Results of Ground-Water, Surface-Water, and Water-Quality Monitoring, Black Mesa Area, Northeastern Arizona—1991–92

By G.R. Littin

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	*By*	*To obtain*
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day
degree Fahrenheit (°F)	°C=5/9(°F-32)	degree Celsius

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—A geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The Black Mesa monitoring program is designed to document long-term effects of ground-water pumping from the N aquifer by industrial and municipal users. The N aquifer is the major source of water in the 5,400-square-mile Black Mesa area, and the water is present under confined and unconfined conditions. Monitoring activities include continuous and periodic measurements of (1) ground-water levels in the confined and unconfined areas of the aquifer, (2) ground-water pumpage from the confined and unconfined areas of the aquifer, (3) surface-water discharge, (4) water quality of the aquifer, and (5) surface-water quality.

Since 1963, water levels in some wells completed in the confined area of the N aquifer have declined as much as 77 feet. In contrast, however, water levels in many wells completed in the unconfined area of the aquifer have risen during the same period. Ground-water withdrawals for industrial and municipal use increased during January through December 1991 as compared with the same period for 1990. Low-flow discharge along Moenkopi Wash has remained fairly constant at about 3 cubic feet per second since the streamflow station was established in 1976. Discharge measured in 1991 at two springs was greater than during previous years. Chemical analyses to date generally indicate no major changes in water quality in the N aquifer.

INTRODUCTION

The N aquifer is the major source of water for industrial and municipal users in the 5,400-square-mile Black Mesa area (fig. 1). The aquifer consists of three rock formations—the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member[1] of the Wingate Sandstone, which are all of early Jurassic age (Peterson, 1988). These formations are hydraulically connected and function as a single aquifer referred to as the N aquifer (fig. 2).

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

Total withdrawals for municipal and industrial use from the N aquifer in the Black Mesa area generally have increased during the last 25 years. Peabody Coal Company began operating a strip mine in the northern part of the mesa in 1968. The quantity of water pumped by the company increased from about 95 acre-ft in 1968 to a maximum of 4,740 acre-ft in 1982 and has decreased to 4,020 acre-ft in 1991. Withdrawals from the N aquifer for municipal use have increased from an estimated 250 acre-ft in 1968 to about 4,500 acre-ft in 1991.

The Navajo and Hopi Tribes have been concerned about the long-term effects of industrial withdrawals from the N aquifer on supplies for domestic and municipal purposes. These concerns led to an investigation of the water resources of the

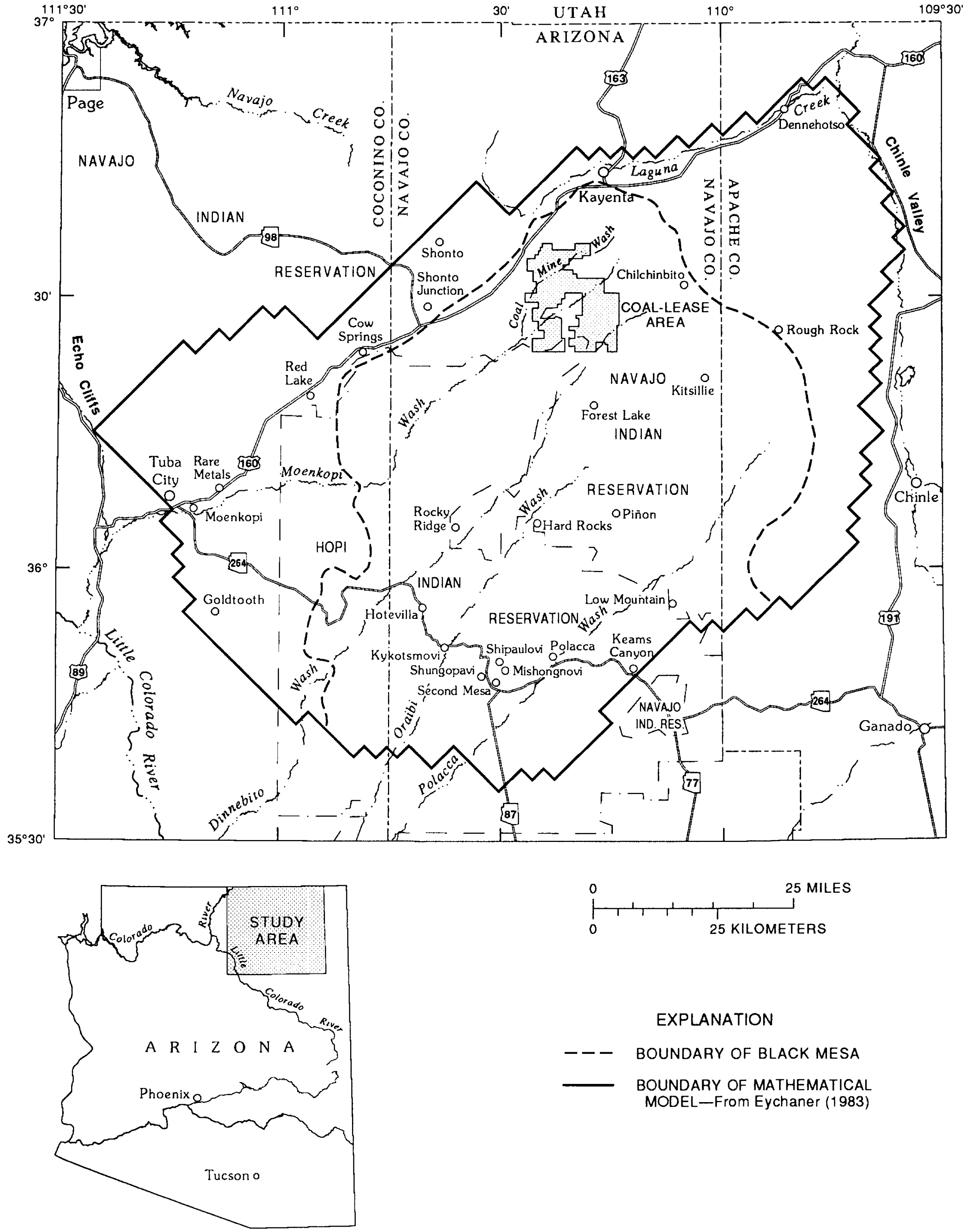


Figure 1. Location of study area.

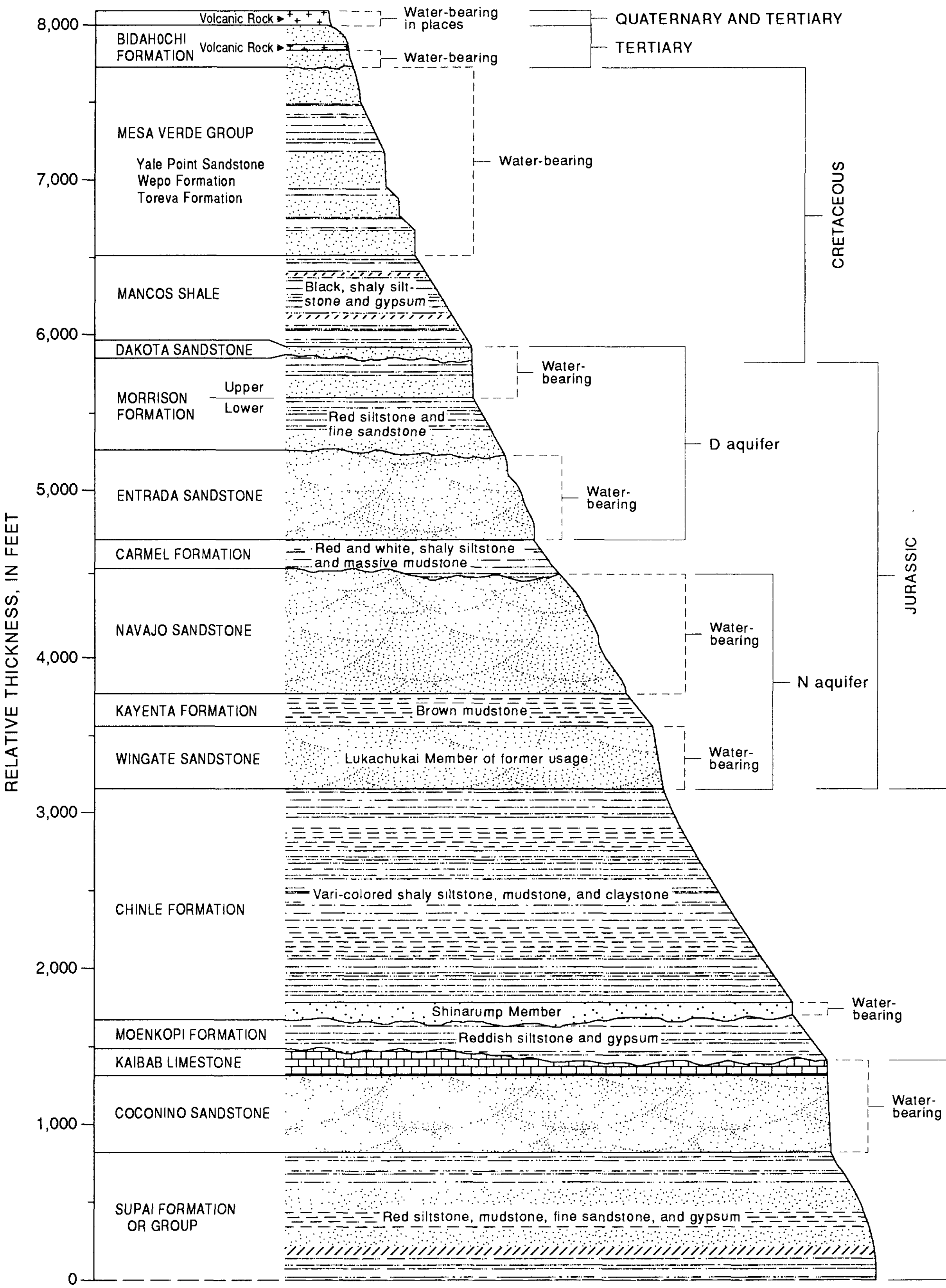


Figure 2. Rock formations of the Black Mesa area.

