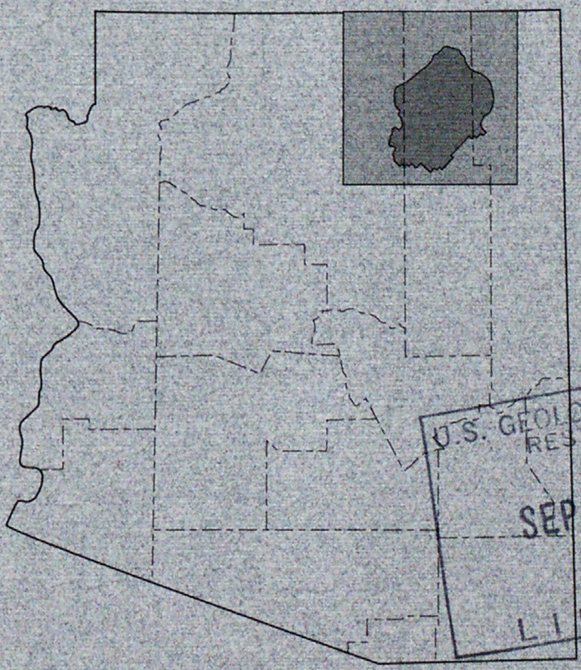
Results of Ground-Water, Surface-Water, and Water-Quality Monitoring, Black Mesa Area, Northeastern Arizona—1992–93

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95—4156



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

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By G.R. LITTIN and S.A. MONROE

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Tucson, Arizona
1995

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

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

Air temperatures are given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 1.8(°C) + 32$$

ABBREVIATED WATER-QUALITY UNITS

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

VERTICAL DATUM

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 occurs under confined and unconfined conditions. Monitoring activities include continuous and periodic measurements of (1) ground-water pumpage from the confined and unconfined areas of the aquifer, (2) ground-water levels in the confined and unconfined areas of the aquifer, (3) surface-water discharge, (4) water quality of the aquifer, and (5) surface-water quality.

Ground-water withdrawals for industrial and municipal use decreased significantly from about 8,500 acre-feet in 1991 to about 6,400 acre-feet in 1992 when large-scale municipal home- and road-construction projects were completed. During 1993, ground-water withdrawals rose slightly to about 6,500 acre-feet. Measured low-flow discharge along Moenkopi Wash decreased from 3 to about 2.8 cubic feet per second in 1992. During 1993, measured low-flow discharge was again at about 3 cubic feet per second. Discharge was measured at six springs. Discharge at Moenkopi School Spring increased by about 1 gallon per minute and is the only spring of the six that has maintained a consistent increase in discharge in recent years. Chemical analyses to date continue to indicate no major changes in water quality because of drawdown in the N aquifer.

The ground-water flow model of the study area developed in 1988 was updated with pumpage data collected from 1990 to 1993. A comparison of simulated to actual water-level changes indicates general agreement throughout much of the Black Mesa area; however, a disparity between simulated and actual water levels in the continuous-record observation wells suggests that analysis of model calibration and sensitivity may be warranted.

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).

Total withdrawals for industrial and municipal 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 3,700 acre-ft in 1993. Withdrawals

[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.

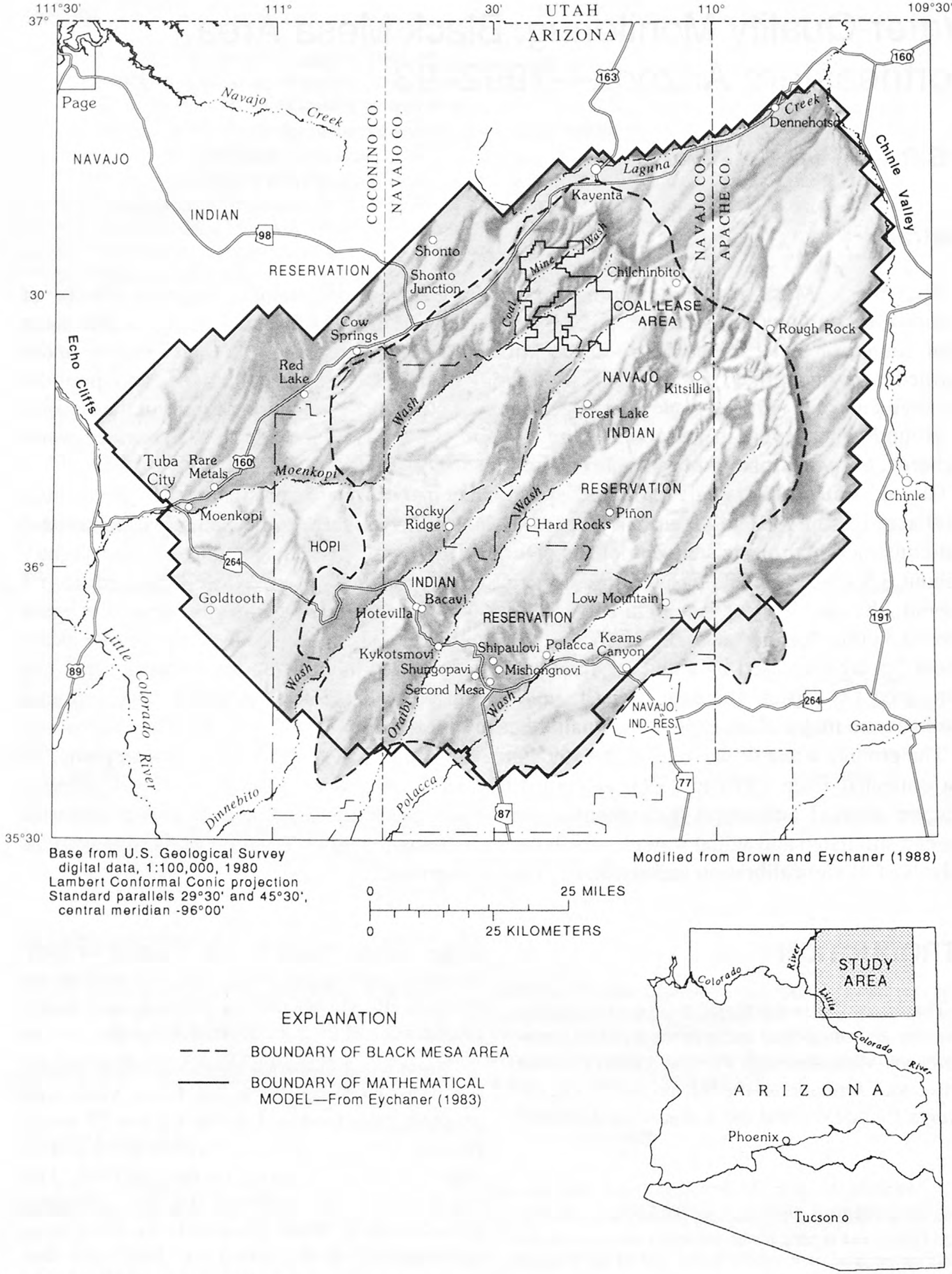


Figure 1. Location of study area.

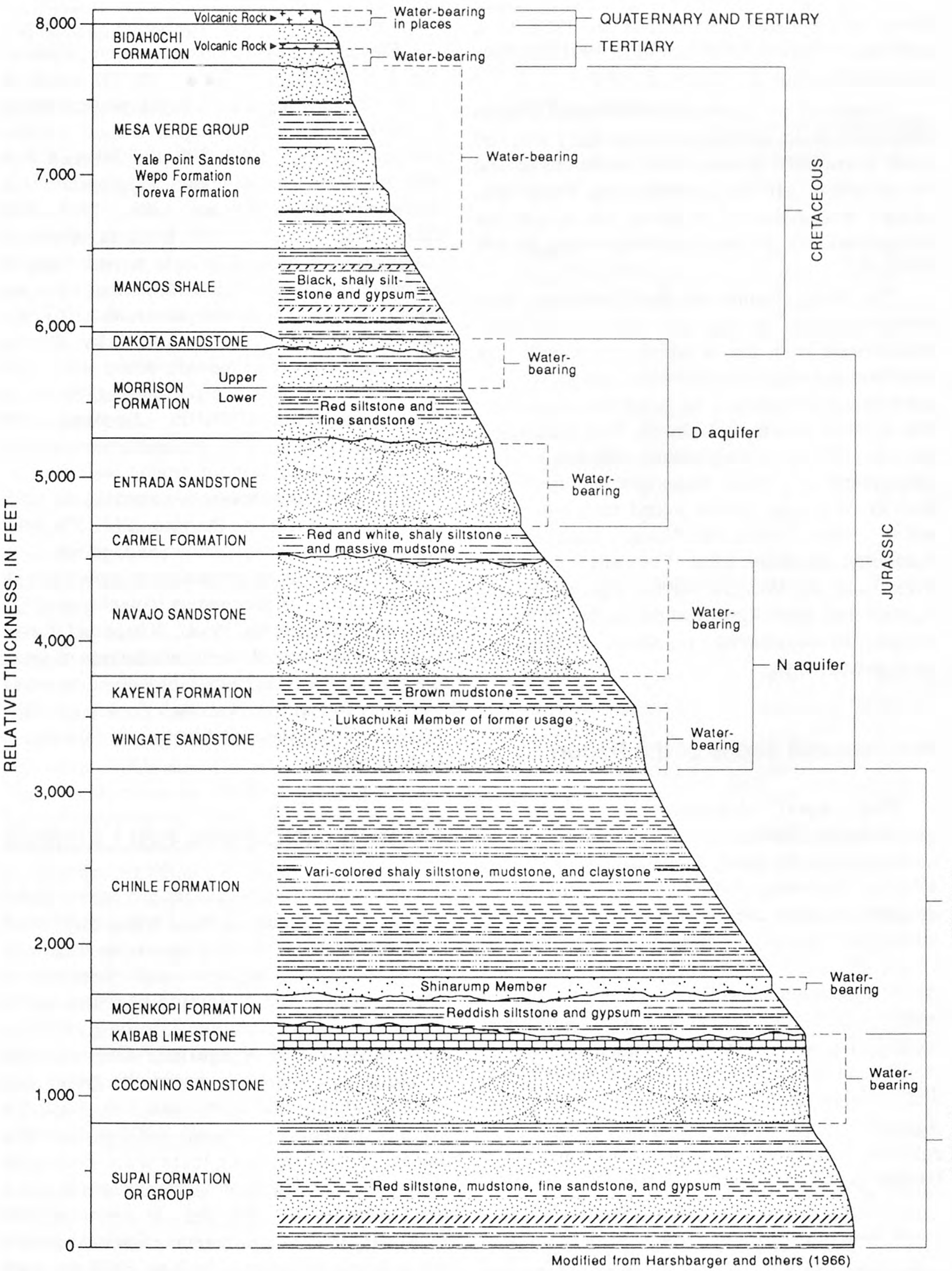


Figure 2. Rock formations of the Black Mesa area.

from the N aquifer for municipal use have increased from an estimated 250 acre-ft in 1968 to a maximum of about 4,500 acre-ft in 1991 and have decreased to about 2,800 acre-ft in 1993.

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. In the confined area, the median change was a decline of about 3.8 ft. In the unconfined area, the median change was a decline of 0.5 ft.

The Navajo Nation and Hopi Tribe 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 Black Mesa area in 1971 by the U.S. Geological Survey (USGS) in cooperation with the Arizona Department of Water Resources; in 1983, the 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 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 January 1992 to December 1993.[2] 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 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 pumpage, water levels, and chemical quality. Surface-water data include discharge measurements and chemical quality at selected springs, and discharge measurements at a continuous-record site.

[2]Flowmeter tests were conducted at eight Peabody well sites during a well-field shutdown in April 1994.

Previous Investigations

Eleven 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, hydrologist, written commun., 1982, 1983; Hill, 1985; Hill and Whetten, 1986; Hill and Sottilare, 1987; Hart and Sottilare, 1988, 1989; Sottilare, 1992; and Littin, 1992, 1993). 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 metered and estimated ground-water withdrawals, well flowmeter tests, measurements of ground-water levels, flow measurements of springs and surface water, and collection of water-quality samples to detect changes in the hydrologic conditions in the N aquifer. Ground-water withdrawals, continuous-record observation-well water-level data, and surface-water discharge data were collected from January 1992 to December 1993. Well flowmeter tests were conducted throughout the Black Mesa area between August and December 1993 and, at the Peabody well sites, in April 1994. Measurements of annual ground-water levels were made in June 1993 and again between October and December 1993. Ground-water quality data were collected from December 1992 through December 1993.

Withdrawals from the N Aquifer

Withdrawals from the N aquifer are separated into three categories (table 1, fig. 3): (1) industrial use from the confined area, (2) municipal use from the confined area, and (3) municipal use from the unconfined areas. The industrial category includes eight wells at the Peabody Coal Company well field in northern Black Mesa (fig. 4). The 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, based on electrical usage, 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.

The total ground-water withdrawal in 1992 was about 6,400 acre-ft (table 1), which is a 25-percent decrease in withdrawals compared with total withdrawals in 1991. Industrial pumpage decreased to 3,800 acre-ft, which was 200 acre-ft less than that withdrawn in 1991. Municipal use at Tuba City (fig. 4) decreased from 3,028 acre-ft in 1991 to 976 acre-ft in 1992 when large-scale home- and road-construction projects were completed.

In 1993, total ground-water withdrawal increased slightly to about 6,500 acre-ft. Industrial pumpage accounted for 3,700 acre-ft, or about 56 percent of the total withdrawal as compared with 60 percent in 1992. Municipal pumpage accounted for 2,800 acre-ft and represents about 44 percent of the total withdrawal as compared with 40 percent in 1992.

