U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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

Ground-Water, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2002–03

Open-File Report 03–503

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By Margot Truini *and* Blakemore E. Thomas

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Tucson, Arizona
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CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
inch (in)	2.54	centimeter
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day

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)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929; horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27). **Altitude**, as used in this report, refers to distance above or below NGVD 29.

ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (μg/L). Milligrams per liter is a unit expressing the solute mass (milligrams) per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations lower than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Ground-Water, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2002–03

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Abstract

The N aquifer is the major source of water in the 5,400-square-mile area of Black Mesa in northeastern Arizona. Availability of water is an important issue in this area because of continued industrial and municipal use, a growing population, and precipitation of about 6 to 14 inches per year.

The monitoring program in the Black Mesa area has been operating since 1971 and is designed to determine the long-term effects of ground-water withdrawals from the N aquifer for industrial and municipal uses. The monitoring program includes measurements of (1) ground-water pumping, (2) ground-water levels, (3) spring discharge, (4) surface-water discharge, (5) ground-water chemistry, and (6) periodic testing of ground-water withdrawal meters.

In 2002, total ground-water withdrawals were 8,000 acre-feet, industrial use was 4,640 acre-feet, and municipal use was 3,360 acre-feet. From 2001 to 2002, total withdrawals increased by 4 percent, industrial use increased by 2 percent, and municipal use increased by 7 percent. Flowmeter testing was completed for 32 municipal wells in 2003. The median difference between pumping rates for the permanent meter and a test meter for all the sites tested was -2.0 percent. Values ranged from -13.7 percent at Hopi High School no. 2 to +12.9 percent at Shonto PM3.

From 2002 to 2003, water levels declined in 5 of 13 wells in the unconfined part of the aquifer, and the median change was 0.0 foot. Water levels declined in 8 of 13 wells in the confined part of the aquifer, and the median change was -1.1 feet.

From the prestress period (prior to 1965) to 2003, the median water-level change for 26 wells was -8.3 feet. Median water-level changes were -0.4 foot for 13 wells in the unconfined part of the aquifer and -60.3 feet for 13 wells in the confined part.

Discharges were measured once in 2002 and once in 2003 at four springs. Discharge decreased by 16 percent at Pasture Canyon Spring, increased 10 percent at Moenkopi Spring and 90 percent at an unnamed spring near Dennehotso, and did not change at Burro Spring. For the past 11 years, discharges from the four springs have fluctuated; however, an increasing or decreasing trend is not apparent.

Continuous records of surface-water discharge have been collected from 1976 to 2002 at Moenkopi Wash, 1996 to 2002 at Laguna Creek, 1993 to 2002 at Dinnebito Wash, and 1994 to 2002 at Polacca Wash. Median flows for November, December, January, and February of each water year were used as an index of ground-water discharge to those streams. Since 1995, the median winter flows have decreased for Moenkopi Wash, Dinnebito Wash, and Polacca Wash. Since the first continuous record of surface-water discharge in 1997, there is no consistent trend in the median winter flow for Laguna Creek.

In 2003, water samples were collected from 12 wells and 4 springs and analyzed for selected chemical constituents. Dissolved-solids concentrations ranged from 118 to 642 milligrams per liter. Water samples from 10 of the wells and from all of the springs had less than 500 milligrams per liter of dissolved solids.

There are no appreciable time trends in the chemistry of water samples from 7 wells and 4 springs; 7 wells had more than 8 years of data, and the 4 springs had more than 10 years of data.

INTRODUCTION

The Black Mesa study area includes about 5,400 mi^2 in northeastern Arizona (**fig. 1**) and has a diverse topography that includes flat plains, mesas, and incised drainages. Black Mesa is about 2,000 mi^2, is bounded by 2,000-foot high cliffs on the north and northeast sides, and slopes gradually downward to the south and southwest. Availability of water is an important issue in the study area because of continued ground-water withdrawals, a growing population, and precipitation that averages about 6 to 14 in/yr (U.S. Department of Agriculture, 1999).

The N aquifer is the major source of water for industrial and municipal uses in the Black Mesa area. The N aquifer consists of three formations—the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member[1] of the Wingate Sandstone—that are hydraulically connected and function as a single aquifer (Eychaner, 1983; **fig. 2**). Within the Black Mesa study area, Peabody Western Coal Company is the principal industrial water user, and the Navajo Nation and Hopi Tribe are the principal domestic and municipal water users.

Withdrawals from the N aquifer in the Black Mesa area have been increasing during the last 31 years (**table 1** and **fig. 3**). Peabody Western Coal Company began operating a strip mine in the northern part of the mesa in 1968. The quantity of water pumped by the company increased from about 100 acre-ft in 1968 to a maximum of 4,740 acre-ft in 1982. About 4,640 acre-ft of water was pumped in 2002 by Peabody Western Coal Company. Withdrawals for municipal use from the N aquifer have increased steadily from an estimated 250 acre-ft in 1968 to 3,360 acre-ft in 2002.

The Navajo Nation and the Hopi Tribe have been concerned about the long-term effects of withdrawals from the N aquifer on available water supplies, on stream and spring discharge, and on ground-water chemistry. In 1971, these concerns led to the establishment of a monitoring program of the water resources in Black Mesa by the U.S. Geological Survey (USGS) in cooperation with the 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); Peabody Western Coal Company; the Hopi Tribe; and the Western Navajo Agency, Chinle Agency, and Hopi Agency of the BIA have assisted in the collection of hydrologic data.

Purpose and Scope

This report presents results of ground-water, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2002 to September 2003. The monitoring is designed to determine the effects of industrial and municipal pumpage from the N aquifer on ground-water levels, stream and spring discharge, and ground-water chemistry. Continuous and periodic data are collected for ground water and surface water. Ground-water data include pumpage, water levels, spring discharges, and water chemistry. Surface-water data include discharges at four continuous-record streamflow-gaging stations. Flowmeter testing included comparing the pumpage measured by permanent meters at each of 32 wells to that measured by a calibrated mechanical flowmeter.

Previous Investigations

Twenty progress reports on the monitoring program for the Black Mesa area 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; and Thomas, 2002a, 2002b).

[1]The name Lukachukai Member was formerly abandoned by Dubiel (1989) and is used herein for report continuity in the monitoring program as it relates to that part of the Wingate Sandstone included in the N aquifer.

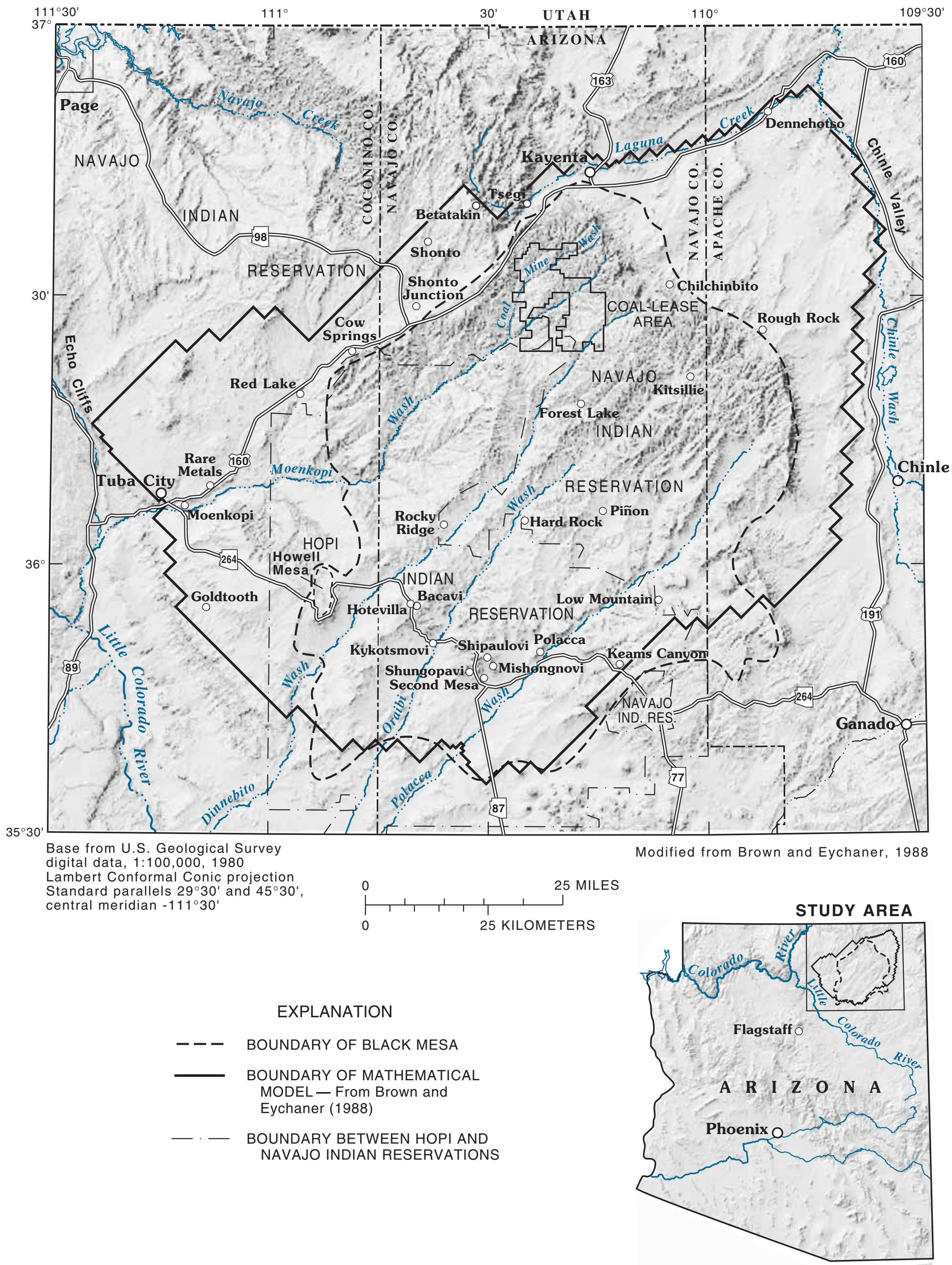


Figure 1. Location of study area.

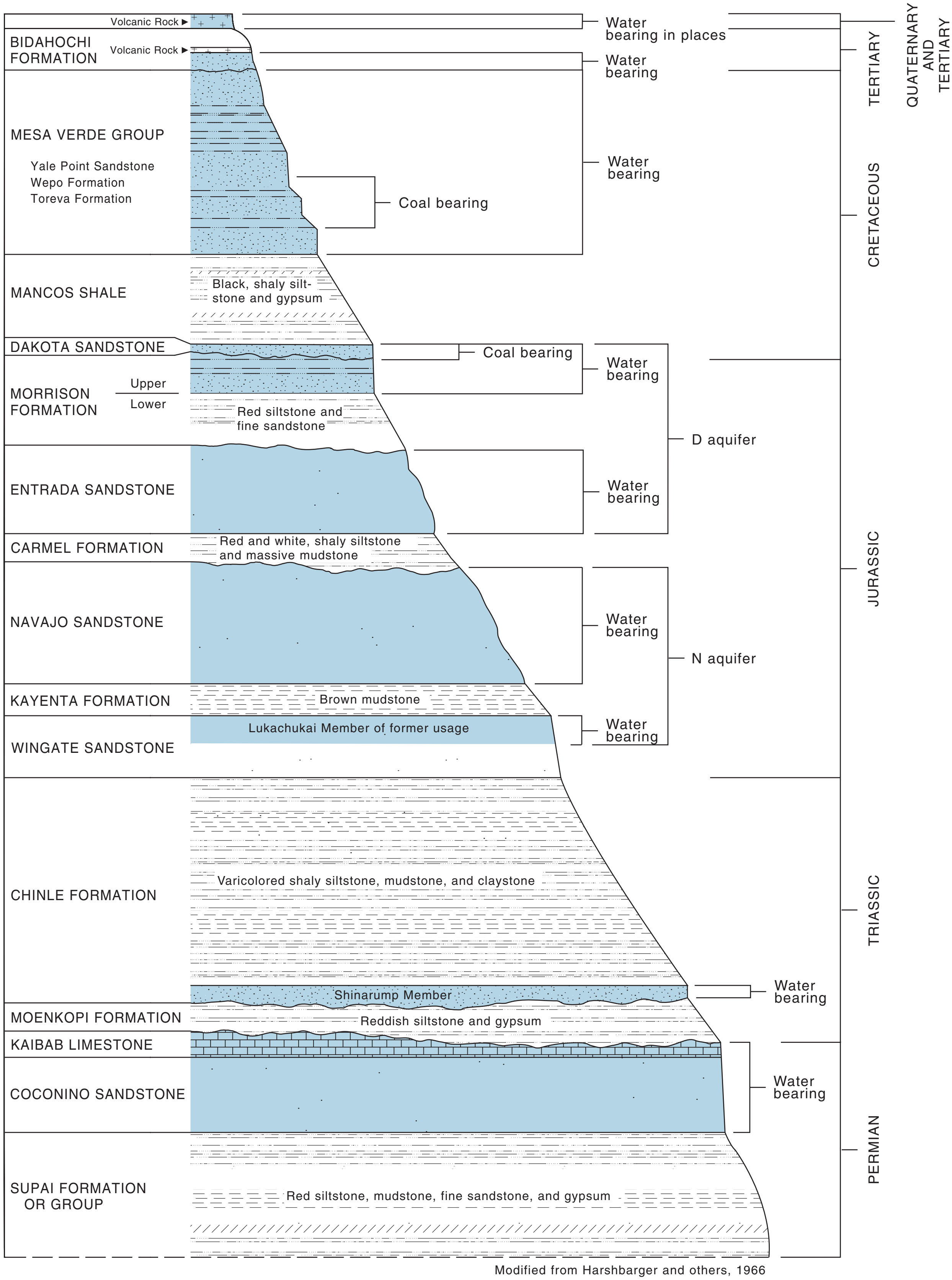


Figure 2. Rock formations and hydrogeologic units of the Black Mesa area, Arizona (not to scale). The N aquifer is approximately 1,000 feet thick.

Table 1. Withdrawals from the N aquifer, Black Mesa area, Arizona, 1965–2002

[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 part of the aquifer]

Year	Industrial[1]	Municipal[2,3] Confined	Municipal[2,3] Unconfined	Total withdrawals	Year	Industrial[1]	Municipal[2,3] Confined	Municipal[2,3] Unconfined	Total withdrawals
1965	0	50	20	70	1984	4,170	1,070	1,400	6,640
1966	0	110	30	140	1985	2,520	1,040	1,160	4,720
1967	0	120	50	170	1986	4,480	970	1,260	6,710
1968	100	150	100	350	1987	3,830	1,130	1,280	6,240
1969	40	200	100	340	1988	4,090	1,250	1,310	6,650
1970	740	280	150	1,170	1989	3,450	1,070	1,400	5,920
1971	1,900	340	150	2,390	1990	3,430	1,170	1,210	5,810
1972	3,680	370	250	4,300	1991	4,020	1,140	1,300	6,460
1973	3,520	530	300	4,350	1992	3,820	1,180	1,410	6,410
1974	3,830	580	360	4,770	1993	3,700	1,250	1,570	6,520
1975	3,500	600	510	4,610	1994	4,080	1,210	1,600	6,890
1976	4,180	690	640	5,510	1995	4,340	1,220	1,510	7,070
1977	4,090	750	730	5,570	1996	4,010	1,380	1,650	7,040
1978	3,000	830	930	4,760	1997	4,130	1,380	1,580	7,090
1979	3,500	860	930	5,290	1998	4,030	1,440	1,590	7,060
1980	3,540	910	880	5,330	1999	4,210	1,420	1,480	7,110
1981	4,010	960	1,000	5,970	2000	4,490	1,610	1,640	7,740
1982	4,740	870	960	6,570	2001	4,530	1,490	1,660	7,680
1983	4,460	1,360	1,280	7,100	2002	4,640	1,500	1,860	8,000

[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, 1986–2002.

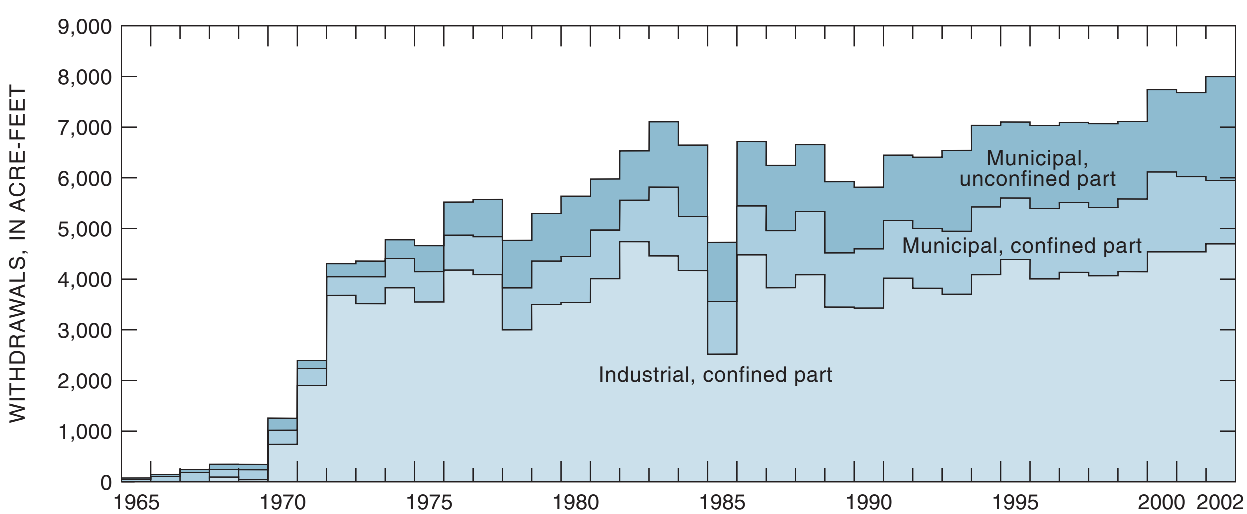


Figure 3. Withdrawals from the N aquifer, Black Mesa area, Arizona, 1965–2002.

Most of the data from the monitoring program are contained in these reports. Stream-discharge and periodic water-quality data from Moenkopi Wash collected before the 1982 water year were published by the U.S. Geological Survey (1963–64a, b; 1965–74a, b; 1976–83). Stream-discharge data from water years 1983 to 2002 for Moenkopi Wash and other streams 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). 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 been done in 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 ground-water flow in the N aquifer. Brown and Eychaner (1988) recalibrated the model using a finer grid and revised estimates of selected aquifer characteristics. GeoTrans, Inc. (1987) also developed a two-dimensional model of the N aquifer in the 1980s. In the late 1990s, HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc. (1999) developed a detailed three-dimensional numerical model of the D and N aquifers.

