RESULTS OF GROUND-WATER, SURFACE-WATER, AND WATER-QUALITY MONITORING, BLACK MESA AREA, NORTHEASTERN ARIZONA—1989-90

By J.P. SOTTILARE

With a section on Simulation of Effects of Pumping

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U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 92—4008

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

Tucson, Arizona
April 1992

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CONTENTS

ILLUSTRATIONS

TABLES

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

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.

RESULTS OF GROUND-WATER, SURFACE-WATER, AND WATER-QUALITY MONITORING, BLACK MESA AREA, NORTHEASTERN ARIZONA–1989-90

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ABSTRACT

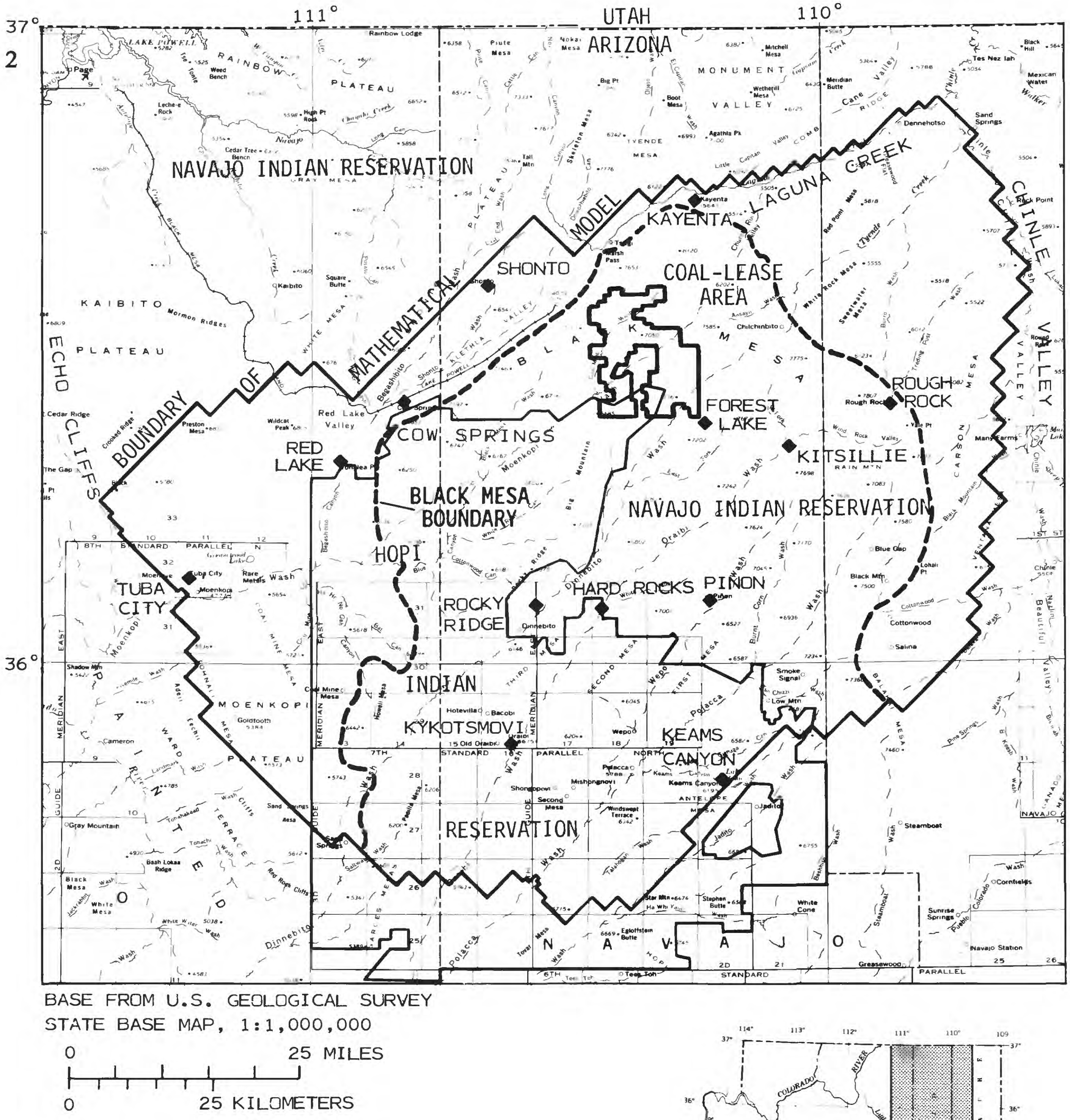
The Black Mesa monitoring program is designed to document long-term effects on the water resources of the area resulting from withdrawals of ground water from the N aquifer by municipal and industrial wells. The N aquifer is an important source of water in the 5,400-square-mile Black Mesa area on the Navajo and Hopi Indian Reservations. Withdrawals from the N aquifer for municipal use increased from about 250 acre-feet in 1968 to about 2,470 acre-feet in 1989, and withdrawals for industrial use increased from 95 acre-feet to 3,450 acre-feet during that period.

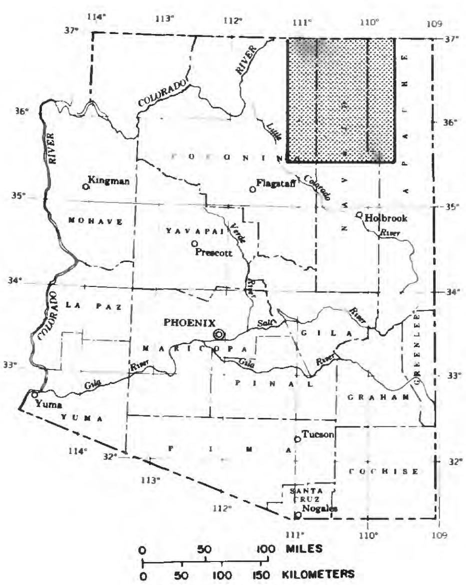
From 1953 to 1989, measured water levels in the confined area of the aquifer declined as much as 113.8 feet. From 1989 to 1990, the water level in observation well 6 near Hard Rocks declined 9.5 feet. From 1965 to 1989, water levels in wells that tap the unconfined area of the aquifer have not declined as much as those in wells in the confined area and have risen in many areas.

The ground-water flow model of the study area developed in 1988 was updated with pumpage data collected from 1985 to 1989 to compare drawdowns caused by industrial pumpage alone, municipal pumpage alone, and industrial and municipal pumpage combined. The model continues to accurately simulate water levels measured in most of the observation wells in the confined area. Simulated water levels in the observation wells in unconfined ground-water areas, however, continue to show a steady decline, whereas the actual measured water levels in these wells either remained the same or rose.

INTRODUCTION

The N aquifer is an important source of water in the 5,400-square-mile Black Mesa area of the Navajo and Hopi Indian Reservations in northeastern Arizona (fig. 1). The aquifer consists of three rock formations that have been historically referred to as the N aquifer (fig. 2). The major water-bearing units are the Navajo Sandstone of Jurassic age and the Lukachukai Member (of former usage) of the Wingate Sandstone of Jurassic age. The Kayenta Formation of Jurassic age, which lies between the Navajo and Wingate Sandstones, yields small quantities of water in places (fig. 2).





INDEX MAP SHOWING AREA OF REPORT (SHADED)

Figure 1.--Location of study area.

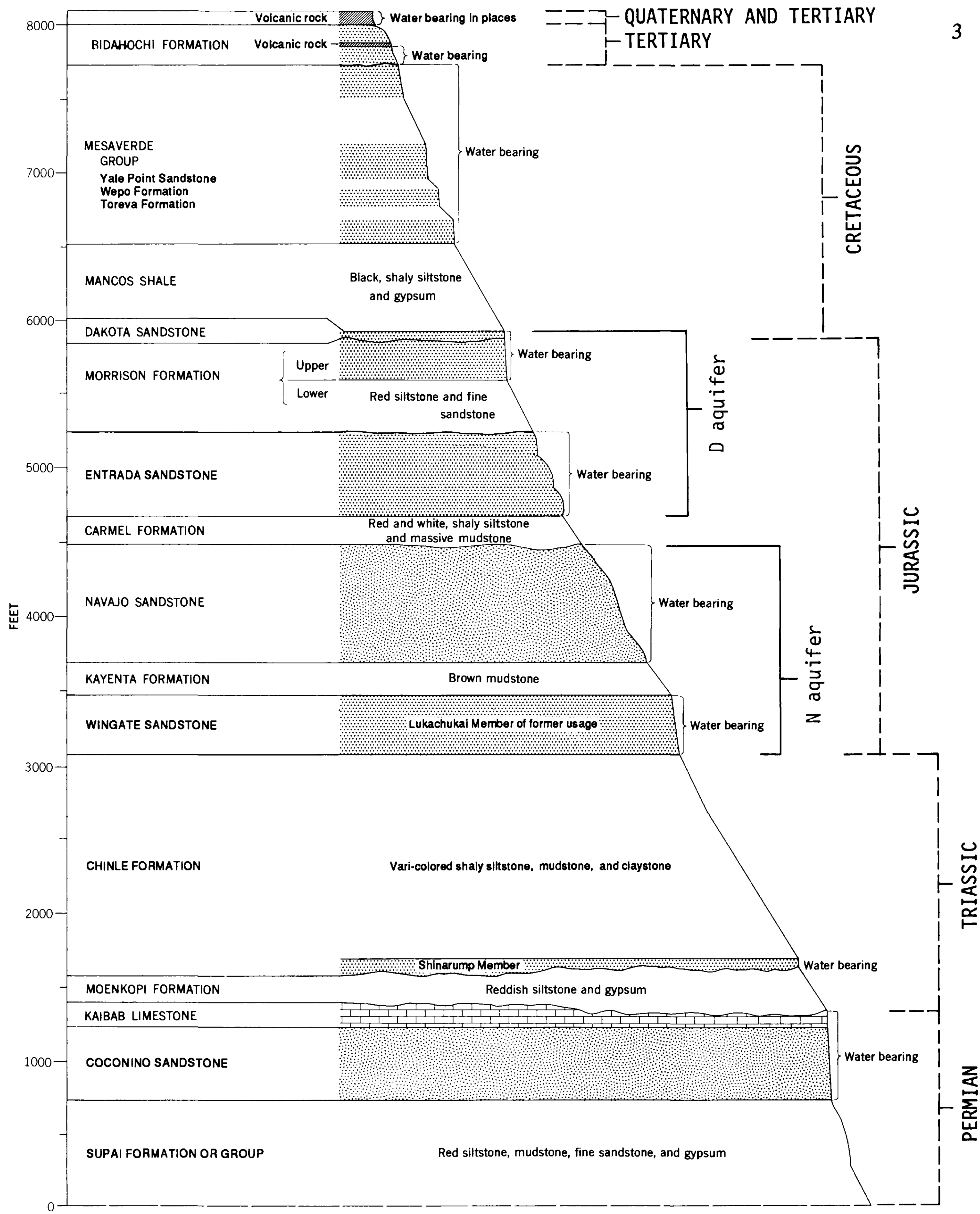


Figure 2.--Rock formations of the Black Mesa area.

On the northern part of the mesa, Peabody Coal Company operates a strip mine in a lease area of about 100 mi^2. When operation of the mine began in 1968, the company pumped about 95 acre-ft of ground water from the N aquifer; in 1989, 3,450 acre-ft was pumped. The water is used to transport mined coal by a slurry line about 250 mi to the Mohave generating station at Bullhead City, Arizona. Municipal withdrawals from the N aquifer increased from an estimated 250 acre-ft in 1968 to about 2,470 acre-ft in 1989.

The Navajo and Hopi Tribes became concerned about the long-term effects of all withdrawals from the N aquifer on supplies for domestic and municipal use. These concerns led to an investigation of the water resources of the Black Mesa area by the U.S. Geological Survey (USGS) in cooperation with the Arizona Department of Water Resources in 1971; in 1983, the U.S. Bureau of Indian Affairs joined the cooperative effort.