In an effort to improve and ensure accuracy of withdrawal data, a quality-assurance program was begun in 1985 and is conducted periodically on all industrial and municipal wells that penetrate the N aquifer. Nearly all industrial and municipal wells in

Table 1. Withdrawals from the N aquifer, 1965–93

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

Year	Industrial[1]	Municipal[2,3]	
		Confined	Unconfined
1965	0	50	20
1966	0	110	30
1967	0	120	50
1968	95	150	100
1969	43	200	100
1970	740	280	150
1971	1,900	340	150
1972	3,680	370	250
1973	3,520	530	300
1974	3,830	580	362
1975	3,500	600	508
1976	4,180	690	645
1977	4,090	750	726
1978	3,000	830	930
1979	3,500	860	930
1980	3,540	910	880
1981	4,010	960	1,000
1982	4,740	870	965
1983	4,460	1,360	1,280
1984	4,170	1,070	1,400
1985	2,520	1,040	1,160
1986	4,480	970	1,260
1987	3,830	1,130	1,280
1988	4,090	1,250	1,310
1989	3,450	1,070	1,400
1990	3,430	1,170	1,210
1991	4,020	1,140	3,360
1992	3,820	1,180	1,410
1993	3,700	1,250	1,570

[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 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, 1986–93.

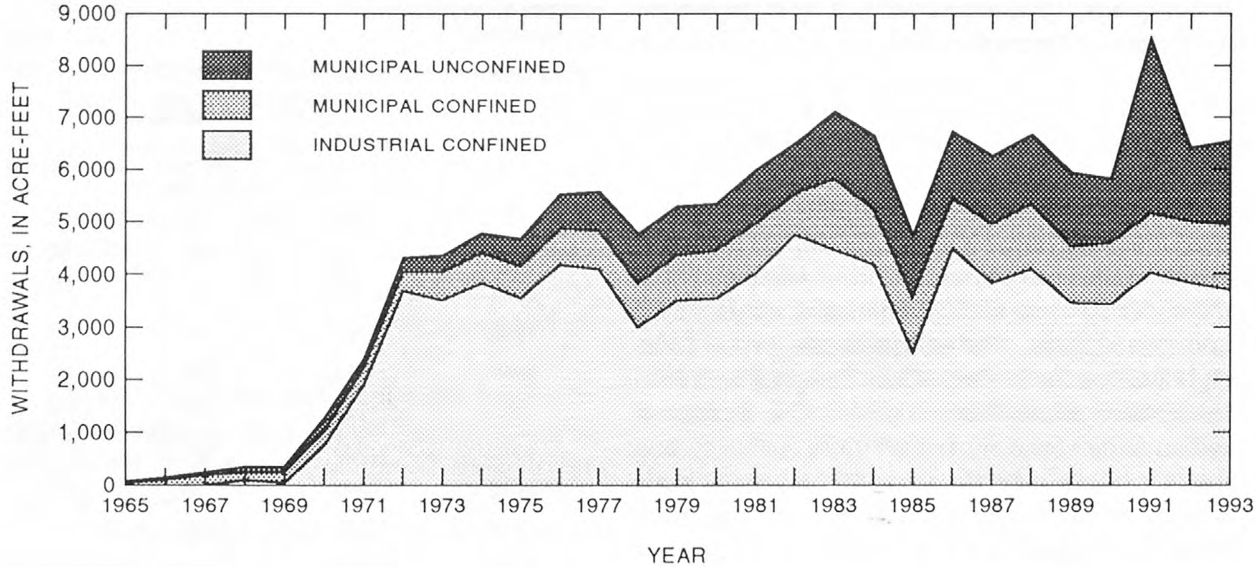


Figure 3. Withdrawals from the N aquifer, 1965–93.

the study area are equipped with totalizing flow meters. A Cox flowmeter was used to measure the larger discharges (greater than 300 gal/min) from industrial wells. Because of high operating pressures in the pipes and the complexity of the piping system, measurements could be made only when the well field was shut down. Measurements made in April 1994 are reported in table 4 because there was no opportunity to measure the wells during 1992–93. Meters on all municipal wells were tested using a Rockwell mechanical flowmeter designed specifically for testing meters. With this method, the flowmeter was attached to the discharge bypass at each site and a flow comparison was made by taking the average of three readings after discharge stabilization was attained. Measurements made using this method accounted for about 90 percent of all meters. Results were compared with the permanent well flowmeter readings. The results include a percent difference between the metered discharge and the measured discharge (table 4). For the purpose of this study, the allowable limit between metered and measured discharge should be no greater than ±10 percent.

Of the 66 meters that were tested, the percent difference between metered and measured ranged from +13.3 to -16.5. The average difference was about -1.2 percent. Six of the meters exceeded the allowable limit and should be repaired or replaced.

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 (fig. 5). Annual ground-water levels were obtained from a network of 36 municipal and stock wells (table 5). Water-level changes from the earliest available data through 1993 ranged from a rise of 12.9 ft to a decline of 147.6 ft (fig. 5). In 1993, the maximum annual recorded rise in water level in the Black Mesa area was 8.2 ft at the Kykotsmovi PM1 well. The maximum annual recorded water-level decline was 33.6 ft at the Keams Canyon No. 2 well; however, that measurement may have been affected by obstructions in the well and (or) nearby pumping. In the confined area, the median change was a decline of about 3.8 ft as opposed to a decline of 2.8 ft for the previous year. In the confined area, half the measured water levels in wells declined between 3.8 and 11.6 ft. In the unconfined area, water-level declines were recorded in 8 of the 16 measured wells from 1992 to 1993; the median

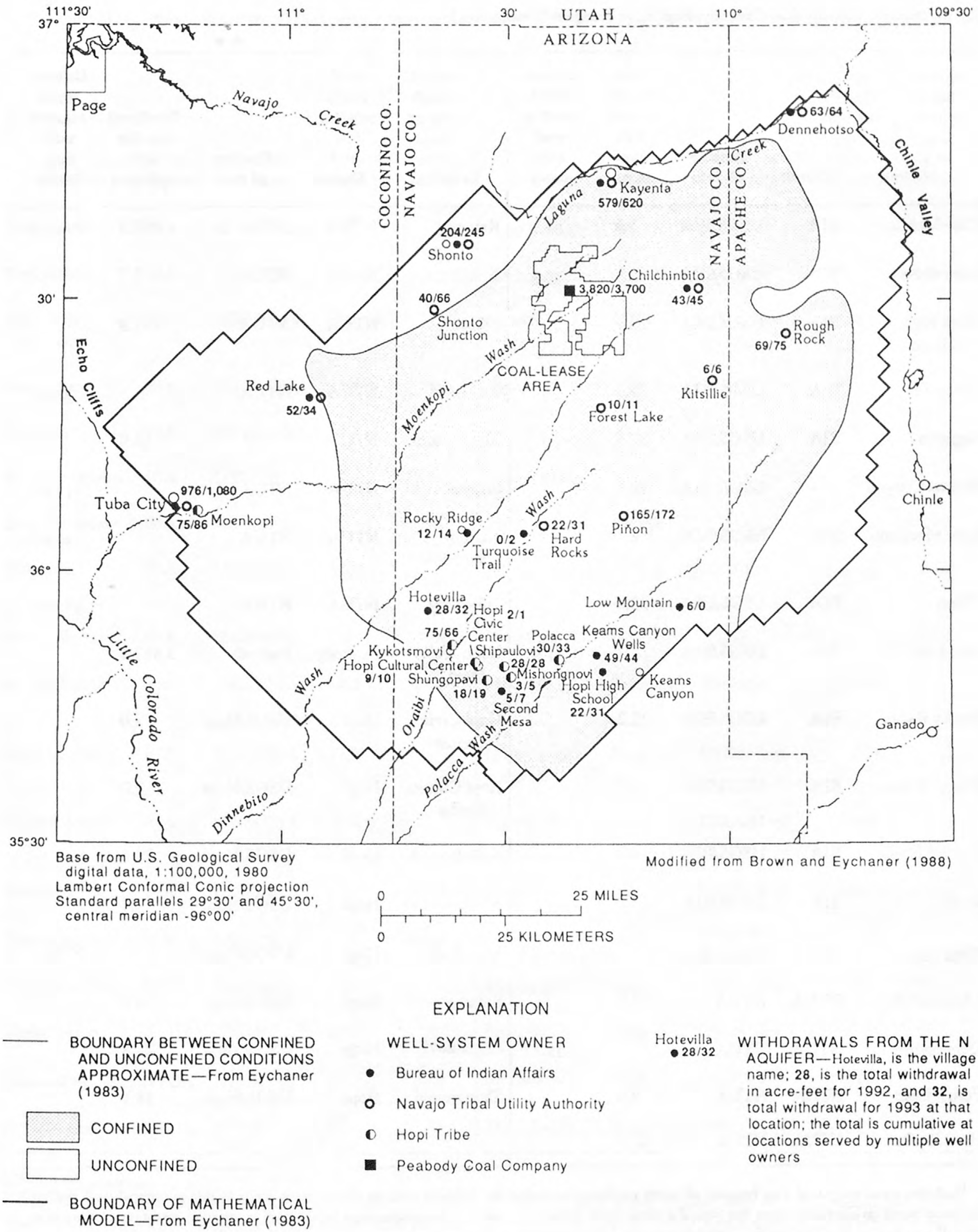


Figure 4. Location of well systems monitored for withdrawals from the N aquifer, 1992–93.

Table 2. Withdrawals from the N aquifer by well system, 1992

[Measurements, in acre-feet, are flowmeter data. BIA, 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
Chilchinbito	BIA	USGS/BIA	7.9	
Dennehotso	BIA	USGS/BIA		29.8
Hopi High School	BIA	USGS/BIA	22.1	
Hotevilla	BIA	USGS/BIA	28.3	
Kayenta	BIA	USGS/BIA	80.5	
Keams Canyon	BIA	USGS/BIA	48.7	
Low Mountain	BIA	USGS/BIA	6.1	
Piñon	BIA	USGS/BIA	33.0	
Red Lake	BIA	USGS/BIA		7.6
Rocky Ridge	BIA	USGS/BIA	12.3	
Rough Rock	BIA	USGS/BIA	51.7	
Second Mesa	BIA	USGS/BIA	4.8	
Shonto	BIA	USGS/BIA		186.4
Tuba City	BIA	USGS/BIA		116.6
Chilchinbito	NTUA	NTUA	35.0	
Dennehotso	NTUA	NTUA		33.1
Forest Lake	NTUA	NTUA	9.6	
Hard Rocks	NTUA	NTUA	22.5	
Kayenta	NTUA	NTUA	498.3	
Kitsillie	NTUA	NTUA	5.7	
Piñon	NTUA	NTUA	131.8	
Red Lake	NTUA	NTUA		44.4
Rough Rock	NTUA	NTUA	16.9	
Shonto	NTUA	NTUA		17.8
Shonto Junction	NTUA	NTUA		39.6
Tuba City	NTUA	NTUA		859.7
Mine Well Field	Peabody	Peabody	3,817.4	
Hopi Civic Center	Hopi	USGS/Hopi	2.0	
Hopi Cultural Center	Hopi	USGS/Hopi	9.0	
Kykotsmovi	Hopi	USGS/Hopi	74.6	
Mishongnovi	Hopi	USGS/Hopi	3.4	
Moenkopi	Hopi	USGS/Hopi		[1]75.3
Polacca	Hopi	USGS/Hopi	[2]30.0	
Shipaulovi	Hopi	USGS/Hopi	27.8	
Shungopovi	Hopi	USGS/Hopi	18.1	

[1]Includes some estimated data because of 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.

[2]Estimated. Well not metered.

Table 3. Withdrawals from the N aquifer by well system, 1993

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

Location	Owner	Source of data	Confined aquifer well systems	Unconfined aquifer well systems
Chilchinbito	BIA	USGS/BIA	7.2	
Dennehotso	BIA	USGS/BIA		28.5
Hopi High School	BIA	USGS/BIA	30.8	
Hotevilla	BIA	USGS/BIA	32.1	
Kayenta	BIA	USGS/BIA	67.3	
Keams Canyon	BIA	USGS/BIA	44.5	
Low Mountain	BIA	USGS/BIA	[1]0	
Piñon	BIA	USGS/BIA	34.0	
Red Lake	BIA	USGS/BIA		6.4
Rocky Ridge	BIA	USGS/BIA	14.3	
Rough Rock	BIA	USGS/BIA	57.6	
Second Mesa	BIA	USGS/BIA	6.9	
Shonto	BIA	USGS/BIA		227.4
Tuba City	BIA	USGS/BIA		123.2
Turquoise Trail	BIA	Contractor	1.5	
Chilchinbito	NTUA	NTUA	38.2	
Dennehotso	NTUA	NTUA		35.8
Forest Lake	NTUA	NTUA	11.2	
Hard Rocks	NTUA	NTUA	30.8	
Kayenta	NTUA	NTUA	553.2	
Kitsillie	NTUA	NTUA	5.8	
Piñon	NTUA	NTUA	137.5	
Red Lake	NTUA	NTUA		27.2
Rough Rock	NTUA	NTUA	17.1	
Shonto	NTUA	NTUA		17.2
Shonto Junction	NTUA	NTUA		65.5
Tuba City	NTUA	NTUA		956.6
Mine Well Field	Peabody	Peabody	3,703.6	
Hopi Civic Center	Hopi	USGS/Hopi	1.0	
Hopi Cultural Center	Hopi	USGS/Hopi	9.8	
Kykotsmovi	Hopi	USGS/Hopi	66.2	
Mishongnovi	Hopi	USGS/Hopi	4.6	
Moenkopi	Hopi	USGS/Hopi		[2]86.4
Polacca	Hopi	USGS/Hopi	[3]33.0	
Shipaulovi	Hopi	USGS/Hopi	27.8	
Shungopovi	Hopi	USGS/Hopi	18.1	

[1]Well not in service.