Black Mesa area in 1971 by the U.S. Geological Survey (USGS) in cooperation with the Arizona Department of Water Resources; in 1983, the U.S. Bureau of Indian Affairs joined the cooperative effort. Since 1983, the Navajo Tribal Utility Authority; Peabody Coal Company; the Hopi Tribe; and the Western Navajo Agency, Chinle Agency, and Hopi Agency of the U.S. Bureau of Indian Affairs have assisted in the collection of ground-water data.

Purpose and Scope of the Report

This report describes the results of ground-water, surface-water, and water-quality monitoring in the Black Mesa area from October 1990 to April 1992. The monitoring is designed to determine the effects of industrial and municipal pumpage from the N aquifer. Data-collection efforts include continuous and periodic measurements of various aspects of ground water and surface water in the Black Mesa area. Ground-water data were collected from wells completed in the N aquifer and include data on water levels, pumpage, and chemical quality. Surface-water data include discharge measurements and chemical quality at selected springs, discharge measurements at one streamflow site, and discharge measurements at continuous-record sites.

Previous Investigations

Ten progress reports have been prepared by the U.S. Geological Survey on the monitoring phase of the program (U.S. Geological Survey, 1978; G.W. Hill, U.S. Geological Survey, written commun., 1982, 1983; Hill, 1985; Hill and Whetten, 1986; Hill and Sottilare, 1987; Hart and Sottilare, 1988, 1989; Sottilare, 1992; and Littin, 1992). Most of the data obtained from the monitoring program are contained in these reports except for stream-discharge and sediment-discharge data from Moenkopi Wash collected prior to the 1986 water year; those data were published by the U.S. Geological Survey (1963-81; White and Garrett, 1984, 1986-88; Wilson and Garrett, 1988-89; and Boner and others, 1989-92). Eychaner (1983) described the results of mathematical-model simulations of the flow of ground water in the N aquifer. The model was used to predict the effects of withdrawals through the year 2014. The model was converted to a new model program and recalibrated by using revised estimates of selected aquifer characteristics and a finer spatial grid (Brown and Eychaner, 1988). Kister and Hatchett (1963) show selected chemical analyses of ground water from wells and springs throughout the Navajo and Hopi Indian Reservations. Cooley and others (1969) provide a detailed description of the regional hydrogeology.

HYDROLOGIC-DATA COLLECTION

Activities of the monitoring program include measurements of ground-water levels, metered and estimated ground-water withdrawals, flow measurements of springs and surface water, and collection of water-quality samples to detect changes in the hydrologic conditions in the N aquifer. New data presented in this report were collected from October 1990 through April 1992. Measurements of annual ground-water levels were made between February and April 1992; continuous-record observation-well water levels and ground-water withdrawals were from January 1991 to December 1991. Surface-water discharge data were collected from October 1990 to September 1991. Ground-water quality data were collected from January through March 1992.

Ground-Water Levels

Ground water occurs under confined or artesian conditions in the central part of the study area and under unconfined or water-table conditions around the periphery. Annual ground-water levels were obtained from a network of 35 municipal and stock wells (table 1). In water year 1992, the maximum annual recorded water-level decline in the Black Mesa area was 8.6 ft at the Keams Canyon 2 well. The maximum annual recorded rise in water level was 13.5 ft at the Forest Lake well (table 1). Water levels generally rose in the unconfined area from early 1991 to early 1992;

Table 1.—*Water-level changes in wells completed in the N aquifer, 1989-92*

[Dashes indicate no data]

Well system or location name	U.S. Bureau of Indian Affairs field number	Change in water level from preceding water year, in feet				Water level at depth below land surface, in feet, 1992
		1989	1990	1991	1992	
Unconfined						
Goldtooth	3A-28	0.0	+0.3	-0.1	([1])	--------
Tuba City	3T-333	+.2	+1.5	+.8	+.7	28.8
	3K-325	-.2	-.1	-.5	+.9	202
	Rare Metals 2	-.2	+.4	+.8	([1])	--------
Tuba NTUA 1	3T-508	-------	[2]-13.7	+2.5	+9.4	51
Tuba NTUA 4	3T-546	[2]-9.3	-3.7	+5.6	+5.1	57.2
White Mesa Arch	1K-214	+1.1	-.3	+.8	+.1	220.5
Cow Springs[3]	1K-225	+.3	.0	-.5	+.9	48
Shonto	2K-300	+1.1	.0	+.6	-.1	171.9
Shonto Southeast	2K-301	-.4	-.6	+.6	-.6	286.9
	2T-502	-1.5	-.2	+.1	+.7	413.6
BM4[3]	2T-514	.0	+.3	0	-.2	216.3
Long House Valley	8T-510	+.8	-.6	-.2	+1.1	116.2
Marsh Pass	8T-522	+.2	-.6	-1.0	+.1	124.7
Northeast Rough Rock	8A-180	-5.1	+.2	-.1	0	43.4
BM1[3]	8T-537	+.2	+.3	0	+.4	373.1
Rough Rock	9Y-95	+2.4	-.7	------	[2]+1.7	105.9
	9Y-92	-1.4	+.1	-1.4	+3.0	166.8
Confined						
Chilchinbito	PM3	-9.9	+40.2	+1.5	-2.8	429.8
Rough Rock	10R-119	+.3	+.6	+.6	-1.9	256.6
	10T-258	+1.8	-1.0	([1])	[2]-3.0	312.8
	10R-111	+.1	-.1	+.2	-3.7	201.4
Forest Lake	4T-523	-12.2	-6.2	-18.7	+13.5	1,140

Table 1.—*Water-level changes in wells completed in the N aquifer, 1989-92*—Continued

Well system or location name	U.S. Bureau of Indian Affairs field number	Change in water level from preceding water year, in feet				Water level at depth below land surface, in feet, 1992
		1989	1990	1991	1992	
		Confined—Continued				
BM6[3]	BM6	-2.6	-9.5	-4.0	-3.4	808
Rocky Ridge	PM2	-3.2	-5.1	-5.4	-.8	492.7
BM5[3]	4T-519	-4.0	-3.5	-4.0	-1.3	378.9
Piñon	PM6	([1])	[2]-41.7	([1])	[2]-3.6	828.6
Keams Canyon	2	-17.2	-1.5	+8.4	-8.6	406.5
Kykotsmovi	PM1	-1.4	-------	+1.5	-3.1	262.4
	PM3	[2]-3.6	-.7	([1])	([1])	--------
Howell Mesa	6H-55	-.5	+.3	-4.6	+2.5	268.3
Kayenta West	8T-541	+7.3	-8.7	+3.6	([1])	--------
BM3[3]	8T-500	-3.6	+4.6	-.4	-7.1	137.1
BM2[3]	8T-538	-3.7	-3.4	-3.7	-2.2	186.8
Sweetwater Mesa	8K-443	([1])	([1])	[2]-1.8	-.2	535.6

[1]Unable to measure.
[2]Change in water level from last measurement 2 or more years earlier.
[3]Continuous recorder.

the median rise was 0.7 ft, and half the measured water levels rose between 0.1 and 1.1 ft. In the confined area, the median change was a decline of 2.8 ft, and half the measured water levels declined between 1.4 and 3.4 ft.