Purpose and Scope of the Report

This report describes the monitoring of ground water, surface water, and water quality in the Black Mesa area from July 1, 1989, to May 31, 1990, to determine effects on the aquifer caused by withdrawals from industrial and municipal wells. Except for some previously collected data that are used for comparison, only data collected during this period appear in this report. The scope of the data collection included water-level measurements, chemical analyses of ground water from wells and springs, compilation of pumpage data, and measurement of spring and surface-water discharge at sites where the principal water source is the N aquifer.

Previous Reports on the Program

Eight progress reports have been prepared by the USGS 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). 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 water year 1986, which were published in U.S. Geological Survey (1976-88). Eychaner (1983) showed the results of a mathematical computer model that was developed to simulate the flow of 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). The new model was used to simulate effects of five pumping scenarios through the year 2051. As reported in the 1988-89 progress report (Hart and Sottilare, 1989), the 1988 model was updated with pumpage data from 1985 to 1988 and continues to accurately simulate water levels in most observation wells developed in the confined ground-water area. The monitoring program is essential to document effects of ground-water withdrawals, check the results of model simulations, and determine the quality of water in the N aquifer as water levels decline.

Acknowledgments

The cooperation and assistance of the Navajo and Hopi Tribes and Peabody Coal Company are gratefully acknowledged. 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 assisted in the collection of pumpage data. The Hopi Tribe, the Navajo Tribal Utility Authority, and the U.S. Bureau of Indian Affairs assisted in the collection of water-level data.

HYDROLOGIC-DATA COLLECTION, 1989-90

Monitoring activities include continuous or periodic measurements of (1) ground-water levels in the confined and unconfined areas of the N aquifer, (2) major withdrawals from the confined and unconfined areas, (3) quality of ground water in the N aquifer, (4) discharge and chemical quality of selected springs that flow from the N aquifer, and (5) surface-water discharge.

Ground-Water Levels

Annual ground-water levels were obtained from various municipal and windmill wells. Daily ground-water levels were obtained from six continuous recording USGS observation wells (BM 1-6). All water levels were referenced to land surface. In an effort to obtain representative water levels in municipal wells, pumps were turned off at least 12 hours before measurements were made. Measurements of water levels in windmills were obtained on calm days when the windmills were not pumping. Pumping was not a factor in water-level measurements in the six recording observation wells because no withdrawals were made from them.

Since 1971, ground-water levels in most of the measured nonindustrial wells in the confined area of the N aquifer have declined. Water-level data collected from December 1989 to April 1990, however, show that water levels in four nonindustrial wells in the confined area of the N aquifer had risen since they were last measured during water year 1989[1] (table 1). The rises were not significant except near Chilchinbito and Kayenta, where the pumping status of nearby community wells may have affected the water levels. Changes in water levels from water year 1989 to water year 1990 in the confined area ranged from -9.5 ft at well BM6 near the center of the mesa to +40.2 ft at Chilchinbito in the northeast corner of the study area. Water-level changes that occurred in the confined area from water year 1953 (prestress) to water year 1990 ranged from a record -113.8 ft in Keams Canyon Well 2 near the south edge of the study area to +1.7 ft in well 8T-522 near Kayenta in the northern part of the study area (fig. 3).

Less substantial water-level changes have occurred in most of the wells in the unconfined area of the N aquifer than in wells in the confined area since 1953. Changes during 1953-90 ranged from -34.2 ft at Tuba City in the western part of the study area to +11.9 ft in well 9Y-95 east of the confined area. Water levels in all measured wells east of the confined area have risen since 1953.

Withdrawals from the N Aquifer

The primary interest is in withdrawals that might significantly affect water levels throughout the N aquifer. The two categories of ground-water use from the N aquifer are

[1]Water year is 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, 1990, is called the "1990 water year."

Table 1.--Water-level changes in wells that tap the N aquifer, water years 1984-90

[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 as depth below land surface, in feet, 1990 water year
		1984 water year	1985 water year	1986 water year	1987 water year	1988 water year	1989 water year	1990 water year	
Tuba City	3T-333	-6.6	-2.0	+3.2	-1.3	+2.8	+0.2	+1.5	30.3
Do.	3K-325	+.7	-.4	+11.0	-10.5	+1.2	-.2	-.1	202.4
Gold Tooth	3A-28	+1.4	-8.6	+17.8	-12.5	+3.4	.0	+.3	229.6
Rocky Ridge	PM2	--	[1]-5.4	-1.3	-3.0	-2.1	-3.2	-5.1	486.5
Kykotsmovi	PM1	-7.7	+8.5	--	[1]-7.7	-1.5	[1]-1.4	--	--
Do.	PM3	--	--	[1]+.3	(2)	(2)	[1]-3.6	-.7	226.2
Keams Canyon	2	--	--	[1]+3.5	-32.6	+18.9	-17.2	-1.5	406.3
Low Mountain	PM2	-3.3	-2.7	-2.5	-2.0	-1.0	-19.7	(2)	(2)
Pinon	PM6	--	--	[1] [3].0	(2)	(2)	(2)	[1]-41.7	825.0
Forest Lake	4T-523	--	--	[1]-18.8	-2.4	-.8	-12.2	-6.2	1,134.8
Kitsillie	4T-521	--	--	[1]-69.6	(2)	(2)	(2)	(2)	(2)
White Mesa Arch	1K-214	+.2	.0	+11.4	-11.1	-.9	+1.1	-.3	221.4
Cow Spring	1K-225	+.9	+.8	+3.5	-2.6	+.7	+.3	0	48.4
Shonto	2K-300	+.5	+.3	+.8	-.8	-.5	+1.1	0	172.4
Chilchinbito	PM3	-14.0	-8.9	+26.5	-8.7	+1.6	-9.9	+40.2	428.5
Rough Rock	10R-111	-12.7	+11.6	+11.1	-12.3	+3.1	+.1	-.1	197.9
Do.	10T-258	+3.7	-5.3	+16.6	-19.1	+6.7	+1.8	-1.0	309.8
Do.	10R-119	+1.7	-2.4	+1.5	+.7	-.9	+.3	+.6	255.3
Do.	9Y-95	+.9	+.7	+4.2	-8.1	+3.6	+2.4	-.7	107.6
Do.	9Y-92	-2.5	+2.3	+8.6	-8.4	+1.6	-1.4	+.1	167.4
Northeast Rough Rock	8A-180	+.4	+.3	+1.3	-1.2	+5.4	-5.1	+.2	43.3
BM5	4T-519	-2.2	-3.1	-2.2	-3.7	-2.8	-4.0	-3.5	373.6
BM6	BM6	-7.0	-7.0	-3.8	-3.3	-2.7	-2.6	-9.5	800.6
Shonto Southeast	2K-301	-.5	--	[1]-.5	+.7	-.5	-.4	-.6	287.0
BM4	2T-514	+.1	+.3	+.1	.0	-.1	.0	+.3	216.1
Sweetwater Mesa	8K-443	-.5	-.9	+.1	-.2	.0	(2)	(2)	(2)
BM1	8T-537	[1]+1.3	+1.1	-1.1	+1.0	-.1	+.2	+.3	373.5
Long House Valley	8T-510	+10.7	-13.5	+5.0	-.1	-1.4	+.8	-.6	117.1
Shonto Southeast	2T-502	+.2	-3.8	+4.1	+.1	+1.8	-1.5	-.2	414.4
BM2	8T-538	-4.5	-3.3	-4.5	-3.3	-2.0	-3.7	-3.4	180.9
Marsh Pass	8T-522	+.8	+.8	-1.0	-1.1	-.3	+.2	-.6	123.8
BM3	8T-500	-2.6	-7.4	+9.0	-15.5	+4.6	-3.6	+4.6	130.4
Kayenta West	8T-541	-2.1	-8.0	-.6	-11.6	-12.6	+7.3	-8.7	275.8
Howell Mesa	3K-311	-15.3	+14.8	+3.1	(2)	(2)	[1]+.5	(2)	(2)
Do.	6H-55	-.9	+1.0	-.4	-.4	-.2	-.5	+.3	266.2
Tuba City	Rare Met.	+.1	+.9	.0	+.4	+.3	-.2	+.4	56.6
Tuba NTUA 1	3T-508	+3.1	-5.5	-6.9	--	[1]+9.7	--	[1]-13.7	62.8
Tuba NTUA 4	3T-546	-2.8	+1.9	+2.1	-4.9	--	[1]-9.3	-3.7	67.9

[1]Change in water level from last measurement of 2 years or more.
[2]Unable to measure.
[3]Figure reported by U.S. Bureau of Indian Affairs.

industrial in the confined area and municipal in the confined and unconfined areas. Pumpage data are collected from wells in which withdrawals are used for mining operations and from municipal wells with withdrawals of significant quantities. Pumpage data have not been collected from wells equipped with windmills.

The U.S. Bureau of Indian Affairs, Navajo Tribal Utility Authority, and Hopi Tribe operate municipal well systems that consist of about 70 wells. These well systems supply the Navajo and Hopi Tribes in the Black Mesa area. The industrial system, which includes eight wells operated by the Peabody Coal Company, withdraws water from the N aquifer. During 1988, the USGS made an inventory of the wells and tested the accuracy of the flowmeters (Hart and Sottilare, 1988). This quality- control program began in 1985-86 and is conducted about once every 3 years on all wells that penetrate the N aquifer except those with windmills. The next flowmeter test is scheduled for the 1992-93 monitoring period.

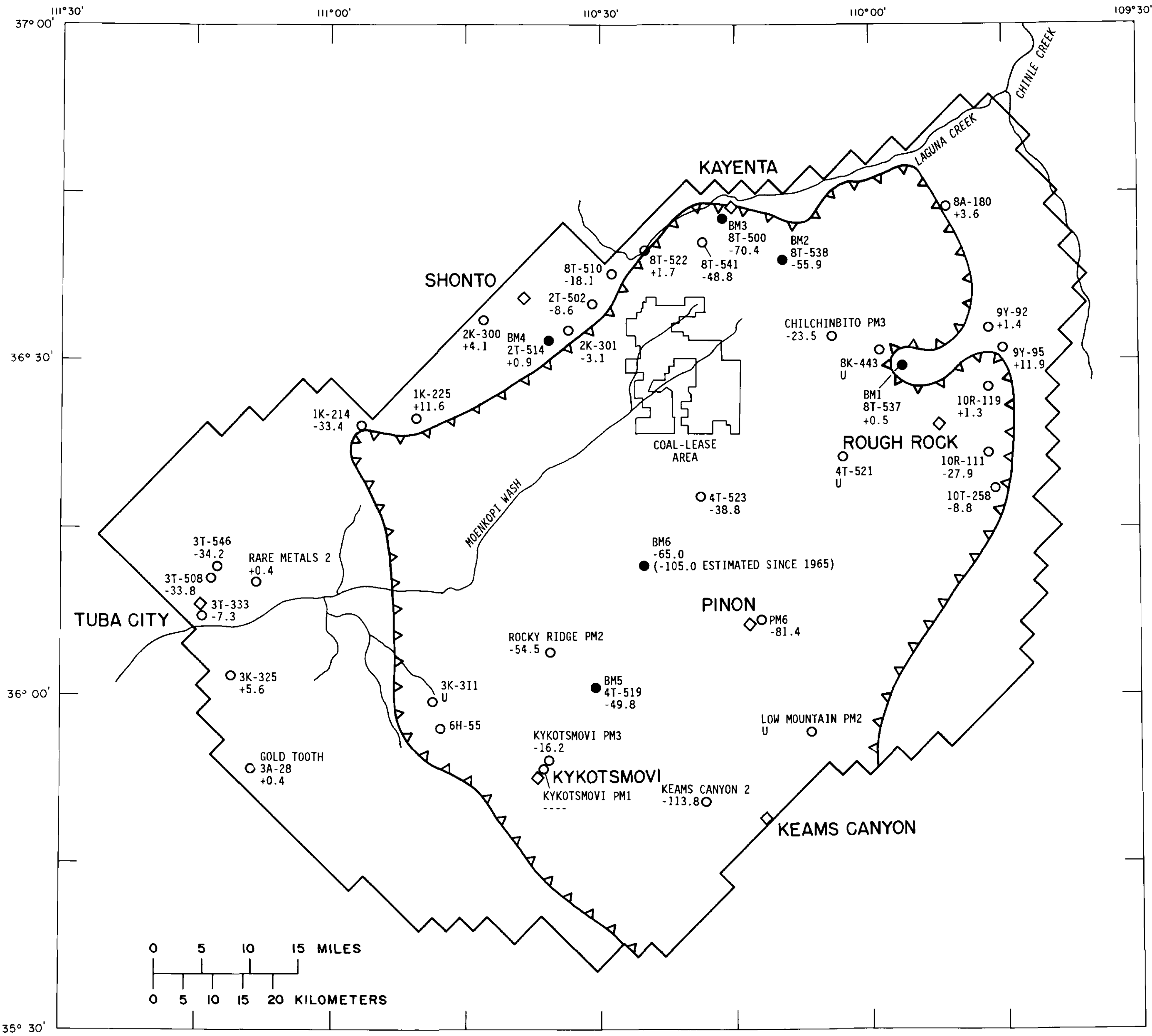
Annual pumpage for the two categories of withdrawals from the N aquifer for 1965-89 is given in table 2. Withdrawals during the 1989 calendar year from individual municipal and industrial well systems that tap the N aquifer are given in table 3, and the locations of these well systems are shown in figure 4.

