Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2007–2008

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

Open-File Report 2009–1148

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

COVER:
This photograph is looking upstream at USGS streamflow gaging station Dinnebito Wash near Sand Springs, AZ (09401110)

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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).

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Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2007–2008

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 2007 to September 2008. The monitoring program includes measurements of (1) groundwater withdrawals, (2) groundwater levels, (3) spring discharge, (4) surface-water discharge, and (5) groundwater chemistry.

In 2007, total groundwater withdrawals were 4,270 acre-feet, industrial withdrawals were 1,170 acre-ft, and municipal withdrawals were 3,100 acre-ft. Total withdrawals during 2007 were about 41 percent less than total withdrawals in 2005. From 2006 to 2007, however, total withdrawals increased by 4 percent, industrial withdrawals decreased by approximately 2 percent, and total municipal withdrawals increased by 7 percent.

From 2007 to 2008, annually measured water levels in the Black Mesa area declined in 6 of 11 wells measured in the unconfined areas of the N aquifer, and the median change was -0.2 feet. Water levels declined in 9 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 2008, the median water-level change for 33 wells in both the confined and unconfined area was -12.9 feet. Median water-level changes were -1.0 feet for 15 wells measured in the unconfined areas and -33.2 feet for 18 wells measured in the confined area.

Spring flow was measured at two springs in 2008. Flow decreased at both Moenkopi School Spring and Pasture Canyon Spring from previous years. Flow fluctuated during the period of record, but a decreasing trend was apparent.

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 2007), Dinnebito Wash near Sand Springs 09401110 (1993 to 2007), Polacca Wash near Second Mesa 09400568 (1994 to 2007), and Pasture Canyon Springs 09401265 (August 2004 to 2007). 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. The period of record is too short to determine if there is a trend at Pasture Canyon Spring.

In 2008, water samples collected from 6 wells and 2 springs in the Black Mesa area were analyzed for selected chemical constituents and the results 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 1980's, and there is no trend in those data.

Introduction

The 5,400-square-mile 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 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

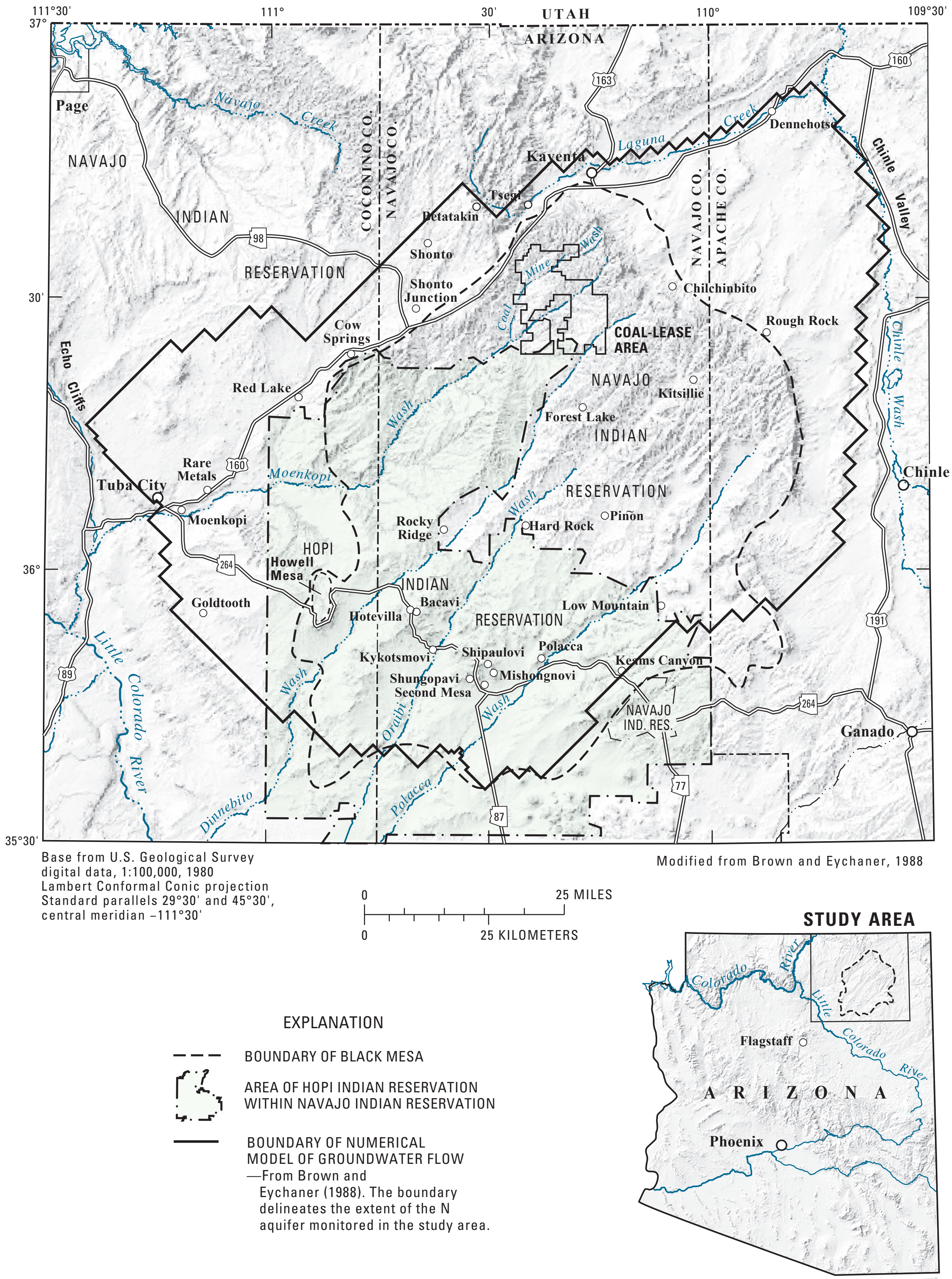


Figure 1. Location of study area, Black Mesa area, northeastern Arizona.

in the Black Mesa area. The N aquifer is composed of three hydraulically connected formations—the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member of the Wingate Sandstone—that function as a single aquifer (fig. 2).

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

Within the Black Mesa study area, the Navajo Nation and Hopi Tribe are the principal municipal water users and Peabody Western Coal Company (PWCC) is the principal industrial water user. Withdrawals from the N aquifer in the Black Mesa area 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. Withdrawals from the N aquifer for municipal use increased from an estimated 250 acre-ft in 1968 to 2,850 acre-ft in 2005. 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 on continuing to pump approximately 1,000 to 1,500 acre-ft per year, primarily for dust control. In 2006 and 2007 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 2007 to September 2008. 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.

Previous Investigations

Twenty-five 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). 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 U.S. Geological Survey (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), and online at (*http://wdr.water.usgs.gov/wy2006/search.jsp*) in the 2006 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 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

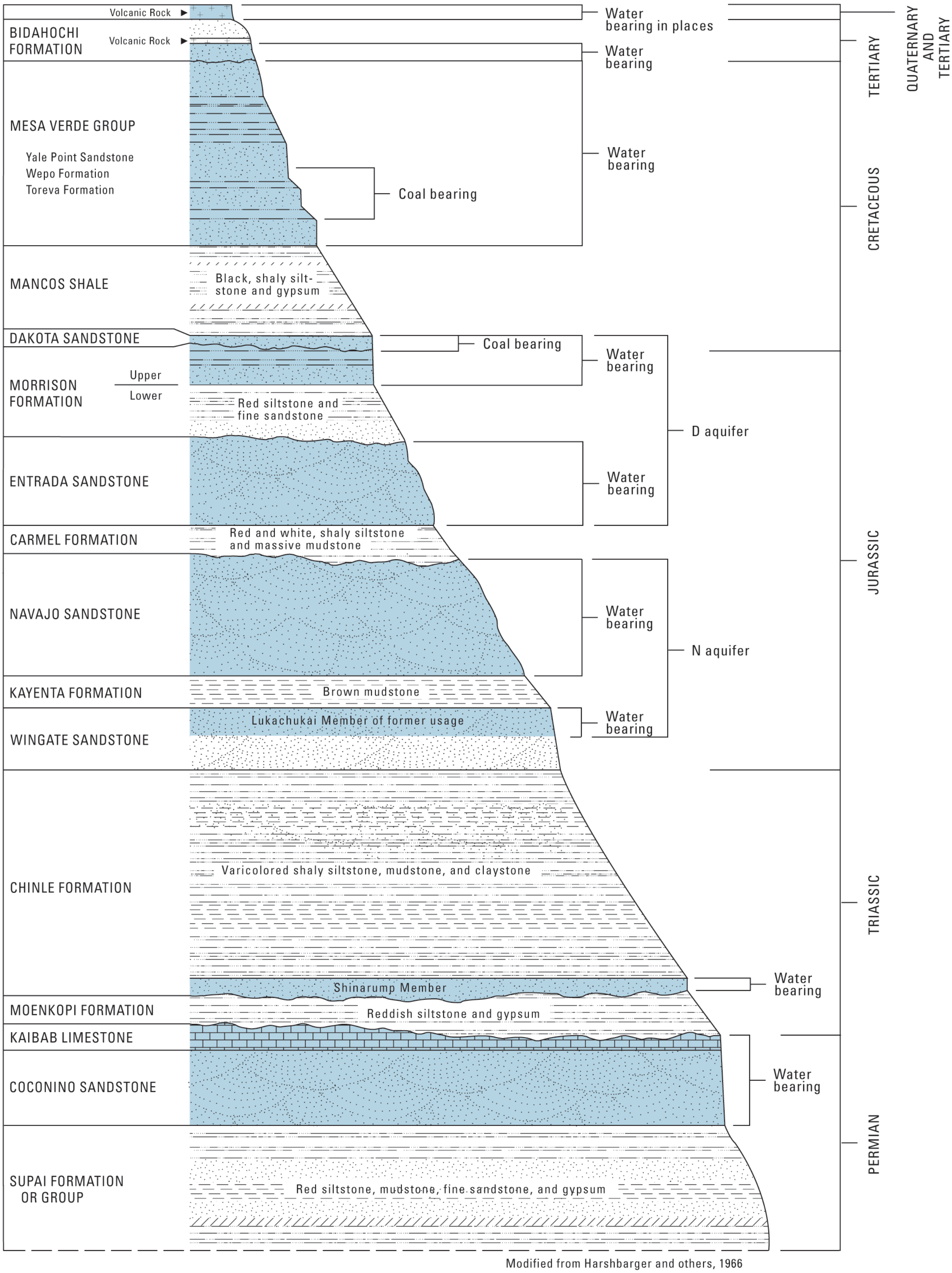


Figure 2. Rock formations and hydrogeologic units of the Black Mesa area, Arizona (not to scale). The N aquifer is approximately 1,000 feet thick.

Table 1. Withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2007.

[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

[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, 1986–2007.

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

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 2007–8, 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, and water-chemistry samples. Annual discharge measurements were made at 2 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. The water-level data from these six continuous-recording observation wells are available on the World Wide Web (http://waterdata.usgs.gov/az/nwis/rt). Groundwater withdrawal data were collected from January to December 2007. Spring discharges and groundwater levels were measured from January to June 2008. Groundwater samples were collected from six wells and two springs in June 2008 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. All annual data reported in this document are for calendar years beginning January 1 and ending December 31.

Withdrawals from the N Aquifer

Total withdrawals from the N aquifer are monitored on a continuing basis to determine the effects from industrial and municipal pumping. Withdrawals from the N aquifer are separated into three categories: (1) industrial withdrawals from the confined area, (2) municipal withdrawals from the confined area, and (3) municipal withdrawals from the unconfined areas. The industrial category includes eight wells in the PWCC well field in the northern Black Mesa area. The BIA, NTUA, and Hopi Tribe operate about 70 municipal wells that are combined into 28 well systems. Information about withdrawals from the N aquifer is compiled primarily on the basis of metered data from individual wells operated by the BIA, NTUA, and Hopi Tribe (table 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 2007, the total groundwater withdrawal from the N aquifer was about 4,270 acre-ft (table 1). Withdrawals for municipal use from the confined area totaled 1,460 acre-ft. Withdrawals for municipal use from the unconfined areas totaled 1,640 acre-ft. Withdrawals for industrial use totaled 1,170 acre-ft, a 2-percent decrease from 2006, and withdrawals for municipal use totaled 3,100 acre-ft (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 1965–2007 totaled 226,670 acre-ft; industrial withdrawals were 62 percent and municipal withdrawals 38 percent of total withdrawals (table 4). From 1965 to 1972, total annual withdrawals increased from 70 to 4,300 acre-ft; industrial withdrawals were 72 percent and municipal withdrawals 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 30 percent of total withdrawals (table 4). In 1985, withdrawals totaled 4,720 acre-ft; industrial withdrawals were 53 percent and municipal withdrawals 47 percent of total withdrawals. From 1986 to 2004, withdrawals totaled 130,850 acre-ft; industrial withdrawals were 60 percent and municipal withdrawals 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 39 percent of total withdrawals (table 4). 2006 marks a distinct change in the amount of water being pumped from the N aquifer; 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 to this number because NTUA metered data were not available for 2006 and therefore had to be estimated based on a 1-percent increase from the year before. Withdrawals in 2007 were much the same as in 2006. Total withdrawals were 4,270 acre-ft, with 27 percent coming from industrial withdrawals and 73 percent from municipal withdrawals (table 4).

Table 2. Identification numbers and names of monitoring program study wells, 2007-8, 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
362823109463101	Rough Rock	10R-119
362936109564101	BM observation well 1	8T-537
363013109584901	Sweetwater Mesa	8K-443
363103109445201	Rough Rock	9Y-95
363130110254501	Peabody 8	---
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 2007.

[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	Withdrawals: Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	2.3	
Dennehotso	BIA	USGS/BIA		13.9
Hopi High School	BIA	USGS/BIA	23.8	
Hotevilla	BIA	USGS/BIA	13.4	
Kayenta	BIA	USGS/BIA	49.4	
Keams Canyon	BIA	USGS/BIA	[1]61.9	
Low Mountain	BIA	USGS/BIA	[2]0	
Piñon	BIA	USGS/BIA	[2]0	
Red Lake	BIA	USGS/BIA		92.7
Rocky Ridge	BIA	USGS/BIA	7.8	
Rough Rock	BIA	USGS/BIA	25.0	
Second Mesa	BIA	USGS/BIA	3.3	
Shonto	BIA	USGS/BIA		124.5
Tuba City	BIA	USGS/BIA		113.6
Chilchinbito	NTUA	USGS/NTUA	36.9	
Dennehotso	NTUA	USGS/NTUA		47.4
Forest Lake	NTUA	USGS/NTUA	10.5	
Hard Rock	NTUA	USGS/NTUA	44.0	
Kayenta	NTUA	USGS/NTUA	490.3	
Kits'iili	NTUA	USGS/NTUA	17.8	
Piñon	NTUA	USGS/NTUA	306.4	
Red Lake	NTUA	USGS/NTUA		62.7
Rough Rock	NTUA	USGS/NTUA	33.8	
Shonto	NTUA	USGS/NTUA		21.8
Shonto Junction	NTUA	USGS/NTUA		81.7
Tuba City	NTUA	USGS/NTUA		959.8
Mine Well Field	Peabody	Peabody	1,172	
Bacavi	Hopi	USGS/Hopi	25.3	
Hopi Civic Center	Hopi	USGS/Hopi	3.6	
Hopi Cultural Center	Hopi	USGS/Hopi	6.6	
Kykotsmovi	Hopi	USGS/Hopi	63.9	
Mishongnovi	Hopi	USGS/Hopi	4.7	
Moenkopi	Hopi	USGS/Hopi		124.8
Polacca	Hopi	USGS/Hopi	179.7	
Shipaulovi	Hopi	USGS/Hopi	18.5	
Shungopovi	Hopi	USGS/Hopi	32.6	

[1]Meters broken in 2007, withdrawal estimated from well operator

[2]Well taken out of service

Table 4. Total, industrial, and municipal withdrawals from the N aquifer for discrete time periods during 1965 to 2007, Black Mesa area, northeastern Arizona.