A mathematical model of the N aquifer was developed on the basis of available information about the aquifer (Eychaner, 1983). Water-level changes were simulated for several municipal wells and continuous-record observation wells that penetrate the N aquifer. In 1985, the model was rerun with measured withdrawals for 1980-84 to check the continued agreement of measured and simulated water levels (Hill and Sottilare, 1987). Brown and Eychaner (1988) recalibrated the 1983 model using a new model program that provided a finer grid and more detailed hydrologic characteristics near Kayenta, Tuba City, Keams Canyon, Oraibi, and the coal-lease area. As part of the recalibration process, the model was used to simulate water-level changes from 1965 to 1984. Hydrographs of the results of this simulation indicated general agreement between measured and simulated water-level changes observed in six continuous-record observation wells (BM1 through BM6; Brown and Eychaner, 1988). The model for 1988 was rerun in 1989 by using measured withdrawals from 1985-88 to check agreement between measured and simulated water levels (Hart and Sottilare, 1989). The 1988 model was again rerun in 1990 by using measured withdrawals from 1965-89 (Sottilare, 1992). Although the model was not run in 1991 or 1992, water-level measurements in the six observation wells for 1991-92 have been used to extend the hydrographs (fig. 3). The hydrographs of the measured water levels are based on annual and continuous-record data beginning about 1963 with well BM3. Water-level data for wells BM1, BM2, BM4, and BM5 began in 1972; water-level data for well BM6 began in 1977.

Since 1972, water levels in wells BM1 and BM4, completed in the unconfined areas of the N aquifer, have risen by 0.9 and 0.7 ft, respectively (figs. 3 and 4). Water levels in wells BM2, BM3, and BM5, completed in the confined areas of the N aquifer, have declined from about 45 ft in well BM3 to about 61.8 ft in well BM2 during that same period. In well BM6, completed in a confined area of the N aquifer, a 72.4-foot decline in water level has been recorded since 1977. Records for the oldest well, BM3, indicate a decline of 77 feet since 1963.

Withdrawals from the N Aquifer

Withdrawals from the N aquifer are separated into three categories: (1) industrial use from the confined area, (2) municipal use from the confined area, and (3) municipal use from the unconfined areas (tables 2 and 3). The industrial category includes eight wells at the Peabody Coal Company well field in northern Black Mesa (fig. 5). The U.S. Bureau of Indian Affairs, Navajo Tribal Utility Authority, and the Hopi Tribe operate about 70 municipal wells that are in categories 2 and 3. Withdrawals from wells equipped with windmills are neither measured nor estimated.

Withdrawals from the N aquifer were compiled on the basis of metered and estimated data (tables 2 and 3). In some areas, only partial data were available because of meter malfunctions, and pumpage was either prorated or computed on a per capita basis of 40 gal/d. The per capita consumption is based on pumpage data and population figures (Arizona Department of Economic Security, 1991) for areas without commercial water use.

In 1991, total ground-water withdrawal increased from about 5,810 acre-ft in 1990 to about 8,520 acre-ft, which is a 46-percent increase in withdrawals compared with total withdrawals in 1991. Most of the increase in pumpage occurred in the municipal category for the unconfined areas and was primarily the result of home and road construction in the Tuba City area (table 2, fig. 6). Although municipal pumpage in the confined area decreased about 30 acre-ft in 1991, industrial pumpage showed an increase of about 590 acre-ft, and resulted in a net increase of about 560 acre-ft from the confined area. Municipal and industrial pumpage was within the range of values for 1983-90.

Surface-Water Discharge

Outflow from the N aquifer appears mainly as surface flow in Moenkopi Wash and Laguna Creek and as springs near the boundaries of the aquifer (Davis and others, 1963). Discharge data were collected at the continuous-record streamflow station, Moenkopi Wash at Moenkopi (09401260; fig. 7, table 4). Low flow in Moenkopi Wash during November through February has remained fairly constant at about 3.0 ft^3/s since the streamflow station was established in 1976. Daily mean discharges for previous water years have been published by U.S. Geological Survey (1963-81), White and Garrett (1984, 1986-88), Wilson and Garrett (1988-89), and Boner and others (1989-92). Measurements formerly made on Laguna Creek have been discontinued because variable amounts of snowmelt and sewage effluent are often included in the flow, and the data did not represent discharge solely from the N aquifer.

Two springs were selected for discharge measurements as part of the monitoring program during 1992 (fig. 7, table 5). The springs were Pasture Canyon Spring (3A-5; alluvium on Navajo Sandstone) and an unnamed spring near Dennehotso (8A-224; Navajo Sandstone). Discharge from the two springs was greater than during previous years and was probably due to the cumulative effect of local recharge in addition to the regional ground-water flow.

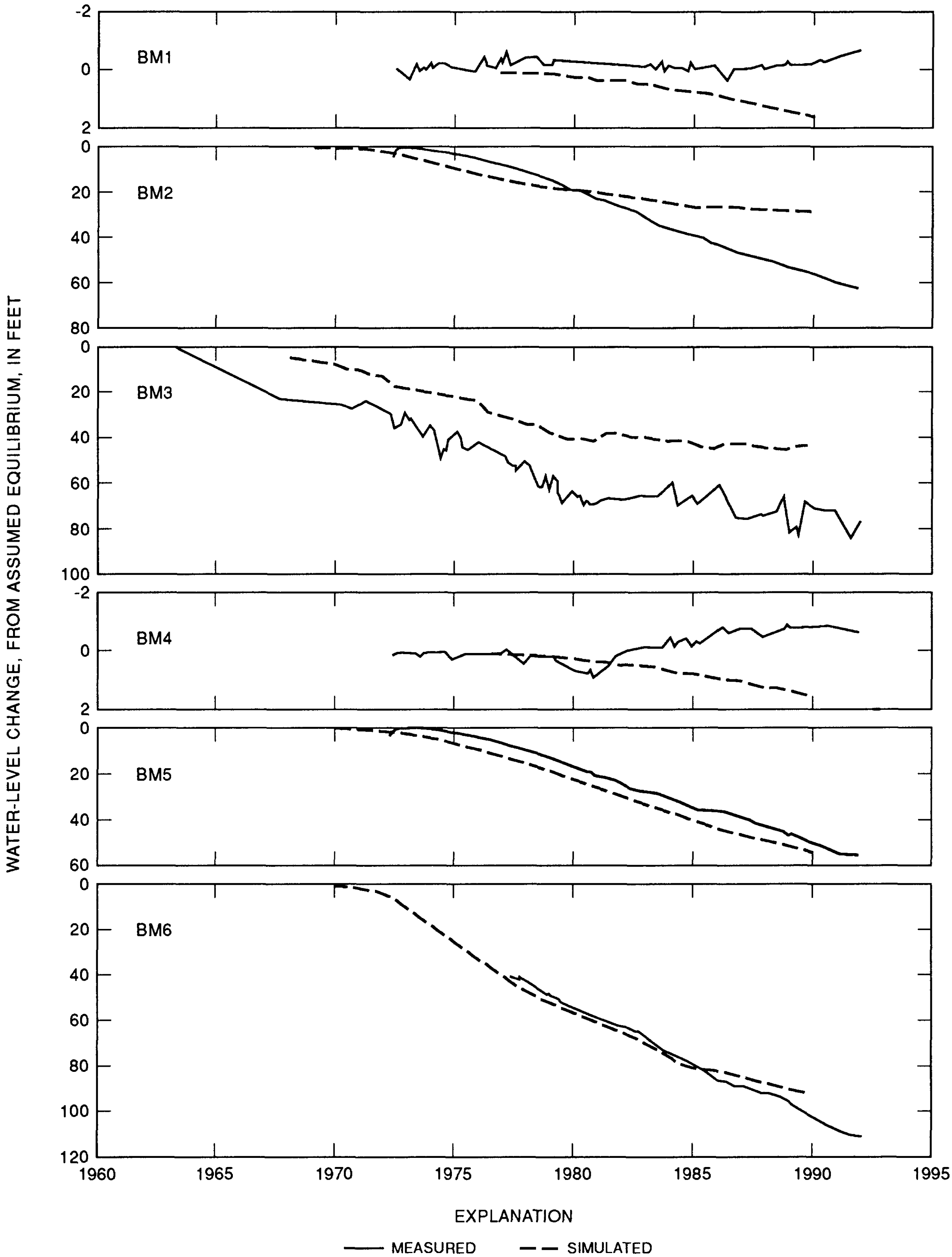
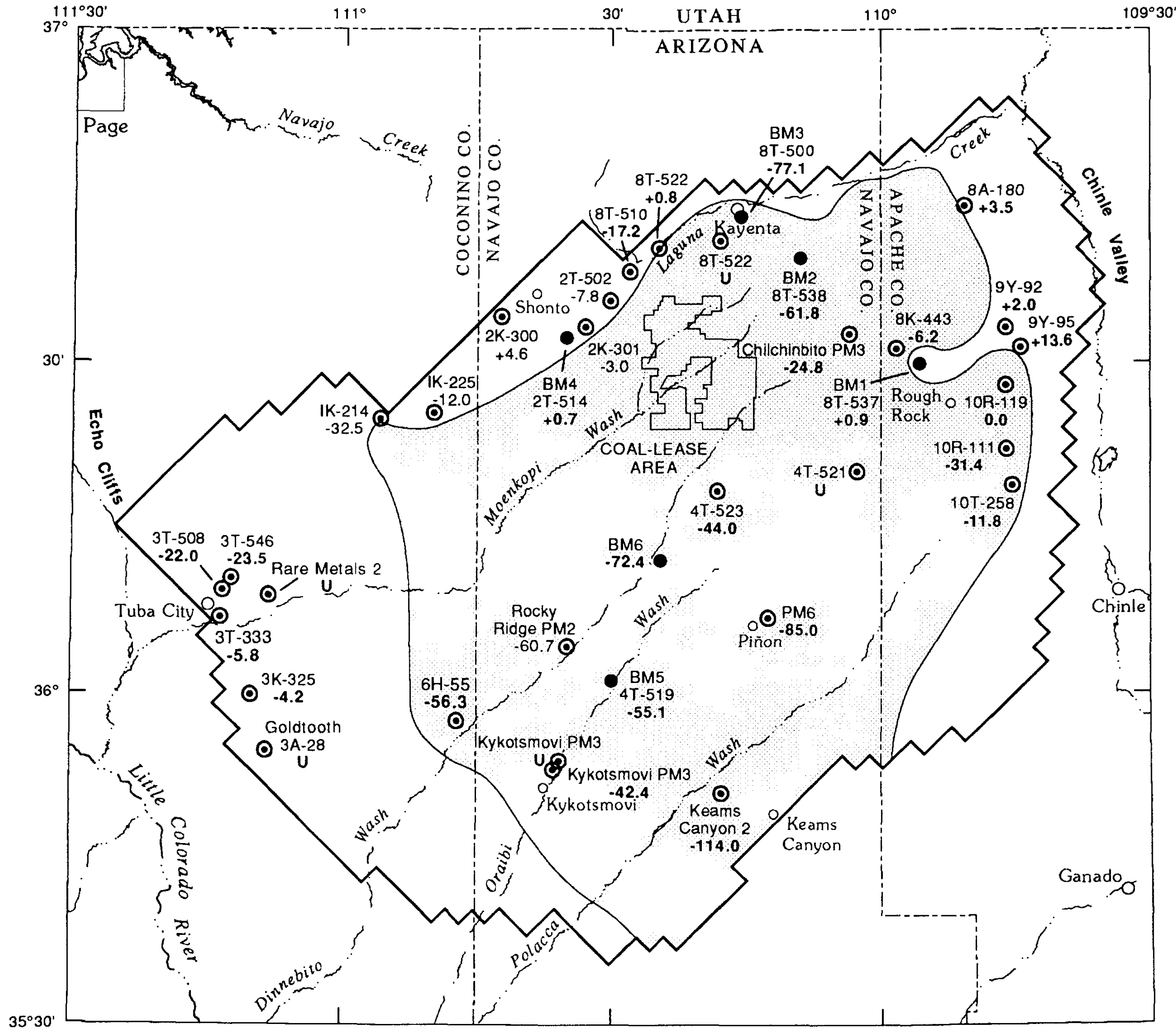