Chemical Quality of Water from Wells that Tap the N Aquifer

Quality of water in the N aquifer is monitored as part of the Black Mesa monitoring program. Eychaner (1983) stated that some water may enter the N aquifer from the upper confining units as a result of the head in the overlying D aquifer (fig. 2), which averaged about 300 ft higher than that in the N aquifer in 1964. Differences in the chemical composition of the water in the D aquifer and the N aquifer indicate that the quantity of downward leakage must be small (Eychaner, 1983). Dissolved-solids concentration in water from the D aquifer generally is about seven times greater than that in water from the N aquifer. Chloride concentration is 11 times greater and sulfate concentration is 30 times greater than those in water from the N aquifer (Eychaner, 1983).

Any increase in the leakage rate as a result of pumping from the N aquifer probably would appear first as an increase in the dissolved-solids concentrations in the water from wells operated by Peabody Coal Company (Eychaner, 1983). Other indicators of leakage caused by pumping from the N aquifer would be increases in specific conductance and in concentrations of dissolved chloride and dissolved sulfate.

During the winter of 1990, water from selected industrial and municipal wells that penetrate the N aquifer was sampled for major ions and fluoride (fig. 5). Municipal wells were pumped continuously for at least 12 hours before a sample was collected. The deeper industrial wells were pumped continuously for at least 24 hours before a sample was collected. Results of chemical analyses of the water from these wells are shown in tables 4 and 5. On the basis of these results, no significant changes have occurred in the quality of water in the N aquifer since pumpage began at the mine.



Base from U.S. Geological Survey
Flagstaff 1:250,000, 1954-70;
Gallup, 1:250,000, 1950-70;
Marble Canyon, 1:250,000, 1956-70;
and Shiprock, 1:250,000, 1954-69.

Modified from Brown and Eychaner, 1988

Figure 3.--Water-level changes in wells that tap the N aquifer, 1953-90 water years.

E X P L A N A T I O N

CONFINED UNCONFINED	APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS—From Eychaner (1983)
	BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)
○ 4T-523 -38.8	WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 4T-523, is Bureau of Indian Affairs identification number; second entry, -38.8, is change in water level, in feet, between measurements made during the prestress period and measurements made during 1987-88. U, unable to measure
● BM3 8T-500 -70.4	CONTINUOUS WATER-LEVEL RECORDING SITE (OBSERVATION WELL) MAINTAINED BY THE U.S. GEOLOGICAL SURVEY—First entry, BM3, is U.S. Geological Survey identification number; second entry, 8T-500, is Bureau of Indian Affairs identification number; third entry, -70.4, is change in water level, in feet, from 1953 to 1988-89
◇	COMMUNITY

Figure 3.--Continued.

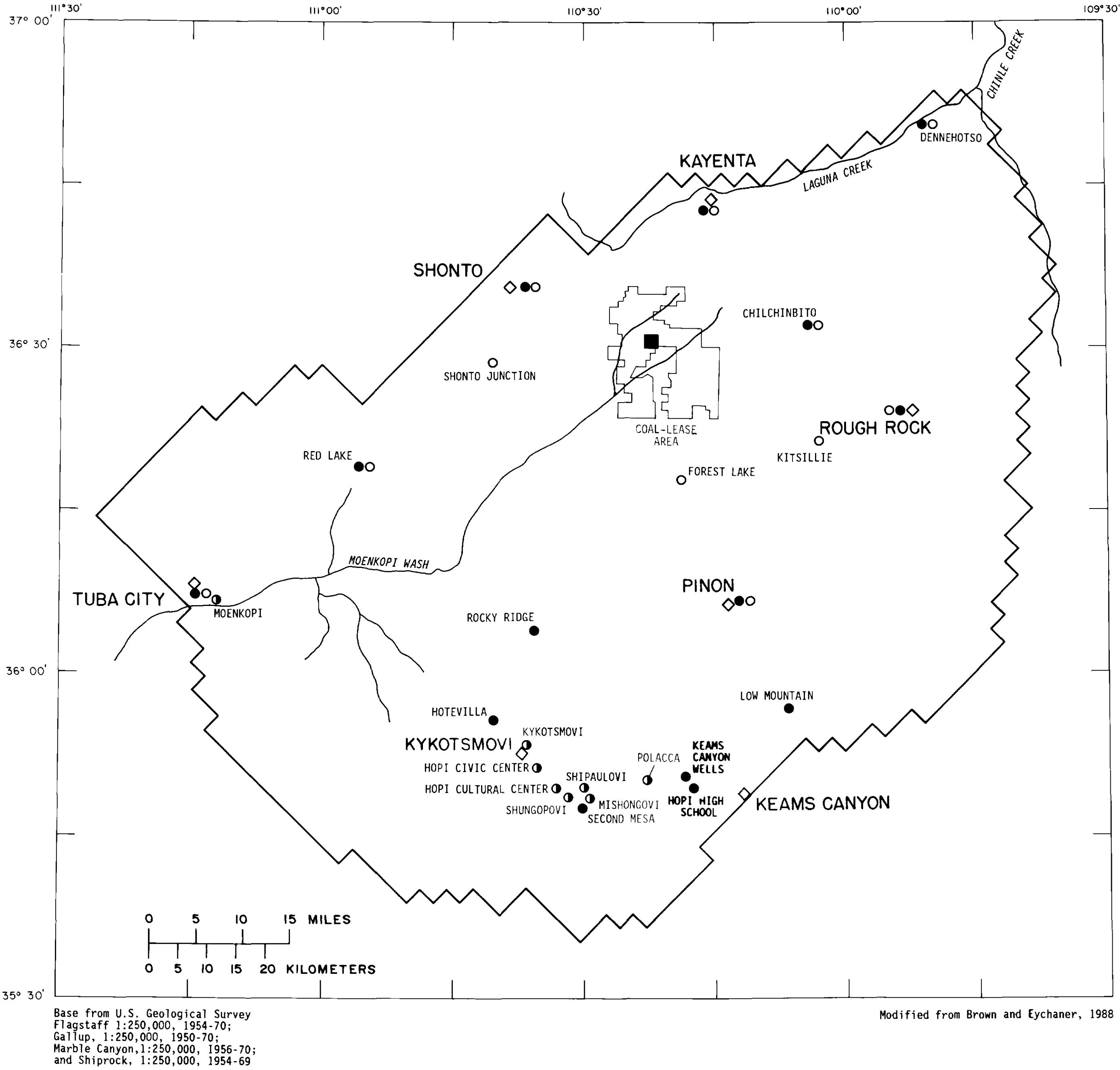


Figure 4.--Location of well systems monitored for withdrawals from the N aquifer, 1989.

EXPLANATION

WELL-SYSTEM OWNER

- ● U.S. Bureau of Indian Affairs
- ○ Navajo Tribal Utility Authority
- ◑ Hopi Tribe
- ■ Peabody Coal Company well field
- □ COMMUNITY

Figure 4.--Continued.

Table 2.--*Withdrawals from the N aquifer, 1965-89*

[Measurements 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	3,550	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

[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, Pinon, 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, 1986-89.

Table 3.--*Withdrawals from the N aquifer by well system, 1989*

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

Location	Owner	Source of data	Confined-aquifer well systems	Unconfined- aquifer well systems
Tuba City	BIA	USGS/BIA		[1]233
Shonto	BIA	USGS/BIA		199
Dennehotso	BIA	USGS/BIA		[1]39.7
Red Lake	BIA	USGS/BIA		11.9
Kayenta	BIA	USGS/BIA	87.7	
Rocky Ridge	BIA	USGS/BIA	12.1	
Chilchinbito	BIA	USGS/BIA	7.6	
Pinon	BIA	USGS/BIA	37.7	
Rough Rock	BIA	USGS/BIA	[1]46.2	
Hotevilla	BIA	USGS/BIA	30.0	
Second Mesa	BIA	USGS/BIA	8.5	
Hopi High School	BIA	USGS/BIA	22.6	
Keams Canyon	BIA	USGS/BIA	84.6	
Low Mountain	BIA	USGS/BIA	9.2	
Red Lake	NTUA	NTUA		43.2
Tuba City	NTUA	NTUA		803
Dennehotso	NTUA	NTUA		25.7
Shonto	NTUA	NTUA		17.9
Shonto Junction	NTUA	NTUA		28.3
Forest Lake	NTUA	NTUA	11.3	
Chilchinbito	NTUA	NTUA	32.4	
Kayenta	NTUA	NTUA	443	
Rough Rock	NTUA	NTUA	12.4	
Pinon	NTUA	NTUA	72.6	
Kitsillie	NTUA	NTUA	7.4	
Hard Rocks	NTUA	NTUA	19.4	
Mine Well Field	Peabody	Peabody	3,450	
Polacca	Hopi	USGS	31.3	
Kykotsmovi	Hopi	USGS/Hopi	55.6	
Shungopavi	Hopi	USGS/Hopi	19.3	
Shipaulovi	Hopi	USGS	18.5	
Mishongnovi	Hopi	USGS/Hopi	2.8	
Hopi Cultural Center	Hopi	([2])	([2])	
Hopi Civic Center	Hopi	([2])	([2])	
Moenkopi	Hopi	([2])	([2])	

[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 or the typical average daily pumpage prior to meter malfunction for the well in question. Does not include possible estimated data provided by cooperating agencies.

[2]Data not available.

