USGS
science for a changing world

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

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2011–2012

Open-File Report 2013–1304

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

FRONT COVER
Photograph of Black Mesa, Arizona, looking southwest towards the San Francisco Peaks on the horizon. U.S. Geological Survey photograph by Jon Mason.

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2011–2012

By Jamie P. Macy and Joel A. Unema

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

Open-File Report 2013–1304

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014

For product and ordering information: World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth,
its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Macy, J.P., and Unema, J.A., 2014, Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2011–2012: U.S. Geological Survey Open-File Report 2014–1304, 42 p., *http://dx.doi.org/10.3133/ofr20131304.*

ISSN 2331-1258 (online)

Contents

Figures

Tables

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per year (gal/yr)	3.785	liter per year (L/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).
Altitude, as used in this report, refers to distance above the vertical datum.
Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).
Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).
Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

This page left intentionally blank.

Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2011–2012

By Jamie P. Macy, and Joel A. Unema

Abstract

The Navajo (N) aquifer is an extensive aquifer and the primary source of groundwater in the 5,400-square-mile Black Mesa area in northeastern Arizona. Availability of water is an important issue in northeastern Arizona because of continued water requirements for industrial and municipal use by a growing population and because of low precipitation in the arid climate of the Black Mesa area. Precipitation in the area typically is between 6 and 14 inches per year.

The U.S. Geological Survey water-monitoring program in the Black Mesa area began in 1971 and provides information about the long-term effects of groundwater withdrawals from the N aquifer for industrial and municipal uses. This report presents results of data collected as part of the monitoring program in the Black Mesa area from January 2011 to September 2012. The monitoring program includes measurements of (1) groundwater withdrawals, (2) groundwater levels, (3) spring discharge, (4) surface-water discharge, and (5) groundwater chemistry.

In 2011, total groundwater withdrawals were 4,480 acre-ft, industrial withdrawals were 1,390 acre-ft, and municipal withdrawals were 3,090 acre-ft. Total withdrawals during 2011 were about 39 percent less than total withdrawals in 2005 because of Peabody Western Coal Company's discontinued use of water to transport coal in a slurry. From 2010 to 2011 total withdrawals increased by 11 percent; industrial withdrawals increased by approximately 19 percent, and total municipal withdrawals increased by 8 percent.

From 2011 to 2012, annually measured water levels in the Black Mesa area declined in 8 of 15 wells that were available for comparison in the unconfined areas of the N aquifer, and the median change was -0.1 feet. Water levels declined in 9 of 18 wells measured in the confined area of the aquifer. The median change for the confined area of the aquifer was 0.0 feet. From the prestress period (prior to 1965) to 2012, the median water-level change for 34 wells in both the confined and unconfined areas was -13.4 feet; the median water-level changes were -2.1 feet for 16 wells measured in the unconfined areas and -39.1 feet for 18 wells measured in the confined area.

Spring flow was measured at four springs in 2012. Flow fluctuated during the period of record for Burro and Unnamed Spring near Dennehotso, but a decreasing trend was apparent at Moenkopi School Spring and Pasture Canyon Spring. Discharge at Burro Spring has remained relatively constant since it was first measured in the 1980s and discharge at Unnamed Spring near Dennehotso has fluctuated for the period of record. Trend analysis for discharge at Moenkopi and Pasture Canyon Springs yielded a slope significantly different from zero.

Continuous records of surface-water discharge in the Black Mesa area were collected from streamflow-gaging stations at the following sites: Moenkopi Wash at Moenkopi 09401260 (1976 to 2010), Dinnebito Wash near Sand Springs 09401110 (1993 to 2010), Polacca Wash near Second Mesa 09400568 (1994 to 2010), and Pasture Canyon Springs 09401265 (2004 to 2010). Median winter flows (November through February) of each water year were used as an index of the amount of groundwater discharge at the above-named sites. For the period of record of each streamflow-gaging station, the median winter flows have generally remained constant, and there are no significant statistical trends in groundwater discharge.

In 2012, water samples collected from 10 wells and 4 springs in the Black Mesa area were analyzed for selected chemical constituents, and the results were compared with previous analyses. Concentrations of dissolved solids, chloride, and sulfate have varied at all 10 wells for the period of record, but neither increasing nor decreasing trends over time were found. Dissolved solids, chloride, and sulfate concentrations increased at Moenkopi School Spring during the more than 12 years of record at that site. Concentrations of dissolved solids, chloride, and sulfate at Pasture Canyon Spring have not varied significantly since the early 1980s, and there is no increasing or decreasing trend in those data. Concentrations of dissolved solids, chloride, and sulfate at Burro Spring and Unnamed Spring near Dennehotso have varied for the period of record, but there is no increasing or decreasing trend in the data.

Introduction

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

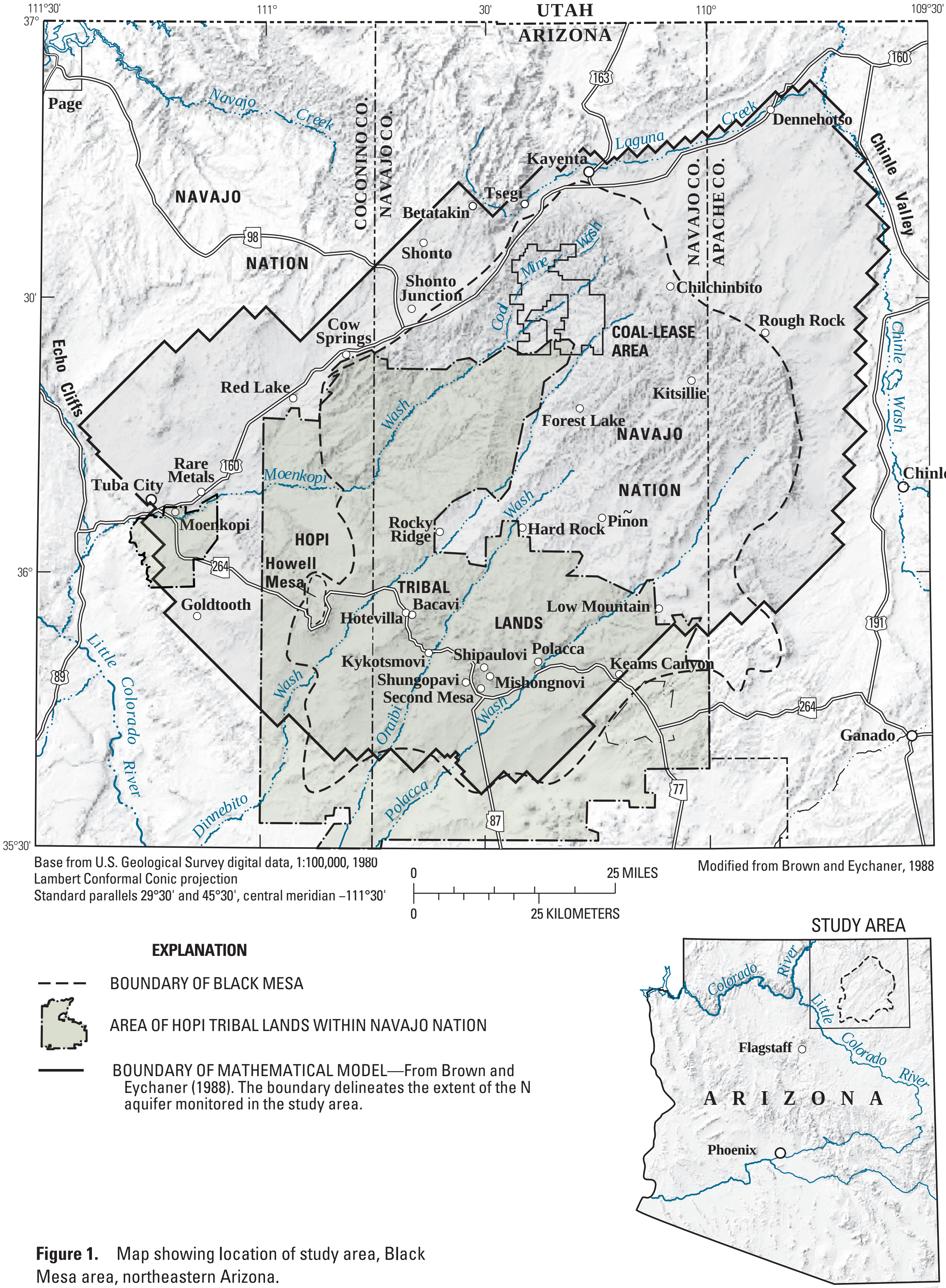


Figure 1. Map showing location of study area, Black Mesa area, northeastern Arizona.

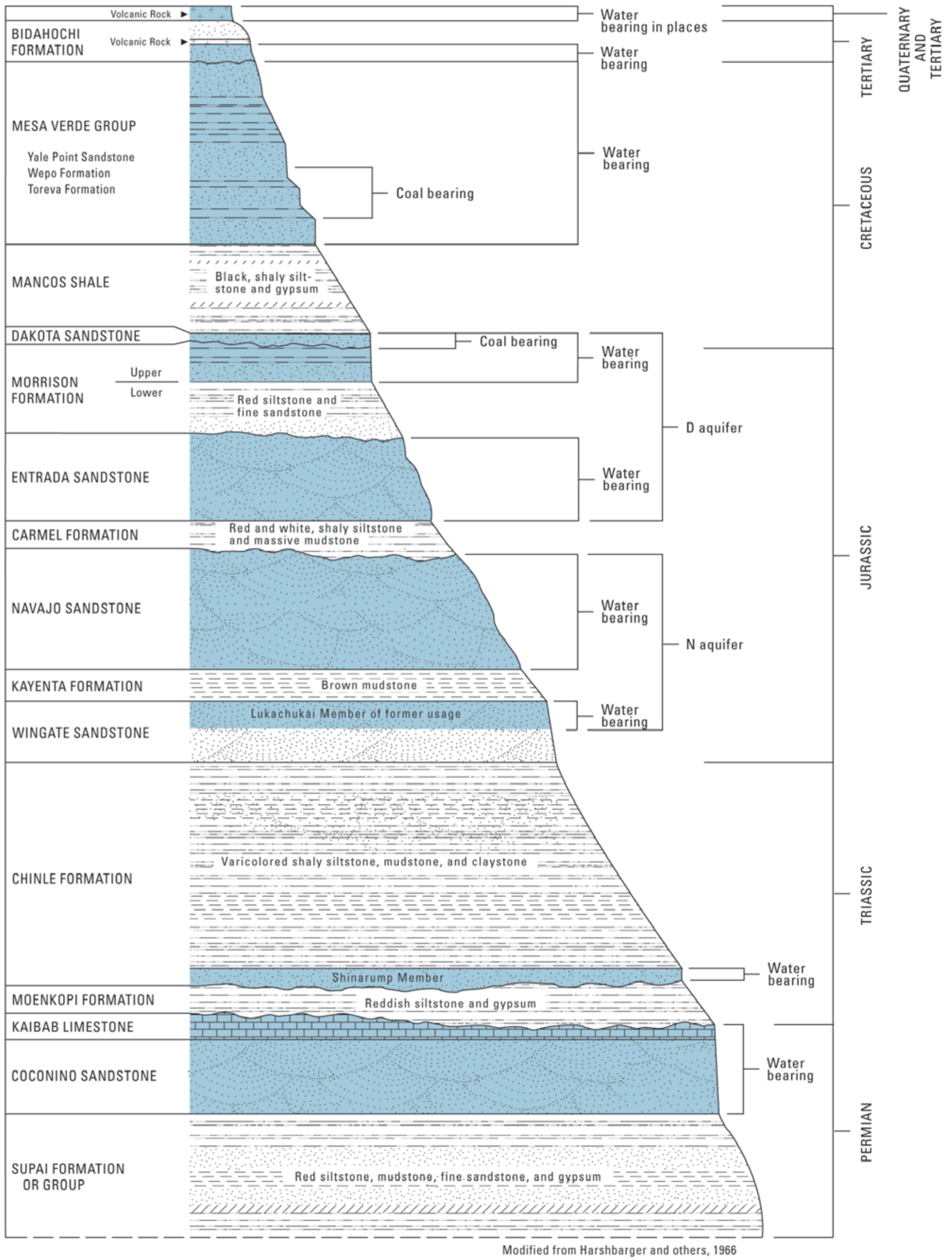


Figure 2. Stratigraphic section showing rock formations and hydrogeologic units of the Black Mesa area, northeastern Arizona (not to scale). The N aquifer is approximately 1,000 feet thick.

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

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

Within the Black Mesa study area, the Navajo Nation and Hopi Tribe are the principal municipal water users, and the Peabody Western Coal Company (PWCC) is the principal industrial water user. Withdrawals from the N aquifer in the Black Mesa area increased fairly consistently from 1965 through 2002 (table 1). The PWCC began operating a strip mine in the northern part of the study area in 1968 (fig. 1). The PWCC's mining operation consisted of two mines on Black Mesa—the Kayenta mine, which transported coal to the Navajo Generating Station by train, and the Black Mesa mine, which transported coal 275 miles to the Mohave Generating Station by a coal slurry pipeline. In 1982, the PWCC sold the largest amount of moisture-adjusted tons of coal to the Mohave Generating Station and the quantity of water pumped by the PWCC increased from about 100 acre-ft in 1968 to a maximum of 4,740 acre-ft in 1982 (John Cochran, Manager of Environmental Hydrology, Peabody Investments Corporation, written commun., 2010). During the same time period, municipal withdrawals grew from about 250 acre-ft in 1968 to 1,830 acre-ft in 1982.

The PWCC operated two mines on Black Mesa from the 1970s until about 2005 when the Mohave Generating Station ceased operations. On December 31, 2005, the PWCC reduced pumping of the N aquifer by approximately 70 percent as a result of discontinued use of a coal slurry pipeline that delivered water to the Mohave Generating Station. The two mines at the PWCC have since been combined into the Black Mesa complex, which still delivers coal to the Navajo Generating Station via an electric train. The PWCC planned to continue to pump approximately 1,000 to 1,500 acre-ft per year after 2005, primarily for dust control (table 1).

The members of the Navajo Nation and the Hopi Tribe have been concerned about the long-term effects of withdrawals from the N aquifer on available groundwater supplies, on stream and spring discharge, and on groundwater chemistry. In 1971, these water-supply concerns led to the establishment of a monitoring program for the water resources in the Black Mesa area by the U.S. Geological Survey (USGS) in cooperation with the Arizona Water Commission, which was the predecessor to the present Arizona Department of Water Resources (ADWR). In 1983, the Bureau of Indian Affairs (BIA) joined the cooperative effort. Since 1983, the Navajo Tribal Utility Authority (NTUA), the PWCC, the Hopi Tribe, and the Western Navajo, Chinle, and Hopi Agencies of the BIA have assisted in the collection of hydrologic data.

Purpose and Scope

This report presents results of groundwater, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2011 to September 2012. Continuous and periodic groundwater and surface-water data are collected to determine the effects of industrial and municipal withdrawals from the N aquifer on groundwater levels, stream and spring discharge, and groundwater chemistry. Groundwater data include water levels, spring-discharge rates, and water chemistry. Surface-water data include discharge rates at four continuous-record streamflow-gaging stations. Together, these data are compared with data from 1965 to 2010 to describe the overall status of and change over time of groundwater conditions in the N aquifer, as well as information on how the aquifer responds to groundwater development stresses. Some statistical analyses of the data are included in this report to examine trends in the data that identify groundwater conditions in the N aquifer.

Previous Investigations

Twenty-seven progress reports on the Black Mesa area monitoring program have been prepared by the USGS, and they are summarized in table 2. Most of the data from the Black Mesa area monitoring program are contained in these progress reports and in the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/az/nwis/).

Stream-discharge and periodic water-quality data collected from Moenkopi Wash before the 1982 water year were published by the USGS (1963–64a, b; 1965–74a, b; and 1976–83). Stream-discharge data from water years 1983 to 2009 for Moenkopi Wash at Moenkopi (09401260), Dinnebito Wash near Sand Springs (09401110), Polacca Wash near Second Mesa (09400568), Laguna Creek at Dennehotso (09379180), and Pasture Canyon Spring (09401265) in the Black Mesa area were published in White and Garrett (1984, 1986, 1987, 1988), Wilson and Garrett (1988, 1989), Boner and others (1989, 1990, 1991, 1992), Smith and others (1993, 1994, 1995, 1996, 1997), Tadayon and others (1998, 1999, 2000, 2001), McCormack and others (2002, 2003), Fisk and others (2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011), and online at (http://wdr.water.usgs.gov/wy2011/search.jsp) in the 2011 annual data report. Before the monitoring program, a large data-collection effort in the 1950s resulted in a compilation of well and spring data for the Navajo and Hopi Indian Reservations (Davis and others, 1963).

Many interpretive studies have investigated the hydrology of the Black Mesa area. Cooley and others (1969) made the first comprehensive evaluation of the regional hydrogeology of the Black Mesa area. Eychaner (1983) developed a two-dimensional numerical model of groundwater flow in the N aquifer. Brown and Eychaner (1988) recalibrated Eychaner's model by using a finer grid and by using revised estimates of selected aquifer characteristics. GeoTrans, Inc.

Table 1. Withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2011.

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

Calendar year	Industrial[1]	Municipal[2,3]		Total withdrawals
		Confined	Unconfined	
1965	0	50	20	70
1966	0	110	30	140
1967	0	120	50	170
1968	100	150	100	350
1969	40	200	100	340
1970	740	280	150	1,170
1971	1,900	340	150	2,390
1972	3,680	370	250	4,300
1973	3,520	530	300	4,350
1974	3,830	580	360	4,770
1975	3,500	600	510	4,610
1976	4,180	690	640	5,510
1977	4,090	750	730	5,570
1978	3,000	830	930	4,760
1979	3,500	860	930	5,290
1980	3,540	910	880	5,330
1981	4,010	960	1,000	5,970
1982	4,740	870	960	6,570
1983	4,460	1,360	1,280	7,100
1984	4,170	1,070	1,400	6,640
1985	2,520	1,040	1,160	4,720
1986	4,480	970	1,260	6,710
1987	3,830	1,130	1,280	6,240
1988	4,090	1,250	1,310	6,650
1989	3,450	1,070	1,400	5,920
1990	3,430	1,170	1,210	5,810
1991	4,020	1,140	1,300	6,460
1992	3,820	1,180	1,410	6,410
1993	3,700	1,250	1,570	6,520
1994	4,080	1,210	1,600	6,890
1995	4,340	1,220	1,510	7,070
1996	4,010	1,380	1,650	7,040
1997	4,130	1,380	1,580	7,090
1998	4,030	1,440	1,590	7,060
1999	4,210	1,420	1,480	7,110
2000	4,490	1,610	1,640	7,740
2001	4,530	1,490	1,660	7,680
2002	4,640	1,500	1,860	8,000
2003	4,450	1,350	1,440	7,240
2004	4,370	1,240	1,600	7,210
2005	4,480	1,280	1,570	7,330
2006	1,200	[4]1,300	[4]1,600	[4]4,100
2007	1,170	1,460	1,640	4,270
2008	1,210	[5,6]1,430	[5]1,560	[6]4,200
2009	1,390	1,440	1,400	4,230
2010	1,170	[4]1,450	1,420	[4]4,040
2011	1,390	[4]1,460	1,630	[4]4,480

[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, 1986–2011.

[4]Navajo Tribal Utility Authority meter data were incomplete; therefore, municipal withdrawals are estmated, and total withdrawal uses an estimation in the calculation.

[5]Confined and unconfined totals were reversed in previous reports.

[6]Confined withdrawals are about 90 acre-ft greater than previously reported.

Table 2. Tabulated list of progress reports for the Black Mesa monitoring program 1978–2012.

Year published	Author(s)	Title	U.S. Geological Survey report type and number
1978	U.S. Geological Survey	Progress report on Black Mesa monitoring program—1977	Open-File Report 78–459
1985	Hill, G.W.	Progress report on Black Mesa monitoring program—1984	Open-File Report 85–483
1986	Hill, G.W., and Whetten, M.I.	Progress report on Black Mesa monitoring program—1985–86	Open-File Report 86–414
1987	Hill, G.W., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987	Open-File Report 87–458
1988	Hart, R.J., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987–88	Open-File Report 88–467
1989	Hart, R.J., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1988–89	Open-File Report 89–383
1992	Sottilare, J.P.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1989–90	Water-Resources Investigations Report 92–4008
1992	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1990–91	Water-Resources Investigations Report 92–4045
1993	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1991–92	Water-Resources Investigations Report 93–4111
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1992–93	Water-Resources Investigations Report 95–4156
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-chemistry monitoring, Black Mesa area, northeastern Arizona—1994	Water-Resources Investigations Report 95–4238
1996	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1995	Open-File Report 96–616
1997	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1996	Open-File Report 97–566
1999	Littin, G.R., Baum, B.M., and Truini, Margot	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1997	Open-File Report 98–653
2000	Truini, Margot, Baum, B.M., Littin, G.R., and Shingoitewa-Honanie, Gayl	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1998	Open-File Report 00–66
2000	Thomas, B.E., and Truini, Margot	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona–1999	Open-File Report 00–453
2002	Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2000–2001, and performance and sensitivity of the 1988 USGS numerical model of the N aquifer	Water-Resources Investigations Report 02–4211
2002	Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2001–02	Open-File Report 02–485
2004	Truini, Margot, and Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2002–03	Open-File Report 03–503
2005	Truini, Margot, Macy, J.P., and Porter, T.J.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2003–04	Open-File Report 2005–1080
2006	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2004–05	Open-File Report 2006–1058
2007	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2005–06	Open-File Report 2007–1041
2008	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2006–07	Open-File Report 2008–1324
2009	Macy, Jamie P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2007–2008	Open-File Report 2009–1148
2010	Macy, Jamie P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2008–2009	Open-File Report 2010–1038
2011	Macy, Jamie P., and Brown, C.R.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2009–2010	Open-File Report 2011–1198
2012	Macy, Jamie P., Brown, C.R., and Anderson, J.R.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2010–2011	Open-File Report 2012–1102

(1987) also developed a two-dimensional numerical model of the N aquifer in the 1980s. In the late 1990s, HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering (1999) developed a three-dimensional numerical model of the N aquifer and the overlying Dakota (D) aquifer.