Figure 3. Measured and simulated water-level changes in observation wells BM1 through BM6, 1963-92 (modified from Brown and Eychaner, 1988; and Sottilare, 1992).



Modified from Brown and Eychaner, 1988

0 — 25 MILES

0 — 25 KILOMETERS

EXPLANATION

BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS APPROXIMATE—From Eychaner (1983)

CONFINED

UNCONFINED

BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)

4T-523 **-44.0** WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 4T-523, is Bureau of Indian Affairs identification number; second entry, **-44.0**, is change in water level, in feet, between measurements made during the prestress period and measurements made during 1991-92. **U**, means unable to measure

BM2 8T-538 **-61.8** CONTINUOUS WATER-LEVEL RECORDING SITE (OBSERVATION WELL) MAINTAINED BY THE U.S. GEOLOGICAL SURVEY—First entry, BM2, is U.S. Geological Survey identification number; second entry, 8T-538, is Bureau of Indian Affairs identification number; third entry, **-61.8**, is change in water level, in feet, from 1953 to 1991-92

Figure 4. Water-level changes in wells completed in the N aquifer from the start of data collection through 1992.

Table 2.—*Withdrawals from the N aquifer, 1965-91*

[Values are in acre-feet. Data for 1965-79 from Eychaner, 1983]

Year	Industrial[1]	Municipal[2,3]		Year	Industrial[1]	Municipal[2,3]	
		Confined	Unconfined			Confined	Unconfined
1965	0	50	20	1979	3,500	860	930
1966	0	110	30	1980	3,540	910	880
1967	0	120	50	1981	4,010	960	1,000
1968	95	150	100	1982	4,740	870	965
1969	43	200	100	1983	4,460	1,360	1,280
1970	740	280	150	1984	4,170	1,070	1,400
1971	1,900	340	150	1985	2,520	1,040	1,160
1972	3,680	370	250	1986	4,480	970	1,260
1973	3,520	530	300	1987	3,830	1,130	1,280
1974	3,830	580	362	1988	4,090	1,250	1,310
1975	3,500	600	508	1989	3,450	1,070	1,400
1976	4,180	690	645	1990	3,430	1,170	1,210
1977	4,090	750	726	1991	4,020	1,140	3,360
1978	3,000	830	930				

[1]Metered pumpage by Peabody Coal Company at its mine on Black Mesa.

[2]Does not include withdrawals from the wells equipped with windmills.

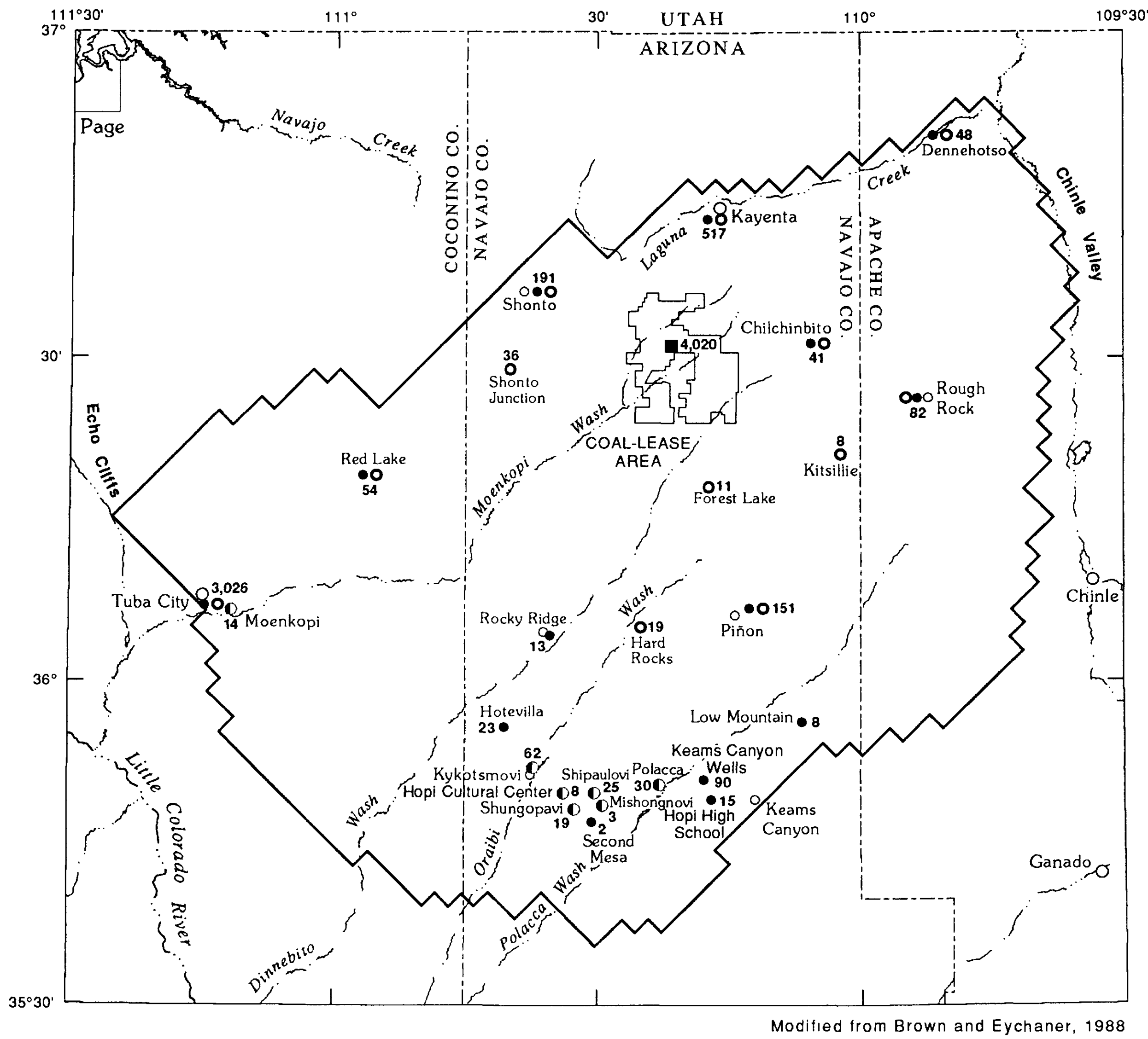
[3]Includes estimated pumpage, 1965-73, and metered pumpage, 1974-79, at Tuba City; metered pumpage at Kayenta and estimated pumpage at Chilchinbito, Rough Rock, Piñon, Keams Canyon, and Kykotsmovi prior to 1980; metered and estimated pumpage furnished by the Navajo Tribal Utility Authority and the U.S. 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 U.S. Bureau of Indian Affairs, various Hopi Village Administrations, and the U.S. Geological Survey, 1986-91.

