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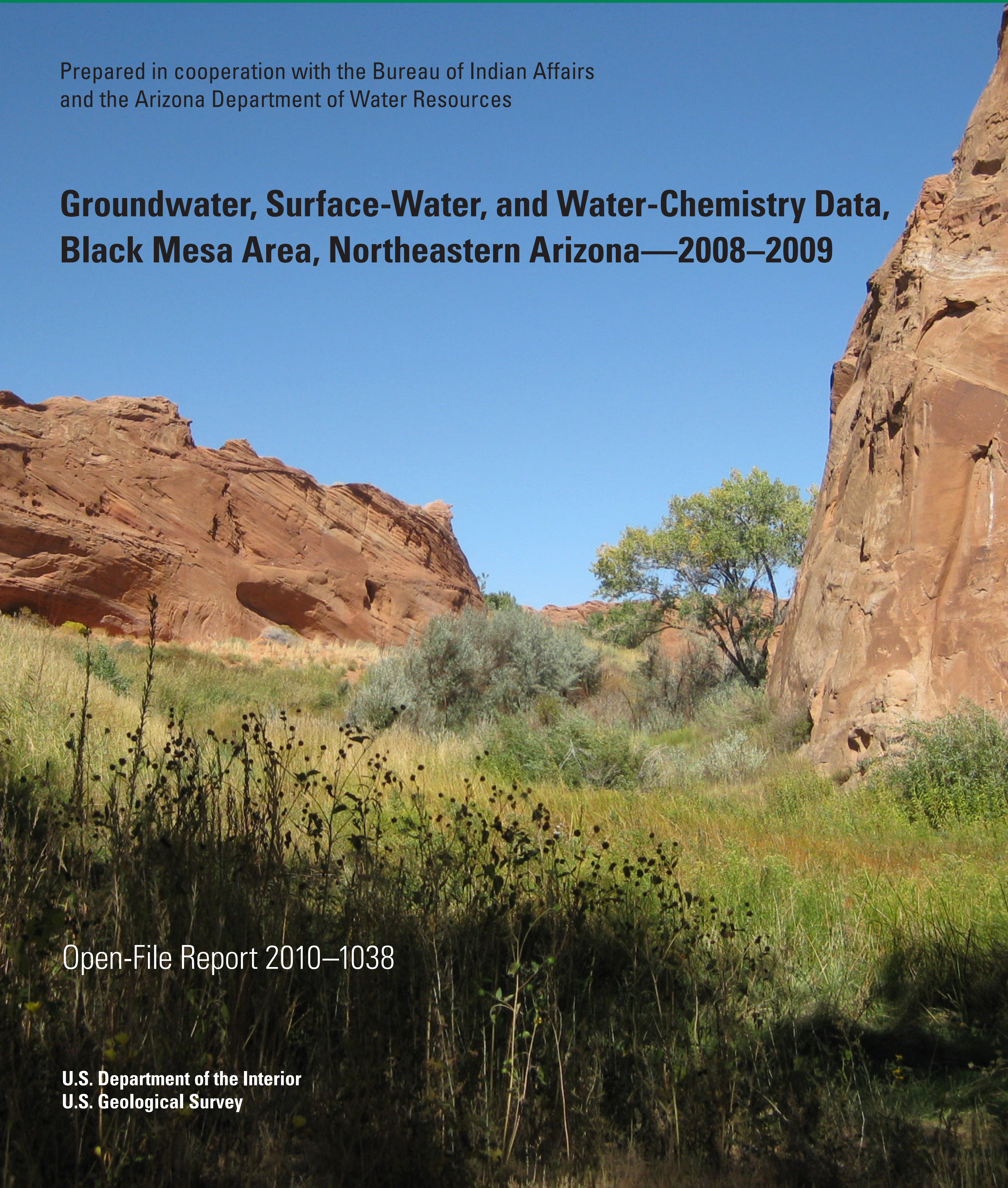

Prepared in cooperation with the Bureau of Indian Affairs
and the Arizona Department of Water Resources

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2008–2009

Open-File Report 2010–1038

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

Cover—Pasture Canyon, Arizona, during the summer. (USGS photograph taken by Geoff DeBenedetto.)

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

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

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Conversion Factors and Datum

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)

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).

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2008–2009

By Jamie P. Macy

Abstract

The 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, which is typically about 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 2008 to September 2009. The monitoring program includes measurements of (1) groundwater withdrawals, (2) groundwater levels, (3) spring discharge, (4) surface-water discharge, and (5) groundwater chemistry.

In 2008, total groundwater withdrawals were 4,110 acre-feet, industrial withdrawals were 1,210 acre-ft, and municipal withdrawals were 2,900 acre-ft. Total withdrawals during 2008 were about 44 percent less than total withdrawals in 2005. From 2007 to 2008 total withdrawals decreased by 4 percent, industrial withdrawals increased by approximately 3 percent, but total municipal withdrawals decreased by 6 percent.

From 2008 to 2009, annually measured water levels in the Black Mesa area declined in 8 of 15 wells that were available for comparison in the unconfined areas of the N aquifer, and the median change was −0.1 feet. 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 −0.2 feet. From the prestress period (prior to 1965) to 2009, the median water-level change for 34 wells in both the confined and unconfined area was −11.8 feet. Also, from the prestress period to 2009, the median water-level changes were −1.6 feet for 16 wells measured in the unconfined areas and −36.7 feet for 18 wells measured in the confined area.

Spring flow was measured at three springs in 2009. 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 constant since it was first measured in 1998.

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 2008), Dinnebito Wash near Sand Springs 09401110 (1993 to 2008), Polacca Wash near Second Mesa 09400568 (1994 to 2008), and Pasture Canyon Springs 09401265 (August 2004 to 2008). 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 2009, water samples collected from 6 wells and 3 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 6 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 trend in those data. Concentrations of dissolved solids, chloride, and sulfate at Burro Spring have varied for the period of record, but there is no trend in the data.

Introduction

The 5,400 mi^2 Black Mesa study area in northeastern Arizona contains a diverse topography that includes flat plains, mesas, and incised drainages (fig. 1). Black Mesa is a topographic high at the center of the study area that covers about 2,000 mi^2. It has 2,000-foot-high cliffs on its northern and northeastern sides, but slopes gradually down to the south and southwest. Availability of water is an important issue in the study area because of continued groundwater withdrawals, the growing population, and average annual precipitation in the arid to semiarid climate, which ranges between 6 and 14 in. (U.S. Department of Agriculture, 1999). The Navajo (N) aquifer is the major source of water for industrial and municipal uses in the Black Mesa area. The N aquifer is composed of three

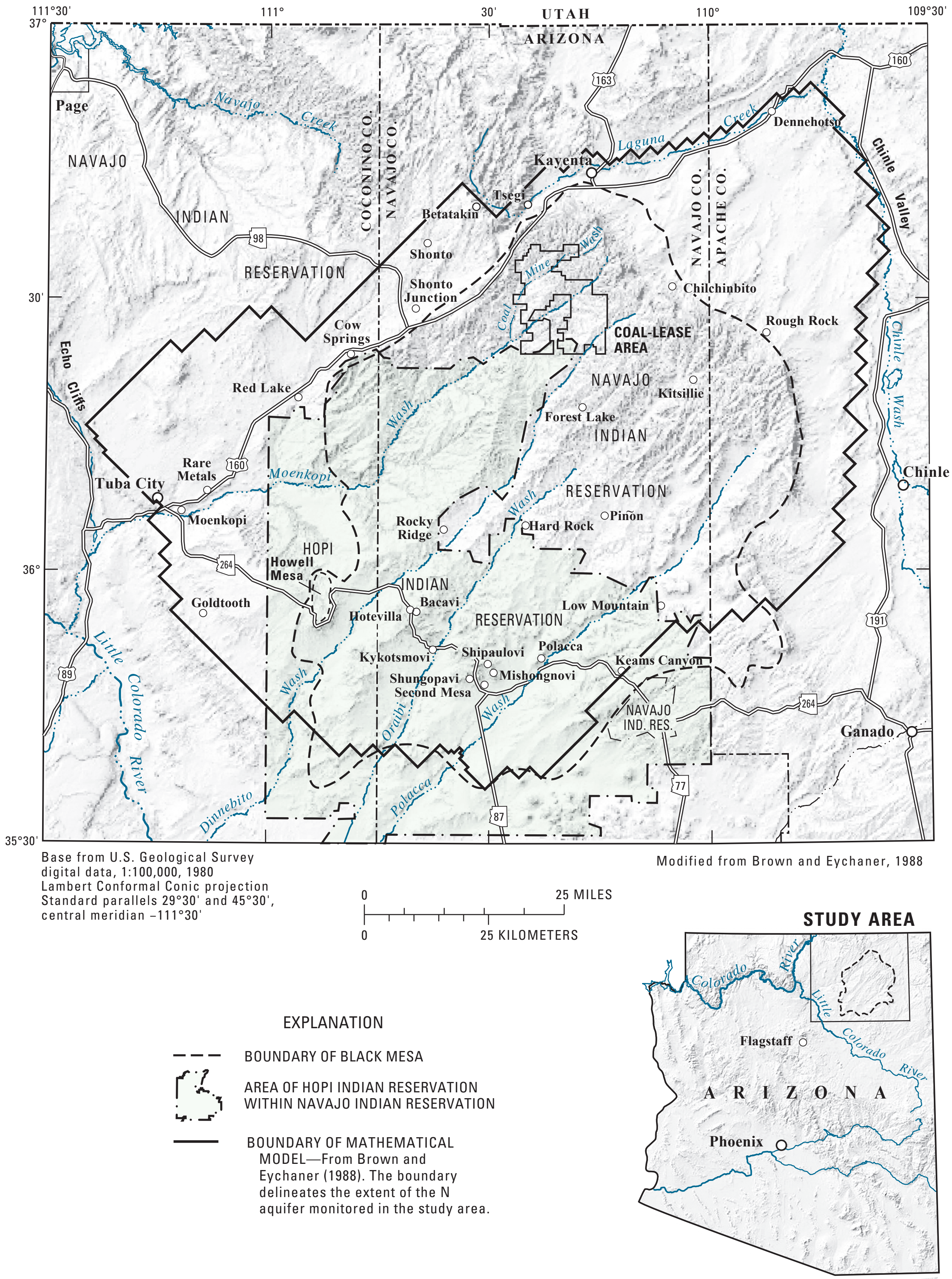


Figure 1. Study area, Black Mesa area, northeastern Arizona.

hydraulically connected formations—the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member of the Wingate Sandstone—that function as a single aquifer (fig. 2).

The N aquifer is confined under most of Black Mesa, and the overlying stratigraphy limits recharge to this part of the aquifer. The N aquifer is unconfined in areas surrounding Black Mesa, and most recharge occurs where the Navajo Sandstone is exposed in the area near Shonto (fig. 1) (Lopes and Hoffmann, 1997).

Within the Black Mesa study area, the Navajo Nation and Hopi Tribe are the principal municipal water users, and Peabody Western Coal Company (PWCC) is the principal industrial water user. Withdrawals from the N aquifer in the Black Mesa area have been increasing during the past 40 years (table 1). PWCC began operating a strip mine in the northern part of the study area in 1968 (fig. 1). 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. In 2005, PWCC pumped about 4,480 acre-ft of water.

The period before appreciable groundwater withdrawals began for mining or municipal purposes (about 1965) is referred to in this report as the prestress period. On December 31, 2005, PWCC reduced pumping of the N aquifer by approximately 70 percent as a result of discontinued use of a coal slurry pipeline. PWCC planned to continue to pump approximately 1,000 to 1,500 acre-ft per year, primarily for dust control. Between 2006 and 2008 PWCC pumped about 1,200 acre-ft of water per year (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 2008 to September 2009. 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, this assemblage of data provides measurements that indicate the

Table 1. Withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2008.

[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	1,300[4]	1,600[4]	4,100[4]
2007	1,170	1,460	1,640	4,270
2008	1,210	1,560	1,340	4,110

[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; metered pumpage furnished by the Navajo Tribal Utility Authority, the Bureau of Indian Affairs, various Hopi Village Administrations, and the U.S. Geological Survey, 1986–2008.

[4]NTUA meter data was not available for 2006, therefore, municipal withdrawals are estmated, and total withdrawal uses an estimation in the calculation.

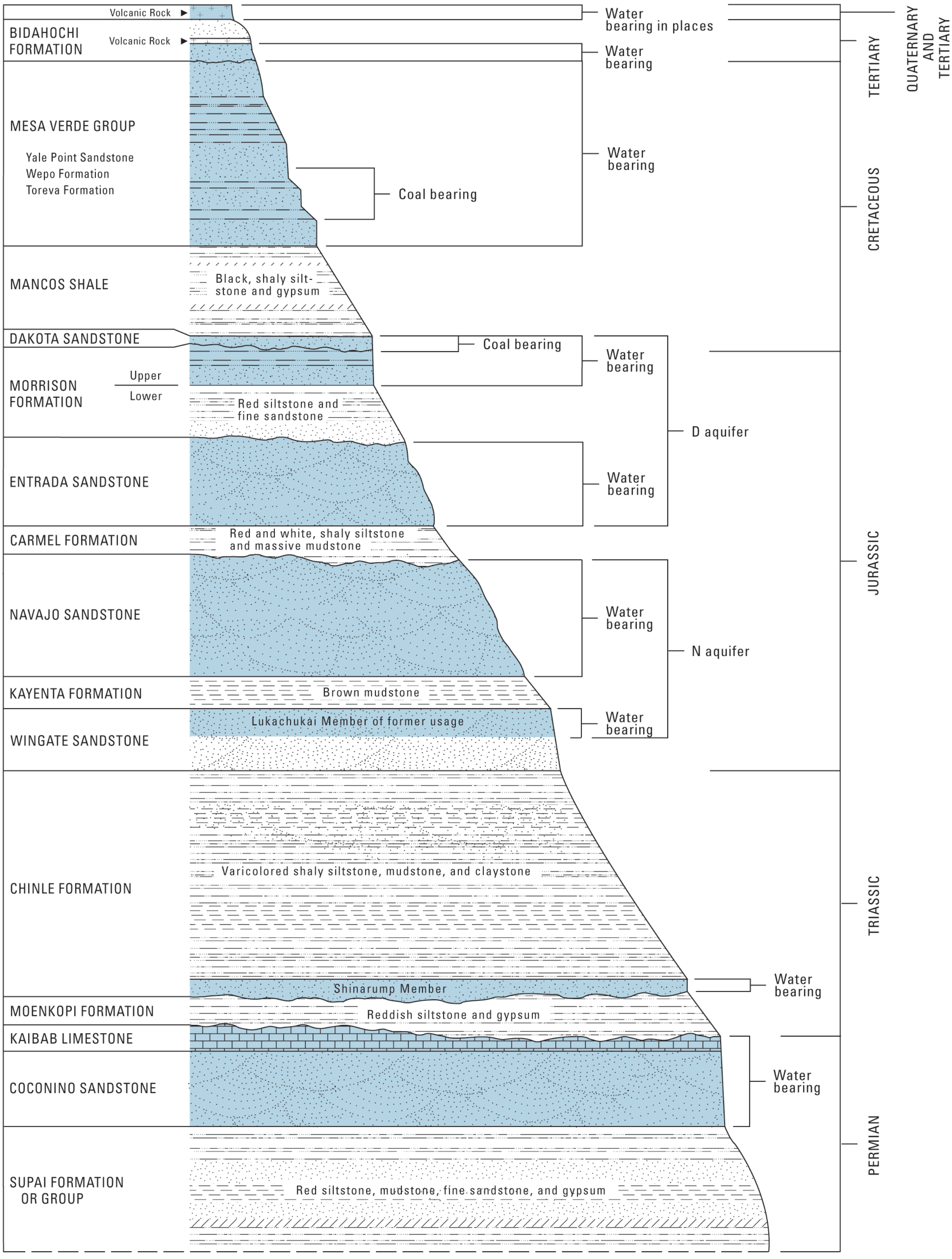


Figure 2. Rock formations and hydrogeologic units of the Black Mesa area, northeastern Arizona (not to scale). The N aquifer is approximately 1,000 feet thick.

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.

Previous Investigations

Twenty-six progress reports on the Black Mesa area monitoring program have been prepared by the USGS (U.S. Geological Survey, 1978; G.W. Hill, Hydrologist, written commun., 1982, 1983; Hill, 1985; Hill and Whetten, 1986; Hill and Sottilare, 1987; Hart and Sottilare, 1988, 1989; Sottilare, 1992; Littin, 1992, 1993; Littin and Monroe, 1995a, 1995b, 1996, 1997; Littin and others, 1999; Truini and others, 2000; Thomas and Truini, 2000; Thomas, 2002a, 2002b; Truini and Thomas, 2004; Truini and others, 2005; Truini and Macy, 2006, 2007, 2008; Macy, 2009). 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 2003 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), and online at (http://wdr.water.usgs.gov/wy2008/search.jsp) in the 2008 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 detailed three-dimensional numerical model of the N aquifer and the overlying Dakota (D) aquifer.