[2]Includes some estimated data because of 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.

[3]Estimated. Well not metered.

Table 4. Flowmeter-test results for industrial and municipal wells that tap the N aquifer, Black Mesa area, 1993

Well system	Well number[1]	Date tested	Pumping rate, in gallons per minute: Test meter[2]	Pumping rate, in gallons per minute: Permanent meter	Percent difference[3]	Meter brand and number
Navajo Tribal Utility Authority						
Chilchinbito	1	08-19-93	42.5	42.2	-0.7	Rockwell 1175064
Do.	2	10-22-93	80.3	82.0	+2.1	Rockwell 1236134
Dennehotso	1	08-19-93	79.5	77.4	-2.6	Rockwell 33447300
Do.	2	08-19-93	86.5	87.6	+1.3	Rockwell 1306471
Forest Lake	1	08-18-93	49.0	45.1	-8.0	Hersey 6049985
Kayenta	1	08-18-93	87.5	86.6	-1.0	Sparling 44210
Do.	2	08-18-93	110.0	112.7	+2.4	Hersey/Sparling 63892
Do.	3	08-18-93	103.0	96.8	-6.0	Rockwell 28316
Do.	4	10-22-93	79.0	69.4	-12.2	Rockwell (no number)
Do.	5	08-18-93	167.5	162.2	-3.2	Rockwell 1276730
Do.	6	08-18-93	120.5	130.4	+8.2	Rockwell 21392492
Do.	7	08-19-93	119.0	117.6	-1.2	Rockwell 1276729
Kitsillie	1	08-25-93	7.3	7.3	0.0	Rockwell 30084111
Do.	2	New well—not in operation				
Piñon	1	08-25-93	101.3	95.7	-5.5	Hersey 6053321
Do.	2	08-25-93	106.3	101.7	-4.3	Rockwell 1305355
Do.	3	08-25-93	108.0	107.5	-0.5	Rockwell 1303039
Red Lake	1	08-17-93	69.0	70.6	+2.3	Hersey 6044826
Rough Rock	1	08-25-93	34.3	33.3	-2.9	Rockwell 1320677
Shonto	1	08-24-93	66.0	62.8	-4.8	Rockwell 28945149
Shonto Junction	1	08-24-93	105.0	104.3	-0.7	Brooks 8403-23219-1-1
Do.	2	08-24-93	95.0	90.6	-4.6	Trident 1130
Tuba City	1	08-18-93	85.5	96.9	+13.3	Sparling 110635
Do.	2	08-17-93	145.5	129.7	-10.9	Sparling 109412
Do.	3	08-17-93	149.0	149.1	+0.1	Sparling 094420
Do.	4	08-17-93	184.0	178.6	-2.9	Sparling 126447
Do.	5	Not in operation				
Do.	6	Well used only (as backup) during summer				

See footnotes at end of table.

Table 4. Flowmeter-test results for industrial and municipal wells that tap the N aquifer, Black Mesa area, 1993—Continued

Well system	Well number[1]	Date tested	Pumping rate, in gallons per minute: Test meter[2]	Pumping rate, in gallons per minute: Permanent meter	Percent difference[3]	Meter brand and number
Bureau of Indian Affairs						
Chilchinbito	PM3	08-26-93	27.5	27.3	-0.7	Precision 0020023
Dennehotso	1			Not accessible		
Do.	2	08-17-93	57.7	55.2	-4.3	Precision 0032231
Hopi High School	1	09-01-93	86.0	84.2	-2.1	Neptune 31625407
Do.	2	09-01-93	81.3	80.4	-1.1	Neptune 31625415
Do.	3	09-01-93	87.6	93.3	+6.5	Neptune 31625412
Hotevilla	PM1	09-29-93	47.0	44.8	-4.7	Rockwell 36726370
Do.	PM2			Not in operation		
Kayenta	PM2			Not in operation		
Do.	PM3	08-17-93	149.3	153.2	+2.6	Rockwell 1305841
Keams Canyon	2	09-01-93	68.3	57.0	-16.5	Hersey/Sparling 116800
Do.	3	09-01-93	88.7	89.1	+0.4	Sparling 115691
Low Mountain	PM2			Not in operation		
Piñon	PM6	08-25-93	98.0	97.2	-0.8	Pollux 3236250
Red Lake	PM1	08-17-93	33.0	33.3	+0.9	Mastermeter 1253388
Do.	PM2	08-17-93	32.0	31.0	-3.1	Rockwell 32722074
Rocky Ridge	PM2	12-30-93	47.3	48.0	+1.5	Rockwell 1331031
Do.	PM3	12-30-93	46.0	43.4	-5.7	Rockwell 1331029
Rough Rock	1	08-26-93	47.5	48.2	+1.5	Rockwell 1331030
Do.	2	08-26-93	39.0	40.3	+3.3	Rockwell 1333354
Do.	3	10-22-93	51.0	50.1	-1.8	Rockwell 36880399
Do.	4	10-22-93	50.0	44.2	-11.6	McCrometer 82-3-317
Second Mesa	PM1	09-16-93	107.3	108.1	+0.7	Rockwell 32658703
Do.	PM2	09-29-93	93.5	91.6	-2.0	Arad 029154
Shonto	1	08-17-93	163.5	161.1	-1.5	Rockwell 1255896
Do.	2	08-17-93	93.0	92.3	-0.8	Rockwell 1300477
Do.	3	08-17-93	69.0	67.8	-1.7	Rockwell 1325584
Tuba City	PM4	08-08-93	132.1	136.5	+3.3	Rockwell 30045571
Do.	PM5			Not in operation		
Do.	PM6	08-16-93	128.0	129.7	+1.3	Rockwell 1305840

See footnotes at end of table.

Table 4. Flowmeter-test results for industrial and municipal wells that tap the N aquifer, Black Mesa area, 1993—Continued

Well system	Well number[1]	Date tested	Pumping rate, in gallons per minute: Test meter[2]	Pumping rate, in gallons per minute: Permanent meter	Percent difference[3]	Meter brand and number
Hopi Tribe						
Bacavi	1		New well—not in operation			
Civic Center	1	12-30-93	52.0	50.6	-2.7	Rockwell 1323855
Cultural Center	1	12-29-93	50.5	50.7	+0.4	Rockwell 37078664
Hotevilla	1		New well—not in operation			
Kykotsmovi	1		Not in operation			
Do.	2	09-29-93	97.3	95.0	-2.4	Kent 77655836
Do.	3	09-16-93	157.0	158.6	+1.0	Rockwell 1266317
Mishongnovi	1	09-29-93	12.0	12.2	+1.7	Precision E569880
Do.	2		New well—not in operation			
Moenkopi[4]	1	12-28-93	57.2	55.3	-3.3	Rockwell 1231000
Polacca	1		Not metered			
Do.	2		New well—not in operation			
Shipaulovi	1	12-29-93	100.3	99.7	-0.6	Kent 88538743
Shungopovi	1	12-29-93	45.1	46.0	+2.0	Rockwell 25766390
Turquoise Trail	1		New well—temporary meter			
Peabody Coal Company[5]						
Black Mesa	2	04-14-94	515.0	500.0	-2.9	McCrometer 93-6-1520
Do.	3	04-14-94	566.0	560.0	-1.1	McCrometer 77-6-785
Do.	4	04-14-94	583.0	580.0	-0.5	McCrometer (no number)
Do.	5	04-14-94	671.0	670.0	-0.2	McCrometer 93-6-1521
Do.	6	04-14-94	523.0	540.0	+3.2	McCrometer 81-6-1084
Do.	7	04-14-94	637.0	650.0	+2.0	McCrometer 77-6-774
Do.	8	04-14-94	569.0	575.0	+1.1	McCrometer 93-6-1230
Do.	9	04-14-94	622.0	620.0	-0.3	McCrometer 81-6-1082

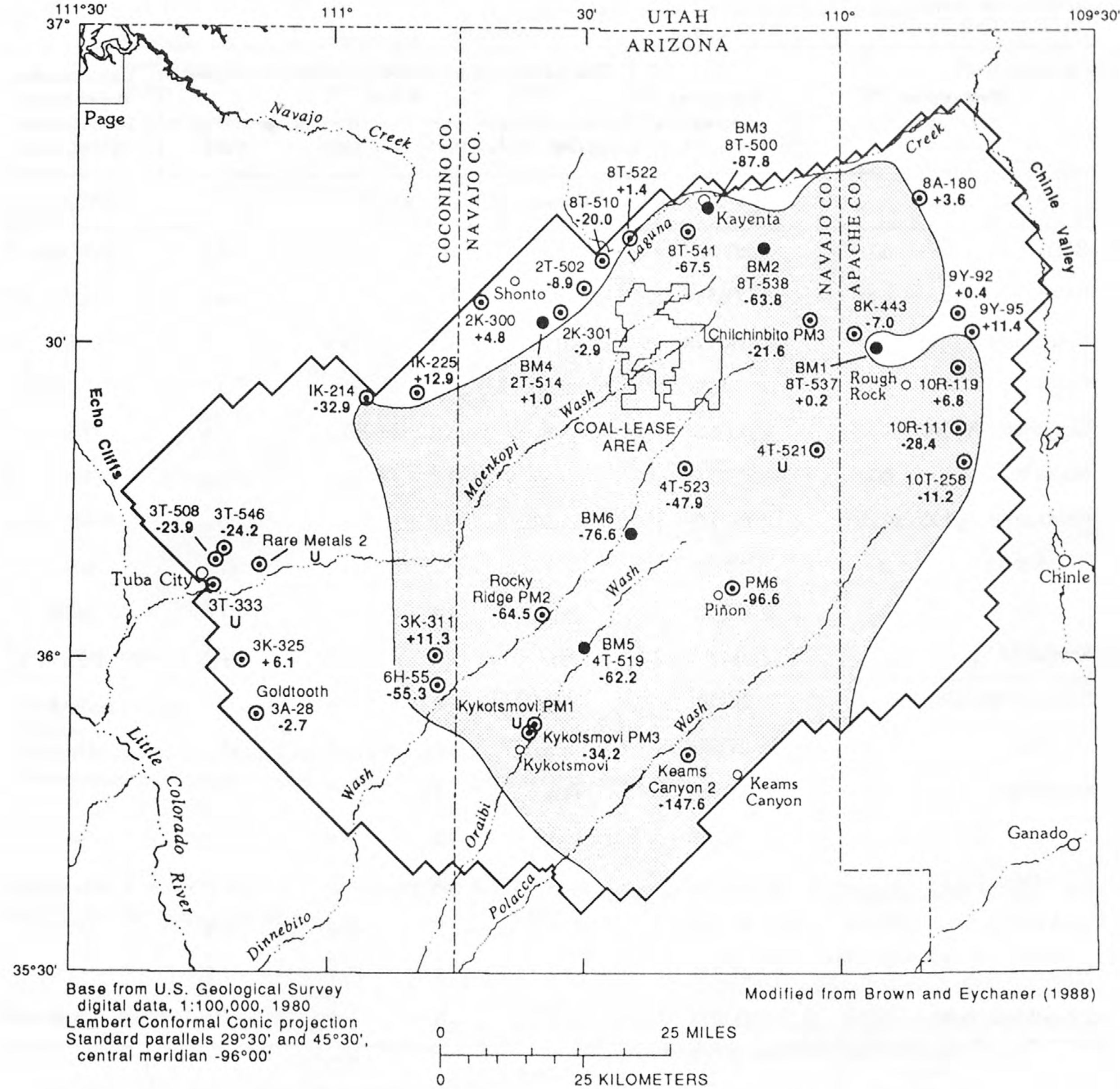
[1]Well numbers do not necessarily coincide with agency well numbers.

[2]Rockwell 125W Turbo at all municipal wells; Cox "Halltube" flowmeter at all Peabody wells.

[3]A positive difference indicates that the meter is registering more pumpage than is actually occurring, whereas a negative difference indicates less pumpage than is actually occurring.

[4]Three-well system. All discharges measured through a common meter.

[5]Measurements made during well field shutdown in April 1994.



EXPLANATION

- BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS APPROXIMATE—From Eychaner (1983)
- CONFINED
- UNCONFINED
- BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)
- 4T-523 -47.9 WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 4T-523, is Bureau of Indian Affairs site number; second entry, -47.9, is change in water level, in feet, between earliest measurement to measurements made during 1992–93. U, means unable to measure
- BM2 8T-538 -63.8 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, -63.8, is change in water level, in feet, from earliest measurement to 1992–93.

Figure 5. Water-level changes in wells completed in the N aquifer from the start of data collection through 1993.