Period	Total withdrawals (acre-feet)	Industrial withdrawals (acre-feet)	Municipal withdrawals (acre-feet)	Percent industrial	Percent municipal
1965–2007	226,670	140,470	86,200	62	38
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

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

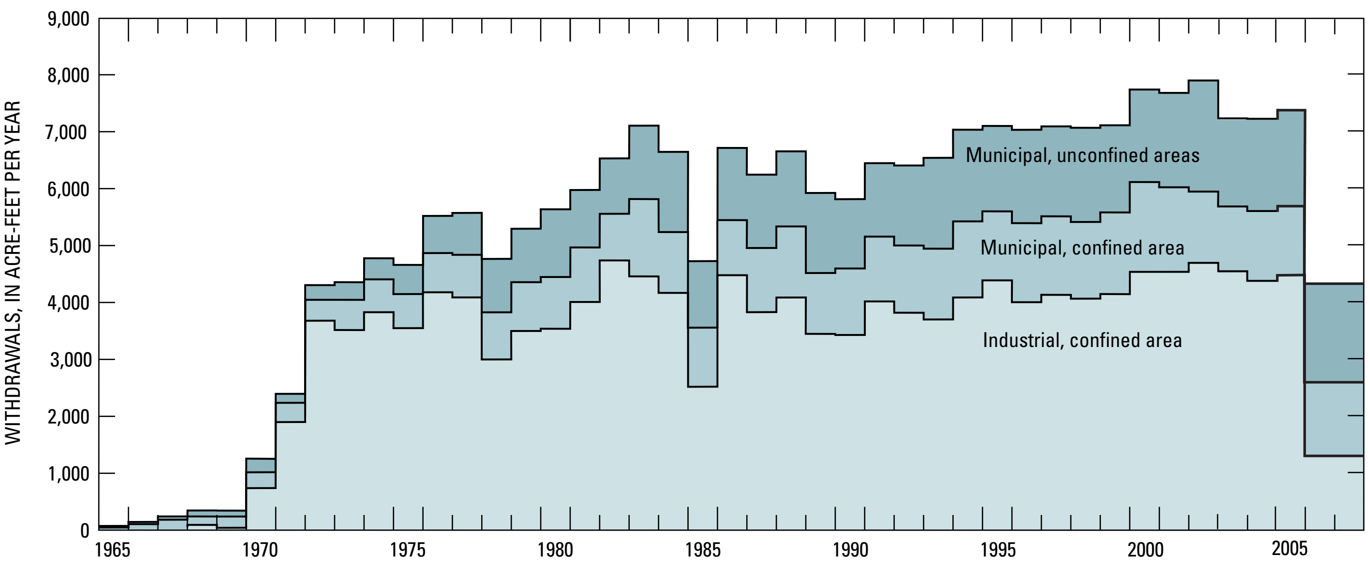


Figure 3. Annual withdrawals from N aquifer, Black Mesa area, northeastern Arizona, 1965–2007.

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 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 February 2008 to March 2008, water levels in 33 of 34 wells having annual measurements met these criteria (table 5). Of the 34 wells, 6 are continuous-recording observation wells, and water levels were measured by steel or electric tape in these 6 wells four times between June 2007 and June 2008. Twenty-nine of 33 water levels measured in 2008 were compared with water levels for the same wells measured in 2007. Water levels measured in 2008 in five of the wells, Goldtooth 3A-28, Shonto 2K-301, Tuba City NTUA 1, Tuba City NTUA 3, and Tuba City NTUA 4, could not be compared to 2007 water levels because measurements are not available for these wells in 2007.

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 2,617 ft near PWCC (table 6).

From 2007 to 2008, water levels decreased in 15 of the 29 wells for which comparisons could be made (table 5). The median water-level change in the 29 wells was -0.2 ft (table 7). From 2007 to 2008, water levels declined in 6 of the 11 wells measured in the unconfined parts of the aquifer (table 5). The median water-level change was -0.2 ft (table 7). Water-level changes in the unconfined part of the aquifer ranged from -4.2 ft at Rough Rock 9Y-95 to +0.5 ft at Tuba City Rare Metals (table 5). In the confined area, water levels declined in 9 of 18 wells measured from 2007 to 2008. The median water-level change was -0.2 ft (table 7). Water-level changes in the confined part of the aquifer ranged from -3.3 ft at Kitsillie NTUA 2 to +6.6 ft at Kykotsmovi PM3 (table 5).

From the prestress period (before 1965) to 2008, the median water-level change in 33 wells was -12.9 ft (table 7). Water levels in 15 unconfined wells had a median change of -1.0 ft. Water-level changes in the unconfined part of the aquifer ranged from -33.1 ft at 8T-510 near Long House Valley to +11.8 ft at 9Y-95 in Rough Rock (fig. 5 and table 5). Water levels in 18 wells in the confined part of the aquifer had a median change of -33.2 ft (table 7). Water-level changes in the confined part of the aquifer ranged from -198.7 ft at Keams Canyon PM2 to +13.4 ft at 3K-311 (fig. 5 and table 5).

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 33 ft (fig. 5 and fig. 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 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 70's until the year 2007, when a distinct change occurred in the trend of the water level from decreasing to increasing.

Spring Discharge from the N Aquifer

The effect of withdrawals from the N aquifer on the water quality and quantity 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 2008, Moenkopi School Spring and Pasture Canyon Spring, two of the four springs that have been measured annually, 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 2008 by the volumetric method and compared to discharge data from previous years to determine changes over time (fig. 9). The trend from discharge measurements at this spring is not corrected for seasonal variability. In 2008, the measured discharge was 8.3 gal/min from Moenkopi School Spring (table 8). From 2007 to 2008, discharge decreased by 7.7 percent; for the period of record, discharge measurements have fluctuated and exhibit a decreasing trend ($p<0.01$) (fig. 9 and table 8).

Pasture Canyon Spring is also located 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 is where the spring issues from the Navajo Sandstone, which is also the water-quality sampling point, and the second 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 2008 by the volumetric method, and when compared to previous years a decreasing trend ($p<0.01$) is seen (fig. 9 and table 8). The trend from discharge measurements at this spring are not corrected for seasonal variability. In 2008 the measured discharge was 29.4 gal/min, which is an 11.7 percent decrease from 2005, the last time Pasture Canyon Spring was measured. Pasture Canyon Spring was not measured in 2006 or 2007 because of budgetary restraints.

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

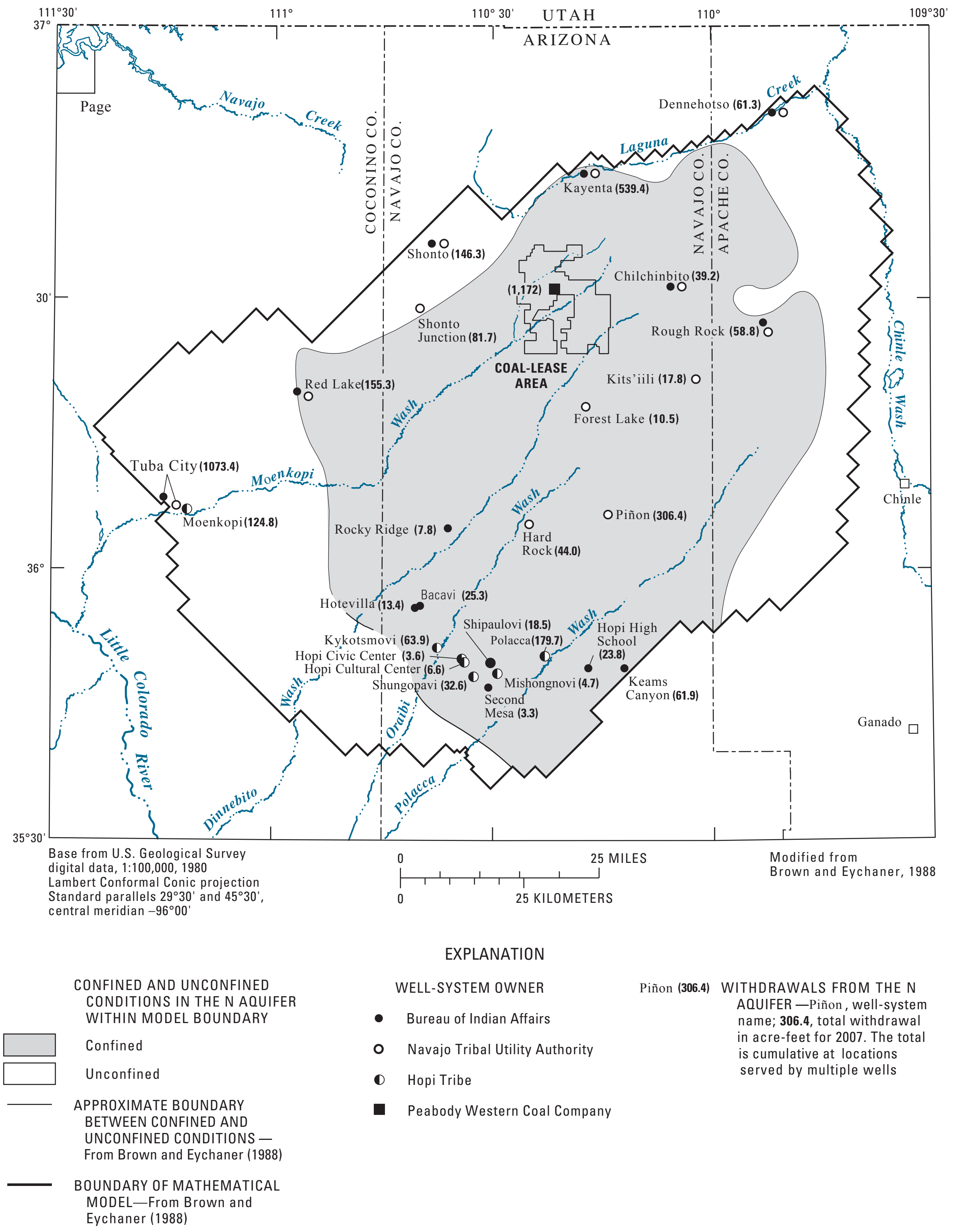


Figure 4. Locations of well systems monitored for annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, calendar year 2007.

Table 5. Water-level changes in monitoring program wells completed in the N aquifer, Black Mesa area, northeastern Arizona, prestress period to 2008 (calendar year).