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water collected from wells and springs in the Black Mesa area. HSIGeoTrans, Inc. (1993) evaluated the major-ion and isotopic chemistry of the D and N aquifers. Lopes and Hoffmann (1997) analyzed groundwater ages, recharge, and hydraulic conductivity of the N aquifer by using geochemical techniques. Zhu and others (1998) estimated groundwater recharge in the Black Mesa area by using isotopic data and flow estimates from the N-aquifer model developed by GeoTrans, Inc. (1987). Zhu (2000) estimated recharge using advective transport modeling and the same isotopic data from the GeoTrans model. Truini and Longsworth (2003) described the hydrogeology of the D aquifer and the movement and ages of groundwater in the Black Mesa area by using data from geochemical and isotopic analyses. Truini and Macy (2005) 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 2008–9, activities of the Black Mesa area monitoring program included metered groundwater withdrawals, measurements of groundwater levels, streamflow gaging, spring discharge measurements, and the collection of water-chemistry samples from wells and springs. Linear regression trend analyses were applied to streamflow data, spring discharge measurements, and water-chemistry samples. Annual discharge measurements were made at 3 springs, and annual groundwater-level measurements were made at 34 wells. Of those 34 wells, 6 are continuous-recording observation wells that have been upgraded for real-time data telemetry (table 2). 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 collected from January to December 2008. Spring discharges and groundwater levels were measured from January to June 2009. Groundwater samples were collected from six wells and three springs in June 2009 and were analyzed for chemical constituents. Annual groundwater-withdrawal data are collected from 28 well systems within the NTUA, BIA, and Hopi municipal systems and the PWCC industrial well field. Identification information for the 34 wells used for water-level measurements and water-quality sampling is shown in table 2. 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 1st and ending December 31st.

Withdrawals from the N Aquifer

Total annual withdrawals from the N aquifer are monitored on a continuing basis to determine the effects from industrial and municipal pumping. Withdrawals from the N aquifer are separated into three categories: (1) industrial withdrawals from the confined area, (2) municipal withdrawals from the confined area, and (3) municipal withdrawals from the unconfined areas. The industrial category includes eight wells in the PWCC well field in the northern Black Mesa area. The BIA, NTUA, and Hopi Tribe operate about 70 municipal wells that are combined into 28 well systems. Information about withdrawals from the N aquifer is

Table 2. Identification numbers and names of monitoring program study wells, 2008–9, 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
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
363005110250901	Peabody 2	—
362406110563201	White Mesa Arch	1K-214
362647110243501	Peabody 4	—
362823109463101	Rough Rock	10R-119
362936109564101	BM observation well 1	8T-537
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
363727110274501	Long House Valley	8T-510
363850110100801	BM observation well 2	8T-538
364226110171701	Kayenta West	8T-541
364248109514601	Northeast Rough Rock	8A-180
364338110154601	BM observation well 3	8T-500
364034110240001	Marsh Pass	8T-522

Table 3. Withdrawals from the N aquifer by well system, Black Mesa area, northeastern Arizona, calendar year 2008.

[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	2.9	
Dennehotso	BIA	USGS/BIA		23.7
Hopi High School	BIA	USGS/BIA	27.5	
Hotevilla	BIA	USGS/BIA	22.6	
Kayenta	BIA	USGS/BIA	39.4	
Keams Canyon	BIA	USGS/BIA	57.3	
Low Mountain	BIA	USGS/BIA	[1]0	
Piñon	BIA	USGS/BIA	[1]0	
Red Lake	BIA	USGS/BIA		2.1
Rocky Ridge	BIA	USGS/BIA	1.8	
Rough Rock	BIA	USGS/BIA	17.5	
Second Mesa	BIA	USGS/BIA	6.4	
Shonto	BIA	USGS/BIA		133.8
Tuba City	BIA	USGS/BIA		97.3
Chilchinbito	NTUA	USGS/NTUA	72.7	
Dennehotso	NTUA	USGS/NTUA		41.8
Forest Lake	NTUA	USGS/NTUA	10.2	
Hard Rock	NTUA	USGS/NTUA	45.4	
Kayenta	NTUA	USGS/NTUA	342.4	
Kits'iili	NTUA	USGS/NTUA	18.4	
Piñon	NTUA	USGS/NTUA	319.1	
Red Lake	NTUA	USGS/NTUA		29.9
Rough Rock	NTUA	USGS/NTUA	32.8	
Shonto	NTUA	USGS/NTUA		27.1
Shonto Junction	NTUA	USGS/NTUA		57.5
Tuba City	NTUA	USGS/NTUA		1,055.
Mine Well Field	Peabody	Peabody	1,210.	
Bacavi	Hopi	USGS/Hopi	23.7	
Hopi Civic Center	Hopi	USGS/Hopi	2.3	
Hopi Cultural Center	Hopi	USGS/Hopi	5.9	
Kykotsmovi	Hopi	USGS/Hopi	20.9	
Mishongnovi	Hopi	USGS/Hopi	5.9	
Moenkopi	Hopi	USGS/Hopi		94.0
Polacca	Hopi	USGS/Hopi	211.1	
Shipaulovi	Hopi	USGS/Hopi	20.2	
Shungopovi	Hopi	USGS/Hopi	32.1	

[1]Well taken out of service.

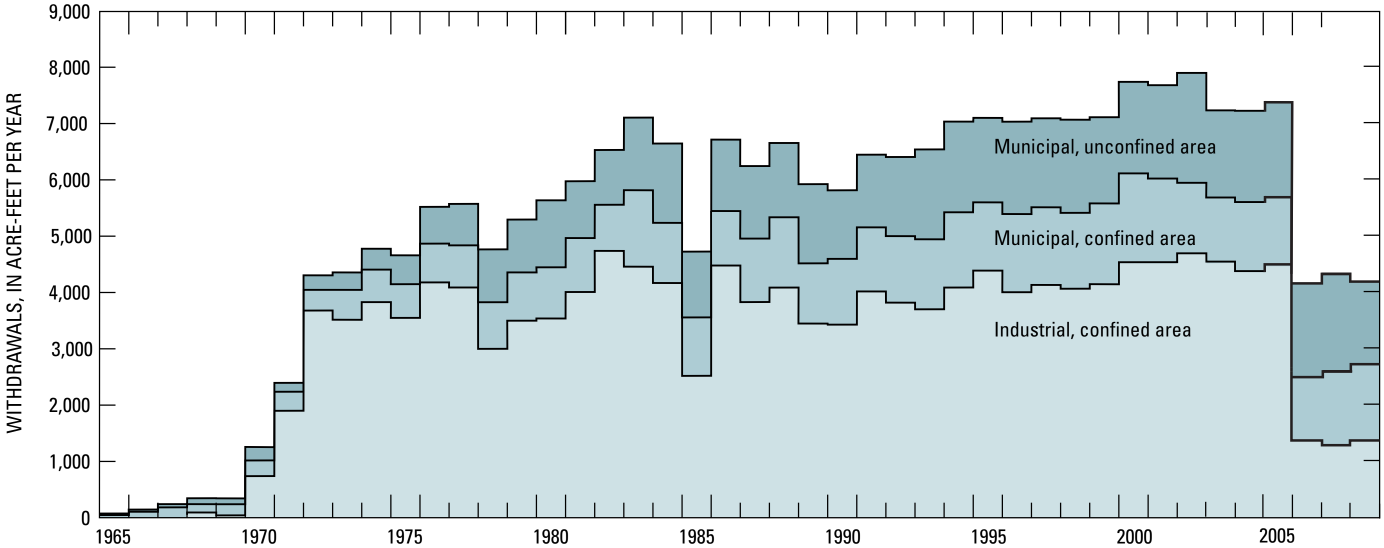


Figure 3. Annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2008.

compiled primarily on the basis of metered data from individual wells operated by the BIA, NTUA, and Hopi Tribe (table 3).

Withdrawals from wells equipped with windmills are not measured in this monitoring program. About 270 windmills in the Black Mesa area withdraw water from the D and N aquifers, and 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.

In 2008, the total groundwater withdrawal from the N aquifer was about 4,110 acre-ft (table 1). Withdrawals for municipal use from the confined area totaled 1,560 acre-ft. Withdrawals for municipal use from the unconfined areas totaled 1,340 acre-ft. Withdrawals for industrial use totaled 1,210 acre-ft, a 3-percent increase from 2007, and withdrawals for municipal use totaled 2,900 acre-ft, a 6-percent decrease from 2007 (table 4).

Withdrawals from the N aquifer have varied from 1965 to the present but generally increased from 1965 to 2005 and decreased between 2005 and 2006. On December 31, 2005, Peabody Western Coal Company reduced their pumping by 70 percent, which reflected a decrease in total annual withdrawals from 2005 by about 44 percent (tables 1 and 4, fig. 3). Total withdrawal for the period of record 1965–2008 totaled 230,780 acre-ft; industrial withdrawals were 61 percent and municipal withdrawals were 39 percent of total withdrawals (table 4). From 1965 to 1972, total annual withdrawals increased from 70 to 4,300 acre-ft (table 1); industrial withdrawals were 72 percent and municipal withdrawals were 28 percent of total withdrawals (table 4). From 1973 to 1984, withdrawals totaled 66,470 acre-ft; industrial withdrawals were 70 percent and municipal withdrawals were 30 percent of total withdrawals (table 4). In 1985, withdrawals totaled 4,720 acre-ft; industrial withdrawals were 53 percent and municipal withdrawals were 47 percent of total withdrawals. From 1986 to 2005, withdrawals totaled 138,180 acre-ft; industrial withdrawals were 60 percent and municipal withdrawals were 40 percent of total withdrawals (table 4). The last of the years of increasing withdrawals was 2005, and total withdrawals for that year were 7,330 acre-ft; industrial withdrawals were 61 percent and municipal withdrawals were 39 percent of total withdrawals (table 4). A distinct change in the amount of water being pumped from the N aquifer occurs in 2006; industrial withdrawals only accounted for about 29 percent of the total withdrawals compared to 61 percent the previous year (table 4). Municipal withdrawals in 2006 were about 71 percent of the total withdrawals, although there is some uncertainty about this number because NTUA metered data were not available for 2006 and,

Table 4. Total, industrial, and municipal withdrawals from the N aquifer for discrete time periods during 1965 to 2008, Black Mesa area, northeastern Arizona.

Period	Total withdrawals, in acre-feet	Industrial withdrawals, in acre-feet	Municipal withdrawals, in acre-feet	Percent industrial	Percent municipal
1965–2008	230,780	141,680	89,100	61	39
1965–1972	8,930	6,460	2,470	72	28
1973–1984	66,470	46,540	19,930	70	30
1985	4,720	2,520	2,200	53	47
1986–2005	138,180	82,580	55,600	60	40
2005	7,330	4,480	2,850	61	39
[1]2006	4,100	1,200	2,900	29	71
2007	4,270	1,170	3,100	27	73
2008	4,110	1,210	2,900	29	71

[1]Municipal withdrawals for NTUA wells were estimated and, consequently, total withdrawals, percent industrial, and percent municipal were calculated using estimated value.

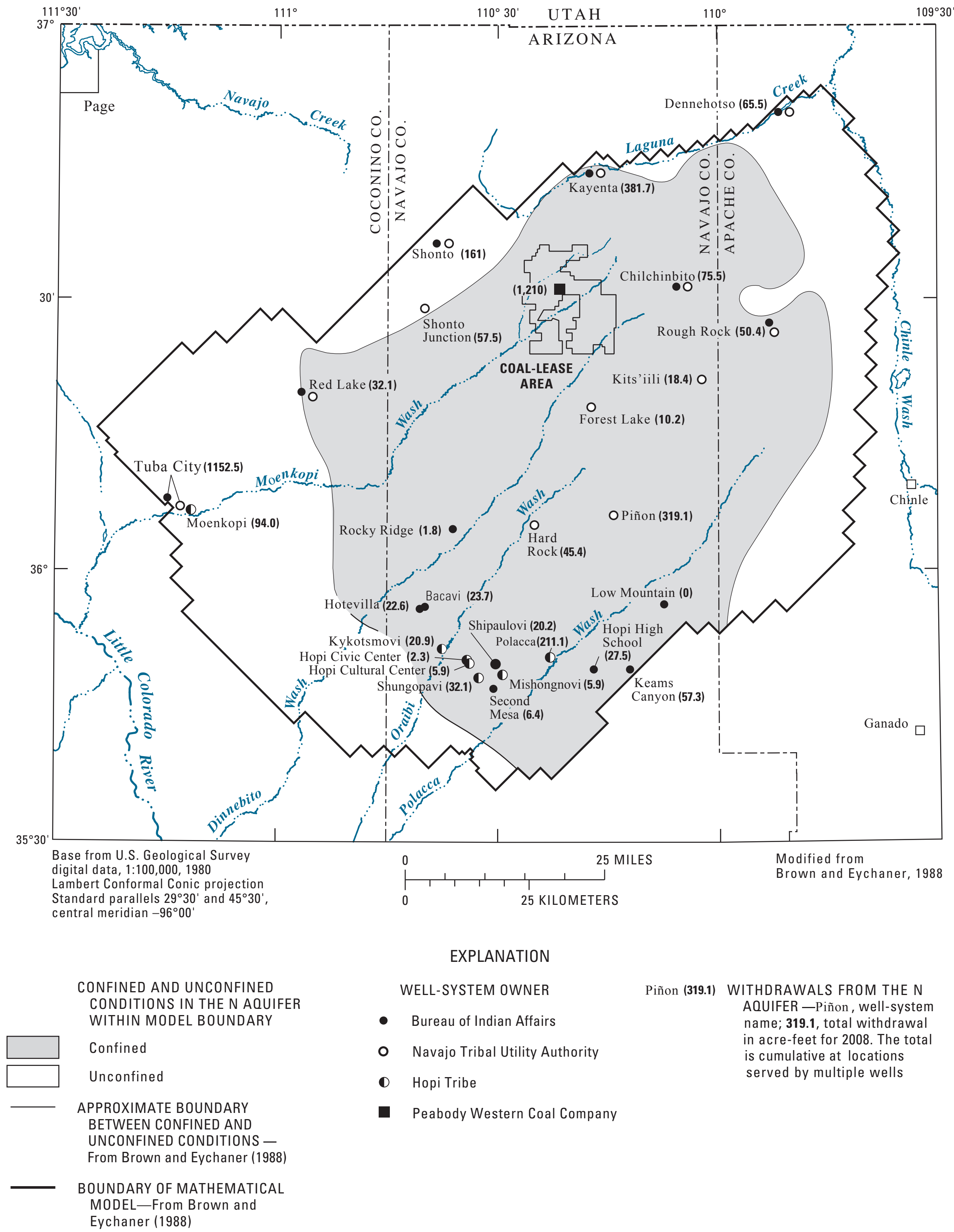


Figure 4. Locations of well systems monitored for annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, calendar year 2008.

therefore, had to be estimated based on a 1-percent increase from the year before. Total withdrawals did not change significantly from 2007 to 2008. Total withdrawals in 2008 were 4,110 acre-ft, with 29 percent from industrial withdrawals and 71 percent from municipal withdrawals (table 4).

In an effort to improve and ensure the accuracy of groundwater-withdrawal data, a quality-assurance program was begun in 1985 for withdrawal data from industrial and municipal wells completed in the N aquifer. Nearly all industrial and municipal wells in the study area are equipped with totalizing flowmeters to measure groundwater withdrawals. The flowmeters on the wells are tested about once every 5 years by measuring pumpage with a calibrated mechanical flowmeter and comparing the measured pumpage to the metered pumpage. For the purpose of this study, the allowable difference between the discharge measured by the permanent totalizing flowmeter and the test meter is 10 percent. Flowmeter testing was done at about 75 percent of the total wells (73 wells were visited and 55 wells were tested) during May and June 2009 (table 5). The median percent difference between pumping rates for the permanent meter and the test meter for all sites tested was −2.6 percent. Values ranged from −38.8 percent at Moenkopi 1 and 2 to +73.6 percent at Kayenta NTUA 5. There were many wells above the 10-percent threshold set for this program: Moenkopi #1 and #2 (−38.8 percent), Tuba City PM5 (−29.9 percent), Red Lake PM1 (−26.0 percent), Kykotsmovi 3 (−21.2 percent), Shonto Junction NTUA 1 (−21.1 percent), Shonto NTUA 1(-18.2 percent), Red Lake NTUA 1 (−15.6 percent), Tuba City NTUA 3 (−15.6 percent), Hopi High 2 (−12.9 percent), Piñon NTUA 4 (−11.8 percent), Kayenta NTUA 7 (−11.4 percent), Bacavi (+11.8 percent), Tuba City NTUA 2 (+25.4 percent), and Kayenta NTUA 5 (+73.6 percent). Flowmeters that tested above the 10-percent threshold will be visited again in 2010 to determine their accuracy, and no corrections were applied to pumping data based on these results.

Groundwater Levels in the N Aquifer

Groundwater is 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 variation. 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, influenced by nearby pumping, or blocked or obstructed are compared. During March 2009 to April 2009, water levels in 34 of 34 wells having annual measurements met these criteria (table 6). Of the 34 wells, six are continuous-recording observation wells, and water levels were measured by electric tape in these 6 wells four times between June 2007 and June 2008. Thirty-three of 34 water levels measured in 2009 were compared with water levels for the same wells measured in 2008. The water level measured in 2009 in one of the wells, Shonto 2K-301, could not be compared to the 2008 water level because a measurement is not available for this well in 2008.

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 Dennehotso (8A-180) to 3,636 ft near PWCC, and depths to the top of the N aquifer range from 0 ft near Tuba City to 2,280 ft near PWCC, (table 7).