Table 5. Water-level changes in wells completed in the N aquifer, 1990–93

[Dashes indicate no data]

Well system or location name	Bureau of Indian Affairs site number	Change in water level from preceding water year, in feet				Water level at depth below land surface, in feet, 1993
		1990	1991	1992	1993	
Unconfined						
BM1[1]	8T-537	+0.3	0	+0.4	+0.2	373.8
BM4[1]	2T-514	+.3	0	-.2	+.3	216.0
Cow Springs	1K-225	0	-.5	+.9	+.9	47.1
Goldtooth	3A-28	+.3	-.1	([2])	[3]-3.0	232.7
Long House Valley	8T-510	-.6	-.2	+1.1	-.6	119.0
Marsh Pass	8T-522	-.6	-1.0	+.1	+.6	124.1
Northeast Rough Rock	8A-180	+.2	-.1	0	0	43.3
Rough Rock	9Y-95	-.7	-----	[3]+1.7	-2.2	108.1
Do.	9Y-92	+.1	-1.4	+3.0	-1.6	168.4
Shonto	2K-300	0	+.6	-.1	+.2	171.7
Shonto Southeast	2K-301	-.6	+.6	-.6	+.1	286.8
Do.	2T-502	-.2	+.1	+.7	-1.1	414.7
Tuba City	3T-333	+1.5	+.8	+.7	([2])	--------
Do.	3K-325	-.1	-.5	+.9	+.1	201.9
Do.	Rare Metals 2	+.4	+.8	([2])	([2])	--------
Tuba NTUA 1	3T-508	[3]-13.7	+2.5	+9.4	-1.9	52.9
Tuba NTUA 4	3T-546	-3.7	+5.6	+5.1	-.7	57.9
White Mesa Arch	1K-214	-.3	+.8	+.1	-.4	220.9
Confined						
BM2[1]	8T-538	-3.4	-3.7	-2.2	-1.1	188.8
BM3[1]	8T-500	+4.6	-.4	-7.1	-4.1	147.8
BM5[1]	4T-519	-3.5	-4.0	-1.3	-3.9	386.0
BM6[1]	BM6	-9.5	-4.0	-3.4	-4.2	812.2
Chilchinbito	PM3	+40.2	+1.5	-2.8	+3.2	426.6
Forest Lake NTUA 1	4T-523	-6.2	-18.7	+13.5	-3.9	1,143.9
Howell Mesa	6H-55	+.3	-4.6	+2.5	+.5	267.8

See footnotes at end of table.

Table 5. Water-level changes in wells completed in the N aquifer, 1990–93—Continued

Well system or location name	Bureau of Indian Affairs site number	Change in water level from preceding water year, in feet				Water level at depth below land surface, in feet, 1993
		1990	1991	1992	1993	
Confined—Continued						
Kayenta West	8T-541	-8.7	+3.6	(2)	[3]-22.3	294.5
Keams Canyon	2	-1.5	+8.4	-8.6	[4]-33.6	440.1
Kykotsmovi	PM1	-------	[3]+1.5	-3.1	+8.2	254.2
Do.	PM3	-.7	(2)	(2)	(2)	-------
Piñon	PM6	[3]-41.7	(2)	[3]-3.6	-11.6	840.2
Do.	3K-311	(2)	(2)	(2)	[3]-7.1	451.7
Rocky Ridge	PM2	-5.1	-5.4	-.8	-3.8	496.5
Rough Rock	10R-119	+.6	+.6	-1.9	+6.8	249.8
Do.	10T-258	-1.0	(2)	[3]-3.0	+.6	312.2
Do.	10R-111	-.1	+.2	-3.7	+3.0	198.4
Sweetwater Mesa	8K-443	(2)	[3]-1.8	-.2	-.8	536.4

[1]Continuous recorder.
[2]Unable to measure.
[3]Change in water level from last measurement 2 or more years earlier.
[4]Measurement may have been affected by obstructions in well and (or) nearby pumping.

change was a decline of 0.5 ft as opposed to a rise of 0.7 ft for the previous year.

Surface-Water Discharge

Outflow from the N aquifer appears mainly as surface flow in Moenkopi Wash and Laguna Creek[3] 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. 6, tables 6 and 7). Low flow in Moenkopi Wash is based on discharge measurements made during November through February. Discharge data collected during these months are considered representative of low flow because the effect of stream loss from evapotranspiration and gain from snowmelt and rainfall, which generally occurs during temperate months, is minimized.

In 1992, low flow in Moenkopi Wash was 2.8 ft^3/s and is based on measurements made in February and November. The mean daily discharge from continuous-stage record for the same period was 2.6 ft^3/s. In 1993, low flow was 3.0 ft^3/s and is based on a single measurement made in November. The mean daily discharge for the same month was 2.4 ft^3/s. Mean daily 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), Boner and others (1989–91), Garrett and Gellenbeck (1991), and Boner and others (1992).

[3]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.

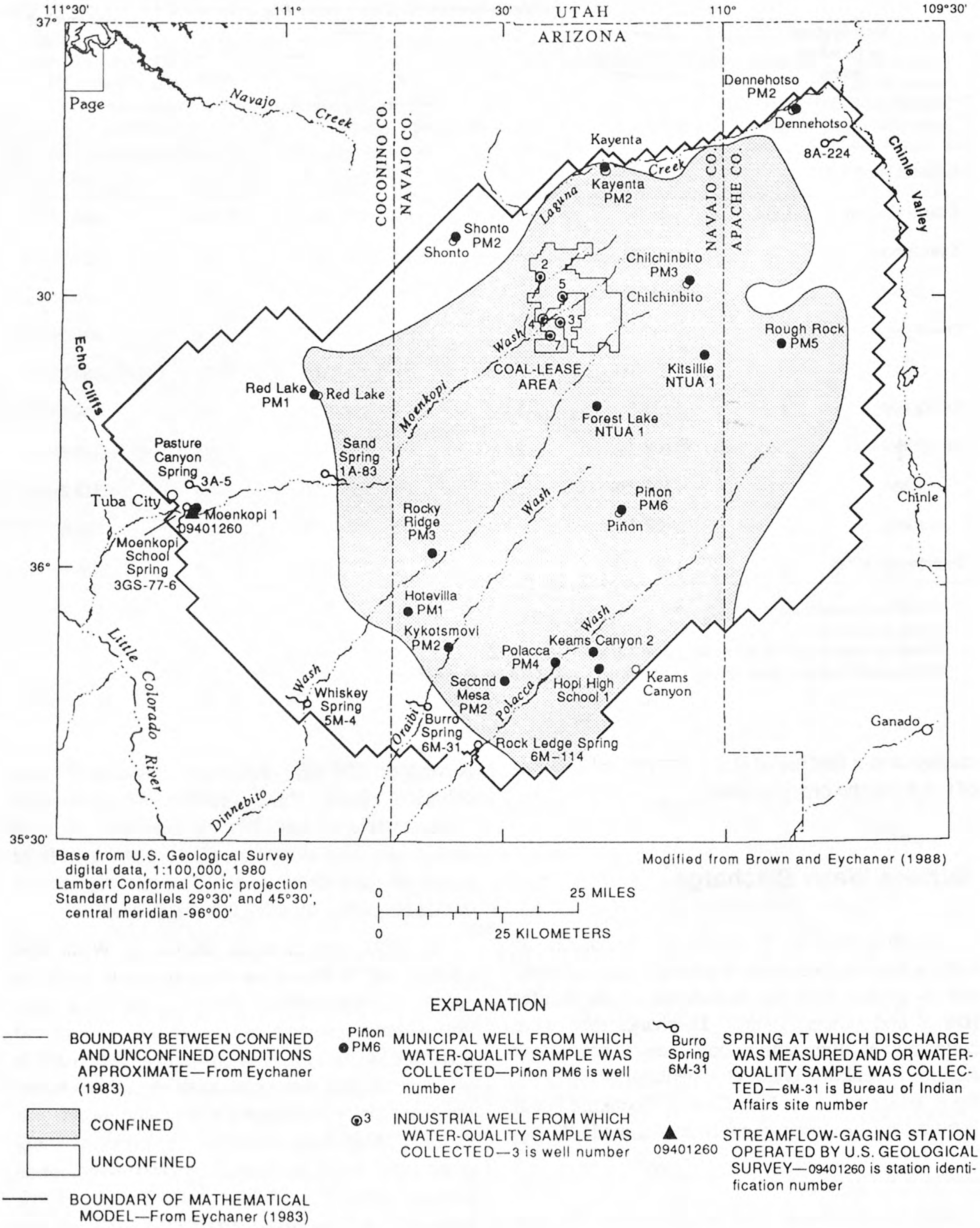


Figure 6. Surface-water and water-quality data-collection sites, 1992–93.

Table 6. Discharge data, Moenkopi Wash at Moenkopi, calendar year 1992

[Dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 1992 DAILY MEAN VALUES												
Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	3.3	[1]2.5	3.5	7.0	0.87	3.4	0.00	0.00	19	0.33	1.4	[1]0.60
2	3.0	2.9	3.5	3.6	.69	3.2	.00	.00	3.4	.26	2.2	[1].70
3	[1]2.0	3.0	4.1	3.0	.64	3.0	.00	.33	1.8	.18	1.6	[1].90
4	[1]1.5	2.9	3.6	2.0	.68	2.6	.00	.00	.52	.13	1.1	[1]1.1
5	[1]1.5	2.4	4.1	1.9	1.1	2.2	.00	.00	.80	.20	1.3	[1].90
6	[1]3.0	2.5	3.4	2.3	2.4	1.9	.00	.00	.48	.24	1.1	[1]1.3
7	[1]20	2.4	3.3	2.4	2.1	.66	.00	1.7	.03	.17	1.1	[1]1.1
8	[1]8.0	4.7	3.1	2.8	2.9	.22	.00	.80	.00	.22	1.3	[1].90
9	[1]3.0	6.4	4.8	2.8	1.7	.00	.00	.03	.00	.37	1.3	[1].90
10	[1]2.0	3.7	4.0	2.3	64	2.7	.00	.19	.81	.44	1.3	[1].90
11	[1]1.5	3.3	3.1	2.8	24	2.5	.00	.01	.00	.43	1.8	[1].70
12	[1]1.5	3.3	2.8	2.6	9.0	.98	.00	.09	.00	.43	1.8	[1].90
13	[1]2.0	4.3	2.8	2.3	6.9	.00	18	.00	.00	.43	1.1	[1]1.3
14	[1]2.0	23	2.6	2.3	3.9	.00	15	.00	.00	.50	1.3	[1]1.0
15	[1]1.5	3.7	2.9	2.3	3.8	.00	2.6	.01	1.6	.47	1.0	[1].90
16	[1]2.0	4.2	3.5	2.3	3.1	.00	[1].20	.00	.91	.44	1.2	[1].70
17	[1]1.5	2.9	3.1	2.1	[1]1.3	.00	.01	.00	1.1	.60	1.3	[1].70
18	[1]1.5	3.0	2.7	1.6	[1]1.1	.00	.00	1.1	.74	.67	1.3	[1].70
19	[1]3.0	3.0	2.9	1.4	[1]1.1	.00	.00	.89	530	.71	1.3	[1]1.0
20	3.2	2.4	2.9	1.9	[1]15	.00	.00	.00	38	.78	1.6	[1].70
21	3.6	3.1	3.6	1.6	[1]31	.00	.00	.00	5.3	.76	1.7	[1].50
22	3.7	3.3	3.6	1.7	[1]32	.00	.00	.63	1.7	.73	[1]1.8	[1].50
23	3.6	3.3	3.7	2.4	[1]70	.00	.00	.39	1.3	.82	[1]1.3	[1].50
24	[1]3.0	2.9	2.5	1.8	[1]37	.00	[1]88	.01	1.0	1.0	[1].90	[1].50
25	[1]2.5	2.8	2.6	1.4	[1]31	7.1	[1]3.5	.78	.76	15	[1].60	[1].50
26	[1]3.0	3.3	2.2	1.4	[1]5.2	3.7	[1]53	10	.57	2.2	[1].50	[1].50
27	[1]3.0	3.4	2.4	1.4	[1]86	1.5	[1]8.5	.00	.51	1.1	[1].50	[1].50
28	[1]3.5	3.4	2.8	1.5	[1]19	.35	2.9	.00	.47	9.7	[1].70	[1]1.0
29	[1]3.5	3.5	3.0	1.2	8.5	.01	.75	.00	.38	13	[1].90	[1]3.0
30	[1]3.5	---	2.1	1.0	10	.00	1.8	.06	.32	3.6	[1].90	[1]3.0
31	[1]3.0	---	2.9	---	5.0	---	.00	[1]78	---	2.8	---	[1]3.0
TOTAL	102.9	115.5	98.1	67.1	480.98	36.02	192.64	95.02	611.50	58.71	37.20	31.40
MEAN	3.32	3.98	3.16	2.24	15.5	1.20	6.21	3.07	20.4	1.89	1.24	1.01
MAX	20	23	4.8	7.0	86	7.1	88	78	530	15	2.2	3.0
MIN	1.5	2.4	2.1	1.0	.64	.00	.00	.00	.00	.13	.50	.50
AC-FT	204	229	195	133	954	71	382	188	1,210	116	74	62

CALENDAR YEAR 1992 TOTAL 1,927.07 MEAN 5.27 MAXIMUM 530 MINIMUM 0.00 ACRE-FT 3,820

WATER YEAR 1992[2] TOTAL 2,011.28 MEAN 5.50 MAXIMUM 530 MINIMUM 0.00 ACRE-FT 3,990

[1]Estimated.

[2]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, 1992, is called "water year 1992."

