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

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

Ground-Water, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2000–2001, and Performance and Sensitivity of the 1988 USGS Numerical Model of the N Aquifer

Water-Resources Investigations Report 02—4211

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By Blakemore E. Thomas

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Tucson, Arizona
2002

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CONVERSION FACTORS AND DATUMS

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

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8°C) + 32$$

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

ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute mass (milligrams) per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations 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 at 25 degrees Celsius (µS/cm at 25°C).

Ground-Water, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—2000–2001, and Performance and Sensitivity of the 1988 USGS Numerical Model of the N aquifer

By Blakemore E. Thomas

Abstract

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

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

In 2000, total ground-water withdrawals were 7,740 acre-feet, industrial use was 4,490 acre-feet, and municipal use was 3,250 acre-feet. From 1999 to 2000, total withdrawals increased by 9 percent, industrial use increased by 7 percent, and municipal use increased by 12 percent.

From 1999 to 2001, water levels declined in 10 of 15 wells in the unconfined part of the aquifer, and the median change was -0.4 foot. Water levels declined in 8 of 16 wells in the confined part of the aquifer, and the median change was -0.2 foot.

From the prestress period (prior to 1965) to 2001, the median water-level change for 33 wells was -17.2 feet. Median water-level changes were -1.2 feet for 15 wells in the unconfined part of the aquifer and -31.0 feet for 18 wells in the confined part.

Discharges were measured once in 1999 and once in 2001 at four springs. Discharges decreased by 5 percent and 33 percent at two springs and increased by 3 percent and 81 percent at two springs. For about the past 10 years, discharges did not significantly change in Burro Spring, the unnamed spring near Dennehotso, and Moenkopi School Spring. The record of discharge from a consistent measuring point for Pasture Canyon Spring is too short for statistical analysis of trends.

Continuous records of surface-water discharge have been collected from July 1976 to 2000 at Moenkopi Wash, July 1996 to 2000 at Laguna Creek, June 1993 to 2000 at Dinnebito Wash, and April 1994 to 2000 at Polacca Wash. Median flows for November, December, January, and February of each water year were used as an index of ground-water discharge to those streams. There is no significant trend in the median winter flows for Moenkopi Wash from 1977 to 2000. The records for the other three streams are too short for a statistical analysis of trends. The median winter flows for Dinnebito Wash and Polacca Wash, however, appear to have decreased during the last 6 years. There is no apparent trend in the median winter flows for Laguna Creek since 1997.

In 2001, water samples were collected from 12 wells and 4 springs and analyzed for selected chemical constituents. Dissolved-solids concentrations ranged from 102 to 628 milligrams per liter. Water samples from 9 of the wells and from the 4 springs had less than 350 milligrams per liter of dissolved solids. Water-chemistry data with sufficient years of record for a statistical analysis of trends over time are available from 7 wells and 4 springs. From about the mid-1980s or early 1990s to 2001 there are no

significant trends in the concentrations of dissolved solids, chloride, and sulfate in water samples from 6 of the 7 wells. The concentration of one tested constituent (dissolved solids) in samples from Rocky Ridge PM3 significantly increased from 1990 to 2001. From the late 1980s to 2001, there are no significant trends in the concentrations of dissolved solids, chloride, and sulfate in water samples from Burro Spring, the unnamed spring near Dennehotso, and Pasture Canyon Spring. From 1987 to 2001, concentrations of chloride and sulfate significantly increased in water samples from Moenkopi School Spring and concentrations of dissolved solids did not significantly change.

The performance and sensitivity of the 1988 USGS numerical model of the N aquifer were analyzed. The overall performance of the model in steady-state conditions is reasonable for residuals of heads (difference between observed and simulated steady-state heads); 80 percent of the absolute values of residuals are less than 38 feet. Simulated flows are about 40 percent different than estimated flows at two of three discharge areas; however, this comparison is only a rough approximation of performance because the accuracy of the estimated steady-state flows is uncertain.

The overall performance of the model for transient conditions is fair for residuals of changes in head (difference between observed and simulated changes in head from steady state to 1999); 80 percent of the absolute values of residuals are less than 31 feet. The model is biased in two areas. In the Tuba City area, simulated changes in head are more negative than observed changes in head; all six residuals are positive, and three residuals are between 75 and 155 feet. In the confined area of the aquifer, observed changes in head are more negative than simulated changes in head; 12 of the 17 residuals are negative, and 8 residuals are between -57 and -20 feet.