Table 3.—*Withdrawals from the N aquifer by well system, 1991*

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

Location	Owner	Source of data	Confined-aquifer well systems	Unconfined-aquifer well systems	Location	Owner	Source of data	Confined-aquifer well systems	Unconfined-aquifer well systems
Tuba City	BIA	USGS/BIA		167.6	Dennehotso	NTUA	NTUA		21.5
Red Lake	BIA	USGS/BIA		8.5	Forest Lake	NTUA	NTUA	11.4	
Shonto	BIA	USGS/BIA		174.6	Chilchinbito	NTUA	NTUA	33.8	
Dennehotso	BIA	USGS/BIA		26.9	Kayenta	NTUA	NTUA	441.0	
Kayenta	BIA	USGS/BIA	75.7		Rough Rock	NTUA	NTUA	25.0	
Rocky Ridge	BIA	USGS/BIA	12.9		Piñon	NTUA	NTUA	120.6	
Chilchinbito	BIA	USGS/BIA	6.9		Kitsillie	NTUA	NTUA	7.5	
Piñon	BIA	USGS/BIA	30.8		Hard Rocks	NTUA	NTUA	19.1	
Rough Rock	BIA	USGS/BIA	56.5		Mine Well Field	Peabody	Peabody	4,020.0	
Hotevilla	BIA	USGS/BIA	22.9		Polacca	Hopi	USGS/Hopi	[1]30.0	
Second Mesa	BIA	USGS/BIA	2.5		Kykotsmovi	Hopi	USGS/Hopi	62.4	
Hopi High School	BIA	USGS/BIA	14.9		Shungopovi	Hopi	USGS/Hopi	18.8	
Keams Canyon	BIA	USGS/BIA	90.4		Shipaulovi	Hopi	USGS/Hopi	25.6	
Low Mountain	BIA	USGS/BIA	8.5		Mishongnovi	Hopi	USGS/Hopi	3.4	
Tuba City	NTUA	NTUA		2,859.0	Hopi Cultural Center	Hopi	USGS/Hopi	8.3	
Red Lake	NTUA	NTUA		45.5	Hopi Civic Center	Hopi	USGS/Hopi	2.0	
Shonto	NTUA	NTUA		16.6	Moenkopi	Hopi	USGS/Hopi	13.7	
Shonto Junction	NTUA	NTUA		35.9					

[1]Includes some estimated data because of temporary meter malfunction during the calendar year on one or more wells in this municipal well system. Estimate based on electrical usage, the typical average daily pumpage prior to meter malfunction for the well in question, or on per capita use of 40 gallons per day. Does not include possible estimated data provided by cooperating agencies.



EXPLANATION

BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)

WELL-SYSTEM OWNER

- ● U.S. Bureau of Indian Affairs
- O Navajo Tribal Utility Authority
- ◐ Hopi Tribe
- ■ Peabody Coal Company

Hotevilla
23● WITHDRAWALS FROM THE N AQUIFER—Hotevilla, is the village name; **23**, is the total withdrawal in acre-feet for 1991 at that location; the total is cumulative at locations served by multiple well owners

Figure 5. Location of well systems monitored for withdrawals from the N aquifer, 1991.

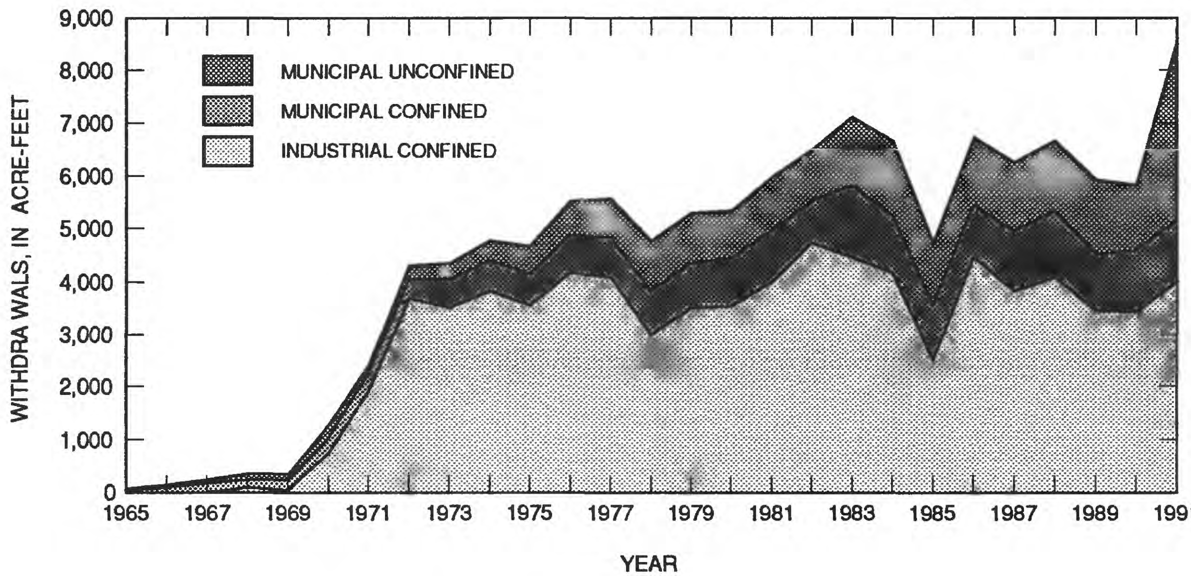


Figure 6. Withdrawals from the N aquifer, 1965-91.