Table 7. Discharge data, Moenkopi Wash at Moenkopi, calendar year 1993

[Dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 1993 DAILY MEAN VALUES												
Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	[1]3.0	18	39	4.4	1.5	0.00	0.00	0.00	14	0.00	1.9	4.0
2	[1]3.0	23	43	3.8	1.6	.00	.00	.00	18	.00	1.9	3.9
3	[1]3.0	17	30	3.2	1.7	.00	.00	.00	7.2	.00	2.0	3.2
4	[1]3.0	17	24	3.2	1.5	.00	.00	.00	3.4	.00	2.4	2.9
5	[1]3.0	17	15	3.6	1.5	.00	.00	.00	1.9	.00	2.4	3.5
6	[1]3.0	15	9.7	3.5	1.6	.00	.00	.00	.66	195	2.0	3.8
7	5.0	12	8.0	3.2	1.7	.00	.00	.00	.04	[1]501	2.1	3.5
8	[1]250	13	8.4	2.7	1.5	.00	.00	.00	.00	[1]84	2.6	3.7
9	60	13	8.0	2.7	1.3	.00	.00	.00	.00	[1]37	2.5	3.7
10	22	29	7.0	2.6	1.2	.34	.00	.00	.00	[1]11	2.5	4.0
11	20	23	7.5	2.6	1.4	.24	.00	94	.00	[1]2.8	2.7	3.7
12	31	19	7.3	2.2	1.4	.03	.00	7.1	.00	[1]1.3	3.1	4.0
13	18	22	8.1	1.8	1.3	.00	.00	.91	.00	[1]1.3	2.9	3.2
14	16	19	6.4	2.3	1.5	.00	.00	.03	.00	[1]1.3	2.7	2.6
15	22	18	5.7	2.4	1.6	.00	.00	.00	.00	.64	2.7	2.8
16	13	16	6.0	2.4	1.3	.00	.00	.00	.00	.61	2.6	3.5
17	44	17	6.0	2.5	1.4	.00	.00	.00	.00	2.2	2.1	[1]4.0
18	52	19	5.6	1.9	1.9	.00	.00	.00	.00	5.9	2.4	4.1
19	56	23	5.6	1.7	1.6	.00	.00	.00	.00	1.9	2.6	3.8
20	52	765	5.8	1.7	1.5	.00	.00	.00	.00	1.2	2.6	4.2
21	26	139	7.4	2.2	.96	.00	.00	.28	.00	1.0	2.9	4.7
22	19	27	6.1	2.2	.92	.00	.00	100	.00	1.0	3.8	[1]4.0
23	16	15	4.8	1.9	.88	.00	[1].00	11	.00	1.1	3.5	[1]4.0
24	17	9.5	4.1	1.6	.73	.00	[1].00	8.8	.00	1.2	3.1	[1]4.0
25	19	8.8	3.8	1.5	.58	.00	[1].00	3.7	.00	1.2	2.4	4.1
26	17	6.9	4.1	1.6	.68	.00	[1].00	.70	.00	1.3	2.2	3.7
27	24	5.2	4.2	1.7	.61	.00	[1].00	1.1	.00	1.2	2.2	3.7
28	15	6.1	7.9	1.6	.55	.00	[1].00	18	.00	1.2	2.9	3.9
29	17	---	10	1.6	.67	.00	[1].00	6.7	.00	1.5	3.7	4.2
30	15	---	8.1	1.5	.56	.00	[1].00	22	.00	1.4	3.8	4.3
31	17	---	9.2	---	.32	---	.00	18	---	1.4	---	3.9
TOTAL	871.0	1,332.5	325.8	71.8	37.46	0.61	0.00	292.32	45.20	860.65	79.2	116.6
MEAN	28.1	47.6	10.5	2.39	1.21	.02	.00	9.43	1.51	27.8	2.64	3.76
MAX	250	765	43	4.4	1.9	.34	.00	100	18	501	3.8	4.7
MIN	3.0	5.2	3.8	1.5	.32	.00	.00	.00	.00	.00	1.9	2.6
AC-FT	1,730	2,640	646	142	74	1.2	.00	580	90	11,710	157	231

CALENDAR YEAR 1993	TOTAL 4,417.79	MEAN 12.10	MAXIMUM 765	MINIMUM 0.00	ACRE-FT 8,756
WATER YEAR 1993[2]	TOTAL 3,104.00	MEAN 8.50	MAXIMUM 765	MINIMUM 0.00	ACRE-FT 6,160

[1]Estimated.

[2]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, 1993, is called "water year 1993."

Six springs were selected for discharge measurements as part of the monitoring program during 1993 (fig. 6, table 8). The discharges from Burro, Dennehotso, Pasture Canyon, and Whisky Springs were less than when previously measured and ranged from 0.1 gal/min less at Burro and Whisky Springs to 22 gal/min less at Pasture Canyon Spring. Because of recent diversions for irrigation, the measurement at Pasture Canyon Spring includes only partial discharge from a nearby seep that was included in the previous years' measurements and may not represent actual change in discharge from that system.

Discharge from Moenkopi School Spring increased by about 1 gal/min from the previous years' measurement and is the only spring that has maintained a consistent increase in discharge in recent years. In general, the changes in discharge probably are caused by the cumulative effect of local recharge in addition to the regional ground-water flow; however, there is no indication that these changes in discharge are being affected by local or regional pumping.

Chemical Quality

Water from Wells Completed in the N Aquifer

Water from the N aquifer is analyzed for selected chemical constituents to determine if declining 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 upgradient or recharge part of the study area northwest of Black Mesa and a sodium bicarbonate type elsewhere throughout the area (Kister and Hatchett, 1963). As water moves from the northwest then under Black Mesa to the discharge areas, ion exchange along the flow path generally converts calcium type water to sodium type water. Locally, however, some wells penetrating the N aquifer may contain large concentrations of sulfate, chloride, and other ions. Because wells tapping the N aquifer must pass through the D aquifer in the confined area and because sealing off the D aquifer is difficult, it is likely that such wells commonly pull a mixture of water from both aquifers. Water-quality data to date (1993), however, do not substantiate leakage through confining beds because of drawdown in the N aquifer.

Eighteen of the 22 wells sampled in 1993 are completed in the confined area of the N aquifer (fig. 7, tables 9 and 11). Twelve of the 18 wells, generally in upgradient areas between the mine, Piñon, and Kykotsmovi, contained a sodium bicarbonate type water and 4 wells, generally in more downgradient areas, contained a sodium sulfate type water. Historically, water from the Hopi High School area (wells 1 and 2) has been a sodium chloride type (table 9; Littin, 1993); 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 1988 to a sodium sulfate type water in 1991. This change is believed to have been caused by failure of the cement seal around the casing because the change was sudden rather than gradual, development in the area has been slight, and neither the pump intake setting nor the lift capacity had changed. The well was sampled in 1992 and again in 1993. Sulfate concentrations decreased from 620 mg/L in 1991, to 430 mg/L in 1992, to 320 mg/L in 1993. In each case, the well was pumped for a longer period than when previously sampled. Water from the Kitsillie NTUA 1 well has undergone a noticeable change from a sodium bicarbonate type water to a sodium

Table 8. Discharge measurements of selected springs, 1952–93

[Dashes indicate no data]

Spring name	Bureau of Indian Affairs site number	Rock formations	Date of measurement	Discharge, in gallons per minute
Burro Spring	6M-31	Navajo Sandstone	12-15-89	0.4
Do.			12-13-90	.4
Do.			03-18-93	.3
Moenkopi School Spring	3GS-77-6	Navajo Sandstone Tongue in the Kayenta Formation	05-16-52	40
Do.			04-22-87	16
Do.			11-29-88	12.5
Do.			02-21-91	[1]13.5
Do.			04-07-93	[1]14.6
Pasture Canyon Spring	3A-5	Navajo Sandstone and alluvium	08-10-54	174
Do.			07-28-82	135
Do.			05-19-86	166
Do.			11-18-88	211
Do.			03-24-92	[2]233
Do.			10-12-93	[3]211
Rock Ledge Spring	6M-114	Navajo Sandstone	04-15-93	[4]2
Spring near Dennehotso	8A-224	Navajo Sandstone	10-06-54	[4]1
Do.			06-27-84	[4]2
Do.			11-17-87	5
Do.			03-26-92	16
Do.			10-22-93	14.4
Whisky Spring	5M-4	Navajo Sandstone	12-14-89	.1
Do.			12-14-90	.2
Do.			04-15-93	.1

[1]Discharge measured at water-quality sampling site only and does not represent the total discharge at Moenkopi School Spring system.

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

[3]Discharge measured in an irrigation ditch about 30 feet upstream from the previous years' measuring point.

[4]Estimated.

sulfate type water. In Kitsillie NTUA 1, sulfate concentrations increased from 4.9 mg/L in 1991 to 520 mg/L in 1993. Unlike the change in the Chilchinbito well, this change is believed to have been caused by a change in the pump intake setting and a marked reduction in lift capacity.

The remaining four wells sampled in 1993 penetrate the unconfined area of the N aquifer (fig. 7, tables 10 and 12). Three of the wells contained a calcium bicarbonate water typical of upgradient areas. Well PM2 at Dennehotso contained a sodium bicarbonate water typical of downgradient areas and may have been influenced by ground-water movement in the N aquifer from Black Mesa.

Dissolved-solids concentrations in water from wells in the N aquifer ranged from 84 mg/L at Red Lake well PM1 to 1,340 mg/L at the Hopi

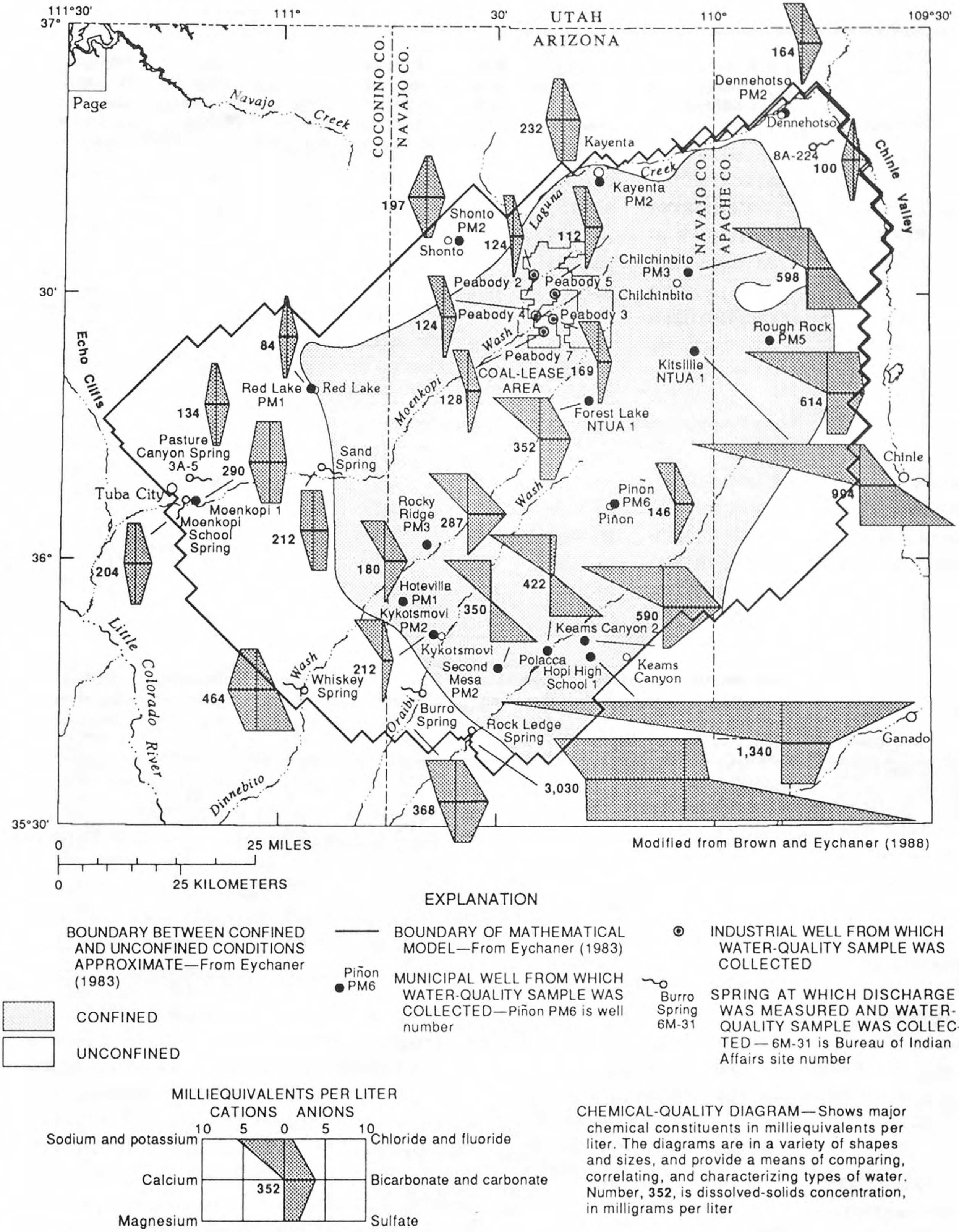


Figure 7. Water quality and distribution of dissolved solids in the N aquifer, 1993.