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

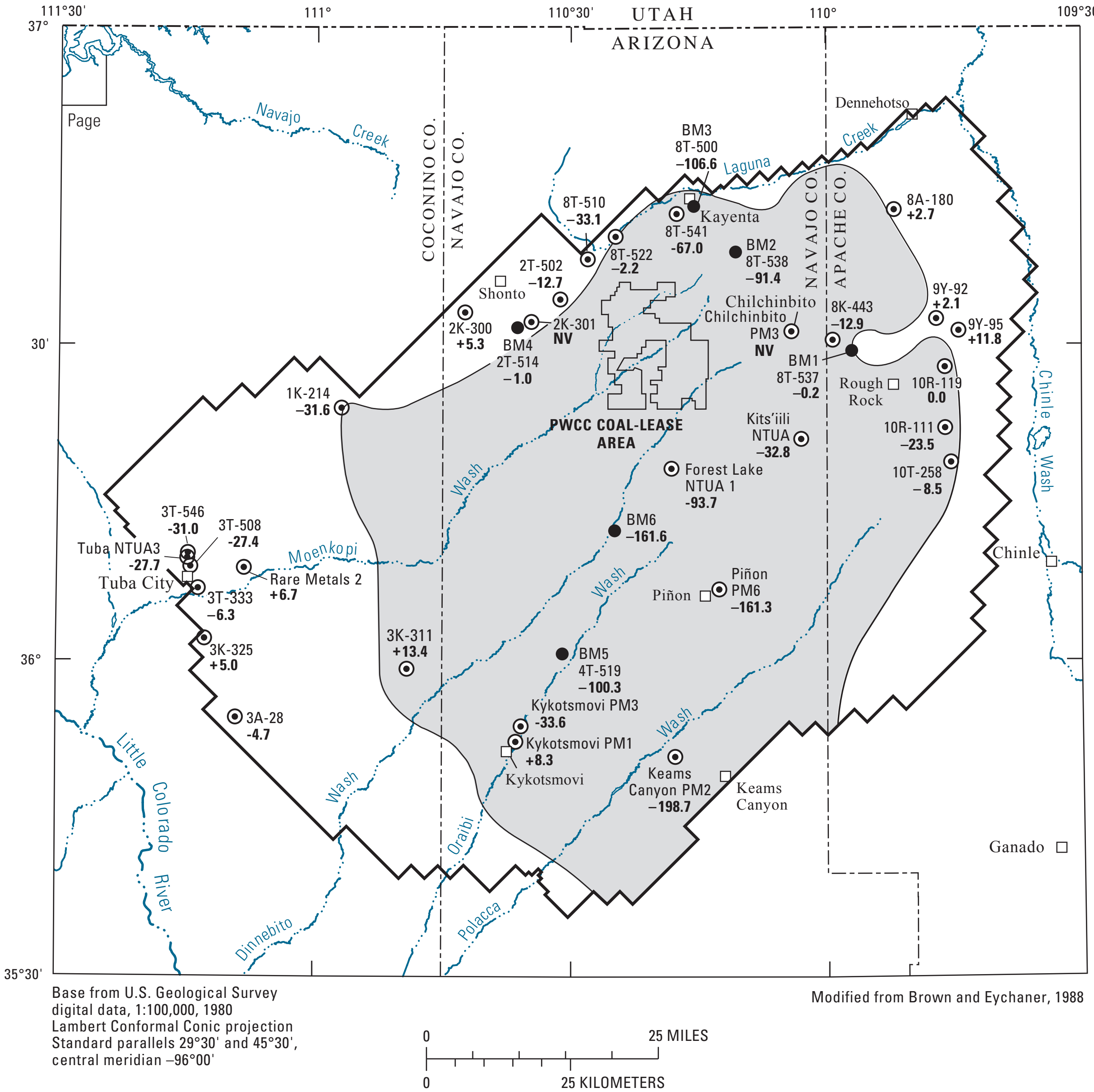
Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year (feet)		Water level (feet below land surface), 2008	Prestress period water level		Change in water level from prestress period to 2008 (feet)
		2007	2008		Feet below land surface	Date	
Unconfined areas							
BM observation well 1[1]	8T-537	0.0	0.0	374.2	374.0	(1)	-0.2
BM observation well 4[1]	2T-514	0.0	-0.2	217.0	216.0	(1)	-1.0
Goldtooth	3A-28	(2)	(2)	234.7	230.0	10–29–53	-4.7
Long House Valley	8T-510	-1.4	-1.1	132.5	99.4	08–22–67	-33.1
Northeast Rough Rock	8A-180	+0.4	-0.2	44.2	46.9	11–13–53	+2.7
Rough Rock	9Y-95	+5.9	-4.2	107.7	119.5	08–03–49	+11.8
Do.	9Y-92	+0.9	-2.0	166.7	168.8	12–13–52	+2.1
Shonto	2K-300	-0.3	+0.4	171.2	176.5	06–13–50	+5.3
Shonto Southeast	2K-301	(2)	(2)	(3)	283.9	12–10–52	(3)
Do.	2T-502	+0.5	-2.8	418.5	405.8	08–22–67	-12.7
Tuba City	3T-333	0.0	0.0	29.3	23.0	12–02–55	-6.3
Do.	3K-325	-0.4	+0.1	203.0	208.0	06–30–55	+5.0
Tuba City Rare Metals 2	---	+0.2	+0.5	50.3	57.0	09–24–55	+6.7
Tuba City NTUA 1	3T-508	(2)	(2)	56.4	29.0	02–12–69	-27.4
Tuba City NTUA 3	---	(2)	(2)	61.9	34.2	11–08–71	-27.7
Tuba City NTUA 4	3T-546	(2)	(2)	64.7	33.7	08–06–71	-31.0
Confined area							
BM observation well 2[1]	8T-538	-2.5	-1.1	216.4	125.0	(1)	-91.4
BM observation well 3[1]	8T-500	-2.5	-0.5	161.6	55.0	04–29–63	-106.6
BM observation well 5[1]	4T-519	-3.9	-2.1	424.3	324.0	(1)	-100.3
BM observation well 6[1]	---	-1.8	+1.9	858.6	697.0	(1)	-161.6
Forest Lake NTUA 1	4T-523	+0.3	+0.1	1189.7	1,096R	05–21–82	-93.7
Howell Mesa	3K-311	+2.1	-1.3	449.6	463.0	11–03–53	+13.4
Kayenta West	8T-541	+8.2	+0.5	297.0	230.0	03–17–76	-67.0
Keams Canyon PM2	---	-8.9	+6.4	491.2	292.5	06–10–70	-198.7
Kits'iili NTUA 2	---	-3.4	-3.3	1330.7	[4]1,297.9	01–14–99	-32.8
Kykotsmovi PM1	---	+0.4	+0.4	211.7	220.0	05–20–67	+8.3
Kykotsmovi PM3	---	(2)	+6.6	243.6	210.0	08–28–68	-33.6
Marsh Pass	8T-522	+0.2	-0.5	127.7	125.5	02–07–72	-2.2
Piñon PM6	---	-5.9	-0.6	904.9	743.6	05–28–70	-161.3
Rough Rock	10R-119	(2)	+0.1	256.6	256.6	12–02–53	0.0
Do.	10T-258	-0.2	+0.2	309.5	301.0	04–14–60	-8.5
Do.	10R-111	+0.3	-1.8	193.5	170.0	08–04–54	-23.5
Sweetwater Mesa	8K-443	+0.2	-0.6	542.3	529.4	09–26–67	-12.9
White Mesa Arch	1K-214	+0.4	+0.3	219.6	188.0	06–04–53	-31.6

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

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

[3]Water level not measured because of obstruction in well.

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



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'

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 +5.3 — WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 2K-300, is Bureau of Indian Affairs site number; second entry, **+5.3**, is change in water level, in feet, between measurement made during the prestress period and measurement made during 2008. **NV**, site not visited

BM2 8T-538 –91.4 — 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, **–91.4**, is change in water level, in feet, from simulated prestress period to 2008

Figure 5. Water-level changes in N-aquifer wells from the prestress period (prior to 1965) to 2008, Black Mesa area, northeastern Arizona.

Table 6. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, northeastern Arizona, 2007-8.

Bureau of Indian Affairs site number, and (or) common name	Date well was completed	Land- surface elevation (feet)	Well depth (feet below land surface)	Screened/open interval(s) (feet below land surface)	Depth to top of N aquifer (feet below land surface[1])	Type of data collected
8T-537 (BM observation well 1)	02–01–72	5,864	851	300–360; 400–420; 500–520; 600–620; 730–780	290	Water level
8T-538 (BM observation well 2)	01–29–72	5,656	1,338	470–1,338	452	Water level
8T-500 (BM observation well 3)	07–29–59	5,724	868	712–868	155	Water level
2T-514 (BM observation well 4)	02–15–72	6,320	400	250–400	160	Water level
4T-519 (BM observation well 5)	02–25–72	5,869	1,683	1,521–1,683	1,520	Water level
BM observation well 6	01–31–77	6,332	2,507	1,954–2,506	1,950	Water level
1K-214	05–26–50	5,771	356	168–356	250	Water level
2K-300	[3]06–00–50	6,264	300	260–300	0	Water level
2K-301	06–12–50	6,435	500	318–328; 378–500	[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
8K-443	08–15–57	6,024	720	619–720	590	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
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

Table 6. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, northeastern Arizona, 2007-8.—Continued

Bureau of Indian Affairs site number, and (or) common name	Date well was com- pleted	Land- surface elevation (feet)	Well depth (feet below land surface)	Screened/open interval(s) (feet below land surface)	Depth to top of N aquifer (feet below land surface[1])	Type of data collected
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	Water level
Peabody 2	[3]06-00-1967	6,530	3,636	1,816-3,603	728	Water chemistry, withdrawals
Peabody 8	07-01-1980	6,675	3,418	2,460-3,180	2,617	Water chemistry, withdrawals
Piñon NTUA 1	02–25–80	6,336	2,350	1,860–2,350	1,850	Water chemistry, withdrawals
Piñon PM6	[3]02–00–70	6,397	2,248	1,895–2,243	1,870	Water level, withdrawals
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 month or day is unknown.

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

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

Table 7. Median changes in water levels in monitoring-program wells, 2007-8 and prestress period (prior to 1965) to 2008, N aquifer, Black Mesa area,northeastern Arizona.

Years	Aquifer conditions	Number of wells	Median change in water level (feet)
2007-08	All	29	-0.2
	Unconfined	11	-0.2
	Confined	18	-0.2
Prestress-2008	All	33	-12.9
	Unconfined	15	-1.0
	Confined	18	-33.2

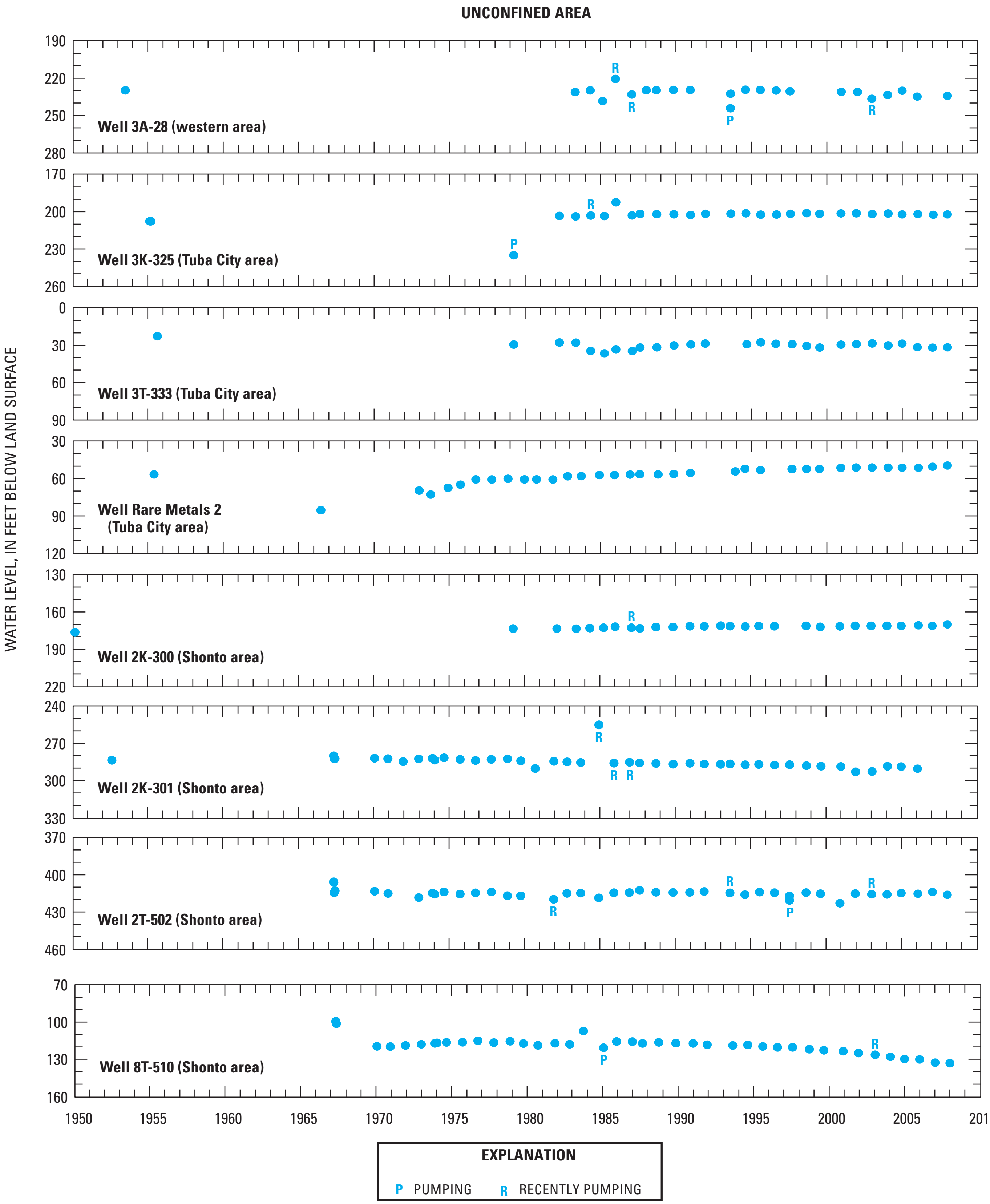


Figure 6. Observed water levels (1950–2008) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.

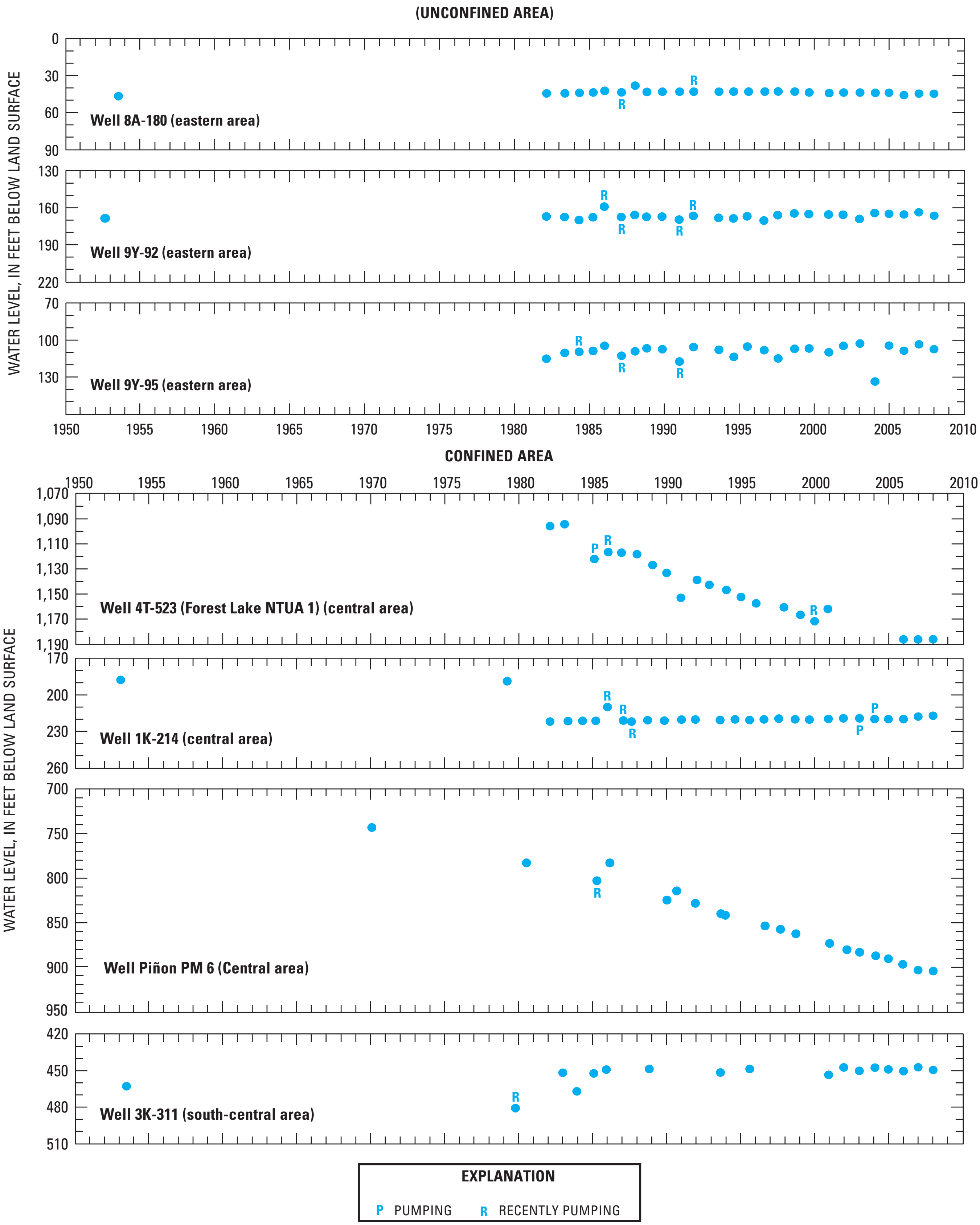
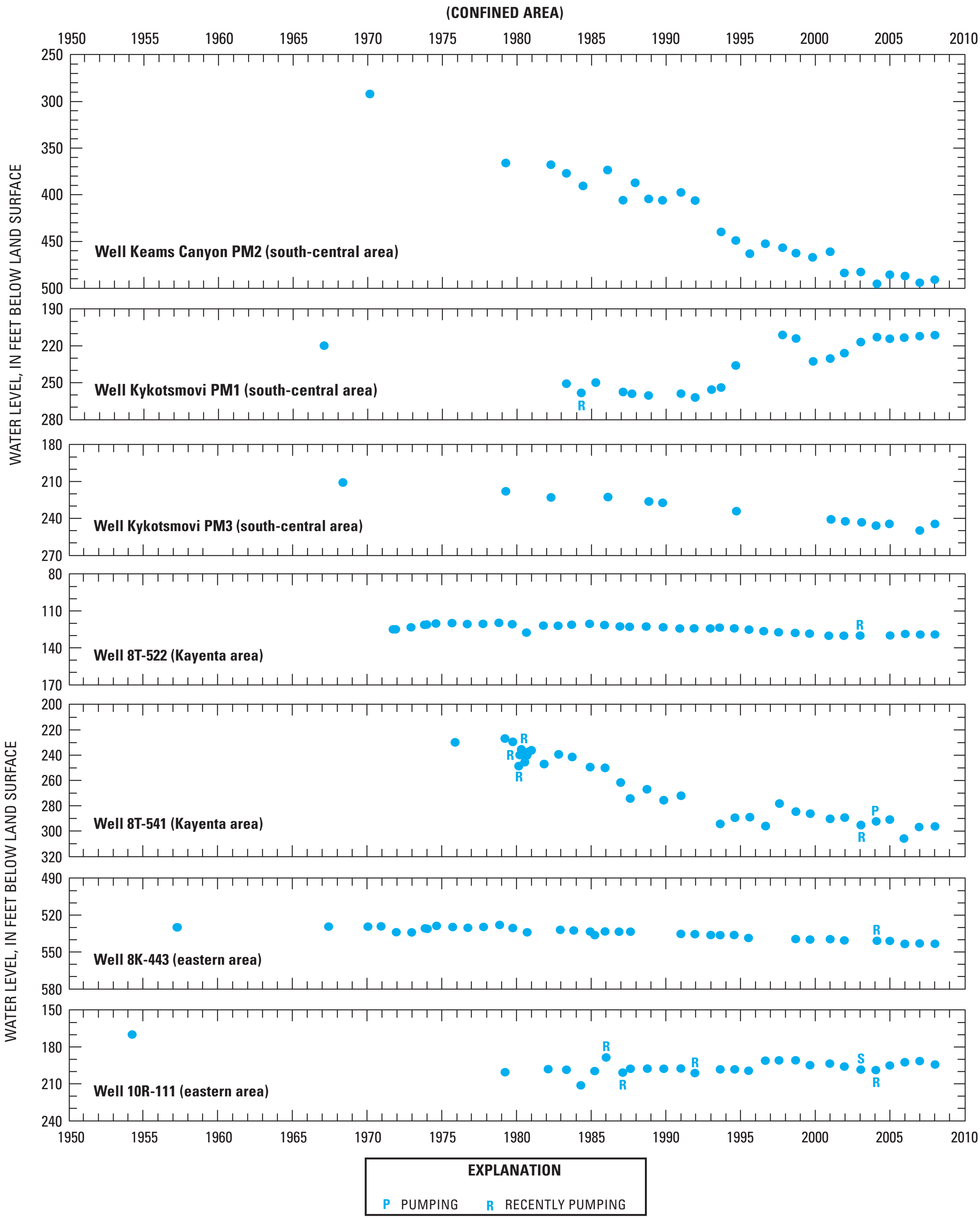