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water collected from wells and springs in the Black Mesa area. HSIGeoTrans, Inc. (1993) evaluated the major-ion and isotopic chemistry of the D and N aquifers. Lopes and Hoffmann (1997) analyzed groundwater ages, recharge, and hydraulic conductivity of the N aquifer by using geochemical techniques. Zhu and others (1998) estimated groundwater recharge in the Black Mesa area by using isotopic data and flow estimates from the N-aquifer model developed by GeoTrans, Inc. (1987). Zhu (2000) estimated recharge using advective transport modeling and the same isotopic data from the GeoTrans model. Truini and Longsworth (2003) described the hydrogeology of the D aquifer and the movement and ages of groundwater in the Black Mesa area by using data from geochemical and isotopic analyses. Truini and Macy (2005) addressed leakage through the confining unit between the D aquifer and the N aquifer as part of an investigation of the Carmel Formation.

Hydrologic Data

In 2011–12, activities of the Black Mesa area monitoring program included metered groundwater withdrawals, measurements of groundwater levels, spring-discharge measurements, streamflow gaging, and the collection of water-chemistry samples from wells and springs. All data were collected by the USGS except withdrawal data from NTUA wells, which were compiled by NTUA personnel. Linear regression and Kendall’s tau trend analyses were applied to streamflow data, spring-discharge measurements, and water-chemistry samples by using TIBCO Spotfire S+ statistical software (TIBCO Software, Inc.; Sommerville, MA). Annual discharge measurements were made at 4 springs, and annual groundwater-level measurements were made at 34 wells. Of the 34 wells measured, six are continuous-recording observation wells that have been upgraded for real-time data telemetry (referred to as “BM observation well” in table 3). The water-level data from these six continuous-recording observation wells are available online (http://waterdata.usgs.gov/az/nwis/gw). Groundwater-withdrawal data were compiled during March 2012. The period before appreciable groundwater withdrawals began for mining or municipal purposes (about 1965) is referred to in this report as the “prestress period.” Spring discharges and groundwater levels were measured from February to June 2012. Groundwater samples were collected from 10 wells and 4 springs in June 2012 and were analyzed for chemical constituents. Annual groundwater-withdrawal data are collected from 36 well systems within the NTUA, BIA, and Hopi municipal systems and the PWCC industrial well field. Identification information for

Table 3. Identification numbers and names of monitoring program study wells, 2011–12, Black Mesa area, northeastern Arizona.

[Dashes indicate no data]

U.S. Geological Survey identification number	Common name or location	Bureau of Indian Affairs site number
354749110300101	Second Mesa PM2	---
355023110182701	Keams Canyon PM2	---
355215110375001	Kykotsmovi PM2	---
355230110365801	Kykotsmovi PM1	---
355236110364501	Kykotsmovi PM3	---
355428111084601	Goldtooth	3A-28
355924110485001	Howell Mesa	3K-311
360055110304001	BM observation well 5	4T-519
360217111122601	Tuba City	3K-325
360527110122501	Piñon NTUA 1	---
360614110130801	Piñon PM6	---
360734111144801	Tuba City	3T-333
360904111140201	Tuba City NTUA 1	3T-508
360918111080701	Tuba City Rare Metals 2	---
360924111142201	Tuba City NTUA 3	---
360953111142401	Tuba City NTUA 4	3T-546
361225110240701	BM observation well 6	---
361737110180301	Forest Lake NTUA 1	4T-523
361832109462701	Rough Rock	10T-258
362043110030501	Kits'iili NTUA 2	---
362149109463301	Rough Rock	10R-111
362418109514601	Rough Rock PM5	---
362406110563201	White Mesa Arch	1K-214
362823109463101	Rough Rock	10R-119
362936109564101	BM observation well 1	8T-537
363005110250901	Peabody 2	---
363013109584901	Sweetwater Mesa	8K-443
363103109445201	Rough Rock	9Y-95
363143110355001	BM observation well 4	2T-514
363213110342001	Shonto Southeast	2K-301
363232109465601	Rough Rock	9Y-92
363309110420501	Shonto	2K-300
363423110305501	Shonto Southeast	2T-502
363558110392501	Shonto PM2	---
363727110274501	Long House Valley	8T-510
363850110100801	BM observation well 2	8T-538
364034110240001	Marsh Pass	8T-522
364226110171701	Kayenta West	8T-541
364248109514601	Northeast Rough Rock	8A-180
364338110154601	BM observation well 3	8T-500
364344110151201	Kayenta PM2	8A-295
365045109504001	Dennehotso PM2	---

Table 4. Withdrawals from the N aquifer by well system, Black Mesa area, northeastern Arizona, calendar year 2011.

[Withdrawals, in acre-feet, are from flowmeter measurements. BIA, Bureau of Indian Affairs; NTUA, Navajo Tribal Utility Authority; USGS, U.S. Geological Survey; Peabody, Peabody Western Coal Company; Hopi, Hopi Village Administrations]

Well system (one or more wells)	Owner	Source of data	Withdrawals	
			Confined aquifer	Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	2.9	
Dennehotso	BIA	USGS/BIA		12.7
Hopi High School	BIA	USGS/BIA	17.3	
Hotevilla	BIA	USGS/BIA	24.5	
Kayenta	BIA	USGS/BIA	26.9	
Keams Canyon	BIA	USGS/BIA	59.1	
Low Mountain	BIA	USGS/BIA	[1]0	
Piñon	BIA	USGS/BIA	[1]0	
Red Lake	BIA	USGS/BIA		5.1
Rocky Ridge	BIA	USGS/BIA	5.7	
Rough Rock	BIA	USGS/BIA	18.8	
Second Mesa	BIA	USGS/BIA	7.5	
Shonto	BIA	USGS/BIA		147.5
Tuba City	BIA	USGS/BIA		80.5
Chilchinbito	NTUA	USGS/NTUA	61.6	
Dennehotso	NTUA	USGS/NTUA		47.4
Forest Lake	NTUA	USGS/NTUA	15.5	
Hard Rock	NTUA	USGS/NTUA	50.2	
Kayenta	NTUA	USGS/NTUA	[2]413.9	
Kits'iili	NTUA	USGS/NTUA	21.1	
Piñon	NTUA	USGS/NTUA	336.5	
Red Lake	NTUA	USGS/NTUA		54.0
Rough Rock	NTUA	USGS/NTUA	41.7	
Shonto	NTUA	USGS/NTUA		18.7
Shonto Junction	NTUA	USGS/NTUA		92.8
Tuba City	NTUA	USGS/NTUA		1,081
Mine Well Field	Peabody	Peabody	1,390	
Bacavi	Hopi	USGS/Hopi	23.6	
Hopi Civic Center	Hopi	USGS/Hopi	1.8	
Hopi Cultural Center	Hopi	USGS/Hopi	7.2	
Kykotsmovi	Hopi	USGS/Hopi	66.9	
Mishongnovi	Hopi	USGS/Hopi	5.2	
Moenkopi	Hopi	USGS/Hopi		87.1
Polacca	Hopi	USGS/Hopi	185.3	
Shipaulovi	Hopi	USGS/Hopi	20.3	
Shungopovi	Hopi	USGS/Hopi	38.1	

[1]Well taken out of service.

[2]Estimated value due to partial record.

the 34 wells used for water-level measurements as well as identification information for wells used for water-quality sampling is shown in table 3. Streamflow data are collected at four USGS gaging stations and are available online (http://waterdata.usgs.gov/az/nwis/rt). All annual data reported in this document are for calendar years beginning January 1 and ending December 31; however, streamflow data are reported in water years beginning October 1 and ending September 30, with the exception of tables 10–13, which are reported in calendar years.

Withdrawals from the N Aquifer

Total annual withdrawals from the N aquifer are monitored on a continuing basis to determine the effects from industrial and municipal pumping. Withdrawals from the N aquifer are separated into three categories: (1) industrial withdrawals from the confined area, (2) municipal withdrawals from the confined area, and (3) municipal withdrawals from the unconfined areas. The industrial category includes eight wells in the PWCC well field in the northern Black Mesa area. The BIA, NTUA, and Hopi Tribe operate about 70 municipal wells that are combined into 36 well systems. Information about withdrawals from N aquifer is compiled primarily on the basis of metered data from individual wells operated by the BIA, NTUA, and Hopi Tribe (table 4).

Withdrawals from wells equipped with windmills are not measured in this monitoring program and are not included in total withdrawal values reported here. About 270 windmills in the Black Mesa area withdraw water from the D, N, Toreva (T), and alluvial aquifers, primarily for feeding livestock. The estimated total withdrawal by the windmills from the N aquifer is about 65 acre-ft / yr (HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., 1999). The total withdrawal by the windmills is less than 1 percent of the total annual withdrawal from the N aquifer.

Withdrawals in Calendar Year 2011 Compared to Previous Years

In 2011, the total groundwater withdrawal from the N aquifer was about 4,480 acre-ft (table 1). Total withdrawals for municipal use in 2011 was about 3,090 acre-ft; withdrawals from the confined area totaled about 1,460 acre-ft, while withdrawals from the unconfined areas totaled about 1,630 acre-ft. Withdrawals for industrial use totaled about 1,390 acre-ft, a 19-percent increase from 2010 (tables 1 and 5). Total withdrawals in 2011 for municipal use increased by about 8 percent from the previous year; this equates to a 1-percent increase in withdrawals from the confined areas of the aquifer, and a 15-percent increase in withdrawals from the unconfined areas.

Table 5. Total, industrial, and municipal withdrawals from the N aquifer for discrete time periods during 1965 to 2011, Black Mesa area, northeastern Arizona.

Period	Withdrawals, in acre-feet			Percent	
	Total	Industrial	Municipal	Industrial	Municipal
1965–2011	243,660	145,630	98,030	60	40
1965–2005	218,300	138,100	80,200	63	37
2006–2011	25,360	7,530	17,830	30	70
2011	4,480	1,390	3,090	31	69

Withdrawals from the N aquifer have varied from 1965 to the present but generally increased from 1965 to 2005 and decreased from 2006 to 2011. Beginning in 2006, the Peabody Western Coal Company reduced their pumping by 70 percent, a reduction that is reflected by a decrease in total annual withdrawals from 2005 by about 42 percent (tables 1 and 5, fig. 3). Total withdrawal for the period of record (1965–2011) totaled 243,663 acre-ft; industrial withdrawals were 60 percent and municipal withdrawals were 40 percent of total withdrawals (table 5). During 1965 to 2005, total annual withdrawals increased from 70 acre-ft to a maximum of 8,000 acre-ft (table 1); industrial withdrawals were 63 percent and municipal withdrawals were 37 percent of total withdrawals (table 5). A change in the amount of water being pumped from the N aquifer occurred in 2006; industrial withdrawals accounted for only about 30 percent of the total withdrawals compared to 63 percent the previous year (table 5). From 2006 to 2011, withdrawals totaled 25,363 acre-ft; industrial withdrawals were 30 percent and municipal withdrawals were 70 percent of total withdrawals (table 5). Total withdrawals in 2011 were 4,483 acre-ft, with 31 percent from industrial withdrawals and 69 percent from municipal withdrawals (table 5).

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

Groundwater Levels in the N Aquifer

Groundwater levels are monitored in the N aquifer to determine the effects that withdrawals have on the potentiometric surface of the aquifer. Groundwater in the N aquifer is under confined conditions in the central part of the study area and under unconfined or water-table conditions around the periphery (fig. 4). From the recharge areas near Shonto, groundwater moves radially to the southwest toward Tuba City, to the south toward the Hopi Reservation, and to the east toward Rough Rock and Dennehotso (Eychaner, 1983).

Groundwater levels are measured once a year at the same time of year to limit the effect of seasonal variability. Groundwater levels are compared with levels from previous years to determine short-term changes and also are compared to prestress water levels to determine long-term changes. Only water levels from municipal and stock wells that were not considered to have been recently pumped, affected by nearby pumping, or blocked or obstructed are compared. During February and March 2012, water levels in 33 of the 34 wells having annual measurements from both 2011 and 2012 met these criteria (table 6). Of the 33 wells, 6 are continuous-recording observation wells. Water levels were measured by electric tape in these six wells three times during water year 2012 to verify or update instrument calibration.

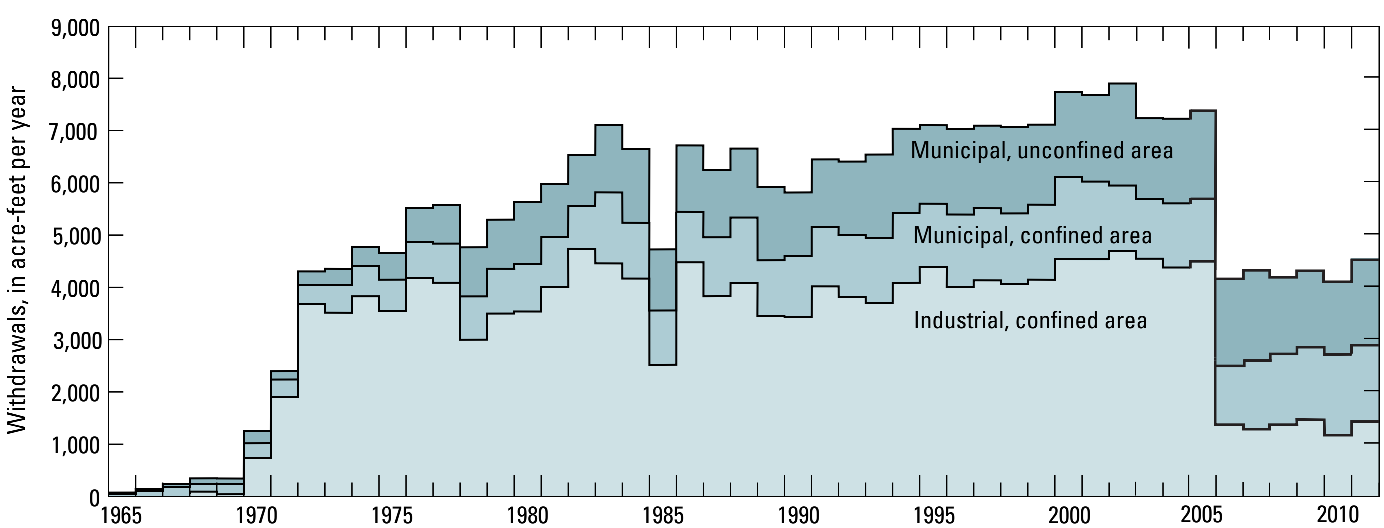
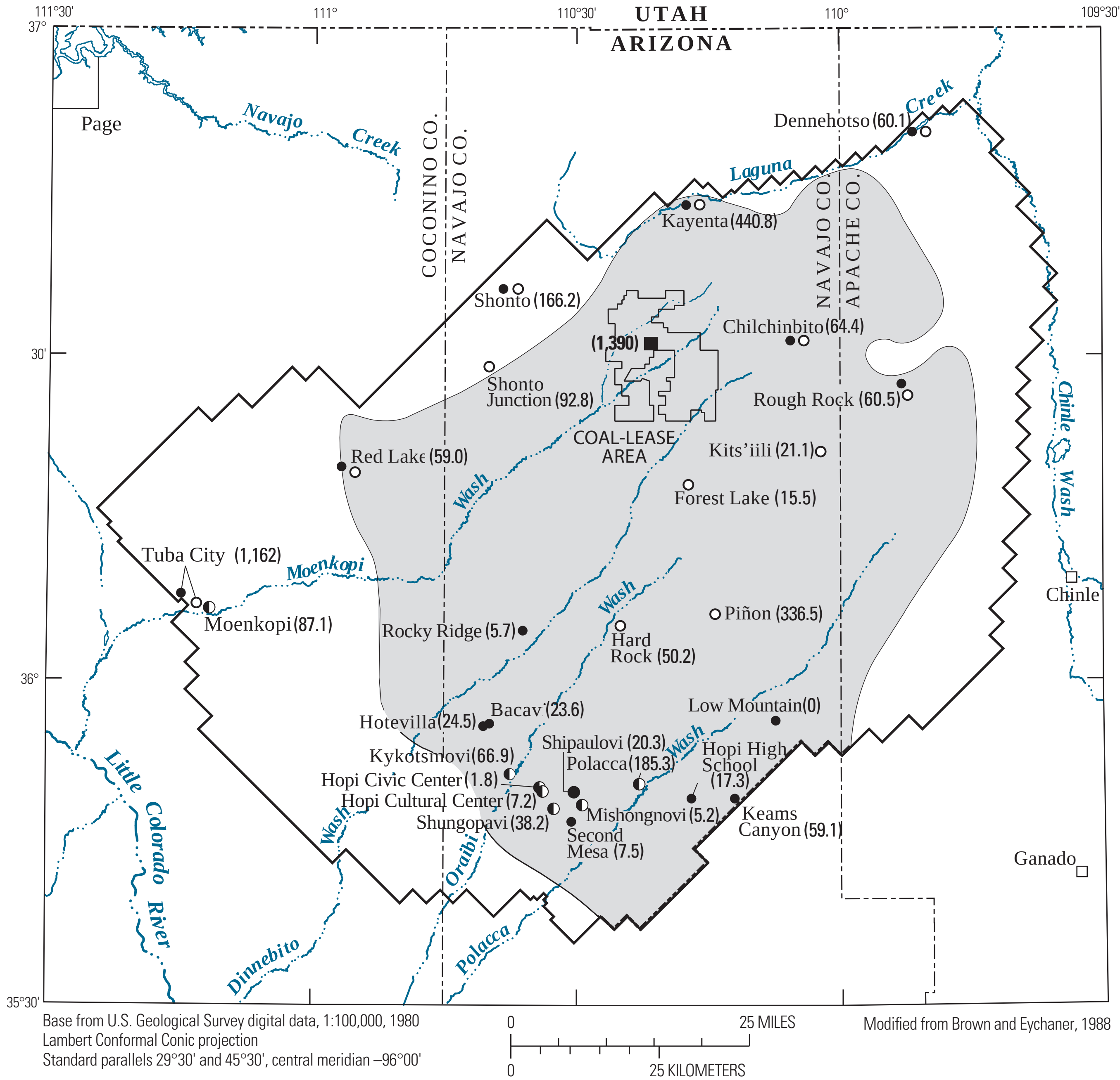


Figure 3. Plot of annual withdrawals from the N aquifer, Black Mesa area, northeastern Arizona, 1965–2011.



EXPLANATION

CONFINED AND UNCONFINED CONDITIONS IN THE N AQUIFER WITHIN MODEL BOUNDARY

- Confined
- Unconfined
- APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS—From Brown and Eychaner (1988)
- BOUNDARY OF MATHEMATICAL MODEL—From Brown and Eychaner (1988)

WELL-SYSTEM OWNER

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

Piñon (336.5) WITHDRAWALS FROM THE N AQUIFER—Piñion, well-system name; 336.5, total withdrawal in acre-feet for 2011. The total is cumulative at locations served by multiple wells

Figure 4. Map showing locations of well systems monitored for annual withdrawals from the N aquifer, Black Mesa area, notheastern Arizona, calendar year 2011.

Table 6. Water-level changes in monitoring program wells completed in the N aquifer, Black Mesa area, northeastern Arizona, prestress period to calendar year 2012.

