the 1950s to September 2011.

In 2010, total groundwater withdrawals were about 3,950 acre-ft; industrial withdrawals were about 1,170 acre-ft, and municipal withdrawals were about 2,780 acre-ft. From 2009 to 2010, total withdrawals from the N aquifer decreased by 7 percent, industrial withdrawals decreased by approximately 16 percent, and total municipal withdrawals decreased by 2 percent.

From 2010 to 2011, annually measured groundwater levels declined in 18 of 33 wells available for comparison. The median water-level change for the 33 wells was -0.2 ft. In unconfined areas of the N aquifer, water levels declined in 7 of 15 annual wells available for comparison, and the median change was 0.0 ft. In the confined area of the N aquifer, water levels declined in 11 of 18 wells, and the median change was -0.7 ft. From the prestress period (before 1965) to 2011, the median groundwater level change in 33 wells was -15.0 ft. Water levels in the 15 wells in the unconfined areas of the N aquifer had a median change of -1.2 ft, and the changes ranged from -35.6 ft to +13.9 ft. Water levels in the 18 wells in the confined area of the N aquifer had a median change of -41.2 ft, and the changes ranged from -213.9 ft to +12.6 ft.

Discharge has been measured annually at Moenkopi School Spring and Pasture Canyon Spring and intermittently at Burro Spring. Between 2010 and 2011, spring flow increased by 21 percent at Moenkopi School Spring, and spring flow decreased by 8 percent at Pasture Canyon Spring. Discharge at Burro Spring 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 discharge at four streamflow-gaging stations—Moenkopi Wash, Dinnebito Wash, Pasture Canyon Springs, and Polacca Wash—varied 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 353 mg/L, 216 mg/L, 146 mg/L, and 172 mg/L, respectively. From the mid 1980s to 2011, 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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