Analysis of model sensitivity indicates that recharge, transmissivity, and storage coefficient are the most important parameters for estimating heads, changes in heads, and flows. A strong correlation between recharge and transmissivity and a lack of independent and reliable estimates of recharge, transmissivity, and discharge create a uniqueness problem in model calibration. Several models could be constructed and calibrated with different values of recharge or transmissivity and still have similar fits to the observed data. Information from recent data and studies and more advanced modeling techniques could be used to develop a more representative and less uncertain model. Future data collection and studies should focus on obtaining a better definition of recharge, discharge, transmissivity, and storage coefficient.

INTRODUCTION

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

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

Withdrawals from the N aquifer in the Black Mesa area have been increasing during the last 35 years (**table 1**). Peabody Western Coal Company began operating a strip mine in the northern part of the mesa in 1968. The quantity of water pumped by the company increased from about 100 acre-ft in 1968 to a maximum of 4,740 acre-ft in 1982. About 4,490 acre-ft of water was pumped in 2000. Withdrawals for municipal use from the N aquifer have increased steadily from an estimated 250 acre-ft in 1968 to 3,250 acre-ft in 2000.

[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.

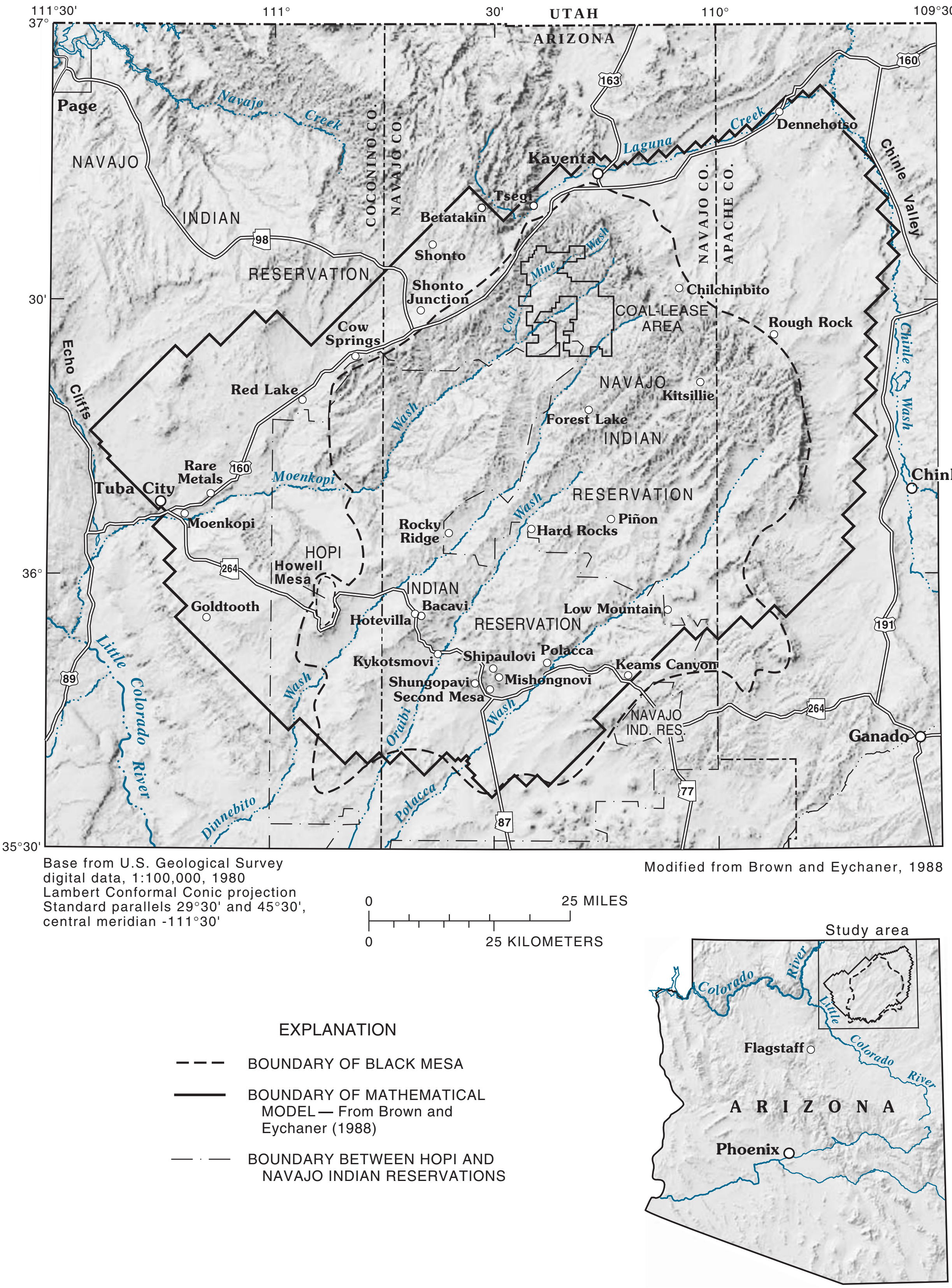


Figure 1. Location of study area.