Table 4.--Chemical analyses of water from selected industrial and municipal wells that tap the N aquifer, 1990

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

Well name	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)
Peabody Well 5	362901110234101	01-12-90	31.5	262	9.4	109	0.94
Peabody Well 8	363130110254501	01-12-90	29.5	440	8.4	101	1.60
Peabody Well 9	362333110250001	01-12-90	32.0	158	9.2	75	.77
Forestlake NTUA 1	361737110180301	01-12-90	29.0	375	9.6	127	.64
Kykotsmovi PM 2	355215110375001	01-17-90	22.5	355	10.0	165	1.20
Rocky Ridge PM 3	360422110353501	01-23-90	26.5	222	9.6	111	1.30
Hotevilla PM 1	355518110400301	01-17-90	24.5	290	9.9	143	1.10

Well name	Identification number	Date of sample	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)
Peabody Well 5	362901110234101	01-12-90	<0.01	3.5	0.8	59
Peabody Well 8	363130110254501	01-12-90	.02	24	3.2	67
Peabody Well 9	362333110250001	01-12-90	<.07	3.9	.04	33
Forestlake NTUA 1	361737110180301	01-12-90	<.01	1.0	.21	82
Kykotsmovi PM 2	355215110375001	01-17-90	.03	.47	.06	78
Rocky Ridge PM 3	360422110353501	01-23-90	.02	.46	<.02	54
Hotevilla PM 1	355518110400301	01-17-90	.03	.77	<.02	64

Well name	Identification number	Date of sample	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)
Peabody Well 5	362901110234101	01-12-90	0.60	4.1	18	0.20
Peabody Well 8	363130110254501	01-12-90	1.9	4.3	109	.10
Peabody Well 9	362333110250001	01-12-90	.50	1.6	3.0	.20
Forestlake NTUA 1	361737110180301	01-12-90	.80	8.2	38	.30
Kykotsmovi PM 2	355215110375001	01-17-90	.40	3.2	9.0	<.10
Rocky Ridge PM 3	360422110353501	01-23-90	.40	1.5	6.0	.10
Hotevilla PM 1	355518110400301	01-17-90	.60	1.6	5.0	<.10

Well name	Identification number	Date of sample	Silica, dissolved (mg/L as SiO_2)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids residue at 180°C (mg/L)
Peabody Well 5	362901110234101	01-12-90	21	30	12	152
Peabody Well 8	363130110254501	01-12-90	20	50	15	287
Peabody Well 9	362333110250001	01-12-90	20	20	28	106
Forestlake NTUA 1	361737110180301	01-12-90	21	80	41	226
Kykotsmovi PM 2	355215110375001	01-17-90	23	30	5	255
Rocky Ridge PM 3	360422110353501	01-23-90	20	20	7	126
Hotevilla PM 1	355518110400301	01-17-90	22	30	10	192

Table 4.--Chemical analyses of water from selected industrial and municipal wells that tap the N aquifer, 1990--Continued

Well name	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)
Polacca PM 4	354950110231501	01-18-90	21.5	830	9.6	333	<0.10
Low Mountain PM 2	355638110064001	01-18-90	20.5	1,480	9.2	376	<.10
Second Mesa PM 2	354749110300101	01-18-90	20.0	590	9.9	287	<.10
Keams Canyon 2	355023110182701	01-22-90	20.0	1,030	9.4	358	<.10
Pinon PM 6	360614110130801	01-18-90	27.0	472	10.0	227	1.40
Kitsillie NTUA 1	362035110032201	01-22-90	29.0	410	9.9	214	1.30

Well name	Identification number	Date of sample	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)
Polacca PM 4	354950110231501	01-18-90	0.02	0.60	0.08	170
Low Mountain PM 2	355638110064001	01-18-90	.03	1.3	.29	320
Second Mesa PM 2	354749110300101	01-18-90	.02	.48	<.02	140
Keams Canyon 2	355023110182701	01-22-90	.01	.88	.11	230
Pinon PM 6	360614110130801	01-18-90	.01	.51	<.02	109
Kitsillie NTUA 1	362035110032201	01-22-90	.01	.77	.11	94

Well name	Identification number	Date of sample	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)
Polacca PM 4	354950110231501	01-18-90	0.60	30	25	0.60
Low Mountain PM 2	355638110064001	01-18-90	1.2	200	61	3.0
Second Mesa PM 2	354749110300101	01-18-90	.40	6.5	16	.20
Keams Canyon 2	355023110182701	01-22-90	.80	94	34	1.3
Pinon PM 6	360614110130801	01-18-90	.40	3.6	5.0	<.10
Kitsillie NTUA 1	362035110032201	01-22-90	.60	3.6	5.0	.20

Well name	Identification number	Date of sample	Silica, dissolved (mg/L as SiO_2)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids residue at 180°C (mg/L)
Polacca PM 4	354950110231501	01-18-90	15	250	8	424
Low Mountain PM 2	355638110064001	01-18-90	11	1,300	10	837
Second Mesa PM 2	354749110300101	01-18-90	20	100	4	364
Keams Canyon 2	355023110182701	01-22-90	12	660	9	600
Pinon PM 6	360614110130801	01-18-90	27	40	<3	288
Kitsillie NTUA 1	362035110032201	01-22-90	24	50	3	268

Table 5.--*Selected properties of and constituents in water from industrial and municipal wells that tap the N aquifer, 1968 and 1980-90*

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

Well name	Year	Specific conductance (µS/cm)	Dissolved-solids concentrations, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Peabody Well 5	1968	224	[1]149	3.5	16
	1980	210	134	2.9	9.5
	1986	398	—	8.0	28
	[2]1986	602	338	12	62
	1987	270	168	4.6	21
	1988	270	184	5.1	22
	1988	263	174	4.1	26
	1990	262	152	4.1	18
Peabody Well 8	1980	420	283	4.8	100
	1983	440	278	4.8	100
	1984	436	264	4.7	100
	1986	445	—	4.9	110
	[3]1988	790	516	7.2	250
	[4]1988	438	300	4.8	120
	1988	418	308	4.5	120
	1990	440	287	4.3	109
Peabody Well 9	1986	181	—	3.1	4.9
	1987	148	102	2.8	4.1
	1990	158	106	1.6	3.0
Forestlake NTUA 1	1982	470	—	11	67
	1990	375	226	8.2	38
Kykotsmovi PM2	1988	368	212	3.2	8.6
	1990	355	255	3.2	9.0
Rocky Ridge PM3	1982	255	—	1.4	6.0
	1990	222	126	1.5	6.0
Hotevilla PM1	1990	290	192	1.6	5.0
Polacca PM4	1990	830	424	30	25
Low Mountain PM2	1988	1,580	851	200	75
	1990	1,480	837	200	61
Second Mesa PM2	1990	590	364	6.5	16
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
Pinon PM6	1982	485	—	3.7	5.0
	1983	505	293	3.6	5.3
	1984	495	273	3.7	5.4
	1987	500	279	3.7	3.8
	1988	455	278	3.5	5.2
	1990	472	288	3.6	5
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	5.0

[1]Dissolved-solids concentrations in 1974.
[2]Volume of well bore not completely displaced prior to sampling.
[3]Well pumped for 16 hours at 470 gallons per minute.
[4]Well pumped for 20 hours at 1, 600 gallons per minute.

Discharge and Chemical Quality of Springs

The effect of withdrawals from the N aquifer on the water quality of springs used for domestic purposes is of concern to some residents of the reservations. Many springs on Black Mesa discharge from several stratigraphic units, including the Navajo Sandstone, where these units crop out.

Four springs were selected for discharge measurements and water-quality analyses during 1989 (tables 6 and 7). The springs were the unnamed spring near Many Farms (10R-114, Luckachukai Member of the Wingate Sandstone), Whisky Spring (5M-4, Navajo Sandstone), Burro Spring (6M-31, Navajo Sandstone), and Sand Spring (1A-83, Navajo Sandstone). The unnamed spring near Many Farms was sampled previously in 1952, Whisky Spring was sampled in 1954, and Sand Spring was sampled in 1954. No previous samples were collected from Burro Spring.

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-gaging stations on Moenkopi Wash at Moenkopi (09401260; table 8 and fig. 5) and Chinle Creek near Mexican Water (09379200; table 9 and fig. 5) and at the low-flow measurement site on Laguna Creek near Church Rock (09379160; fig. 5).

Low flow in Moenkopi Wash during November through February has remained fairly constant since the streamflow-gaging station was established in 1976. Daily mean discharges during water year 1989 are shown in table 8. Daily mean discharges for previous water years have been published in U.S. Geological Survey (1963-81), White and Garrett (1984-88), Wilson and Garrett (1988-89), and Boner and others (1989-90).

Chinle Creek, which is along the northeastern perimeter of the study area, receives water from the N aquifer principally from Laguna Creek. Laguna Creek flows along the northern boundary of the study area and flows into Chinle Creek about 5 mi above the gaging station (fig. 5). The daily mean discharge data for water year 1989 is shown in table 9. All previous daily mean discharge data have been published in U.S. Geological Survey (1963-81), White and Garrett (1984-88), Wilson and Garrett (1988-89), and Boner and others (1989-90).

The mean low-flow discharge of measurements made on Laguna Creek during November through February since the station was established in 1981 is 3.54 ft^3/s or about 2,560 acre-ft/yr. Four monthly low-flow measurements were made during the same months in water year 1990; the mean of those measurements was 3.35 ft^3/s, or 2,430 acre-ft/yr. No continuous-recording streamflow-gaging station has been established at this site.

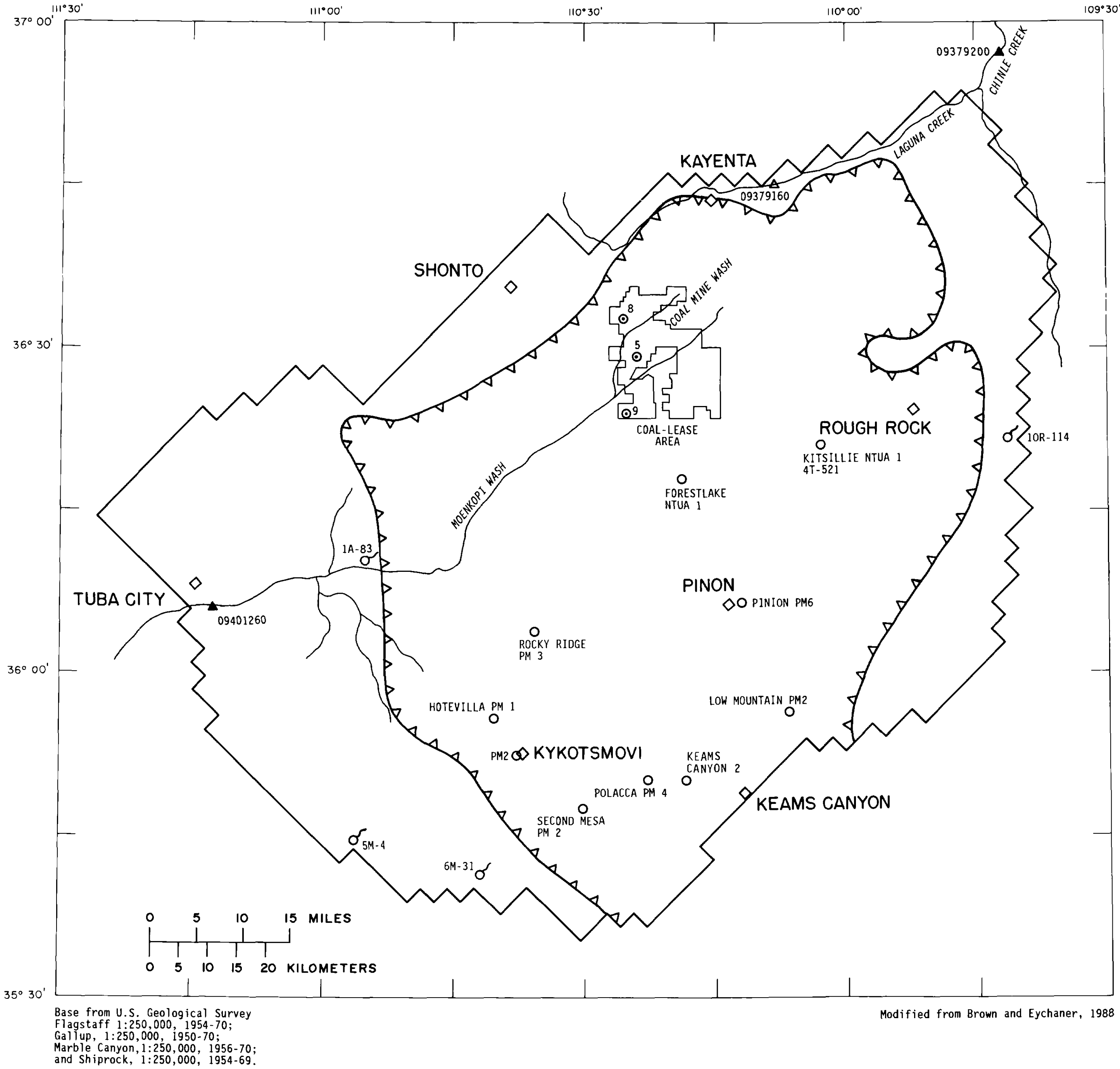


Figure 5.--Surface-water and water-quality data-collection sites, 1989-90.