From 2008 to 2009, water levels decreased in 19 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 2008 to 2009, water levels declined in 8 of the 15 wells measured in the unconfined parts of the aquifer (table 6), and the median water-level change was −0.1 ft (table 8). Water-level changes in the unconfined part of the aquifer ranged from −0.7 ft at Long House Valley 8T-510 to +2.7 ft at Goldtooth 3A-28 (table 6). In the confined area, water levels declined in 11 of 18 wells measured from 2008 to 2009. The median water-level change was −0.2 ft (table 8). Water-level changes in the confined part of the aquifer ranged from −7.2 ft at Keams Canyon PM2 to +4.3 ft at Howell Mesa 3K-311 (table 6).

From the prestress period (before 1965) to 2009, the median water-level change in 34 wells was −11.8 ft (table 8). Water levels in 16 unconfined wells had a median change of −1.6 ft. Water-level changes in the unconfined part of the aquifer ranged from −33.8 ft at 8T-510 near Long House Valley to +14.2 ft at 9Y-95 in Rough Rock (fig. 5 and table 6). Water levels in 18 wells in the confined part of the aquifer had a median change of −36.7 ft (table 8). Water-level changes in the confined part of the aquifer ranged from −205.9 ft at Keams Canyon PM2 to +17.7 ft at Howell Mesa 3K-311 (fig. 5 and table 6).

Hydrographs of groundwater levels in the network of wells observed annually show the time trends of 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 feet). Near Long House Valley, however, the water level in well 8T-510 has declined about 34 ft (fig. 5 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; fig. 5).

Hydrographs for the Black Mesa continuous-record observation wells show continuous water-levels since the early 1970s (fig. 7). Water levels in the two wells in the unconfined areas (BM1 and BM4) have had small seasonal or year-to-year

Table 5. Flowmeter-test results for municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, 2009.

Well name	Date visited	Permanent meter	Test meter	Percent difference	Manufacture	Serial number
Bureau of Indian Affairs						
Chilchinbito PM3	06-12-09	26	26	0.0	Master Meter	253390
Dennehotso PM 1	06-12-09	59	62	−4.8	Master Meter	1450251
Dennehotso PM 1	06-12-09	61	59	3.4	Master Meter	5523179
Dennehotso PM 1	06-12-09	58	57	1.8	Master Meter	5523184
Dennehotso PM 2	06-12-09	48	48	0.0	Sensus	1543870
Kayenta PM 2	05-27-09	122	117	4.3	Rockwell	1305841
Kayenta PM 3	05-27-09	104	100	4.0	Neptune	31973644
Red Lake PM1	05-26-09	37	50	−26.0	Master Meter	1699087
Rocky Ridge PM2	06-04-09	([1])	([1])	([1])	Rockwell	1331031
Rocky Ridge PM3	06-04-09	47	49	−4.1	Sensus	66361351
Rough Rock PM1	05-28-09	52	48	8.3	Rockwell	1331030
Rough Rock PM2	05-28-09	29	30	−3.3	Sensus	1471001
Rough Rock PM3	05-28-09	([2])	([2])	([2])	Rockwell	1323856
Rough Rock PM4	05-28-09	38	38	0.0	Sensus	1429548
Shonto PM1	06-11-09	180	181	−0.6	Rockwell	1255896
Shonto PM2	06-11-09	113	117	−3.4	Rockwell	1300477
Shonto PM3	06-11-09	75	77	−2.6	Rockwell	1325584
Tuba City PM4	05-15-09	107	108	−0.9	SENSUS	5191201207003
Tuba City PM5	05-15-09	40	57	−29.8	SENSUS	5191201207003
Tuba City PM6	05-15-09	114	124	−8.1	SENSUS	W# 471506
Hopi Tribal Authority						
Bacavi	06-11-09	76	68	11.8	Sensus	1403844
Hopi Civic Center	05-19-09	59	58	1.7	SENSUS	W# 477945
Hopi Cultural Center	05-19-09	48	49	−2.0	Rockwell	37678664
Hopi High 1	06-09-09	([3])	([3])	([3])	([3])	([3])
Hopi High 2	06-09-09	88	101	−12.9	Neptune	31625415
Hopi High 3	06-09-09	([3])	([3])	([3])	Hersey	4922900
Hotevilla Community	06-23-09	36	36	0.0	Rockwell	36726381
Hotevilla PM1	06-24-09	56	54	3.7	Sensus	1424710
Keams Canyon #2	06-26-09	([2])	([2])	([2])	Neptune	31625415
Keams Canyon #3	06-26-09	92	96	−4.2	Badger	16900120
Kykosmovi 2	05-22-09	73	78	−6.4	Kent	7655836
Kykosmovi 3	05-22-09	115	146	−21.2	Rockwell	W#454868
Mishungnovi	06-04-09	13	14	−7.1	Neptune	30033783
Moenkopi 1 and 2	05-15-09	82	134	−38.8	SENSUS	34512895
Polacca 5	06-24-09	([4])	([4])	([4])	McCrometer	9369087
Polacca 6	06-24-09	([4])	([4])	([4])	McCrometer	9261586
Polacca 8	06-24-09	164	165	−0.6	Sensus	1628041
Second Mesa Day School 2	06-10-09	([4])	([4])	([4])	([4])	([4])
Shungopavi	06-04-09	76	81	−6.2	Sensus	3880400
Sipaulovi #2	06-04-09	92	92	0.0	Kent	88538743

Table 5. Flowmeter-test results for municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, 2009—Continued.

Well name	Date visited	Permanent meter	Test meter	Percent difference	Manufacture	Serial number
			Navajo Tribal Utility Authority (NTUA)			
Chilchinbito NTUA 1	05-28-09	44	44	0.0	Sensus	62969678
Chilchinbito NTUA 2	05-28-09	57	58	−1.7	Sensus	1593741
Dennehotso NTUA 1	05-28-09	66	72	−8.3	Rockwell	33447300
Dennehotso NTUA 2	05-28-09	104	102	2.0	Rockwell	1306471
Forest Lake NTUA 1	06-03-09	36	40	−10.0	Hersey	6049985
Hard Rocks NTUA 1	06-10-09	117	118	−0.8	Brooks	8405-24272-1-1
Hard Rocks NTUA 2	06-10-09	104	102	2.0	Sensus	1469178
Kayenta NTUA 1	05-27-09	([2])	([2])	([2])	Sensus	60645246
Kayenta NTUA 2	05-27-09	([4])	([4])	([4])	Sensus	60645245
Kayenta NTUA 3	05-27-09	123	125	−1.6	Sensus	1385421
Kayenta NTUA 4	05-27-09	([1])	([1])	([1])	([1])	([1])
Kayenta NTUA 5	05-27-09	210	121	73.6	Rockwell	1276730
Kayenta NTUA 6	05-27-09	108	112	−3.6	Sensus	62532599
Kayenta NTUA 7	05-27-09	93	105	−11.4	Sensus	1436356
Kitsillie NTUA 1	06-03-09	([1])	([1])	([1])	Rockwell	53189191
Kitsillie NTUA 2	06-03-09	66	68	−2.9	Sensus	1451526
Pinon NTUA 1	06-03-09	102	104	−1.9	Sensus	1442406
Pinon NTUA 2	06-03-09	120	129	−7.0	Rockwell	1305355
Pinon NTUA 3	06-03-09	([3])	([3])	([3])	Rockwell	1303039
Pinon NTUA 4	06-03-09	30	34	−11.8	Sensus	1552341
Red Lake NTUA	05-20-09	54	64	−15.6	SENSUS	1550832
Rough Rock NTUA 1	06-02-09	([3])	([3])	([3])	([3])	([3])
Rough Rock NTUA 2	06-02-09	85	81	4.9	Sensus	1329324
Shonto NTUA 1	05-26-09	45	55	−18.2	Rockwell	28945149
Shonto Junction NTUA 1	05-26-09	75	95	−21.1	Sensus	62532598
Shonto Junction NTUA 2	05-26-09	([4])	([4])	([4])	Unknown	105708
Tuba City NTUA 1	05-20-09	([1])	([1])	([1])	([1])	([1])
Tuba City NTUA 2	05-20-09	178	142	25.4	Sparkling	125709
Tuba City NTUA 3	05-19-09	135	160	−15.6	SENSUS	46571
Tuba City NTUA 4	05-19-09	180	195	−7.7	Sparkling	126447
Tuba City NTUA 5	05-20-09	([4])	([4])	([4])	Sparkling	126189
Tuba City NTUA 6	05-20-09	([5])	([5])	([5])	Rockwell	1153829

[1]Well inactive.

[2]Meter broken.

[3]Well not in service.

[4]Unable to test.

[5]Flow too high for test meter.

Table 6. Water-level changes in monitoring-program wells completed in the N aquifer, Black Mesa area, northeastern Arizona, prestress period (prior to 1965) to 2009 (calendar year).

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

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year, in feet		Water level 2009, in feet below land surface	Prestress period water level		Change in water level from pre-stress period to 2009, in feet
		2008	2009		Feet below land surface	Date	
Unconfined areas							
BM observation well 1[1]	8T-537	0.0	−0.4	374.6	374.0	([1])	−0.6
BM observation well 4[1]	2T-514	−0.2	−0.2	217.2	216.0	([1])	−1.2
Goldtooth	3A-28	([2])	+2.7	232.0	230.0	10–29–53	−2.0
Long House Valley	8T-510	−1.1	−0.7	133.2	99.4	08–22–67	−33.8
Northeast Rough Rock	8A-180	−0.2	−0.5	44.7	46.9	11–13–53	+2.2
Rough Rock	9Y-95	−4.2	+2.4	105.3	119.5	08–03–49	+14.2
Do.	9Y-92	−2.0	+0.7	166.0	168.8	12–13–52	+2.8
Shonto	2K-300	+0.4	−0.2	171.4	176.5	06–13–50	+5.1
Shonto Southeast	2K-301	([2])	([2])	289.4	283.9	12–10–52	−5.5
Do.	2T-502	−2.8	+1.7	416.8	405.8	08–22–67	−11.0
Tuba City	3T-333	0.0	+0.4	28.9	23.0	12–02–55	−5.9
Do.	3K-325	+0.1	−0.2	203.2	208.0	06–30–55	+4.8
Tuba City Rare Metals 2	—	+0.5	−0.1	50.4	57.0	09–24–55	+6.6
Tuba City NTUA 1	3T-508	([2])	+2.0	54.4	29.0	02–12–69	−25.4
Tuba City NTUA 3	—	([2])	0.0	61.9	34.2	11–08–71	−27.7
Tuba City NTUA 4	3T-546	([2])	−0.3	65.0	33.7	08–06–71	−31.3
Confined area							
BM observation well 2[1]	8T-538	−1.1	−1.2	217.6	125.0	([1])	−92.6
BM observation well 3[1]	8T-500	−0.5	−0.2	161.9	55.0	04–29–63	−106.9
BM observation well 5[1]	4T-519	−2.1	−1.4	425.7	324.0	([1])	−101.7
BM observation well 6[1]	—	+1.9	+2.2	856.4	697.0	([1])	−159.4
Forest Lake NTUA 1	4T-523	+0.1	+3.3	1186.4	1,096R	05–21–82	−90.4
Howell Mesa	3K-311	−1.3	+4.3	445.3	463.0	11–03–53	+17.7
Kayenta West	8T-541	+0.5	−2.6	299.6	230.0	03–17–76	−69.6
Keams Canyon PM2	—	+6.4	−7.2	498.4	292.5	06–10–70	−205.9
Kits'iili NTUA 2	—	−3.3	−1.7	1332.4	1,297.9[3]	01–14–99	−34.5
Kykotsmovi PM1	—	+0.4	−0.1	211.8	220.0	05–20–67	+8.2
Kykotsmovi PM3	—	+6.6	−5.3	248.9	210.0	08–28–68	−38.9
Marsh Pass	8T-522	−0.5	+0.1	127.6	125.5	02–07–72	−2.1
Piñon PM6	—	−0.6	0.0	904.9	743.6	05–28–70	−161.3
Rough Rock	10R-119	+0.1	−0.2	256.8	256.6	12–02–53	−0.2
Do.	10T-258	+0.2	−0.4	309.9	301.0	04–14–60	−8.9
Do.	10R-111	-1.8	+0.2	193.3	170.0	08–04–54	−23.3
Sweetwater Mesa	8K-443	-0.6	+0.4	541.9	529.4	09–26–67	−12.5
White Mesa Arch	1K-214	+0.3	−0.3	219.9	188.0	06–04–53	−31.9

[1]Continuous recorder. Prestress water levels were estimated from a groundwater 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.

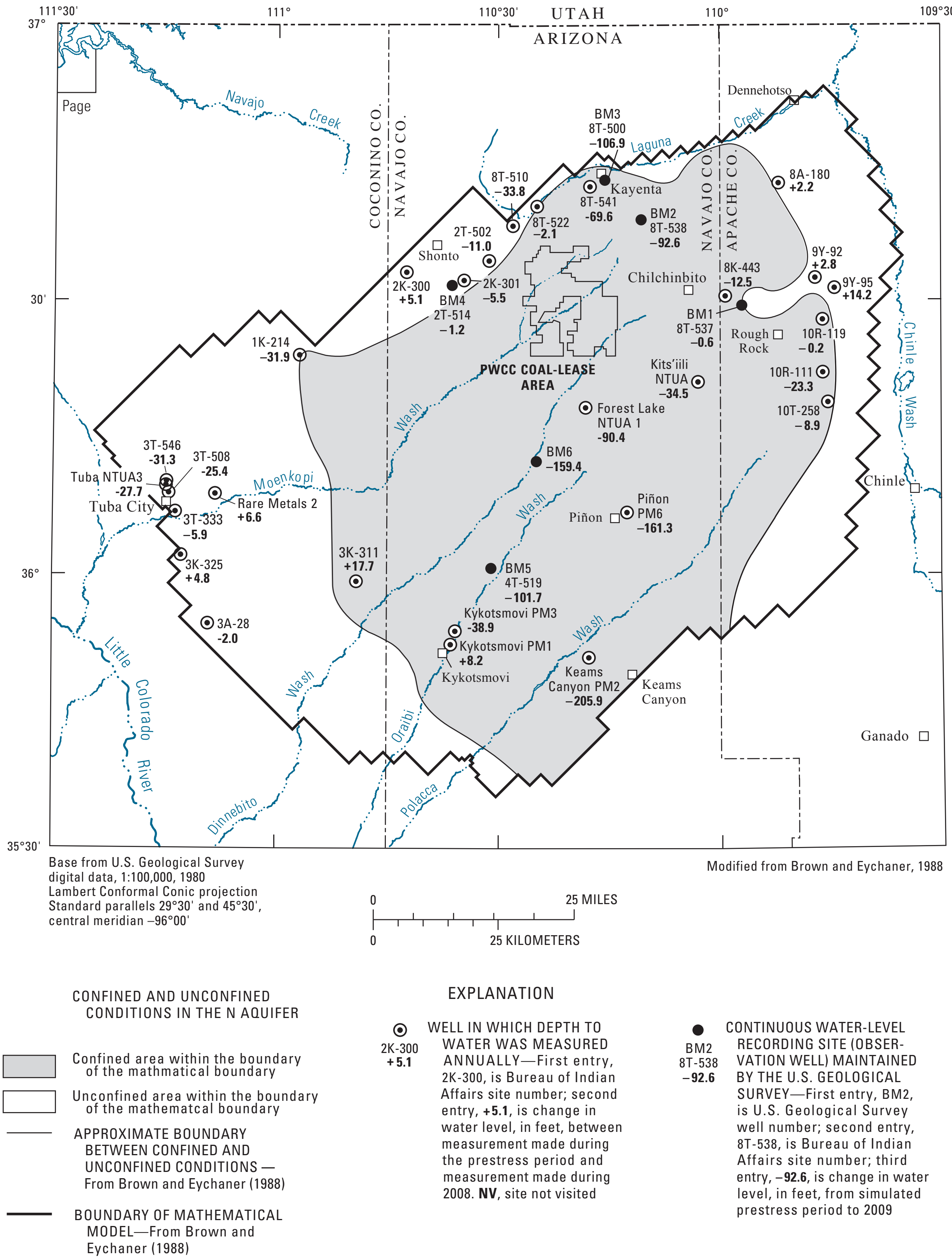


Figure 5. Water-level changes in N-aquifer wells from the prestress period (prior to 1965) to 2009, Black Mesa area, northeastern Arizona.

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, 2008–9.

Bureau of Indian Affairs site number, and (or) common name	Date well was completed	Land-surface elevation, in feet	Well depth, in feet below land surface	Screened/open interval(s), in feet below land surface	Depth to top of N aquifer, in feet below land surface	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	06–00–50[3]	6,264	300	260–300	0	Water level
2K-301	06–12–50	6,435	500	318–328; 378–500	30[2]	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	11–00–34[3]	5,855	745	380–395 605–745	615	Water level
3K-325	06–01–55	5,250	450	75-450	30[2]	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)	08–00–71[3]	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	40[2]	Water level
8K-443	08–15–57	6,024	720	619–720	590	Water level
8T-510	02–11–63	6,262	314	130–314	125[2]	Water level
8T-522	07–00–63[3]	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
Keams Canyon PM2	05–00–70[3]	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	04–00–72[3]	6,123	1,343	1,181–1,262	1,153	Withdrawals
Peabody 2	06-00-67[3]	6,530	3,636	1,816-3,603	728	Water chemistry, withdrawals
Peabody 4	05-00-68[3]	6,229	3,535	2,029-3,458	2,280	Water chemistry, withdrawals
Piñon NTUA 1	02–25–80	6,336	2,350	1,860–2,350	1,850	Water chemistry, withdrawals
Piñon PM6	02–00–70[3]	6,397	2,248	1,895–2,243	1,870	Water level, withdrawals
Tuba City NTUA 3	10–00–71[3]	5,176	442	142–442	34	Water level, withdrawals
Tuba City Rare Metals 2	09–00–55[3]	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, 2008–9 and prestress period (prior to 1965) to 2009, N aquifer, Black Mesa area,northeastern Arizona.