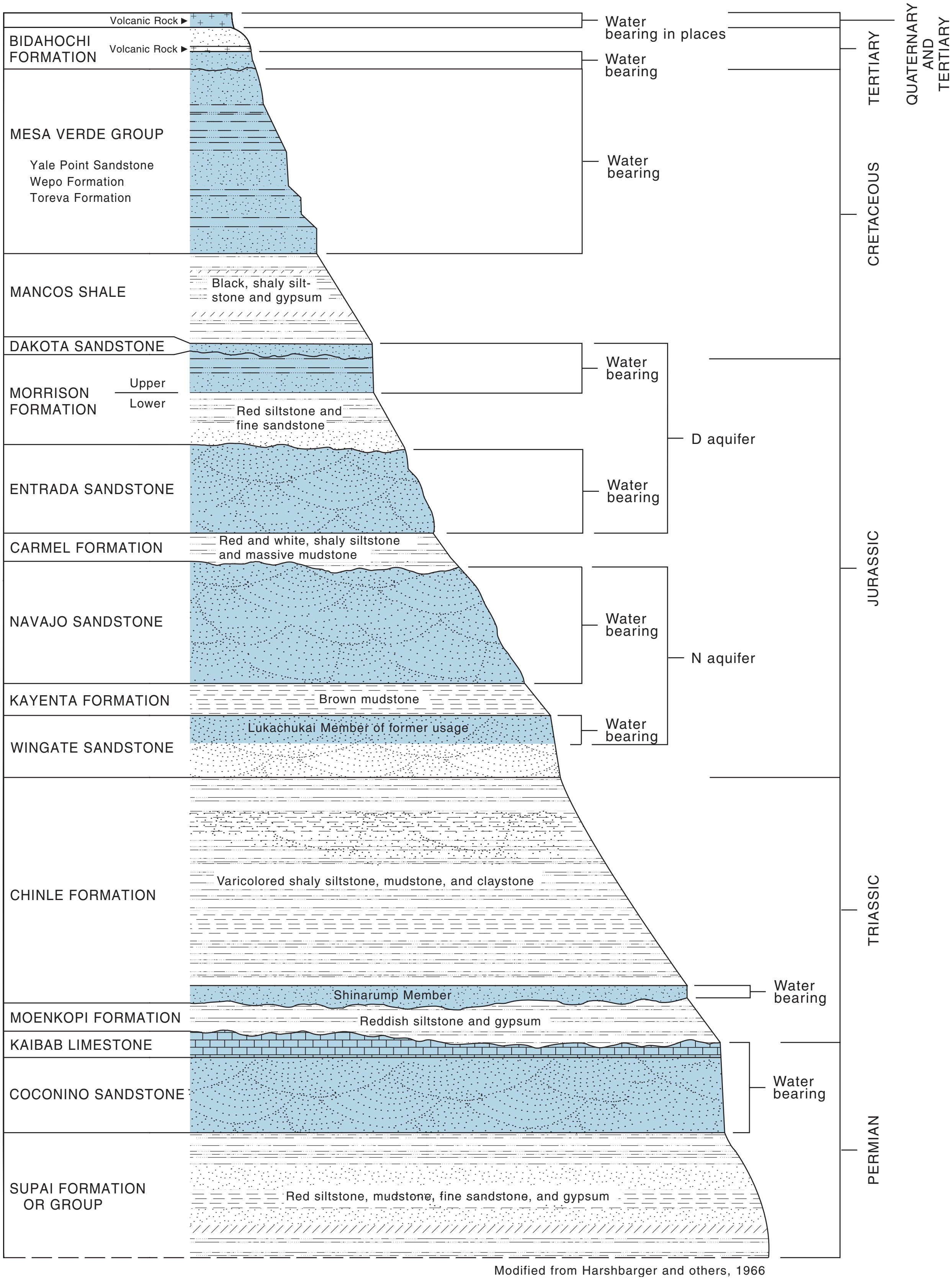


Figure 2. Rock formations and hydrogeologic units of the Black Mesa area, Arizona (not to scale). The N aquifer is approximately 1,000 feet thick.

Table 1. Withdrawals from the N aquifer, Black Mesa area, Arizona, 1965–2000

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

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

[1]Metered pumpage from the confined part of the aquifer by Peabody Western Coal Company.
[2]Does not include withdrawals from the wells equipped with windmills.
[3]Includes estimated pumpage, 1965–73, and metered pumpage, 1974–79, at Tuba City; metered pumpage at Kayenta and estimated pumpage at Chilchinbito, Rough Rock, Piñon, Keams Canyon, and Kykotsmovi before 1980; metered and estimated pumpage furnished by the Navajo Tribal Utility Authority and the Bureau of Indian Affairs and collected by the U.S. Geological Survey, 1980–85; and metered pumpage furnished by the Navajo Tribal Utility Authority, the Bureau of Indian Affairs, various Hopi Village Administrations, and the U.S. Geological Survey, 1986–2000.

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

Purpose and Scope

This report presents results of ground-water, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2000 to June 2001, and results of analyses of the performance and sensitivity of a numerical model of the N aquifer developed by the USGS in 1988. The monitoring is designed to determine the effects of industrial and municipal pumpage from the N aquifer on ground-water levels, stream and spring discharge, and ground-water chemistry. Continuous and periodic data are collected for ground water and surface water. Ground-water data include pumpage, water levels, spring discharges, and water chemistry. Surface-water data include discharges at four continuous-record streamflow-gaging stations. The performance analysis was done to determine how well the model has simulated water-level data collected since the model was constructed. The sensitivity analysis was done to determine relations among the model parameters, observation data, and simulated values. The performance and sensitivity analyses are also a logical first step for updating and improving the model.