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water 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 ground-water ages, recharge, and hydraulic conductivity of the N aquifer using geochemical techniques. Zhu and others (1998) estimated ground-water recharge using isotopic data and flow estimates from the model developed by GeoTrans, Inc. (1987). Zhu (2000) estimated recharge again using the same isotopic data, but added numerical flow and transport modeling to the method. Truini and Longsworth (2003) described the hydrogeology of the D aquifer and movement and ages of ground water using geochemical and isotopic analyses.

HYDROLOGIC DATA

In 2002–03, the Black Mesa monitoring program included metering and estimating ground-water withdrawals, measuring depth to ground water, measuring discharge in streams and springs, collecting and analyzing water samples from wells and springs, and periodic testing of flowmeters for accuracy. Ground-water withdrawals from 36 well systems, water levels at 6 observation wells, and surface-water discharge at 4 sites were monitored continuously during this period. Annual measurements were made of discharge at 4 springs and ground-water levels at 26 wells. Spring discharges and ground-water levels were measured between April and May 2003. Ground-water samples were collected from 12 wells and 4 springs in April–May 2003 and analyzed for chemical constituents. Identification information for the 49 wells used for water-level measurements and water-quality sampling is shown in table 2.

Withdrawals from the N Aquifer

Withdrawals from the N aquifer are separated into three categories: (1) industrial use from the confined part of the aquifer, (2) municipal use from the confined part of the aquifer, and (3) municipal use from the unconfined part of the aquifer (**table 1** and **fig. 3**). The industrial category includes eight wells in the well field of Peabody Western Coal Company in the northern part of Black Mesa (**fig. 4**). The BIA, NTUA, and Hopi Tribe operate about 70 municipal wells that are combined into 36 well systems (fig. 4). Withdrawals from the N aquifer were compiled primarily on the basis of metered data (tables 1 and 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 estimated total withdrawals by the windmills are about 65 acre-ft/yr (HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., 1999). This amount is less than 1 percent of the total annual withdrawal from the N aquifer.

Table 2. Identification numbers and names of study wells, Black Mesa area, Arizona

[Dashes indicate no data.]

U.S. Geological Survey identification number	Common name or location	Bureau of Indian Affairs site number	U.S. Geological Survey identification number	Common name or location	Bureau of Indian Affairs site number
354749110300101	Second Mesa PM2	---	362149109463301	Rough Rock	10R-111
355023110182701	Keams Canyon PM2	---	363130110254501	Peabody 8	---
355034110183001	Keams Canyon PM3	---	362406110563201	White Mesa Arch	1K-214
355215110375001	Kykotsmovi PM2	---	362418109514601	Rough Rock PM5	---
355230110365801	Kykotsmovi PM1	---	362456110503001	Cow Springs	1K-225
355236110364501	Kykotsmovi PM3	---	362647110243501	Peabody 4	---
355428111084601	Goldtooth	3A-28	362823109463101	Rough Rock	10R-119
355518110400301	Hotevilla PM1	---	362936109564101	BM observation well 1	8T-537
355638110060401	Low Mountain PM2	---	363013109584901	Sweetwater Mesa	8K-443
355648110475501	Howell Mesa	6H-55	363103109445201	Rough Rock	9Y-95
355924110485001	Howell Mesa	3K-311	363137110044702	Chilchinbito PM3	---
360055110304001	BM observation well 5	4T-519	363143110355001	BM observation well 4	2T-514
360217111122601	Tuba City	3K-325	363213110342001	Shonto Southeast	2K-301
360418110352701	Rocky Ridge PM2	---	363232109465601	Rough Rock	9Y-92
360527110122501	Piñon NTUA 1	---	363309110420501	Shonto	2K-300
360614110130801	Piñon PM6	---	363423110305501	Shonto Southeast	2T-502
360734111144801	Tuba City	3T-333	363558110392501	Shonto PM2	---
360904111140201	Tuba City NTUA 1	3T-508	363727110274501	Long House Valley	8T-510
360918111080701	Tuba City Rare Metals 2	---	363850110100801	BM observation well 2	8T-538
360924111142201	Tuba City NTUA 3	---	364034110240001	Marsh Pass	8T-522
360953111142401	Tuba City NTUA 4	3T-546	364226110171701	Kayenta West	8T-541
361225110240701	BM observation well 6	---	364248109514601	Northeast Rough Rock	8A-180
361737110180301	Forest Lake NTUA 1	4T-523	364338110154601	BM observation well 3	8T-500
361832109462701	Rough Rock	10T-258	364344110151201	Kayenta PM2	8A-295
362043110030501	Kitsillie NTUA 2	---			

In 2002, the total ground-water withdrawal from the N aquifer was about 8,000 acre-ft (table 1), which is about a 4-percent increase from the total withdrawal in 2001. Withdrawals for municipal use from the confined part of the aquifer totaled 1,500 acre-ft, which is a 0.7-percent increase from 2001. Withdrawals for municipal use from the unconfined part of the aquifer totaled 1,860 acre-ft, which is a 12-percent increase from 2001. Withdrawals for industrial use totaled 4,640 acre-ft, which is a 2-percent increase from 2001.

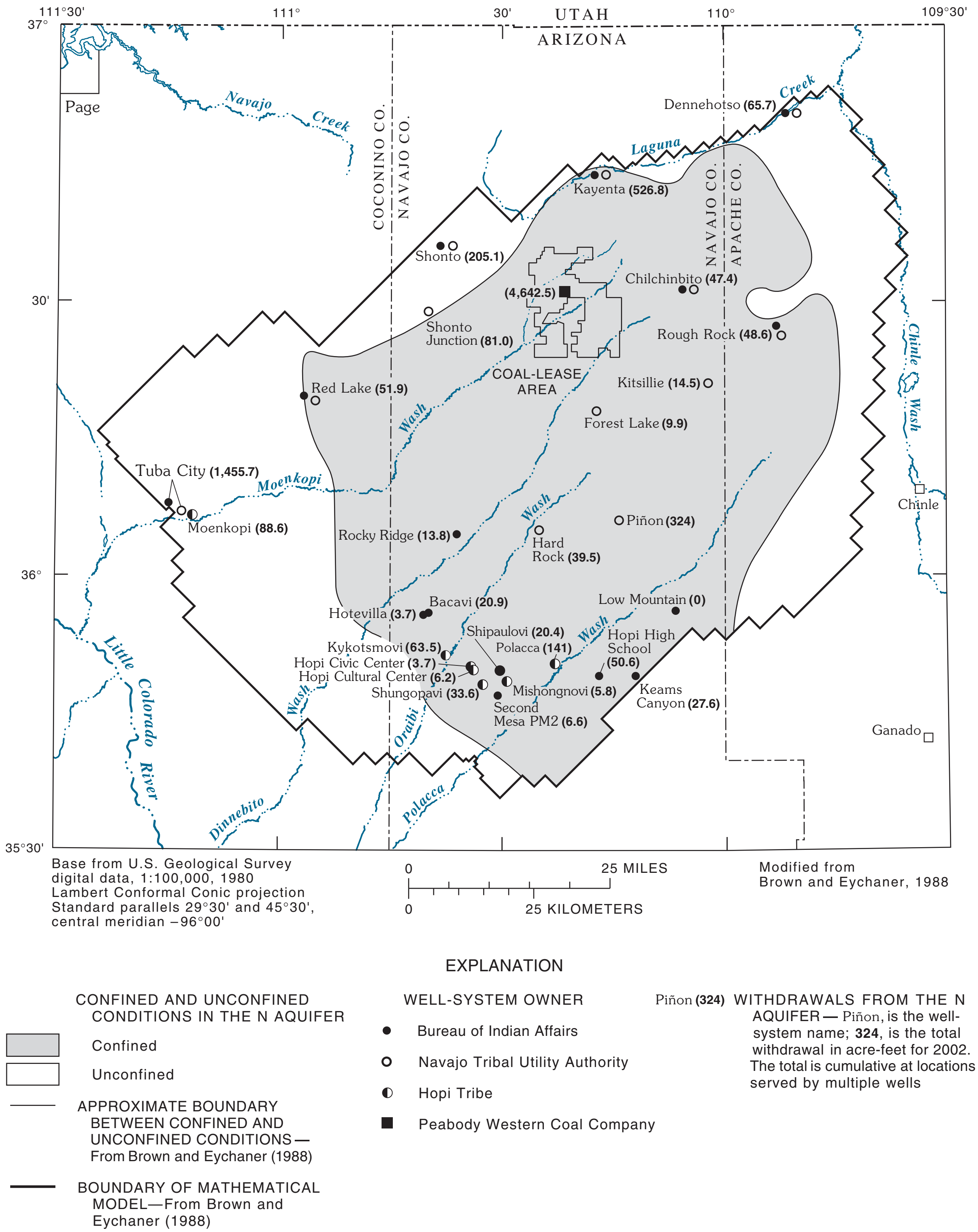


Figure 4. Locations of well systems monitored for withdrawals from the N aquifer, Black Mesa area, Arizona, 2002.

Table 3. Withdrawals from the N aquifer by well system, Black Mesa area, Arizona, 2002

[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; BIA Roads, Bureau of Indian Affairs, Division of Roads]

Well system (one or more wells)	Owner	Source of data	Withdrawals	
			Confined aquifer	Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	4.1	
Dennehotso	BIA	USGS/BIA		25.7
Hopi High School	BIA	USGS/BIA	50.6	
Hotevilla	BIA	USGS/BIA	3.7	
Kayenta	BIA	USGS/BIA	59.1	
Keams Canyon	BIA	USGS/BIA	27.6	
Low Mountain	BIA	USGS/BIA	[1]0	
Piñon	BIA	USGS/BIA	[1]0	
Red Lake	BIA	USGS/BIA		6.4
Rocky Ridge	BIA	USGS/BIA	13.8	
Rough Rock	BIA	USGS/BIA	33.5	
Second Mesa	BIA	USGS/BIA	6.6	
Shonto	BIA	USGS/BIA		187.5
Tuba City	BIA	USGS/BIA		135.1
Chilchinbito	NTUA	NTUA	43.3	
Dennehotso	NTUA	NTUA		40.0
Forest Lake	NTUA	NTUA	9.9	
Hard Rock	NTUA	NTUA	39.5	
Kayenta	NTUA	NTUA	467.7	
Kitsillie	NTUA	NTUA	14.5	
Piñon	NTUA	NTUA	324.0	
Red Lake	NTUA	NTUA		45.5
Rough Rock	NTUA	NTUA	15.1	
Shonto	NTUA	NTUA		17.6
Shonto Junction	NTUA	NTUA		81.0
Tuba City	NTUA	NTUA		1,320.6
Mine Well Field	Peabody	Peabody	[2]4,642.5	
Bacavi	Hopi	USGS/Hopi	20.9	
Hopi Civic Center	Hopi	USGS/Hopi	3.7	
Hopi Cultural Center	Hopi	USGS/Hopi	6.2	
Kykotsmovi	Hopi	USGS/Hopi	63.5	
Mishongnovi	Hopi	USGS/Hopi	5.8	
Moenkopi	Hopi	USGS/Hopi		88.6
Polacca	Hopi	USGS/Hopi	[3]141.0	
Shipaulovi	Hopi	USGS/Hopi	20.4	
Shungopovi	Hopi	USGS/Hopi	33.6	

[1]Well taken out of service.
[2]Industrial pumpage.
[3]Estimated. Well PM4 not metered. Annual pumpage from PM4 was estimated as 40 acre-feet on the basis of previous metered data and a per capita consumption of 40 gallons per day. Pumping from the remaining wells (PM5 and PM6) may include some water from the D aquifer.

Withdrawals from the N aquifer have been increasing since the 1970s (**table 1** and **fig. 3**). Total withdrawals increased from 1,170 acre-ft in 1970 to 4,300 acre-ft in 1972 when industrial use increased from 740 to 3,680 acre-ft. Since 1973, industrial use has fluctuated between 2,520 and 4,740 acre-ft/yr. Municipal use increased by about 20 percent per year during the 1970s, but increased only about 4 percent per year in the 1980s, and increased only about 2 percent per year in the 1990s.

In the 1970s, industrial use was about 75 percent of the total withdrawal. With the increase in municipal use over the last 30 years, industrial use, as a percentage of total withdrawals, has declined to about 60 percent in the late 1990s and in 2002.

In an effort to improve and ensure the accuracy of ground-water 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 ground-water 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 on approximately one-half of the wells (38 wells were visited and 32 wells were tested) during August–September 2003 (**table 4**). The median percent difference between pumping rates for the permanent meter and the test meter for all the sites tested was -2.0 percent. Values ranged from -13.7 percent at Hopi High School no. 2 to +12.9 percent at Shonto PM3 (table 4). Three wells were above the 10 percent allowable range: Hopi High School no. 2 (-13.7 percent), Moenkopi no. 1 and 2 (+11.5 percent), and Shonto PM 3 (+12.9 percent).

Ground-Water Levels in the N Aquifer

Ground water 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 (Eychaner, 1983; **fig. 5**). The ground water generally flows radially outward from recharge areas near Shonto to the southwest, south, southeast, and east (Thomas, 2002).

Ground-water levels are measured each year and compared with levels from previous years to determine changes over time. In April–May 2003, water levels were measured in 26 wells that are used for observation, municipal supply, or stock supply (**table 5**). Six of the 26 wells are observation wells that were operated on a continuous basis; water levels were recorded daily. Water levels were measured manually five times between April 2002 and April 2003 in the six continuous-observation wells.

The wells used for water-level measurements are distributed throughout the study area (**fig. 5**). Although all the wells are completed in the N aquifer, characteristics of the wells vary considerably. Construction dates range from 1934 to 1993, depths range from 107 to 3,535 ft, and depths to the top of the N aquifer range from 0 to 2,617 ft (**table 6**).

From 2002 to 2003, water levels declined in 13 of 26 wells. The median water-level change in the 26 wells was -0.2 ft (table 7). Changes ranged from -5.5 ft in the Goldtooth well near Tuba City to +10.6 ft in well 10T-258 near Rough Rock (table 5).

From 2002 to 2003, water levels declined in 5 of 13 wells in unconfined areas. The median change was 0.0 ft, and the changes ranged from -5.5 ft to +5.6 ft. In the confined area, water levels declined in 8 of 13 wells. The median change was -1.1 ft, and the changes ranged from -2.8 ft to +10.6 ft (tables 5 and 7).

Median annual water-level changes for the water-level network wells from 1983 to 2003 are shown in **figure 6**. Median annual changes before 1983 are not shown because there were insufficient water-level data to compute median values. For wells in the confined area, the average annual median water-level change was -1.8 ft, and there is no appreciable trend in the annual water-level changes from 1983 to 2003. For wells in unconfined areas, the average annual median water-level change was +0.2 ft, and there is no appreciable trend from 1983 to 2003 (**table 7**).

From the prestress period (prior to 1965) to 2003, the median water-level change in 26 wells was -8.3 ft. Water levels in 13 wells in unconfined areas had a median change of -0.4 ft and ranged from -36.6 ft to +16.5 ft (table 5). Water levels in 13 wells in the confined area had a median change of -60.3 ft and ranged from -190.5 ft to +12.7 ft.

Table 4. Flowmeter-test results for selected municipal wells that are completed in the N aquifer, Black Mesa area, Arizona, 2003