Figure 6. Continued



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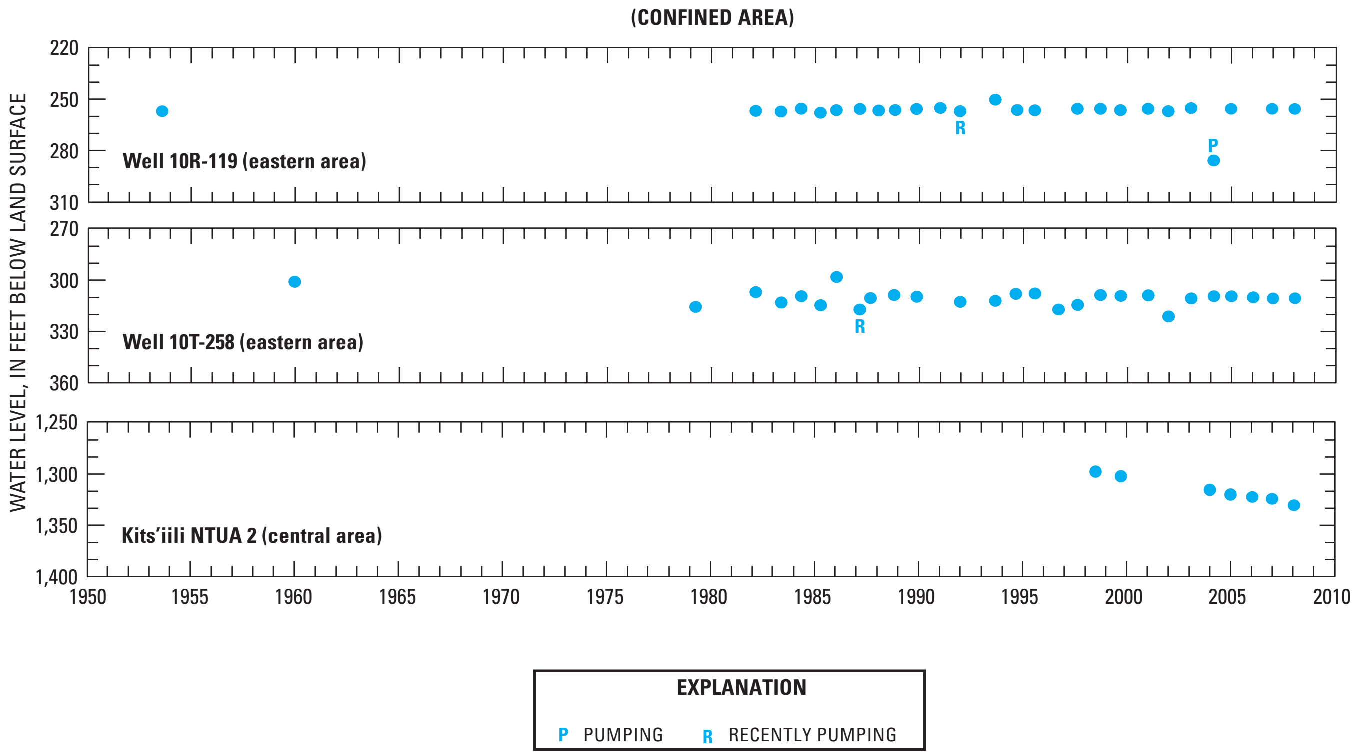


Figure 6. Continued

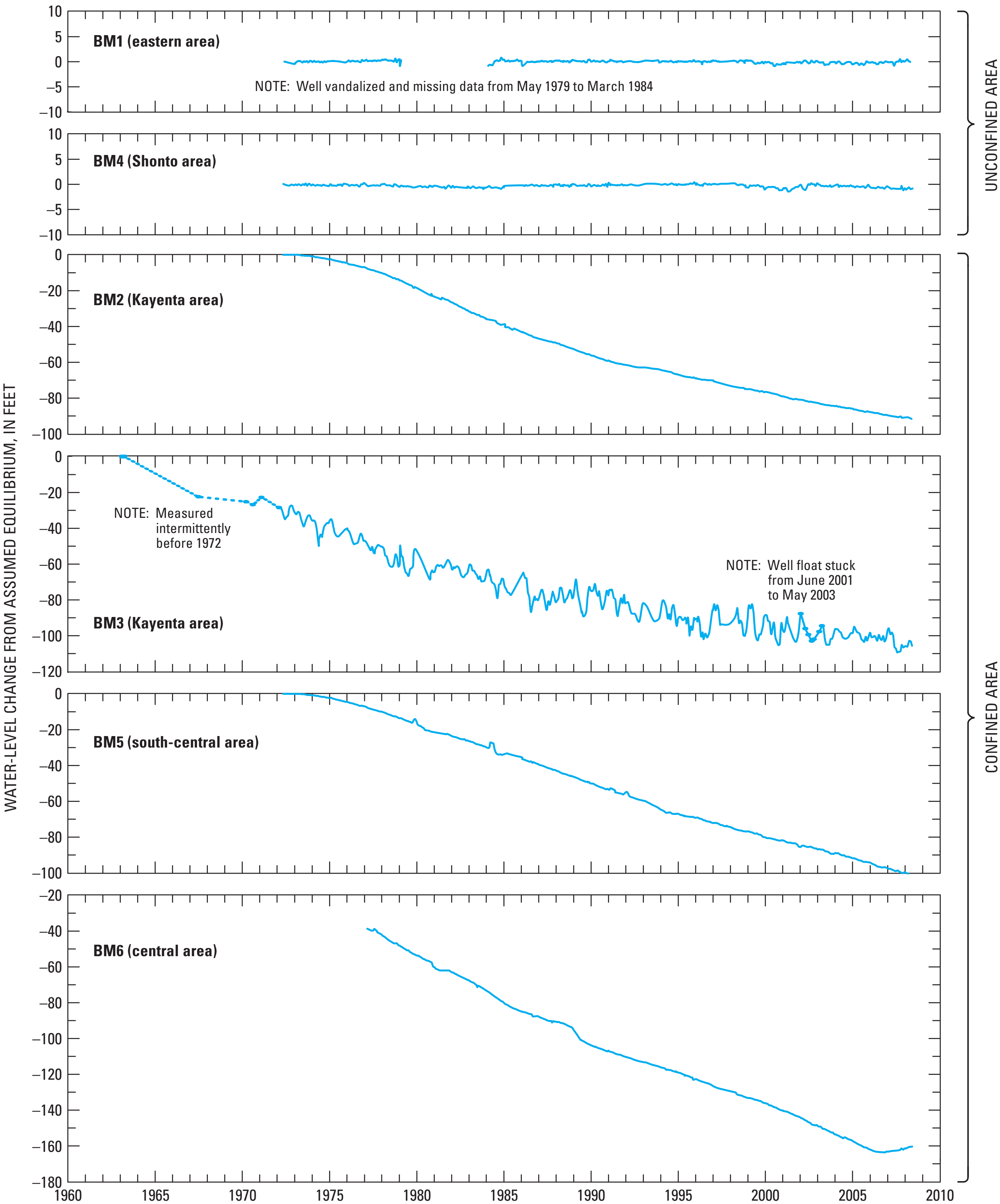


Figure 7. Observed water-level changes in continuous-record observation wells, BM1-BM6, 1963-2008, N aquifer, Black Mesa area, northeastern Arizona.

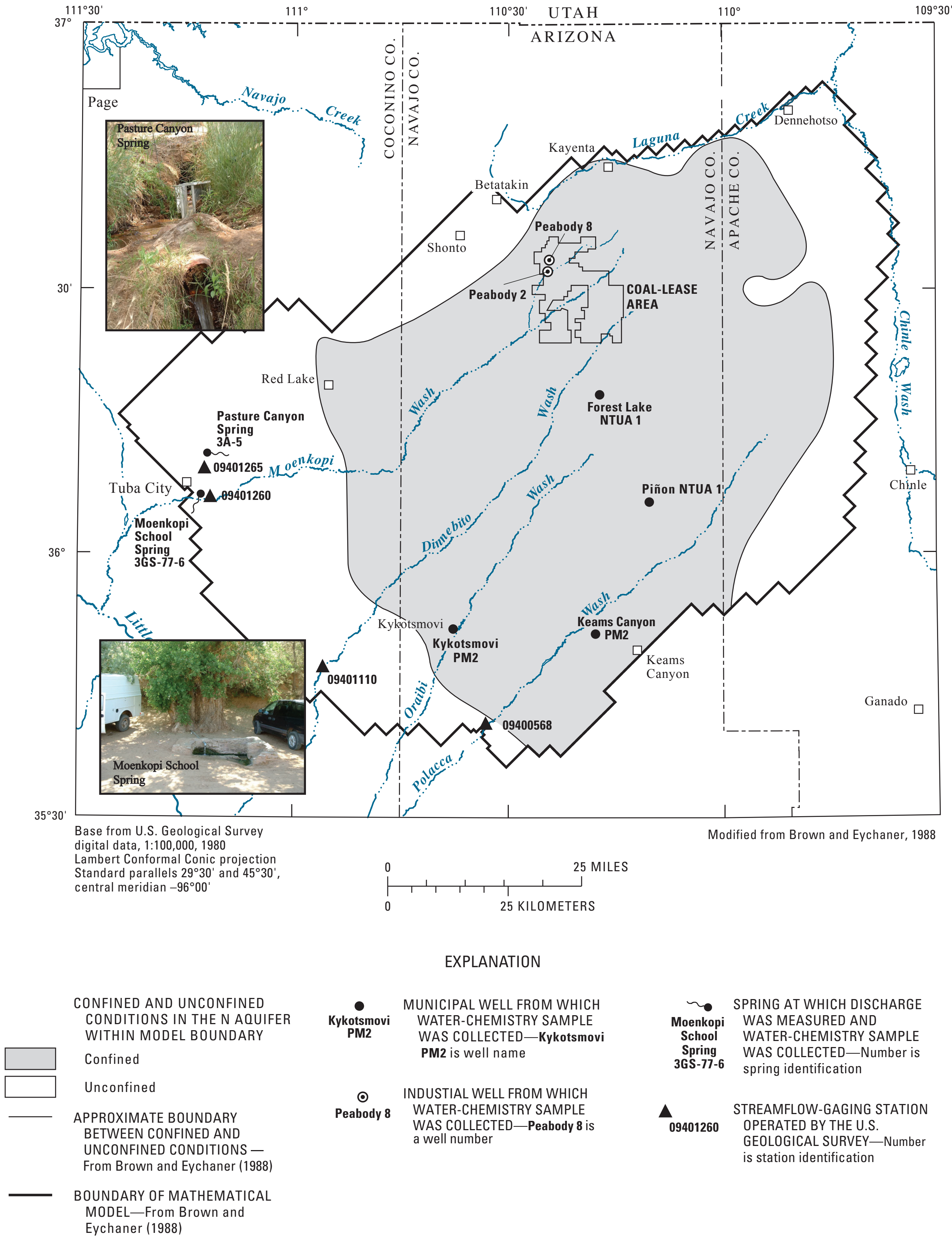
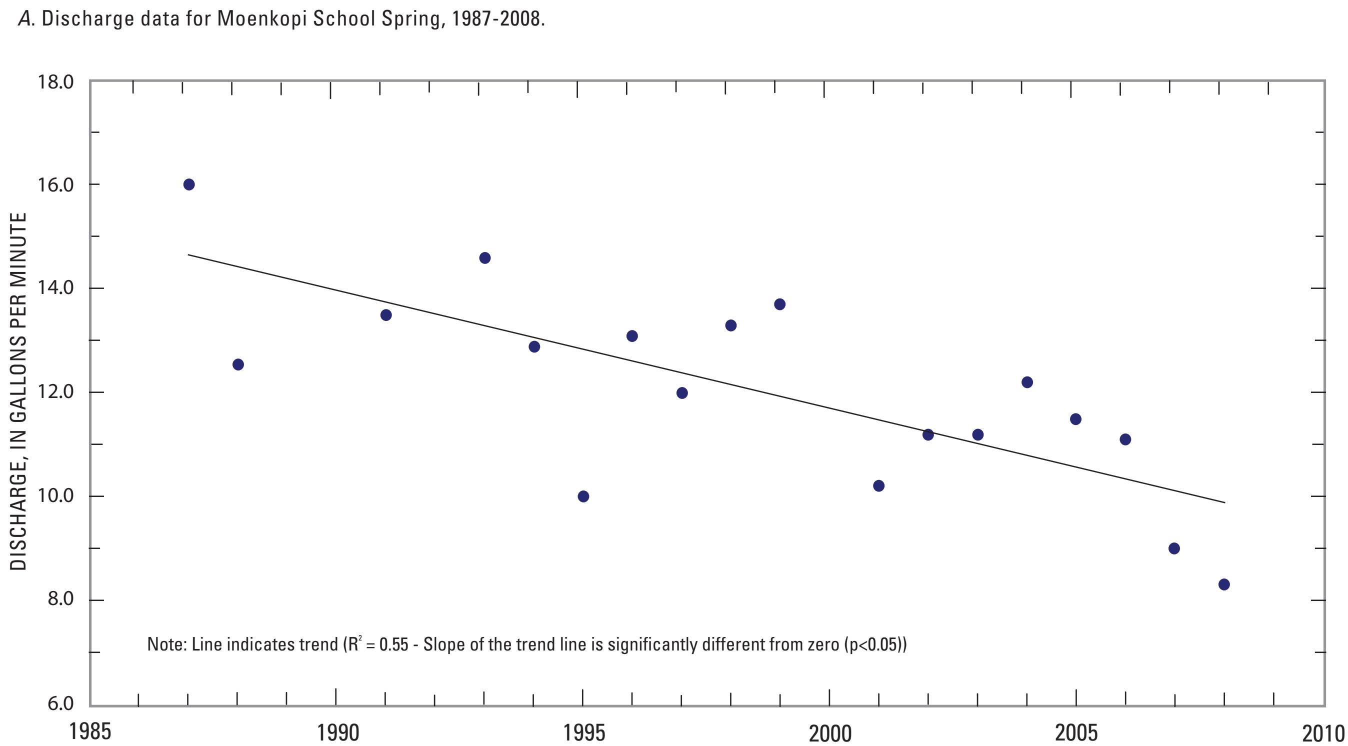