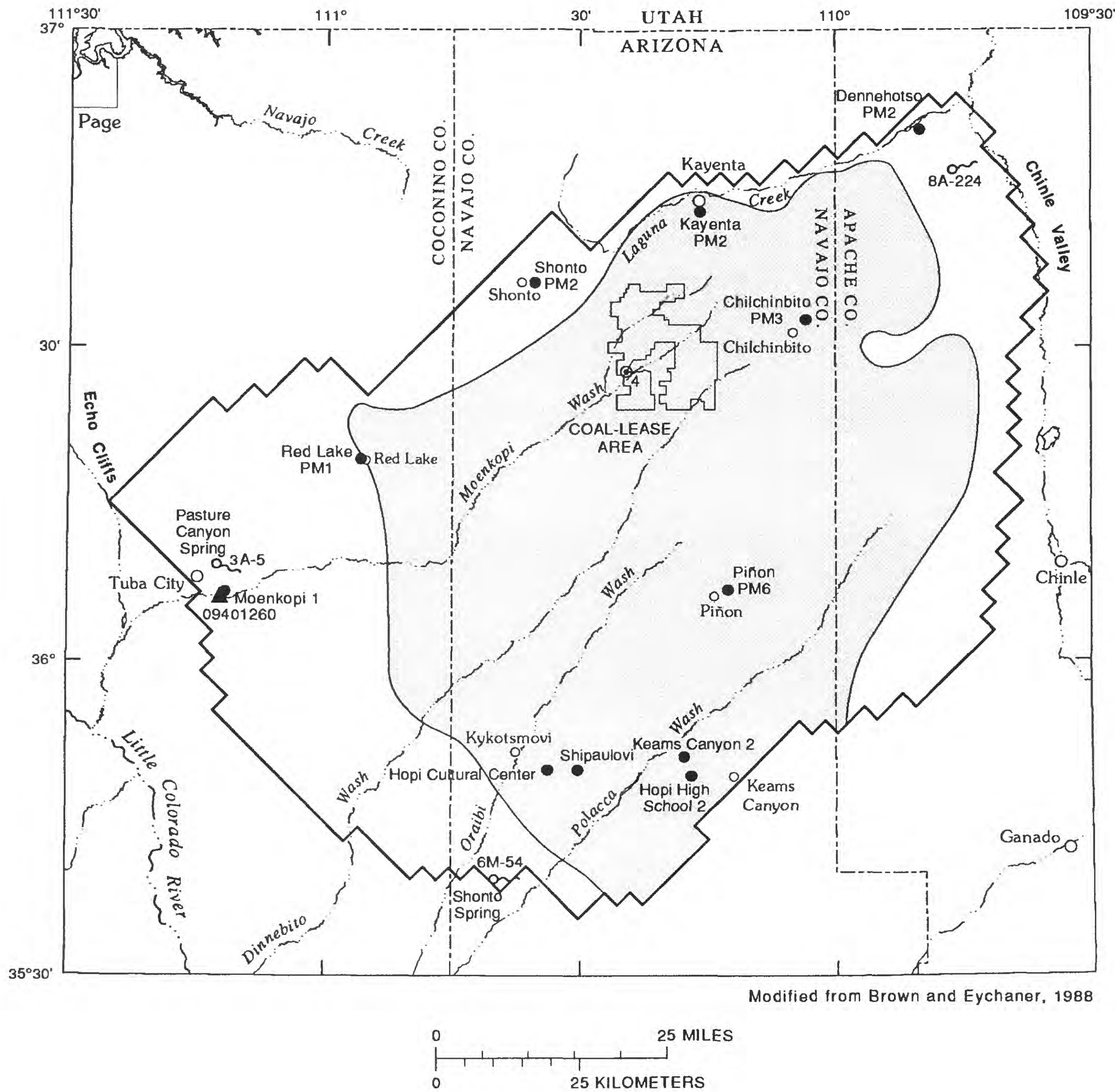
Chemical Quality

Water from Wells Completed in the N Aquifer

Water from the N aquifer is analyzed for selected chemical constituents to determine if falling hydraulic heads are inducing vertical leakage from overlying formations. The hydraulic head in the overlying D aquifer in 1964 averaged about 300 ft higher than that in the N aquifer. This higher head may cause water to move downward through the confining beds from the D aquifer to the N aquifer (Eychaner, 1983). Differences in the concentration of dissolved constituents in the water from the D aquifer and the N aquifer, however, indicate that the quantity of downward leakage must be small. On the average, the concentration 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 the concentration of sulfate ions is about 30 times greater (Eychaner, 1983). Any increase in the leakage rate as a result of pumping from the N aquifer probably would become evident as an increase in concentrations of dissolved solids, chloride, and sulfate in the most heavily pumped wells.

In general, water in the N aquifer is a calcium bicarbonate type in the part of the study area northwest of Black Mesa and a sodium bicarbonate type elsewhere throughout the area (Kister and Hatchett, 1963). Locally, however, some wells penetrating the N aquifer may contain large concentrations of sulfate, chloride, and other ions. The large concentrations of sulfate, chloride, and other ions may result from the movement of water downward from the D aquifer to the N aquifer through wells not adequately sealed to prevent vertical movement of water through the well bore or by leakage through confining beds. Water-quality data to date, however, do not substantiate leakage through confining beds because of drawdown in the N aquifer.

Eight of the wells sampled in 1992 are completed in the confined area of the N aquifer. All the wells except Hopi High School 2, Kayenta PM2, and Chilchinbito PM3 contained a sodium bicarbonate type water (fig. 8). Historically, water from the high school well has been a sodium chloride type, and water from Kayenta PM2 has been a calcium bicarbonate type. Water from well PM3 at Chilchinbito, however, indicated a marked change from a sodium bicarbonate type water in



EXPLANATION

BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS APPROXIMATE—From Eychaner (1983)

CONFINED

UNCONFINED

BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)

Piñon PM6 — MUNICIPAL WELL FROM WHICH WATER-QUALITY SAMPLE WAS COLLECTED—Piñon PM6 is well name

4 — INDUSTRIAL WELL FROM WHICH WATER-QUALITY SAMPLE WAS COLLECTED—4 is well number

3A-5 — SPRING AT WHICH DISCHARGE WAS MEASURED AND WATER-QUALITY SAMPLE WAS COLLECTED—3A-5 is spring identification number

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

Figure 7. Surface-water and water-quality data-collection sites, 1991-92.

Table 4.—*Discharge data, Moenkopi Wash at Moenkopi, water year 1991*

[Water year is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1991, is called "water year 1991." Dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, WATER YEAR 1991
DAILY MEAN VALUES

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	1.7	1.6	3.4	[1]3.0	0.61	6.4	1.1	1.5	0.45	0.00	31	0.17
2	164.0	1.6	3.2	[1]3.0	1.1	7.7	1.2	1.3	1.4	.00	7.4	26
3	60.0	1.6	2.8	[1]3.0	1.5	6.0	1.2	1.2	1.4	.00	.73	.57
4	15.0	1.9	2.5	[1]3.1	10	4.4	1.2	1.3	.97	.00	7.0	.11
5	5.1	2.1	2.7	[1]3.1	5.9	4.9	1.1	1.2	.64	.00	4.4	.16
6	2.0	2.1	3.0	[1]3.0	6.0	4.3	1.1	1.4	.46	.00	12	40
7	1.3	3.0	3.0	3.1	5.5	4.4	1.0	1.6	.36	.00	24	16
8	1.3	2.9	2.9	5.8	4.2	4.6	.91	1.4	.25	.00	4.0	12
9	1.0	2.4	3.0	8.7	3.4	3.5	.80	1.1	.16	.00	.65	.59
10	1.2	2.8	2.9	7.6	3.4	4.4	.90	.84	.01	.00	.17	.37
11	1.0	2.2	3.3	14	3.4	3.4	.80	.75	.00	.00	.01	.16
12	1.0	2.1	4.9	1.1	3.6	3.1	.87	.82	.00	.00	.00	.00
13	.93	2.1	5.5	2.3	3.1	3.4	1.1	1.0	.00	.00	.49	.00
14	1.0	2.3	4.3	4.4	3.3	2.9	1.2	.98	.00	.00	1.0	.00
15	.83	2.1	3.0	8.1	3.4	4.0	1.1	.91	.00	.00	.29	.00
16	.80	2.1	2.9	15	3.3	5.4	1.2	.96	.00	.00	.10	.00
17	.64	2.1	3.8	11	4.0	5.0	1.0	.89	.00	.00	.05	.00
18	1.3	2.4	2.8	1.6	3.3	4.3	1.2	.75	.00	.00	.00	.00
19	1.9	2.8	2.1	2.9	2.8	4.0	1.2	.46	.00	.00	.25	.00
20	1.6	2.7	2.3	3.5	3.0	4.1	.94	.53	.00	.00	.00	.00
21	2.0	2.9	3.3	1.9	3.3	4.6	1.6	.53	.00	.00	.00	.00
22	4.3	2.2	[1]3.2	1.5	3.6	4.7	1.2	.51	.00	.00	.00	.00
23	2.7	2.6	[1]3.2	1.5	3.8	3.5	1.2	.55	.00	.00	.00	.00
24	2.3	2.8	[1]3.1	1.0	3.8	3.0	1.2	.73	.00	.00	.00	.00
25	3.5	3.1	[1]3.2	1.2	3.7	1.1	1.2	.77	.00	.00	.00	.00
26	2.8	3.8	[1]3.1	1.2	3.8	1.1	1.0	.57	.00	.00	.00	.00
27	2.4	3.6	[1]3.0	1.1	4.1	1.9	1.2	.36	.00	.00	56	.00
28	1.3	3.3	[1]3.0	3.6	5.1	1.8	1.3	.23	.00	.00	5.4	.00
29	1.3	2.1	[1]3.0	9.3	-----	1.9	1.5	.20	.00	.00	.56	.00
30	2.5	2.2	[1]3.1	2.4	-----	1.1	1.6	.21	.00	.00	.12	.00
31	2.2	----	[1]3.0	.55	-----	1.1	------	.17	-----	.00	.12	-------
TOTAL	290.90	73.5	98.5	132.55	106.01	116.0	34.12	25.72	6.10	0.00	155.74	96.13
MEAN	9.38	2.45	3.18	4.28	3.79	3.74	1.14	.83	.20	.00	5.02	3.20
MAX	164	3.8	5.5	15	10	7.7	1.6	1.6	1.4	.00	56	40
MIN	.64	1.6	2.1	55	61	1.1	.80	.17	.00	.00	.00	.00
AC-FT	577	146	195	263	210	230	68	51	12	.00	309	191

CALENDAR YEAR 1990	TOTAL 3,839.02	MEAN 10.5	MAXIMUM 320	MINIMUM 0.00	ACRE-FT 7,610
WATER YEAR 1991	TOTAL 1,135.27	MEAN 3.11	MAXIMUM 164	MINIMUM 0.00	ACRE-FT 2,250