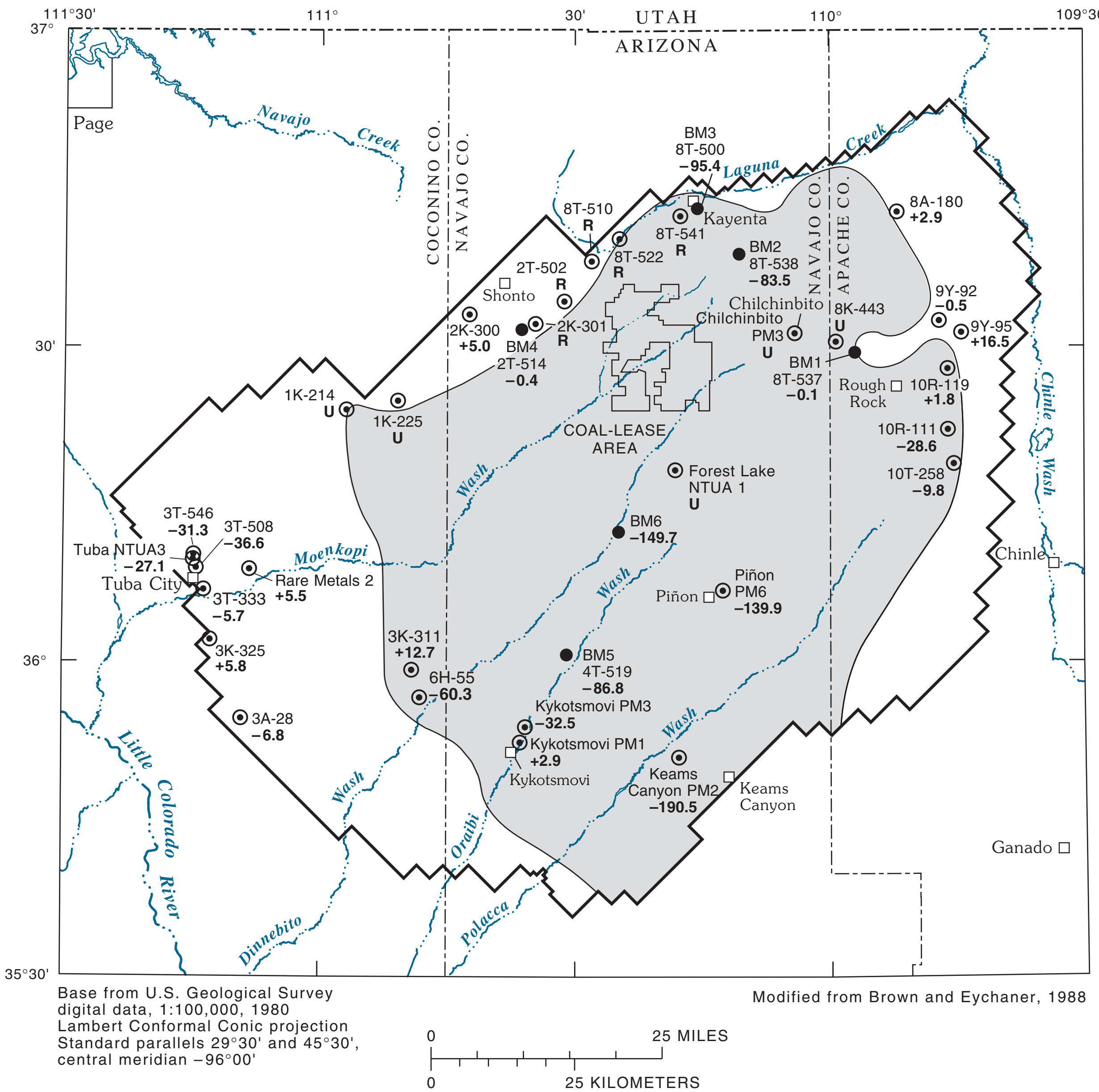
Well name	Date tested	Pumping rate, in gallons per minute: Permanent meter	Pumping rate, in gallons per minute: Test meter[1]	Percent difference[2]	Name and number of permanent meter	
Bureau of Indian Affairs						
Chilchinbito PM3	08–05–03	18	19	-4.1	Master Meter	253390
Dennehotso PM1	08–05–03	(3)	(3)	(3)	Master Meter	1450251
Dennehotso PM2	08–05–03	45	46	-2.3	Sensus	1543870
Kayenta PM2	07–25–03	(3)	(3)	(3)	Neptune	31973644
Kayenta PM3	07–25–03	105	107	-1.4	Rockwell	1305841
Red Lake PM1	08–11–03	42	41	2.4	Rockwell	32722074
Rocky Ridge PM2	08–12–03	(4)	(4)	(4)	Rockwell	1331031
Rocky Ridge PM3	08–12–03	50	51	-0.8	Rockwell	1331029
Rough Rock PM3	08–06–03	42	42	0.7	Rockwell	36880399
Rough Rock PM5	08–06–03	38	39	-2.6	Rockwell	36726380
Rough Rock PM6	08–06–03	49	50	-0.1	Rockwell	1331030
Rough Rock PM7	08–06–03	39	42	-6.5	McCrometer	823317
Tuba City PM4	07–29–03	103	105	-2.1	Rockwell	1323857
Tuba City PM5	07–29–03	91	95	-3.5	Sensus	1585386
Tuba City PM6	07–29–03	127	128	-1.0	Rockwell	1305840
Hopi Tribal Authority						
Bacavi	08–13–03	68	68	0.4	Sensus	1403844
Hopi Civic Center (Vet Center)	08–07–03	52	55	-5.0	Rockwell	1323855
Hopi Cultural Center	08–07–03	48	49	-2.1	Rockwell	37078664
Hopi High School no. 1	07–31–03	58	64	-9.0	Neptune	31625407
Hopi High School no. 2	07–31–03	55	64	-13.7	Neptune	31625415
Hopi High School no. 3	07–31–03	92	95	-3.2	Hersey	0300108
Hotevilla Community	08–13–03	56	54	4.2	Sensus	1424710
Hotevilla PM1	07–31–03	42	42	0.0	Rockwell	36726381
Keams Canyon #2	07–31–03	63	66	-3.8	Neptune	31625412
Keams Canyon #3	07–31–03	76	82	-7.7	Rockwell	32658702
Kykotsmovi PM2	07–23–03	80	82	-3.2	Kent	77655836
Kykotsmovi PM3	07–23–03	134	138	-2.9	Rockwell	1266317
Mishungnovi	07–30–03	14	14	3.0	Precision	E569880
Moenkopi #1 and #2	08–15–03	70	63	11.5	Rockwell	1231000
Polacca 5	08–07–03	(3)	(3)	(3)	McCrometer	9369087
Polacca 6	08–07–03	(3)	(3)	(3)	McCrometer	9261586
Second Mesa Day School 1	07–31–03	(4)	(4)	(4)	Rockwell	32658703
Second Mesa Day School 2	07–31–03	63	67	-5.2	ARAD	029154
Shonto PM2	08–11–03	171	173	-1.6	Rockwell	1255896
Shonto PM3	08–11–03	127	113	12.9	Rockwell	1300477
Shonto PM4	08–11–03	70	73	-3.9	Sensus	1325584
Shungopavi	08–12–03	63	64	-2.2	Rockwell	36880400
Sipaulovi #2	07–30–03	42	41	2.4	Kent	88538743

[1]Invensys Testing Meter.

[2]Percent difference = ((([Permanent average]/[test average])*[accuracy])-100)/100. A positive difference indicates that the permanent meter is registering more pumpage than the test flowmeter, whereas a negative difference indicates that it is registering less. NOTE: percent difference values reported in earlier reports in this series were calculated without using the accuracy coefficient as suggested by the test meter manufacturer.

[3]Well not tested because test flowmeter could not be connected.

[4]Well not used since 2002.



EXPLANATION

CONFINED AND UNCONFINED CONDITIONS IN THE N AQUIFER

Confined

Unconfined

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

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

2K-300 +5.0 WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 2K-300, is Bureau of Indian Affairs site number; second entry, **+5.0**, is change in water level, in feet, between measurement made during the prestress period and measurement made during 2002. **U**, unable to measure. **R**, recently pumping

BM2 8T-538 −83.5 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, **−83.5**, is change in water level, in feet, from simulated prestress period to 2003

Figure 5. Water-level changes in N aquifer wells from the prestress period to 2003, Black Mesa area, Arizona.

Table 5. Water-level changes in wells completed in the N aquifer, Black Mesa area, Arizona, prestress period to 2003

[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: 2002	Change in water level from preceding year, in feet: 2003	Water level, in feet below land surface, 2003[1]	Prestress period water level[2]: Feet below land surface	Prestress period water level[2]: Date	Change in water level from prestress period to 2003, in feet
Unconfined area							
BM observation well 1[3]	8T-537	+0.2	+0.2	374.1	374	([3])	-0.1
BM observation well 4[3]	2T-514	-1.3	+1.8	216.4	[4]216	([3])	-0.4
Cow Springs	1K-225	([4])	([4])	([4])	60	07–04–54	([4])
Goldtooth	3A-28	-0.1	-5.5	236.8	230.0	10–29–53	-6.8
Long House Valley	8T-510	-1.5	([6])	([6])	99.4	08–22–67	([6])
Northeast Rough Rock	8A-180	+0.4	+0.0	44.0	46.9	11–13–53	+2.9
Rough Rock	9Y-95	([5])	+1.9	103.0	119.5	08–03–49	+16.5
Do	9Y-92	-0.2	-3.4	169.3	168.8	12–13–52	-0.5
Shonto	2K-300	+0.4	+0.0	171.5	176.5	06–13–50	+5.0
Shonto Southeast	2K-301	([6])	([6])	([6])	283.9	12–10–52	([6])
Do	2T-502	+7.7	([6])	([6])	405.8	08–22–67	([6])
Tuba City	3T-333	+0.4	+0.6	28.7	23.0	12–02–55	-5.7
Do	3K-325	+0.1	-0.6	202.2	208	06–30–55	+5.8
Tuba City Rare Metals 2	---	+0.3	+0.0	51.5	57	09–24–55	+5.5
Tuba NTUA 1	3T-508	-3.4	+5.6	65.6	29	02–12–69	-36.6
Tuba NTUA 3	---	+0.2	-0.4	61.3	34.2	11–08–71	-27.1
Tuba NTUA 4	3T-546	+0.5	-1.4	65.0	33.7	08–06–71	-31.3
Confined area							
BM observation well 2[3]	8T-538	-2.1	-2.0	208.5	125	([3])	-83.5
BM observation well 3[3]	8T-500	-0.5	+1.6	150.4	55.0	04–29–63	-95.4
BM observation well 5[3]	4T-519	-3.7	-1.1	410.8	324	([3])	-86.8
BM observation well 6[3]	---	-6.9	-1.8	846.7	[4]697	([3])	-149.7
Chilchinbito PM3	---	([4])	([4])	([4])	405.3	09–25–65	([4])
Forest Lake NTUA 1	4T-523	([4])	([4])	([4])	1,096R	05–21–82	([4])
Howell Mesa	3K-311	+6.1	-2.8	450.3	463.0	11–03–53	+12.7
Howell Mesa	6H-55	-0.3	-2.0	272.3	212	07–08–54	-60.3
Kayenta West	8T-541	+1.0	([6])	([6])	230	03–17–76	([6])
Keams Canyon PM2	---	-22.7	+1.0	483.0	292.5	06–10–70	-190.5
Kykotsmovi PM1	---	+4.5	+9.0	217.1	220	05–20–67	+2.9
Kykotsmovi PM3	---	-1.6	-0.8	242.5	210	08–28–68	-32.5
Marsh Pass	8T-522	0.0	([6])	([6])	125.5	02–07–72	([6])
Piñon PM6	---	-7.1	-2.8	883.5	743.6	05–28–70	-139.9
Rough Rock	10R-119	-1.4	+1.8	254.8	256.6	12–02–53	+1.8
Do	10T-258	-12.4	+10.6	310.8	301.0	04–14–60	-9.8
Do	10R-111	-2.4	-2.5	198.6	170	08–04–54	-28.6
Sweetwater Mesa	8K-443	-1.0	([4])	([4])	529.4	09–26–67	([4])
White Mesa Arch	1K-214	+0.5	([6])	([6])	188	06–04–53	([6])

[1]Water level measured during April to May 2003.

[2]Prestress refers to the period of record before appreciable ground-water withdrawals for mining or municipal purposes—about 1965. For wells that had no water-level measurement before 1965, the earliest water-level measurement is shown.

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

[4]Water level not measured because of obstruction in well, no access to well, or not visited.

[5]2001 water level influenced by pumping.

[6]Well recently pumped.

Table 6. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, Arizona, 2002–03

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[1]	Type of data collected
8T-537 (BM observation well 1)	02–01–72	5,864	850	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
1K-225	07–04–54	5,722	251	19–251	[2]10	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	[2]5	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	[2]4	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
6H-55	12–08–44	5,635	361	310–335	310	Water level
8A-180	01–20–39	5,200	107	60–107	[2]40	Water level
8A-295 (Kayenta PM2)	[3]00–00–36	5,623	840	268–280; 691–788	95	Water chemistry, withdrawals
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

See footnotes at end of table.

Table 6. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, Arizona, 2002–03—Continued

Bureau of Indian Affairs site number, 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[1]	Type of data collected
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
Chilchinbito PM3	09–25–65	5,950	1,600	1,140–1,570	1,136	Withdrawals
Hotevilla PM1	[3]06–00–57	6,357	1,757	1,500–1,750	1,450	Water chemistry withdrawals
Keams Canyon PM2	[3]05–00–70	5,809	1,106	906–1,106	900	Water level, withdrawals
Keams Canyon PM3	[3]01–00–76	5,806	1,090	931–1,090	930	Water chemistry
Kitsillie NTUA 2	11–09–93	6,780	2,620	2,217–2,223 2,240–2,256 2,314–2,324 2,344–2,394 2,472–2,527	2,205	Water chemistry, withdrawals
Kykotsmovi PM1	02–20–67	5,657	995	655–675 890–990	880	Water level, withdrawals
Kykotsmovi PM2	10–14–77	5,717	1,160	950–1,160	890	Water chemistry, withdrawals
Kykotsmovi PM3	08–07–68	5,618	1,220	850–1,220	840	Water level, withdrawals
Low Mountain PM2	[3]04–00–72	6,123	1,343	1,181–1,262	1,153	Water level
Peabody 4	[3]05–00–68	6,229	3,535	2,029–3,458	2,280	Water chemistry, withdrawals
Peabody 8	07-01-80	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
Rocky Ridge PM2	06–26–63	5,985	1,780	1,480–1,780	1,442	Water level
Rough Rock PM5	06–27–64	6,299	1,420	1,180–1,420	1,156	Water chemistry, withdrawals
Second Mesa PM2	[3]10–00–68	5,777	1,090	740–1,090	720	Water chemistry, withdrawals
Shonto PM2	05–05–61	6,465	554	485–510	0	Water chemistry
Tuba City NTUA 3	[3]10–00–71	5,176	442	142–442	34	Water level, withdrawals
Tuba City Rare Metals 2	[3]09–00–55	5,108	705	100–705	[2]55	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, 2002–03 and prestress period to 2003, Black Mesa area, Arizona

Number of wells	Aquifer conditions	Median change in water levels (feet)
2002–03		
26	Both	-0.2
13	Unconfined	0.0
13	Confined	-1.1
Prestress period–2003		
26	Both	-8.3
13	Unconfined	-0.4
13	Confined	-60.3

The areal distribution of water-level changes from the prestress period to 2003 is shown in **figure 5**. Hydrographs of water levels in the annual observation-well network show the time trends of changes since the 1950s, 1960s, or 1970s (**fig. 7**). In most of the unconfined areas, water levels have changed only slightly. In the Tuba City area, however, water levels have declined 30 to 40 ft in a few of the wells. In most of the confined area, water levels have declined; however, the magnitudes of declines are varied. Larger declines are near the municipal pumping centers (wells Piñon PM6 and Keams Canyon PM2) or near the wells for Peabody Western Coal Company. Smaller declines occur away from the pumping centers (wells 8T-522 and 10R-119).

Hydrographs for the Black Mesa observation wells show continuous water-level changes since about 1972 (**fig. 8**). Water levels in the two wells in unconfined areas (BM1 and BM4) have had small seasonal or year-to-year variation and have had small long-term changes since 1972. Water levels in wells in the confined area, except BM3, also have had little seasonal variation; however, the water levels have consistently declined in all these wells since 1972.

Spring Discharge from the N Aquifer

Ground water in the N aquifer discharges from many springs around the margins of the Black Mesa area. Discharge from selected springs is measured annually and compared to discharge from previous years to determine changes over time. In April–May 2003, discharge was measured at four springs (**table 8**). Three springs are in the western or southwestern part of the Black Mesa area, and one is in the northeastern part (**fig. 9**). The discharge measured at all four springs represents only part of the total discharge from each spring. Measurement of the total discharge at those sites is difficult because of separate seeps and problematic measuring conditions.

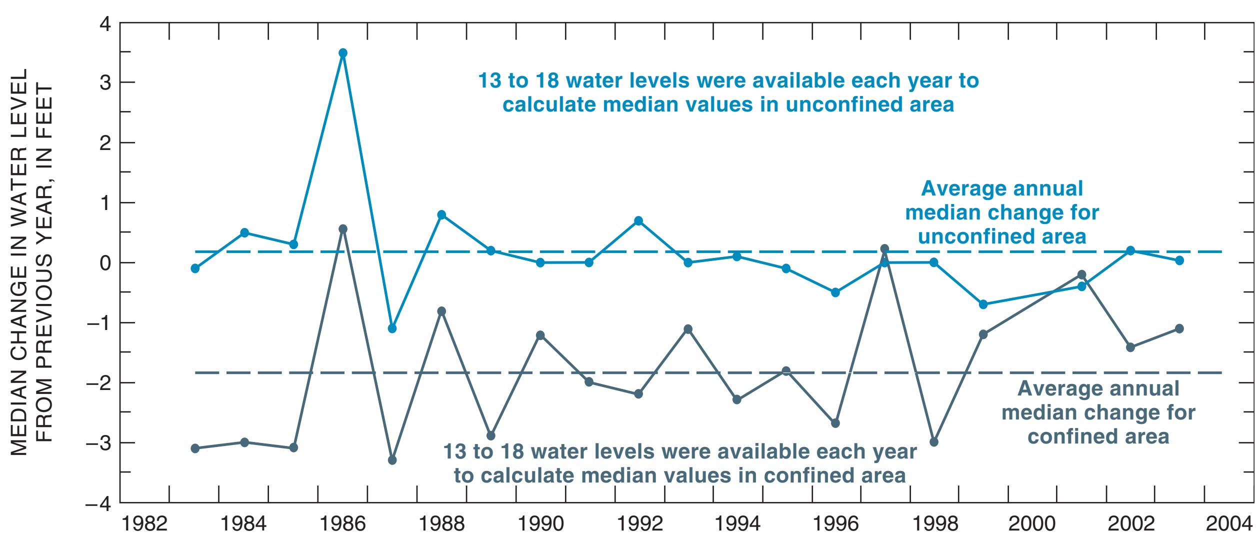


Figure 6. Annual water-level changes for observation wells completed in the N aquifer, Black Mesa area, Arizona, 1983–2003.

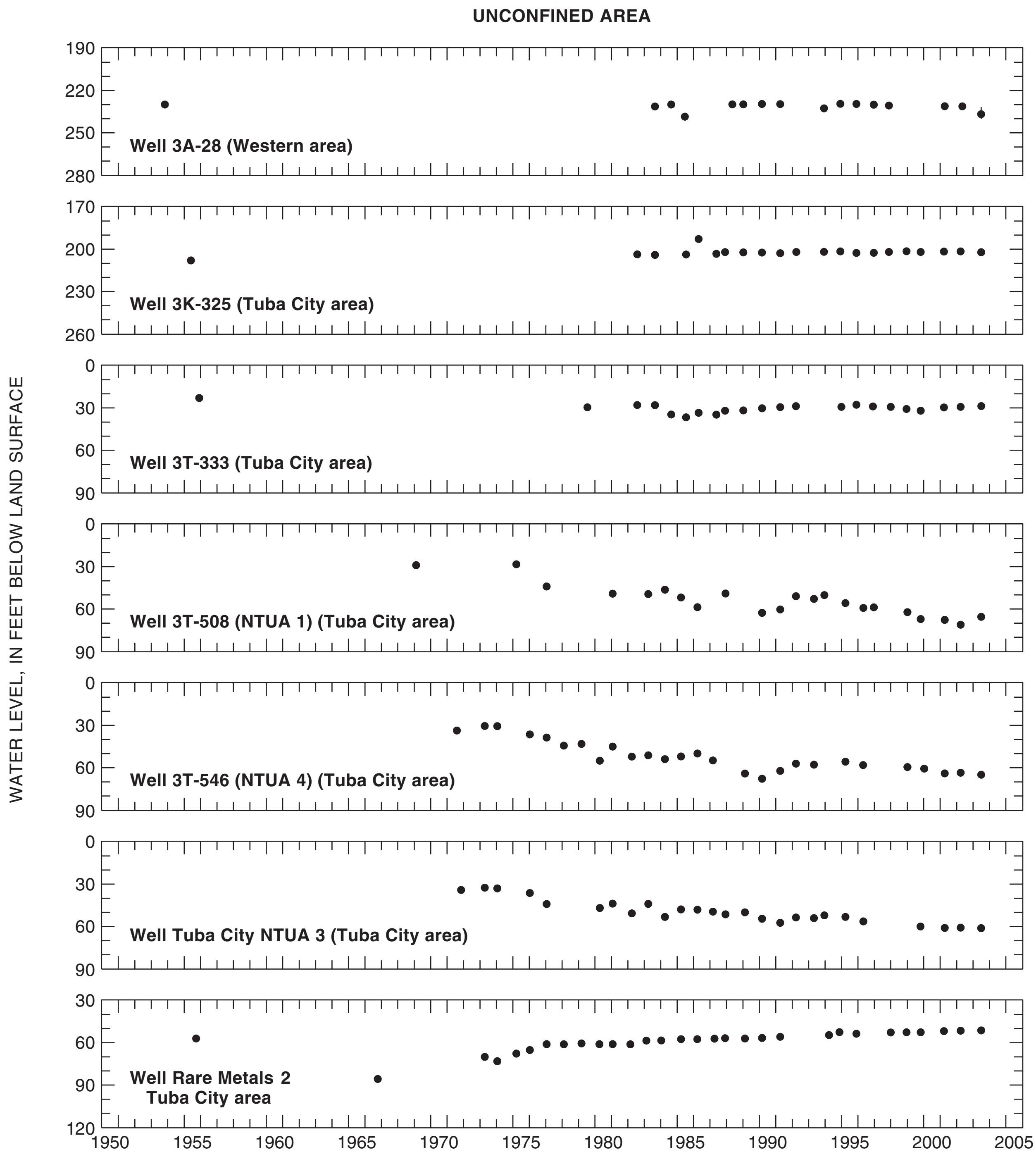


Figure 7. Observed water levels (1950–2003) in annual observation-well network, Black Mesa area, Arizona.