Previous Investigations

Eighteen progress reports on the monitoring program for the Black Mesa area have been prepared by the USGS (U.S. Geological Survey, 1978; G.W. Hill, hydrologist, U.S. Geological Survey, written commun., 1982, 1983; Hill, 1985; Hill and Whetten, 1986; Hill and Sottilare, 1987; Hart and Sottilare, 1988, 1989; Sottilare, 1992; Littin, 1992, 1993; Littin and Monroe, 1995a, 1995b, 1996, 1997; Littin and others, 1999; Truini and others, 2000; and Thomas and Truini, 2000). Most of the data from the monitoring program are contained in these reports. Stream-discharge and periodic water-quality data from Moenkopi Wash collected before the 1986 water year were published in U.S. Geological Survey (1963–64a, b; 1965–74a, b; 1976–83), White and Garrett (1984, 1986, 1987, 1988), Boner and others (1989, 1990, 1991, 1992), Smith and others (1993, 1994, 1995, 1996, 1997), and Tadayon and others (1998, 1999, 2000, 2001). Before the monitoring program, a large data-collection effort in the 1950s resulted in a compilation of well and spring data for the Navajo and Hopi Indian Reservations (Davis and others, 1963).

Many interpretive studies have been done in the Black Mesa area. Cooley and others (1969) made the first comprehensive evaluation of the regional hydrogeology of the Black Mesa area. Eychaner (1983) developed a two-dimensional numerical model of ground-water flow in the N aquifer. Brown and Eychaner (1988) recalibrated the model using a finer grid and revised estimates of selected aquifer characteristics. GeoTrans, Inc. (1987) also developed a two-dimensional model of the N aquifer in the 1980s. In the late 1990s, HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc. (1999) developed a detailed three-dimensional numerical model of the D and N aquifers.