Figure 8. Surface-water and water-chemistry data-collection sites, N aquifer, Black Mesa area, northeastern Arizona, 2007-8.



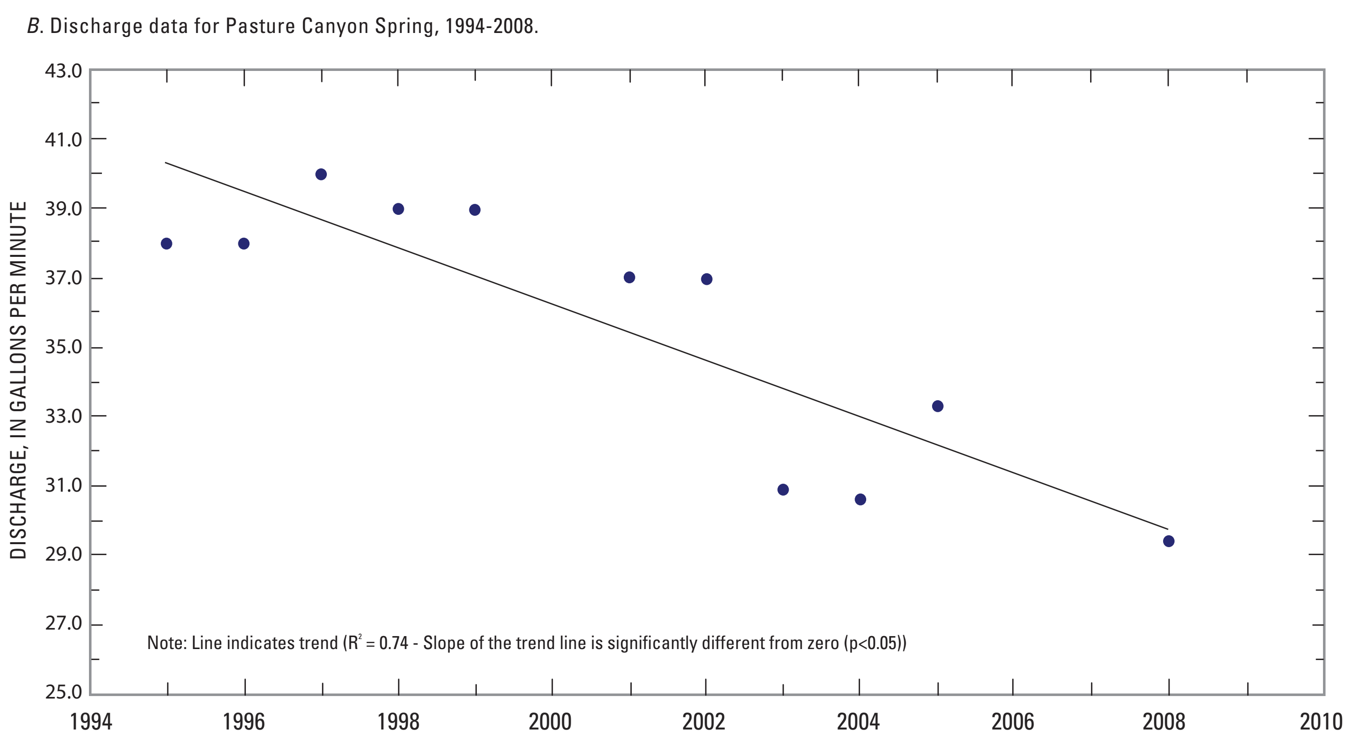


Figure 9. Discharge from Moenkopi School Spring (*A*) and Pasture Canyon Spring (*B*), N Aquifer, northeastern Black Mesa area, northeastern Arizona, 1987-2008. Data from 1952 meaasurement at Moenkopi School Spring is not shown because it is from a different measuring location. Data from 1988 to 1993 measurements at Pasture Canyon Spring are not shown because they are from a different measuring location. Linear trend lines were generated using method of least squares.

Table 8. Discharge measurements for Moenkopi School Spring and Pasture Canyon Spring, Black Mesa area, northeastern Arizona, 1952–2008.

[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	[3]16.0
		11–29–88	[3]12.5
		02–21–91	[3]13.5
		04–07–93	[3]14.6
		12–07–94	[3]12.9
		12–04–95	[3]10.0
		12–16-96	[3]13.1
		12–17–97	[3]12.0
		12–08–98	[3]13.3
		12–13–99	[3]13.7
		03–12–01	[3]10.2
		06–19–02	[3]11.2
		05–01–03	[3]11.2
		03–29–04	[3]12.2
		04–04–05	[3]11.5
		03–13–06	[3]11.1
		05-31-07	[3]9.0
		06-03-08	[3]8.3
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

[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.

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 2007, discharge data were collected at four continuous-recording streamflow-gaging stations (tables 9-12). 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 Spring, 09401265; table 13). The annual average discharges at the four streamflow-gaging stations vary during the periods of record (fig. 10A), and no trends are apparent for Moenkopi Wash, Polacca Wash, and Dinnebito Wash. No trends can be determined for Pasture Canyon Wash either, because the length of record is insufficient to determine a trend.

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 2007 is 12.6 in. (fig. 10B). 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.), and below the average for calendar years 2006 (11.24 in.) and 2007 (8.26 in.; fig. 8B).

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 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 2008 water year were 2.7 ft^3/s for Moenkopi Wash at Moenkopi, 0.51 ft^3/s for Dinnebito Wash near Sand Springs, and 0.33 ft^3/s for Polacca Wash near Second Mesa (fig. 11A-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. 11A-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 2008 the well-sampling sites were reduced. A sample was collected at six sites: Keams canyon PM2, Kykotsmovi PM2, Piñon NTUA 1, Forest Lake NTUA 1, Peabody 2, and Peabody 8. 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 2008, samples were collected from only two of these—Moenkopi School Spring and Pasture Canyon 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 concentrations 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), or 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 2008, water

Table 9. Discharge data (daily mean values), Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2007.

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

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2007 DAILY MEAN VALUES

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	e3.5	e2.5	e2.5	2.3	2.5	e0.21	0.00	78	0.00	e0.35	0.71	51
2	e4.4	e2.4	e2.6	2.3	3.3	0.04	0.00	517	0.00	e0.66	0.71	48
3	e5.1	e2.3	e2.7	2.2	2.0	0.01	0.00	150	0.00	e1.2	0.74	12
4	e4.8	e2.2	e2.7	2.2	1.7	0.00	0.00	128	4.0	e0.70	0.76	4.2
5	e4.6	e2.2	2.8	2.1	1.6	0.00	0.00	211	10	e0.27	0.80	3.0
6	e4.5	e2.3	2.8	2.1	1.7	0.00	0.00	480	0.55	0.01	0.84	2.6
7	e4.4	e2.5	2.9	2.1	1.4	0.00	0.00	80	0.57	0.00	0.84	2.5
8	e4.3	2.6	3.2	2.1	1.2	0.00	0.00	e30	0.00	0.00	0.86	2.1
9	e4.2	2.7	3.2	2.3	1.3	0.00	0.00	e15	0.00	0.06	0.97	1.9
10	e4.1	e2.5	3.1	2.1	1.2	0.00	0.00	e10	0.00	0.17	1.1	2.4
11	e4.0	e2.3	2.9	1.8	1.2	0.00	0.00	7.4	0.00	0.20	1.1	2.9
12	e3.9	e2.3	2.8	2.0	1.1	0.00	0.00	2.7	0.00	0.19	1.1	2.5
13	e3.8	e2.3	2.8	2.4	0.85	0.00	0.00	0.28	0.00	0.15	1.1	2.2
14	e3.8	e2.3	2.8	2.0	0.79	0.00	0.00	135	0.00	0.25	1.2	e2.2
15	e3.7	e2.3	2.7	1.7	0.67	0.00	0.00	227	0.00	0.29	1.2	e2.2
16	e3.6	e2.2	2.6	1.7	0.70	0.00	0.00	172	0.00	0.34	1.2	e2.2
17	e3.4	2.4	2.7	1.9	0.71	0.00	0.00	68	0.00	0.35	1.3	e2.2
18	e3.3	2.3	2.8	1.7	0.69	0.00	0.00	15	0.00	0.35	1.4	e2.2
19	e3.3	2.4	2.7	1.7	0.51	0.00	0.00	4.7	0.00	0.36	1.4	e2.2
20	e3.3	2.6	2.4	1.8	0.67	0.00	0.00	1.8	0.00	0.32	1.4	e2.2
21	e3.2	2.5	2.6	2.0	0.47	0.00	0.00	0.50	0.00	0.30	1.4	2.4
22	e3.1	2.3	2.7	2.0	0.29	0.00	0.00	0.00	0.00	0.34	1.3	2.0
23	e3.0	2.2	3.1	3.3	32	0.00	e118	0.00	63	0.34	1.4	1.5
24	e3.0	2.5	3.5	4.0	5.5	0.00	e328	0.00	93	0.45	1.4	2.6
25	e2.9	2.4	3.3	3.1	1.2	0.00	9.9	0.00	14	0.54	1.6	2.7
26	e2.9	2.2	2.9	2.3	e0.50	0.00	e25	0.00	1.3	0.60	2.0	2.5
27	e2.9	2.2	2.7	2.6	e0.40	0.00	52	0.00	e0.70	0.65	1.7	2.9
28	e2.8	e2.4	2.6	1.8	e0.35	0.00	369	0.00	e0.50	0.61	1.5	2.8
29	e2.8	---	2.6	2.4	e0.30	0.00	535	0.00	e0.30	0.59	1.6	3.1
30	e2.7	---	2.5	2.6	e0.30	0.00	400	0.00	e0.30	0.64	1.8	3.3
31	e2.6	---	2.3	---	e0.25	---	40	0.00	---	0.67	---	3.3
TOTAL	111.9	66.3	86.5	66.6	67.35	0.26	1876.90	2333.38	188.22	11.95	36.43	181.8
MEAN	3.61	2.37	2.79	2.22	2.17	0.01	60.5	75.3	6.27	0.39	1.21	5.86
MAX	5.1	2.7	3.5	4.0	32	0.21	535	517	93	1.2	2.0	51
MIN	2.6	2.2	2.3	1.7	0.25	0.00	0.00	0.00	0.00	0.00	0.71	1.5
MED	3.5	2.3	2.7	2.1	0.85	0.00	0.00	7.4	0.00	0.34	1.2	2.5
AC-FT	222	132	172	132	134	0.5	3720	4630	373	24	72	361
CFSM	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.00	0.00	0.00	0.00

Calendar year 2007 Total 5,027.6 mean 13.8 Max 535 Min 0.00 Median 1.8 Acre-ft 9,970 CFSM 0.008

Table 10. Discharge data (daily mean values), Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2007.