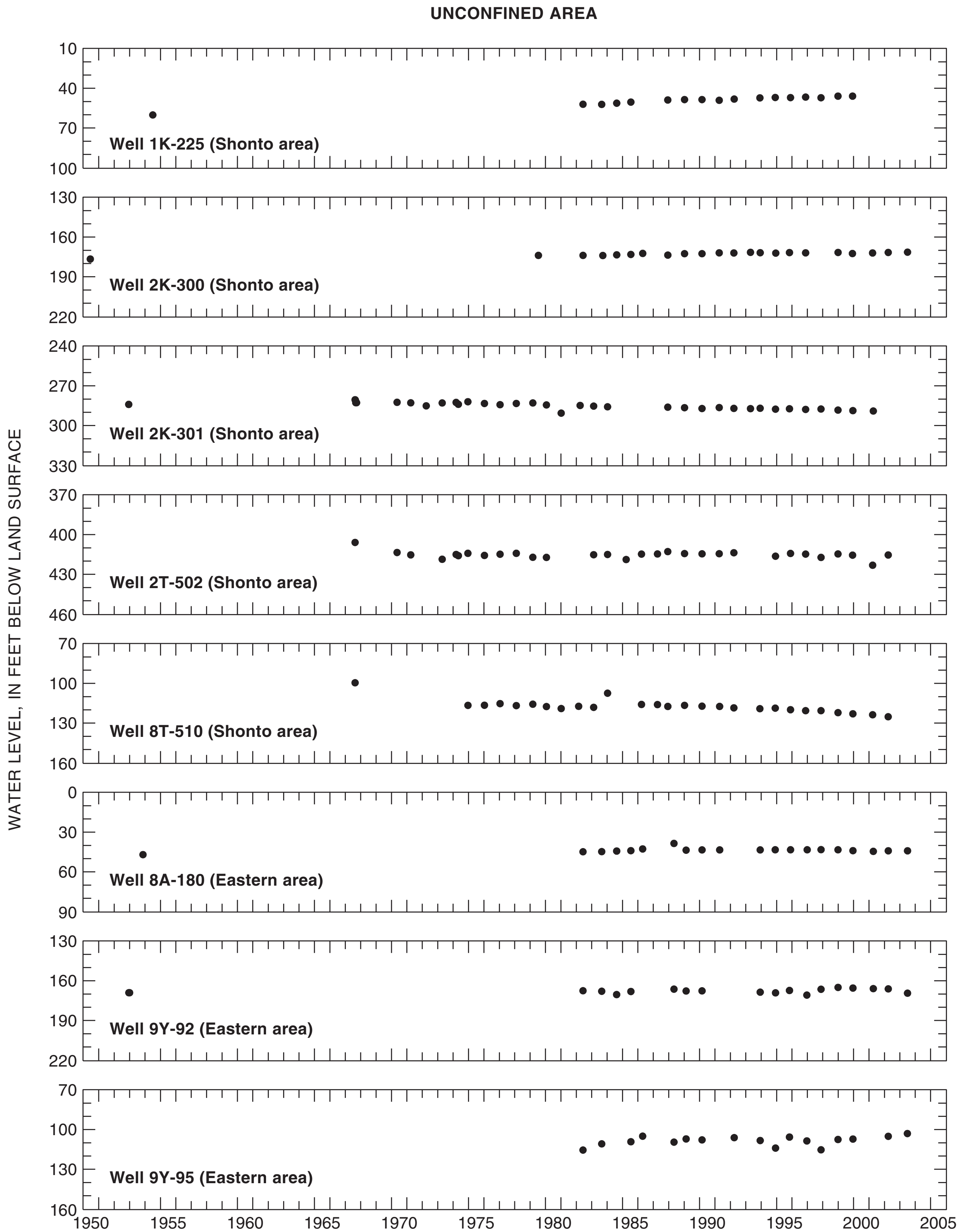


Figure 7. Continued.

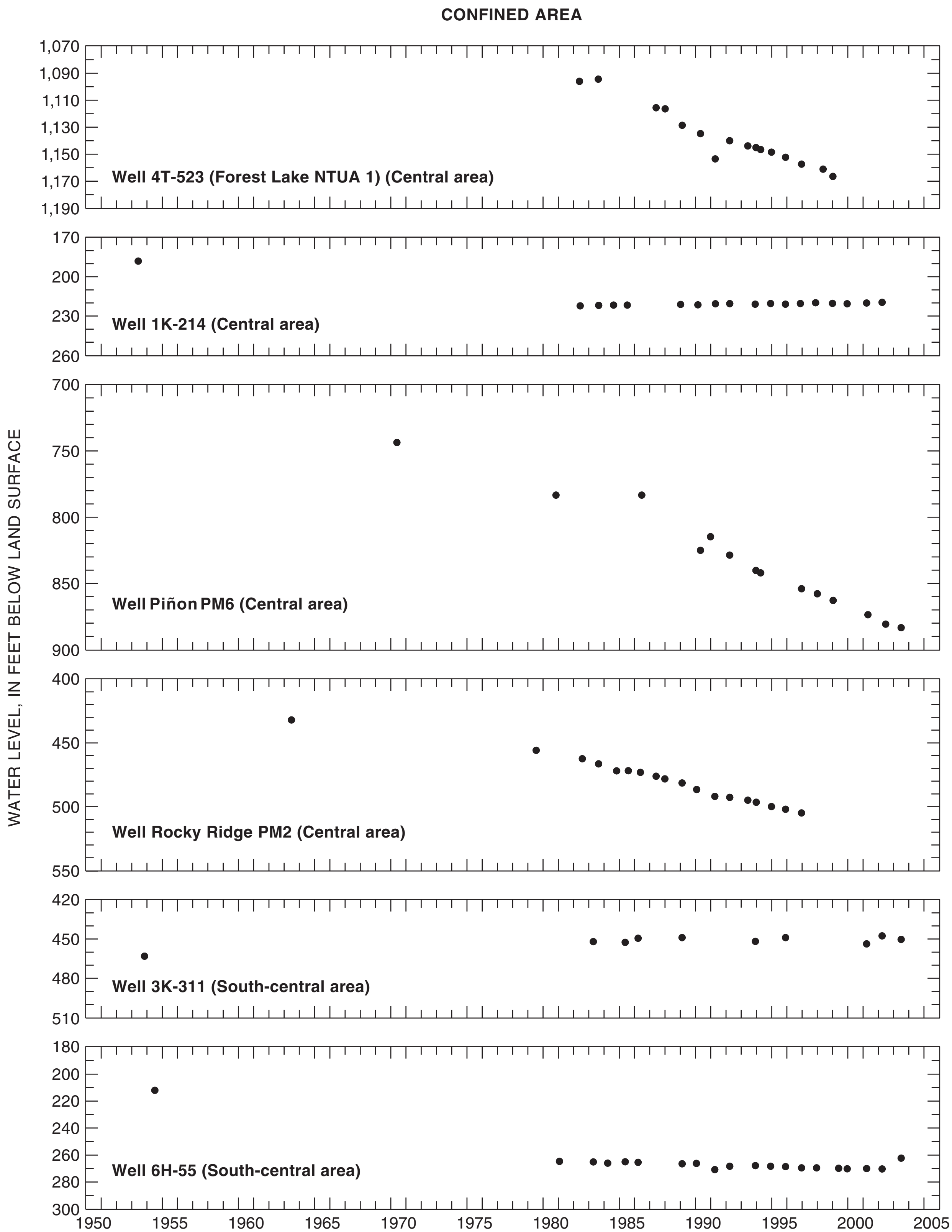


Figure 7. Continued.

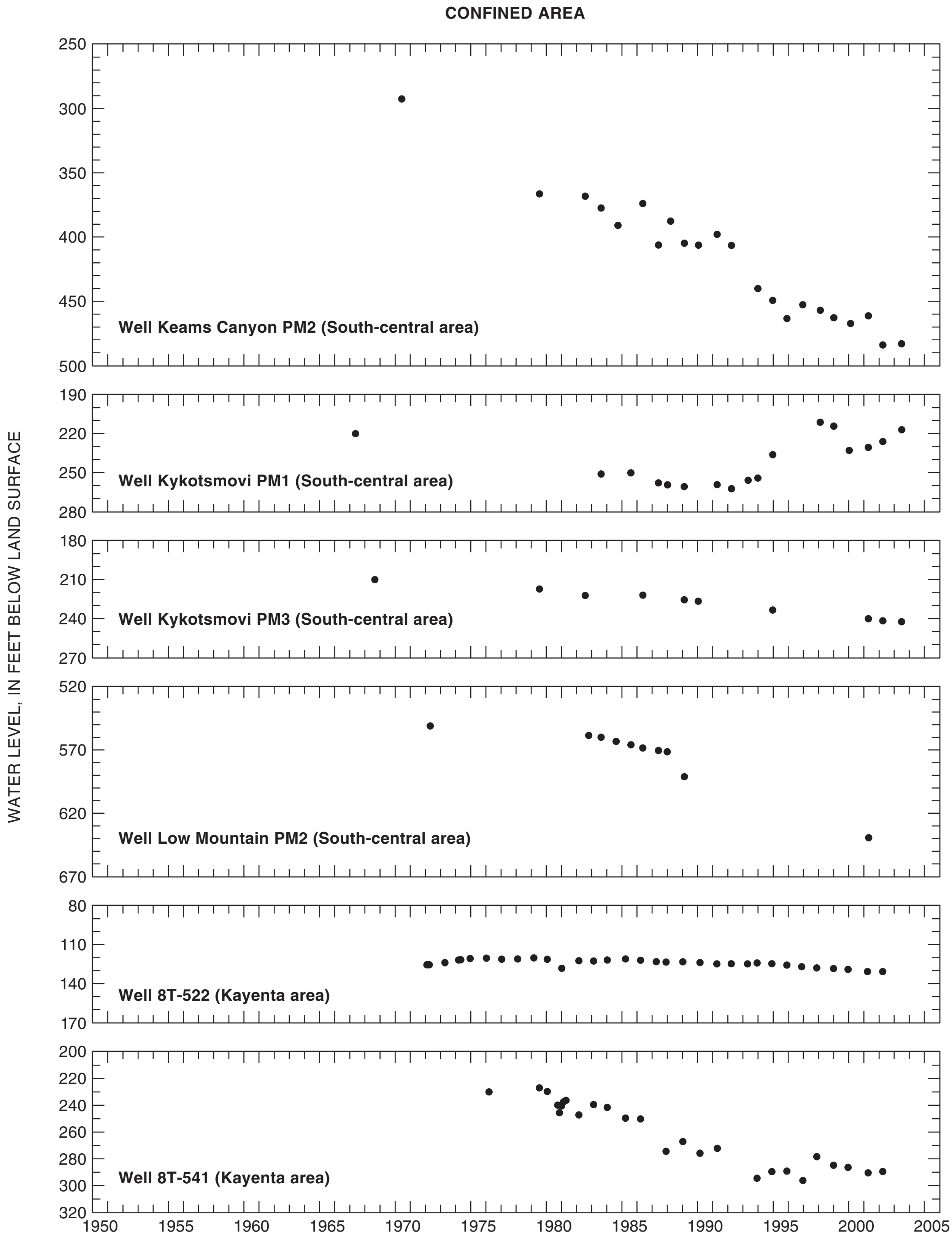


Figure 7. Continued.

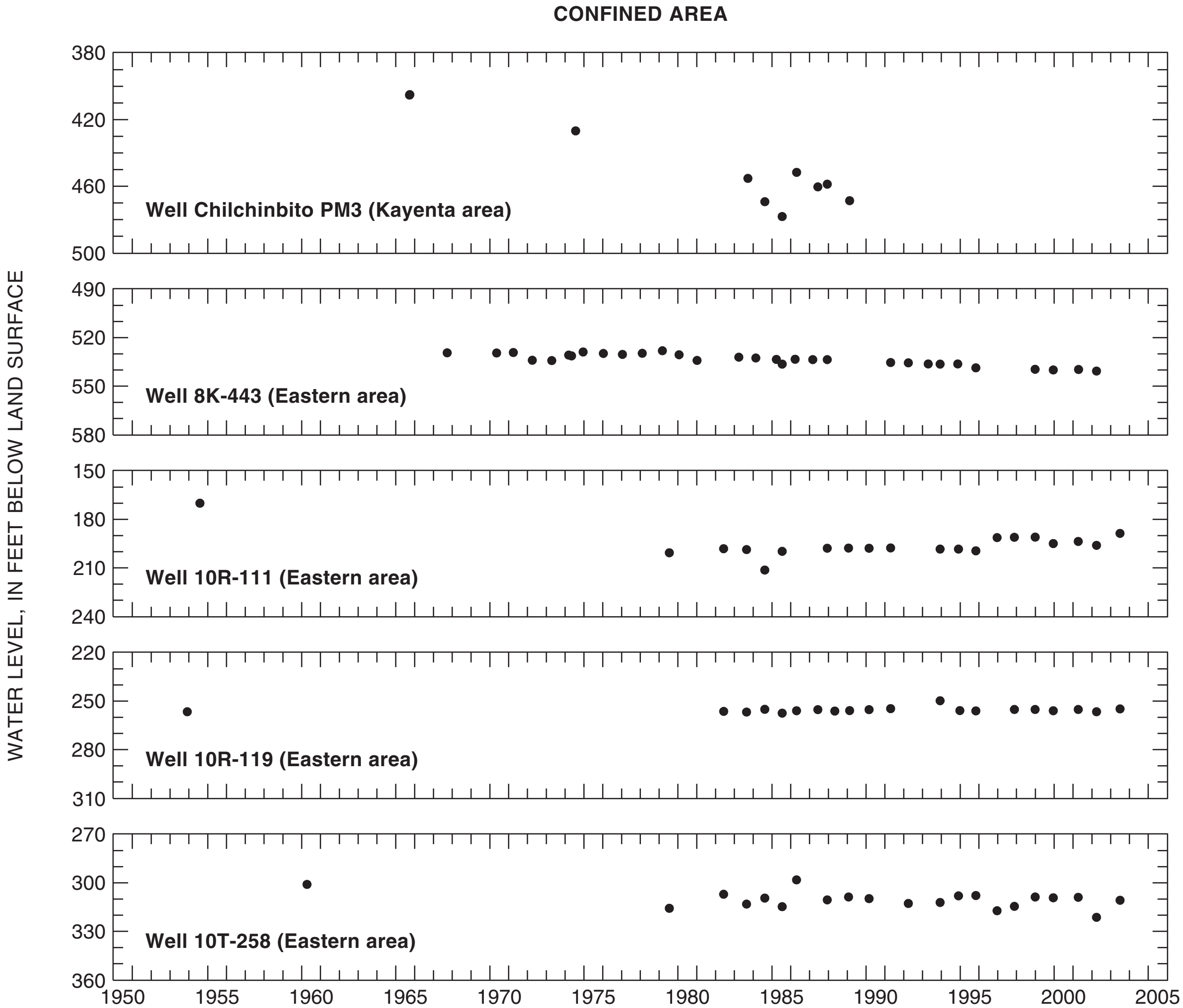


Figure 7. Continued.

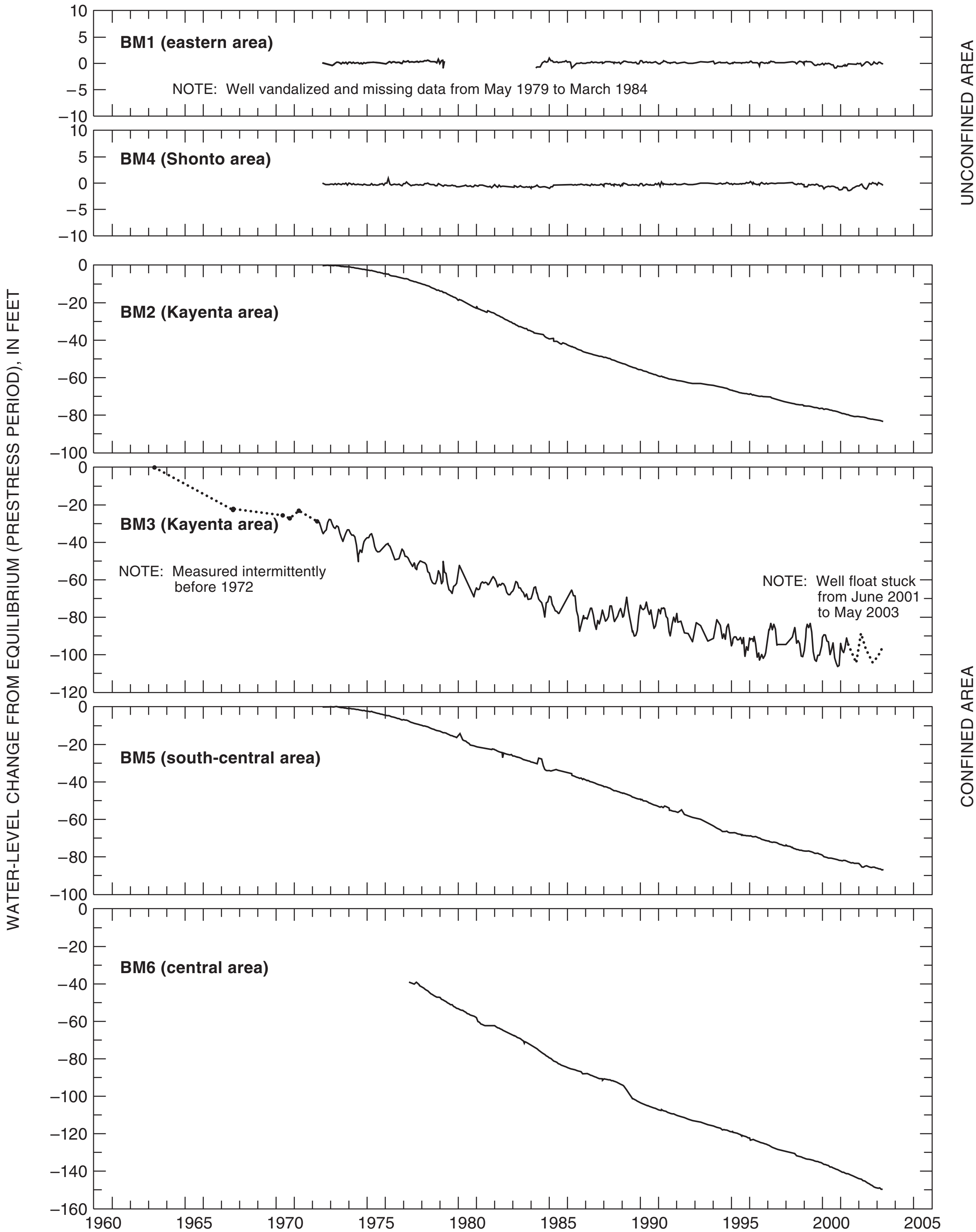


Figure 8. Observed water-level changes in continuous-record observation wells, BM1–BM6, 1963–2003, Black Mesa area, Arizona.