Years	Aquifer conditions	Number of wells	Median change in water level, in feet
2008-9	All	33	−0.2
	Unconfined	15	−0.1
	Confined	18	−0.2
Prestress-2009	All	34	−11.8
	Unconfined	16	−1.6
	Confined	18	−36.7

variation since 1972. Water levels in wells BM2, BM3, and BM5 in the confined area have consistently declined since the early to mid 1960s (fig. 7). 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 854.8 ft below land surface on July 23, 2009, about 6 feet of total recovery to date.

Spring Discharge from the N Aquifer

The effect of withdrawals from the N aquifer on the water quality and discharge of springs around Black Mesa is a concern. 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 2009, Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring, three of the four springs that have been measured as part of this monitoring program, were measured for discharge. Moenkopi School Spring is in the western part of the Black Mesa area and is also referred to as Susunova Spring by the Hopi Tribe (fig. 8). Discharge from Moenkopi School Spring was measured in June 2009 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. In 2009, the measured discharge was 8.0 gal/min from Moenkopi School Spring (table 9). From 2008 to 2009, discharge decreased by 3.6 percent; for the period of record, discharge measurements have fluctuated and exhibit a decreasing trend ($p<0.01$) (fig. 9 and table 9).

Pasture Canyon Spring is also in the western part of the study area and issues 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 and the additional discharge from seeps along Pasture Canyon. Discharge was measured at Pasture Canyon Spring in June 2009 by the volumetric method, and when compared to previous years a decreasing trend ($p<0.01$) is seen (fig. 9 and table 9). The trend from discharge measurements at this spring is not corrected for seasonal variability. In 2009 the measured discharge was 31.1 gal/min, which is a 5.7 percent increase from 2008 (table 9).

A third spring measured in 2009 was Burro Spring. 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 2009 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 appreciable trend (fig. 9). Discharge was not measured in 2007–8 at Burro Spring, therefore, a comparison could not be made. In 2009 the measured discharge was 0.3 gal/min (fig. 9 and table 9).

Surface-Water Discharge

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 channel 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 2008, discharge data were collected at four continuous-recording streamflow-gaging stations (tables 10–13). Data collection at these stations began in July 1976 (Moenkopi Wash at Moenkopi, 09401260), June 1993 (Dinnebito Wash near Sand Springs, 09401110), April 1994 (Polacca Wash near Second Mesa, 09400568), and August 2004 (Pasture Canyon Springs, 09401265; table 14). The annual average discharges at the four streamflow-gaging stations vary during the periods of record (fig. 10*A*), and no trends are apparent 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 average annual precipitation measured at Navajo National Monument (Betatakin; fig. 1) from 1976 to

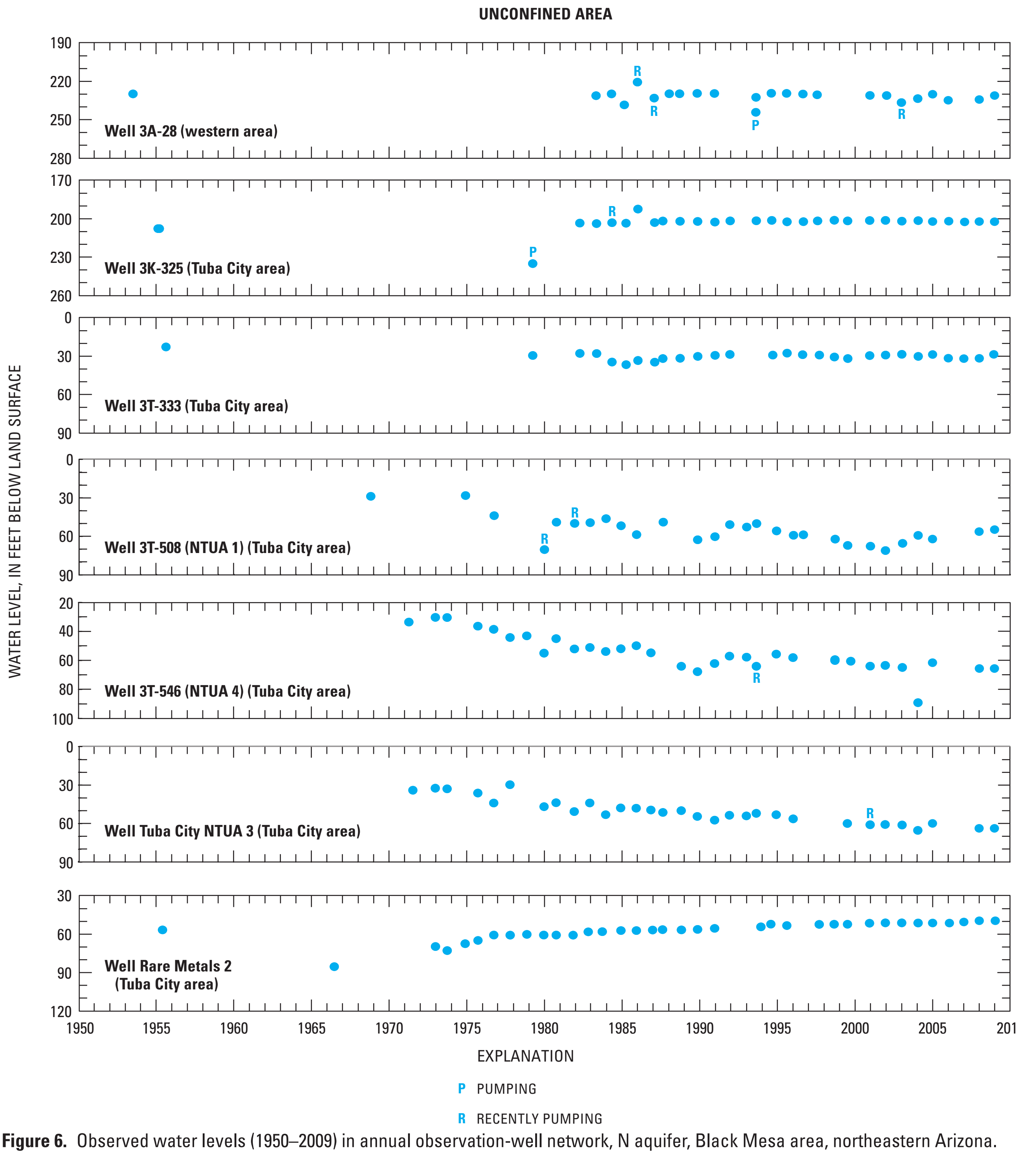


Figure 6. Observed water levels (1950–2009) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.

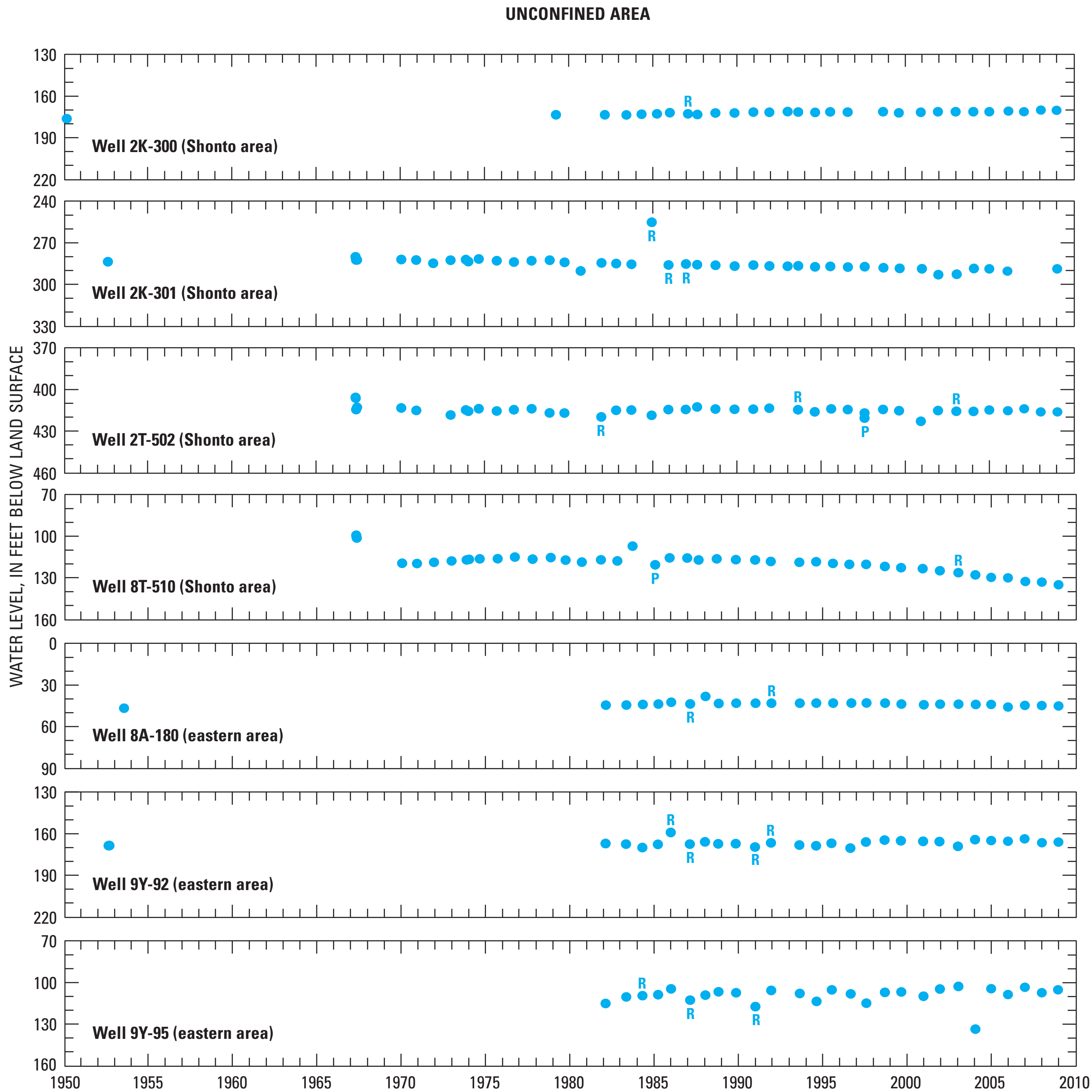


Figure 6. Observed water levels (1950–2009) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona—Continued.

Figure 6. Observed water levels (1950–2009) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona—Continued.

Figure 6. Observed water levels (1950–2009) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona—Continued.

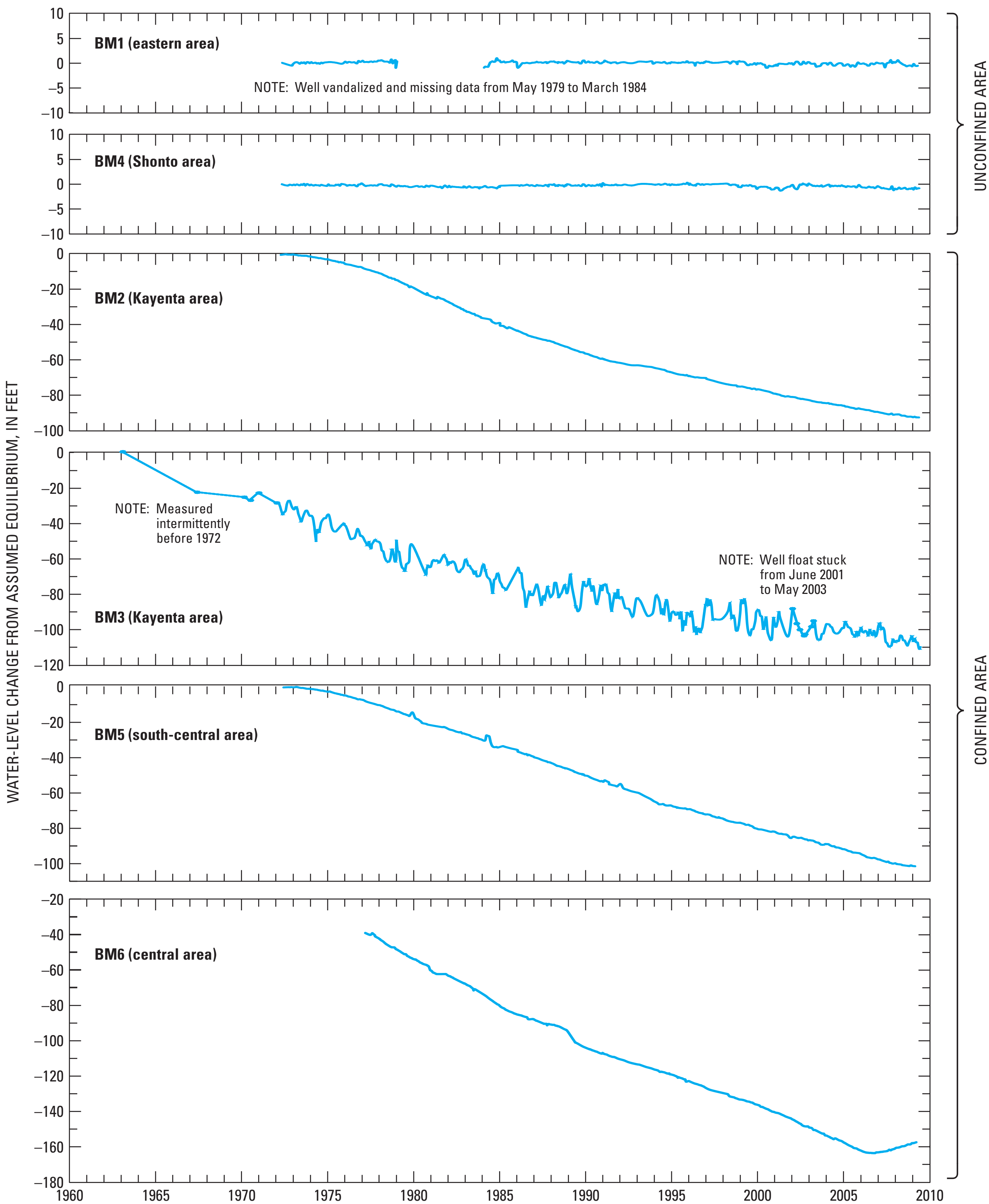


Figure 7. Observed water-level changes in continuous-record observation wells, BM1-BM6, 1963-2009, N aquifer, Black Mesa area, northeastern Arizona.

Table 9. Discharge measurements for Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring, Black Mesa area, northeastern Arizona, 1952–2009.

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

Bureau of Indian Affairs site Number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Moenkopi School Spring[1]			
3GS-77-6	Navajo Sandstone[2]	05–16–52	40.0
		04–22–87	16.0[3]
		11–29–88	12.5[3]
		02–21–91	13.5[3]
		04–07–93	14.6[3]
		12–07–94	12.9[3]
		12–04–95	10.0[3]
		12–16-96	13.1[3]
		12–17–97	12.0[3]
		12–08–98	13.3[3]
		12–13–99	13.7[3]
		03–12–01	10.2[3]
		06–19–02	11.2[3]
		05–01–03	11.2[3]
		03–29–04	12.2[3]
		04–04–05	11.5[3]
		03–13–06	11.1[3]
		05-31-07	9.0[3]
		06-03-08	8.3[3]
		06-03-09	8.0[3]
Pasture Canyon Spring[1]			
3A-5	Navajo Sandstone, alluvium		
		11-18-88	4211[4]
		03-24-92	4233[4]
		10-12-93	4211[4]
		12-04-95	38.0[5]
		12-16-96	38.0[5]
		12-17-97	40.0[5]
		12-10-98	39.0[5]
		12-21-99	39.0[5]
		06-12-01	37.0[5]
		04-04-02	37.0[5]
		05-01-03	30.9[5]
		04-26-04	30.6[5]
		04-27-05	33.3[5]
		06-03-08	29.4[5]
		06-03-09	31.1[5]

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Burro Spring[1]			
6M-31	Navajo Sandstone	12-15-1989	0.4
		12-13-1990	0.4
		03-18-1993	0.3
		12-08-1994	0.2
		12-17-1996	0.4
		12-30-1997	0.2
		12-08-1998	0.3
		12-07-1999	0.3
		04-02-2001	0.2
		04-04-2002	0.4
		04-30-2003	0.4
		04-06-2004	0.2[6]
		03-28-2005	0.2
		03-28-2006	0.2
		06-04-2009	0.3

[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.

2008 is 12.8 in. (fig. 10*B*). Annual precipitation at Betatakin has been mostly less than that average from 1995 through 2002 (11.4 in.); precipitation data was incomplete for 2003, above average for calendar year 2004 and 2005 (17.4 in.), below average for calendar years 2006 (11.24 in.) and 2007 (8.26 in.; fig. 10*B*), and above average for 2008 (16.63 in.; fig. 10*B*).