[1]Estimated

Table 5.—*Discharge measurements of selected springs, 1924-92*

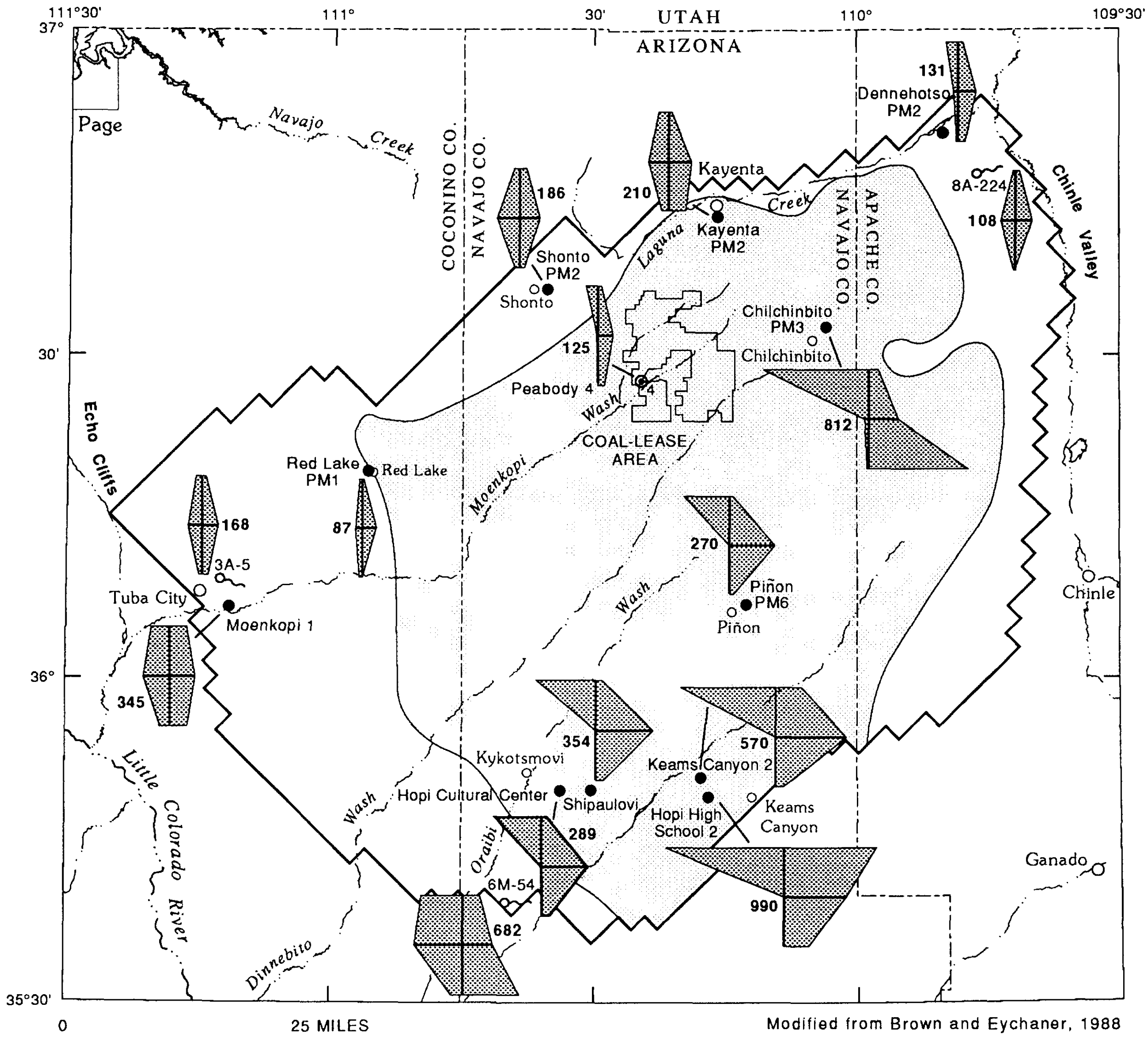
[Dashes indicate no data]

Spring name	U.S. Bureau of Indian Affairs well number	Year	Discharge, in gallons per minute
Pasture Canyon	3A-5	1954	174
		1982	135
		1986	166
		1988	211
		1992	[1]233
Shonto	6M-54	1924	[2]1
		1952	[3]1
		1984	39
		1987	-----
		1992	-----
Unnamed spring near Dennehotso	8A-224	1954	[3]1
		1984	[3]2
		1987	5
		1992	16

[1]Discharge measured in an irrigation ditch about 0.25 mile below water-quality sampling point and does not represent the total discharge into Pasture Canyon.
[2]Reported.
[3]Estimated.

1988 to a sodium sulfate type water in 1991. This change is believed to be caused by failure of the cement seal around the casing because the change was sudden rather than gradual and because development in the area has been slight. The well was sampled again in 1992. Sulfate concentrations decreased from 620 to 430 milligrams per liter (mg/L), possibly because the well was pumped for a longer period before the sample was collected. Most of the common ion concentrations in water from well PM3 were less in 1992 than those measured in 1991. The remaining five wells sampled in 1992 penetrate the unconfined area of the N aquifer. All the wells, except well PM2 at Dennehotso, contained a calcium bicarbonate type water (fig. 8). Water from well PM2 at Dennehotso was a sodium bicarbonate type and may have been influenced by ground-water movement in the N aquifer from Black Mesa. Calcium type water in upgradient or recharge areas and sodium type water in downgradient or discharge area indicates ion exchange during longer residence time. Dennehotso, near the Laguna Creek discharge, is consistent with this pattern.

Dissolved-solids concentrations in water from the N aquifer ranged from 87 mg/L at Red



EXPLANATION

BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS APPROXIMATE—From Eychaner (1983)

CONFINED

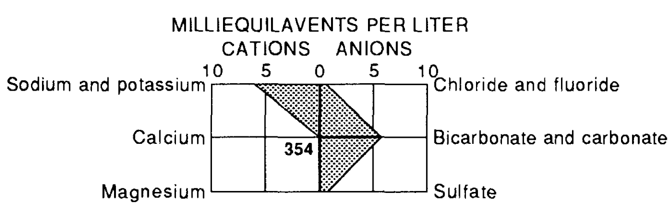
UNCONFINED

BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)

Piñon PM6 — MUNICIPAL WELL FROM WHICH WATER-QUALITY SAMPLE WAS COLLECTED—Piñon PM6 is well name

4 — INDUSTRIAL WELL FROM WHICH WATER-QUALITY SAMPLE WAS COLLECTED—4 is well number

3A-5 — SPRING AT WHICH DISCHARGE WAS MEASURED AND WATER-QUALITY SAMPLE WAS COLLECTED—3A-5 is spring identification number



CHEMICAL-QUALITY DIAGRAM—Shows major chemical constituents in milliequivalents per liter.The diagrams are in a variety of shapes and sizes, and provide a means of comparing, correlating and characterizing types of water. Number, **354**, is dissolved-solids concentration, in milligrams per liter

Figure 8. Water quality and distribution of dissolved solids in the N aquifer, 1992.

Lake well PM1 to 990 mg/L at the Hopi High School well 2 (fig. 8; tables 6 and 7). In the N aquifer, dissolved-solids concentrations in the sodium bicarbonate waters ranged from 125 to 570 mg/L; whereas concentrations in the calcium bicarbonate waters ranged from 87 to 345 mg/L. Long-term comparison of dissolved-solids concentrations in water from wells, Keams Canyon 2 and Piñon PM6, show no significant change from 1983 to 1992 (fig. 9, table 7).

Arsenic concentrations in the 12 wells ranged from 1 to 44 micrograms per liter (μg/L, table 6). Most samples contained from 1 to 3 μg/L of arsenic. The U.S. Environmental Protection Agency (EPA) has established 50 μg/L as the maximum contaminant level (MCL) for the safe drinking water standard for arsenic.

Surface Water

Three springs were selected for water-quality analyses as part of the monitoring program during 1991-92 (figs. 7 and 8; table 8). The springs were Pasture Canyon Spring near Tuba City, Shonto Spring near Kykotsmovi, and an unnamed spring near Dennehotso.

Water from Pasture Canyon Spring and the spring near Dennehotso was a calcium bicarbonate type. Water from Shonto Spring was a calcium sulfate type. Dissolved-solids concentrations in water from the three springs ranged from 104 to 652 mg/L, and arsenic concentrations were 3 μg/L or less. On the basis of previous data, the quality of water in the springs has not changed (table 8).

SUMMARY

The N aquifer is a major source of water for industrial and municipal uses in the Black Mesa area in northeastern Arizona, and water occurs under confined and unconfined conditions. Since 1963, water levels in some wells completed in the confined area of the aquifer have declined as much as 77 feet. Water levels in many wells completed in the unconfined areas of the aquifer have risen during the same period. Combined ground-water withdrawals were from about 350 acre-ft in 1968, between 4,500 and 6,800 during 1975-90, and 8,520 acre-ft in 1991. Outflow from the N aquifer is mainly surface flow along Moenkopi Wash and Laguna Creek and discharge from springs near the