E X P L A N A T I O N

CONFINED / UNCONFINED	APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS—From Eychaner (1983)
	BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)
PINON PM6	MUNICIPAL WELL FROM WHICH WATER-QUALITY SAMPLE WAS COLLECTED—Pinon PM6 is well name
5	INDUSTRIAL WELL OWNED BY PEABODY COAL COMPANY FROM WHICH WATER-QUALITY SAMPLE WAS COLLECTED—5 is well number
5M-4	SPRING AT WHICH DISCHARGE WAS MEASURED AND WATER-QUALITY SAMPLE WAS COLLECTED—5M-4 is spring identification number
09401260	STREAMFLOW-GAGING STATION OPERATED BY THE U.S. GEOLOGICAL SURVEY AT WHICH SURFACE-WATER DISCHARGE WAS MEASURED—09401260 is station number
09379160	LOW-FLOW MEASUREMENT SITE—09379160 is site-identification number
	COMMUNITY

Figure 5.--Continued.

Table 6.--*Discharge of measured springs, 1929-89*

Spring name	U.S. Bureau of Indian Affairs well number	Year	Discharge, in gallons per minute
Unnamed spring near Many Farms	10R-114	1929	1.5
		1952	[1].5
		1989	.1
Whisky Spring	5M-4	1954	.4
		1989	.1
Burro Spring	6M-31	1927	.5
		1955	.5
		1989	.4
Sand Spring	1A-83	1954	.1
		1989	([2])

[1]Estimated.
[2]Collection box; unmeasurable

Table 7.--Results of chemical analyses of water from selected springs, Black Mesa area, 1952-89

[°C, degree Celsius; μS/cm, microsiemens per centimeter; mg/L, milligrams per liter; μg/L, micrograms per liter; <, less than. 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)
Unnamed spring near Many Farms	10R-114	362208109411301	Wingate (Luckachukai)	08-27-52	22	461	---	---	----
				11-09-89	10	441	7.8	209	0.15
Whisky Spring	5M-4	354446110562001	Navajo Sandstone	05-13-54	20	639	---	---	----
				12-14-89	8	560	7.9	117	<.10
Burro Spring	6M-31	354156110413701	Navajo Sandstone	12-15-89	3.5	485	7.6	180	<.10
Sand Spring	1A-83	361011110554401	Navajo Sandstone	06-25-54	29	230	---	---	----
				12-19-89	8	315	7.6	88	.23

Spring name	U.S. Bureau of Indian Affairs field number	U.S. Geological Survey identification number	Rock formation	Date of sample	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)
Unnamed spring near Many Farms	10R-114	362208109411301	Wingate (Luckachukai)	08-27-52	---	110	0	36	4.7
				11-09-89	0.02	---	---	48	5.4
Whisky Spring	5M-4	354446110562001	Navajo Sandstone	05-13-54	---	270	144	---	---
				12-14-89	<.01	---	---	72	17
Burro Spring	6M-31	354156110413701	Navajo Sandstone	12-15-89	<.01	---	---	49	3.8
Sand Spring	1A-83	361011110554401	Navajo Sandstone	06-25-54	---	54	0	19	1.6
				12-19-89	.02	---	---	29	2.8

Spring name	U.S. Bureau of Indian Affairs field number	U.S. Geological Survey identification number	Rock formation	Date of sample	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio	Percent sodium	Sodium+ Potassium, dissolved (mg/L as Na+K)
Unnamed spring near Many Farms	10R-114	362208109411301	Wingate (Luckachukai)	08-27-52	---	2.5	54	59
				11-09-89	50	---	---	---
Whisky Spring	5M-4	354446110562001	Navajo Sandstone	05-13-54	---	.8	31	31
				12-14-89	45	---	---	---
Burro Spring	6M-31	354156110413701	Navajo Sandstone	12-15-89	56	---	---	---
Sand Spring	1A-83	361011110554401	Navajo Sandstone	06-25-54	---	1.8	55	30
				12-19-89	35	---	---	---

Table 7.--Results of chemical analyses of water from selected springs, Black Mesa area, 1952-89--Continued

Spring name	U.S. Bureau of Indian Affairs field number	U.S. Geological Survey identification number	Rock formation	Date of sample	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)
Unnamed spring near Many Farms	10R-114	362208109411301	Wingate (Luckachukai)	08-27-52	---	20	50	0.6
				11-09-89	2.6	11	32	.4
Whisky Spring	5M-4	354446110562001	Navajo Sandstone	05-13-54	---	10	189	.4
				12-14-89	2.6	7.8	219	.3
Burro Spring	6M-31	354156110413701	Navajo Sandstone	12-15-89	.5	22	59	.3
Sand Spring	1A-83	361011110554401	Navajo Sandstone	06-25-54	---	3	36	1.0
				12-19-89	.4	4.1	67	.4

Spring name	U.S. Bureau of Indian Affairs field number	U.S. Geological Survey identification number	Rock formation	Date of sample	Silica, dissolved (mg/L as SiO^2)	Boron, dissolved (µg/L B)	Iron, dissolved (µg/L Fe)	Dissolved solids: Residue at 180°C (mg/L)	Dissolved solids: Sum of constituents (mg/L)
Unnamed spring near Many Farms	10R-114	362208109411301	Wingate (Luckachukai)	08-27-52	22	---	---	---	289
				11-09-89	16	60	13	293	---
Whisky Spring	5M-4	354446110562001	Navajo Sandstone	05-13-54	17	---	---	---	---
				12-14-89	15	50	12	455	---
Burro Spring	6M-31	354156110413701	Navajo Sandstone	12-15-89	15	50	10	308	---
Sand Spring	1A-83	361011110554401	Navajo Sandstone	06-25-54	10	---	---	---	149
				12-19-89	11	180	9	215	---

Table 8.--Discharge data, Moenkopi Wash at Moenkopi, water year 1989

[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, 1989, is called the "water year 1989." Dashes indicate no data]

DISCHARGE, CUBIC FEET PER SECOND, WATER YEAR 1989
MEAN VALUES

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
1	1.6	1.7	[1]1.6	[1]2.2	[1]2.2	2.3	2.3	0.92	0.00	0.00	429	0.00
2	1.6	1.9	[1]1.6	[1]2.2	3.0	2.7	2.7	.70	.00	.00	64	.00
3	1.6	2.1	[1]1.6	[1]2.2	2.8	2.5	2.5	.54	.00	.00	23	.00
4	1.6	2.1	[1]1.2	[1]2.2	3.4	2.6	2.6	.60	.00	.00	22	.02
5	1.6	1.9	[1]1.2	[1]2.2	3.7	2.6	2.6	.72	.00	.00	21	3.6
6	1.6	1.9	[1]1.2	[1]2.2	[1]2.3	2.5	1.4	.44	.00	.00	3.7	4.7
7	2.2	2.1	[1]1.6	[1]2.2	[1]1.9	2.4	1.6	.64	.00	.00	.62	1.3
8	2.8	2.1	[1]2.2	[1]2.2	[1]3.8	2.7	1.8	.36	.00	.00	.49	.22
9	2.2	2.1	[1]2.2	[1]2.2	4.5	2.8	1.7	.37	.00	.00	3.3	.00
10	2.2	2.1	[1]1.6	[1]2.2	4.9	2.5	1.4	.32	.00	7.3	3.1	.00
11	2.2	12	[1]1.2	4.7	[1]2.8	2.2	1.4	.32	.00	4.0	3.3	.00
12	2.2	11	[1]1.6	[1]4.4	13	2.5	1.3	.47	.00	.34	3.1	.00
13	1.8	5.1	[1]2.3	[1]5.6	19	3.2	1.2	.71	.00	.35	2.9	.00
14	1.6	4.3	[1]2.3	[1]4.4	[1]5.6	2.4	1.3	1.6	.00	.28	2.5	.00
15	1.6	4.1	[1]2.3	[1]3.6	[1]2.2	2.4	1.2	1.9	.00	.00	1.2	.00
16	1.6	4.0	[1]2.3	[1]4.4	[1]2.2	2.6	1.2	1.2	.00	.00	.70	.00
17	1.2	5.2	[1]2.3	[1]5.6	[1]2.8	2.4	1.2	1.2	.00	.00	63	.60
18	1.2	3.7	[1]2.3	[1]4.4	3.4	2.5	1.2	.94	.00	.00	38	1.2
19	1.2	[1]3.6	[1]2.3	5.4	2.8	2.5	1.2	.55	.00	.00	97	1.1
20	1.2	[1]3.6	[1]2.3	5.2	2.8	2.3	1.3	.39	.00	.00	35	1.0
21	1.2	[1]2.8	[1]2.3	4.6	2.7	2.4	1.2	.37	.00	.00	69	.73
22	1.6	[1]2.8	[1]2.3	4.9	2.5	2.5	1.2	.16	.00	.02	6.8	.45
23	1.6	[1]2.8	[1]2.3	6.4	2.1	2.8	1.1	.00	.00	.45	2.4	.58
24	1.6	[1]3.6	[1]2.3	7.0	1.6	2.4	.99	.00	.00	9.0	1.0	.53
25	1.6	[1]3.6	[1]2.2	4.8	1.9	2.2	.94	.00	.00	.90	.22	.14
26	1.2	[1]3.6	[1]2.2	[1]2.8	2.1	3.1	.86	.00	.00	36	.20	.62
27	1.2	[1]3.6	[1]2.2	[1]2.8	2.1	3.5	.73	.00	.00	3.0	.20	.31
28	1.2	[1]2.2	[1]2.2	[1]2.8	2.4	2.5	.97	.00	.00	1.5	.20	.24
29	1.2	[1]1.6	[1]2.2	[1]2.8	---	2.5	.88	.00	.00	21	.67	.03
30	1.2	[1]1.6	[1]2.2	[1]2.2	---	2.4	.56	.00	.00	3.4	.82	.06
31	1.2	---	[1]2.2	[1]2.2	---	2.1	---	.00	---	1.3	.00	---
TOTAL	49.6	104.8	61.8	78.5	106.5	79.0	38.93	15.42	0.00	88.84	898.42	17.43
MEAN	1.60	3.49	1.99	2.53	3.80	2.55	1.30	.50	.00	2.87	29.0	.58
MAX	2.8	12	2.3	4.2	19	3.5	2.2	1.9	.00	36	429	4.7
MIN	1.2	1.6	1.2	1.6	1.6	2.1	.56	.00	.00	.00	.00	.00
AC-FT	98	208	123	156	211	157	77	31	.0	176	1,780	35

WATER YEAR 1989 TOTAL 1,539.24 MEAN 4.22 MAXIMUM 429 MINIMUM 0.00 ACRE-FEET 3,050

[1]Estimated.