Table 9. Chemical analyses of confined water from selected industrial and municipal wells completed in the N aquifer, 1992–93

[°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)
Chilchinbito PM3	363137110044702	10-20-93	19.5	1,030	9.2	151	0.51
Forest Lake NTUA 1	361737110180301	04-07-93	28.3	693	9.5	147	.53
Hopi High School 1	354856110183201	03-19-93	20.7	2,230	9.0	283	.05
Hotevilla PM1	355518110400301	10-14-93	25.7	305	9.7	139	1.1
Kayenta PM2	364344110151201	10-18-93	15.8	374	8.1	104	.96
Keams Canyon 2	355023110182701	02-04-93	19.5	1,040	9.3	349	.05
Kitsillie NTUA 1	362035110032201	10-22-93	23.8	1,580	8.8	224	.05
Kykotsmovi PM2	355215110375001	12-10-92	22.5	363	9.8	164	1.3
Peabody 2	363005110250901	10-18-93	30.1	163	8.9	70	.95
Peabody 3	362625110223701	01-28-93	31.0	177	9.1	106	.97
Peabody 4	362647110243501	12-02-93	31.4	214	9.3	84	.99
Peabody 5	362901110234101	01-28-93	25.3	257	9.3	81	.87
Peabody 7	362456110242301	10-21-93	31.7	228	9.2	90	.84
Piñon PM6	360614110130801	03-18-93	26.3	488	10.2	228	1.4
Polacca PM4	354950110231501	10-14-93	22.0	755	9.5	324	.05
Rocky Ridge PM3	360422110353501	03-25-93	27.2	254	9.6	112	1.3
Rough Rock PM5	362418109514601	03-10-93	21.0	1,040	9.0	220	1.10
Second Mesa PM2	354749110300101	05-11-93	20.6	630	9.5	289	.05

Well name	Phosphorus, ortho, dissolved (mg/L as P)	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)
Chilchinbito PM3	0.01	5.6	2.2	210	2.2	7.5	320
Forest Lake NTUA 1	.01	1.2	.12	130	.8	35	88
Hopi High School 1	.01	3.2	.8	510	1.8	460	190
Hotevilla PM1	.02	.68	.02	67	.3	1.2	5.5
Kayenta PM2	.01	43	6.8	25	1.1	3.7	78
Keams Canyon 2	.01	.8	.15	230	.8	92	36
Kitsillie NTUA 1	.01	3.7	.55	350	2.1	8.5	520
Kykotsmovi PM2	.03	.46	.02	79	.4	3.3	8.4
Peabody 2	.01	8.9	.14	29	.7	1.7	8.9
Peabody 3	.01	3.1	.04	56	.8	4.2	19
Peabody 4	.01	5.1	.04	44	.6	3	12
Peabody 5	.01	3.6	.03	37	.6	2.3	4.8
Peabody 7	.01	3.7	.03	46	.6	3.8	16
Piñon PM6	.01	.55	.01	110	.4	3.6	4.5
Polacca PM4	.01	.62	.07	170	.3	27	23
Rocky Ridge PM3	.01	.41	.02	54	.4	1.3	5.5
Rough Rock PM5	.01	2	.26	230	1.4	130	110
Second Mesa PM2	.01	.47	.03	130	.4	7.5	15

Table 9. Chemical analyses of confined water from selected industrial and municipal wells completed in the N aquifer, 1992–93—Continued

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)
Chilchinbito PM3	0.5	12	2	150	22	598
Forest Lake NTUA 1	.7	20	3	230	55	352
Hopi High School 1	2.4	11	14	1,500	10	1,340
Hotevilla PM1	.1	23	3	30	6	180
Kayenta PM2	.2	17	2	20	4	232
Keams Canyon 2	1.5	12	46	670	3	590
Kitsillie NTUA 1	.7	12	29	200	25	994
Kykotsmovi PM2	.2	24	5	30	3	212
Peabody 2	.1	23	3	20	6	124
Peabody 3	.2	22	3	30	12	169
Peabody 4	.2	23	3	20	10	124
Peabody 5	.2	21	4	40	3	112
Peabody 7	.2	23	3	20	3	128
Piñon PM6	.2	28	4	40	21	287
Polacca PM4	.6	15	21	270	6	422
Rocky Ridge PM3	.1	21	4	20	3	146
Rough Rock PM5	1.6	13	48	40	14	614
Second Mesa PM2	.3	19	17	100	3	350

High School well 1 (fig. 7, tables 9, 10, 11, and 12). In the N aquifer, dissolved-solids concentrations in the sodium bicarbonate waters ranged from 112 to 614 mg/L; whereas, concentrations in the calcium bicarbonate waters ranged from 84 to 290 mg/L. Long-term comparison of dissolved-solids concentrations in water taken from Keams Canyon 2, Piñon PM6, and Kayenta PM2 wells show no significant change from 1983 to 1993 (fig. 8, table 11). Well selection was based on sample frequency, length of record, consistency in sampling conditions, and representative spatiality.

Arsenic concentrations in the wells ranged from 2 to 48 µg/L in the confined waters and 1 to 6 µg/L in the unconfined waters (tables 9 and 10). Most samples contained from 2 to 5 µg/L of arsenic. From the Kitsillie well, concentrations of arsenic increased from 4 µg/L in 1991 to 29 µg/L in 1993 and may be associated with mixing of D aquifer water in that area. At Chilchinbito PM3, however, arsenic concentrations remained low even though a marked increase in concentrations of dissolved solids and sulfate, between 1988 and 1991, indicates mixing of D aquifer water. In general, arsenic concentrations greater than 10 µg/L appear to be localized. The U.S. Environmental Protection Agency (1986) has established 50 µg/L as the maximum contaminant level (MCL) for the safe drinking-water standard for arsenic.

Surface Water

Seven springs were selected for water-quality analyses as part of the monitoring program during 1993 (fig. 7, table 13). The springs all issue from the Navajo Sandstone and consist of Pasture Canyon Spring near Tuba City, Moenkopi School Spring at Moenkopi, Sand Spring near Red Lake, an unnamed spring near Dennehotso, Rock Ledge Spring near Second Mesa, Burro Spring near Kykotsmovi, and Whisky Spring near Howell Mesa.

Water from Pasture Canyon, the spring near Dennehotso, and Moenkopi School Spring was a

Table 10. Chemical analyses of unconfined water from selected municipal wells completed in the N aquifer, 1993

[°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)
Dennehotso PM2	365045109504001	10-20-93	15.9	298	9.1	121	1.5
Moenkopi 1	360718111130401	10-18-93	17.0	517	7.8	106	1.8
Red Lake PM1	361933110565001	10-19-93	16.7	156	8.2	74	1.3
Shonto PM2	363558110392501	12-16-93	13.3	324	7.8	109	3.9

Well name	Phosphorus, ortho, dissolved (mg/L as P)	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)
Dennehotso PM2	0.01	9.3	2.2	53	0.6	8.2	16
Moenkopi 1	.01	51	12	36	1.9	48	69
Red Lake PM1	.01	19	5.2	4.4	1.7	1.6	2.1
Shonto PM2	.01	47	6.1	6.4	2	17	16

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)
Dennehotso PM2	0.2	13	6	30	3	164
Moenkopi 1	.2	15	2	70	7	290
Red Lake PM1	.2	11	1	20	3	84
Shonto PM2	.1	16	1	130	6	197

calcium bicarbonate type water. Water from Burro and Sand Springs was a sodium bicarbonate type, and water from Whisky Spring was a calcium sulfate type. Rock Ledge Spring discharges into the headwaters of a perennial reach of Polacca Wash about 10 mi south of Second Mesa on the Hopi Reservation. Water from Rock Ledge Spring was a sodium sulfate type. Dissolved-solids concentrations in water from the seven springs ranged from 100 mg/L at the spring near Dennehotso to 3,030 mg/L at Rock Ledge Spring, 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, although no historical water-quality data are known to exist for Rock Ledge Spring.

SIMULATION OF EFFECTS OF PUMPING

A mathematical model of the N aquifer in the Black Mesa area 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. The results indicated reasonable agreement of measured and simulated water levels (Hill and Sottilare, 1987).

Table 11. Selected properties and concentrations of chemical constituents in confined water from industrial and municipal wells completed in the N aquifer, 1980–93

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

Well name	Year	Specific conductance (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Chilchinbito PM3	1986	390	231	2.5	11
	1988	414	256	2.7	31
	1991	1,500	952	11	620
	1992	1,287	812	33	430
	1993	1,030	598	7.5	320
Forest Lake NTUA 1	1982	470	-------	11	67
	1990	375	226	8.2	38
	1993	693	352	35	88
Hopi High School 1	1993	2,420	1,340	460	190
Hotevilla PM1	1990	290	192	1.6	5
	1991	304	208	.7	5.4
	1993	305	180	1.2	5.5
Kayenta PM2	1982	360	228	4.5	58
	1983	375	230	------	60
	1984	365	309	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
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
	1993	1,040	590	92	36
Kitsillie NTUA 1	1982	580	365	5.4	84
	1983	505	291	4.4	37
	1984	460	258	5.2	20
	1988	418	241	3.7	5.7
	1990	410	268	3.6	4.9
	1991	435	232	6.6	520
	1993	1,580	994	8.5	
Kykotsmovi PM2	1988	368	212	3.2	8.6
	1990	355	255	3.2	9
	1991	372	203	4.4	7.9
	1993	363	212	3.3	8.4
Peabody 2	1980	225	145	11	20
	1986	172	----	2.6	8.1
	1987	149	113	5	9.1
	1993	163	124	1.7	8.9

Table 11. Selected properties and concentrations of chemical constituents in confined water from industrial and municipal wells completed in the N aquifer, 1980–93—Continued

Well name	Year	Specific conductance (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Peabody 3	1980	230	151	3.5	14
	1986	175	----	2.4	9.7
	1987	171	112	3.6	6.1
	1993	177	169	4.2	19
Peabody 4	1980	230	139	4.3	13
	1986	205	----	4.2	12
	1987	194	135	5	13
	1992	224	125	4.3	12
	1993	214	124	3	12
Peabody 5	1980	210	134	2.9	9.5
	1986	398	----	8	28
	1987	270	168	4.6	21
	1988	270	183	5.1	22
	1988	263	174	4.1	26
	1990	262	152	4.1	18
	1991	260	178	3	18
	1993	257	112	2.3	4.8
Peabody 7	1980	210	136	3.7	11
	1986	217	----	3.6	12
	1988	240	151	4.4	18
	1993	228	128	3.8	16
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
	1993	488	287	3.6	4.5
Polacca PM4	1990	830	424	30	25
	1991	746	431	29	27
	1993	755	422	27	23
Rocky Ridge PM3	1982	255	----	1.4	6
	1990	222	126	1.5	6
	1993	254	146	1.3	5.5
Rough Rock PM5	1983	1,090	628	130	110
	1984	1,090	613	130	99
	1986	1,010	633	140	120
	1988	1,120	624	130	109
	1991	1,060	574	130	110
	1993	1,040	614	130	110
Second Mesa PM2	1990	590	364	6.5	16
	1991	613	292	10	15
	1993	630	350	7.5	15

Table 12. Selected properties and concentrations of chemical constituents in unconfined water from municipal wells completed in the N aquifer, 1986–93

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

Well name	Year	Specific conductance (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Dennehotso PM2	1992	226	131	9.8	19
	1993	298	164	8.2	16
Moenkopi 1	1992	589	345	59	80
	1993	517	290	48	69
Red Lake PM1	1992	164	87	2.6	1.9
	1993	156	84	1.6	2.1
Shonto PM2	1986	290	----	10	14
	1988	285	171	13	14
	1992	321	186	22	19
	1993	324	197	17	16

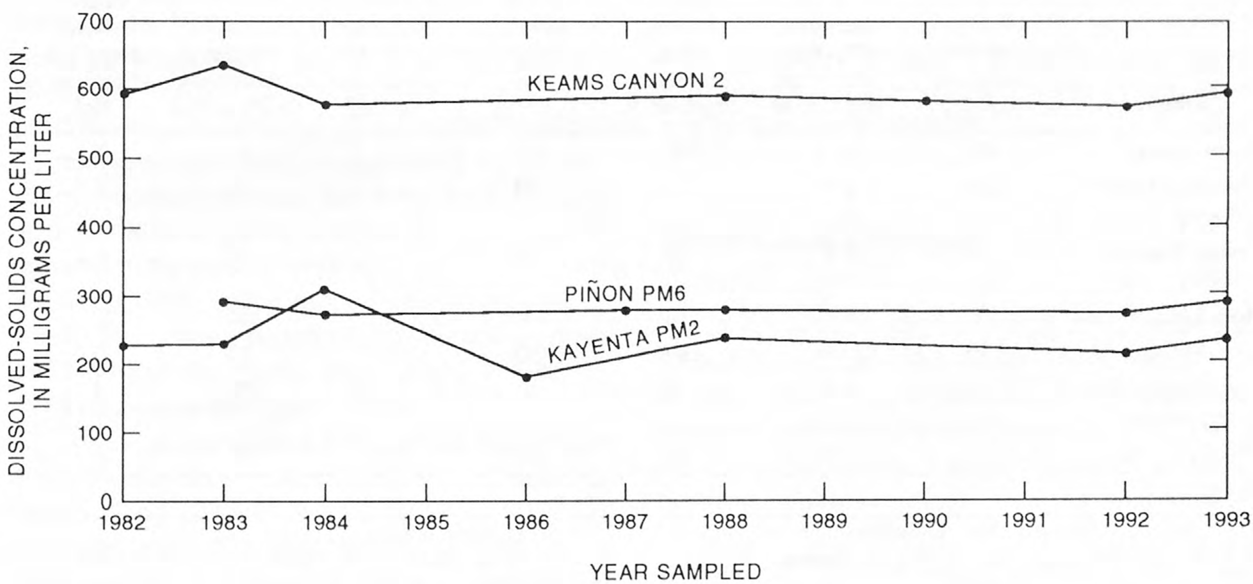


Figure 8. Dissolved-solids concentrations in water from wells Keams Canyon 2, Piñon PM6, and Kayenta PM2, 1982–93.