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

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year (feet)		Water level (feet below land surface), 2012	Prestress period water level		Change in water level from prestress period to 2011 (feet)
		2011	2012		Feet below land surface	Date	
Unconfined areas							
BM observation well 1[1]	8T-537	0.0	-0.1	374.5	374.0	([1])	-0.5
BM observation well 4[1]	2T-514	-0.2	0.2	217.0	216.0	([1])	-1.0
Goldtooth	3A-28	-0.4	-2.3	233.2	230.0	10–29–53	-3.2
Long House Valley	8T-510	-0.8	-1.0	136.0	99.4	08–22–67	-36.6
Northeast Rough Rock	8A-180	([2])	([2])	44.6	46.9	11–13–53	2.3
Rough Rock	9Y-95	1.0	-1.4	107.0	119.5	08–03–49	12.5
Do.	9Y-92	3.1	0.3	164.8	168.8	12–13–52	4.0
Shonto	2K-300	-0.2	0.2	171.4	176.5	06–13–50	5.1
Shonto Southeast	2K-301	-0.4	0.3	289.3	283.9	12–10–52	-5.4
Do.	2T-502	4.0	-1.4	416.6	405.8	08–22–67	-10.8
Tuba City	3T-333	-0.2	0.6	28.2	23.0	12–02–55	-5.2
Do.	3K-325	-0.8	1.1	202.0	208.0	06–30–55	6.0
Tuba City Rare Metals 2	---	0.2	0.2	49.4	57.0	09–24–55	7.6
Tuba City NTUA 1	3T-508	8.5	-4.2	68.6	29.0	02–12–69	-39.6
Tuba City NTUA 3	---	5.4	-4.6	63.4	34.2	11–08–71	-29.2
Tuba City NTUA 4	3T-546	9.3	-7.1	64.1	33.7	08–06–71	-30.4
Confined area							
BM observation well 2[1]	8T-538	0.1	1.1	216.6	125.0	([1])	-91.6
BM observation well 3[1]	8T-500	-2.0	0.2	163.8	55.0	04–29–63	-108.8
BM observation well 5[1]	4T-519	-0.8	-0.3	427.2	324.0	([1])	-103.2
BM observation well 6[1]	---	2.1	2.5	848.0	697.0	([1])	-151.0
Forest Lake NTUA 1	4T-523	2.4	4.6	1,173.8	1,096R	05–21–82	-77.8
Howell Mesa	3K-311	-2.0	6.4	444.0	463.0	11–03–53	19.0
Kayenta West	8T-541	9.7	-1.9	298.1	230.0	03–17–76	-68.1
Keams Canyon PM2	---	-1.4	8.4	498.0	292.5	06–10–70	-205.5
Kits'iili NTUA 2	---	-3.6	4.2	1,335.6	[3]1,297.9	01–14–99	-37.7
Kykotsmovi PM1	---	0.5	-0.1	212.1	220.0	05–20–67	7.9
Kykotsmovi PM3	---	-1.4	-0.1	250.6	210.0	08–28–68	-40.6
Marsh Pass	8T-522	0.5	-0.5	127.6	125.5	02–07–72	-2.1
Piñon PM6	---	-4.2	-4.0	917.0	743.6	05–28–70	-173.4
Rough Rock	10R-119	-1.7	1.5	256.9	256.6	12–02–53	-0.3
Do.	10T-258	-2.8	0.8	311.8	301.0	04–14–60	-10.8
Do.	10R-111	6.0	-6.1	198.8	170.0	08–04–54	-28.8
Sweetwater Mesa	8K-443	-0.6	-1.0	545.4	529.4	09–26–67	-16.0
White Mesa Arch	1K-214	-0.1	-0.1	219.8	188.0	06–04–53	-31.8

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

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

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

Table 7. Well-construction characteristics, depth to top of N aquifer, and type of data collected for wells in monitoring program 2011–12, Black Mesa area, northeastern Arizona.

Bureau of Indian Affairs site number, and (or) common name	Date well was completed	Land-surface elevation (feet)	Well depth	Screened/open interval(s)	Depth to top of N aquifer[1]	Type of data collected
			In feet below land surface			
8T-537 (BM observation well1)	02–01–72	5,864	851	00–360; 400–420; 500–520; 600–620; 730–780	290	Water level
8T-538 (BM observation well 2)	01–29–72	5,656	1,338	470–1,338	452	Water level
8T-500 (BM observation well 3)	07–29–59	5,724	868	712–868	155	Water level
2T-514 (BM observation well 4)	02–15–72	6,320	400	250–400	160	Water level
4T-519 (BM observation well 5)	02–25–72	5,869	1,683	1,521–1,683	1,520	Water level
BM observation well 6	01–31–77	6,332	2,507	1,954–2,506	1,950	Water level
1K-214	05–26–50	5,771	356	168–356	250	Water level
2K-300	[3]06–00–50	6,264	300	260–300	0	Water level
2K-301	06–12–50	6,435	500	318–328; 378–500	[2]30	Water level
2T-502	08–10–59	6,670	523	12–523	25	Water level
3A-28	04–19–35	5,381	358	([4])	60	Water level
3K-311	[3]11–00–34	5,855	745	380–395; 605–745	615	Water level
3K-325	06–01–55	5,250	450	75–450	[2]30	Water level
3T-333	12–02–55	4,940	229	63–229	24	Water level
3T-508 (Tuba City NTUA1)	08–25–59	5,119	475	([4])	0	Water level, withdrawals
3T-546 (Tuba City NTUA4)	[3]08–00–71	5,206	612	256–556	0	
4T-523 (Forest Lake NTUA1)	10–01–80	6,654	2,674	1,870–1,910; 2,070–2,210; 2,250–2,674	([5])	Water level, water chemistry, withdrawals
8A-180	01–20–39	5,200	107	60–107	[2]40	Water level
8A-295 (Kayenta PM2)	[3]00–00–36	5,623	840	268–280; 691–788	95	Water chemistry
8K-443	08–15–57	6,024	720	619–720	590	Water level
8T-510	02–11–63	6,262	314	130–314	[2]125	Water level
8T-522	[3]07–00–63	6,040	933	180–933	480	Water level
8T-541	03–17–76	5,885	890	740–890	700	Water level
9Y-92	01–02–39	5,615	300	154–300	[2]50	Water level
9Y-95	11–05–37	5,633	300	145–300	[2]68	Water level
10R-111	04–11–35	5,757	360	267–360	210	Water level
10R-119	01–09–35	5,775	360	([4])	310	Water level
10T-258	04–12–60	5,903	670	465–670	460	Water level
Dennehotso PM2	06–05–64	5,005	675	475–675	8	Water chemistry
Keams Canyon PM2	[3]05–00–70	5,809	1,106	906–1,106	900	Water level, withdrawals,water chemistry
Kits'iili NTUA2	10–30–93	6,780	2,549	2,217–2,223 2,240–2,256 2,314–2,324 2,344–2,394 2,472–2,527	2,205	Water level, withdrawals
Kykotsmovi PM1	02–20–67	5,657	995	655–675 890–990	880	Water level, withdrawals
Kykotsmovi PM2	10–14–77	5,760	1,155	950–1,155	890	Water chemistry, withdrawals
Kykotsmovi PM3	08–07–68	5,618	1,220	850–1,220	840	Water level, withdrawals
Low Mountain PM2	[3]04–00–72	6,123	1,343	1,181–1,262	1,153	Withdrawals
Peabody 2	[3]06–00–67	6,530	3,636	1,816–3,603	728	Water chemistry, withdrawals
Piñon NTUA 1	02–25–80	6,336	2,350	1,860–2,350	1,850	Water chemistry, withdrawals
Rough Rock PM5	06–27–64	6,299	1,425	1,175–1,425	1,156	Water chemistry, withdrawals
Second Mesa PM2	[3]10–00–68	5,777	1,090	740–1,090	720	Water chemistry, withdrawals
Piñon PM6	[3]02–00–70	6,397	2,248	1,895–2,243	1,870	Water level, withdrawals
Shonto PM2	05–05–61	6,465	554	485–510; 514–539	0	Water chemistry
Tuba City NTUA 3	[3]10–00–71	5,176	442	142–442	34	Water level, withdrawals
Tuba City Rare Metals 2	[3]09–00–55	5,108	705	100–705	255	Water level

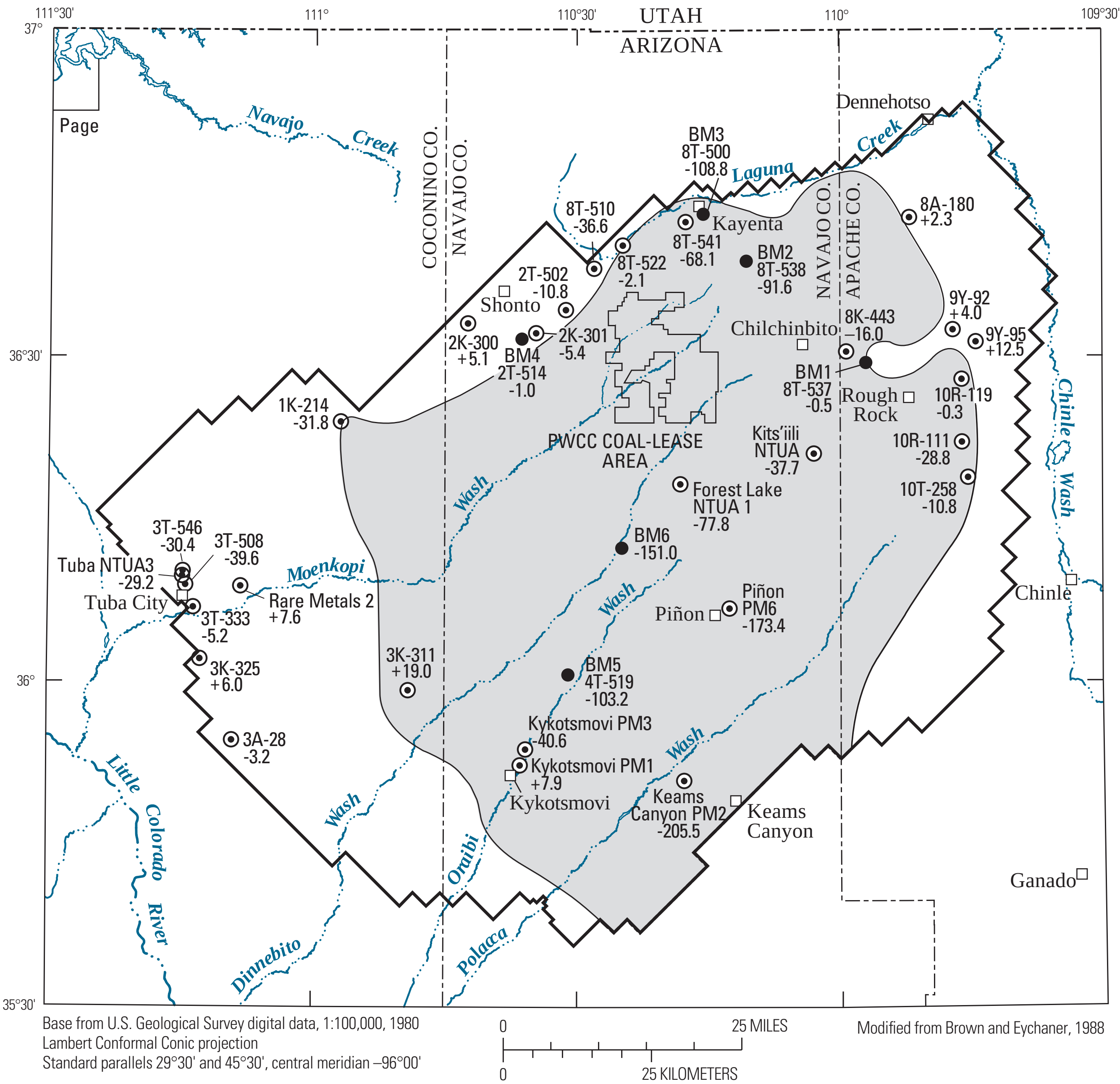
[1]Depth to top of N aquifer from Eychaner (1983) and Brown and Eychaner (1988).

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

[3]00 indicates day is unknown.

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

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



EXPLANATION

CONFINED AND UNCONFINED CONDITIONS IN THE N AQUIFER

Confined area within the boundary of the mathematical boundary

Unconfined area within the boundary of the mathematical boundary

APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS–from Brown and Eychaner (1988)

BOUNDARY OF MATHEMATICAL MODEL–from Brown and Eychaner (1988)

2K-300 +5.1 — WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 2K-300, is Bureau of Indian Affairs site number; second entry, +5.1, is change in water level, in feet, between measurement made during the prestress period and measurement made during 2012

BM2 8T-538 –91.6 — CONTINUOUS WATER-LEVEL RECORDING SITE (OBSERVATION WELL) MAINTAINED BY THE U.S. GEOLOGICAL SURVEY—First entry, BM2, is U.S. Geological Survey well number; second entry, 8T-538, is Bureau of Indian Affairs site number; third entry, –91.6, is change in water level, in feet, from simulated prestress period to 2012

Figure 5. Map showing water-level changes in N-aquifer wells from the prestress period (prior to 1965) to 2012, Black Mesa area, northeastern Arizona.

Table 8. Median changes in water levels in monitoring-program wells, 2011–12 and prestress period (prior to 1965) to 2012, N aquifer, Black Mesa area, northeastern Arizona.

Years	Aquifer conditions	Number of wells	Median change in water level (feet)
2011–2012	All	33	-0.1
	Unconfined	15	-0.1
	Confined	18	0.0
Prestress–2012	All	34	-13.4
	Unconfined	16	-2.1
	Confined	18	-39.1

The wells used for water-level measurements are distributed throughout the study area (fig. 5). The wells were constructed between 1934 and 1993 and the total well depths range from 107 ft near Northeast Rough Rock (8A-180) to 3,636 ft near the PWCC. Depths to the top of the N aquifer range from 0 ft near Tuba City to 2,205 ft at Kits'iili NTUA2 (table 7).

From 2011 to 2012, water levels decreased in 17 of the 33 wells for which comparisons could be made (table 6). The median water-level change in the 33 wells was -0.1 ft (table 8). In the unconfined parts of the aquifer, water levels declined in 8 of the 15 wells measured (table 6), and the median water-level change was -0.1 ft (table 8). Water-level changes ranged from -7.1 ft at Tuba City NTUA 4 (3T-546) to +1.1 ft at Tuba City (3K-325) (table 6). In the confined parts of the aquifer, water levels declined in 9 of 18 wells measured from 2011 to 2012. The median water-level change was 0.0 ft (table 8). Water-level changes ranged from -4.0 ft at Piñon PM6 to +8.4 ft at Keams Canyon PM2 (table 6).

From the prestress period (before 1965) to 2012, the median water-level change in 34 wells measured in 2012 was -13.4 ft (table 8). Water levels in 16 unconfined wells had a median change of -2.1 ft (table 8), and water-level changes ranged from -39.6 ft at Tuba City NTUA 1(3T-508) to +12.5 ft at Rough Rock (9Y-95) (fig. 5 and table 6). Water levels in 18 wells in the confined part of the aquifer had a median change of -39.1 ft (table 8), and water-level changes ranged from -205.5 ft at Keams Canyon PM2 to +19.0 ft at Howell Mesa 3K-311 (fig. 5 and table 6).

Hydrographs of groundwater levels in the network of wells observed annually show the temporal changes from the 1950s to the present (fig. 6). In most of the unconfined area, water levels have changed only slightly (generally less than 10 ft). Near the Shonto area, however, the water level in well 8T-510 has declined about 36.6 ft (figs. 5 and 6; table 6). Water levels have declined in most of the confined area but the magnitudes of declines are varied. Larger declines have occurred near the municipal pumping centers (wells Piñon PM6, Keams Canyon PM2) and near the wells for PWCC (BM6). Smaller declines occurred away from pumping centers in or near towns in the study area (wells 10T-258, 8K-443, 10R-111, 8T-522; figs. 5 and 6)

Hydrographs for the Black Mesa continuous-record observation wells show water levels since the early 1970s (fig. 7). The two wells in the unconfined areas (BM1 and BM4) have shown small seasonal or year-to-year variation since 1972 but no apparent long-term decline. In the confined area, water levels (that have not been corrected for barometric pressure effects or seasonal effects) in wells BM2, BM3, and BM5 have consistently declined since the early 1970s (fig. 7). Since October 2009, water levels in BM2 have not declined and have flattened out. Water levels in BM6 in the confined area had consistently declined between the mid-1970s and 2007, when a distinct change occurred in the trend of the water level from decreasing to increasing. The level in BM6 reached a maximum depth to water of 861.2 ft below land surface on December 4, 2006, and recovered to a water level of 847.1 ft below land surface on September 11, 2012, about 14 feet of total recovery to date.

Spring Discharge from the N Aquifer

The effect of withdrawals from the N aquifer on the water quality and discharge of springs around Black Mesa is a concern of the cooperators of this program. Groundwater in the N aquifer discharges from many springs around the margins of Black Mesa, and changes to the discharge from those springs, could indicate effects of withdrawals from the N aquifer. Moenkopi School Spring, Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso have been measured intermittently since the late 1980's and all four springs were measured for discharge in 2012.

Moenkopi School Spring is in the western part of the Black Mesa area and is also called Susunova Spring by the Hopi Tribe (fig. 8). Discharge from Moenkopi School Spring was measured in June 2012 by the volumetric method and compared to discharge data from previous years to determine changes over time (fig. 9). The trend for discharge measurements at this spring is not corrected for seasonal variability, but discharge measurements are made annually at or close to the same time of year. In 2012, the measured discharge from Moenkopi School Spring was 6.3 gal/min (table 9). From 2011 to 2012, discharge decreased by 30 percent; for the period of record, discharge measurements have a significant ($p<0.05$) decreasing trend, and linear regression analysis indicates that spring discharge decreases an average of about 0.3 gal/yr (fig. 9 and table 9).

Burro Spring is in the southwestern part of the study area and discharges from the Navajo Sandstone and alluvium (fig. 8). Burro Spring discharges from the aquifer through a metal pipe and into a cement trough for livestock. The 2012 discharge measurement and water-quality sampling point was from the end of the metal pipe before the livestock trough. Discharge at Burro Spring has fluctuated since 1989

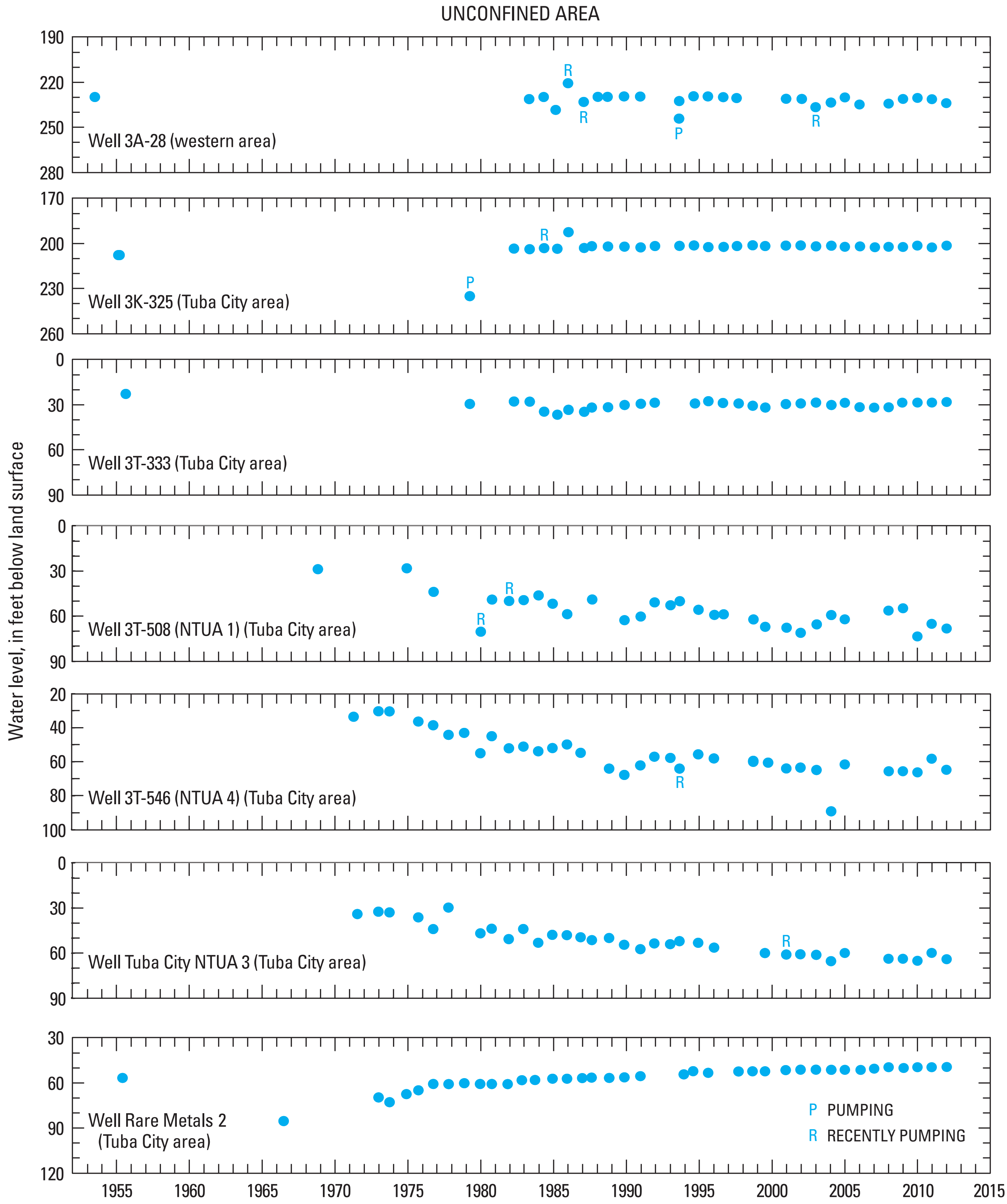


Figure 6. Plots of observed water levels (1950–2012) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.