Trends in the groundwater-discharge component of total flow at the three streamflow-gaging stations were evaluated on the basis of the median flow for 120 consecutive daily mean flows for four winter months (November, December, January, and February) as a surrogate measure for base flow (fig. 11). Groundwater discharge was assumed to be constant throughout the year, and the median winter flow was assumed to represent the constant annual groundwater discharge. Most flow that occurs during the winter is groundwater discharge; rainfall and snowmelt runoff are infrequent. Most of the precipitation in the winter falls as snow, and the cold temperatures prevent appreciable snowmelt. Evapotranspiration is at a minimum during the winter. Rather than the average flow, the median flow for November, December, January, and February is used to estimate groundwater discharge because the median is less affected by occasional winter runoff. Nonetheless, the median flow for November, December, January, and February is an index of groundwater discharge rather than an absolute estimate of groundwater discharge. A more rigorous and accurate estimate would involve detailed evaluations of streamflow hydrographs, flows into and out of bank storage, gain and

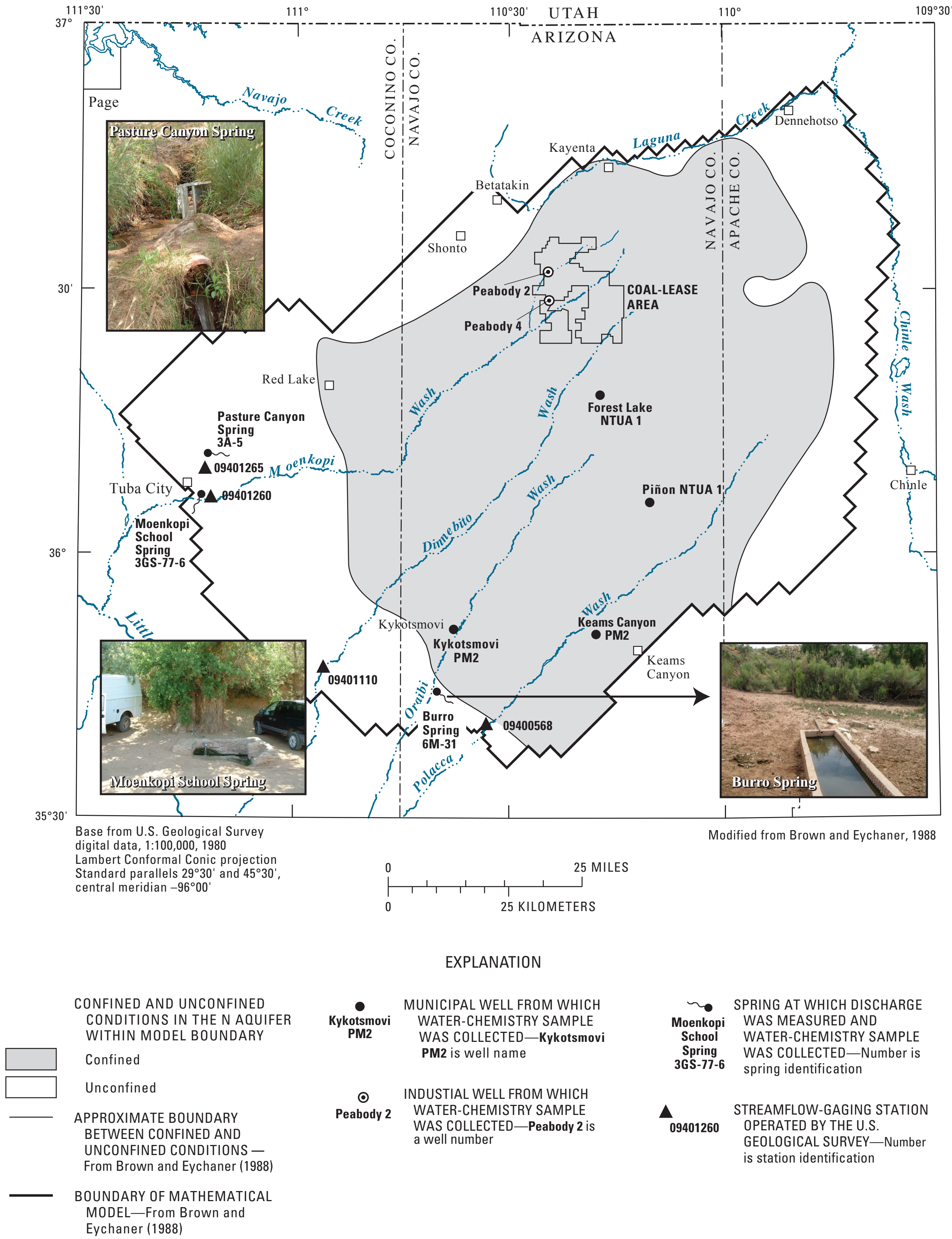


Figure 8. Surface-water and water-chemistry data-collection sites, N aquifer, Black Mesa area, northeastern Arizona, 2008–9.

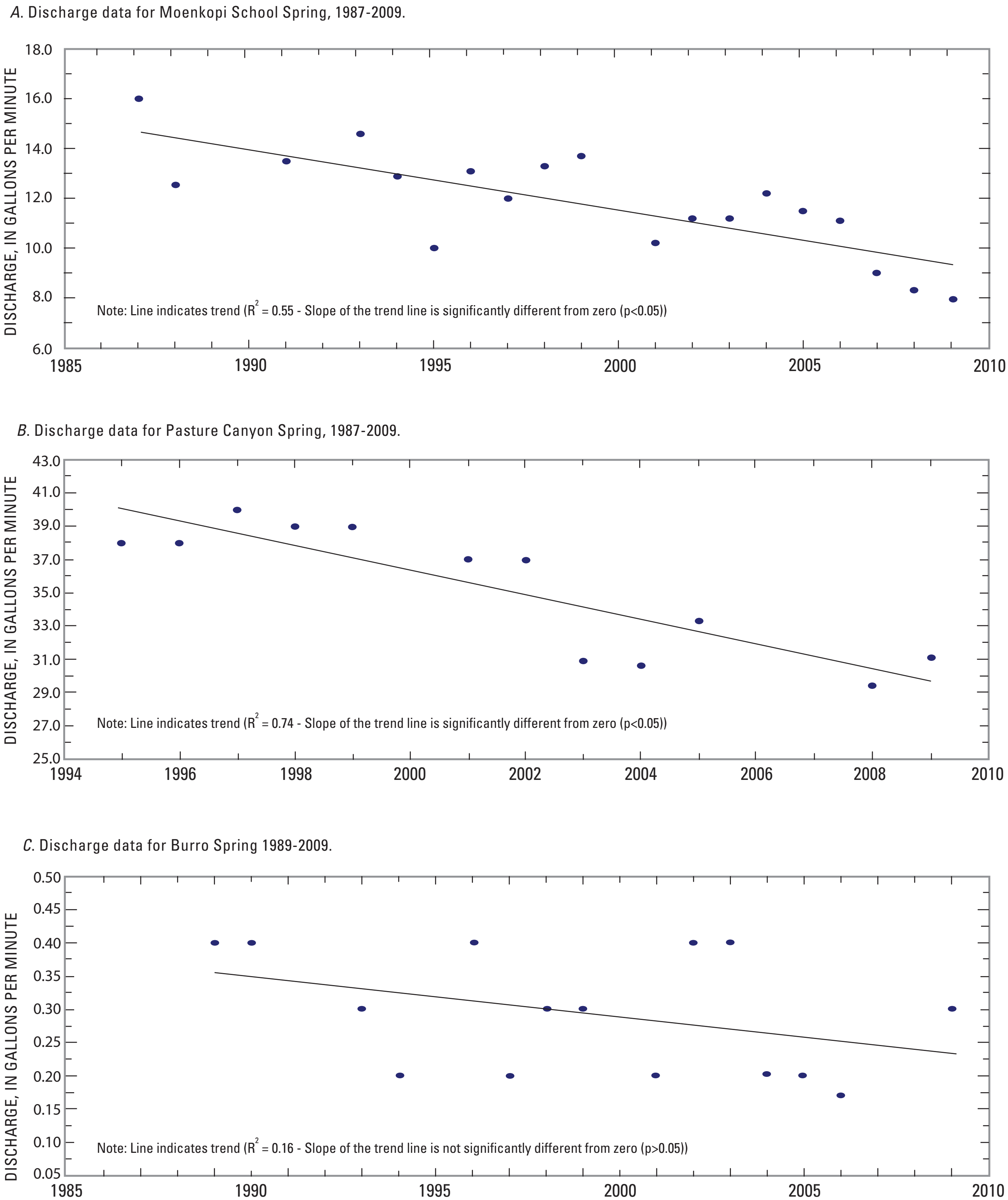
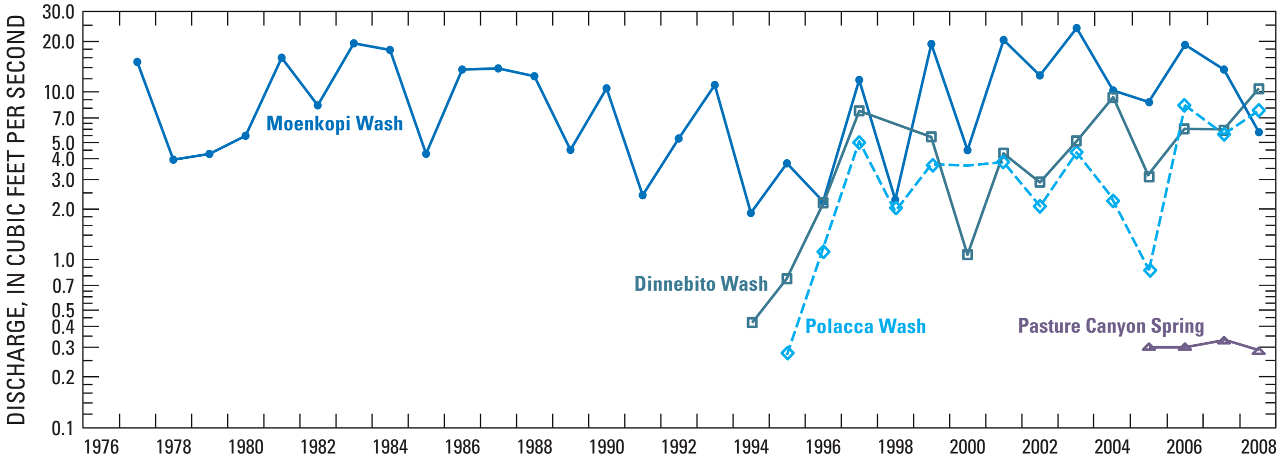


Figure 9. Discharge from *A*, Moenkopi School Spring and *B*, Pasture Canyon Spring, and *C*, Burro Spring, N Aquifer, northeastern Black Mesa area, Arizona, 1987–2009. Data from 1952 measurement at Moenkopi School Spring is not shown because it is from a different measuring location. Data from 1988 to 1993 measurements at Pasture Canyon Spring are not shown because they are from a different measuring location. Trend lines were generated using method of least squares.

A. Annual average discharge for calendar years 1977–2008.



B. Annual precipitation at Betatakin, Arizona, calendar years 1976–2008 (National Weather Service).

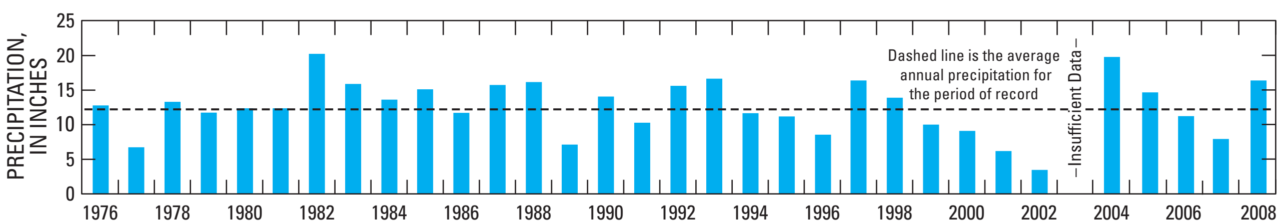
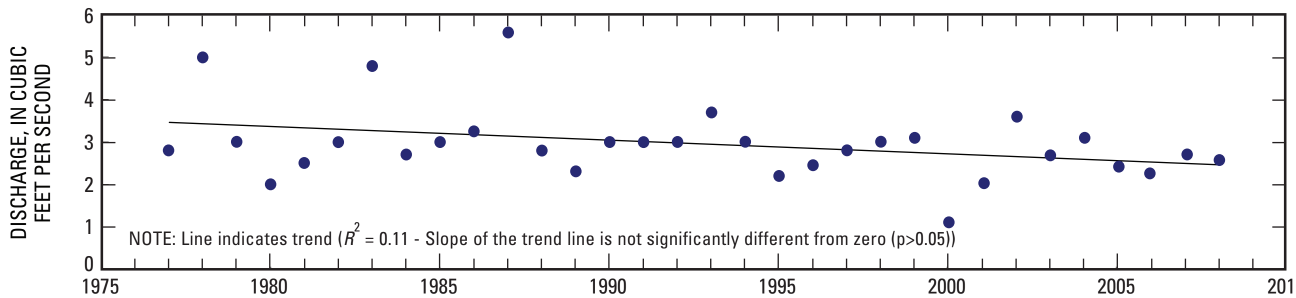
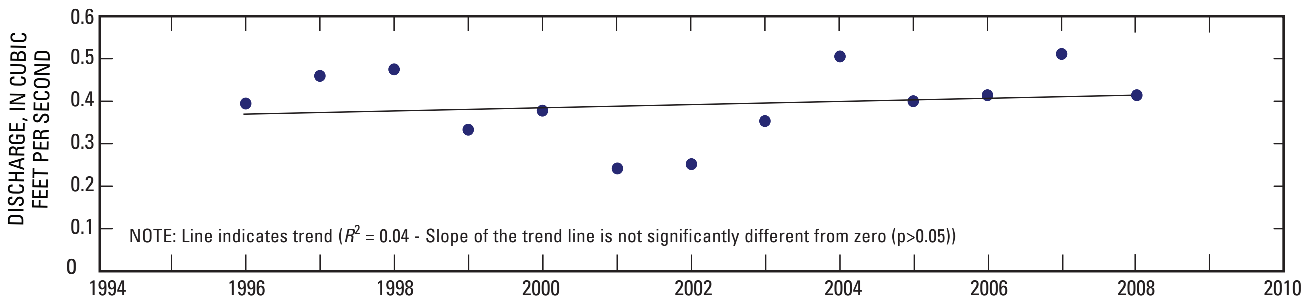


Figure 10. Annual average discharge at Moenkopi Wash at Moenkopi (09401260), Pasture Canyon Springs(09401265), Dinnebito Wash near Sand Springs (09401110), and Polacca Wash near Second Mesa (09400568), and annual precipitation at Betatakin, Arizona, Black Mesa area, northeastern Arizona. *A*, Annual average discharge for calendar years 1977–2008; *B*, Annual precipitation at Betatakin, northeastern Arizona, calendar years 1976–2008 (National Park Service, Betatakin National Monument, written commun., 2009).

A. Median winter flow for November, December, January, February, 1977–2008, for Moenkopi Wash at Moenkopi (09401260).



B. Median winter flow for November, December, January, February, 1996–2008, Dinnebito Wash near Sand Springs (09401110).



C. Median winter flow for November, December, January, February, 1996–2008, Polacca Wash near Second Mesa (09400568).

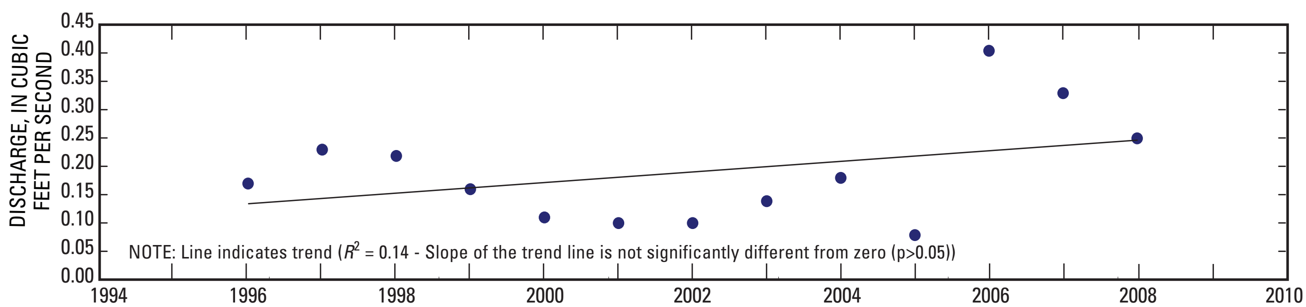


Figure 11. Median winter flow for November, December, January, and February for water years 1977–2008 for *A*, Moenkopi Wash at Moenkopi (09401260), *B*, Dinnebito Wash near Sand Springs (09401110), and *C*, Polacca Wash near Second Mesa (09400568), Black Mesa area, northeastern Arizona. Median winter 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 using the method of least squares.

Table 10. Discharge data (daily mean values), Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2008.