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, Kykotsmovi, and the coal-lease area. Withdrawals of 23 acre-ft/yr by windmills were simulated in all model runs (fig. 9). 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 the six continuous-record observation wells (BM1 through BM6; Brown and Eychaner, 1988). The 1988 model was rerun in 1989 by using measured withdrawals from 1985–88 and, again, the

Table 13. Chemical analyses of water from selected springs in the Black Mesa area, 1993

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

Spring name	Bureau of Indian Affairs site number	U.S. Geological Survey identification number	Rock formation	Date of sample	Temperature (°C)	Specific conductance (µS/cm)	pH (units)
Burro Spring	6M-31	354156110413701	Navajo Sandstone	03-18-93	19.2	595	8.5
Moenkopi School Spring	3GS-77-6	360632111131101	Navajo Sandstone Tongue in the Kayenta Formation	04-07-93	16.0	313	7.7
Pasture Canyon Spring	3A-5	361021111115901	Navajo Sandstone and alluvium	10-12-93	16.6	242	7.8
Rock Ledge Spring	6M-114	354011110331501	Navajo Sandstone	04-15-93	14.0	3,480	7.9
Sand Spring	1A-83	361011110554401	Navajo Sandstone	10-13-93	20.8	358	7.5
Spring near Dennehotso	8A-224	364656109425400	Navajo Sandstone	10-22-93	13.2	184	8.0
Whisky Spring	5M-4	354446110562001	Navajo Sandstone	04-15-93	12.0	660	8.2

Spring name	Alkalinity (mg/L as $CaCO_3$)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Hardness (mg/L as $CaCO_3$)	Hardness noncarbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
Burro Spring	183	0.18	0.01	120	---	44	3.1
Moenkopi School Spring	100	2.3	.01	98	---	29	6.1
Pasture Canyon Spring	78	4.8	.01	91	---	29	4.5
Rock Ledge Spring	150	5.1	.01	990	---	200	120
Sand Spring	93	.14	.01	93	---	32	3.2
Spring near Dennehotso	80	1.8	.02	86	---	28	4
Whisky Spring	118	.05	.01	240	---	68	16

Spring name	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio	Percent sodium	Sodium plus potassium, dissolved (mg/L as Na+K)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)
Burro Spring	84	3	60	84.5	0.5	30
Moenkopi School Spring	26	1	37	27.4	1.4	17
Pasture Canyon Spring	12	.5	23	12.8	.8	5.3
Rock Ledge Spring	320	4	42	321.2	1.2	74
Sand Spring	35	2	45	35.2	.2	4.4
Spring near Dennehotso	4.2	.2	10	5.1	.9	3.2
Whisky Spring	42	1	28	44.8	2.8	9.1

Table 13. Chemical analyses of water from selected springs in the Black Mesa area, 1993—Continued

Spring name	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)
Burro Spring	85	0.4	12	2	80	13	368
Moenkopi School Spring	27	.2	14	3	50	3	204
Pasture Canyon Spring	17	.2	10	2	30	3	134
Rock Ledge Spring	1,700	.6	17	1	230	10	3,030
Sand Spring	69	.4	14	2	130	14	212
Spring near Dennehotso	8	.2	14	3	10	4	100
Whisky Spring	220	.3	16	1	50	4	464

simulation indicated general agreement between measured and simulated water-level changes but only in the three continuous-record observation wells in the confined area of Black Mesa (BM3, BM5, and BM6). The two observation wells in the unconfined areas (BM1 and BM4) recorded little or no change in water levels as opposed to the models' simulated steady decline; well BM2 in the confined area recorded a greater change in water level as opposed to the models' simulated decline (Hart and Sottilare, 1989). The model was again rerun in 1990 by using measured withdrawals from 1965–89 and the results were consistent with the 1989 simulation (Sottilare, 1992).

Although the model was not run in 1991 or 1992, water-level measurements in the six observation wells for 1991–92 were used to extend the hydrographs (fig. 10). 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 0.2 and 1.0 ft, respectively (fig. 5). Water levels in wells BM2, BM3, and BM5, completed in the confined areas of the N aquifer, have declined from about 49 ft in well BM3 to about 62.9 ft in well BM2 during that same period. Well BM6, completed in a confined area of the N aquifer, recorded a water-level decline of 76.6 ft since 1977. Records for the oldest well, BM3, indicate a water-level decline of 87 ft since 1963. During 1963–67, a water-level decline of 23 ft was recorded at well BM3 even though there was no significant pumpage.

Water-Level Changes

In 1994, the model was rerun using measured withdrawals from 1965–93 to check agreement between measured and simulated water levels and to determine how much of the water-level decline is the result of industrial or municipal pumping. Three pumping scenarios were used in the model. Scenario "A" included all reported pumpage, scenario "B" included industrial pumpage only, and scenario "C" included municipal pumpage only. The simulation results are shown in figures 11A–C.

Contours of simulated water-level changes for all reported pumpage are shown in figure 11A. A comparison of figure 11A to actual water-level changes (fig. 5) indicates general agreement throughout much of the Black Mesa area. An apparent disparity; however, between simulated and actual water-level changes in the continuous-record observation wells and in the Chilchinbito PM3 well suggest the need for analysis of model calibration and sensitivity.

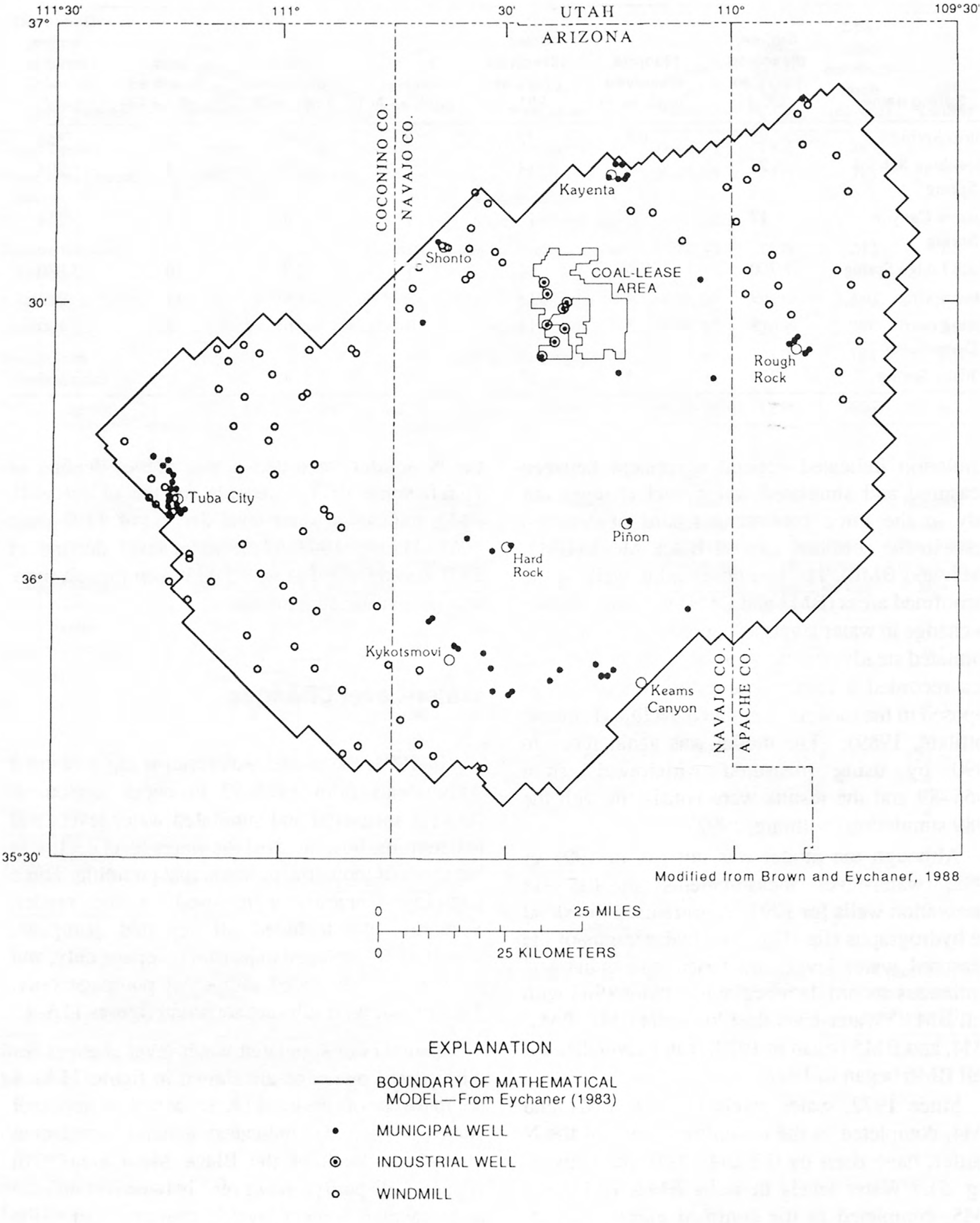


Figure 9. Location of municipal wells, industrial wells, and windmills that discharge water from the N aquifer.

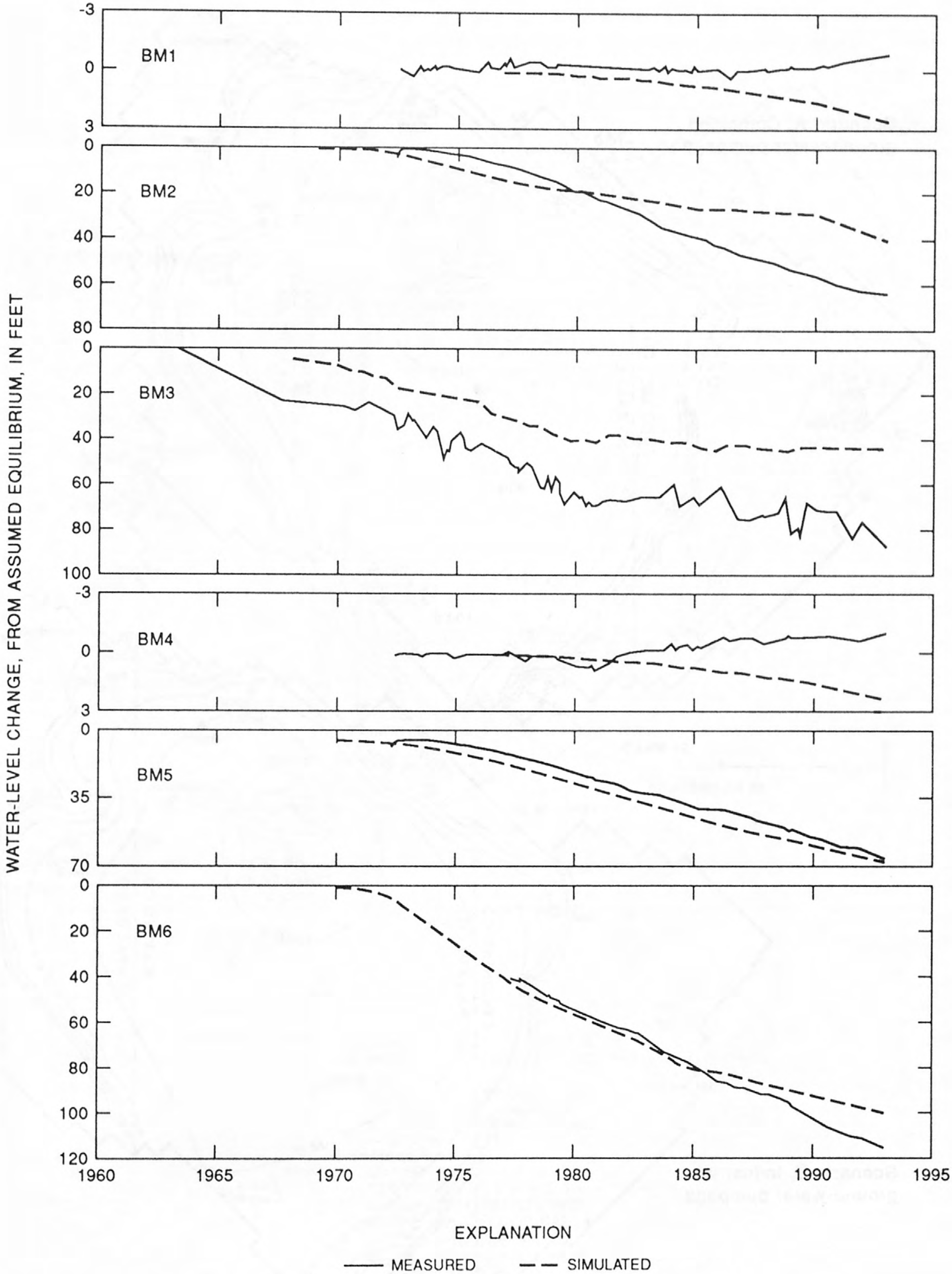


Figure 10. Measured and simulated water-level changes in continuous-record observation wells BM1 through BM6, 1963–93 (modified from Brown and Eychaner, 1988; and Sottilare, 1992).

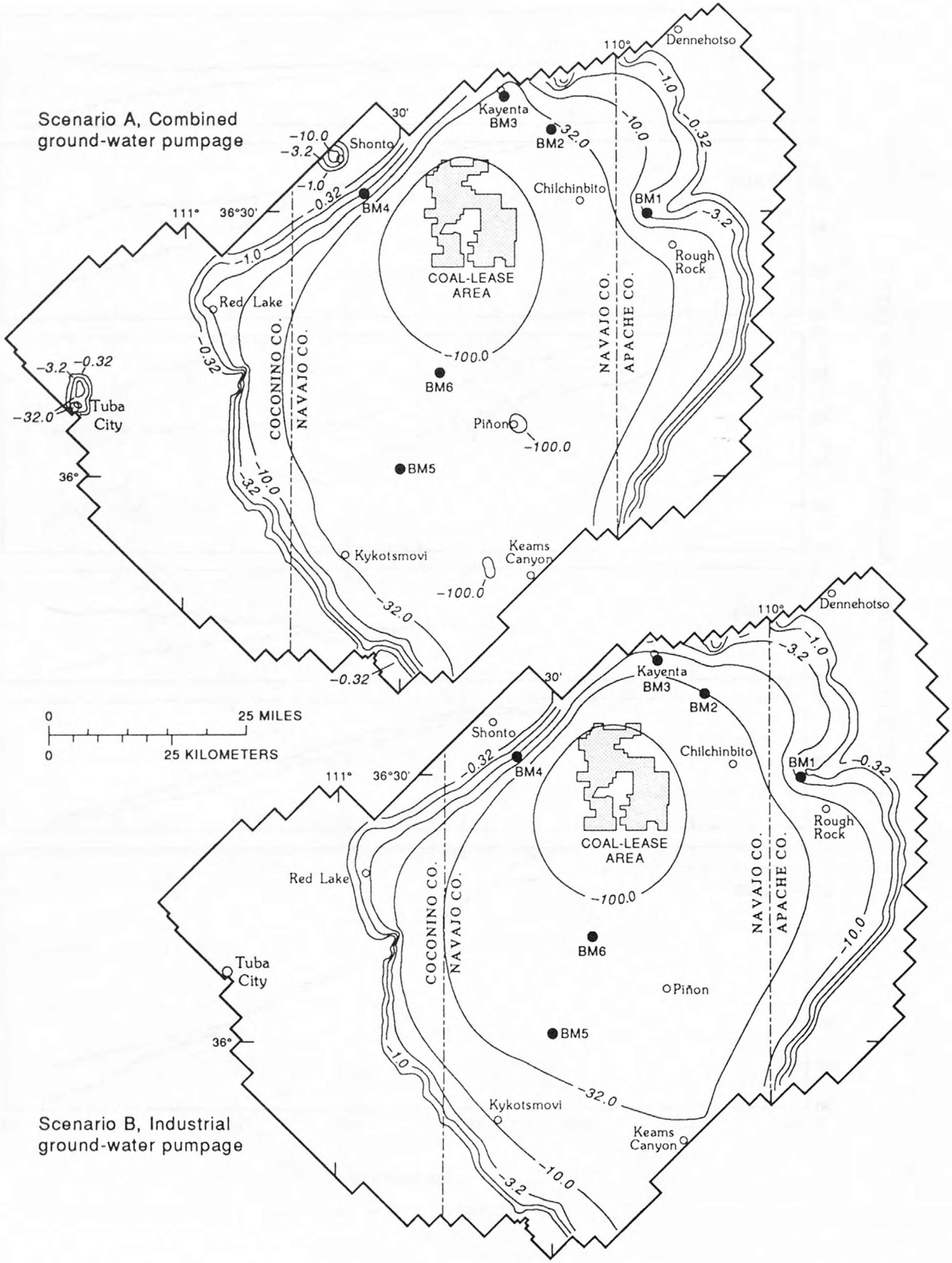


Figure 11. Contours of simulated water-level changes, 1965–93.