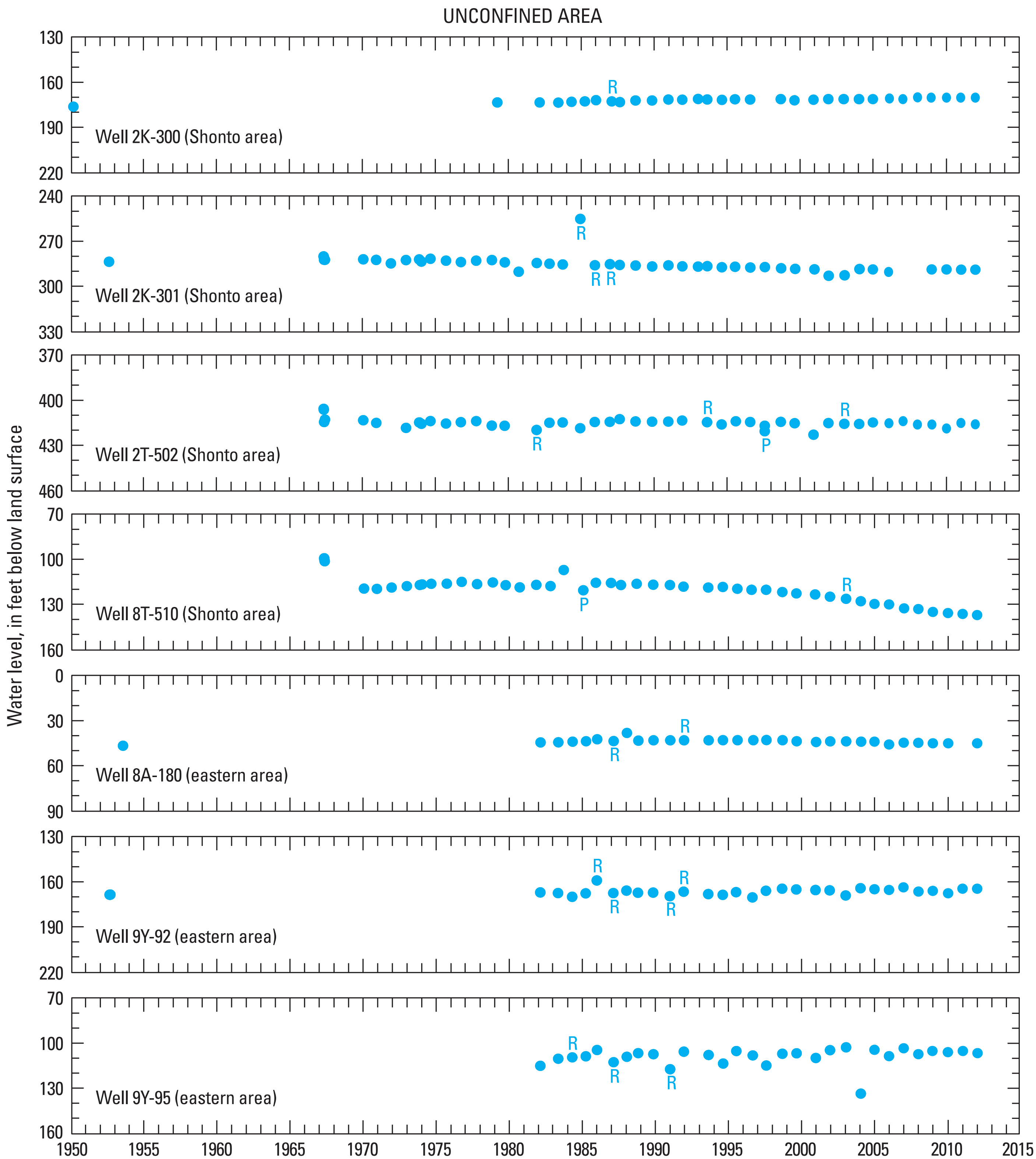


Figure 6. Plots of observed water levels (1950–2012) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.—Continued

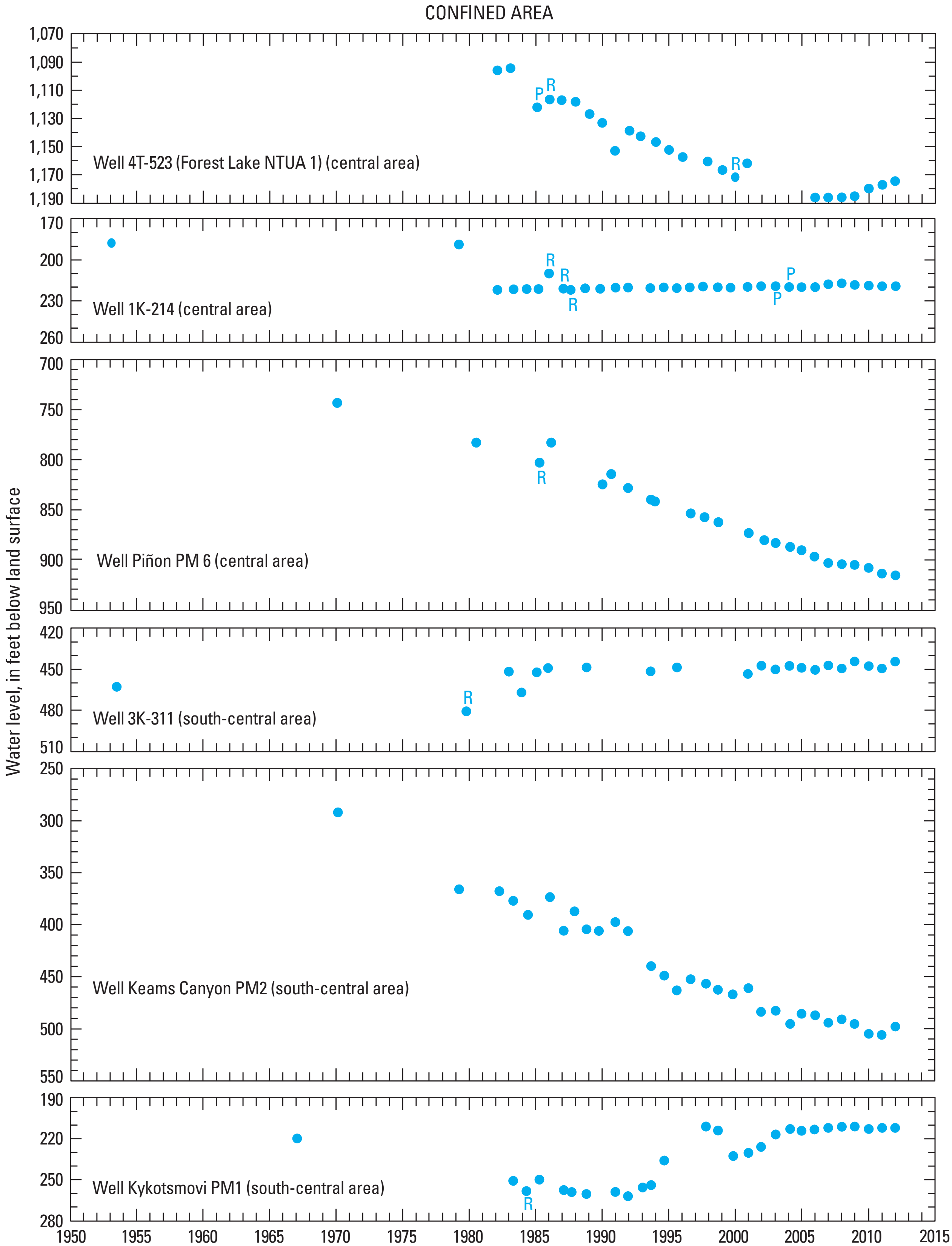


Figure 6. Plots of observed water levels (1950–2012) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.—Continued

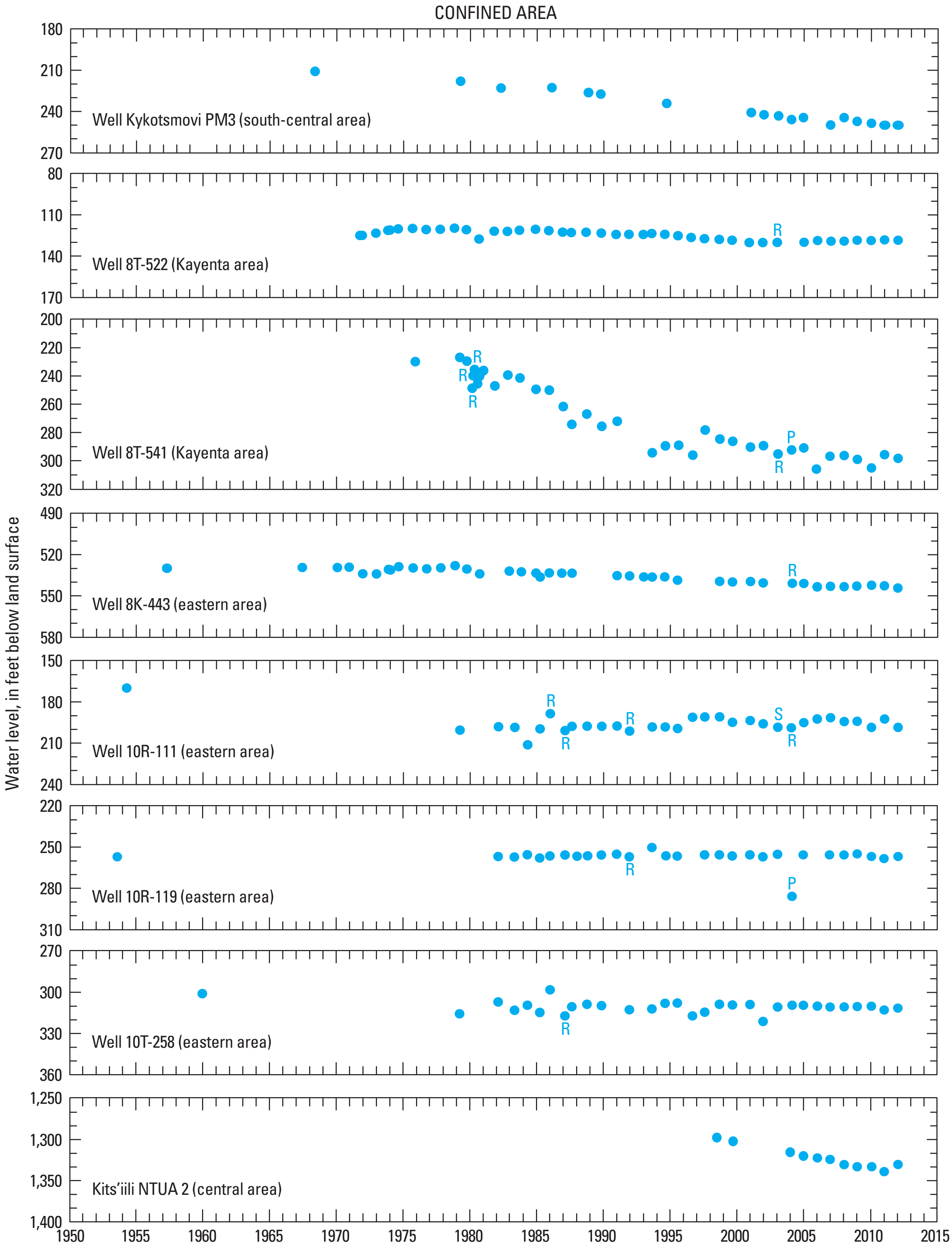


Figure 6. Plots of observed water levels (1950–2012) in annual observation-well network, N aquifer, Black Mesa area, northeastern Arizona.—Continued

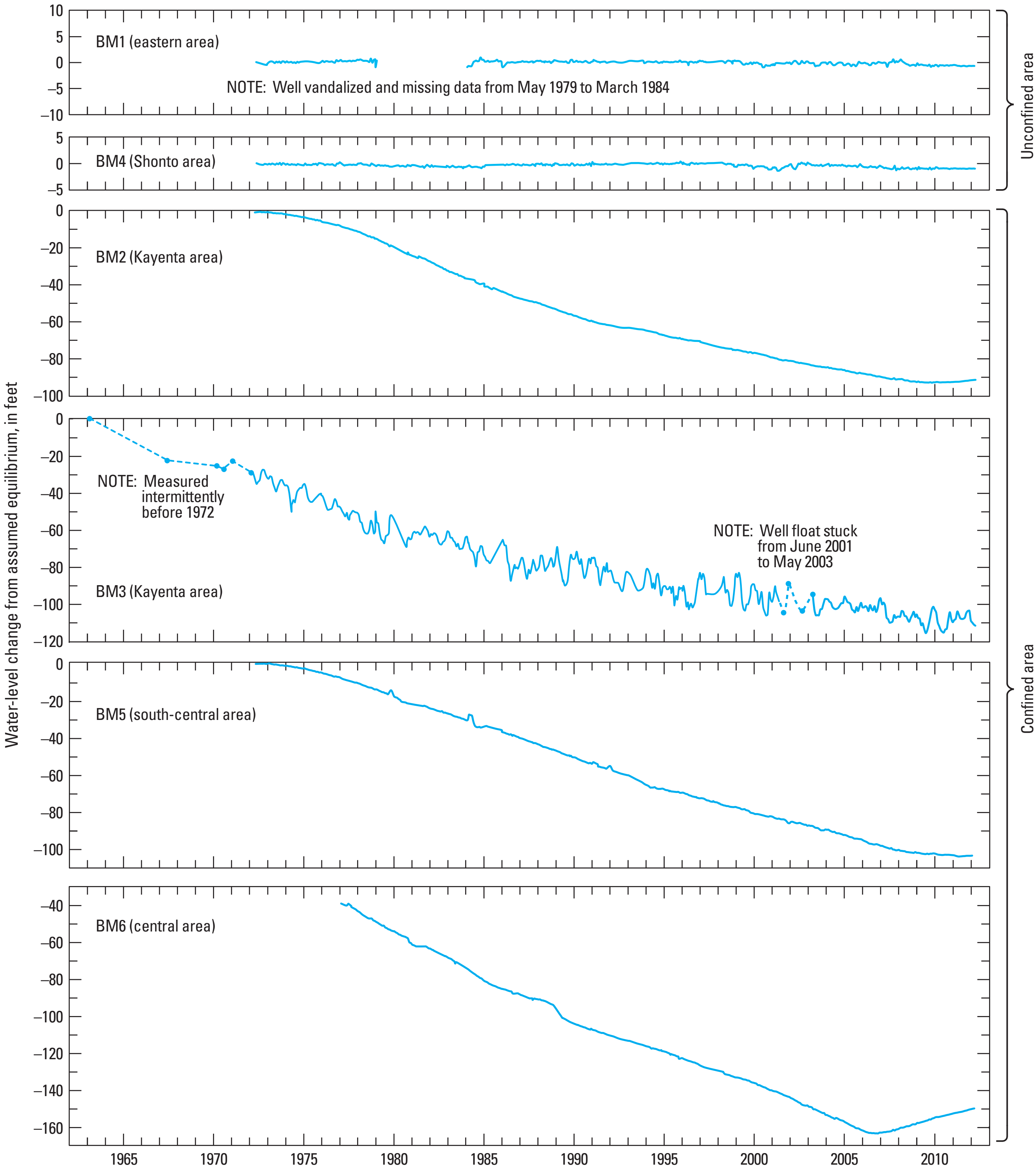
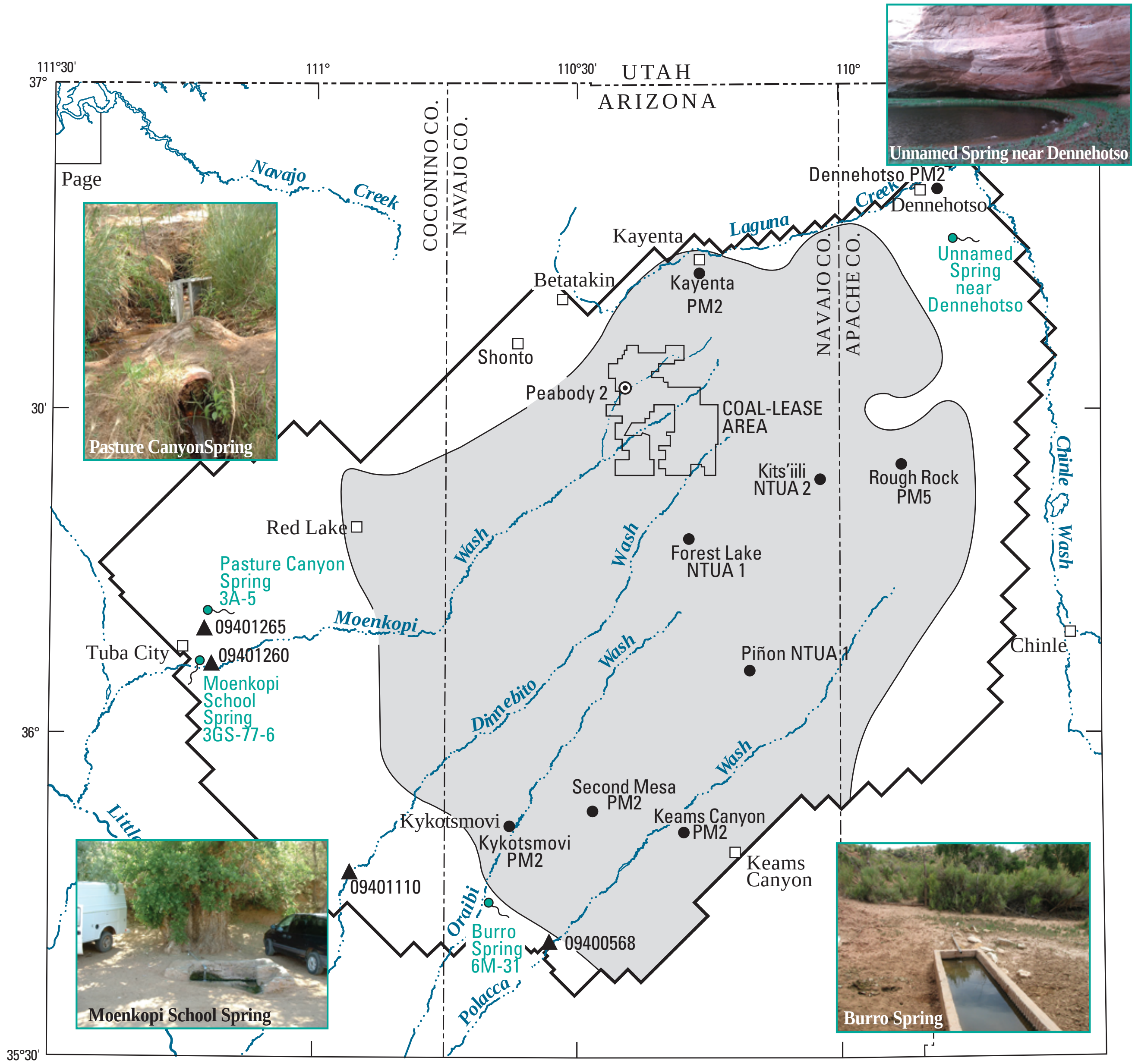


Figure 7. Plots of observed water-level changes in continuous-record observation wells BM1–BM-6 over 1963–2012 in the N aquifer, Black Mesa area, northeastern Arizona.



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

0 25 MILES
0 25 KILOMETERS

Modified from Brown and Eychaner, 1988

EXPLANATION

CONFINED AND UNCONFINED CONDITIONS IN THE N AQUIFER WITHIN MODEL BOUNDARY
- Confined
- Unconfined

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

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

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

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

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

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

Figure 8. Map of surface-water and water-chemistry data-collection sites, N aquifer, Black Mesa area, northeastern Arizona, 2011–12.

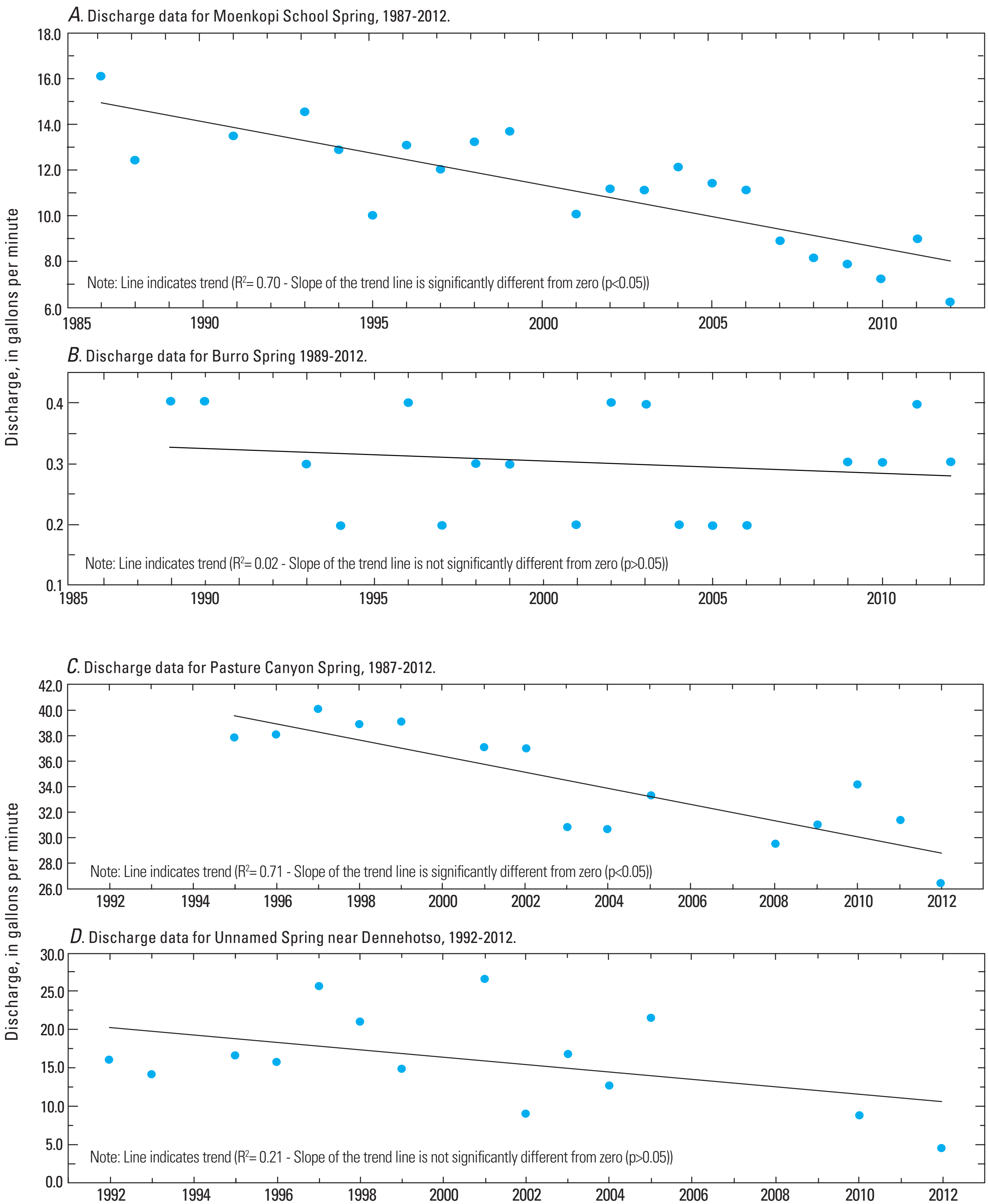


Figure 9. Plots of discharge from *A*, Moenkopi School Spring; *B*, Burro Spring; *C*, Pasture Canyon Spring; and *D*, Unnamed Spring near Dennehotso, N aquifer, Black Mesa area, northeastern Arizona, 1987–2012. Data from 1952 measurement at Moenkopi School Spring are not shown because measurement was from a different measuring location. Data from 1988 to 1993 measurements at Pasture Canyon Spring are not shown because they were from a different measuring location. Trend lines were generated using method of least squares.