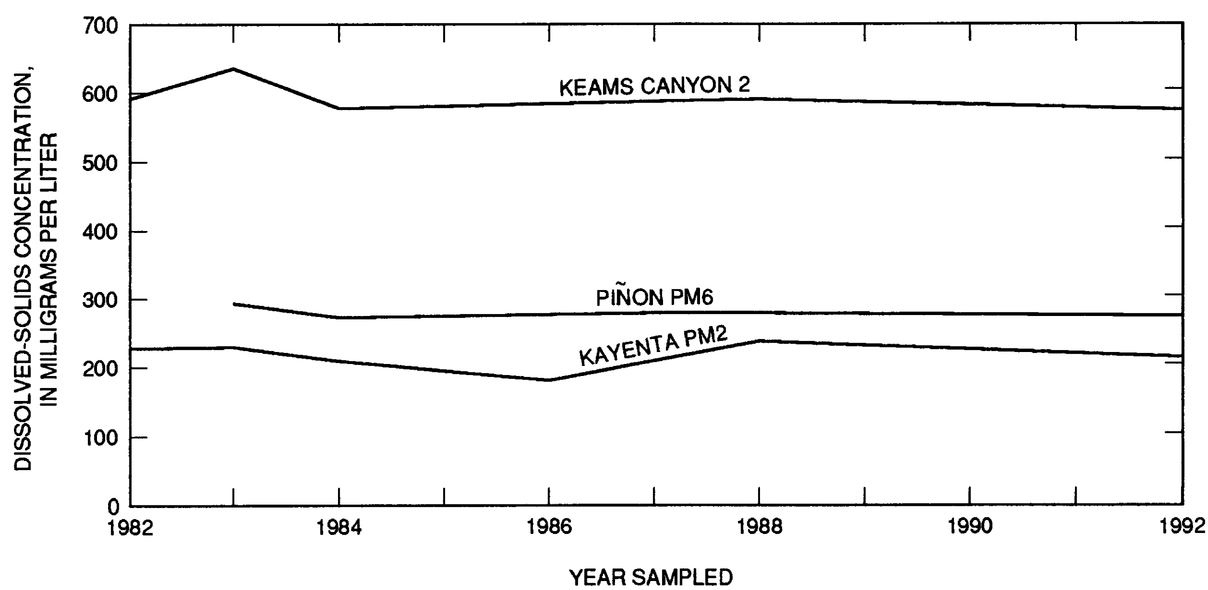


Figure 9. Dissolved-solids concentrations in water from wells Keams Canyon 2, Piñon PM6, and Kayenta PM2, 1982-92.

Table 6.—*Chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, 1992*

[°C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; µg/L, micrograms per liter]

Well name	U.S. Geological Survey identification number	Date of sample	Temperature (°C)	Specific conductance (µS/cm)	pH (units)	Alkalinity (mg/L as $CaCO_3$)	Nitrogen, NO_2+NO_3 dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)
Moenkopi 1	360718111130401	01-31-92	16.3	589	8.0	129	1.2	0.01
Red Lake PM1	361933110565001	01-31-92	16.7	164	8.5	75	1.2	.01
Shonto PM2	363558110392501	02-06-92	13.8	321	7.4	106	3.9	.01
Kayenta PM2	364344110151201	02-05-92	16.2	383	8.1	108	.9	.01
Dennehotso PM2	365045109504001	02-05-92	16.5	226	8.9	89	1.3	.01
Chilchinbito PM3	363137110044702	02-19-92	18.9	1,287	8.8	143	.2	.01
Piñon PM6	360614110130801	02-18-92	25.9	488	9.8	225	1.4	.01
Keams Canyon 2	355023110182701	02-12-92	19.6	1,008	9.3	349	.05	.01
Hopi High School 2	354910110182201	02-11-92	20.1	1,793	8.8	315	.05	.01
Shipaulovi	354742110294701	02-13-92	20.0	615	9.7	290	.05	.01
Hopi Arts and Crafts	355041110313701	02-20-92	23.8	521	9.8	232	.05	.01
Peabody 4	362647110243501	02-04-92	31.9	224	9.3	86	.96	.01

Well name	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Moenkopi 1	56	13	42	2.1	59	80
Red Lake PM1	18	5.1	4.6	2.0	2.6	1.9
Shonto PM2	48	5.9	5.8	1.7	22	19
Kayenta PM2	43	6.7	25	1.2	5.6	78
Dennehotso PM2	13	2.9	30	.9	9.8	19
Chilchinbito PM3	11	4.4	250	3.1	33	430
Piñon PM6	.6	.03	110	.4	7.0	8.6
Keams Canyon 2	.8	.15	220	.8	93	36
Hopi High School 2	2.1	.46	390	1.3	320	120
Shipaulovi	.5	.06	140	.6	12	17
Hopi Arts and Crafts	.5	.06	110	.4	6.5	20
Peabody 4	4.9	.03	39	.4	4.3	12

Well name	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Moenkopi 1	0.3	14	2	80	3	345
Red Lake PM1	.1	11	1	20	5	87
Shonto PM2	.1	15	1	10	6	186
Kayenta PM2	.2	15	2	30	8	210
Dennehotso PM2	.2	13	3	30	15	131
Chilchinbito PM3	.5	10	1	190	19	812
Piñon PM6	.3	28	4	50	4	270
Keams Canyon 2	1.3	12	44	620	3	570
Hopi High School 2	2.5	10	28	1,400	3	990
Shipaulovi	.4	19	24	100	3	354
Hopi Arts and Crafts	.3	25	13	50	5	289
Peabody 4	.2	22	3	20	8	125

Table 7.—*Selected properties and concentrations of chemical constituents in water from industrial and municipal wells completed in the N aquifer, 1982-92*

[μS/cm, microsiemens per centimeter; mg/L, milligrams per liter. Dashes indicate no data]

Well name	Year	Specific conductance (μS/cm)	Dissolved-solid concentrations, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Moenkopi 1	1992	589	345	59	80
Red Lake PM1	1992	164	87	2.6	1.9
Shonto PM2	1986	290	----	10	14
	1988	285	171	13	14
	1992	321	186	22	19
Kayenta PM2	1982	360	228	4.5	58
	1983	375	230	------	60
	1984	365	209	4.2	51
	1986	300	181	8.2	30
	1988	358	235	3.8	74
	1992	383	210	5.6	78
Dennehotso PM2	1992	226	131	9.8	19
Chilchinbito PM3	1986	390	231	2.4	11
	1988	414	256	2.7	31
	1991	1,500	952	11	620
	1992	1,287	812	33	430
Piñon PM6	1982	485	----	3.7	5
	1983	505	293	3.6	3.5
	1984	495	273	3.7	5.4
	1987	500	279	3.7	3.8
	1988	455	278	3.5	5.2
	1992	488	270	7	8.6
Keams Canyon 2	1982	1,010	592	94	35
	1983	1,120	636	120	42
	1984	1,040	578	96	36
	1988	1,040	591	97	34
	1990	1,030	600	94	34
	1992	1,008	570	93	36
Hopi High School 2	1992	1,793	990	320	120
Shipaulovi	1992	621	354	12	17
Hopi Arts and Crafts	1992	521	289	6.5	20
Peabody 4	1986	205	----	4.2	12
	1987	194	135	5	13
	1992	224	125	4.3	12

Table 8.—*Chemical analyses of water from selected springs in the Black Mesa area, 1992*

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

Spring name	U.S. Bureau of Indian Affairs field number	U.S. Geological Survey identification number	Rock formation	Date of sample	Temperature (°C)	Specific conductance (µS/cm)	pH (units)	Alkalinity (mg/L as $CaCO_3$)	Nitrogen, NO_2+NO_3 dissolved (mg/L as N)
Pasture Canyon..	3A-5	361021111115901	Navajo Sandstone	03-24-92	16.2	235	8.0	78	4.8
Shonto................	6M-54	354032110443901	Navajo Sandstone	03-23-92	10.2	1,026	7.6	143	3.7
Spring near Dennehotso.....	8A-224	364656109425400	Navajo Sandstone	03-26-92	12.0	178	8.0	74	1.7

Spring name	Phosphorus ortho, dissolved (mg/L as P)	Hardness (mg/L as $CaCO_3$)	Hardness noncarbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio	Percent sodium	Sodium+potassium, dissolved (mg/L as Na+K)
Pasture Canyon..	0.01	96	--	31	4.5	12	0.5	22	13.5
Shonto................	.01	310	--	100	14	99	2	42	100.7
Spring near Dennehotso.....	.01	86	--	28	4	4.7	.2	11	5.7

Spring name	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Pasture Canyon..	1.5	7.1	17	0.1	8.7	2	30	6	168
Shonto................	1.7	58	280	.6	13	1	160	32	682
Spring near Dennehotso.....	1.0	3.6	7.3	.3	11	3	30	16	108

boundaries of the aquifer. Discharge in some springs was greater than during previous years. Low flow along Moenkopi Wash has remained constant at about 3 ft³/s since the streamflow station was established in 1976. In 1991, ground-water withdrawals from the N aquifer were used mainly for industrial (4,020 acre-ft) and municipal uses (4,500 acre-ft).

Calcium bicarbonate water and sodium bicarbonate water are the primary types of water that occur in the N aquifer. Calcium bicarbonate water occurs in the part of the study area northwest of Black Mesa. The sodium bicarbonate water generally occurs elsewhere throughout the area. Calcium sulfate and sodium sulfate waters have been found in a few wells. In 1991-92, dissolved-solids concentrations ranged from about 87 to 990 mg/L in samples from 12 wells and 2 springs. Arsenic concentrations ranged from 1 to 44 µg/L.

Although a potential exists for downward movement of water from the D aquifer to the N aquifer, the water-quality data to date do not substantiate any leakage through confining beds because of drawdown in the N aquifer. In general, long-term water-quality data for wells and springs show no discernible change in water quality.

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