Table 9.–Discharge data, Chinle Creek near Mexican Water, water year, 1989

[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, 1989, is called the "water year 1989." Dashes indicate no data]

DISCHARGE, CUBIC FEET PER SECOND, WATER YEAR 1989
MEAN VALUES

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
1	4.8	4.4	[1]2.8	1.2	12	17	10	0.67	0.00	0.00	27	0.67
2	4.1	4.1	[1]2.4	2.5	12	15	4.3	.80	.00	.00	108	1.4
3	3.8	4.4	[1]2.2	3.1	24	11	2.0	.54	.00	.00	19	1.1
4	3.1	4.1	[1]2.8	3.1	34	9.8	1.6	.43	.00	.00	6.6	2.3
5	3.7	4.1	[1]3.2	3.7	37	10	1.8	.37	.00	.00	2.9	2.3
6	4.1	4.1	[1]2.5	8.0	7.7	7.5	1.4	.36	.00	.00	1.7	4.4
7	8.2	3.7	[1]4.8	6.2	5.1	8.4	1.3	.34	.00	.00	.85	2.5
8	14	3.7	11	3.4	4.3	8.5	1.3	.30	.00	.00	.33	1.4
9	9.6	3.4	[1]7.6	[1]3.1	3.4	7.6	1.1	.28	.00	.00	.08	.86
10	7.6	3.4	[1]3.8	[1]2.8	4.9	7.4	1.2	.24	.00	.00	1.4	.64
11	4.8	4.8	[1]3.5	[1]2.8	22	6.7	1.2	.13	.00	.00	74	.69
12	3.6	15	[1]2.9	[1]3.1	19	6.5	1.2	.15	.00	.00	[1]24	.54
13	3.4	21	[1]3.0	[1]3.4	55	4.7	1.3	.24	.00	.00	[1]15	.59
14	3.4	11	[1]4.9	[1]3.4	90	2.8	1.3	.82	.00	.00	11	.57
15	3.4	8.4	[1]8.8	[1]4.1	51	3.1	1.2	.47	.00	.00	4.3	1.0
16	3.1	16	[1]9.2	[1]4.4	31	3.5	1.0	.45	.00	.00	1.9	.62
17	2.8	25	[1]7.0	[1]5.3	32	2.6	1.0	.42	.00	.00	36	.54
18	3.1	12	[1]7.6	[1]5.3	31	2.4	1.1	.32	.00	.00	[1]485	.51
19	2.5	7.2	9.2	[1]5.7	34	2.4	.98	.19	.00	.00	[1]1,450	.49
20	2.8	6.2	8.4	[1]6.2	88	2.6	.81	.25	.00	.00	471	1.2
21	2.8	5.7	9.2	[1]6.9	40	2.9	.84	.16	.00	.00	524	.78
22	2.8	4.4	[1]4.4	8.4	27	3.8	.64	.00	.00	.00	29	.72
23	2.2	4.1	[1]6.5	[1]6.9	25	1.8	.50	.00	.00	.00	9.5	.79
24	1.0	6.9	2.2	5.7	21	2.7	.44	.00	.00	14	3.9	.71
25	1.3	10	3.7	7.4	20	1.5	.41	.00	.00	3.7	1.2	.64
26	2.0	12	[1]6.5	[1]10	22	1.9	.41	.00	.00	23	3.1	.71
27	5.4	10	4.1	[1]10	21	10	.49	.00	.00	105	3.1	.75
28	3.7	8.0	3.2	[1]11	18	25	.58	.00	.00	102	3.0	.78
29	3.7	[1]3.7	[1]5.9	[1]7.6	---	17	.59	.00	.00	[1]294	1.7	.81
30	2.8	[1]2.1	1.9	[1]7.1	---	9.8	.70	.00	.00	240	2.9	.52
31	3.1	---	1.4	[1]6.5	---	6.6	---	.00	---	22	2.1	---
TOTAL	126.7	232.9	156.6	168.3	791.4	222.5	42.69	7.93	0.00	803.70	3,323.56	31.53
MEAN	4.09	7.76	5.05	5.43	28.3	7.18	1.42	.26	.00	25.9	107	1.05
MAX	14	25	11	11	90	25	10	.82	.00	294	1,450	4.4
MIN	1.0	2.1	1.4	1.2	3.4	1.5	.41	.00	.00	.00	.08	.49
AC-FT	251	462	311	334	1570	441	85	16	.0	1,590	6,590	63

WATER YEAR 1989 TOTAL 5,907.81 MEAN 16.2 MAXIMUM 1,450 MINIMUM 0.00 ACRE-FEET 11,720

[1]Estimated.

SIMULATION OF EFFECTS OF PUMPING

By

D.J. Bills and J.G. Brown

A mathematical model of the N aquifer (fig. 2) was developed by Eychaner (1983) using available information about the aquifer. Simulated water-level changes in several nonindustrial wells and continuous-record observation wells that penetrate the N aquifer were compared with measured changes. During 1985, the model was rerun with measured withdrawals from 1980-84 to check the continued agreement of measured and simulated water levels. Results of these model runs are given in the progress report for 1987 (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 representation 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. 6). As part of the recalibration process, the model was used to simulate water-level changes from 1965 to 1984. Withdrawals of 23 acre-ft/yr by windmills were simulated in all model runs (fig. 6). Results of this simulation indicated general agreement between measured and simulated water-level changes, observed in six continuous-record observation wells (BM 1-6).

Water-Level Changes

The 1988 model was rerun in 1989 by using measured withdrawals from 1985-88 to check agreement between measured and simulated water levels. Results of this effort (fig. 7) again indicate a general agreement between measured and simulated water-level changes in the four continuous-record observation wells in the areas of confined ground water (BM2, BM3, BM5, BM6). As before, however, the model simulated a steady decline in the two observation wells in the unconfined areas (BM1, BM4). Measured water levels in these wells remained the same or rose (Hart and Sottilare, 1989).

The 1988 model was rerun in 1990 by using measured withdrawals from 1965-89 to check the agreement between measured and simulated water levels and to determine how much of the water-level decline is the result of industrial or municipal pumpage. Three pumping scenarios were used in the model. Scenario "A" included all reported pumpage, scenario "B" included only industrial pumpage, and scenario "C" included only municipal pumpage. The results of the simulation are shown in figures 8A-C.

Simulated water-level declines at Tuba City (figs. 8A-C) were caused entirely by local municipal pumpage. Declines of more than 1 ft, which were caused by industrial pumpage, were no closer than 18 mi from Tuba City (J.G. Brown, U.S. Geological Survey, written commun., 1990).

Simulated water-level declines at Kykotsmovi from 1965 to 1989 were about 40 ft. Industrial pumpage caused about 12 ft of drawdown, and local municipal pumpage caused the rest of the drawdown (figs. 8A-C).

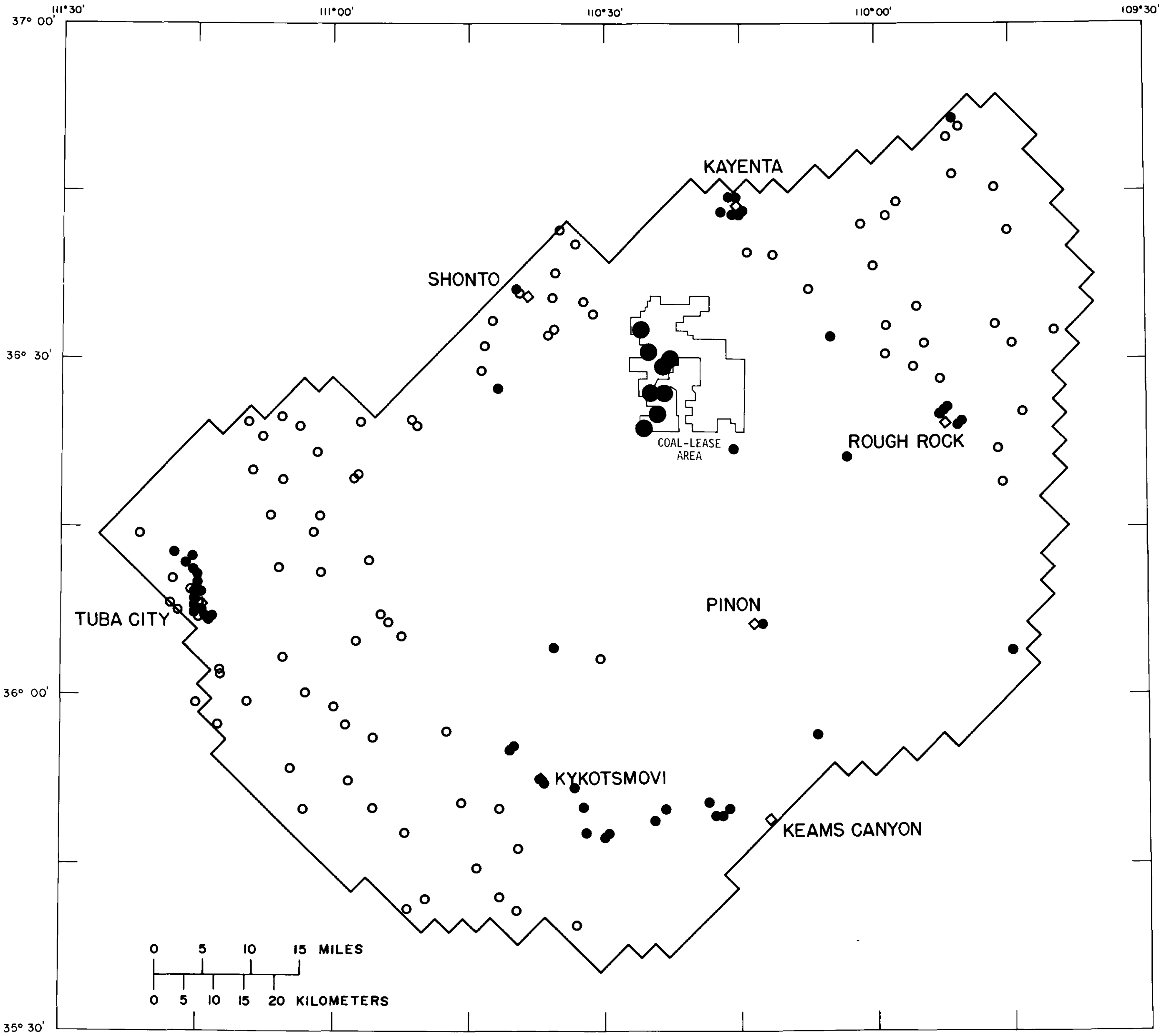
At well BM5, about 10 mi northeast of Kykotsmovi, simulated water-level declines for 1965-89 under scenario "A" were about 55 ft ; 40 ft of this drawdown was caused by industrial pumpage (figs. 8A-C). Measured water-level declines closely matched simulated declines (fig. 7).

Near Pinon, simulated water-level declines were about 130 ft. Of this decline, 54 ft was caused by industrial pumping, and the remainder was the result of local municipal pumping. Measured water levels in well PM-6 have declined about 80 ft since 1970.

At Chilchinbito, simulated water levels declined about 54 ft from 1965 to 1989 (figs. 8A-C). About 45 ft of the decline was caused by industrial pumpage. Measured water-level declines at well PM-3 are slightly less than simulated declines, and water levels appear to have been in recovery since 1986.

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 2.65 ft^3/s in 1989. By using industrial pumpage alone, low flow declined to 3.24 ft^3/s by 1989 (J.G. Brown, U.S. Geological Survey, 1990). The simulated low flow in Moenkopi Wash and the simulated flow of springs near Tuba City decreased less than 1 percent--about 0.03 ft^3/s--under all three pumpage scenarios (J.G. Brown, U.S. Geological Survey, oral commun., 1990).



Base from U.S. Geological Survey Flagstaff 1:250,000, 1954-70; Gallup, 1:250,000, 1950-70; Marble Canyon, 1:250,000, 1956-70; and Shiprock, 1:250,000, 1954-69

Modified from Brown and Eychaner, 1988

EXPLANATION

BOUNDARY OF MATHEMATICAL MODEL—Simulated ground-water flow across boundary was zero.

MUNICIPAL WELL

INDUSTRIAL WELL

WINDMILL

Figure 6.--Municipal and industrial wells and windmills.