Table 9. Discharge from Moenkopi School Spring, Burro Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso, N aquifer, Black Mesa area, northeastern Arizona, 1987–2012.

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

Rock formation(s)	Date of measurement	Discharge, in gallons per minute	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Bureau of Indian Affairs site number (3GS-77-6), at Moenkopi School Spring[1]			Bureau of Indian Affairs site number (6M-31), at Burro Spring[1]		
Navajo Sandstone[2]	05–16–52	40.0	Navajo Sandstone	12–15–89	0.4
	04–22–87	[3]16.0		12–13–90	0.4
	11–29–88	[3]12.5		03–18–93	0.3
	02–21–91	[3]13.5		12–08–94	0.2
	04–07–93	[3]14.6		12–17–96	0.4
	12–07–94	[3]12.9		12–30–97	0.2
	12–04–95	[3]10.0		12–08–98	0.3
	12–16-96	[3]13.1		12–07–99	0.3
	12–17–97	[3]12.0		04–02–01	0.2
	12–08–98	[3]13.3		04–04–02	0.4
	12–13–99	[3]13.7		04–30–03	0.4
	03–12–01	[3]10.2		04–06–04	[6]0.2
	06–19–02	[3]11.2		03–28–05	0.2
	05–01–03	[3]11.2		03–28–06	0.2
	03–29–04	[3]12.2		06–04–09	0.3
	04–04–05	[3]11.5		06–07–10	0.3
	03–13–06	[3]11.1		06–08–11	0.4
	05–31–07	[3]9.0		06–14–12	0.3
	06–03–08	[3]8.3			
	06–03–09	[3]8.0			
	06–14–10	[3]7.4			
	06–10–11	[3]9.0			
	06–07–12	[3]6.3			
Bureau of Indian Affairs site number (3A-5), at Pasture Canyon Spring[1]			Bureau of Indian Affairs site number (8A-224), at Unnamed Spring at Dennehotso[4]		
Navajo Sandstone, alluvium			Navajo Sandstone	10–06–54	[7]1
	11–18–88	[4]211		06–27–84	[7]2
	03–24–92	[4]233		11–17–87	[7]5
	10–12–93	[4]211		03–26–92	16.0
	12–04–95	[5]38.0		10–22–93	14.4
	12–16–96	[5]38.0		12–05–95	17.0
	12–17–97	[5]40.0		12–19–96	15.7
	12–10–98	[5]39.0		12–30–97	25.6
	12–21–99	[5]39.0		12–14–98	21.0
	06–12–01	[5]37.0		12–15–99	14.8
	04–04–02	[5]37.0		03-14-01	26.8
	05–01–03	[5]30.9		04-03-02	5.8
	04–26–04	[5]30.6		7-15-02	9.0
	04–27–05	[5]33.3		05-01-03	17.1
	06–03–08	[5]29.4		04-01-04	12.6
	06–03–09	[5]31.1		04-06-05	21.5
	06–14–10	[5]34.3		06-17-10	9.0
	06–09–11	[5]31.4		06-04-12	4.5
	06–07–12	[5]26.5			

[1]Volumetric discharge measurement.

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

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

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

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

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

[7]Discharge measured at a different point than later measurements.

between 0.2 and 0.4 gal/min, but there is no significant ($p<0.05$) trend from linear regression and Kendall's tau analyses (fig. 9). In 2012, the measured discharge was 0.3 gal/min, a decrease of 25 percent from the previous year (fig. 9 and table 9).

Pasture Canyon Spring is in the western part of the study area and discharges from the Navajo Sandstone and alluvium (fig. 8). Discharge is measured at two locations: where the spring issues from the Navajo Sandstone (also the water-quality sampling point), and farther down the canyon at the USGS gaging station. The USGS gaging station at Pasture Canyon measures the discharge from Pasture Canyon Spring as well as additional discharge from seeps in Pasture Canyon. Discharge was measured at Pasture Canyon Spring at its emergence point in June 2012 using the volumetric method and showed a decrease in discharge of about 5 gal/min from the previous year (fig. 9 and table 9). When compared to discharge in previous years, a decreasing trend ($p<0.05$) is evident from both linear regression and Kendall's tau analyses. The trend in discharge data measured at this spring is not corrected for seasonal variability, but annual discharge measurements are made as close to the same time of year as is logistically possible. In 2012, the measured discharge was 26.5 gal/min, about a 16-percent decrease from 2011 (table 9).

Unnamed Spring near Dennehotso is the only spring in the northeastern part of the study area (fig. 8), and it discharges from the Navajo Sandstone. Measurements at Unnamed Spring near Dennehotso are made using a flume. There have been marked decreases in discharge at Unnamed Spring near Dennehotso since 2005. That year, the discharge at the spring was 21.5 gal/min, in 2010 the discharge was 9.0 gal/min, and in 2012 the measured discharge was only 4.5 gal/min— a 50-percent decrease from 2010 to 2012 (table 10). For the period of record, which includes a gap in data from 2005 to 2010, there is no appreciable trend in the data based on linear regression (p>0.05) and Kendall's tau analyses.

Surface-Water Discharge, Calendar Year 2011

Continuous surface-water discharge data have been collected at selected streams since the monitoring program began in 1971. Surface-water discharge in the study area generally originates as groundwater that discharges to streams and as surface runoff from rainfall or snowmelt. Groundwater discharges to some stream reaches at a fairly constant rate throughout the year; however, the amount of groundwater discharge that results in surface flow is affected by seasonal fluctuations in evapotranspiration (Thomas, 2002a). In contrast, the amount of rainfall or snowmelt runoff varies widely throughout the year. In the winter and spring, the amount and timing of snowmelt runoff are a result of the temporal variation in snow accumulation, air temperatures, and rate of snowmelt. Although rainfall can occur throughout the year, most occurs during the summer months. The amount and timing of rainfall runoff depend on the intensity and duration of thunderstorms during the summer and cyclonic storms during the fall, winter, and spring.

In 2011, discharge data were collected at four continuous-recording streamflow-gaging stations (tables 10–13). Data collection at these stations began in July 1976 (Moenkopi Wash at Moenkopi, 09401260), June 1993 (Dinnebito Wash near Sand Springs, 09401110), April 1994 (Polacca Wash near Second Mesa, 09400568), and August 2004 (Pasture Canyon Springs, 09401265; fig. 10*A*; table 14). The annual average discharges at the four streamflow-gaging stations vary during the periods of record (fig. 10*A*), and there are no significant trends in annual average discharge for Moenkopi Wash, Polacca Wash, Dinnebito Wash, and Pasture Canyon Springs.

Annual discharge can be influenced by precipitation; more precipitation generally results in greater annual discharge at a streamflow-gaging station. The annual precipitation measured at Navajo National Monument (Betatakin; fig. 1) from 1976 to 2011 averaged 12.6 in. (fig. 10*B*). In 2011, total precipitation measured 12.0 in. (fig 10*B*; National Climatic Data Center, 2012).

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

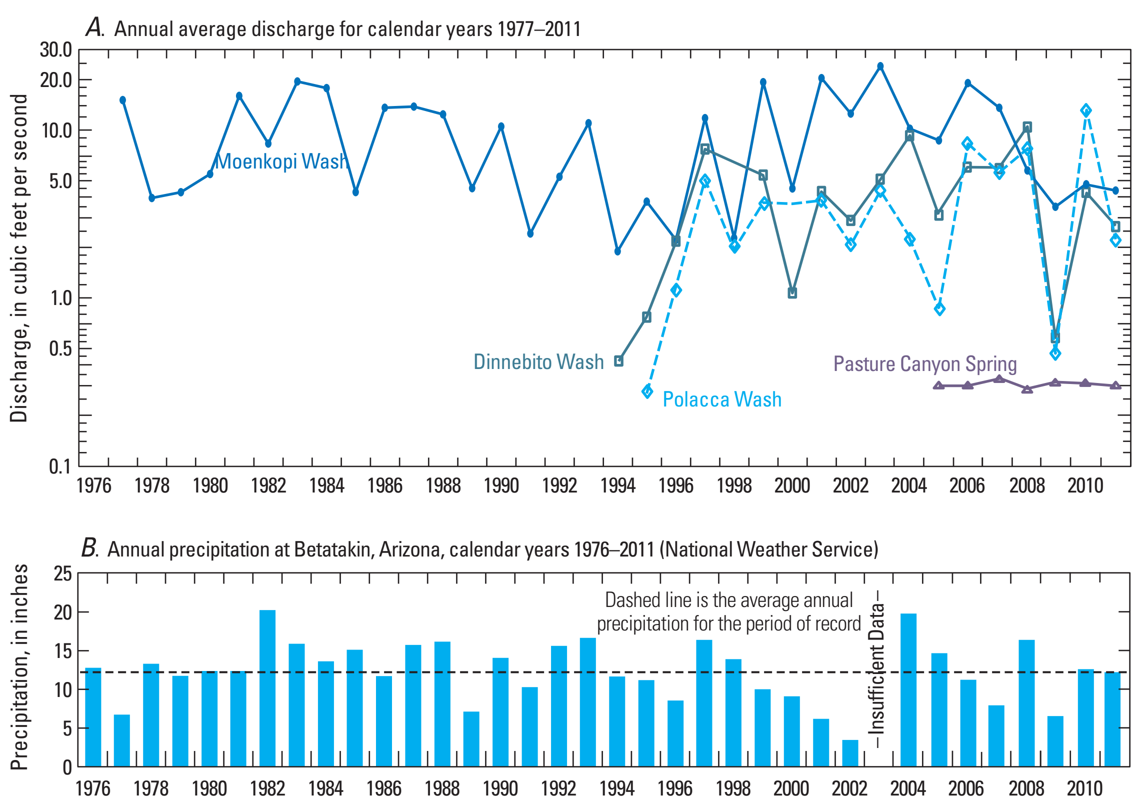


Figure 10. Plots of annual average discharge at Sand Springs (09401110), and Polacca Wash near Second Mesa (09400568), and annual precipitation at Betatakin, Arizona, Black Mesa area, northeastern Arizona. *A*, Annual average discharge for calendar years 1977–2011. *B*, Annual precipitation at Betatakin, northeastern Arizona, calendar years 1976–2011 (National Climatic Data Center, 2012).

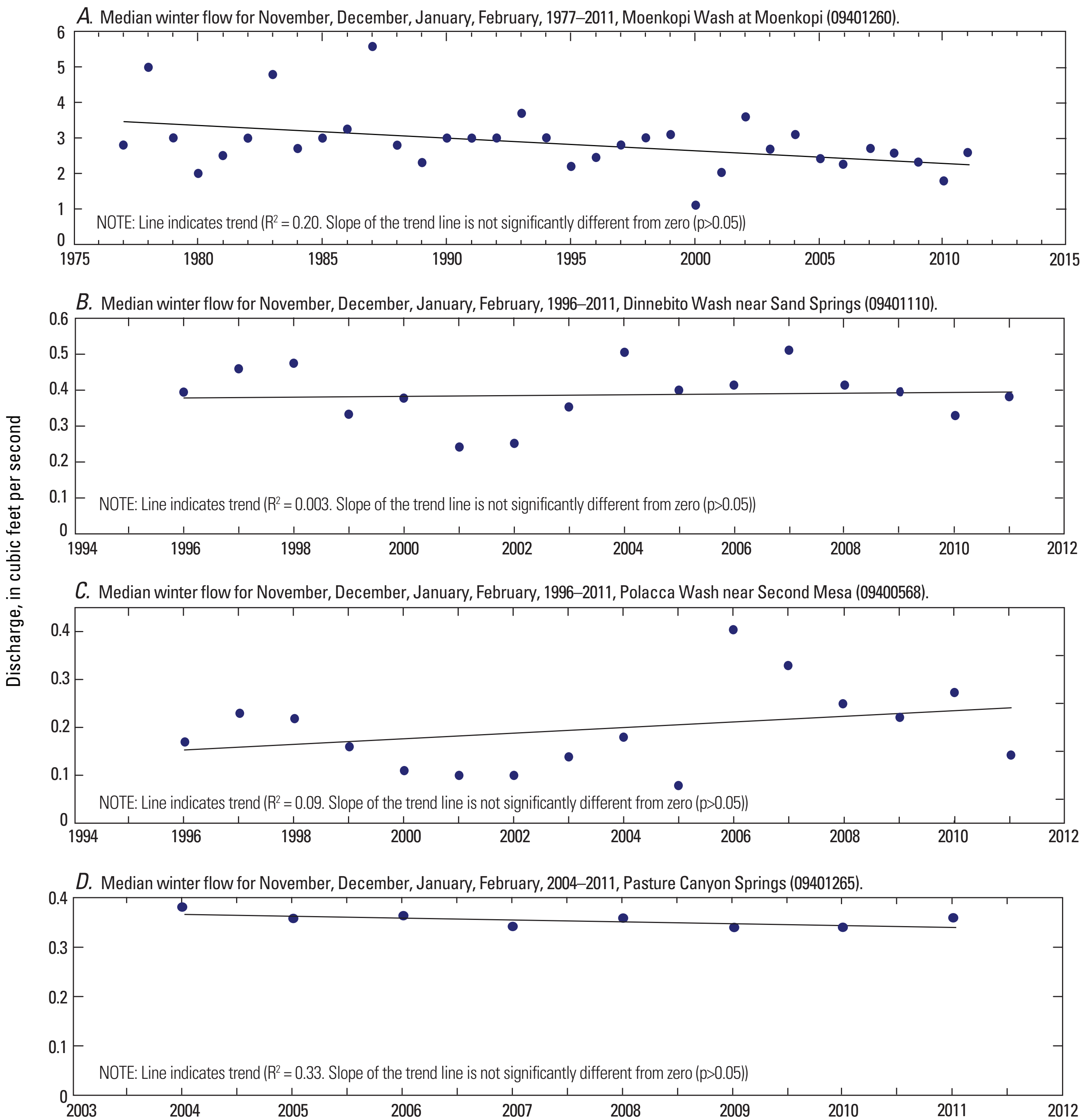


Figure 11. Plots of median winter flow for November, December, January, and February for water years 1977–2011 for *A*, Moenkopi Wash at Moenkopi (09401260); *B*, Dinnebito Wash near Sand Springs (09401110); *C*, Polacca Wash near Second Mesa (09400568); and *D*, Pasture Canyon Springs (09401265), Black Mesa area, northeastern Arizona. Median winter flow is calculated by computing the median flow for 120 consecutive daily mean flows for winter months—November, December, January, and February. Note: Trend lines were generated by using the method of least squares.

Table 10. Discharge data (daily mean values), Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2011.

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

Discharge, in cubic feet per second, calendar year 2011 Daily mean values												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	e0.08	1.7	2.8	2.1	1.2	0	0	0.08	0.12	2	0	e0.49
2	e0.51	2.1	2.8	2	1.4	0	0	169	0.43	3.1	0	e1.1
3	0.77	2.8	2.9	1.9	1.5	0	0	10	0	1.3	0	1.4
4	0.4	e3.4	2.8	1.9	1.5	0	0	0.1	0	3.9	0.21	e1.5
5	e0.71	e3.4	2.7	1.9	1.5	0	0	0.01	0	0.5	2.1	e1.6
6	0.52	e3.2	2.7	2.1	1.4	0	0	0.02	0	0.41	26	e1.8
7	0.62	e3.3	2.8	2.4	1.2	0	0	0	0	0.78	5.2	e2.0
8	1.2	2.7	3.1	2.3	0.85	0	0	0	0	0.66	11	e2.3
9	1.7	2.4	2.8	2.1	0.74	0	0	0	0	0.46	4	e2.4
10	1.4	e2.8	2.6	2.2	0.63	0	0	0	81	0.35	1.8	e2.6
11	e2.0	e2.9	2.7	2.2	0.94	0	0	0	382	0.65	1.1	e2.7
12	2.4	e3.0	2.7	2	0.98	0	0	0	115	0.47	1.4	e3.0
13	2.3	e2.7	2.7	2	0.92	0	0	0	30	0.43	1.7	e3.0
14	2.5	2.6	2.5	1.9	0.69	0	0	0	1.3	0.56	1.1	e2.5
15	3.3	2.6	2.5	1.9	0.59	0	0	7.4	16	0.6	0.84	1.4
16	e5.2	2.7	2.5	1.9	0.65	0	0	42	8.6	0.62	0.83	e1.4
17	e5.5	2.7	2.3	1.9	0.5	0	0	0.25	12	0.48	0.74	e1.2
18	e4.0	2.4	2.3	1.8	0.53	0	0.01	0	7.9	0.23	0.54	1.2
19	1.7	2.9	2.2	1.8	1	0	17	0	0.99	0.63	e0.52	0.9
20	1.1	3.6	2.1	1.3	1.2	0	0.35	0	0.52	0.33	0.34	0.79
21	2.9	3.2	2.1	1.3	1.1	0	0.39	134	0.43	0.48	0.39	e0.70
22	2.7	3.1	2.1	1.5	0.84	0	0.26	22	0	0.27	0.28	e0.54
23	1.8	2.8	2.1	1.4	0.6	0	0	0.12	0	0.3	0.34	e0.76
24	e1.8	2.6	2	1.8	0.42	0	0.09	0.02	0	0.73	e0.40	e2.1
25	e1.9	2.6	1.9	1.7	0.48	0	0.08	0	0	0.75	0.71	e3.4
26	e1.8	2.9	2.3	1.5	0.41	0	0.05	0	0	0.96	0.67	e3.2
27	e1.9	3	2.3	1.3	0.31	0	30	0	0.02	35	e0.37	e3.7
28	e2.0	3.1	2.5	1.4	0.53	0	44	0	2	1.5	e0.38	e3.7
29	1.5	---	2.4	1.2	0.22	0	0.08	0.48	2.3	0	e0.38	e3.1
30	1.6	---	2.4	1.1	0	0	0.01	1.2	2	0	e0.47	e3.7
31	1.8	---	2.3	---	0	---	0.04	0.42	---	0	---	e3.2
TOTAL	59.61	79.2	76.9	53.8	24.83	0	92.36	387.1	662.61	58.45	63.81	63.38
MEAN	1.92	2.83	2.48	1.79	0.8	0	2.98	12.5	22.1	1.89	2.13	2.04
MAX	5.5	3.6	3.1	2.4	1.5	0	44	169	382	35	26	3.7
MIN	0.08	1.7	1.9	1.1	0	0	0	0	0	0	0	0.49
MED	1.8	2.8	2.5	1.9	0.74	0	0	0.01	0.43	0.56	0.61	2
AC-FT	118	157	153	107	49	0	183	768	1310	116	127	126
CFSM	0	0	0	0	0	0	0	0.01	0.01	0	0	0
Calendar year 2011	Total 1,622		Mean 4.44		Max 382	Min 0.00	Median 1.1		Acre-ft 3,214		CFSM 0.003	

Table 11. Discharge data (daily mean values), Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2011.