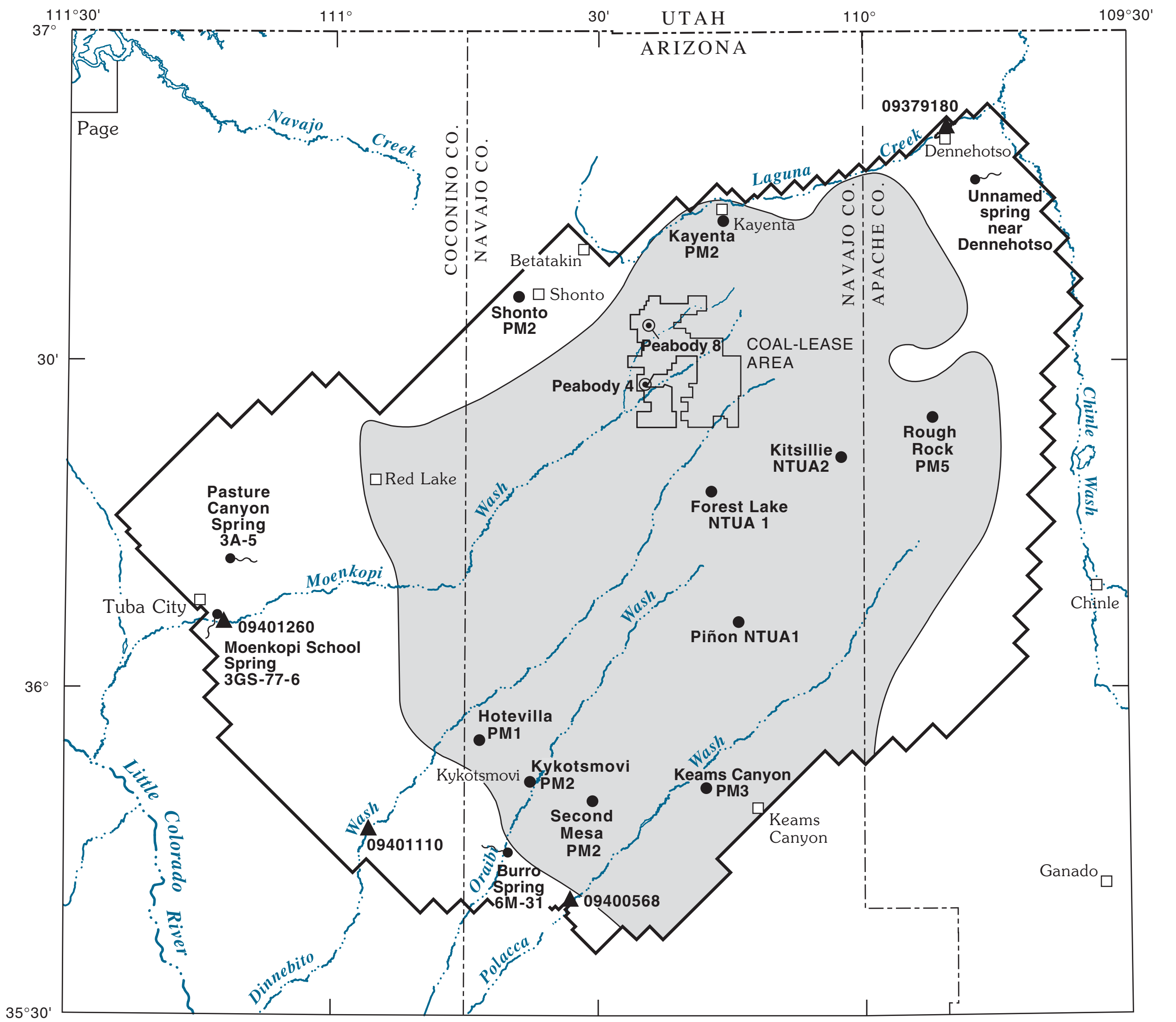
Table 8. Discharge measurements of selected springs, Black Mesa area, Arizona, 1952–2003

[All the 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
Burro Spring			
6M-31	Navajo Sandstone	12–15–89	0.4
		12–13–90	0.4
		03–18–93	0.3
		12–08–94	0.2
		12–17–96	0.4
		12–30–97	0.2
		12–08–98	0.3
		12–07–99	0.3
		04–02–01	0.2
		04–04–02	0.4
		04–30–03	0.4
Unnamed spring near Dennehotso			
8A-224	Navajo Sandstone	10–06–54	[3]1
		06–27–84	[3]2
		11–17–87	[3]5
		03–26–92	16
		10–22–93	14.4
		12–05–95	17
		12–19–96	15.7
		12–31–97	25.6
		12–14–98	21.0
		12–15–99	14.8
		03–14–01	26.8
		07–15–02	9.0
		05–01–03	17.1

Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Moenkopi School Spring			
3GS-77-6	Navajo Sandstone[1]	05–16–52	40
		04–22–87	[2]16
		11–29–88	[2]12.5
		02–21–91	[2]13.5
		04–07–93	[2]14.6
		12–07–94	[2]12.9
		12–04–95	[2]12.1
		12-16-96	[2]10
		12–17–97	[2]13.1
		12–08–98	[2]12.0
		12–13–99	[2]13.3
		03–12–01	[2]13.7
		06–19–02	[2]10.2
		05–01–03	[2]11.2
Pasture Canyon Spring			
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
		12–16–96	[5]38
		12–17–97	[5]40
		12–10–98	[5]39
		12–21–99	[5]39.0
		06–12–01	[5]37.0
		06–19–02	[5]37.0
		05–01–03	[5]30.9

[1]Tongue in the Kayenta Formation.
[2]Discharge measured at water-quality sampling site and at a different point than the measurement in 1952.
[3]Discharge measured at a different point than later measurements.
[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.



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

0 25 MILES
0 25 KILOMETERS

EXPLANATION

CONFINED AND UNCONFINED CONDITIONS IN THE N AQUIFER

Confined

Unconfined

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

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

Rough Rock PM5 — MUNICIPAL WELL FROM WHICH WATER-CHEMISTRY SAMPLE WAS COLLECTED—Rough Rock PM5 is well name

Peabody 8 — INDUSTRIAL WELL FROM WHICH WATER-CHEMISTRY SAMPLE WAS COLLECTED—Peabody 8 is well number

Burro Spring 6M-31 — SPRING AT WHICH DISCHARGE WAS MEASURED AND WATER-CHEMISTRY SAMPLE WAS COLLECTED—Number is spring identification

09401260 — STREAMFLOW-GAGING STATION OPERATED BY THE U.S. GEOLOGICAL SURVEY—Number is station identification

Figure 9. Surface-water and water-chemistry data-collection sites, Black Mesa area, Arizona, 2002–03.

In 2003, measured discharges were 0.4 gal/min from Burro Spring, 17.1 gal/min from the unnamed spring near Dennehotso, 11.2 gal/min from Moenkopi School Spring, and 30.9 gal/min from Pasture Canyon Spring. Compared with discharges measured in 2002, discharges stayed the same for Burro Spring, increased by 90 percent for the unnamed spring near Dennehotso, increased by 10 percent for Moenkopi School Spring, and decreased by 16 percent for Pasture Canyon Spring.

Long-term changes in spring discharge can be evaluated for the entire record at Burro Spring but can be evaluated only for parts of the records for the other three springs because discharge measuring points changed during the periods of record. Consistent measuring points are available for 1992–2003 at the unnamed spring near Dennehotso, for 1987–2003 at Moenkopi School Spring, and for 1995–2003 at Pasture Canyon Spring (**table 8**). For the consistent periods of record at all four springs, the discharges have fluctuated; however, increasing or decreasing trends are not apparent (fig. 10).

Surface-Water Discharge

Surface-water discharge in the study area includes ground-water discharge and direct or shallow subsurface runoff of rainfall or snowmelt. Ground water discharges to surface water at a fairly constant rate throughout the year. 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 is a result of the temporal variation in snow accumulation, air temperatures, and rate of snowmelt. Although most rainfall runoff is in the summer, rainfall can result in surface-water runoff throughout the year. The amount and timing of rainfall runoff depend on the intensity and duration of thunderstorms in the summer and cyclonic storms in the fall, winter, and spring.

Continuous surface-water discharge data have been collected at selected streams each year since the monitoring program began in 1971 to provide information about ground-water discharge and about runoff from rainfall and snowmelt. In this study, the total discharge in streams is roughly separated into ground-water discharge and runoff so that the temporal trends in ground-water discharge can be monitored.

In 2002, continuous discharge data were collected at four streamflow-gaging stations (tables 9–12). Data collection began at the gaging stations July 1976 for Moenkopi Wash, July 1996 for Laguna Creek, June 1993 for Dinnebito Wash, and April 1994 for Polacca Wash (**fig. 9** and **table 13**).

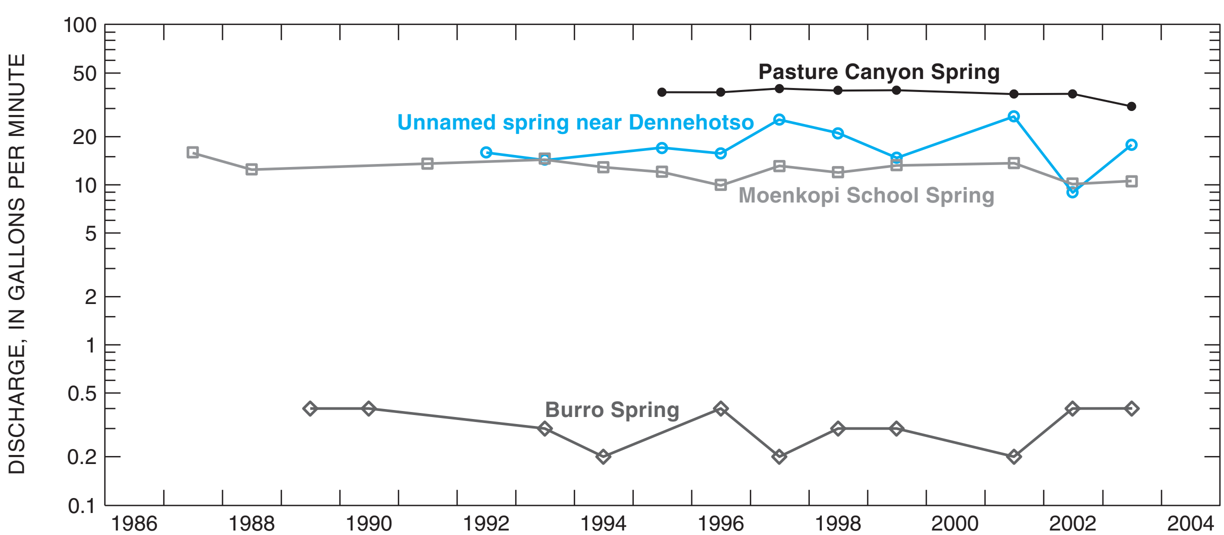


Figure 10. Discharge from selected springs, Black Mesa area, Arizona, 1987–2003.

Table 9. Discharge data, Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2002

[dashes indicate no data. AC-FT, acre-feet]

Discharge, in cubic feet per second, calendar year 2002 Daily mean values												
Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.[1]	Nov.[1]	Dec.[1]
1	2.7	[2]1.0	[2]2.2	[2]2.1	2.4	0.0	0.0	0.0	0.86	1.2	1.8	6.2
2	2.2	[2]1.7	2.2	2.2	2.0	.0	.0	.0	.41	1.2	1.6	3.3
3	2.1	[2]2.0	[2]2.2	2.2	1.9	.0	.0	.0	.02	1.3	1.8	2.7
4	2.1	[2]2.0	[2]2.2	2.2	1.7	.0	.0	.0	.0	1.3	1.7	2.8
5	2.0	[2]2.0	2.5	2.2	1.3	.0	.0	.0	.0	1.2	1.7	2.6
6	2.2	[2]1.8	2.7	2.3	1.3	.0	.0	.0	.0	1.1	1.5	2.6
7	2.1	[2]1.9	2.9	2.6	1.2	.0	.0	.0	676	1.2	1.4	2.7
8	2.0	[2]2.0	2.6	2.2	[2]1.0	.0	.0	.0	[2]1,800	1.2	1.3	2.7
9	[2]2.0	[2]2.0	2.9	2.2	[2].80	.0	.0	.0	[2]170	1.8	1.5	2.5
10	[2]2.0	[2]2.3	[2]3.0	2.2	.73	.0	.0	.0	46	1.7	27	2.5
11	[2]2.0	2.2	[2]3.0	2.2	.55	.0	.0	.0	840	1.5	14	2.6
12	[2]2.0	2.3	[2]3.0	2.2	.48	.0	.0	.0	72	1.3	3.3	2.6
13	[2]2.0	[2]2.2	[2]2.9	2.2	.39	.0	.0	.0	71	1.4	2.8	2.7
14	[2]2.0	[2]2.4	[2]2.9	2.1	.40	.0	.0	.0	16	1.4	2.9	3.0
15	[2]1.4	2.3	2.8	2.2	.30	.0	.0	.0	5.9	1.3	3.0	3.1
16	[2]1.2	2.5	2.7	2.2	.14	.0	.35	.0	3.4	1.2	2.5	2.7
17	[2]1.4	[2]2.4	2.6	2.0	[2].14	.0	[2].10	.0	2.6	1.2	2.6	2.8
18	[2]2.3	2.5	2.9	1.8	[2].14	.0	.0	.0	2.0	1.2	2.6	3.0
19	[2].90	2.6	2.9	1.8	[2].14	.0	.0	.0	1.9	1.3	2.6	3.2
20	[2]1.2	2.8	2.8	1.9	[2].13	.0	.0	.0	1.8	1.5	2.5	3.5
21	[2]2.2	2.9	2.9	2.0	[2].13	.0	.0	.0	1.6	1.5	2.5	4.0
22	[2]2.2	2.8	3.0	2.2	[2].13	.0	.0	.0	1.4	1.4	2.4	5.4
23	[2]2.3	2.8	2.7	2.1	.06	.0	.0	.0	1.3	1.6	2.4	6.3
24	[2]1.3	3.0	[2]3.0	2.1	.04	.0	.0	.0	1.3	1.5	2.4	4.8
25	[2]1.1	2.7	3.0	1.9	.04	.0	38	.0	1.3	1.6	2.3	4.9
26	[2]2.0	2.8	2.5	1.9	.03	.0	12	.0	1.2	1.5	2.2	5.1
27	[2]2.1	2.3	2.2	1.8	.04	.0	51	.0	1.2	1.5	2.1	6.0
28	[2]2.0	2.2	[2]2.2	1.8	.04	.0	18	.0	1.2	1.4	1.9	6.1
29	[2]1.9	---	2.2	1.8	.03	.0	1.2	.0	1.2	1.4	2.3	7.4
30	[2]1.6	---	[2]2.2	2.0	.01	.0	.06	144	1.2	1.3	2.6	8.7
31	[2]1.0	---	[2]2.2	---	.01	---	.01	5.5	---	1.4	---	9.0
TOTAL	57.50	64.4	82.0	62.6	17.70	.0	120.72	149.50	3,722.79	42.6	103.2	127.5
MEAN	1.85	2.30	2.65	2.09	.57	.0	3.89	4.82	124	1.37	3.44	4.11
MAX	2.7	3.0	3.0	2.6	2.4	.0	51	144	1,800	1.8	27	9.0
MIN	.90	1.0	2.2	1.8	.01	.0	.0	.0	.0	1.1	1.3	2.5
AC-FT	114	128	163	124	35	.0	239	297	7,380	84	205	253
CALENDAR YEAR 2002		TOTAL 4,550.51		MEAN 12.5			MAXIMUM 1,800		MINIMUM 0.0		AC-FT 9,028	

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 10. Discharge data, Laguna Creek at Dennehotso, Arizona (09379180), calendar year 2002

[dashes indicate no data. AC-FT, acre-feet]