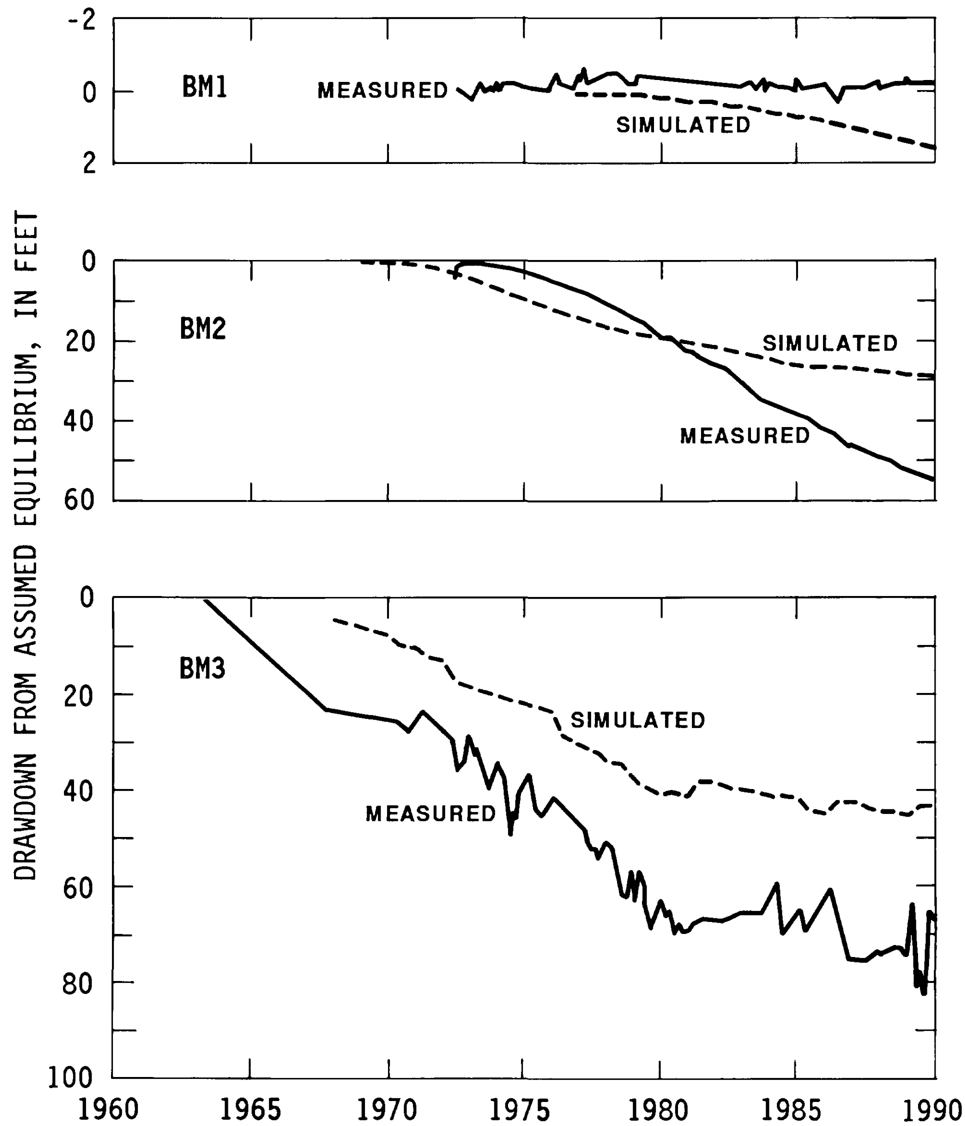


Figure 7.--Measured and simulated water-level changes in observation wells, 1960-90.

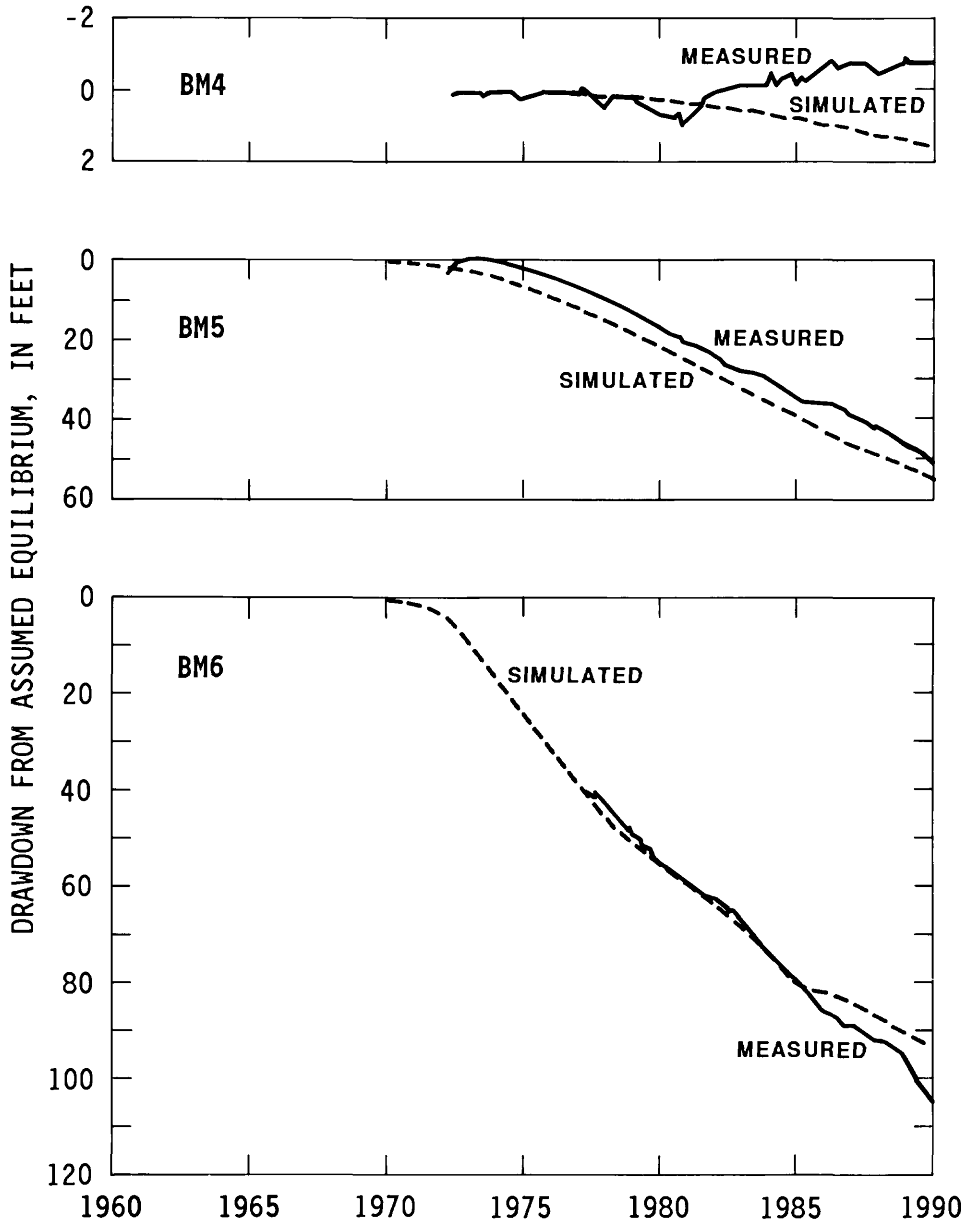
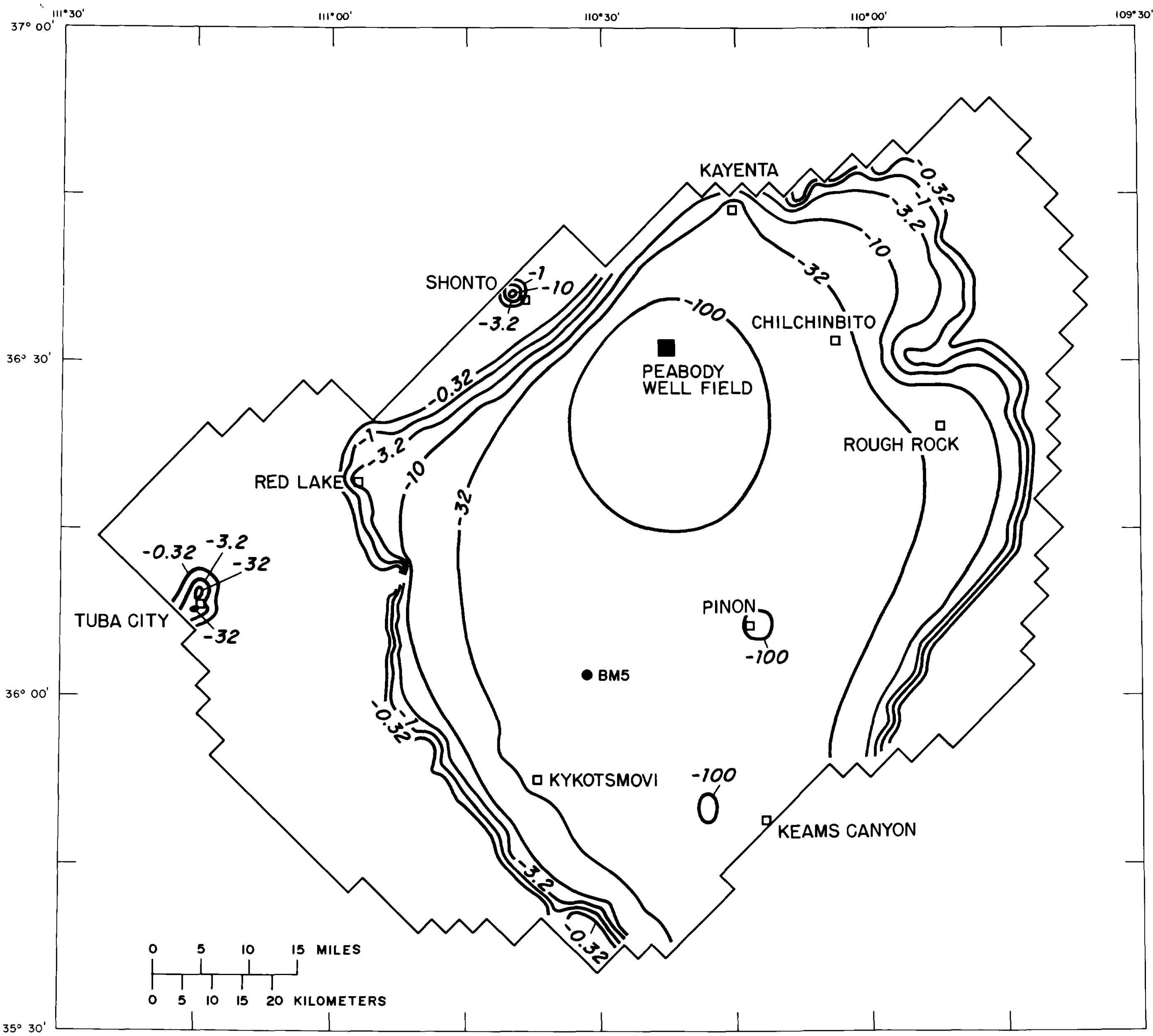


Figure 7.--Measured and simulated water-level changes in observation wells, 1960-90--Continued.