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

Discharge, in cubic feet per second, calendar year 2011 Daily mean values												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.25	0.29	0.31	0.31	0.25	0.17	0.11	101	0.15	0.26	0.65	0.39
2	0.26	0.23	0.33	0.31	0.26	0.16	0.11	129	0.14	0.27	0.59	0.53
3	0.28	0.23	0.32	0.3	0.26	0.16	0.11	6	0.14	0.27	0.64	0.43
4	0.29	0.27	0.31	0.3	0.26	0.15	0.12	0.49	0.14	0.28	0.67	0.39
5	0.27	0.34	0.31	0.31	0.26	0.15	0.13	0.28	0.16	0.35	6.2	0.34
6	0.27	0.34	0.32	0.34	0.25	0.14	0.11	0.2	0.26	1.4	15	0.31
7	0.28	0.33	0.43	0.39	0.24	0.15	0.11	0.17	0.18	35	3.8	0.34
8	0.32	0.33	0.48	0.3	0.23	0.14	0.12	0.15	0.11	7.7	1.1	0.34
9	0.34	0.3	0.33	0.4	0.23	0.15	0.12	0.15	16	3	0.43	0.34
10	0.33	0.28	0.34	0.33	0.22	0.15	0.12	0.16	32	0.64	0.41	0.34
11	0.3	0.28	0.33	0.32	0.23	0.15	0.12	0.14	4.6	0.52	0.43	0.36
12	0.32	0.29	0.32	0.32	0.22	0.14	0.21	0.14	22	0.43	0.42	0.42
13	0.31	0.29	0.32	0.3	0.22	0.15	0.14	0.14	20	0.42	0.43	0.5
14	0.34	0.29	0.33	0.3	0.22	0.15	0.11	0.15	17	0.42	0.39	0.44
15	0.37	0.29	0.33	0.31	0.21	0.15	0.1	0.15	6.4	0.43	0.35	0.39
16	0.39	0.31	0.32	0.31	0.2	0.13	0.07	1.6	48	0.43	0.34	0.39
17	0.4	0.31	0.31	0.29	0.21	0.13	0.06	0.37	135	0.42	0.34	0.38
18	0.4	0.3	0.31	0.28	0.28	0.14	0.07	0.16	11	0.43	0.34	0.41
19	0.4	0.4	0.31	0.28	0.3	0.13	0.07	0.14	2.2	0.44	0.34	0.47
20	0.36	0.36	0.32	0.28	0.25	0.14	0.07	43	0.37	0.45	0.34	0.41
21	0.34	0.31	0.32	0.27	0.24	0.14	0.07	56	0.31	0.46	0.36	0.4
22	0.34	0.31	0.32	0.28	0.22	0.14	0.07	14	0.29	0.47	0.35	0.37
23	0.33	0.31	0.32	0.28	0.21	0.13	0.07	1.4	0.28	0.48	0.36	0.34
24	0.32	0.31	0.32	0.29	0.21	0.12	0.07	0.21	0.28	0.5	0.36	0.35
25	0.33	0.32	0.32	0.27	0.21	0.12	0.07	0.17	0.28	1.8	0.36	0.34
26	0.33	0.31	0.33	0.26	0.2	0.11	0.17	0.16	0.25	1.4	0.34	0.35
27	0.33	0.32	0.33	0.26	0.19	0.12	47	0.14	0.31	37	0.34	0.35
28	0.33	0.3	0.32	0.26	0.17	0.11	20	0.14	0.29	8.2	0.35	0.36
29	0.34	---	0.31	0.26	0.16	0.11	1.6	0.13	0.27	5	0.37	0.38
30	0.34	---	0.31	0.24	0.17	0.1	0.23	0.13	0.26	0.93	0.36	0.4
31	0.32	---	0.32	---	0.17	---	0.22	0.14	---	0.7	---	0.39
TOTAL	10.13	8.55	10.2	8.95	6.95	4.13	71.75	356.21	318.67	110.5	36.76	11.95
MEAN	0.33	0.31	0.33	0.3	0.22	0.14	2.31	11.5	10.6	3.56	1.23	0.39
MAX	0.4	0.4	0.48	0.4	0.3	0.17	47	129	135	37	15	0.53
MIN	0.25	0.23	0.31	0.24	0.16	0.1	0.06	0.13	0.11	0.26	0.34	0.31
MED	0.33	0.31	0.32	0.3	0.22	0.14	0.11	0.16	0.29	0.47	0.37	0.38
AC-FT	20	17	20	18	14	8.2	142	707	632	219	73	24
Calendar year 2011	Total 954.8		Mean 2.6		Max 135	Min 0.06	Median 0.31		Acre-ft 1,894		CFSM 0.005	

Table 12. Discharge data (daily mean values), Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2011.

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

Discharge, in cubic feet per second, calendar year 2011 Daily mean values												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	e0.26	e0.32	e0.31	0.22	0.1	0.07	0.02	49	0.03	0.2	0.07	0.14
2	e0.25	e0.27	e0.31	0.19	0.1	0.07	0.02	61	0.03	0.28	0.07	0.22
3	e0.24	e0.27	e0.30	0.21	0.1	0.06	0.02	e47	0.03	0.24	0.08	0.15
4	e0.24	e0.33	e0.29	0.2	0.11	0.06	0.02	e0.33	0.03	0.29	0.09	0.12
5	e0.23	e0.39	e0.30	0.23	0.09	0.06	0.04	e0.07	0.03	0.36	0.2	e0.13
6	e0.24	e0.40	e0.30	0.26	0.09	0.06	0.03	e0.06	0.06	0.8	56	e0.13
7	e0.24	e0.43	e0.42	0.32	0.09	0.05	0.03	e0.06	0.05	e45	3.4	e0.13
8	e0.24	e0.45	e0.48	0.24	0.1	0.05	0.03	e0.06	0.05	e20	0.32	e0.13
9	e0.26	e0.45	e0.32	0.28	0.1	0.05	0.04	e0.06	14	e1.8	0.1	e0.13
10	e0.28	e0.45	e0.32	0.27	0.11	0.05	0.04	e0.06	e55	e0.28	0.1	e0.13
11	e0.38	e0.45	e0.32	0.23	0.14	0.05	0.04	e0.06	e0.15	e0.18	0.1	e0.14
12	e0.31	e0.46	e0.31	0.21	0.13	0.05	0.05	e0.06	e0.05	e0.14	0.11	0.14
13	e0.29	e0.46	e0.30	0.19	0.1	0.04	0.04	e0.06	e98	e0.14	0.12	0.2
14	e0.27	e0.44	e0.30	0.17	0.08	0.04	0.03	e0.06	31	e0.13	0.12	0.21
15	e0.28	e0.42	e0.29	0.17	0.08	0.04	0.02	e0.06	12	e0.12	0.13	0.16
16	e0.27	e0.42	0.23	0.16	0.09	0.04	0.02	e0.06	104	e0.11	0.13	0.15
17	e0.28	e0.41	0.21	0.17	0.09	0.04	0.03	e0.06	e59	e0.10	0.13	0.16
18	e0.28	e0.39	0.21	0.13	0.14	0.04	0.03	e0.06	e1.2	e0.09	0.14	0.17
19	e0.28	e0.43	0.18	0.12	0.12	0.04	0.03	e0.06	e0.23	e0.08	0.15	0.44
20	e0.27	e0.40	0.17	0.12	0.1	0.04	0.03	e0.06	e0.13	e0.07	0.14	0.15
21	e0.26	e0.38	0.2	0.14	0.1	0.04	0.03	e0.06	0.12	0.06	0.15	0.14
22	e0.31	e0.37	0.19	0.13	0.09	0.03	0.03	e0.06	0.14	0.06	0.15	0.14
23	e0.30	e0.35	0.19	0.14	0.09	0.02	0.02	e0.06	0.13	0.06	0.15	e0.13
24	e0.31	e0.32	0.23	0.15	0.08	0.02	0.03	e0.06	0.13	0.06	0.15	e0.13
25	e0.29	e0.32	0.24	0.13	0.09	0.02	0.06	e0.06	0.16	0.07	0.14	e0.13
26	e0.26	e0.31	0.21	0.13	0.09	0.02	0.25	e0.06	0.18	0.07	0.13	e0.13
27	e0.27	e0.32	0.21	0.1	0.08	0.01	0.09	e0.06	0.17	62	0.14	e0.13
28	e0.27	e0.31	0.21	0.11	0.08	0.01	0.08	e0.06	0.18	20	0.13	e0.13
29	e0.26	---	0.22	0.11	0.06	0.01	0.07	e0.06	0.19	0.85	0.12	e0.13
30	e0.31	---	0.22	0.1	0.07	0.01	0.07	e0.06	0.19	0.08	0.12	0.13
31	0.35	---	0.22	---	0.07	---	20	e0.04	---	0.07	---	0.13
TOTAL	8.58	10.72	8.21	5.33	2.96	1.19	21.34	158.94	376.66	153.79	63.08	4.78
MEAN	0.28	0.38	0.26	0.18	0.1	0.04	0.69	5.13	12.6	4.96	2.1	0.15
MAX	0.38	0.46	0.48	0.32	0.14	0.07	20	61	104	62	56	0.44
MIN	0.23	0.27	0.17	0.1	0.06	0.01	0.02	0.04	0.03	0.06	0.07	0.12
MED	0.27	0.4	0.24	0.17	0.09	0.04	0.03	0.06	0.16	0.14	0.13	0.13
AC-FT	17	21	16	11	5.9	2.4	42	315	747	305	125	9.5
CFSM	0	0	0	0	0	0	0	0.01	0.01	0.01	0	0

Calendar year 2011	Total	Mean	Max	Min	Median	Acre-ft	CFSM
	815.6	2.2	104	0.01	0.13	1,617	0.002

Table 13. Discharge data (daily mean values), Pasture Canyon Springs near Tuba City, Arizona (09401265), calendar year 2011.

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

Discharge, in cubic feet per second, calendar year 2011 Daily mean values												
DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.33	0.34	0.32	0.33	0.36	0.3	0.28	0.32	0.33	0.32	0.32	0.35
2	0.32	0.36	0.32	0.33	0.36	0.3	0.28	0.35	0.33	0.32	0.32	0.44
3	0.32	0.36	0.32	0.33	0.36	0.3	0.29	0.37	0.33	0.32	0.32	0.41
4	0.32	0.37	0.32	0.34	0.36	0.3	0.29	0.36	0.33	0.32	0.32	0.4
5	0.32	0.38	0.32	0.34	0.36	0.29	0.28	0.37	0.33	0.32	0.37	0.39
6	0.32	0.38	0.32	0.34	0.35	0.3	0.29	0.37	0.33	0.32	0.35	0.38
7	0.32	0.37	0.32	0.34	0.35	0.3	0.29	0.37	0.33	0.32	0.37	0.38
8	0.32	0.37	0.32	0.34	0.34	0.3	0.29	0.37	0.33	0.32	0.39	0.38
9	0.32	0.36	0.32	0.34	0.34	0.3	0.29	0.37	0.33	0.32	0.36	0.37
10	0.32	0.34	0.32	0.34	0.34	0.3	0.29	0.37	0.33	0.32	0.36	0.36
11	0.32	0.33	0.32	0.33	0.34	0.29	0.29	0.37	0.34	0.32	0.36	0.36
12	0.32	0.32	0.32	0.35	0.36	0.28	0.3	0.37	0.34	0.32	0.36	0.36
13	0.32	0.3	0.3	0.35	0.36	0.28	0.29	0.37	0.35	0.32	0.36	0.37
14	0.32	0.31	0.3	0.34	0.35	0.28	0.29	0.36	0.42	0.32	0.36	0.38
15	0.32	0.33	0.3	0.34	0.36	0.28	0.32	0.37	e0.43	0.32	0.36	0.38
16	0.32	0.33	0.32	0.32	0.36	0.28	0.33	0.37	e0.32	0.32	0.36	0.38
17	0.32	0.35	0.32	0.32	0.36	0.28	0.33	0.36	e0.29	0.32	0.36	0.37
18	0.32	0.34	0.32	0.32	0.36	0.28	0.33	0.35	e0.28	0.32	0.36	0.36
19	0.33	0.41	0.32	0.32	0.36	0.28	0.33	0.34	e0.28	0.32	0.36	0.36
20	0.34	0.4	0.32	0.32	0.36	0.3	0.32	0.34	e0.28	0.32	0.36	0.36
21	0.34	0.38	0.32	0.32	0.36	0.28	0.33	0.34	e0.28	0.32	0.37	0.36
22	0.34	0.36	0.32	0.32	0.36	0.28	0.33	0.35	0.3	0.32	0.38	0.36
23	0.34	0.35	0.34	0.32	0.36	0.29	0.33	0.34	0.3	0.32	0.36	0.36
24	0.34	0.34	0.34	0.32	0.36	0.3	0.32	0.35	0.3	0.32	0.36	0.35
25	0.34	0.34	0.34	0.33	0.36	0.29	0.32	0.34	0.3	0.32	0.36	0.35
26	0.34	0.34	0.34	0.34	0.34	0.28	0.32	0.34	0.3	0.32	0.38	0.34
27	0.34	0.33	0.34	0.36	0.3	0.28	0.32	0.34	0.3	0.32	0.36	0.34
28	0.34	0.32	0.34	0.36	0.3	0.28	0.32	0.34	0.31	0.32	0.36	0.34
29	0.34	---	0.34	0.36	0.3	0.28	0.32	0.34	0.32	0.32	0.35	0.34
30	0.34	---	0.33	0.36	0.3	0.28	0.32	0.34	0.32	0.32	0.34	0.34
31	0.34	---	0.33	---	0.3	---	0.32	0.35	---	0.32	---	0.34
TOTAL	10.18	9.81	10.02	10.07	10.73	8.66	9.55	10.99	9.66	9.92	10.7	11.36
MEAN	0.33	0.35	0.32	0.34	0.35	0.29	0.31	0.35	0.32	0.32	0.36	0.37
MAX	0.34	0.41	0.34	0.36	0.36	0.3	0.33	0.37	0.43	0.32	0.39	0.44
MIN	0.32	0.3	0.3	0.32	0.3	0.28	0.28	0.32	0.28	0.32	0.32	0.34
MED	0.32	0.35	0.32	0.34	0.36	0.29	0.32	0.35	0.32	0.32	0.36	0.36
AC-FT	20	19	20	20	21	17	19	22	19	20	21	23
Calendar year 2011	Total 121.6		Mean 0.33		Max 0.44	Min 0.28	Median 0.33		Acre-ft 241			

during the winter. Rather than the average flow, the median flow for November, December, January, and February is used to estimate groundwater discharge because the median is less affected by occasional winter runoff. Nonetheless, the median flow for November, December, January, and February is an index of groundwater discharge rather than a calculation of base-flow groundwater discharge. A more rigorous and accurate calculation of base-flow would involve detailed evaluations of streamflow hydrographs, flows into and out of bank storage, gain and loss of streamflow as it moves down the stream channel, and interaction of groundwater in the N aquifer with groundwater in the shallow alluvial aquifers in the stream valleys. The median winter flow, however, is useful as a consistent index for evaluating possible time trends in groundwater discharge.

Median winter flows calculated for the 2011 water year were 1.9 ft^3/s for Moenkopi Wash at Moenkopi, 0.38 ft^3/s for Dinnebito Wash near Sand Springs, 0.14 ft^3/s for Polacca Wash near Second Mesa, and 0.36 ft^3/s for Pasture Canyon Springs (fig. 11*A-D*). For the period of record at each streamflow-gaging station, there have been no significant trends in median winter flows, as indicated by trends calculated using the method of least squares and Kendall's tau ($p>0.05$; fig. 11*A-D*).

Water Chemistry

Water samples for water-chemistry analyses are collected each year from selected wells and springs as part of the Black Mesa monitoring program. Field measurements are made and water samples are analyzed for major ions, trace elements, nutrients, iron, boron, and arsenic. Field measurements are made in accordance with standard USGS protocols documented in the USGS National Field Manual for the Collection of Water-Quality Data and in several USGS Techniques of Water-Resources Investigations Reports (Friedman and Erdmann, 1982; Koterba and others, 1995; Wilde and others, 1998a, b, c; and Wilde and others, 1999). Field measurements include pH, specific conductance, temperature, dissolved oxygen, alkalinity, and discharge rates at springs. Field alkalinities were determined using incremental equivalence (Wilde, 1998). Major ion, nutrient, trace element, iron, boron, arsenic, and alkalinity samples were filtered through a 0.45-micron pore size filter and preserved according to sampling and analytical protocols. Laboratory analyses for samples were done at the USGS National Water Quality Laboratory (NWQL) according to techniques described in Fishman and Friedman (1989), Fishman (1993), Struzeski and others (1996), and Garbarino and others (2006).

Quality assurance for this study was maintained through the use of proper training of field personnel, use of standard USGS field and laboratory protocols, collection of quality control samples, and a thorough review of the analytical results. All USGS scientists involved with this study have participated in the USGS National Field Quality Assurance Program, which requires participants to successfully determine pH, specific conductance, and alkalinity of reference samples supplied by the USGS Branch of Quality Systems. Field personnel were trained in water-quality field methods by USGS personnel or through formal instruction at the USGS water-quality field-methods class.

Quality control samples were collected and compared with the past 9 years of quality control samples from the Black Mesa project. Results from quality control samples indicate that calcium was the only constituent with risk of contamination and the potential contamination of calcium is estimated, with an 83-percent confidence, to be no greater than 0.1 mg/L in at least 80 percent of the samples. A replicate sample collected in 2010 indicated about 30 percent difference in iron between the replicate and environmental sample.

Water-chemistry samples have been collected from 12 wells during the past 10 years of the project; 4 of the wells have been sampled every year, and the other 8 wells have been selected on the basis of a sampling rotation. In 2012, water samples were collected at 10 of those 12 well sites: Second Mesa PM2, Keams Canyon PM2, Kykotsmovi PM2, Piñon NTUA 1, Forest Lake NTUA 1, Kits'iili NTUA 2, Rough Rock PM5, Peabody 2, Kayenta PM2, and Dennehotso PM2. Since 1989, samples have been collected from the same four springs (Moenkopi School Spring, Pasture Canyon Spring, Unnamed spring near Dennehotso, and Burro Spring), and in 2012 all four springs were sampled. Long-term data for specific conductance, dissolved solids, chloride, and sulfate for the wells and springs sampled each year are shown in the annual reports (table 2). These constituents are monitored on an annual basis because increased concentrations in the N aquifer could indicate leakage from the overlying D aquifer. On average, the concentrations of dissolved solids in water from the D aquifer is about 7 times greater than that of water from the N aquifer; concentration of chloride ions is about 11 times greater, and concentration of sulfate ions is about 30 times greater (Eychaner, 1983). Historical data for other constituents for all the wells and springs in the Black Mesa study area are available from the USGS water-quality database (*http://waterdata.usgs.gov/az/nwis/qw*), and they can be found in monitoring reports cited in the "Previous Investigations" section of this report and listed in table 2.

Water-Chemistry Data for Wells Completed in the N Aquifer

The primary types of water in the N aquifer in the Black Mesa study area are calcium bicarbonate water and sodium bicarbonate water. Calcium bicarbonate water is mostly found in the recharge and unconfined areas of the northern and northwestern parts of the Black Mesa study area. Sodium bicarbonate water is mostly found in the area that is confined and downgradient to the south and east (Lopes and Hoffmann, 1997). Water-chemistry results from well samples in 2012 are presented in figures 12 and 13 and in table 15.

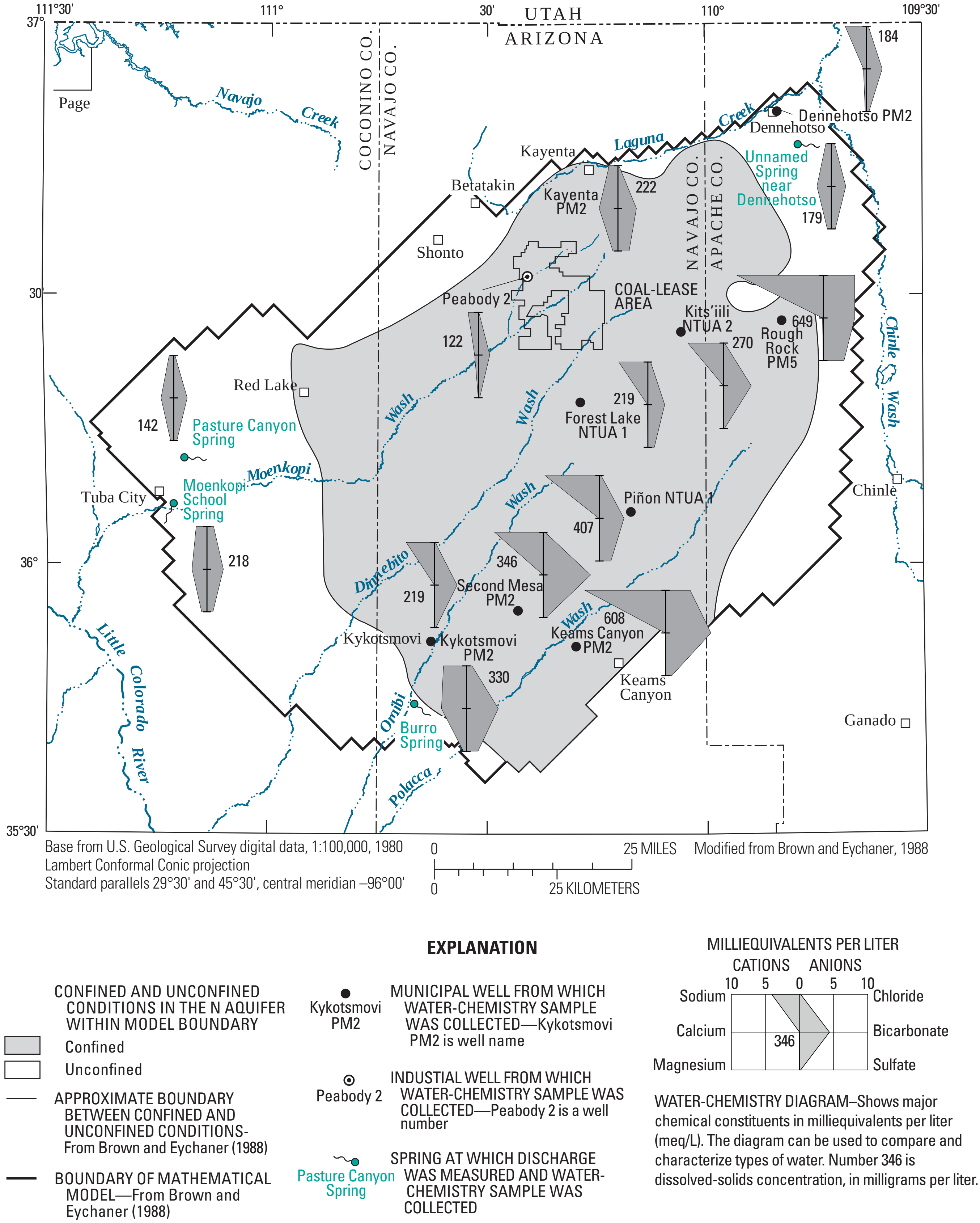


Figure 12. Map showing water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, northeastern Arizona, 2012.