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

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2007DAILY MEAN VALUES

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.45	0.54	0.39	0.37	0.34	0.20	0.14	20	3.8	e0.22	0.28	1.4
2	0.44	0.44	0.40	0.35	0.44	0.21	0.14	62	15	e0.20	0.28	25
3	0.44	0.43	0.38	0.35	0.30	0.21	0.11	163	1.4	e0.18	0.27	9.5
4	0.44	0.45	0.40	0.37	0.28	0.19	0.14	197	21	0.20	0.29	2.6
5	0.49	0.46	0.42	0.37	0.34	0.18	0.13	292	13	0.18	0.30	0.87
6	0.37	0.47	0.42	0.37	0.33	0.15	0.12	336	15	0.16	0.30	0.62
7	0.39	0.49	0.44	0.35	0.32	0.18	0.13	13	2.8	0.17	0.30	0.59
8	0.40	0.48	0.47	0.35	0.31	0.19	0.12	1.7	0.25	0.18	0.30	0.61
9	0.41	0.49	0.42	0.37	0.31	0.19	0.12	0.38	0.18	0.19	0.31	0.56
10	0.45	0.53	0.41	0.32	0.30	0.18	0.11	0.32	0.16	0.19	0.31	1.3
11	0.45	0.60	0.38	0.34	0.29	0.20	0.10	0.30	0.16	0.18	0.31	1.3
12	0.43	0.54	0.40	0.37	0.28	0.23	0.13	0.28	0.16	0.18	0.37	0.57
13	0.40	0.51	0.41	0.35	0.27	0.19	0.13	0.24	0.16	0.18	0.33	0.63
14	0.34	0.86	0.40	0.33	0.26	0.18	0.13	0.23	0.15	0.19	0.33	0.56
15	0.30	0.44	0.40	0.33	0.26	0.17	0.12	154	0.16	0.21	0.34	0.41
16	0.31	0.35	0.39	0.33	0.27	0.16	0.12	21	0.16	0.23	0.35	0.48
17	0.30	0.34	0.40	0.34	0.27	0.15	0.12	14	0.16	0.20	0.34	0.56
18	0.31	0.35	0.38	0.31	0.27	0.15	0.12	6.6	0.15	0.18	0.33	0.61
19	0.31	0.40	0.39	0.31	0.26	0.15	0.12	1.8	0.15	0.21	0.34	0.65
20	0.43	0.37	0.41	0.34	0.26	0.15	0.12	0.52	0.15	0.23	0.33	0.63
21	0.45	0.34	0.37	0.35	0.24	0.15	0.09	0.42	0.15	0.21	0.32	e0.58
22	0.43	0.33	0.45	0.33	0.24	0.15	0.09	0.23	0.18	0.21	0.31	0.46
23	0.42	1.3	0.71	0.38	0.45	0.15	0.10	0.15	0.41	0.24	0.32	0.48
24	0.41	0.44	0.47	0.38	0.29	0.15	0.09	0.15	150	0.25	0.31	0.52
25	0.43	0.43	0.44	0.34	0.26	0.14	0.08	0.12	18	0.26	0.32	0.51
26	0.43	0.44	0.42	0.36	0.25	0.15	21	0.12	6.4	0.27	0.34	0.44
27	0.44	0.41	0.37	0.34	0.24	0.14	25	0.13	0.50	0.27	0.33	0.49
28	0.44	0.39	0.28	0.32	0.23	0.14	194	0.13	0.31	0.28	0.34	0.39
29	0.48	---	0.44	0.36	0.21	0.14	14	0.14	0.25	0.28	0.33	0.43
30	0.55	---	0.39	0.33	0.21	0.14	99	0.17	0.22	0.27	0.56	0.46
31	0.72	---	0.37	---	0.21	---	66	0.17	---	0.27	---	0.47
TOTAL	13.06	13.62	12.82	10.41	8.79	5.06	421.92	1286.30	250.57	6.67	9.79	54.68
MEAN	0.42	0.49	0.41	0.35	0.28	0.17	13.6	41.5	8.35	0.22	0.33	1.76
MAX	0.72	1.3	0.71	0.38	0.45	0.23	194	336	150	0.28	0.56	25
MIN	0.30	0.33	0.28	0.31	0.21	0.14	0.08	0.12	0.15	0.16	0.27	0.39
MED	0.43	0.44	0.40	0.35	0.27	0.16	0.12	0.38	0.23	0.21	0.32	0.57
AC-FT	26	27	25	21	17	10	837	2550	497	13	19	108
CFSM	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.09	0.02	0.00	0.00	0.00

Calendar year 2007 Total 2,093.7 mean 5.74 Max 336 Min 0.08 Median 0.33 Acre-ft 4,150 CFSM 0.012

Table 11. Discharge data (daily mean values), Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2007.

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

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2007 DAILY MEAN VALUES

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	e0.36	e0.47	e0.41	0.26	0.20	0.10	0.07	36	0.29	0.18	0.18	2.5
2	e0.35	e0.46	e0.41	0.24	0.18	0.11	0.07	232	e0.29	0.20	0.22	41
3	e0.38	e0.47	e0.43	0.22	0.17	0.11	0.06	199	e0.29	0.20	0.20	4.5
4	e0.36	e0.47	e0.42	0.22	0.19	0.11	0.07	107	e15	0.24	0.21	0.96
5	e0.34	e0.47	e0.41	0.22	0.17	0.14	0.07	119	e22	1.5	e0.21	0.38
6	e0.34	e0.45	e0.40	0.23	0.21	0.13	0.06	325	e8.0	0.89	0.18	0.37
7	e0.34	0.43	e0.38	0.23	e0.19	0.10	0.06	420	e0.25	0.18	0.22	0.42
8	e0.33	0.43	e0.37	0.26	0.19	0.15	0.05	194	0.25	0.17	0.22	0.33
9	e0.32	0.42	e0.36	0.24	e0.19	0.16	0.07	13	0.21	0.19	0.21	0.36
10	e0.32	0.44	e0.36	0.24	e0.19	0.11	0.11	8.2	0.18	0.20	0.19	0.33
11	e0.33	0.48	e0.35	0.20	0.18	0.11	0.15	7.7	0.18	0.19	0.23	0.32
12	e0.33	0.45	e0.34	0.22	e0.17	0.08	0.09	7.1	e0.18	0.20	0.20	0.39
13	e0.34	0.51	e0.31	0.21	e0.16	0.08	0.05	7.9	0.18	e0.21	e0.20	0.29
14	e0.34	1.4	e0.32	0.21	e0.15	0.11	0.03	9.6	0.16	0.21	e0.20	e0.29
15	e0.33	0.56	0.34	0.22	e0.14	0.07	0.04	14	0.13	0.20	0.20	e0.30
16	e0.37	0.45	0.33	0.20	0.13	0.07	0.07	122	0.13	e0.20	0.19	e0.31
17	e0.38	0.42	0.31	0.20	0.12	0.09	0.04	2.9	0.14	e0.21	0.19	e0.32
18	e0.38	0.42	0.31	0.24	0.10	0.08	0.02	2.6	e5.0	0.22	0.20	e0.32
19	e0.36	e0.43	0.32	0.21	0.10	e0.10	0.02	1.1	0.27	0.20	0.21	0.33
20	e0.37	e0.45	0.34	0.20	0.09	0.10	0.03	0.54	0.12	0.21	0.21	e0.29
21	e0.35	e0.44	0.41	0.19	0.10	0.11	0.04	0.27	0.11	0.17	0.21	0.26
22	e0.32	0.43	0.45	0.20	0.10	0.07	0.05	0.22	0.14	0.17	e0.23	e0.28
23	e0.29	0.42	0.38	0.23	0.11	0.10	0.04	0.19	0.18	0.14	e0.25	e0.29
24	e0.27	e0.41	0.26	0.20	0.10	e0.12	0.05	0.20	e8.2	0.15	e0.26	e0.29
25	e0.25	e0.40	0.27	0.19	0.10	0.13	0.05	0.21	e1.3	0.18	e0.29	e0.29
26	e0.24	e0.41	0.28	0.19	0.11	0.12	0.07	0.21	e0.19	0.19	e0.27	e0.33
27	e0.23	e0.42	0.37	0.19	0.11	0.08	0.14	0.36	0.16	e0.26	e0.27	e0.31
28	0.22	e0.42	0.32	0.20	0.09	0.08	0.06	e22	0.15	e0.23	e0.27	e0.29
29	e0.39	---	0.30	0.17	0.10	0.08	0.08	e5.0	0.17	e0.20	e0.27	e0.30
30	e0.47	---	0.28	0.21	0.10	0.08	0.77	e2.7	0.15	0.17	e0.35	e0.31
31	0.48	---	0.26	---	0.10	---	5.8	e0.29	---	0.15	---	e0.31
TOTAL	10.48	13.43	10.80	6.44	4.34	3.08	8.38	1860.29	64.00	8.01	6.74	57.57
MEAN	0.34	0.48	0.35	0.21	0.14	0.10	0.27	60.0	2.13	0.26	0.22	1.86
MAX	0.48	1.4	0.45	0.26	0.21	0.16	5.8	420	22	1.5	0.35	41
MIN	0.22	0.40	0.26	0.17	0.09	0.07	0.02	0.19	0.11	0.14	0.18	0.26
MED	0.34	0.44	0.34	0.21	0.13	0.10	0.06	7.7	0.18	0.20	0.21	0.32
AC-FT	21	27	21	13	8.6	6.1	17	3690	127	16	13	114
CFSM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00

Calendar year 2007 Total 2,053.6 mean 5.63 Max 420 Min 0.02 Median 0.23 Acre-ft 4,070 CFSM 0.006

Table 12. Discharge data (daily mean values), Pasture Canyon Springs near Tuba City, Arizona (09401265), calendar year 2007.

[e, estimated; dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2007 DAILY MEAN VALUES

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.36	0.43	0.38	0.36	0.32	0.28	0.28	0.28	0.28	0.30	0.34	0.49
2	0.36	0.43	0.38	0.36	0.31	0.28	0.27	0.28	0.28	0.30	0.33	0.44
3	0.36	0.42	0.38	0.36	0.31	0.29	0.26	0.28	0.28	0.30	0.32	0.43
4	0.36	0.41	0.38	0.36	0.30	0.30	0.25	0.28	0.28	0.30	0.33	0.43
5	0.36	0.41	0.37	0.36	0.30	0.30	0.25	0.28	0.28	0.31	0.34	0.42
6	0.36	0.41	0.37	0.36	0.30	0.30	0.25	0.28	0.28	0.32	0.34	0.41
7	0.36	0.41	0.36	0.36	0.30	0.30	0.25	0.28	0.28	0.32	0.32	0.41
8	0.37	0.41	0.36	0.34	0.30	0.30	0.25	0.28	0.28	0.32	0.32	0.41
9	0.38	0.41	0.36	0.33	0.30	0.30	0.25	0.28	0.28	0.32	0.32	0.41
10	0.38	0.41	0.36	0.33	0.30	0.30	0.25	0.27	0.28	0.32	0.32	0.41
11	0.38	0.41	0.36	0.33	0.30	0.30	0.25	0.27	0.27	0.32	0.33	0.39
12	0.38	0.41	0.36	0.33	0.30	0.30	0.25	0.27	0.27	0.32	0.32	0.37
13	0.38	0.41	0.36	0.34	0.30	0.30	0.25	0.27	0.27	0.32	0.33	0.36
14	0.38	0.41	0.35	0.34	0.30	0.30	0.25	0.27	0.27	0.32	0.34	0.36
15	0.38	0.41	0.35	0.33	0.30	0.30	0.25	0.27	0.27	0.32	0.34	0.36
16	0.38	0.41	0.36	0.34	0.30	0.30	0.25	0.27	0.27	0.32	0.33	0.36
17	0.38	0.41	0.36	0.33	0.30	0.30	0.25	0.27	0.28	0.32	0.30	0.36
18	0.38	0.41	0.35	0.32	0.30	0.30	0.25	0.28	0.28	0.32	0.30	0.36
19	0.40	0.41	0.35	0.32	0.30	0.30	0.25	0.29	0.28	0.32	0.30	0.36
20	0.41	0.41	0.35	0.32	0.30	0.30	0.25	0.28	0.28	0.32	0.30	0.36
21	0.41	0.41	0.36	0.32	0.30	0.29	0.25	0.28	0.28	0.34	0.31	0.35
22	0.41	0.40	0.36	0.32	0.30	0.28	0.25	0.28	0.29	0.34	0.32	0.34
23	0.41	0.38	0.48	0.32	0.58	0.28	0.26	0.28	0.30	0.34	0.32	0.34
24	0.41	0.38	e0.44	0.32	0.38	0.29	0.27	0.29	0.30	0.34	0.32	0.34
25	0.41	0.38	e0.40	0.32	0.33	0.28	0.27	0.29	0.30	0.34	0.32	0.34
26	0.41	0.38	e0.37	0.32	0.31	0.32	0.26	0.29	0.30	0.34	0.32	0.34
27	0.41	0.38	0.36	0.32	0.30	0.30	0.27	0.30	0.30	0.34	0.32	0.34
28	0.41	0.38	0.36	0.32	0.28	0.29	0.29	0.30	0.30	0.34	0.32	0.36
29	0.41	---	0.36	0.32	0.28	0.29	0.28	0.30	0.30	0.34	0.33	0.36
30	0.43	---	0.36	0.32	0.28	0.28	0.28	0.29	0.30	0.35	0.36	0.36
31	0.43	---	0.36	---	0.28	---	0.28	0.29	---	0.34	---	0.36
TOTAL	12.05	11.34	11.46	10.02	9.66	8.85	8.02	8.72	8.51	10.06	9.71	11.73
MEAN	0.39	0.41	0.37	0.33	0.31	0.29	0.26	0.28	0.28	0.32	0.32	0.38
MAX	0.43	0.43	0.48	0.36	0.58	0.32	0.29	0.30	0.30	0.35	0.36	0.49
MIN	0.36	0.38	0.35	0.32	0.28	0.28	0.25	0.27	0.27	0.30	0.30	0.34
MED	0.38	0.41	0.36	0.33	0.30	0.30	0.25	0.28	0.28	0.32	0.32	0.36
AC-FT	24	22	23	20	19	18	16	17	17	20	19	23

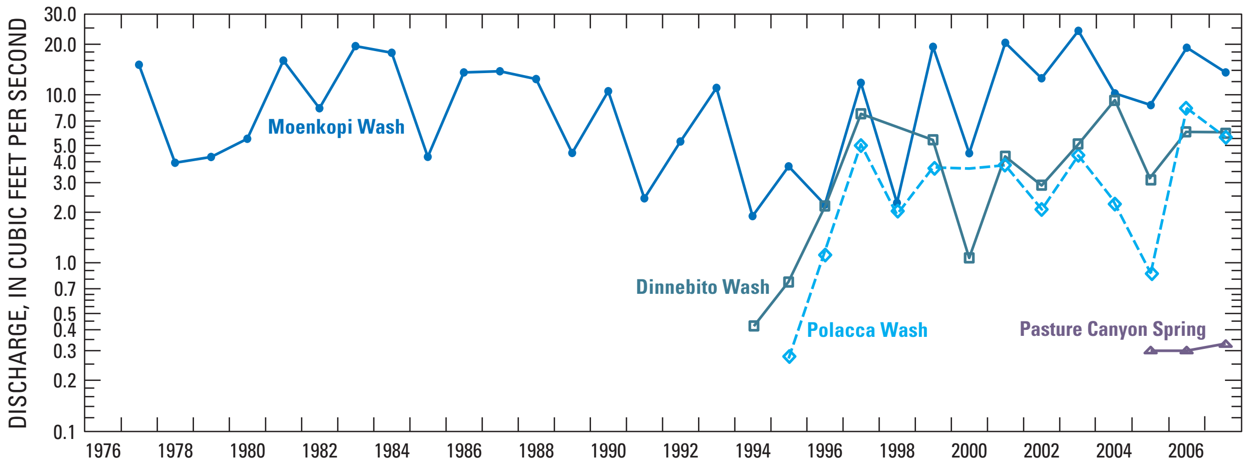
Calendar year 2007 Total 120.13 Mean 0.33 Max 0.58 Min 0.25 Median 0.32 Acre-ft 238

Table 13. Date that monitoring program data collection began and drainage areas for streamflow-gaging stations, Black Mesa area, northeastern Arizona.