Discharge, in cubic feet per second, calendar year 2002 Daily mean values												
Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.[1]	Nov.[1]	Dec.[1]
1	[2]1.6	[2]1.8	3.7	[2]1.5	0.0	0.0	0.0	0.0	0.0	.0	8.7	7.0
2	[2]1.7	[2]1.4	[2]3.0	.87	.0	.0	.0	.0	.0	.0	2.8	6.7
3	[2]1.8	[2]1.1	1.2	.71	.0	.0	.0	.0	.0	1.5	.81	5.4
4	[2]2.8	[2]1.1	.62	.59	.0	.0	.0	.0	.0	12	.59	3.6
5	[2]3.2	[2]1.1	1.8	1.6	.0	.0	.0	.0	.0	2.2	.73	4.8
6	[2]3.2	[2]1.1	2.7	1.1	.0	.0	.0	.0	1.7	.26	.40	3.5
7	[2]2.8	[2]1.2	[2]4.4	1.0	.0	.0	.0	.0	309	.03	.43	.42
8	[2]2.5	[2]1.3	3.5	.95	.0	.0	.0	.0	[2]371	.0	.80	2.3
9	[2]3.2	[2]1.4	1.7	2.2	.0	.0	.0	.0	132	.0	.91	1.9
10	[2]3.1	[2]1.9	2.3	2.2	.0	.0	.0	.0	7.5	.0	27	1.8
11	[2]2.7	[2]2.6	3.6	.45	.0	.0	.0	.0	544	.0	25	3.2
12	[2]2.7	[2]2.6	2.9	.32	.0	.0	.0	.0	253	.0	8.2	1.1
13	[2]3.1	[2]2.8	2.4	.0	.0	.0	.0	.0	16	.0	2.5	1.0
14	[2]3.3	[2]3.9	1.0	.0	.0	.0	.0	.0	4.6	.0	1.3	.37
15	[2]3.1	[2]3.8	.75	.0	.0	.0	.0	.0	.56	.0	1.2	1.7
16	[2]4.5	[2]4.8	.53	.0	.0	.0	.0	.0	.02	.0	1.0	8.5
17	[2]2.4	9.5	.18	.0	.0	.0	.0	.0	.0	.0	.27	5.3
18	[2]1.4	[2]10	.67	4.2	.0	.0	.0	.0	.0	.0	.70	2.3
19	[2]1.1	8.2	.72	3.1	.0	.0	.0	.0	.0	.0	1.2	.62
20	[2]1.4	6.2	[2]3.6	.54	.0	.0	.0	.0	.0	.0	1.4	1.7
21	[2]1.7	[2]7.8	[2]4.8	.51	.0	.0	.0	.0	.0	.0	1.2	2.7
22	[2]1.8	6.8	[2]4.9	.25	.0	.0	.0	.0	.0	.0	1.7	.98
23	[2]2.0	5.5	[2]4.6	.0	.0	.0	.0	.0	.0	.0	.38	2.4
24	1.3	5.8	[2]4.2	.0	.0	.0	.0	.0	.0	.0	2.4	3.8
25	.81	3.7	3.8	.0	.0	.0	.0	.0	.0	.29	1.7	.04
26	.86	2.7	3.0	.0	.0	.0	.0	.0	.0	.31	1.0	.0
27	1.9	2.4	[2]2.6	.0	.0	.0	.0	.0	.0	22	.52	.0
28	3.6	[2]1.9	[2]3.7	.0	.0	.0	.0	.0	.0	8.2	.43	.0
29	[2]4.2	---	[2]3.6	.0	.0	.0	.0	.01	.0	4.6	.53	.0
30	[2]2.4	---	[2]2.9	.0	.0	.0	.0	.0	.0	14	3.6	.0
31	[2]2.3	---	[2]2.1	---	.0	---	.0	.0	---	12	---	.0
TOTAL	148	207	162	44	.0	.0	.0	.02	3,250	154	197	145
MEAN	2.40	3.73	2.63	.74	.0	.0	.0	.0	54.6	2.50	3.31	2.36
MAX	4.5	10	4.9	4.2	.0	.0	.0	.01	544	22	27	8.5
MIN	.81	1.1	.18	.0	.0	.0	.0	.0	.0	.0	.27	.0
AC-FT	.01	.01	.01	.0	.0	.0	.0	.0	.13	.01	.01	.01
CALENDAR YEAR 2002			TOTAL 2,171.74		MEAN 6.0		MAXIMUM 544		MINIMUM 0.0		AC-FT 4,308	

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 11. Discharge data, Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2002

[dashes indicate no data. AC-FT, acre-feet]

Discharge, in cubic feet per second, calendar year 2002 Daily mean values												
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.[1]**	**Nov.[1]**	**Dec.[1]**
1	[2]0.23	0.14	0.36	0.40	0.34	0.17	0.08	0.08	4.7	0.06	0.13	0.27
2	[2].23	.19	.30	.39	.33	.16	.07	.07	.34	.06	.14	.21
3	.24	.20	.23	.38	.33	.17	.07	.09	.14	.06	.14	.21
4	.30	.22	.29	.40	.32	.17	.09	.09	.12	.06	.14	.22
5	.23	.22	.38	.39	.34	.17	.09	.09	.10	.06	.20	.21
6	.24	.20	.43	.54	.32	.17	.07	.08	.10	.06	.16	.21
7	.25	.21	.41	.73	.31	.16	.07	.09	525	.16	.15	.22
8	.27	.27	.38	.47	.30	.14	.07	.08	211	.10	.14	.22
9	.27	.24	.35	.40	.30	.12	.08	.08	63	.09	.14	.21
10	.26	.22	.39	.40	.27	.13	.10	.08	4.2	.09	.14	.22
11	.22	.23	.40	.41	.26	.14	.11	.07	[2]33	.10	.14	.21
12	.22	.27	.38	.39	.28	.15	.09	.07	[2]5.3	.10	.15	.21
13	.21	.26	.38	.39	.29	.13	.07	.07	[2].50	.10	.17	.21
14	.21	.29	.36	.38	.27	.13	.06	.06	[2].30	.10	.18	.22
15	.23	.28	.37	.35	.25	.11	.06	.06	[2].30	.11	.18	.25
16	.21	.30	.37	.36	.24	.11	8.7	.05	[2].20	.11	.18	.23
17	.18	.31	.39	.34	.24	.11	.44	.06	[2].20	.13	.19	.24
18	.18	.29	.41	.32	.23	.10	.15	.06	[2].20	.12	.19	.24
19	.15	.29	.39	.32	.23	.10	.12	.06	[2]1.0	.11	.18	.19
20	.16	.33	.39	.32	.23	.09	.15	.07	[2].40	.12	.19	.19
21	.17	.32	.41	.34	.21	.09	.10	.07	[2].23	.11	.19	.20
22	.21	.31	.40	.37	.23	.09	.08	.07	[2].16	.11	.19	.19
23	.21	.35	.36	.37	.24	.09	.07	.05	[2].14	.13	.20	.22
24	.14	.34	.41	.37	.24	.08	31	.07	[2].10	.12	.20	.24
25	.14	.32	.44	.37	.24	.10	7.6	.08	[2].10	.12	.20	.20
26	.18	.33	.42	.34	.24	.09	.50	.08	[2].10	.13	.20	.16
27	.25	.31	.41	.34	.25	.10	6.4	.07	[2].10	.14	.19	.17
28	.24	.38	.41	.36	.23	.08	1.0	.06	[2].08	.13	.20	.15
29	.21	---	.41	.36	.22	.08	.14	.06	[2].07	.13	.21	.18
30	.20	---	.39	.29	.20	.08	.11	54	[2].07	.13	.40	.20
31	.15	---	.39	---	.19	---	.09	23	---	.13	---	.20
TOTAL	6.59	7.62	11.81	11.59	8.17	3.61	57.83	79.07	851.25	3.28	5.41	6.50
MEAN	.21	.27	.38	.39	.26	.12	1.87	2.55	28.4	.11	.18	.21
MAX	.30	.38	.44	.73	.34	.17	31	54	525	.16	.40	.27
MIN	.14	.14	.23	.29	.19	.08	.06	.05	.07	.06	.13	.15
AC-FT	13	15	23	23	16	7.2	115	157	1,690	6.5	11	13
CALENDAR YEAR 2002			TOTAL 1,052.73		MEAN 2.9		MAXIMUM 525		MINIMUM 0.05		AC-FT 2,085	

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 12. Discharge data, Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2002

[Dashes indicate no data. AC-FT, acre-feet]

Discharge, in cubic feet per second, calendar year 2002 Daily mean values												
Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.[1]	Nov.[1]	Dec.[1]
1	0.19	0.08	0.08	0.07	0.06	0.02	0.0	0.0	0.0	0.03	0.07	0.11
2	.14	.12	.06	.07	.06	.01	.0	.0	.0	.03	.08	.10
3	.13	.10	.05	.07	.06	.02	.0	.0	.0	.05	.07	.11
4	.13	.12	.07	.08	.06	.02	.0	.0	.0	.04	.07	.10
5	.11	.10	.07	.08	.06	.02	.0	.0	.0	.04	.08	.10
6	.11	.09	.08	.20	.06	.02	.0	.0	.0	.04	.08	.10
7	.13	.10	.08	.22	.06	.03	.0	.0	.13	.04	.08	.10
8	.13	.11	.07	.10	.05	.02	.0	.0	88	.04	.08	.10
9	.14	.09	.06	.09	.05	.0	.0	.0	70	.05	.09	.10
10	.13	.09	.08	.09	.05	.0	.0	.0	21	.05	.09	.10
11	.11	.10	.08	.10	.03	.0	.0	.0	138	.04	.08	.10
12	.11	.11	.08	.10	.03	.0	.0	.0	180	.05	.08	.09
13	.11	.09	.08	.10	.05	.01	.0	.0	67	.05	.09	.09
14	.10	.11	.06	.10	.05	.01	.0	.0	.30	.05	.09	.10
15	.12	.11	.07	.11	.04	.01	.04	.0	.07	.05	.09	.10
16	.13	.11	.07	.09	.04	.0	.14	.0	.01	.05	.09	.10
17	.10	.10	.07	.09	.05	.0	.01	.0	.01	.05	.09	.10
18	.09	.10	.08	.07	.04	.0	.0	.0	.01	.07	.09	.10
19	.06	.10	.07	.07	.03	.0	.0	.0	.01	.06	.10	.09
20	.11	.10	.07	.07	.03	.0	.0	.0	.02	.06	.10	.08
21	.10	.10	.08	.08	.02	.0	.0	.0	.02	.06	.10	.10
22	.13	.09	.07	.08	.03	.0	.0	.0	.02	.06	.10	.09
23	.12	.09	.07	.08	.03	.0	121	.0	.03	.08	.10	.11
24	.05	.09	.07	.08	.03	.0	59	.0	.03	.07	.09	.12
25	.11	.09	.08	.08	.03	.0	11	.0	.03	.07	.10	.08
26	.13	.08	.07	.07	.04	.0	.52	.0	.02	.06	.10	.08
27	.15	.08	.07	.06	.05	.0	.0	.0	.02	.07	.10	.06
28	.13	.08	.07	.07	.04	.0	.0	.0	.03	.07	.09	.03
29	.11	---	.07	.07	.04	.0	.0	.0	.03	.07	.10	.06
30	.11	---	.07	.07	.03	.0	.0	.0	.03	.07	.12	.11
31	.07	---	.07	---	.03	---	.0	.0	---	.07	---	.11
TOTAL	3.59	2.73	2.22	2.71	1.33	.19	191.71	.0	564.82	1.69	2.69	2.92
MEAN	.12	.098	.072	.090	.043	.06	6.18	.00	18.8	.055	.090	.094
MAX	.19	.12	.08	.22	.06	.03	121	.0	180	.08	.12	.12
MIN	.05	.08	.05	.06	.02	.0	.0	.0	.0	.03	.07	.03
AC-FT	7.1	5.4	4.4	5.4	2.6	.4	380	.0	1120	3.4	5.3	5.8
CALENDAR YEAR 2002			TOTAL 776.60		MEAN 2.1		MAXIMUM 180		MINIMUM 0.0		AC-FT 1,542	

[1]Month in which data are provisional, subject to revision.

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

Station name	Station number	Date data collection began	Drainage area, in square miles
Moenkopi Wash at Moenkopi	09401260	July 1976	1,629
Laguna Creek at Dennehotso	09379180	July 1996	414
Dinnebito Wash near Sand Springs	09401110	June 1993	473
Polacca Wash near Second Mesa	09400568	April 1994	905

The annual average discharges at the four gaging stations vary considerably during their periods of record (**fig. 11**). The discharges in Moenkopi Wash appear to have become more variable during the last 13 years with no long-term trend, discharges in Laguna Creek decreased for 3 years and increased during the last 2 years, and discharges in Dinnebito Wash and Polacca Wash have been variable with no trend during the last 7 years.

The ground-water discharge component of total flow at the four streamflow-gaging stations was estimated by computing the median flow for four winter months—November, December, January, and February. Ground-water discharge is assumed to be constant throughout the entire year, and the median winter flow is assumed to represent this constant annual ground-water discharge. Most flow during the winter is ground-water discharge because rainfall and snowmelt runoff are minimal. Most of the precipitation in the winter falls as snow, and the cold temperatures prevent appreciable snowmelt. Also, evapotranspiration from streams is at a minimum during the winter. During the summer, much of the flow in streams evaporates or is transpired by plants. The median flow for November, December, January, and February, rather than the average flow, is used to estimate ground-water discharge because the median is less affected by occasional winter runoff. The 120 consecutive daily mean flows for those four months were used to compute the median flow.

The median flow for November, December, January, and February is an index of ground-water discharge rather than an absolute estimate of discharge. A more rigorous and accurate estimate would include 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 ground water in the N aquifer with ground water 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 ground-water discharge.

Median winter flows were calculated for the 2002 water year; thus, daily mean flows for November and December 2001 (Thomas, 2002) were combined with daily mean flows for January and February 2002. These median winter flows were 2.05 ft^3/s for Moenkopi Wash, 1.95 ft^3/s for Laguna Creek, 0.24 ft^3/s for Dinnebito Wash, and 0.10 ft^3/s for Polacca Wash. Since 1995, the median flows for Moenkopi Wash, Dinnebito Wash, and Polacca Wash have generally decreased (fig. 11). Median flows for Laguna Creek are only available since 1997, and there is no consistent trend in these flows. Annual precipitation at Betatakin, about 15 miles west of Kayenta, has been less than average for 6 of the 8 years since 1995 (fig. 11).

Water Chemistry

Water samples are collected from selected wells and springs each year of the Black Mesa monitoring program. Field measurements are made and water samples are analyzed for major ions, nutrients, iron, boron, and arsenic. During the past 11 years, water samples have been collected from about 30 different wells and 10 different springs. Samples are collected from about 12 wells and 4 springs in each year of the program. Samples are collected from about the same 8 wells every year and from the other 4 wells on a rotational basis. Since 1996, samples have been collected from the same 4 springs. Long-term data for specific conductance, total dissolved solids, chloride, and sulfate for the wells and springs sampled each year are shown in the report published for that year. Historical data for other constituents for all the wells and springs are available from the USGS water-quality database (**http://waterdata.usgs.gov/az/nwis/qw**) or can be found in the past monitoring reports that are cited in the section entitled "**Previous Investigations**."

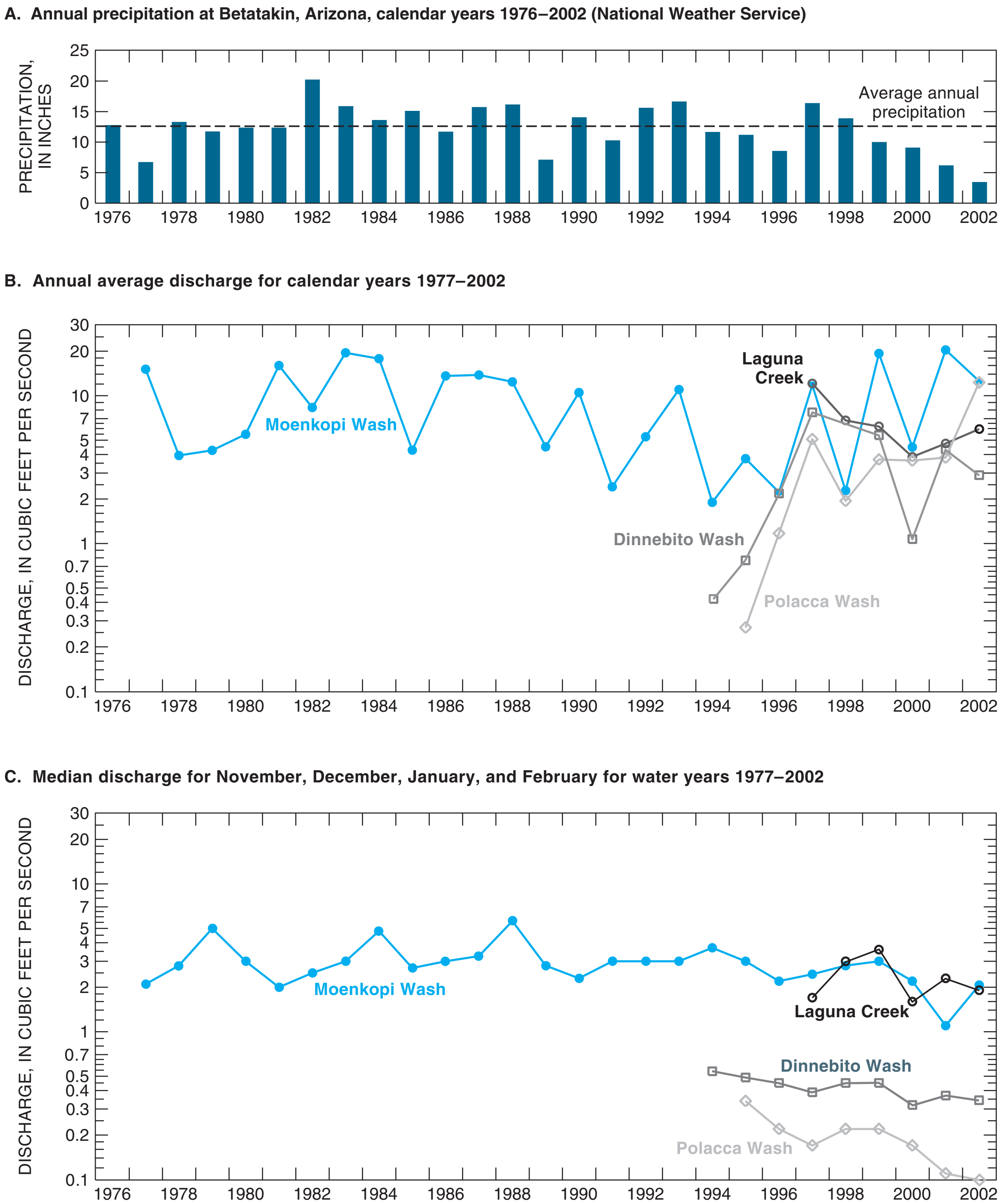


Figure 11. Annual precipitation at Betatakin, Arizona, and streamflow characteristics at Moenkopi Wash (09401260), Laguna Creek (09379180), Dinnebito Wash (09401110), and Polacca Wash (09400568), Black Mesa area, Arizona. *A*, Annual precipitation at Betatakin, Arizona, calendar years 1976–2002 (National Weather Service). *B*, Annual average discharge for calendar years 1977–2002. *C*, Median discharge for November, December, January, and February for water years 1977–2002.