Rough Rock PM5 and Keams Canyon PM2 consistently yielded the highest dissolved-solids concentrations and the highest chloride concentrations of the 10 wells sampled, at 649 mg/L and 608 mg/L dissolved solids, respectively (fig. 13 and table 15), and 130 mg/L and 102 mg/L chloride (table 15). Dissolved-solids concentrations in the other 8 wells ranged from 122 mg/L at Peabody 2 to 407 mg/L at Piñon NTUA 1, and chloride concentrations ranged from 2.04 mg/L at Peabody 2 to 11.3 mg/L at Forest Lake NTUA 1 (table 15). Rough Rock PM5 had the highest sulfate concentration (116 mg/L) of the 10 wells, and the concentrations at the other wells ranged from 4.94 mg/L at Kits'iili NTUA 2 to 64.3 mg/L at Piñon NTUA 1 (table 15).

Samples from 1998 to present at Piñon NTUA 1 have shown varying sulfate, chloride, and dissolved-solids concentrations (table 16). Purge times greater than 12 hours from Piñon NTUA 1 appear to induce leakage from the overlying D aquifer and result in higher concentrations in samples. The confining layer of the Carmel Formation, in the area of Piñon, is about 120 ft thick and composed of a more sandy siltstone rather than the clayey siltstone observed in the northern part of the study area, where leakage has not been detected (Truini and Macy, 2005). Areas where the Carmel Formation is 120 ft thick or less coincide with areas where isotopic ratios of $^{87}Sr/^{86}Sr$ and major-ion data for groundwater indicate that D aquifer water has mixed with N aquifer water as a result of leakage (Truini and Longsworth, 2003). Both the lithologic difference in and the thickness of the Carmel Formation near Piñon indicate that leakage could be possible. Purge times may have an effect on samples taken from Piñon NTUA 1 and will be more closely monitored during future sampling.

Chemical constituents analyzed from the 10 wells were compared to the U.S. Environmental Protection Agency (USEPA) primary and secondary drinking water standards (U.S. Environmental Protection Agency, 2003). Maximum Contaminant Levels (MCLs), which are the primary regulations, are legally enforceable standards that apply to public water systems. They protect drinking-water quality by limiting the levels of specific contaminants that can adversely affect public health. Secondary Maximum Contaminant Levels (SMCLs) provide guidelines for the control of contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. The USEPA recommends compliance with SMCLs for public water systems; however, compliance is not enforced.

In 2012, most of the analyzed constituents from the 10 wells were below the USEPA MCL or SMCL for drinking water. Three of the 10 wells sampled exceeded the USEPA MCL for arsenic (10.0 µg/L): Second Mesa PM2 had a concentration of 17.7 µg/L, Rough Rock PM5 had a concentration of 49.8 µg/L, and Keams Canyon PM2 had a concentration of 42.4 µg/L (table 15). The USEPA SMCL for concentration of dissolved solids (500 mg/L) was exceeded at Keams Canyon PM2 (608 mg/L) and Rough Rock MP5 (649 mg/L). In addition, the USEPA SMCL for pH (6.5 to 8.5) was exceeded at Second Mesa PM2, Keams Canyon PM2, Kykotsmovi PM2, Piñon NTUA 1, Forest Lake NTUA1, Kits'iili NTUA 2, Rough Rock PM5, Peabody 2, and Dennehotso PM2 (U.S. Environmental Protection Agency, 2003; table 15).

Table 14. Streamflow-gaging stations used in the Black Mesa monitoring program, their periods of record, and drainage areas. .

[Dashes indicate not determined]

Station name	Station number	Date data collection began	Drainage area (square miles)
Moenkopi Wash at Moenkopi	09401260	July 1976	1,629
Dinnebito Wash near Sand Springs	09401110	June 1993	473
Polacca Wash near Second Mesa	09400568	April 1994	905
Pasture Canyon Springs	09401265	August 2004	---

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

In 2012, water samples were collected from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso (figs. 8 and 12). These four springs discharge water from the unconfined part of the N aquifer. At Moenkopi School Spring, samples were collected from a horizontal metal pipe built into the hillside to collect water from the spring. At Pasture Canyon Spring, samples were collected from a pipe at the end of a channel that is approximately 50 ft away from the spring. At Burro Spring, samples were collected from the end of a pipe that fills a trough for cattle. At Unnamed Spring near Dennehotso, samples were collected from a pool along the bedrock wall from which the spring discharges.

The samples from all four springs yielded calcium bicarbonate-type water (fig. 12 and table 17). Dissolved solid concentrations measured 330 mg/L at Burro Spring, 218 mg/L at Moenkopi School Spring, 142 mg/L at Pasture Canyon Spring, and 179 mg/L at Unnamed Spring near Dennehotso (tables 17 and 18). Concentration of chloride was highest at Moenkopi School Spring (27.5 mg/L; tables 17 and 18). Concentration of sulfate was highest at Burro Spring (64.7 mg/L; tables 17 and 18). Concentrations of all the analyzed constituents in samples from all four springs were less than current USEPA MCLs and SMCLs (U.S. Environmental Protection Agency, 2003).

There are significant increasing trends in concentrations of dissolved solids, chloride, and sulfate in water from Moenkopi School Spring ($p<0.05$; table 18 and fig. 14). Concentrations of the same constituents in Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso did not show any significant trends (table 18 and fig. 14). However, in the last 2 years, Unnamed Spring near Dennehotso has shown an increase in dissolved solid concentrations (fig. 14).

Table 15. Physical properties and chemical analyses of water samples from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, 2012.

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

Common well name	U.S. Geological Survey identification number	Date of samples	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)	Dissolved, mg/L				
						Nitrogen, $NO_2 + NO_3$ (N)	Orthophosphate (P)	Calcium (Ca)	Magnesium (Mg)	Potassium (K)
Second Mesa PM2	354749110300101	06-13-12	19.0	570	8.7	<.040	0.012	0.500	0.034	0.43
Keams Canyon PM2	355023110182701	06-13-12	19.9	1060	8.8	<.040	0.009	0.860	0.168	0.74
Kykotsmovi PM2	355215110375001	06-12-12	22.8	367	9.3	1.13	0.031	0.494	0.014	0.41
Piñon NTUA 1	360527110122501	06-20-12	26.6	652	9.8	1.26	0.014	1.09	0.155	0.49
Forest Lake NTUA 1	361737110180301	06-12-12	28.9	391	9.4	0.568	0.006	0.823	0.080	0.62
Kitsillie NTUA 2	362043110030501	06-20-12	28.9	443	9.7	1.37	0.012	0.518	0.014	0.51
Rough Rock PM5	362418109514601	06-05-12	21.1	1080	8.7	1.04	0.009	2.08	0.296	1.34
Peabody 2	363005110250901	06-06-12	31.2	155	8.7	0.956	0.007	8.69	0.137	0.70
Kayenta PM2	364344110151201	06-05-12	19.8	363	7.5	0.839	0.006	44.0	7.11	1.27
Denehotso PM2	365045109504001	06-05-12	16.2	295	8.7	1.41	0.006	7.13	1.90	0.70

Common well name	U.S. Geological Survey identification number	Date of samples	Dissolved, in mg/L				Dissolved, in µg/L			Dissolved solids, residue at 180 °C (mg/L)
			Sodium (Na)	Chloride (Cl)	Flourid (F)	Sulfate (SO_4)	Arsenic (As)	Boron (B)	Iron (Fe)	
Second Mesa PM2	354749110300101	06-13-12	131	7.26	.32	14.9	17.7	93	4.3	346
Keams Canyon PM2	355023110182701	06-13-12	217	102	1.41	35.2	42.4	642	13.8	608
Kykotsmovi PM2	355215110375001	06-12-12	76.0	3.07	.18	7.75	5.3	31	<3.2	219
Piñon NTUA 1	360527110122501	06-20-12	146	7.09	.26	64.3	4.6	74	<3.2	407
Forest Lake NTUA 1	361737110180301	06-12-12	78.3	11.3	.35	36.0	3.2	90	13.8	219
Kitsillie NTUA 2	362043110030501	06-20-12	96.3	3.77	.18	4.94	4.0	45	<3.2	270
Rough Rock PM5	362418109514601	06-05-12	232	130	1.86	116	49.8	415	11.4	649
Peabody 2	363005110250901	06-06-12	27.6	2.04	.13	7.25	2.9	16	<3.2	122
Kayenta PM2	364344110151201	06-05-12	23.4	3.71	.20	62.5	2.3	28	<3.2	222
Denehotso PM2	365045109504001	06-05-12	57.6	7.59	.29	13.6	6.2	43	<3.2	184

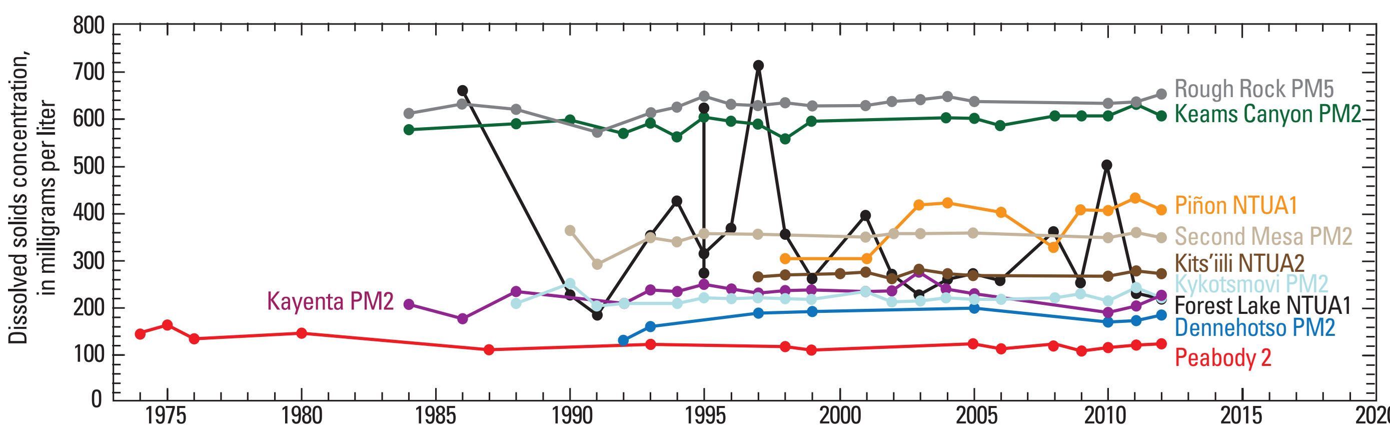


Figure 13. Plot of dissolved-solids concentrations for water samples from selected wells during 1974–2012, N aquifer, Black Mesa area, northeastern Arizona: Rough Rock PM5, 1984–2012; Keams Canyon PM2, 1984–2012; Forest Lake NTUA 1, 1986–2012; Piñon NTUA 1, 1998–2012; Second Mesa PM2, 1990–2012; Kits'iili NTUA 2, 1997–2012; Kykotsmovi, 1988–2012; Kayenta PM2, 1984–2012; Dennehotso PM2, 1992–2012; and Peabody 2, 1974–2012.

Table 16. Specific conductance and concentrations of selected chemical constituents in water samples from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, during 1974–2012.

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

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180 °C (mg/L)	Dissolved, in mg/L Chloride (Cl)	Dissolved, in mg/L Sulfate (SO_4)
		Second Mesa PM2		
1968	670	---	14	35
1990	590	364	6.5	16
1991	595	292	10	15
1993	630	350	7.5	15
1994	605	342	7.6	15
1995	610	357	7.2	14
1997	646	356	7.08	14.4
2001	597	352	7.11	14.9
2002	608	357	7.53	14.4
2003	601	359	6.26	14.2
2005	615	361	6.83	13.4
2010	553	349	7.02	15.3
2011	550	355	7.71	16.3
2012	570	346	7.26	14.9
		Keams Canyon PM2		
1982	1,010	---	94	35
1983	1,120	---	120	42
1984	1,060	578	96	36
1988	1,040	591	97	34
1990	1,020	600	94	34
1992	1,010	570	93	36
1993	1,040	590	92	36
1994	975	562	86	32
1995	1,010	606	99	32
1996	1,020	596	96	34
1997	1,070	590	95.8	33.5
1998	908	558	78.1	28.5
1999	1,040	595	97.1	35.2
2004	945	[3]603	96.7	32.4
2005	828	601	97.4	33.6
2006	1,070	588	98.9	34
2008	1,080	607	95.1	34.5
2009	1,030	609	100	35.5
2010	965	607	104	34.9
2011	1,080	629	117	39.6
2012	1,060	608	102	35.2
		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	3.02	7.97
1998	348	223	3.33	7.33
1999	317	221	3.50	7.94
2001	339	230	3.48	8.18
2002	350	215	3.39	7.86
2003	364	219	3.49	7.76
2004	261	223	3.46	8.32
2005	316	221	3.08	6.93
2006	367	221	3.25	7.69
2008	373	226	3.04	8.22
2009	369	230	3.13	8.11
2010	382	217	3.17	8.38
2011	367	229	3.10	8.35
2012	367	219	3.07	7.75

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180 °C (mg/L)	Dissolved, in mg/L Chloride (Cl)	Dissolved, in mg/L Sulfate (SO_4)
		Piñon NTUA 1		
1998	460	304	4.59	4.74
2001	473	304	4.86	5.53
2002	512	---	5.04	5.47
2003	716	421	6.71	82.8
2004	691	429	7.04	75.9
2006	709	399	6.56	66.9
2008	565	328	6.15	8.70
2009	670	409	7.09	68.4
2010	675	407	7.06	63.8
2011	629	422	7.78	77.8
2012	652	407	7.09	64.3
		Forest Lake NTUA 1		
1982	470	([2])	11	67
1986	---	660	35	300
1990	375	226	8.2	38
1991	[1]350	183	10	24
1993	693	352	35	88
1994	[1]734	430	56	100
1995	470	274	13	60
1995	1,030	626	86	160
1995	488	316	16	71
1996	684	368	44	79
1997	[1]1,140	714	77.8	247
1998	489	350	37.3	70.8
1999	380	259	15.7	48.5
2001	584	398	49.6	83.9
2002	452	268	21.7	49.5
2003	385	228	10.5	39.8
2004	222	263	16.0	40.5
2005	402	272	17.9	43.8
2006	445	258	13.9	48.6
2008	424	362	36.5	73.2
2009	400	250	12.1	43.6
2010	524	503	60.3	125
2011	369	227	10.9	38.3
2012	391	219	11.3	36.0
		Kits'iili NTUA 2		
1997	[1]524	269	3.6	4.3
1998	379	270	3.8	4.07
2000	454	274	4.0	4.11
2001	409	276	5.0	4.52
2002	439	264	4.5	4.38
2003	445	275	4.2	4.42
2004	367	273	4.0	4.60
2005	424	271	3.67	3.70
2010	457	269	3.81	4.65
2011	449	274	3.89	4.85
2012	443	270	3.77	4.94

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

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

[3]Value is different in Black Mesa monitoring report printed in 2004.

Table 16. Specific conductance and concentrations of selected chemical constituents in water samples from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, northeastern Arizona, during 1974–2012.—Continued

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

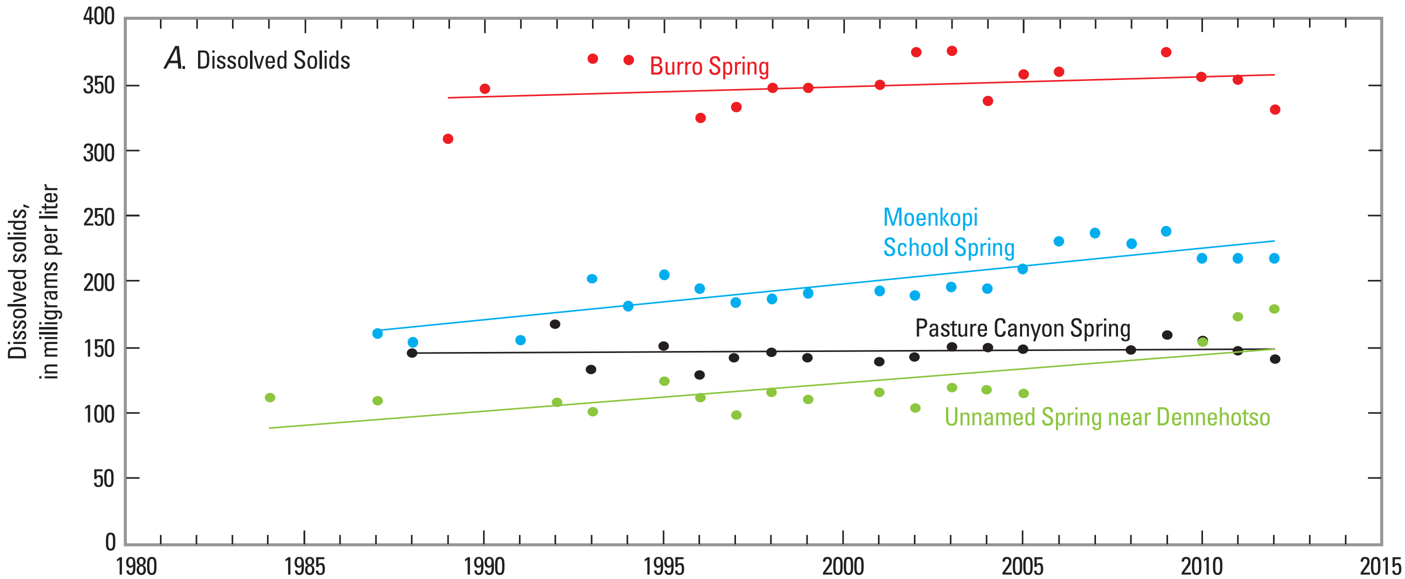
Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180 °C (mg/L)	Dissolved, in mg/L	
			Chloride (Cl)	Sulfate (SO_4)
		Rough Rock PM5		
1964	1120	([2])	100	110
1970	610	([2])	13	50
1983	1,090	([2])	130	110
1984	[1]1,100	613	130	99
1986	1,010	633	140	120
1988	1,120	624	130	[3]110
1991	[1]1,210	574	130	110
1993	1,040	614	130	110
1994	[1]1,180	626	130	110
1995	1,110	648	140	110
1996	1,100	634	130	110
1997	[1]1,060	628	130	112
1998	894	637	133	112
1999	1,050	630	129	110
2001	980	628	125	110
2002	1,120	636	129	109
2003	1,080	642	127	110
2004	653	649	128	109
2005	1,050	639	128	113
2010	1,100	635	129	114
2011	1,090	629	135	119
2012	1,080	649	130	116
		Peabody2		
1967	221	---	5.0	21
1971	211	---	2.8	18
1974	210	144	2.8	17
1975	230	163	5.0	20
1976	260	133	3.6	16
1979	220	---	3.4	24
1980	225	145	11.0	20
1986	172	---	2.6	8.1
1987	149	113	5.0	9.1
1993	163	124	1.7	8.9
1998	93	119	2.22	7.87
1999	167	115	2.31	8.14
2005	134	124	2.09	8.22
2006	167	118	2.16	8.23
2008	160	120	2.04	7.47
2009	146	113	2.08	7.16
2010	168	119	2.08	7.37
2011	162	114	2.13	8.12
2012	155	122	2.04	7.25
		Dennehotso PM2		
1964	350	---	12	31
1992	226	131	9.8	19
1993	298	164	8.2	16
1997	[1]305	190	10.9	14.3
1999	314	196	13.7	15.3
2005	339	205	10.5	14.4
2010	279	173	7.41	13.2
2011	279	178	7.64	13.9
2012	295	184	7.59	13.6
		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	3.93	76.9
1998	349	236	3.75	71.0
1999	364	236	3.99	72.4
2001	331	234	5.04	73.4
2002	363	237	5.08	66.9
2003	378	273	5.88	87.7
2004	303	241	4.03	71.8
2005	374	231	3.69	76.3
2010	308	191	4.71	11.1
2011	302	192	4.82	11.1
2012	363	222	3.71	62.5

[1]Value is different in Black Mesa monitoring reports printed before2000. The earlier reports showed values determined by laboratory analysis.

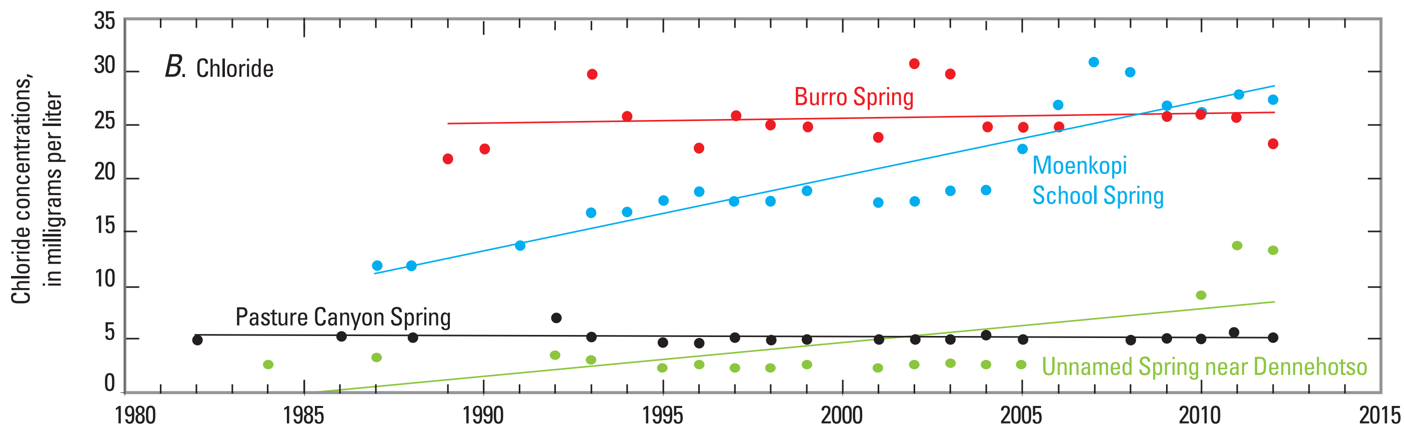
[2]Value is different in Black Mesa monitoring reports printed before2000. The earlier reports showed values determined by the sum of constituents.