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

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	3.1	6.5	2.2	1.4	0.93	0.15	0.00	0.00	117	0.00	0.73	2.3
2	3.4	5.1	2.1	1.4	1.0	0.00	0.00	0.00	19	0.00	0.73	2.1
3	3.6	4.7	2.0	1.4	1.1	0.00	0.00	0.00	1.3	0.00	0.74	1.9
4	3.5	4.4	2.0	1.5	1.2	0.00	0.00	0.00	0.05	0.00	0.79	1.8
5	4.0	4.4	2.0	1.6	1.2	0.00	0.00	0.00	0.00	0.00	0.80	1.7
6	e4.0	e4.0	2.0	1.6	1.2	0.00	0.00	31	0.00	0.00	0.79	2.1
7	e3.6	3.6	2.0	1.5	1.2	0.00	0.00	146	0.00	0.00	0.81	2.1
8	e3.3	3.7	2.1	1.4	1.1	0.00	0.00	79	0.00	0.00	0.87	2.5
9	e2.7	3.6	2.1	1.5	0.99	0.00	0.00	58	0.00	0.00	0.91	2.2
10	e2.5	66	1.9	1.6	0.86	0.00	0.00	47	14	0.00	0.98	e2.1
11	e1.7	223	1.8	1.5	0.85	0.00	0.00	17	12	0.00	0.97	e2.0
12	e1.8	102	1.9	1.3	0.75	0.00	0.00	4.5	4.1	0.00	0.88	e2.2
13	e1.9	111	1.9	1.3	1.5	0.00	0.00	0.29	0.00	0.00	0.95	e2.2
14	e2.0	94	1.9	1.4	1.7	0.00	3.6	0.29	0.00	0.00	0.95	e2.4
15	e2.1	28	1.8	1.3	1.3	0.00	6.8	0.29	e0.00	0.00	0.91	2.6
16	e2.5	8.1	1.9	1.1	0.92	0.00	3.3	0.29	0.00	0.00	0.87	3.7
17	e3.1	4.1	2.3	1.2	0.72	0.00	0.07	9.2	0.00	0.26	0.94	3.7
18	e3.6	3.4	2.1	1.3	0.67	0.00	0.00	10	0.00	0.26	0.98	4.0
19	e3.6	3.8	1.9	1.4	0.65	0.00	0.00	4.1	0.00	0.41	1.0	e4.1
20	e3.6	e3.2	1.8	1.4	0.58	0.00	0.00	1.8	0.00	0.40	1.0	e3.8
21	e3.4	e3.0	1.8	1.3	0.45	0.00	0.00	0.53	0.00	0.41	1.1	e3.6
22	3.4	e3.0	1.7	1.3	0.54	0.00	0.00	0.29	0.00	0.42	1.2	e3.5
23	3.3	e3.0	1.7	1.3	1.1	0.00	0.00	0.29	0.00	0.41	1.2	3.3
24	3.6	e2.8	1.7	1.1	1.5	0.00	1.0	0.29	0.00	0.49	1.3	2.4
25	4.1	e2.6	1.9	1.0	1.2	0.00	0.00	0.29	0.00	0.59	1.1	3.6
26	5.8	2.7	1.7	1.1	0.78	0.00	0.00	25	0.00	0.64	1.1	6.8
27	4.0	2.3	1.5	1.0	0.74	0.00	0.00	24	0.00	0.64	9.9	4.8
28	264	2.3	1.6	1.1	0.60	0.00	0.00	8.7	0.00	0.64	21	e4.1
29	64	2.3	1.5	1.3	0.41	0.00	0.00	0.43	0.00	0.70	5.7	4.0
30	6.8	—	1.2	1.0	0.31	0.00	0.00	0.48	0.00	0.70	3.0	e3.7
31	5.2	—	1.1	—	0.19	—	0.00	3.8	—	0.72	—	e3.4
TOTAL	427.2	710.6	57.1	39.6	28.24	0.15	14.77	472.86	167.45	7.69	64.20	94.7
MEAN	13.8	24.5	1.84	1.32	0.91	0.01	0.48	15.3	5.58	0.25	2.14	3.05
MAX	264	223	2.3	1.6	1.7	0.15	6.8	146	117	0.72	21	6.8
MIN	1.7	2.3	1.1	1.0	0.19	0.00	0.00	0.00	0.00	0.00	0.73	1.7
MED	3.5	3.8	1.9	1.3	0.92	0.00	0.00	0.53	0.00	0.00	0.96	2.6
AC-FT	847	1410	113	79	56	0.3	29	938	332	15	127	188
CFSM	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00

Calendar year 2008 Total 2,084.6 Mean 5.7 Max 264 Min 0.0 Median 1.2 Acre-ft 4,134 CFSM 0.003

Table 11. Discharge data (daily mean values), Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2008.

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

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.38	e19	98	0.26	0.21	0.21	0.21	0.25	5.6	0.30	0.69	0.53
2	0.39	e17	115	0.25	0.22	0.21	0.20	0.23	0.66	0.30	0.40	0.50
3	0.42	e19	25	0.26	0.23	0.21	0.20	0.21	0.24	0.29	0.35	0.52
4	e0.56	15	4.3	0.26	0.22	0.21	0.19	0.21	0.16	0.73	0.34	0.43
5	e0.63	13	0.75	0.25	0.22	0.23	0.20	0.21	0.15	0.32	0.34	0.37
6	e0.65	12	0.39	0.26	0.25	0.20	0.21	e157	0.15	1.9	0.34	0.37
7	e0.47	18	0.38	0.25	0.22	0.19	0.21	e129	0.15	0.38	0.35	0.39
8	e0.42	18	0.37	0.25	0.36	0.21	0.21	e40	0.16	0.40	0.36	0.41
9	e0.40	17	0.34	0.26	0.24	0.22	0.21	182	0.16	0.39	0.35	0.39
10	e0.40	18	0.32	0.25	0.24	0.21	0.22	e159	0.16	0.37	0.36	0.36
11	e0.41	258	0.33	0.24	0.22	0.21	0.22	e16	75	0.33	1.3	0.42
12	e0.38	253	0.33	0.25	0.22	0.21	0.21	2.2	16	0.33	0.41	0.44
13	e0.39	273	0.31	0.26	0.37	0.20	0.25	0.31	3.1	0.32	0.40	0.44
14	e0.39	220	0.29	0.25	0.25	0.21	0.27	0.27	0.27	0.32	0.39	0.44
15	e0.37	45	0.28	0.24	0.25	0.23	14	0.24	0.29	0.32	0.37	0.37
16	e0.35	5.8	0.31	0.24	0.25	0.23	12	0.25	0.63	0.32	0.39	0.48
17	0.30	17	0.32	0.24	0.25	0.23	4.1	23	0.31	0.32	0.40	e0.46
18	0.32	13	0.30	0.25	0.24	0.21	0.23	16	0.29	0.34	0.40	e0.44
19	0.34	13	0.30	0.24	0.23	0.20	0.15	0.33	0.28	0.31	0.40	0.41
20	0.36	12	0.30	0.23	0.22	0.21	0.17	0.23	0.28	0.31	0.40	0.37
21	0.37	56	0.29	0.23	0.23	0.21	0.17	0.22	0.28	0.31	0.40	0.43
22	0.45	24	0.29	0.24	0.39	0.21	46	0.21	0.28	0.31	0.40	0.44
23	0.44	8.0	0.30	0.23	0.31	0.21	151	0.21	0.29	0.31	0.40	0.64
24	e0.50	2.0	0.31	0.23	0.26	e0.19	222	0.37	0.29	0.32	0.40	0.42
25	e0.53	0.66	0.31	0.23	0.25	0.19	127	0.24	0.30	0.33	0.43	0.61
26	0.54	0.54	0.30	0.23	0.24	0.21	77	0.24	0.34	0.33	0.46	0.56
27	0.81	0.53	0.27	0.22	0.23	0.21	e37	21	0.34	0.33	5.7	0.34
28	224	23	0.26	0.23	0.20	0.20	e7.7	23	0.33	0.34	0.76	0.36
29	e74	68	0.25	0.22	0.21	0.20	e2.1	5.6	0.33	0.34	0.53	0.35
30	e22	—	0.24	0.21	0.21	0.20	0.41	0.29	0.32	0.34	0.52	0.36
31	e22	—	0.25	—	0.21	—	0.25	0.23	—	1.6	—	0.39
TOTAL	353.97	1458.53	250.99	7.26	7.65	6.27	704.29	778.55	107.14	13.46	18.74	13.44
MEAN	11.4	50.3	8.10	0.24	0.25	0.21	22.7	25.1	3.57	0.43	0.62	0.43
MAX	224	273	115	0.26	0.39	0.23	222	182	75	1.9	5.7	0.64
MIN	0.30	0.53	0.24	0.21	0.20	0.19	0.15	0.21	0.15	0.29	0.34	0.34
MED	0.42	17	0.31	0.24	0.23	0.21	0.23	0.29	0.29	0.33	0.40	0.42
AC-FT	702	2890	498	14	15	12	1400	1540	213	27	37	27
CFSM	0.02	0.11	0.02	0.00	0.00	0.00	0.05	0.05	0.01	0.00	0.00	0.00

Calendar year 2008 Total 3,720.3 Mean 10.2 Max 273 Min 0.15 Median 0.33 Acre-ft 7,375 CFSM 0.021

Table 12. Discharge data (daily mean values), Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2008.

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

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	e0.33	3.7	5.6	0.29	0.25	0.16	e0.15	e0.15	e0.10	e0.12	0.02	0.17
2	e0.33	0.36	22	0.30	0.30	0.15	e0.12	e0.14	e0.09	e0.13	0.02	0.18
3	e0.33	e0.42	e3.6	0.30	0.30	0.15	e0.14	e0.13	e0.09	0.16	0.01	0.19
4	e0.33	0.35	0.71	0.29	0.26	0.18	e0.15	e0.13	e0.08	0.20	0.01	e0.21
5	0.33	e0.39	e0.43	0.29	0.19	0.15	e0.14	e0.12	0.10	0.17	0.03	e0.22
6	0.29	0.43	e0.37	0.29	0.21	0.13	e0.14	2.2	0.09	0.16	e0.05	e0.21
7	e3.5	0.40	e0.35	0.28	0.43	0.14	e0.14	7.9	0.09	0.16	e0.06	e0.21
8	33	0.32	e0.34	0.30	0.34	0.14	e0.14	2.7	e0.08	0.15	e0.06	e0.21
9	e3.0	0.32	e0.32	0.29	0.21	0.14	0.16	160	e0.09	0.14	e0.35	0.17
10	e0.42	3.8	e0.30	0.28	0.21	0.16	0.31	5.9	e0.09	0.15	0.16	e0.18
11	e0.38	132	0.32	0.28	0.22	0.15	0.18	0.56	e0.10	0.17	0.19	e0.17
12	e0.39	272	0.31	0.28	0.26	0.15	0.74	0.37	e0.10	0.14	0.18	0.16
13	e0.37	323	0.27	0.27	0.22	0.15	e0.17	0.32	e0.80	e0.14	0.19	0.17
14	e0.35	492	0.27	0.27	0.23	0.16	e0.21	0.26	e0.31	e0.14	0.20	0.22
15	e0.34	72	e0.38	0.28	0.24	0.17	e0.13	0.36	e0.28	e0.15	0.23	0.24
16	e0.33	12	e0.39	0.30	0.21	0.14	e0.17	0.33	e1.3	e0.15	0.22	0.17
17	e0.34	89	e0.38	0.29	0.19	0.13	0.10	0.33	e0.29	0.15	0.21	0.18
18	e0.32	34	e0.33	0.28	0.20	0.14	0.08	0.25	e0.12	e0.16	0.21	0.19
19	e0.32	29	0.30	0.27	0.16	0.19	0.11	0.24	e0.12	e0.16	0.22	0.20
20	e0.31	30	e0.30	0.30	0.15	0.20	0.30	0.20	e0.12	e0.16	0.22	0.27
21	e0.32	34	e0.30	0.31	0.18	0.17	0.52	e0.16	e0.12	e0.15	0.22	0.26
22	e0.29	6.6	e0.29	0.25	0.16	0.18	0.33	0.27	e0.12	e0.15	0.22	0.22
23	e0.28	2.2	e0.30	0.26	0.20	0.18	5.2	0.16	e0.13	e0.15	0.23	e0.23
24	e0.27	0.81	e0.30	0.28	0.18	0.16	3.9	e0.33	e0.12	0.12	0.25	e0.24
25	e0.27	1.1	0.31	0.32	0.15	0.17	2.4	0.07	e0.12	0.10	0.22	0.24
26	e0.28	0.44	0.35	0.31	0.15	0.18	0.45	0.08	e0.12	0.08	0.24	0.25
27	e0.29	0.44	0.35	0.29	0.12	0.15	1.1	0.26	e0.12	0.07	0.30	e0.26
28	453	e0.74	0.30	0.25	0.14	0.18	0.64	0.25	e0.12	0.07	0.19	e0.23
29	e500	5.0	0.32	0.27	0.17	0.23	e0.21	0.15	e0.12	0.07	0.16	e0.25
30	e36	—	0.32	0.30	0.15	e0.14	e0.15	e0.30	e0.12	0.06	0.17	e0.28
31	20	—	0.27	—	0.14	—	e0.15	e0.23	—	0.04	—	0.27
TOTAL	1056.31	1546.82	40.68	8.57	6.52	4.82	18.83	184.85	5.65	4.12	5.04	6.65
MEAN	34.1	53.3	1.31	0.29	0.21	0.16	0.61	5.96	0.19	0.13	0.17	0.21
MAX	500	492	22	0.32	0.43	0.23	5.2	160	1.3	0.20	0.35	0.28
MIN	0.27	0.32	0.27	0.25	0.12	0.13	0.08	0.07	0.08	0.04	0.01	0.16
MED	0.33	3.7	0.32	0.29	0.20	0.15	0.17	0.26	0.12	0.15	0.20	0.21
AC-FT	2100	3070	81	17	13	9.6	37	367	11	8.2	10	13
CFSM	0.04	0.06	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00

Calendar year 2008 Total 2,888.9 Mean 7.89 Max 500 Min 0.01 Median 0.23 Acre-ft 5,737 CFSM 0.008

Table 13. Discharge data (daily mean values), Pasture Canyon Springs near Tuba City, Arizona (09401265), calendar year 2008.

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

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.34	0.34	0.32	0.36	0.27	0.19	0.22	0.27	0.22	0.25	0.32	0.34
2	0.34	0.34	0.32	0.36	0.27	0.19	0.20	0.27	0.20	0.25	0.33	0.34
3	0.34	0.35	0.32	0.36	0.27	0.19	0.20	0.27	0.20	0.26	0.34	0.33
4	0.34	0.35	0.32	0.36	0.27	0.19	0.20	0.27	0.19	0.27	0.34	0.32
5	0.34	0.34	0.32	0.36	0.27	0.19	0.20	0.26	0.18	0.26	0.34	0.34
6	0.34	0.33	0.34	0.35	0.27	0.19	0.20	0.27	0.18	0.26	0.34	0.34
7	0.34	0.32	0.34	0.34	0.26	0.20	0.20	0.27	0.19	0.26	0.34	0.34
8	0.34	0.32	0.34	0.34	0.25	0.20	0.20	0.27	0.20	0.27	0.34	0.36
9	0.34	0.33	0.34	0.34	0.25	0.20	0.19	0.27	0.20	0.29	0.34	0.36
10	0.34	0.34	0.34	0.34	0.25	0.20	0.19	0.27	0.26	0.32	0.34	0.36
11	0.33	0.34	0.34	0.34	0.25	0.21	0.19	0.26	0.22	0.33	0.34	0.36
12	0.32	0.34	0.34	0.34	0.25	0.20	0.19	0.26	0.20	0.32	0.34	0.35
13	0.32	0.34	0.34	0.33	0.25	0.20	0.19	0.26	0.20	0.32	0.34	0.36
14	0.32	0.33	0.34	0.32	0.25	0.20	0.26	0.26	0.19	0.32	0.34	0.36
15	0.32	0.32	0.34	0.31	0.25	0.20	0.26	0.26	0.19	0.32	0.34	0.36
16	0.32	0.32	0.34	0.30	0.25	0.20	0.26	0.27	0.20	0.30	0.35	0.38
17	0.32	0.32	0.34	0.31	0.25	0.20	0.28	0.26	0.20	0.30	0.36	0.38
18	0.32	0.32	0.34	0.30	0.27	0.19	0.28	0.25	0.20	0.32	0.36	0.41
19	0.32	0.32	0.34	0.30	0.27	0.19	0.26	0.25	0.20	0.32	0.36	0.41
20	0.32	0.32	e0.34	0.30	0.26	0.19	0.27	0.25	0.21	0.31	0.36	0.40
21	0.32	0.33	e0.35	0.30	0.27	0.19	0.26	0.25	0.20	0.30	0.36	0.40
22	0.34	0.34	e0.35	0.28	0.27	0.19	0.26	0.25	0.20	0.31	0.37	0.41
23	0.34	0.34	e0.36	0.28	0.27	0.19	0.26	0.25	0.20	0.30	0.38	0.41
24	0.34	0.33	e0.36	0.28	0.26	0.19	0.26	0.25	0.21	0.32	0.38	0.42
25	0.34	0.32	e0.37	0.28	0.25	0.19	0.26	0.25	0.24	0.31	0.38	0.44
26	0.34	0.32	e0.38	0.28	0.25	0.19	0.26	0.25	0.25	0.31	0.38	0.44
27	0.35	0.32	0.37	0.28	0.23	0.19	0.27	0.25	0.25	0.32	0.43	0.44
28	0.36	0.32	0.36	0.28	0.20	0.19	0.27	0.25	0.24	0.32	0.34	0.42
29	0.35	0.32	0.36	0.28	0.19	0.20	0.27	0.24	0.24	0.33	0.34	0.40
30	0.34	—	0.36	0.27	0.19	0.20	0.27	0.23	0.25	0.32	0.34	0.41
31	0.34	—	0.36	—	0.19	—	0.27	0.23	—	0.32	—	0.41
TOTAL	10.37	9.57	10.68	9.47	7.75	5.84	7.35	7.97	6.31	9.31	10.56	11.80
MEAN	0.33	0.33	0.34	0.32	0.25	0.19	0.24	0.26	0.21	0.30	0.35	0.38
MAX	0.36	0.35	0.38	0.36	0.27	0.21	0.28	0.27	0.26	0.33	0.43	0.44
MIN	0.32	0.32	0.32	0.27	0.19	0.19	0.19	0.23	0.18	0.25	0.32	0.32
MED	0.34	0.33	0.34	0.31	0.25	0.19	0.26	0.26	0.20	0.31	0.34	0.38
AC-FT	21	19	21	19	15	12	15	16	13	18	21	23

Calendar year 2008 Total 107.0 Mean 0.29 Max 0.44 Min 0.18 Median 0.31 Acre-ft 213 loss of streamflow as it moves down the stream channel, and interaction of groundwater in the N aquifer with groundwater in the shallow alluvial aquifers in the stream valleys. The median winter flow, however, is useful as a consistent index for evaluating possible time trends in groundwater discharge.