Base from U.S. Geological Survey
Flagstaff 1:250,000, 1954-70;
Gallup, 1:250,000, 1950-70;
Marble Canyon, 1:250,000, 1956-70;
and Shiprock, 1:250,000, 1954-69

Modified from Brown and Eychaner, 1988

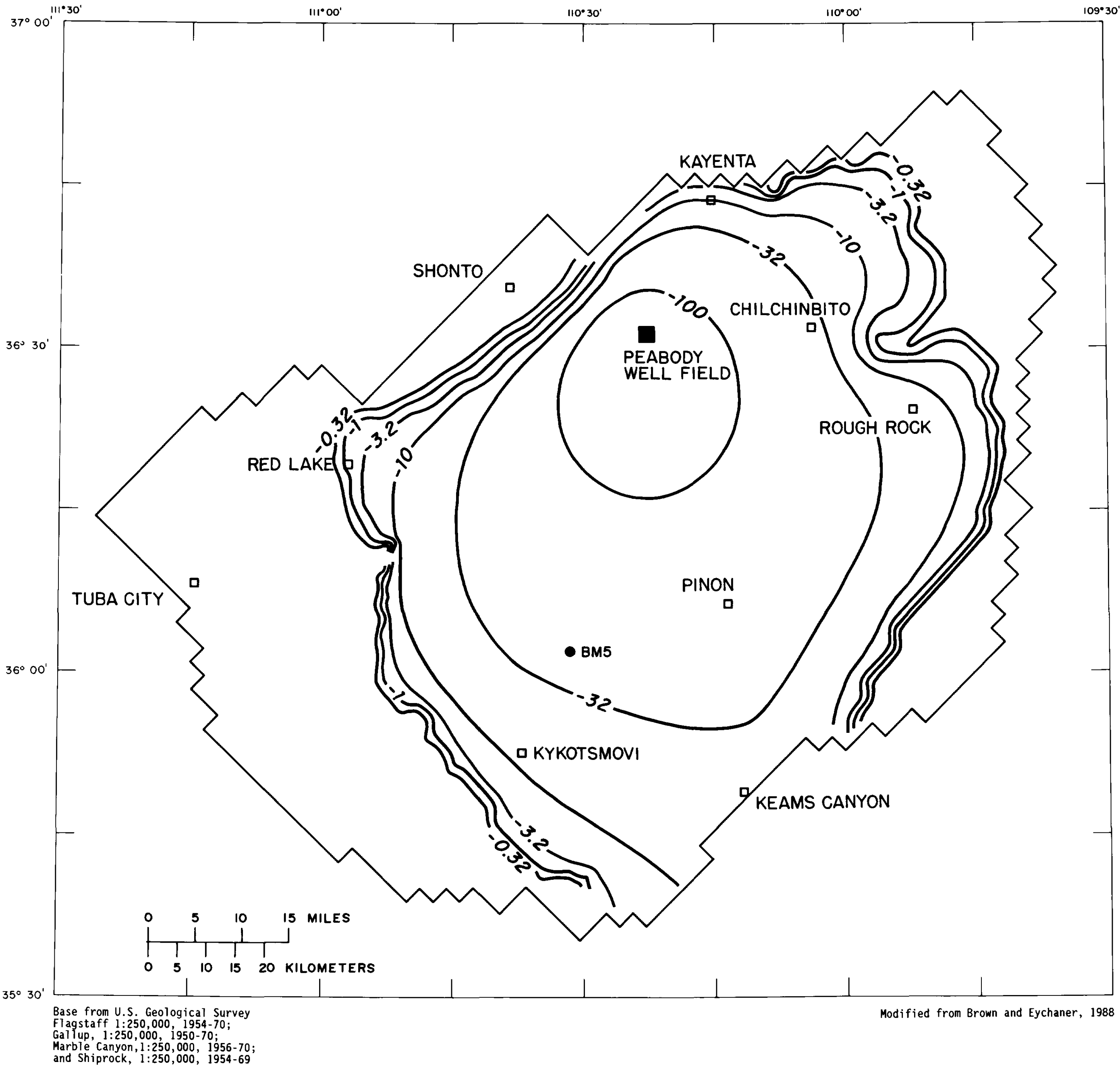
Scenario A, Simulated effect of combined ground-water pumpage.

Figure 8.--Contours of simulated water-level changes, 1965-89.

EXPLANATION

——— -10 ———	CONTOUR OF DRAWDOWN FROM ASSUMED EQUILIBRIUM, IN FEET
———————	BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)
● BM5	CONTINUOUS WATER-LEVEL RECORDING SITE (OBSERVATION WELL) MAINTAINED BY THE U.S. GEOLOGICAL SURVEY—Number, BM5, is U.S. Geological Survey identification number
□	COMMUNITY

Figure 8.--Continued.



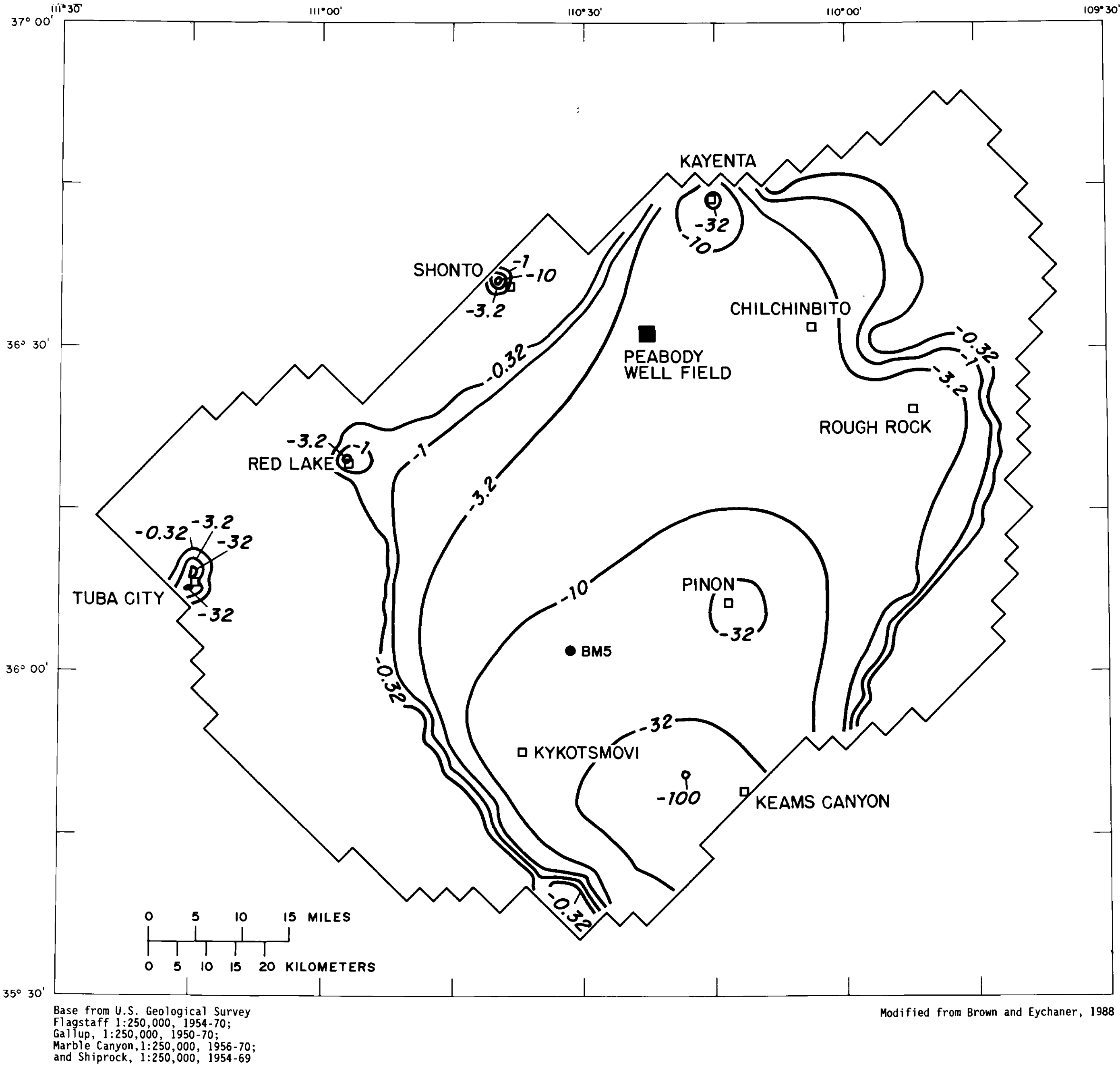
Scenario B, Simulated effect of industrial ground-water pumpage.

Figure 8.--Contours of simulated water-level changes, 1965-89--Continued.

EXPLANATION

——— -10 ———	CONTOUR OF DRAWDOWN FROM ASSUMED EQUILIBRIUM, IN FEET
————————	BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)
● BM5	CONTINUOUS WATER-LEVEL RECORDING SITE (OBSERVATION WELL) MAINTAINED BY THE U.S. GEOLOGICAL SURVEY—Number, BM5, is U.S. Geological Survey identification number
▫	COMMUNITY

Figure 8.--Continued.



Scenario C, Simulated effect of municipal ground-water pumpage.

Figure 8.--Contours of simulated water-level changes, 1965-89--Continued.

EXPLANATION

—— -10 ——	CONTOUR OF DRAWDOWN FROM ASSUMED EQUILIBRIUM, IN FEET
————	BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)
● BM5	CONTINUOUS WATER-LEVEL RECORDING SITE (OBSERVATION WELL) MAINTAINED BY THE U.S. GEOLOGICAL SURVEY—Number, BM5, is U.S. Geological Survey identification number
▫	COMMUNITY

Figure 8.--Continued.

SUMMARY

The Black Mesa monitoring program is an ongoing investigation begun by the USGS in 1971. The water-resources investigation was begun because of concerns of the Navajo and Hopi Tribes about possible effects of industrial and municipal pumpage on the N aquifer. The N aquifer is the main source of ground water in the Black Mesa area. In 1968, strip-mining operations began in a lease area of about 100 mi^2 on the Black Mesa area of the Navajo and Hopi Indian Reservations. During 1968, about 95 acre-ft of ground water was withdrawn from the N aquifer for mining operations and, in 1989, 3,450 acre-ft was withdrawn.

This report is the ninth in a series of progress reports on the monitoring phase of the program. The monitoring program includes ground-water measurements, simulation of water-level changes by use of a mathematical ground-water model, chemical analyses of ground water from wells and springs, compilation of pumpage data, and measurement of spring and surface-water discharge at sites where the N aquifer is the main water source.

Measured ground-water levels in the confined area showed changes ranging from -113.8 ft near the south edge of the study area to +1.7 ft at the north edge from 1953 to 1990. Measured water-level changes generally closely match simulated water-level changes. During the same period, water-level changes in the unconfined area ranged from -34.2 ft in the northwestern part of the study area to +11.9 ft in the eastern part. Simulated water levels declined at a steady, gradual rate of a few feet per year from 1953 to 1990 in the unconfined area.

The two categories of ground-water use from the N aquifer are industrial in the confined area and municipal in the confined and unconfined areas. In 1989, annual pumpage for industrial use in the confined area was 3,450 acre-ft, and annual pumpage for municipal use in the confined and unconfined areas was 1,070 and 1,400 acre-ft, respectively.

Chemical water-quality samples were collected from 13 wells in the study area that tap the N aquifer. Samples were collected from three industrial wells operated by the Peabody Coal Company and from 10 municipal wells operated by the tribes. Results of analyses of these samples indicate that the quality of water in the N aquifer has not changed significantly since pumping began.

During water year 1990, water-quality samples were collected at four springs that discharge from the N aquifer in the southern half of the study area. Dissolved-solids concentrations in water from these springs ranged from 215 mg/L at Sand Spring (1A-83) to 455 mg/L at Whisky Spring (5M-4). Dissolved-chloride concentrations ranged from 4.1 mg/L at Sand Spring (1A-83) to 22 mg/L at Burro Spring (6M-31). Dissolved-sulfate concentrations ranged from 32 mg/L at the unnamed spring near Many Farms (10R-119) to 219 mg/L at Whisky Spring (5M-4). Comparison of these results with those of previous chemical analyses indicates that no significant changes in water quality have taken place in the sampled springs. Discharges from the springs are 0.1 gal/min at Whisky Spring and the unnamed spring near Many Farms, and 0.4 gal/min at Burro Spring. Sand Spring could not be measured accurately. Discharge of all three measured springs has declined since measurements were first made during 1954, 1929, and 1927, respectively.

Surface-water low-flow measurements were made from November 1989 to February 1990 at Laguna Creek near Church Rock (09379160). The average of these measurements is about 5 percent less than the long-term average (1981-89) but well above the discharge simulated by the model. Continuous records of daily discharge were maintained at Moenkopi Wash at Moenkopi (09401260)

and Chinle Creek near Mexican Water (09379200). Low flows at both Moenkopi Wash and Chinle Creek have remained fairly constant since the stations were established.

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