Water from Wells Completed in the N Aquifer

In 2003, water samples were collected from 12 wells completed in the N aquifer. Eleven of the wells are in the confined part of the aquifer, and one well (Shonto PM2) is in an unconfined part of the aquifer (**fig. 9**). The primary types of water in the N aquifer are calcium bicarbonate and sodium bicarbonate. Calcium bicarbonate water generally is in the recharge areas of the northern and northwestern parts of the Black Mesa area, and sodium bicarbonate water is in the area that is downgradient to the south and east (Thomas, 2002). In 2003, water samples from Kayenta PM2 and from Shonto PM2 in the north were calcium bicarbonate water, and samples from the other 10 wells were sodium bicarbonate water (**fig. 12**). Dissolved-solids concentrations in water from the 12 wells ranged from 144 mg/L at Peabody 4 to 642 mg/L at Rough Rock PM5 (**table 14** and fig. 12).

Two wells had appreciably higher concentrations of dissolved solids than the other 10 wells; Keams Canyon PM3 had a concentration of 521 mg/L, and Rough Rock PM5 had a concentration of 642 mg/L. Concentrations of dissolved solids in water samples from the other 10 wells ranged from 144 to 421 mg/L, and concentrations of chloride ranged from 1.6 to 20 mg/L. The areal distribution of dissolved solids generally was similar to the distribution of water types. Lower concentrations of dissolved solids are in or near the recharge areas in the northern and northwestern parts of the study area, and higher concentrations of dissolved solids are in areas to the south and east (fig. 12).

There are no appreciable time trends in the chemistry of water samples from 7 wells having more than 8 years of data (**table 15** and **fig. 13**). Water-chemistry data from these wells are available for various periods. In the 7 wells, there are small year-to-year variations in concentrations of dissolved solids, chloride, and sulfate; however, increasing or decreasing trends are not apparent. There may be an increasing trend in dissolved-solids and chloride concentrations in samples from Shonto PM2; however, additional data are needed to confirm this trend (table 15). The chemistry of water samples from the Forest Lake NTUA 1 well has varied considerably between 1982 and 2003 (table 15 and fig. 13), but the cause of this variation is unknown.

Constituents analyzed from the 12 well samples were compared to U.S. Environmental Protection Agency (USEPA) Primary and Secondary Drinking-Water Regulations (U.S. Environmental Protection Agency, 2002). 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 SMCLs for public water systems; however, compliance with SMCLs is not mandatory.

The concentrations of most of the analyzed constituents from the 12 well samples were below MCLs and SMCLs. The pH level, however, exceeded the SMCL maximum pH of 8.5 units in samples from 9 of the 12 wells (table 14). The dissolved-solids SMCL of 500 mg/L was exceeded in the samples from Rough Rock PM5 (642 mg/L) and Keams Canyon PM3 (521 mg/L). Samples from three wells had arsenic concentrations that exceeded the MCL of 10 μg/L. Arsenic concentrations were 34 μg/L in the sample from Keams Canyon PM3, 49 μg/L in the sample from Rough Rock PM5, and 16 μg/L in the sample from Second Mesa PM2.

Water from Springs that Discharge from the N Aquifer

In 2003, water samples were collected from four springs in the study area. Burro Spring is in the southern part of the study area, the unnamed spring near Dennehotso is in the northeastern part, and Moenkopi School Spring and Pasture Canyon Spring are in the western part (fig. 9). The four springs discharge water from unconfined parts of the N aquifer.

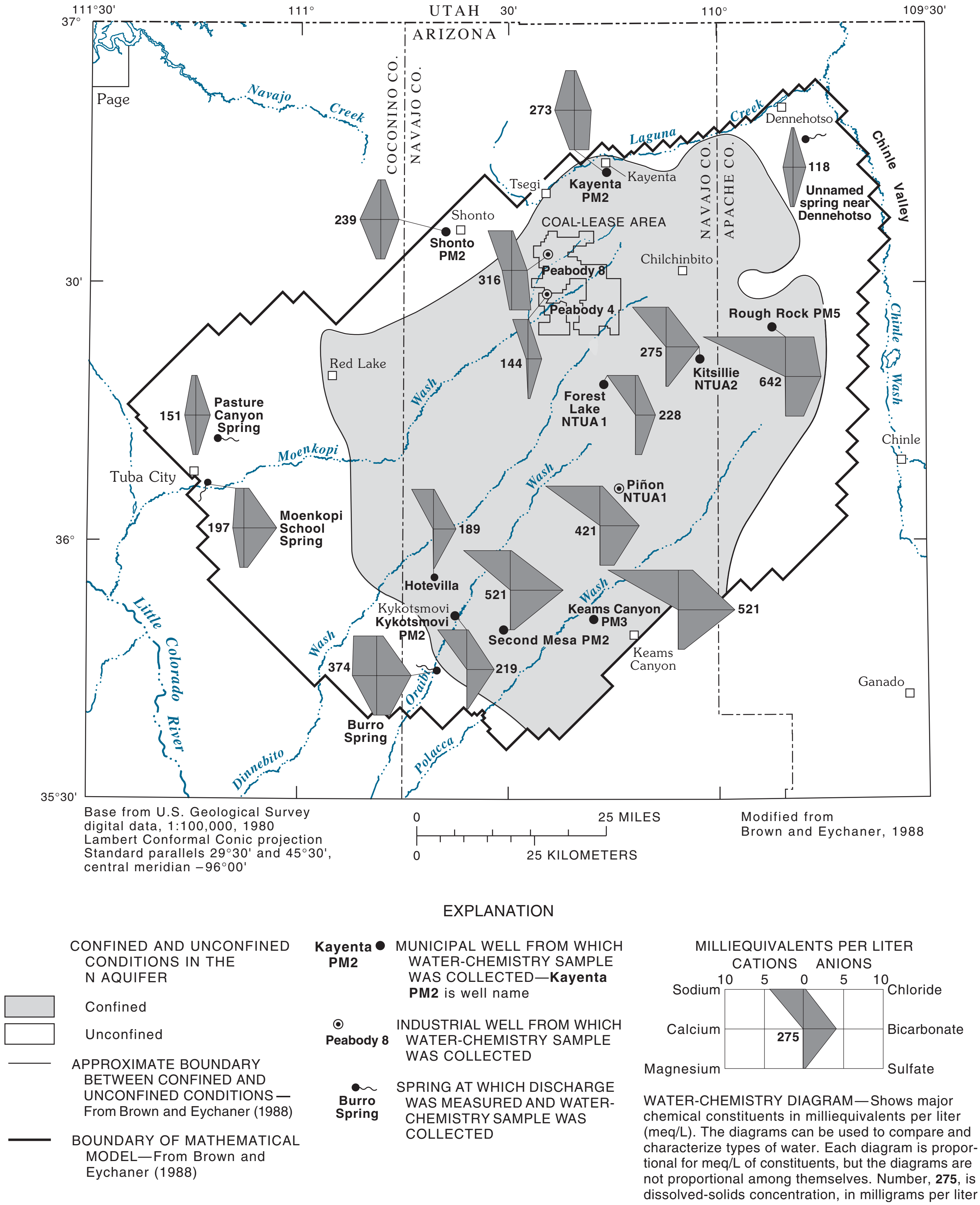


Figure 12. Water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, Arizona, 2003.

Table 14. Physical properties and chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 2003

[°C, degrees 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]

Common well name	U.S. Geological Survey identification number	Date of sample	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)
Forest Lake NTUA1	361737110180301	04-24-03	28.7	385	9.5
Hotevilla PM1	355518110400301	04-29-03	14.7	303	9.7
Kayenta PM2	364344110151201	04-22-03	15.5	378	8.0
Keams Canyon PM3	355034110183001	04-30-03	20.1	881	9.3
Kitsillie NTUA 2	362043110030501	04-24-03	14.8	445	9.7
Kykotsmovi PM2	355215110375001	05-02-03	22.5	364	9.7
Peabody 4	362647110243501	04-23-03	31.6	221	9.3
Peabody 8	363130110254501	04-23-03	29.2	487	8.3
Piñon NTUA1	360527110122501	04-25-03	26.0	716	9.7
Rough Rock PM5	362418109514601	04-22-03	19.9	1,080	8.9
Second Mesa PM2	354749110300101	04-30-03	20.0	601	9.6
Shonto PM2	363558110392501	04-21-03	14.0	357	7.4

Common well name	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen NO_2+NO_3 dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
Forest Lake NTUA1	118	0.59	<0.02	0.84	0.08
Hotevilla PM1	138	1.1	[1].02	.88	.04
Kayenta PM2	97	1.1	<.20	49	7.2
Keams Canyon PM3	340	<.06	<.20	.66	.12
Kitsillie NTUA 2	198	1.4	[1].01	.51	.01
Kykotsmovi PM2	162	1.2	.03	.49	.01
Peabody 4	82	.97	[1].01	4.7	.03
Peabody 8	92	1.7	<.02	25	3.6
Piñon NTUA1	226	1.3	[1].01	1.3	.22
Rough Rock PM5	213	1.0	.02	2.0	.27
Second Mesa PM2	280	<.06	[1].01	.43	.03
Shonto PM2	108	4.4	.06	53	6.8

See footnote at end of table.

Table 14. Physical properties and chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 2003—Continued

Common well name	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)
Forest Lake NTUA1	82	0.69	10	40	0.32
Hotevilla PM1	64	.50	1.6	5.1	<.17
Kayenta PM2	25	1.4	5.9	88	<.17
Keams Canyon PM3	210	.70	60	25	1.0
Kitsillie NTUA 2	100	.61	4.2	4.4	1.0
Kykotsmovi PM2	85	.39	3.5	7.8	<.17
Peabody 4	44	.66	3.5	13	.18
Peabody 8	70	2.9	4.5	118	<.17
Piñon NTUA1	161	.68	6.7	83	.33
Rough Rock PM5	239	1.5	127	110	1.7
Second Mesa PM2	134	.47	6.3	14	<.17
Shonto PM2	8.3	1.9	20	22	<.17

Common well name	Silica, dissolved (mg/L as SiO_2)	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)
Forest Lake NTUA1	21	3.0	90	38	228
Hotevilla PM1	23	3.2	30	42	189
Kayenta PM2	16	1.3	30	14	273
Keams Canyon PM3	12	34	470	<10	521
Kitsillie NTUA 2	26	4.1	50	<10	275
Kykotsmovi PM2	23	5.3	30	<10	219
Peabody 4	22	3.0	30	[1]5	144
Peabody 8	20	1.8	50	[1]5	316
Piñon NTUA1	26	4.4	100	15	421
Rough Rock PM5	12	49	420	18	642
Second Mesa PM2	20	16	100	<10	359
Shonto PM2	15	0.7	20	<10	239

[1]Estimated value.

Table 15. Specific conductance and concentrations of selected chemical constituents in water from industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1961–2003

[μS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; mg/L, milligrams per liter. 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
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
Hotevilla PM1				
1990	290	192	1.6	5
1991	[1]304	208	0.7	5.4
1993	305	180	1.2	5.5
1994	[1]307	166	1.4	4.8
1995	282	196	1.4	3.7
1996	328	186	1.3	5.3
1997	[1]307	185	1.5	5.2
2001	267	170	1.4	5.2
2002	287	182	1.3	4.8
2003	303	189	1.6	5.1
Kayenta PM2				
1982	360	([2])	4.5	58
1983	375	([2])	5.9	60
1984	[1]370	209	4.2	51
1986	300	181	8.2	30
1988	358	235	3.8	74
1992	383	210	5.6	78
1993	374	232	3.7	78
1994	[1]371	236	4.2	77
1995	371	250	4.2	72
1996	370	238	3.8	76
1997	379	230	3.9	77
1998	349	236	3.7	71
1999	364	236	4.0	72
2001	331	234	5.0	73
2002	363	237	5.1	67
2003	378	273	5.9	88
Keams Canyon PM3				
1976	940	---	71	36
1994	907	---	61	26
2002	870	514	63	26
2003	881	521	60	25
Kitsillie NTUA 2				
1997	[1]524	269	3.6	4.3
1998	379	270	3.8	4.1
1999	454	274	4.0	4.1
2001	409	276	5.0	4.5
2002	439	264	4.5	4.4
2003	445	275	4.2	4.4
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
Peabody 4				
1974	200	140	3.8	13
1975	220	144	3.4	13
1976	240	138	2.9	19
1979	220	---	3.9	19
1980	230	139	4.3	13
1986	205	---	4.2	12
1987	194	135	[3]5.0	13
1992	224	125	4.3	12
1993	214	124	[3]3.0	12
1996	214	140	3.8	12
1997	[1]203	139	3.5	12
1999	216	142	4.0	13
2001	181	138	4.0	13
2002	214	133	3.9	13
2003	221	144	3.5	13

See footnotes at end of table.

Table 15. Specific conductance and concentrations of selected chemical constituents in water from industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1961–2003—Continued

Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Peabody 8					**Second Mesa PM2**				
1986	453	---	4.9	110	1968	670	---	14	35
1988	812	516	7.2	250	1990	590	364	6.5	16
1990	456	287	4.3	110	1991	[1]595	292	10	15
1991	452	280	6.1	110	1993	630	350	7.5	15
2003	460	316	4.5	118	1994	[1]605	342	7.6	15
Piñon NTUA 1					1995	610	357	7.2	14
1998	460	304	4.6	4.7	1997	[1]646	356	7.1	14
2001	473	304	4.9	5.5	2001	597	352	7.1	15
2002	512	---	5.0	5.5	2002	608	357	7.5	14
2003	716	421	6.7	83	2003	601	521	6.3	14
Rough Rock PM5					**Shonto PM2**				
1983	1,090	([2])	130	110	1961	290	---	10	16
1984	[1]1,100	613	130	99	1973	280	---	7.1	20
1986	1,010	633	140	120	1986	302	---	10	14
1988	1,120	624	130	[3]110	1988	285	171	13	14
1991	[1]1,210	574	130	110	1992	321	186	22	19
1993	1,040	614	130	110	1993	324	197	17	16
1994	[1]1,070	626	130	110	1996	232	188	15	17
1995	1,110	648	140	110	2002	355	215	22	22
1996	1,100	634	130	110	2003	357	239	20	22
1997	[1]1,060	628	130	110					
1998	894	637	130	110					
1999	1,050	630	130	110					
2001	980	628	120	110					
2002	1,120	636	130	110					
2003	1,080	642	127	110					

[1]Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports showed values determined by laboratory analysis.
[2]Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports showed values determined by the sum of constituents.
[3]Value is different in Black Mesa monitoring reports printed before 2000. The earlier reports applied a different rounding definition.

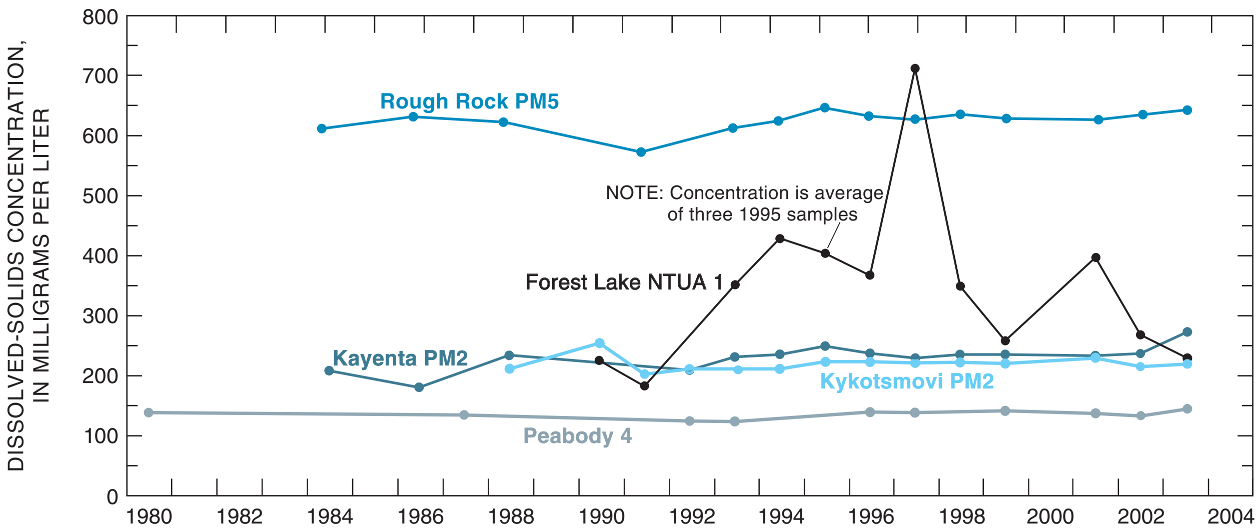


Figure 13. Dissolved-solids concentrations in water from selected wells, Black Mesa area, Arizona, 1980–2003.

Two water types were identified from the samples from the four springs. The unnamed spring near Dennehotso and Pasture Canyon Spring were a calcium bicarbonate type, and Burro Spring and Moenkopi School Spring were a calcium sodium bicarbonate type (fig. 12). Samples from the unnamed spring near Dennehotso, Moenkopi School Spring, and Pasture Canyon Spring had low dissolved-solids concentrations of 118 to 197 mg/L (table 16). The sample from Burro Spring, however, had a dissolved-solids concentration of 374 mg/L. Concentrations of all the analyzed constituents in samples from the four springs were below current USEPA MCLs and SMCLs (U.S. Environmental Protection Agency, 2002).

From the mid 1980s to 2003, trends are not apparent in the concentrations of dissolved solids, chloride, and sulfate in water samples from Burro Spring, the unnamed spring near Dennehotso, and Pasture Canyon Spring (table 16 and fig. 14). In water samples from Moenkopi School Spring, there appear to be no trends in concentrations of dissolved solids or sulfate; however, there appears to be an increasing trend in the concentration of chloride.