Median winter flows calculated for the 2009 water year were 2.6 ft^3/s for Moenkopi Wash at Moenkopi, 0.41 ft^3/s for Dinnebito Wash near Sand Springs, and 0.25 ft^3/s for Polacca Wash near Second Mesa (fig. 11*A–C*). For the period of record at each streamflow-gaging station, the median winter flows have generally remained constant, as indicated by trends calculated using the method of least squares ($p>0.05$; fig. 11*A–C*).

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, nutrients, iron, boron, and arsenic. Water-chemistry samples have been collected from 12 wells; 8 of the wells have been sampled every year, and the other 4 wells have been selected on the basis of a sampling rotation. In 2009 a sample was collected at six well sites: Keams Canyon PM2, Kykotsmovi PM2, Piñon NTUA 1, Forest Lake NTUA 1, Peabody 2, and Peabody 4. Since 1989, samples have been collected from the same four springs (Moenkopi School Spring, Pasture Canyon Spring, Unnamed spring near Dennehotso, and Burro Spring); however, in 2009, samples were collected from only three of these—Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring. Long-term data for specific conductance, total dissolved solids, chloride, and sulfate for the wells and springs sampled each year are shown in the reports published each year. These constituents are monitored on an annual basis because increased concentrations in the N aquifer could indicate leakage from the overlying D aquifer. On average, the concentrations of dissolved solids in water from the D aquifer is about 7 times greater than that of water from the N aquifer; concentration of chloride ions is about 11 times greater, and concentration of sulfate ions is about 30 times greater (Eychaner, 1983). Historical data for other constituents for all the wells and springs in the Black Mesa study area are available from the USGS water-quality database (http://waterdata.usgs.gov/az/nwis/qw), and they can be found in the past monitoring reports cited in the Previous Investigations section of this report.

Water-Chemistry Data for Wells Completed in the N Aquifer

The primary types of water in the N aquifer in the Black Mesa study area are calcium bicarbonate water and sodium bicarbonate water. Calcium bicarbonate water generally is in the recharge and unconfined areas of the northern and northwestern parts of the Black Mesa study area, and sodium bicarbonate water is generally in the area that is confined and downgradient to the south and east (Lopes and Hoffmann, 1997). In 2009, water samples were collected from six wells: Keams Canyon PM2, Kykotsmovi PM2, Piñon NTUA 1, Forest Lake NTUA 1, Peabody 2, and Peabody 4 (figs. 8, 12 and table 15).

Keams Canyon PM2 yielded the highest dissolved-solids concentration (609 mg/L) and chloride concentration (100 mg/L) of the six wells sampled (table 16 and fig. 13). Dissolved-solids concentrations in the other five wells ranged from 113 mg/L at Peabody 2 to 409 mg/L at Piñon NTUA 1, and their chloride concentrations ranged from 2.1 mg/L at Peabody 2 to 12 mg/L at Forest Lake NTUA 1 (table 16 and fig. 13). Piñon NTUA 1 had the highest sulfate concentration (68 mg/L) of the six wells, and the concentrations at the other wells ranged from 7.2 mg/L at Peabody 2 to 44 mg/L at Forest Lake NTUA 1 (table 16 and fig. 13). Samples from 1998 to present at Piñon NTUA 1 have shown varying sulfate concentrations from 4.7 mg/L to 83 mg/L (table 16). Samples from Piñon NTUA 1 with purge times greater than 12 hours appear to be inducing leakage from the overlying D aquifer and result in higher sulfate concentrations. The confining layer, Carmel Formation, in the area of Piñon is about 120 ft thick and comprised 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 or less coincide with areas where $^{87}Sr/^{86}Sr$ values and major-ion data for groundwater indicate that D aquifer water has mixed with N aquifer water as a result of leakage (Truini and Longsworth, 2003). Purge times may have an effect on samples taken from Piñon NTUA 1 and will be more closely monitored for future samples.

Chemical constituents analyzed from the six 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 2009, most of the analyzed constituents from the six wells were below the USEPA MCL or SMCL for drinking water. Only one MCL was exceeded from constituents analyzed from the six wells—Keams Canyon PM2 had an arsenic value of 0.0437 mg/L, and that exceeds the USEPA MCL of 0.01 mg/L for arsenic. The USEPA SMCL for concentration of dissolved solids (500 mg/L) was exceeded at Keams Canyon PM2 (609 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, Peabody 2, and Peabody 4 (U.S. Environmental Protection Agency, 2003; table 15). A linear regression analysis was used to determine trends in concentrations of dissolved solids (fig. 13), chloride, and sulfate from the six wells; for the period of record, no trends were found ($p>0.05$).

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

In 2009, water samples were collected from Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring in the southwestern part of the Black Mesa study area (fig. 8). These three 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 feet away from the spring. At Burro Spring, samples were collected from the end of a pipe that fills a trough for cattle.

The samples from Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring yielded a calcium bicarbonate-type water (fig. 12 and table 17). Samples from Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring had dissolved solid concentrations of 240 mg/L, 160 mg/L, and 372 mg/L, respectively (tables 17 and 18). Concentrations of chloride were highest at Moenkopi School Spring (27 mg/L; tables 17 and 18). Concentrations of sulfate were highest at Burro Spring (72.5 mg/L; tables 17 and 18). Concentrations of all the analyzed constituents in samples from both springs were less than current USEPA MCLs and SMCLs (U.S. Environmental Protection Agency, 2003).

There are 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 and Burro Spring did not show any trends ($p>0.05$; table 18 and fig. 14).

Summary

The N aquifer is an extensive aquifer and the primary source of groundwater for industrial and municipal users in the Black Mesa area of northeastern Arizona. Availability of water is an important issue in the Black Mesa area because of continued industrial and municipal use, a growing population, and limited precipitation of about 6 to 14 inches per year.

This report presents results of groundwater, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2008 to September 2009. The monitoring data for 2008–9 are compared to data for 2007–8 and to historical data from the 1950s to September 2009.

In 2008, total groundwater withdrawals were 4,110 acre-ft, industrial withdrawals were 1,210 acre-ft, and municipal withdrawals were 2,900 acre-ft. From 2007 to 2008, total withdrawals from the N aquifer decreased by 4 percent, industrial withdrawals increased by approximately 3 percent, and total municipal withdrawals decreased by 6 percent.

From 2008 to 2009, annually measured groundwater levels declined in 19 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 8 of 15 annual wells available for comparison, and the median change was −0.1 ft. In the confined area of the N aquifer, water levels declined in 11 of 18 wells, and the median change was −0.2 ft.

From the prestress period (before 1965) to 2009, the median groundwater level change in 34 wells was −11.8 ft. Water levels in the 16 wells in the unconfined areas of the N aquifer had a median change of −1.6 ft, and the changes ranged from −33.8 ft to +14.2 ft. Water levels in the 18 wells in the confined area of the N aquifer had a median change of −36.7 ft, and the changes ranged from −205.9 ft to +17.7 ft.

Discharge has been measured annually at Moenkopi School Spring and Pasture Canyon Spring and intermittently at Burro Spring. Between 2008 and 2009, spring flow decreased by 3.6 percent at Moenkopi School Spring, and spring flow increased by 5.7 percent at Pasture Canyon Spring. Discharge at Burro Spring has remained relatively constant since it was first measured in 1989. 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, but no trend is apparent for Burro Spring.

Annual average discharges at four streamflow-gaging stations—Moenkopi Wash, Dinnebito Wash, Pasture Canyon Springs, and Polacca Wash—vary during the periods of record. No trends are apparent in streamflow at the four streamflow-gaging stations. Median flows for November, December, January, and February of each water year are used as an indicator of groundwater discharge to those streams. For the period of record at each streamflow-gaging station, the median winter flows have generally remained constant, showing neither a significant increase nor decrease.

In 2009, water samples were collected from six wells and analyzed for selected chemical constituents. 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 the water samples from Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring were 240 mg/L, 160 mg/L, and 372 mg/L, respectively. From the mid 1980s to 2009, 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 and Burro Spring do not indicate a trend for the period of record.

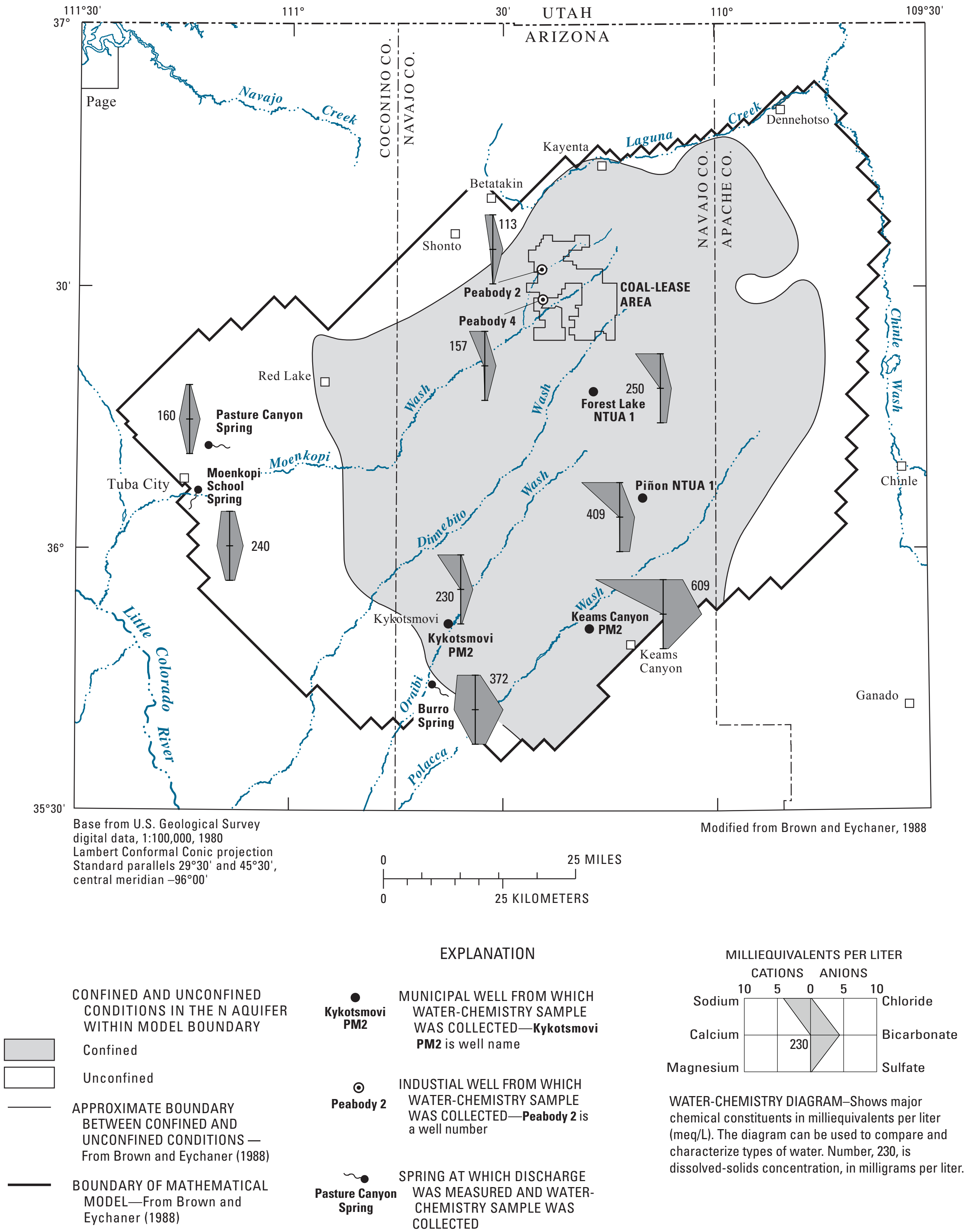


Figure 12. Water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, northeastern Arizona, 2009.

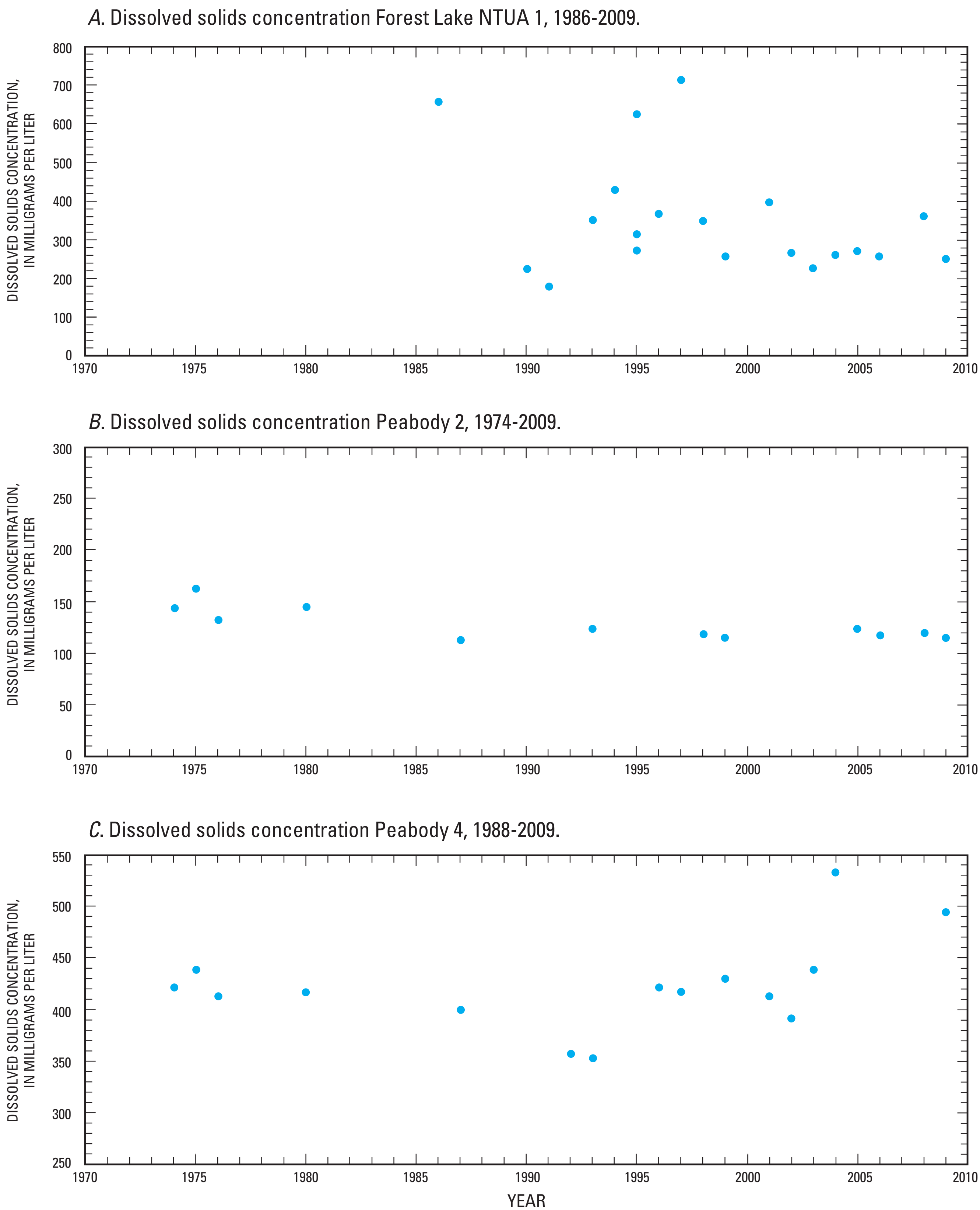


Figure 13. Dissolved-solids concentrations for water samples from selected wells, N aquifer, Black Mesa area, northeastern Arizona, 1974–2009. *A*, Forest Lake NTUA 1, 1986–2009; *B*, Peabody 2, 1974–2009; *C*, Peabody 4, 1988–2009; *D*, Keams Canyon PM2, 1984–2009; *E*, Pinon NTUA 1, 1998–2009; and *F*, Kykotsmovi PM2, 1988–2009.