[3]Value is different in Black Mesa monitoring report printed in2004.

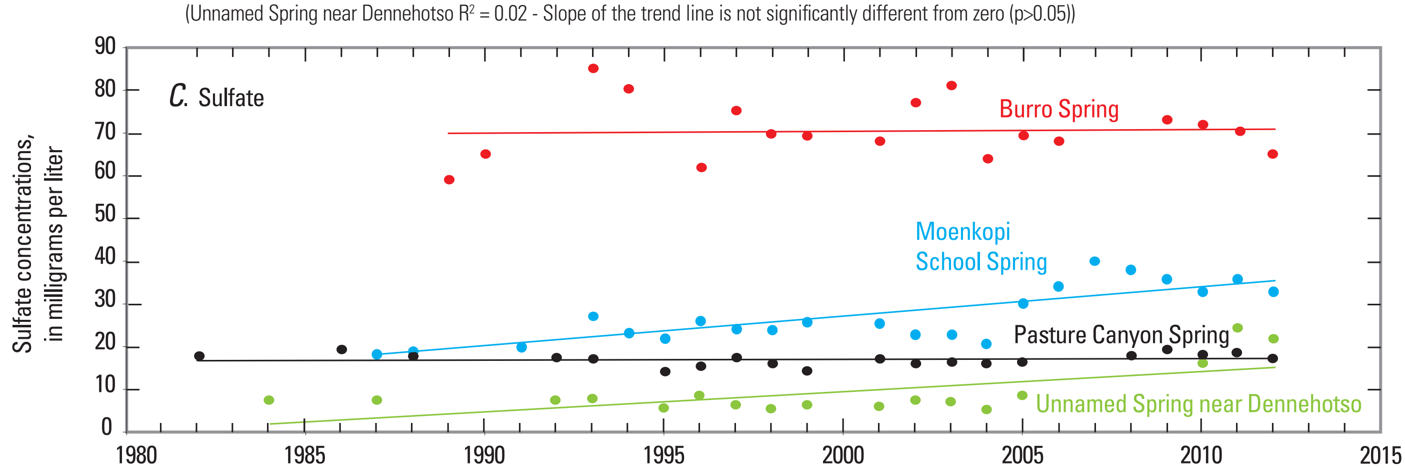
Figure 14. Plots showing concentrations of dissolved solids, chloride, and sulfate for water samples from Moenkopi School Spring, Pasture Canyon Spring, Burro Spring and Unnamed Spring near Dennehotso, which discharge from the N aquifer in Black Mesa area, northeastern Arizona, measured from 1982 to 2012. *A*, Dissolved solids; *B*, chloride; and *C*, sulfate. (Trend lines were generated using the method of least squares.)



NOTE: Lines indicate trends (Moenkopi School Spring R^2 = 0.70 - Slope of the trend line is significantly different from zero (p<0.05))
(Pasture Canyon Spring R^2 = 0.02 - Slope of the trend line is not significantly different from zero (p>0.05))
(Burro Spring R^2 = 0.08 - Slope of the trend line is not significantly different from zero (p>0.05))
(Unnamed Spring near Dennehotso R^2 = 0.51 - Slope of the trend line is not significantly different from zero (p>0.05))



NOTE: Lines indicate trends (Moenkopi School Spring R^2 = 0.82 - Slope of the trend line is significantly different from zero (p<0.05))
(Pasture Canyon Spring R^2 = 0.43 - Slope of the trend line is not significantly different from zero (p>0.05))
(Burro Spring R^2 = 0.02 - Slope of the trend line is not significantly different from zero (p>0.05))
(Unnamed Spring near Dennehotso R^2 = 0.02 - Slope of the trend line is not significantly different from zero (p>0.05))



NOTE: Lines indicate trends (Moenkopi School Spring R^2 = 0.66 - Slope of the trend line is significantly different from zero (p<0.05))
(Pasture Canyon Spring R^2 = 0.001- Slope of the trend line is not significantly different from zero (p>0.05))
(Burro Spring R^2 = 0.000001 - Slope of the trend line is not significantly different from zero (p>0.05))
(Unnamed Spring near Dennehotso R^2 = 0.42 - Slope of the trend line is not significantly different from zero (p>0.05))

Table 17. Physical properties and chemical analyses of water samples from four springs in the Black Mesa area, northeastern Arizona, in 2012.

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

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples in 2012	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)	Dissolved, in mg/L					
							Alkalinity field ($CaCO_3$)	Nitrogen $NO_2 + NO_3$ (N)	Ortho-Phosphate (P)	Calcium (Ca)	Magnesium (Mg)	Potassium (K)
354156110413701	6M-31	Burro Spring	06-14	22.5	553	7.2	186	<.040	0.005	58.6	4.37	.33
360632111131101	3GS-77-6	Moenkopi School Spring	06-07	17.9	382	6.6	96	2.01	0.005	35.1	7.58	1.15
361021111115901	3A-5	Pasture Canyon Spring	06-07	16.8	248	8.0	78.8	4.33	0.017	29.8	4.48	1.35
364656109425400	8A-224	Unnamed Spring near Dennehotso	06-04	14.6	298	7.8	84.5	1.73	0.03	33.9	5.72	1.14

U.S. Geological Survey identification number	Bureau of Indian Affairs site number	Common spring name	Date of samples in 2012	Dissolved, in mg/L					Dissolved, in µg/L			Dissolved solids, residue at 180 °C (mg/L)
				Sodium (Na)	Chloride (Cl)	Flouride (F)	Silica (SiO_2)	Sulfate (SO_4)	Arsenic (As)	Boron (B)	Iron (Fe)	
354156110413701	6M-31	Burro Spring	06-14	61.9	23.1	0.35	16.1	64.7	.94	82	16.1	330
360632111131101	3GS-77-6	Moenkopi School Spring	06-07	29.1	27.5	0.15	13.3	33.3	2.3	43	3.8	218
361021111115901	3A-5	Pasture Canyon Spring	06-07	12.2	5.2	0.14	9.97	17.5	1.8	33	<3.2	142
364656109425400	8A-224	Unnamed Spring near Dennehotso	06-04	14.9	13.5	0.64	14.6	21.9	2.1	49	9.1	179

Table 18. Specific conductance and concentrations of selected chemical constituents in N-aquifer water samples from four springs in the Black Mesa area, northeastern Arizona, 1948–2012.

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

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180 °C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Burro Spring				
1989	485	308	22.0	59.0
1990	[1]545	347	23.0	65.0
1993	595	368	30.0	85.0
1994	[1]597	368	26.0	80.0
1996	525	324	23.0	62.0
1997	[1]511	332	26.0	75.0
1998	504	346	24.6	70.4
1999	545	346	24.8	69.2
2001	480	348	23.6	67.8
2002	591	374	30.6	77.0
2003	612	374	30.5	81.1
2004	558	337	24.9	63.6
2005	558	357	25.8	68.9
2006	576	359	25.0	68.2
2009	577	372	25.7	72.5
2010	583	355	25.9	71.5
2011	560	353	25.7	69.5
2012	553	330	23.1	64.7
Moenkopi School Spring				
1952	222	---	6	---
1987	270	161	12.0	19.0
1988	270	155	12.0	19.0
1991	297	157	14.0	20.0
1993	313	204	17.0	27.0
1994	305	182	17.0	23.0
1995	314	206	18.0	22.0
1996	332	196	19.0	26.0
1997	[1]305	185	17.8	23.8
1998	296	188	17.6	23.7
1999	305	192	18.7	25.6
2001	313	194	18.3	25.5
2002	316	191	18.3	23.1
2003	344	197	18.6	23.4
2004	349	196	19.1	21.3
2005	349	212	23.3	29.6
2006	387	232	27.2	34.2
2007	405	238	30.6	39.9
2008	390	230	28.3	37.6
2009	381	240	27.0	35.4
2010	480	217	26.2	33.4
2011	374	216	28.5	36.2
2012	382	218	27.5	33.3
Pasture Canyon Spring				
1948	[1]227	([2])	6.0	13.0
1982	240	---	5.1	18.0
1986	257	---	5.4	19.0
1988	232	146	5.3	18.0
1992	235	168	7.10	17.0
1993	242	134	5.3	17.0
1995	235	152	4.80	14.0
1996	238	130	4.70	15.0
1997	232	143	5.27	16.9
1998	232	147	5.12	16.2
1999	235	142	5.06	14.2
2001	236	140	5.06	17.0
2002	243	143	5.14	16.5
2003	236	151	5.09	16.1
2004	248	150	5.50	16.4
2005	250	149	5.07	16.3
2008	240	149	5.01	18.3
2009	241	160	5.10	18.6
2010	314	157	5.25	17.9
2011	236	146	5.47	18.5
2012	248	142	5.20	17.5
Unnamed Spring near Dennehotso				
1984	195	112	2.8	7.1
1987	178	[2]109	3.4	7.5
1992	178	108	3.60	7.30
1993	184	100	3.2	8.00
1995	184	124	2.60	5.70
1996	189	112	2.80	8.20
1997	[1]170	98	2.40	6.10
1998	179	116	2.43	5.36
1999	184	110	2.76	6.30
2001	176	116	2.61	5.96
2002	183	104	2.67	7.38
2003	180	118	2.95	7.16
2004	170	117	2.72	5.05
2005	194	114	2.65	8.67
2010	259	155	9.38	15.5
2011	292	172	14.5	24.1
2012	298	179	13.5	21.9

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

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

Summary

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

This report presents results of groundwater, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2011 to September 2012. The monitoring data for 2011–12 are compared to data for 2010–11 and to historical data from the 1950s to September 2012.

In 2011, total groundwater withdrawals were about 4,480 acre-ft; industrial withdrawals were about 1,390 acre-ft, and municipal withdrawals were about 3,090 acre-ft. From 2010 to 2011, total withdrawals from the N aquifer increased by 11 percent, industrial withdrawals increased by approximately 19 percent, and total municipal withdrawals increased by 8 percent.

From 2011 to 2012, annually measured groundwater levels declined in 17 of 33 wells available for comparison. The median water-level change for the 33 wells was -0.1 ft. In unconfined areas of the N aquifer, water levels declined in 8 of 15 annual wells available for comparison, and the median change was -0.1 ft. In the confined area of the N aquifer, water levels declined in 9 of 18 wells, and the median change was 0.0 ft. From the prestress period (before 1965) to 2012, the median groundwater-level change in 34 wells was -13.4 ft. Water levels in the 16 wells in the unconfined areas of the N aquifer had a median change of -2.1 ft, and the changes ranged from -39.6 ft to +12.5 ft. Water levels in the 18 wells in the confined area of the N aquifer had a median change of -39.1 ft, and the changes ranged from -205.5 ft to +19.0 ft.

Discharge has been measured annually at Moenkopi School Spring and Pasture Canyon Spring and intermittently at Burro Spring and Unnamed Spring near Dennehotso. Between 2011 and 2012, spring flow decreased by 30 percent at Moenkopi School Spring, and by 16 percent at Pasture Canyon Spring. Discharge at Burro Spring has remained relatively constant since it was first measured in 1989. For the period of record, discharge at Moenkopi School Spring and Pasture Canyon Spring has fluctuated, and the data indicate a decreasing trend in discharge for both springs; however, no trend is apparent for either Burro Spring or Unnamed Spring near Dennehotso.

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

In 2012, water samples were collected from 10 wells and 4 springs and analyzed for selected chemical constituents. In the 10 wells, concentrations of dissolved solids, chloride, and sulfate have varied for the period of record, and the data do not indicate a trend.

Dissolved-solids concentrations in water samples from Burro Spring, Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso were 330 mg/L, 218 mg/L, 142 mg/L, and 179 mg/L, respectively. From the mid-1980s to 2012, long-term data from Moenkopi School Spring indicate increasing concentrations of dissolved solids, chloride, and sulfate. Concentrations of dissolved solids, chloride, and sulfate from Pasture Canyon Spring, Burro Spring, and Unnamed Spring near Dennehotso do not indicate a trend for the period of record.

References Cited

Boner, F.C., Davis, R.G., and Duet, N.R., 1992, Water-resources data, 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, 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, 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, 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.

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.

Fishman, M.J., ed., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 93–125, 217 p.

Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Fisk, G.G., Duet, N.R., Evans, D.W., Angeroth, C.E., Castillo, N.K., and Longsworth, S.A., 2004, Water-resources data, Arizona, water year 2003: U.S. Geological Survey Water-Data Report AZ–03–1, 326 p.

Fisk, G.G., Duet, N.R., McGuire, E.H., Angeroth, C.E., Castillo, N.K., and Smith, C.F., 2005, Water-resources data, Arizona, water year 2004: U.S. Geological Survey Water-Data Report AZ–04–1, 415 p.

Fisk, G.G., Duet, N.R., McGuire, E.H., Roberts, W.P., Castillo, N.K., and Smith, C.F., 2006, Water-resources data, Arizona, water year 2005: U.S. Geological Survey Water-Data Report AZ–05–1, 347 p.

Fisk, G.G., Duet, N.R., McGuire, E.H., Castillo, N.K., and Smith, C.F., 2007, Water-resources data, Arizona, water year 2006: U.S. Geological Survey Water-Data Report AZ–06–1.

Fisk, G.G., Duet, N.R., McGuire, E.H., Castillo, N.K., and Smith, C.F., 2008, Water-resources data, Arizona, water year 2007: U.S. Geological Survey Water-Data Report AZ–07–1.

Fisk, G.G., Duet, N.R., McGuire, E.H., Castillo, N.K., and Smith, C.F., 2009, Water-resources data, Arizona, water year 2008: U.S. Geological Survey Water-Data Report AZ–08–1.

Fisk, G.G., Duet, N.R., McGuire, E.H., Castillo, N.K., and Smith, C.F., 2010, Water-resources data, Arizona, water year 2009: U.S. Geological Survey Water-Data Report AZ–09–1.

Fisk, G.G., Duet, N.R., McGuire, E.H., Castillo, N.K., and Smith, C.F., 2011, Water-resources data, Arizona, water year 2010: U.S. Geological Survey Water-Data Report AZ–10–1.

Friedman, L.C., and Erdmann, D.E., 1982, Quality Assurance practices for the chemical and biological analyses of water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A6, 181 p.

Garbarino, J.R., Kanagy, L.K., and Cree, M.E., 2006, Determination of elements in natural-water, biota, sediment, and soil samples using collision/reaction cell inductively coupled plasma-mass spectrometry: U.S. Geological Survey Techniques and Methods, book 5, sec. B, chap.1, 88 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.

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.

Hart, R.J., and Sottilare, J.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, Colo., HSIGeoTrans, Inc., report prepared for Peabody Coal Company, 400 p.

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, Colo., HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., report prepared for Peabody Western Coal Company, 75 p.

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.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program- Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95–399, 113 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.

Littin, G.R., 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—1997: 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.

Littin, G.R., and Monroe, S.A., 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.

Littin, G.R., and Monroe, S.A., 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.

Littin, G.R., and Monroe, S.A., 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.

Macy, J.P., 2009, Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2007–2008: U.S. Geological Survey Open-File Report 2009–1148, 43 p.

Macy, J.P., 2010, Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2008–2009: U.S. Geological Survey Open-File Report 2010–1038, 43 p.

Macy, J.P., and Brown, C.R., 2011, Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2009–2010: U.S. Geological Survey Open-File Report 2011–1198, 41 p.

Macy, J.P., Brown, C.R., and Anderson, J.R., 2012, Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2010–2011: U.S. Geological Survey Open-File Report 2012–1102, 41 p.

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

National Climatic Data Center, 2011, Record of Climatological Observations: Washington, D.C., U.S. Department of Commerce, accessed October 11, 2011, at http://cdo.ncdc.noaa.gov/dly/DLY.

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, 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, Arizona, water year 1992: U.S. Geological Survey Water-Data Report AZ–92–1, 360 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, Arizona, water year 1996: U.S. Geological Survey Water-Data Report AZ–96–1, 328 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, Arizona, water year 1995: U.S. Geological Survey Water-Data Report AZ–95–1, 306 p.

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

Struzeski, T.M., DeGiacomo, W.J., and Zayhowski, E.J., 1996, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of dissolved aluminum and boron in water by inductively compled plasma-atomic emission spectrometry: U.S. Geological Survey Open-File Report 96–149, 17 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, Arizona, water year 1998: U.S. Geological Survey Water-Data Report AZ–98–1, 454 p.

Tadayon, Saeid, Duet, N.R., Fisk, G.G., McCormack, H.F., Partin, C.K., Pope, G.L., and Rigas, P.D., 2000, Water-resources data, Arizona, water year 1999: U.S. Geological Survey Water-Data Report AZ–99–1, 389 p.

Tadayon, Saeid, Duet, N.R., Fisk, G.G., McCormack, H.F., Partin, C.K., Pope, G.L., and Rigas, P.D., 2001, Water-resources data, 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, Arizona, water year 1997: U.S. Geological Survey Water-Data Report AZ–97–1, 416 p.

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.

Thomas, B.E., 2002b, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2001–02: U.S. Geological Survey Open-File Report 02–485, 43 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 p.

Truini, Margot, Baum, B.M., Littin, G.R., and Shingoitewa-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.

Truini, Margot, and Macy, J.P., 2005, Lithology and thickness of the Carmel Formation as related to leakage between the D and N aquifer, Black Mesa, Arizona: U.S. Geological Survey Scientific Investigations Report 2005–5187, 7 p.

Truini, Margot, and Macy, J.P., 2006, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2004–05: U.S. Geological Survey Open-File Report 2006–1058, 42 p.

Truini, Margot, and Macy, J.P., 2007, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2005–06: U.S. Geological Survey Open-File Report 2007–1041, 42 p.

Truini, Margot, and Macy, J.P., 2008, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2006–07: U.S. Geological Survey Open-File Report 2008–1324, 33 p.

Truini, Margot, Macy, J.P., and Porter T.J., 2005, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2003–04: U.S. Geological Survey Open-File Report 2005–1080, 44 p.

Truini, Margot, and Thomas, B.E., 2004, Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2002–03: U.S. Geological Survey Open-File Report 03–503, 43 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, 2003, Current drinking water standards, national primary and secondary drinking water regulations: Washington, D.C., U.S. Environmental Protection Agency, accessed October 5, 2010, at http://www.epa.gov/safewater/mcl.html.

U.S. Geological Survey, 1963–64a, Surface-water records of Arizona: 91 p.

U.S. Geological Survey, 1963–64b, Ground-water records of Arizona: 80 p.

U.S. Geological Survey, 1965–74a, Water-resources data for Arizona—Part 1, surface-water records: 212 p.

U.S. Geological Survey, 1965–74b, Water-resources data for Arizona—Part 2, ground-water records: 89 p.

U.S. Geological Survey, 1976–83, Water-resources data for Arizona, water years 1975–81: U.S. Geological Survey Water-Data Reports AZ–75–1 to AZ–81–1, [pagination varies].

U.S. Geological Survey, 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, Arizona, water year 1982: U.S. Geological Survey Water-Data Report AZ–82–1, 440 p.

White, N.D., and Garrett, W.B., 1986, Water resources data, Arizona, water year 1983: U.S. Geological Survey Water-Data Report AZ–83–1, 387 p.

White, N.D., and Garrett, W.B., 1987, Water resources data, Arizona, water year 1984: U.S. Geological Survey Water-Data Report AZ–84–1, 381 p.

White, N.D., and Garrett, W.B., 1988, Water resources data, Arizona, water year 1985: U.S. Geological Survey Water-Data Report AZ–85–1, 343 p.

Wilde, F.D., ed., variously dated, Field measurements: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A6, with sec. 6.0-6.8, available at http://pubs.water.usgs.gov/twri9A6/.

Wilde, F.D., Radtke, D.B., Gibs, Jacob, and Iwatsubo, R.T., 1998a, National field manual for the collection of water-quality data—Preparations for water sampling: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A1, 38 p.

_____1998b, National field manual for the collection of water-quality data—Selection of equipment for water sampling: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A2, 82 p.

_____1998c, National field manual for the collection of water-quality data—Cleaning of equipment for water sampling: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A3, 65 p.

_____1999, National field manual for the collection of water-quality data—Collection of water samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A4, 103 p.

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

Wilson, R.P., and Garrett, W.B., 1989, Water-resources data, Arizona, water year 1987: U.S. Geological Survey Water-Data Report AZ–87–1,385 p.

Zhu, Chen, Waddell, R.K., Jr., Star, Ira, and Ostrander, Murray, 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.

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.

Menlo Park Publishing Service Center, California
Manuscript approved for publication December 23, 2013
Edited by Claire M. Landowski
Design and layout by Jeanne S. DiLeo

USGS

Macy and Unema—**Groundwater, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2011–2012**—Open-File Report 2013–1304

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20131304