[Dashes indicate not determined]

Station name	Station No.	Date data collection began	Drainage area (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 Spring	9401265	August 2004	---

A. Annual average discharge for calendar years 1977–2007



B. Annual precipitation at Betatakin, Arizona, calendar years 1976–2007 (National Weather Service)

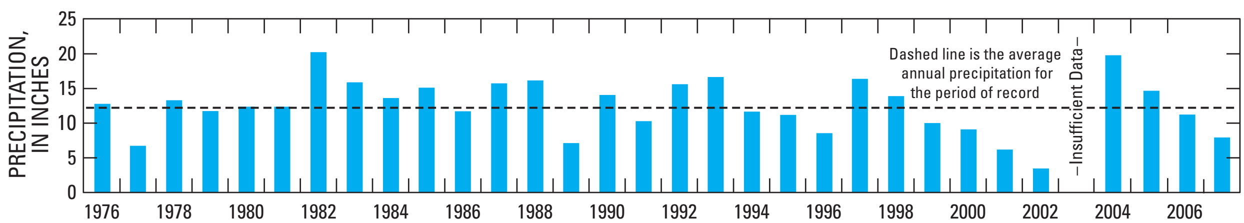


Figure 10. Annual average discharge at Moenkopi Wash at Moenkopi (09401260), Pasture Canyon Springs (09401265), Dinnebito Wash near Sand Spring (09401110), and Polacca Wash near Second Mesa (09400568), and annual precipitation at Betatakin, Arizona, Black Mesa area, northeastern Arizona. A, Annual average discharge for calendar years 1977–2007; B, Annual precipitation at Betatakin, northeastern Arizona, calendar years 1976–2007 (National Park Service, Betatakin National Monument, written commun., 2008).

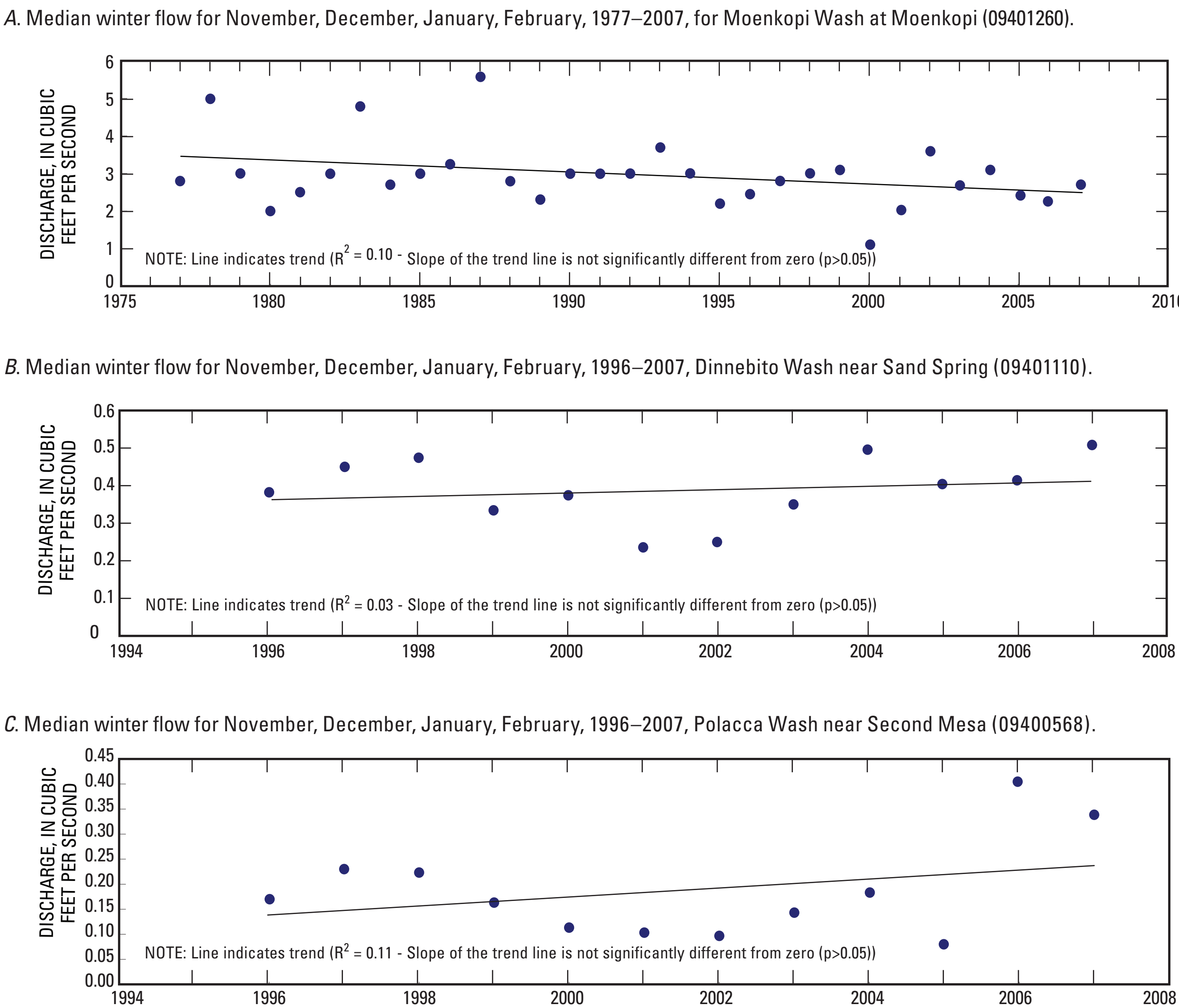


Figure 11. Median winter flow for November, December, January, and February for water years 1977–2007 for (*A*) Moenkopi Wash at Moenkopi (09401260), (*B*) Dinnebito Wash near Sand Springs (09401110), and (*C*) Polacca Wash near Second Mesa (09400568), Black Mesa area, northeastern Arizona. Median winter 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.

samples were collected from six wells: Keams Canyon PM2, Kykotsmovi PM2, Piñon NTUA 1, Forest Lake NTUA 1, Peabody 2, and Peabody 8 (figs. 8, 12 and table 14).

Keams Canyon PM2 yielded the highest dissolved-solids concentration (607 mg/L) and chloride concentration (95 mg/L) of the six wells sampled (table 15 and fig. 13). Dissolved-solids concentrations in the other five wells ranged from 120 mg/L at Peabody 2 to 362 mg/L at Forest Lake NTUA 1, and their chloride concentrations ranged from 2.0 mg/L at Peabody 2 to 36 mg/L at Forest Lake NTUA 1 (table 15 and fig. 13). Peabody 8 had the highest sulfate concentration (117 mg/L) of the six wells, and the others ranged from 7.5 mg/L at Peabody 2 to 73 mg/L at Forest Lake NTUA 1 (table 15 and fig. 13).

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 2008, 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 0.0419 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 also exceeded at Keams Canyon PM2 (607 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, and Peabody 2 (U.S. Environmental Protection Agency, 2003; table 14). A linear regression analysis was used to determine trends in concentrations of dissolved solids, chloride, and sulfate from the six wells, and for the period of record no trends were found ($p>0.05$).

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

In 2008, water samples were collected from Moenkopi School Spring and Pasture Canyon Spring in the southwestern part of the Black Mesa study area (fig. 8). Both 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, and 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.

The samples from Moenkopi School Spring and Pasture Canyon Spring yielded a calcium bicarbonate-type water (fig. 12 and table 16). Samples from Moenkopi School Spring and Pasture Canyon Spring had dissolved solid concentrations of 230 mg/L and 149 mg/L, respectively (tables 16 and 17). Concentrations of chloride and sulfate were higher at Moenkopi School Spring than Pasture Canyon Spring. 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 (table 17 and fig. 14). Concentrations of the same constituents in Pasture Canyon Spring did not show any trends (table 17 and fig. 14).

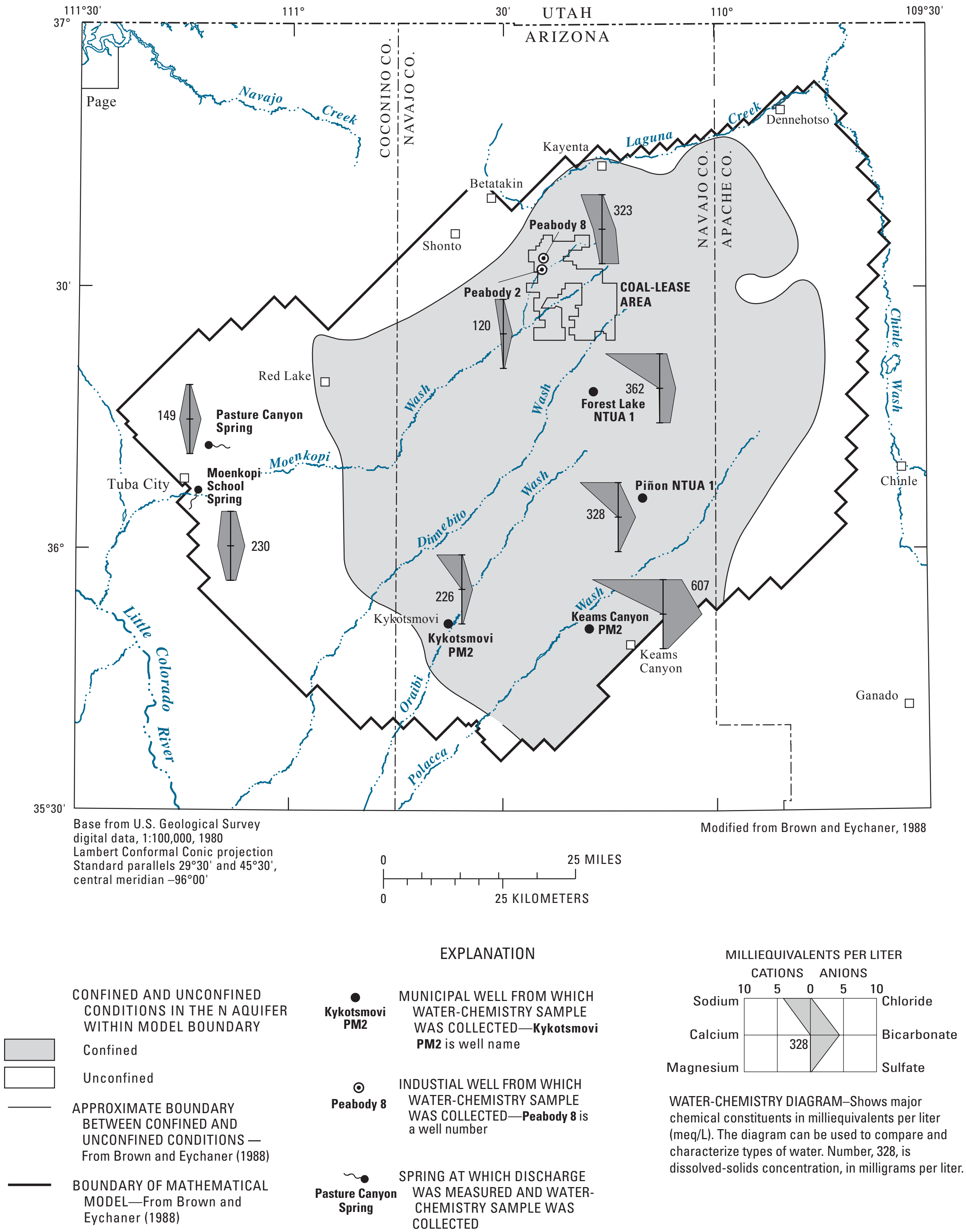


Figure 12. Water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, northeastern Arizona, 2008.

Table 14. Physical properties and chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, 2008.

[°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 (°C)	Specific conductance field µS/cm	pH field (units)	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen NO2 + NO3 dissolved mg/L as N	Ortho-Phosphate dissolved (mg/L as P)	Calcium dissolved (mg/L as Ca)	Magnesium dissolved (mg/L as Mg)	Potassium dissolved (mg/L as K)
Keams Canyon PM2	355023110182701	05-06-08	19.8	1079	9.2	356.0	<.04	0.011	0.81	0.159	0.78
Kykotsmovi PM	2355215110375001	05-06-08	23.1	373	9.8	166.7	1.17	0.033	0.48	E.013	0.41
Pinon NTUA 1	360527110122501	05-07-08	20.5	565	10.0	266.4	1.05	0.019	0.49	0.026	0.41
Forest Lake NTUA 1	361737110180301	05-07-08	27.8	424	9.6	162.5	0.37	0.011	1.92	0.226	1.00
Peabody 2	363005110250901	05-08-08	31.0	160	8.8	72.5	0.95	0.012	8.15	0.132	0.71
Peabody 8	363130110254501	05-08-08	29.7	457	8.2	101.7	1.69	0.011	25.5	3.670	2.79

Common well name	U.S. Geological Survey identification number	Date of samples	Sodium dissolved (mg/L as Na)	Chloride dissolved (mg/L as Cl)	Flouride dissolved (mg/L as F)	Silica dissolved (mg/L as SiO_2)	Sulfate dissolved (mg/L as SO_4)	Arsenic dissolved (ug/L as As)	Boron dissolved (ug/L as B)	Iron dissolved (ug/L as Fe)	Dissolved solids residue at 180°C (mg/L)
Keams Canyon PM2	355023110182701	05-06-08	234	95.1	1.40	12.6	34.5	41.9	634	<8	607
Kykotsmovi PM2	355215110375001	05-06-08	83.3	3.04	0.18	24.2	8.2	5.2	31	<8	226
Pinon NTUA 1	360527110122501	05-07-08	126	6.15	0.29	25.9	8.7	4.8	67	<8	328
Forest Lake NTUA 1	361737110180301	05-07-08	179	36.5	0.70	19.6	73.2	1.4	384	100	362
Peabody 2	363005110250901	05-08-08	27.6	2.04	E.12	22.5	7.5	2.7	17	<8	120
Peabody 8	363130110254501	05-08-08	69.9	4.44	0.15	20.0	117	1.8	43	<8	323

Table 15. Specific conductance and concentrations of selected chemical constituents in water samples from industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, 1974–2008.

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

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
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
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
Peabody 8				
1986	453	---	4.9	110
1988	812	516	7.2	250
1990	456	287	4.3	110
1991	452	280	6.1	110
2003	460	316	4.5	118
2004	402	326	4.9	116
2008	457	323	4.4	117
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	[2]603	97	32
2005	828	601	97	34
2006	1,067	588	99	34
2008	1,079	607	95	34
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
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

[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 16. Physical properties and chemical analyses of water samples from Moenkopi School Spring and Pasture Canyon Spring, Black Mesa area, northeastern Arizona, 2008.