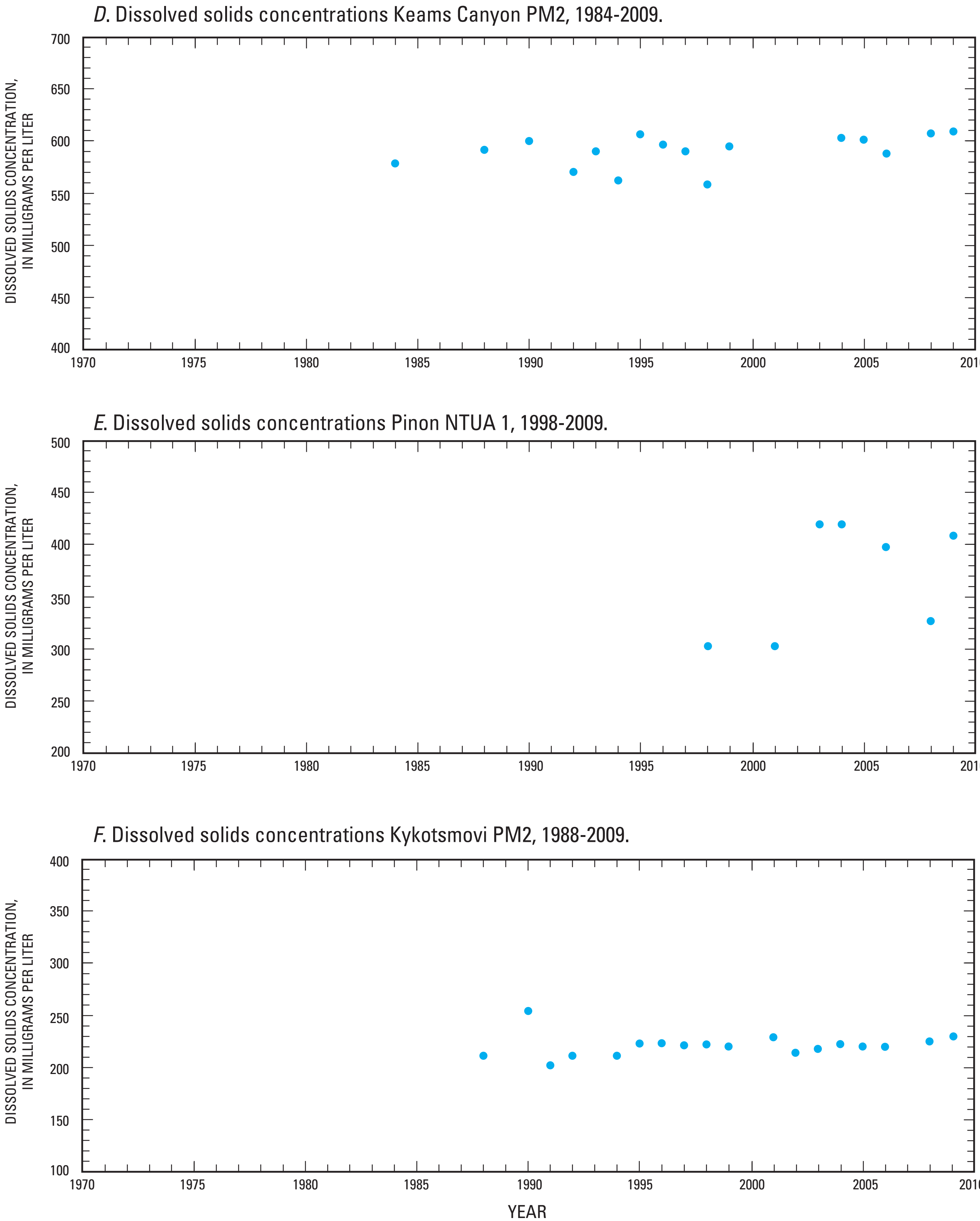


Figure 13. Dissolved-solids concentrations for water samples from selected wells, N aquifer, Black Mesa area, northeastern Arizona, 1974-2009. *A*, Forest Lake NTUA 1, 1986-2009; *B*, Peabody 2, 1974-2009; *C*, Peabody 4, 1988-2009; *D*, Keams Canyon PM2, 1984-2009; *E*, Pinon NTUA 1, 1998-2009; and *F*, Kykotsmovi PM2, 1988-2009—Continued.

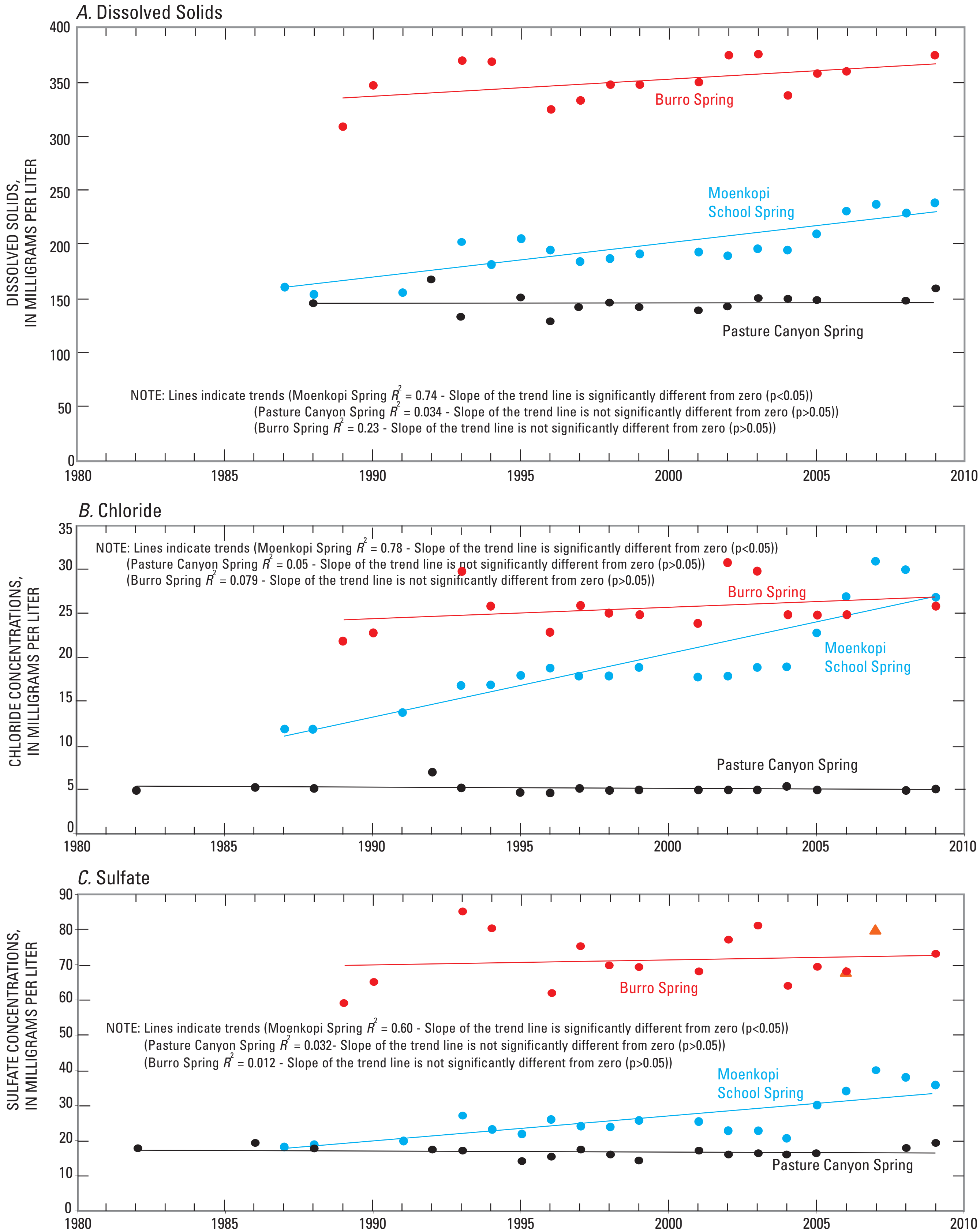


Figure 14. Concentrations of dissolved solids, chloride, and sulfate for water samples from Moenkopi School Spring, Pasture Canyon Spring, and Burro Spring, N aquifer, Black Mesa area, northeastern Arizona, 1982–2009. *A*, Dissolved solids; *B*, Chloride; *C*, Sulfate. (Trend lines were generated by using the method of least squares).

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, in square miles
Moenkopi Wash at Moenkopi	9401260	July 1976	1,629
Dinnebito Wash near Sand Springs	9401110	June 1993	473
Polacca Wash near Second Mesa	9400568	April 1994	905
Pasture Canyon Springs	9401265	August 2004	—

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, 2009.

[°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. Dashes indicate no data]

Common well name	U.S. Geological Survey identification number	Date of samples	Temperature field, in °C	Specific conductance field, in µS/cm	pH field, in units	Alkalinity, field, dissolved, in mg/L as $CaCO_3$	Nitrogen NO_2+ NO_3 dissolved, in mg/L as N	Ortho-Phosphate dissolved, in mg/L as P	Calcium dissolved, in mg/L as Ca	Magnesium dissolved, in mg/L as Mg	Potassium dissolved, in mg/L as K
Keams Canyon PM2	355023110182701	06-02-09	21.2	1050	9.3	347	<.04	0.014	0.82	0.157	0.79
Kykotsmovi PM2	355215110375001	06-02-09	23.3	371	9.8	172	1.17	0.034	0.47	0.014	0.40
Pinon NTUA 1	360527110122501	06-04-09	26.9	646	9.8	230	1.28	0.016	0.85	0.127	0.46
Forest Lake NTUA 1	361737110180301	06-03-09	29.1	384	9.5	121	0.6	0.01	0.88	0.085	0.63
Peabody 2	363005110250901	06-09-09	30.1	146	8.8	82.5	0.97	0.011	7.87	0.128	0.71
Peabody 4	362647110243501	06-09-09	30.8	258	9.4	96.6	1.0	0.013	2.96	0.031	0.76

Common well name	U.S. Geological Survey identification number	Date of samples	Sodium dissolved, in mg/L as Na	Chloride dissolved, in mg/L as Cl	Flouride dissolved, in mg/L as F	Silica dissolved, in mg/L as SiO_2	Sulfate dissolved, in mg/L as SO_4	Arsenic dissolved, in ug/L as As	Boron dissolved, in ug/L as B	Iron dissolved, in ug/L as Fe	Dissolved solids residue at 180°C, in mg/L
Keams Canyon PM2	355023110182701	06-02-09	223.0	100.0	1.36	12.8	35.5	43.7	720	<4	609
Kykotsmovi PM2	355215110375001	06-02-09	76.6	3.1	0.14	24.6	8.11	5.8	32	6	230
Pinon NTUA 1	360527110122501	06-04-09	126.0	7.1	0.28	27.0	68.40	4.7	77	6	409
Forest Lake NTUA 1	361737110180301	06-03-09	82.5	12.1	0.31	21.5	43.60	3.3	101	22	250
Peabody 2	363005110250901	06-09-09	26.0	2.1	0.12	22.1	7.16	3.1	17	<4	113
Peabody 4	362647110243501	06-09-09	50.9	4.8	0.19	21.5	17.90	3.2	28	<4	157

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, 1974–2009.

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

Year	Specific conductance, field, in µS/cm	Dissolved solids, residue at 180°C, in mg/L	Chloride, dissolved, in mg/L as Cl	Sulfate, dissolved, in mg/L as SO_4
		Forest Lake NTUA 1		
1982	470	—	11	67
1986	—	660	35	300
1990	375	226	8.2	38
1991	350[1]	183	10	24
1993	693	352	35	88
1994	734[1]	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	1,140[1]	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
		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
		Peabody 4		
1974	200	140	3.8	13
1975	220	144	3.4	13
1976	240	138	2.9	19
1979	220	—	—	19
1980	230	139	3.9	13
1986	205	—	4.2	12
1987	194	135	5.0	13
1992	224	125	4.3	12
1993	214	124	3.0	12
1996	214	140	3.8	12
1997	203	139	3.5	12
1999	216	142	4.0	13
2001	181	138	4.0	13

Year	Specific conductance, field, in µS/cm	Dissolved solids, residue at 180°C, in mg/L	Chloride, dissolved, in mg/L as Cl	Sulfate, dissolved, in mg/L as SO_4
		Peabody 4—Continued		
2002	214	133	3.9	13
2003	221	144	3.5	13
2004	198	166	4.5	12
2009	258	157	4.8	18
		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	603[2]	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
		Pinon 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
		Kykotsmovi PM2		
1988	368	212	3.2	8.6
1990	355	255	3.2	9.0
1991	374[1]	203	4.4	7.9
1992	363	212	3.3	8.4
1994	365[1]	212	3.6	8.5
1995	368	224	3.1	6.2
1996	365	224	3.3	8.5
1997	379[1]	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

[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 report printed in 2004.

Table 17. Physical properties and chemical analyses of water samples from Burro Spring, Moenkopi School Spring, and Pasture Canyon Spring, Black Mesa area, northeastern Arizona, 2009.

[°C, degree Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than. Dashes indicate no data; e, estimated]

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Temperature field, in °C	Specific conductance field, in µS/cm	pH field, in units	Alkalinity, field, dissolved, in mg/L as $CaCO_3$	Nitrogen NO_2+NO_3 dissolved, in mg/L as N	Ortho-Phosphate dissolved, in mg/L as P	Calcium dissolved, in mg/L as Ca	Magnesium dissolved, in mg/L as Mg	Potassium dissolved, in mg/L as K
354156110413701	6M-31	Burro Spring	06-04-09	23	577	7.8	201	<.04	0.01	61.4	4.31	0.4
360632111131101	3GS-77-6	Moenkopi School Spring	06-03-09	18	381	7.4	99	2.42	0.008	36.8	7.41	1.37
361021111115901	3A-5	Pasture Canyon Spring	06-03-09	16	241	7.7	76	4.38	0.019	30.2	4.34	1.3

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Sodium dissolved, in mg/L as Na	Chloride dissolved, in mg/L as Cl	Flouride disolved, in mg/L as F	Silica dissolved, in mg/L as SiO_2	Sulfate dissolved, in mg/L as SO_4	Arsenic dissolved, in ug/L as As	Boron dissolved, in ug/L as B	Iron dissolved, in ug/L as Fe	Dissolved solids residue at 180°C, in mg/L
354156110413701	6M-31	Burro Spring	06-04-09	43	25.7	0.4	17.1	72.5	—	83	11	372
360632111131101	3GS-77-6	Moenkopi School Spring	06-03-09	33	27.0	0.16	14.0	35.6	2.5	47	<4	240
361021111115901	3A-5	Pasture Canyon Spring	06-03-09	22	5.1	0.13	10.1	18.6	1.9	36	<4	160

Table 18. Specific conductance and concentrations of selected chemical constituents in N-aquifer water samples from Burro Spring, Moenkopi School Spring, and Pasture Canyon Spring, Black Mesa area, northeastern Arizona, 1948–2009.

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

Year	Specific conductance, field, in µS/cm	Dissolved solids, residue at 180°C, in mg/L	Chloride, dissolved, in mg/L as Cl	Sulfate, dissolved, in mg/L as SO_4
Burro Spring				
1989	485	308	22	59
1990	545[1]	347	23	65
1993	595	368	30	85
1994	597[1]	368	26	80
1996	525	324	23	62
1997	511[1]	332	26	75
1998	504	346	25	70
1999	545	346	25	69
2001	480	348	24	68
2002	591	374	31	77
2003	612	374	30	81
2004	558	337	25	64
2005	558	357	25	69
2006	576	359	25	68
2009	577	372	26	73
Pasture Canyon Spring				
1948	227[1]	([2])	5.0	13
1982	240	—	5.1	18
1986	257	—	5.4	19
1988	232	146	5.3	18
1992	235	168	7.1	17
1993	242	134	5.3	17
1995	235	152	4.8	14
1996	238	130	4.7	15
1997	232	143	5.3	17
1998	232	147	5.1	16
1999	235	142	5.1	14
2001	236	140	5.1	17
Pasture Canyon Spring—Continued				
2002	243	143	5.1	16
2003	236	151	5.1	16
2004	248	150	5.5	16
2005	250	149	5.1	16
2008	240	149	5.0	18
2009	241	160	5.1	19
Moenkopi School Spring				
1952	222	—	6	—
1987	270	161	12	19
1988	270	155	12	19
1991	297	157	14	20
1993	313	204	17	27
1994	305	182	17	23
1995	314	206	18	22
1996	332	196	19	26
1997	305[1]	185	18	24
1998	296	188	18	24
1999	305	192	19	26
2001	313	194	18	26
2002	316	191	18	23
2003	344	197	19	23
2004	349	196	19	21
2005	349	212	23	30
2006	387	232	27	34
2007	405	238	31	40
2008	390	230	30	38
2009	381	240	27	36

[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.

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