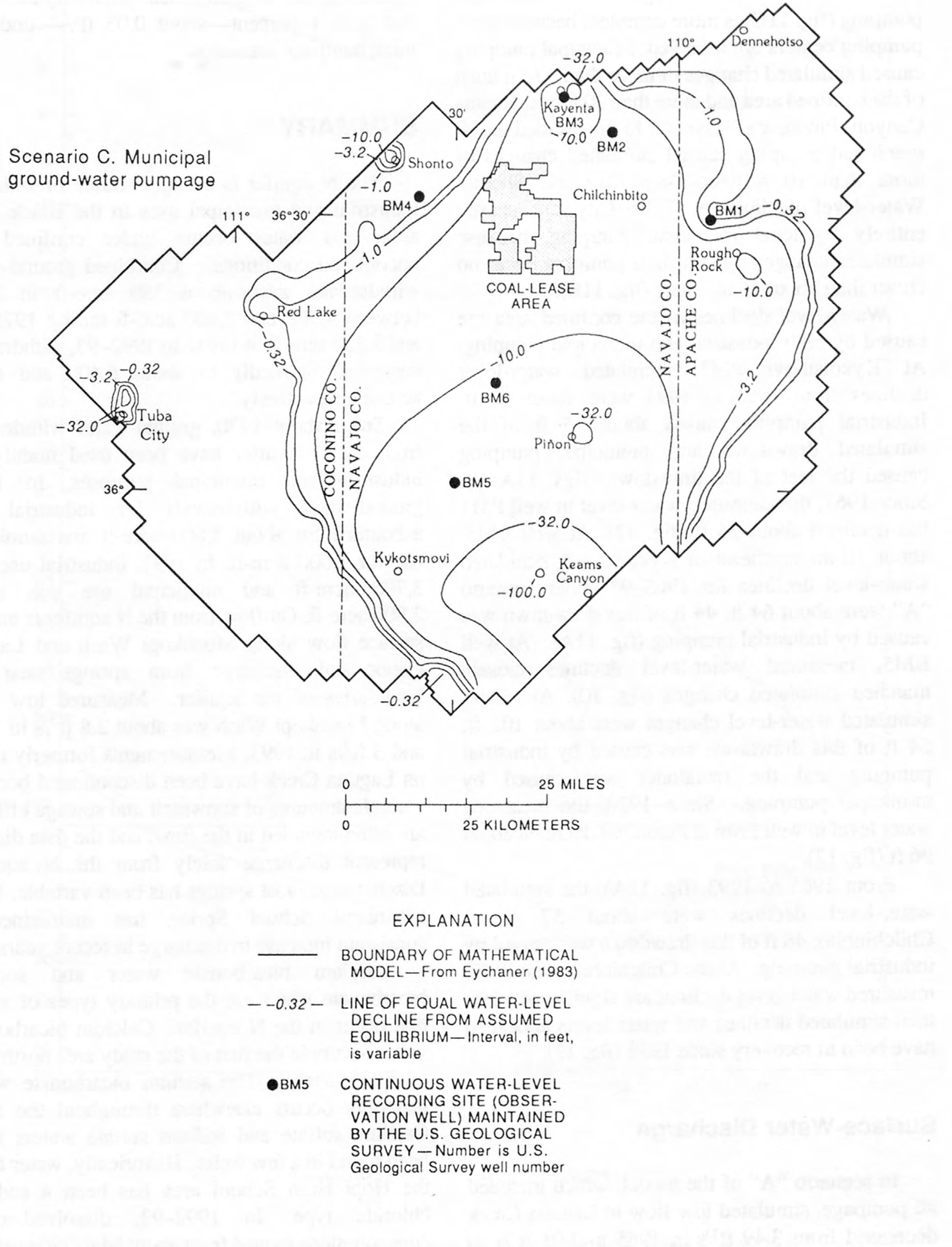


Figure 11. Continued.

Industrial pumping (fig. 11B) caused simulated changes of more than 30 ft in most of the confined area and less than 1 ft in the unconfined areas. The pattern of simulated changes from municipal pumping (fig. 11C) is more complex, because more pumping centers are involved. Municipal pumping caused simulated changes of more than 3 ft in most of the confined area and more than 30 ft near Keams Canyon, Piñon, and Kayenta. In unconfined areas, municipal pumping caused simulated changes of more than 10 ft near Tuba City and Shonto. Water-level declines at Tuba City are caused entirely by local municipal pumping, because simulated changes by industrial pumping occur no closer than about 16 mi away (fig. 11B).

Water-level declines in the confined area are caused by both industrial and municipal pumping. At Kykotsmovi PM1, simulated water-level declines from 1965 to 1993 were about 42 ft. Industrial pumping caused about 15 ft of the simulated drawdown and municipal pumping caused the rest of the drawdown (figs. 11A–C). Since 1967, the measured water level in well PM1 has declined about 34 ft (fig. 12). At well BM5, about 10 mi northeast of Kykotsmovi, simulated water-level declines for 1965–93 under scenario "A" were about 64 ft; 44 ft of this drawdown was caused by industrial pumping (fig. 11A). At well BM5, measured water-level declines closely matched simulated changes (fig. 10). At Piñon, simulated water-level changes were about 102 ft; 64 ft of this drawdown was caused by industrial pumping and the remainder was caused by municipal pumping. Since 1970, the measured water level in well PM6 at Piñon has declined about 96 ft (fig. 12).

From 1965 to 1993 (fig. 11A), the simulated water-level declines were about 57 ft at Chilchinbito; 46 ft of this drawdown was caused by industrial pumping. At the Chilchinbito well PM3, measured water-level declines are significantly less than simulated declines and water levels appear to have been in recovery since 1986 (fig. 12).

Surface-Water Discharge

In scenario "A" of the model, which included all pumpage, simulated low flow in Laguna Creek decreased from 3.49 ft^3/s in 1965 to 3.01 ft^3/s in 1993. By using industrial pumpage alone, simulated low flow decreased to 3.36 ft^3/s in 1993. The simulated low flow in Moenkopi Wash and the simulated flow in springs near Tuba City decreased less than 1 percent—about 0.03 ft^3/s—under all three pumpage scenarios.

SUMMARY

The N aquifer is a major source of water for industrial and municipal uses in the Black Mesa area, and water occurs under confined and unconfined conditions. Combined ground-water withdrawals were about 350 acre-ft in 1968, between 4,500 and 6,800 acre-ft during 1975–90, and 8,520 acre-ft in 1991. In 1992–93, withdrawals decreased markedly to about 6,400 and 6,500 acre-ft, respectively.

Since about 1970, ground-water withdrawals from the N aquifer have been used mainly for industrial and municipal purposes. In 1992, ground-water withdrawals for industrial use accounted for about 3,800 acre-ft and municipal use for 2,600 acre-ft. In 1993, industrial use was 3,700 acre-ft and municipal use was about 2,800 acre-ft. Outflow from the N aquifer is mainly surface flow along Moenkopi Wash and Laguna Creek and discharge from springs near the boundaries of the aquifer. Measured low flow along Moenkopi Wash was about 2.8 ft^3/s in 1992 and 3 ft^3/s in 1993. 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. Discharge at most springs has been variable. Only Moenkopi School Spring has maintained a consistent increase in discharge in recent years.

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. Historically, water from the Hopi High School area has been a sodium chloride type. In 1992–93, dissolved-solids concentrations ranged from about 84 to 290 mg/L in

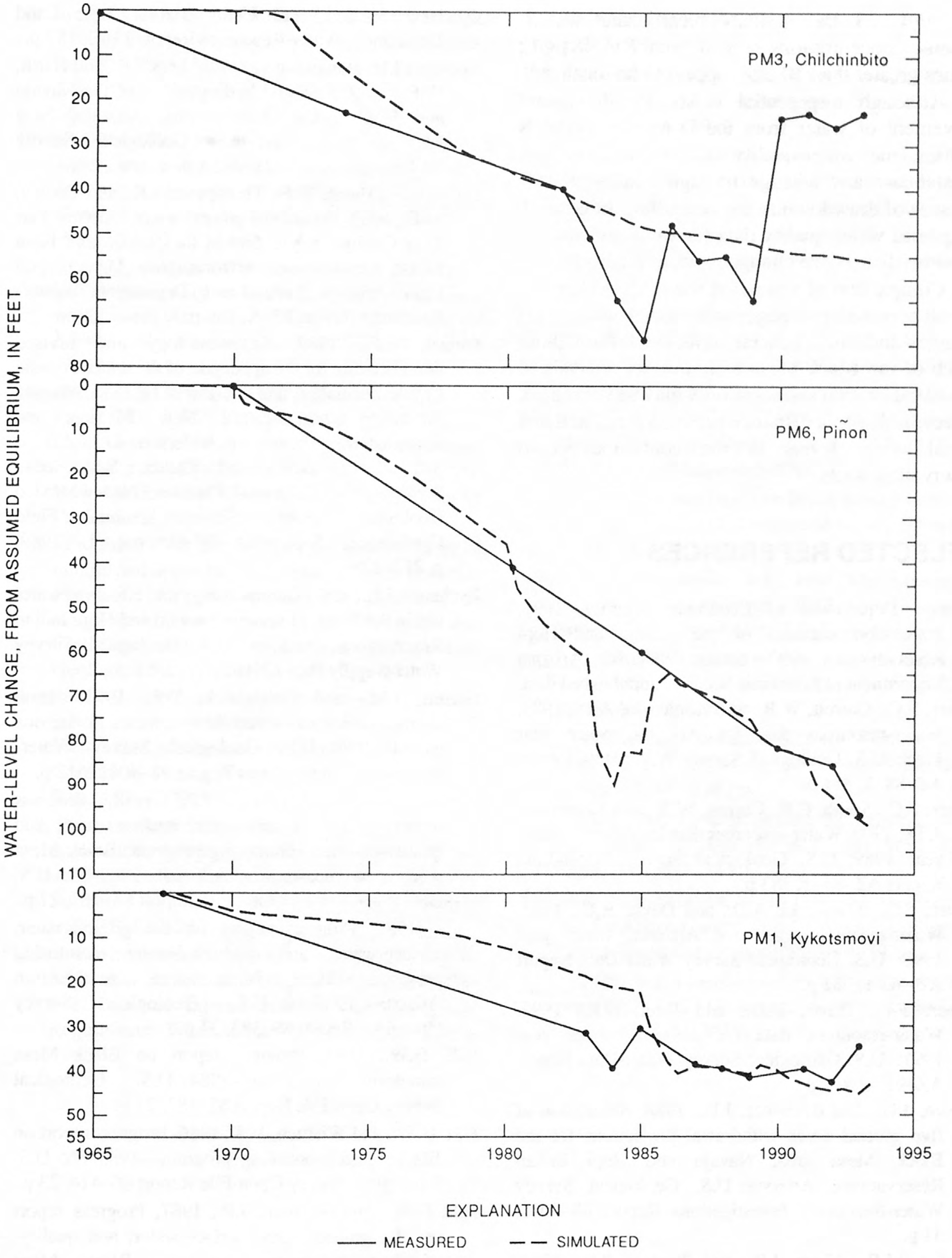


Figure 12. Measured and simulated water-level changes in observation wells Chilchinbito PM3, Piñon PM6, and Kykotsmovi PM1, 1965–94 (modified from Brown and Eychaner, 1988; and Sottilare, 1992).

the calcium bicarbonate waters and 112 to 614 mg/L in the sodium bicarbonate waters. Arsenic concentrations ranged from 2 to 48 µg/L; values greater than 10 µg/L appear to be localized.

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.

Comparison of simulated water-level changes, for all reported pumpage, with actual water-level changes indicates general agreement throughout much of the Black Mesa area. Further analysis of model calibration and sensitivity may be warranted, however, due to a disparity between simulated and actual water levels in the continuous-record observation wells.

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