[°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 (oC)	Specific Conductance Field (µS/cm)	pH field (units)	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen NO2 + NO3 dissolved mg/L as N	Ortho-Phosphate dissolved (mg/L as P)	Calcium dissolved (mg/L as Ca)	Magnesium dissolved (mg/L as Mg)	Potassium dissolved (mg/L as K)
360632111131101	3GS-77-6	Moenkopi School Spring	05-28-08	17.5	390	7.3	103.5	2.58	0.010	37.3	7.90	1.45
361021111115901	3A-5	Pasture Canyon Spring	05-28-08	17.4	240	7.9	82.5	4.34	0.018	29.7	4.39	1.28

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples	Sodium dissolved (mg/L as Na)	Chloride dissolved (mg/L as Cl)	Flouride dissolved (mg/L as F)	Silica dissolved (mg/L as SiO_2)	Sulfate dissolved (mg/L as SO_4)	Arsenic dissolved (µg/L as As)	Boron dissolved (µg/L as B)	Iron dissolved (µg/L as Fe)	Dissolved solids residue at 180°C (mg/L)
360632111131101	3GS-77-6	Moenkopi School Spring	05-28-08	29.9	28.3	0.18	14.1	37.6	2.4[(1)]	43	<8	230
361021111115901	3A-5	Pasture Canyon Spring	05-28-08	12.4	5.01	0.16	10.1	18.3	1.8[(1)]	33	<8	149

[1] Arsenic sample was collected on 06-03-08

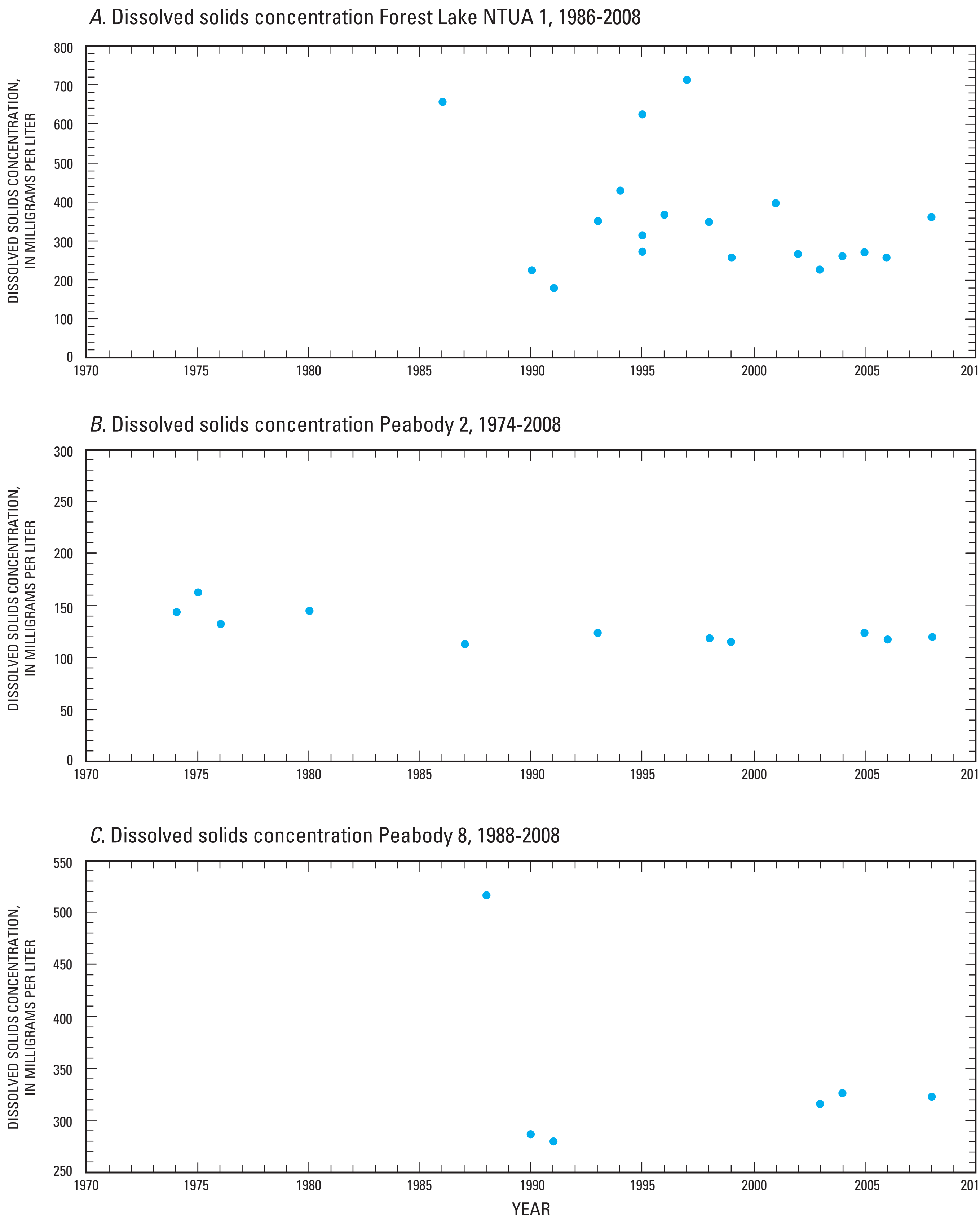


Figure 13. Dissolved-solids concentrations for water samples from selected wells, N aquifer, Black Mesa area, northeastern Arizona, 1974-2008. *A*, Forest Lake NTUA 1, 1986-2008. *B*, Peabody 2, 1974-2008. *C*, Peabody 8, 1988-2008. *D*, Keams Canyon PM2, 1984-2008. *E*, Pinon NTUA 1, 1998-2008. *F*, Kykotsmovi PM2, 1988-2008

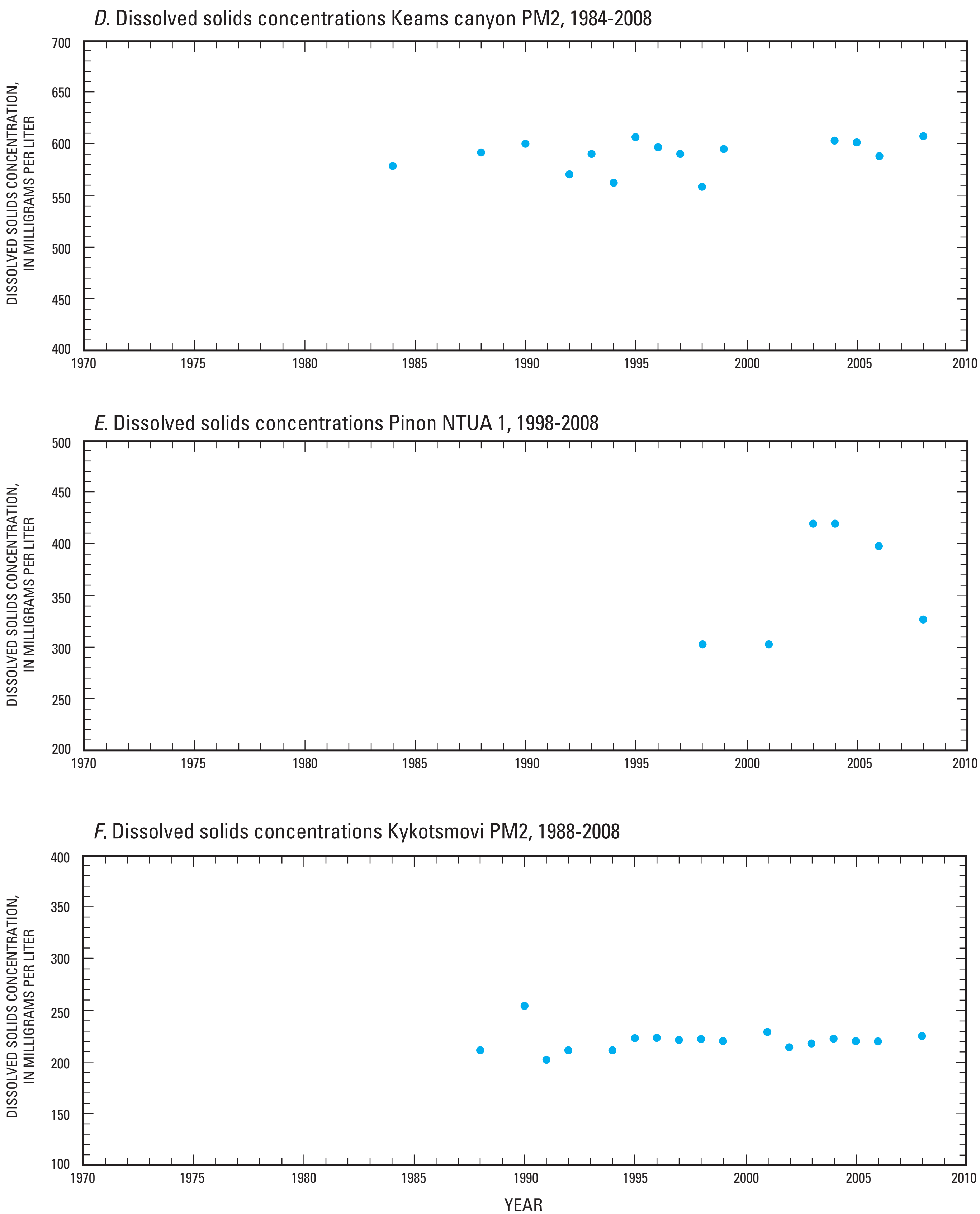


Figure 13. Continued

Table 17. Specific conductance and concentrations of selected chemical constituents in N-aquifer water samples from Moenkopi School Spring and Pasture Canyon Spring, Black Mesa area, northeastern Arizona, 1948–2008.

[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
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	[1]305	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
Pasture Canyon Spring				
1948	[1]227	(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
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

[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.

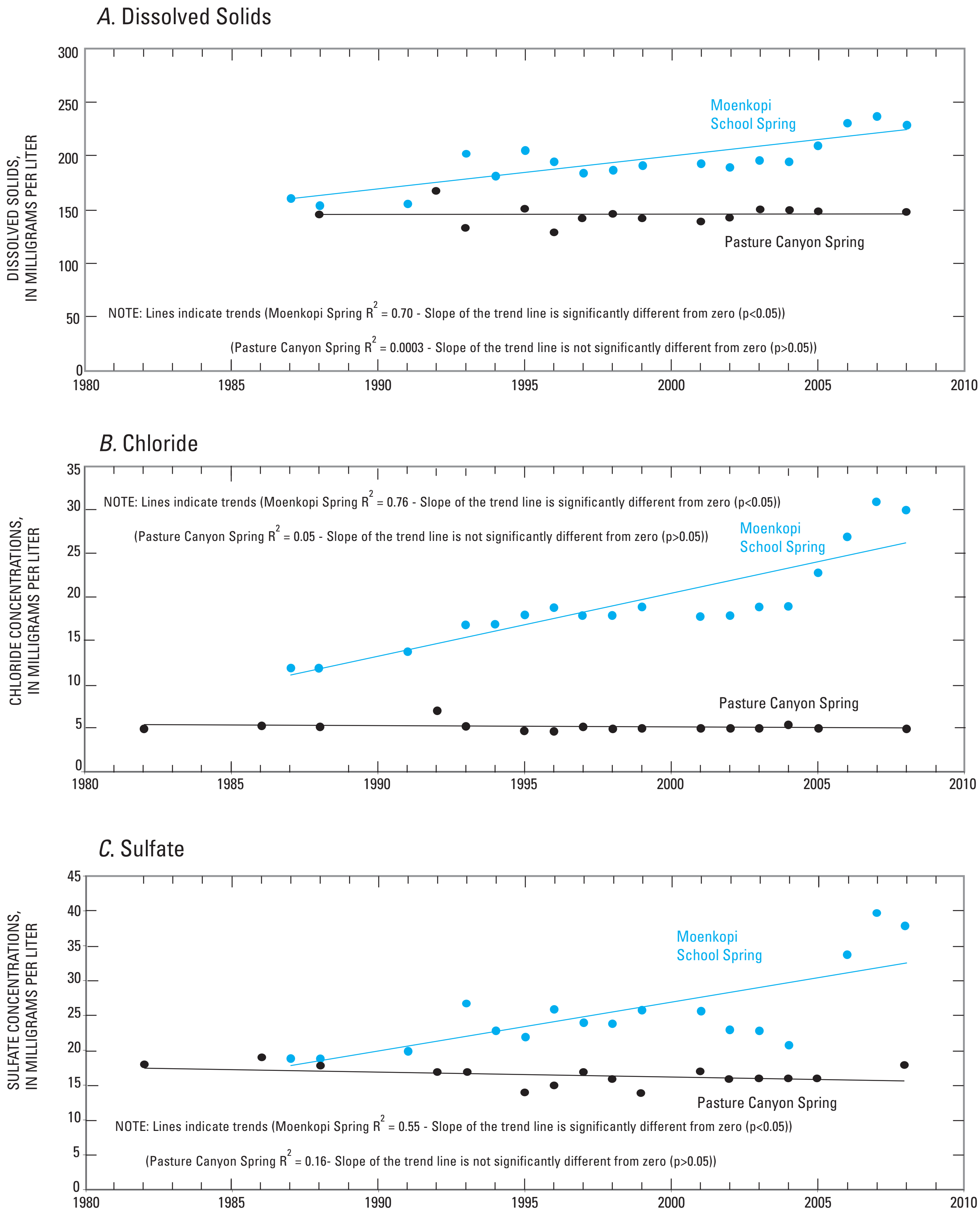


Figure 14. Concentrations of dissolved solids, chloride, and sulfate for water samples from Moenkopi School Spring and Pasture Canyon Spring, N aquifer, Black Mesa area, northeastern Arizona, 1982–2008. *A*, Dissolved solids; *B*, Chloride; *C*, Sulfate. (Trend lines were generated by using the method 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 2007 to September 2008. The monitoring data for 2007–8 are compared to data for 2006–7 and to historical data from the 1950s to September 2008.

In 2007, total groundwater withdrawals were 4,310 acre-ft, industrial withdrawals were 1,170 acre-ft, and municipal withdrawals were 3,140 acre-ft. From 2006 to 2007, total withdrawals from the N aquifer increased by 5 percent, industrial withdrawals decreased by approximately 2 percent, and municipal withdrawals increased by 8 percent.

From 2007 to 2008, annually measured groundwater levels declined in 15 of 29 wells. The median water-level change for the 29 wells was -0.2 ft. In unconfined areas of the N aquifer, water levels declined in 6 of 11 annual wells, and the median change was -0.2 ft. In the confined area of the N aquifer, water levels declined in 9 of 18 wells, and the median change was -0.2 ft.

From the prestress period (before 1965) to 2008, the median groundwater level change in 33 wells was -12.9 ft. Water levels in the 15 wells in the unconfined areas of the N aquifer had a median change of -1.0 ft, and the changes ranged from -33.1 ft to +11.8 ft. Water levels in the 18 wells in the confined area of the N aquifer had a median change of -33.2 ft, and the changes ranged from -198.7 ft to +13.4 ft.

Discharge has been measured annually at Moenkopi School Spring and Pasture Canyon Spring. Between 2007 and 2008, spring flow decreased by 8 percent at Moenkopi School Spring and by 12 percent at Pasture Canyon Spring. 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.

Annual average discharges at four streamflow-gaging stations—Moenkopi Wash, Dinnebito Wash, Pasture Canyon Spring, 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 2008, 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 and Pasture Canyon Spring were 230 mg/L and 149 mg/L, respectively. From the mid 1980s to 2008, 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 do not indicate a trend for the period of record.

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