Table 16. Physical properties and chemical analyses of water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 2003

[°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]

Spring name	Bureau of Indian Affairs site number	U.S. Geological Survey identification number	Date of sample	Temperature (°C)	Specific conductance, field (µS/cm)	pH, field (units)
Burro Spring	6M-31	354156110413701	05-30-03	11.5	612	7.2
Unnamed spring near Dennehotso	8A-224	364656109425400	05-01-03	11.4	180	8.0
Moenkopi School Spring	3GS–77–6	360632111131101	05-01-03	17.0	344	7.6
Pasture Canyon Spring	3A-5	361021111115901	04-30-03	16.4	236	7.7

Table 16. Physical properties and chemical analyses of water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 2003—Continued

Spring name	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)
Burro Spring	184	<0.06	<0.02	170	---	61
Unnamed spring near Dennehotso	76	1.8	E.02	80	3	25
Moenkopi School Spring	93	2.3	<.02	95	3	28
Pasture Canyon Spring	74	4.5	<.02	88	15	28

Spring name	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)
Burro Spring	4.7	66	0.35	30	81	0.4
Unnamed spring near Dennehotso	3.9	4.5	1.0	2.9	7.2	<.17
Moenkopi School Spring	6.1	25	1.3	19	23	.2
Pasture Canyon Spring	4.3	12	1.3	5.1	16	<.17

Spring name	Silica, dissolved (mg/L as SiO_2)	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)
Burro Spring	15	0.9	70	<10	374
Unnamed spring near Dennehotso	13	2.5	20	<10	118
Moenkopi School Spring	13	2.5	30	<10	197
Pasture Canyon Spring	10	1.8	30	<10	151

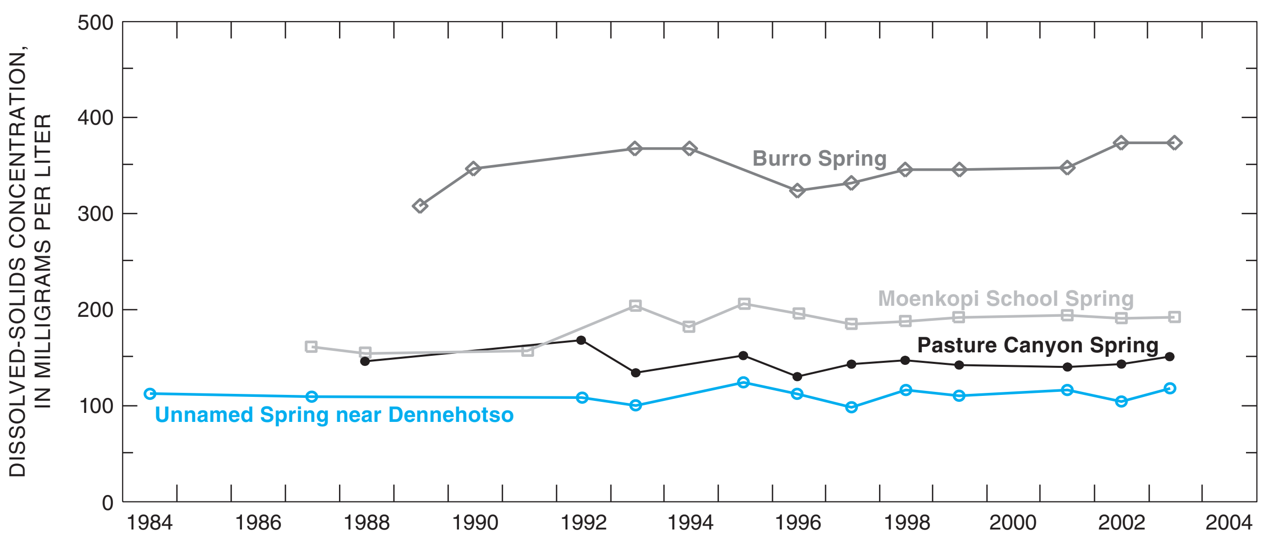


Figure 14. Dissolved-solids concentrations in water from selected springs, Black Mesa area, Arizona, 1984–2003.

SUMMARY

The N aquifer is the major source of water 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 precipitation of about 6 to 14 in/yr.

This report presents results of ground-water, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2002 to September 2003. The monitoring data for 2002–03 are compared with data for 2001–02 and with historical data from the 1950s to the present.

In 2002, total ground-water withdrawals were 8,000 acre-ft, industrial withdrawals were 4,640 acre-ft, and municipal withdrawals were 3,360 acre-ft. From 2001 to 2002, total withdrawals increased by 4 percent, municipal withdrawals increased by 7 percent, and industrial withdrawals increased by 2 percent. Flowmeter testing was completed for 32 municipal wells in August–September 2003. The median difference between pumping rates for the permanent meter and a test meter for all the sites tested was -2.0 percent. Differences ranged from -13.7 percent at Hopi High School no. 2 to +12.9 percent at Shonto PM3.

From 2002 to 2003, ground-water levels declined in 13 of 26 wells. The median water-level change for the 26 wells was -0.2 ft, and changes ranged from -5.5 ft to +10.6 ft. In unconfined areas, water levels declined in 5 of 13 wells, and the median change was 0.0 ft. In the confined area, water levels declined in 8 of 13 wells, and the median change was -1.1 ft.

For wells in the confined area, the average annual median water-level change was -1.8 ft, and there is no appreciable trend in the annual water-level changes from 1983 to 2003. For wells in unconfined areas, the average annual median water-level change was +0.2 ft, and there is no appreciable trend from 1983 to 2003.

From the prestress period (prior to 1965) to 2003, the median water-level change in 26 wells was -8.3 ft. Water levels in the 13 wells in unconfined parts of the aquifer had a median change of -0.4 ft, and the changes ranged from -36.6 ft to +16.5 ft. Water levels in the 13 wells in the confined part of the aquifer had a median change of -60.3 ft, and the changes ranged from -190.5 ft to +12.7 ft.

Discharges were measured annually at four springs in 2002 and 2003. Burro Spring had no change in discharge, the unnamed spring near Dennehotso had a 90-percent increase, Moenkopi School Spring had a 10-percent increase, and Pasture Canyon Spring had a 16-percent decrease. For about the past 11 years, discharges in the four springs have fluctuated; however, increasing or decreasing trends are not apparent.

Continuous records of surface-water discharge have been collected from 1976 to 2002 at Moenkopi Wash, 1996 to 2002 at Laguna Creek, 1993 to 2002 at Dinnebito Wash, and 1994 to 2002 at Polacca Wash. The annual average discharges at the four streamflow-gaging stations varied considerably during the periods of record. There appears to be an increasing trend in annual average discharge for Laguna Creek and no trend for the other three streamflow-gaging stations. Median flows for November, December, January, and February of each water year are used as an index of ground-water discharge to those streams. Since 1995, the median winter flows have decreased in Moenkopi Wash, Dinnebito Wash, and Polacca Wash. Since 1997, there is no consistent trend in the median winter flow in Laguna Creek.

In 2003, water samples were collected from 12 wells and analyzed for selected chemical constituents. Dissolved-solids concentrations ranged from 144 to 642 mg/L, and samples from 10 of the wells had dissolved-solids concentrations less than 500 mg/L. There are no appreciable time trends in the chemistry of water samples from 7 wells with more than 8 years of data. Samples from Keams Canyon PM3 and Rough Rock PM5 exceeded SMCLs of 500 mg/L for dissolved solids, and samples from 9 out of 12 wells exceeded the SMCL maximum for pH of 8.5.

Dissolved-solids concentrations in water samples from the unnamed spring near Dennehotso, Pasture Canyon Spring, and Moenkopi School Spring ranged from 118 to 197 mg/L, and the dissolved-solids concentration in the water sample from Burro Spring was 374 mg/L. From the mid 1980s to 2003, trends are not apparent in the concentrations of dissolved solids, chloride, and sulfate in water samples from Burro Spring, the unnamed spring near Dennehotso, and Pasture Canyon Spring. There appear to be no trends in concentrations of dissolved solids and sulfate, and an increasing trend in the concentration of chloride in water samples from Moenkopi School Spring.

SELECTED REFERENCES

Boner, F.C., Davis, R.G., and Duet, N.R., 1992, Water-resources data for Arizona, water year 1991: U.S. Geological Survey Water-Data Report AZ–91–1, 411 p.

Boner, F.C., Garrett, W.B., and Konieczki, A.D., 1989, Water-resources data for Arizona, water year 1988: U.S. Geological Survey Water-Data Report AZ–88–1, 391 p.

Boner, F.C., Konieczki, A.D., and Davis, R.G., 1991, Water-resources data for Arizona, water year 1990: U.S. Geological Survey Water-Data Report AZ–90–1, 381 p.

Boner, F.C., Smith, C.F., Garrett, W.B., and Konieczki, A.D., 1990, Water-resources data for Arizona, water year 1989: U.S. Geological Survey Water-Data Report AZ–89–1, 383 p.

Brown, J.G., and Eychaner, J.H., 1988, Simulation of five ground-water withdrawal projections for the Black Mesa area, Navajo and Hopi Indian Reservations, Arizona: U.S. Geological Survey Water-Resources Investigations Report 88—4000, 51 p.

Cooley, M.E., Harshbarger, J.W., Akers, J.P., and Hardt, W.F., 1969, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 521–A, 61 p.

Davis, G.E., Hardt, W.F., Thompson, L.K., and Cooley, M.E., 1963, Records of ground-water supplies, part 1, *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Department Water- Resources Report 12–A, 159 p.

Dubiel, R.F., 1989, Sedimentology and revised nomenclature for the upper part of the upper Triassic Chinle Formation and the lower Jurassic Wingate Sandstone, northwestern New Mexico and northeastern Arizona, *in* Anderson, O.J., Lucas, S.G., Love, D.W., and Cather, S.M., eds., Southeastern Colorado Plateau: New Mexico Geological Society 40th Annual Field Conference, September 28–October 1, 1989, p. 213–223.

Eychaner, J.H., 1983, Geohydrology and effects of water use in the Black Mesa area, Navajo and Hopi Indian Reservations, Arizona: U.S. Geological Survey Water-Supply Paper 2201, 26 p.

GeoTrans, Inc., 1987, A two-dimensional finite-difference flow model simulating the effects of withdrawals to the N aquifer, Black Mesa area, Arizona: Boulder, Colorado, GeoTrans, Inc., report prepared for Peabody Western Coal Company.

Harshbarger, J.W., Lewis, D.D., Skibitzke, H.E., Heckler, W.L., and Kister, L.R., 1966, Arizona water: U.S. Geological Survey Water-Supply Paper 1648, 85 p.

Hart, R.J., and Sottilare, J.P., 1988, Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987–88: U.S. Geological Survey Open-File Report 88—467, 27 p.

____1989, Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1988–89: U.S. Geological Survey Open-File Report 89—383, 33 p.

Hill, G.W., 1985, Progress report on Black Mesa monitoring program—1984: U.S. Geological Survey Open-File Report 85—483, 24 p.

Hill, G.W., and Sottilare, J.P., 1987, Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987: U.S. Geological Survey Open-File Report 87—458, 29 p.

Hill, G.W., and Whetten, M.I., 1986, Progress report on Black Mesa monitoring program—1985–86: U.S. Geological Survey Open-File Report 86—414, 23 p.

HSIGeoTrans, Inc., 1993, Investigation of the N- and D-aquifer geochemistry and flow characteristics using major ion and isotopic chemistry, petrography, rock stress analyses, and dendrochronology in the Black Mesa area, Arizona: Boulder, Colorado, HSIGeoTrans, Inc., report prepared for Peabody Coal Company.

HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., 1999, A three-dimensional flow model of the D and N aquifers, Black Mesa Basin, Arizona: Boulder, Colorado, HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., report prepared for Peabody Western Coal Company.

Kister, L.R., and Hatchett, J.L., 1963, Selected chemical analyses of the ground water, part 2 *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Department Water-Resources Report 12–B, 58 p.

Littin, G.R., 1992, Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1990–91: U.S. Geological Survey Water-Resources Investigations Report 92—4045, 32 p.

____1993, Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1991–92: U.S. Geological Survey Water-Resources Investigations Report 93—4111, 23 p.

Littin, G.R., Baum, B.M., and Truini, Margot, 1999, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1999: U.S. Geological Survey Open-File Report 98—653, 27 p.

Littin, G.R., and Monroe, S.A., 1995a, Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1992–93: U.S. Geological Survey Water- Resources Investigations Report 95—4156, 37 p.

____1995b, Results of ground-water, surface-water, and water-chemistry monitoring, Black Mesa area, northeastern Arizona—1994: U.S. Geological Survey Water-Resources Investigations Report 95—4238, 25 p.

____1996, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1995: U.S. Geological Survey Open-File Report 96—616, 22 p.

____1997, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1996: U.S. Geological Survey Open-File Report 97—566, 27 p.

Lopes, T.J., and Hoffmann, J.P., 1997, Geochemical analyses of ground-water ages, recharge rates, and hydraulic conductivity of the N Aquifer, Black Mesa area, Arizona: U.S. Geological Survey Water-Resources Investigations Report 96—4190, 42 p.

McCormack, H.F., Fisk, G.G., Duet, N.R., Evans, D.W., and Castillo, N.K, 2002, Water-resources data for Arizona, water year 2001: U.S. Geological Survey Water-Data Report AZ–01–1, 399 p.

McCormack, H.F., Fisk, G.G., Duet, N.R., Evans, D.W., Roberts, W.P., and Castillo, N.K., 2003, Water-resources data for Arizona, water year 2002: U.S. Geological Survey Water-Data Report AZ–02–1, 337 p.

Smith, C.F., Anning, D.W., Duet, N.R., Fisk, G.G., McCormack, H.F., Pope, G.L., Rigas, P.D., and Wallace, B.L., 1995, Water-resources data for Arizona, water year 1994: U.S. Geological Survey Water-Data Report AZ–94–1, 320 p.

Smith, C.F., Boner, F.C., Davis, R.G., Duet, N.R., and Rigas, P.D., 1993, Water-resources data for Arizona, water year 1992: U.S. Geological Survey Water-Data Report AZ–92–1, 360 p.

Smith, C.F., Rigas, P.D., Ham, L.K., Duet, N.R., and Anning, D.W., 1994, Water-resources data for Arizona, water year 1993: U.S. Geological Survey Water-Data Report AZ–93–1, 360 p.

Smith, C.F., Duet, N.R., Fisk, G.G., McCormack, H.F., Partin, C.K., Pope, G.L., Rigas, P.D., and Tadayon, Saeid, 1996, Water-resources data for Arizona, water year 1995: U.S. Geological Survey Water- Data Report AZ–95–1, 306 p.

Smith, C.F., Duet, N.R., Fisk, G.G., McCormack, H.F., Partin, C.K., Pope, G.L., and Rigas, P.D., 1997, Water-resources data for Arizona, water year 1996: U.S. Geological Survey Water-Data Report AZ–96–1, 328 p.

Sottilare, J.P., 1992, Results of ground-water, surface- water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1989–90: U.S. Geological Survey Water-Resources Investigations Report 92—4008, 38 p.

Tadayon, Saeid, Duet, N.R., Fisk, G.G., McCormack, H.F., Partin, C.K., Pope, G.L., and Rigas, P.D., 1999, Water-resources data for Arizona, water year 1998: U.S. Geological Survey Water-Data Report AZ–98–1, 454 p.

____2000, Water-resources data for Arizona, water year 1999: U.S. Geological Survey Water-Data Report AZ–99–1, 389 p.

____2001, Water-resources data for Arizona, water year 2000: U.S. Geological Survey Water-Data Report AZ–00–1, 390 p.

Tadayon, Saeid, Duet, N.R., Fisk, G.G., McCormack, H.F., Pope, G.L., and Rigas, P.D., 1998, Water-resources data for Arizona, water year 1997: U.S. Geological Survey Water-Data Report AZ–97–1, 416 p.

Thomas, B.E., and Truini, Margot, 2000, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona–1999: U.S. Geological Survey Open-File Report 00—453, 42

Thomas, B.E., 2002a, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2000–2001, and performance and sensitivity of the 1988 USGS numerical model of the N aquifer: U.S. Geological Survey Water-Resources Investigations Report 02—4211, 75 p.

____2000b, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2001–02: U.S. Geological Survey Open-File Report 02—485, 43p.

Truini, Margot, Baum, B.M., Littin, G.R., and Singoitewa-Honanie, Gayl, 2000, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1998: U.S. Geological Survey Open-File Report 00—66, 37 p.

Truini, Margot, and Longsworth, S.A., 2003, Hydrogeology of the D aquifer and movement and ages of ground water determined from geochemical and isotopic analyses, Black Mesa area, northeastern Arizona: U.S. Geological Survey Water-Resources Investigations Report 03—4189, 38 p.

U.S. Department of Agriculture, Natural Resources Conservation Service, 1999, Arizona Annual Precipitation: Fort Worth, Texas, USDA-NRCS National Cartography & Geospatial Center, scale 1:1,300,000.

U.S. Environmental Protection Agency, 2002, Current drinking water standards, national primary and secondary drinking water regulations: Washington, D.C., U.S. Environmental Protection Agency, accessed April 1, 2002, at URL http://www.epa.gov/safewater/mcl.html.

U.S. Geological Survey, 1963–64a, Surface-water records of Arizona: U.S. Geological Survey report.

____1963–64b, Ground-water records of Arizona: U.S. Geological Survey report.

____1965–74a, Water-resources data for Arizona— Part 1, surface-water records: U.S. Geological Survey Water-Resources Data Report.

____1965–74b, Water-resources data for Arizona— Part 2, ground-water records: U.S. Geological Survey Water-Resources Data Report.

____1976–83, Water-resources data for Arizona, water years 1975–81: U.S. Geological Survey Water Resources Data Report AZ–75–1 to AZ–81–1.

____1978, Progress report on Black Mesa monitoring program—1977: U.S. Geological Survey Open-File Report 78—459, 38 p.

White, N.D., and Garrett, W.B., 1984, Water resources data for Arizona, water year 1982: U.S. Geological Survey Water-Data Report AZ–82–1, 440 p.

____1986, Water resources data for Arizona, water year 1983: U.S. Geological Survey Water-Data Report AZ–83–1, 387 p.

____1987, Water resources data for Arizona, water year 1984: U.S. Geological Survey Water-Data Report AZ–84–1, 381 p.

____1988, Water resources data for Arizona, water year 1985: U.S. Geological Survey Water-Data Report AZ–85–1, 343 p.

Wilson, R.P., and Garrett, W.B., 1988, Water resources data for Arizona, water year 1986: U.S. Geological Survey Water-Data Report AZ–86–1, 341 p.

____1989, Water-resources data for Arizona, water year 1987: U.S. Geological Survey Water-Data Report AZ–87–1, 385 p.

Zhu, Chen, 2000, Estimate of recharge from radiocarbon dating of groundwater and numerical flow and transport modeling: Water Resources Research, v. 36, no. 9, p. 2607–2620.

Zhu, Chen, Waddell, R.K., Star, I., and Ostrander, M., 1998, Responses of ground water in the Black Mesa Basin, northeastern Arizona, to paleoclimatic changes during the late Pleistocene and Holocene: Geology, v. 26, no. 2, p. 127–130.

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