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water from wells and springs in the Black Mesa area. HSIGeoTrans, Inc. (1993) evaluated the major-ion and isotopic chemistry of the D and N aquifers. Lopes and Hoffmann (1997) analyzed ground-water ages, recharge, and hydraulic conductivity of the N aquifer using geochemical techniques. Zhu and others (1998) estimated ground-water recharge using isotopic data and flow estimates from the model developed by GeoTrans, Inc. (1987).

HYDROLOGIC DATA

The timing of data collection was changed in 2000–2001 for the Black Mesa monitoring program, but the frequency and interval of data collection remains the same as in previous years. Continuous data are still compiled for January to December. These data include ground-water withdrawals from wells and daily mean discharges at four streamflow gaging stations. Data collected annually and compared from year to year are now collected in the spring (March–June). Previously, these data were collected in the fall-winter (October–December). These annual data include ground-water levels, ground-water chemistry, and spring discharges. This transition from winter to spring data collection for this report has resulted in about a 16-month interval between measurements (December 1999 to April 2001) instead of the previous 12-month interval. Annual data collection in the future will be from spring to spring (12 months).

The annual data collection was changed from winter to spring because traveling conditions in the winter in the Black Mesa area are problematic, and it was often difficult to drive to well and spring sites. Several times in the past few years, the data collection could not be completed in the planned 3-month winter period. After 2001, the interval will be 12 months between measurements, and the spring-to-spring hydrologic changes should be comparable to the previous winter-to-winter changes. During most of the 1980s, measurements of water levels and collection of water-quality samples for this monitoring program were done in the spring.

In 2000–2001, the Black Mesa monitoring program included metering and estimating ground-water withdrawals, measuring depth to ground water, measuring discharge in streams and springs, and collecting and analyzing water samples from wells and springs. Ground-water withdrawals from 33 well systems, water levels at 6 observation wells, and surface-water discharge at 4 sites were monitored continuously. Discharge at 4 springs and ground-water levels at 27 wells were measured annually. Spring discharges and ground-water levels were measured between March and June 2001. Ground-water samples were collected from 12 wells and 4 springs in March–June 2001 and analyzed for chemical constituents. Identification information for the 47 wells used for water-level measurements and water-quality sampling is shown in **table 2**.

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

[Dashes indicate no data]

U.S. Geological Survey identification number	Common name or location	Bureau of Indian Affairs site number
354749110300101	Second Mesa PM2	---
355023110182701	Keams Canyon PM2	---
355215110375001	Kykotsmovi PM2	---
355230110365801	Kykotsmovi PM1	---
355236110364501	Kykotsmovi PM3	---
355428111084601	Goldtooth	3A-28
355518110400301	Hotevilla PM1	---
355648110475501	Howell Mesa	6H-55
355924110485001	Howell Mesa	3K-311
360055110304001	BM observation well 5	4T-519
360217111122601	Tuba City	3K-325
360422110353501	Rocky Ridge PM3	---
360527110122501	Piñon NTUA 1	---
360614110130801	Piñon PM6	---
360734111144801	Tuba City	3T-333
360904111140201	Tuba City NTUA 1	3T-508
360918111080701	Tuba City Rare Metals 2	---
360924111142201	Tuba City NTUA 3	---
360953111142401	Tuba City NTUA 4	3T-546
361225110240701	BM observation well 6	---
361737110180301	Forest Lake NTUA 1	4T-523
361832109462701	Rough Rock	10T-258
361933110565001	Red Lake PM1	---
362043110030501	Kitsillie NTUA 2	---
362149109463301	Rough Rock	10R-111
362333110250001	Peabody 9	---
362406110563201	White Mesa Arch	1K-214
362418109514601	Rough Rock PM5	---
362456110503001	Cow Springs	1K-225
362647110243501	Peabody 4	---
362823109463101	Rough Rock	10R-119
362936109564101	BM observation well 1	8T-537
363013109584901	Sweetwater Mesa	8K-443
363103109445201	Rough Rock	9Y-95
363137110044702	Chilchinbito PM3	---
363143110355001	BM observation well 4	2T-514
363213110342001	Shonto Southeast	2K-301
363232109465601	Rough Rock	9Y-92
363309110420501	Shonto	2K-300
363423110305501	Shonto Southeast	2T-502
363727110274501	Long House Valley	8T-510
363850110100801	BM observation well 2	8T-538
364034110240001	Marsh Pass	8T-522
364226110171701	Kayenta West	8T-541
364248109514601	Northeast Rough Rock	8A-180
364338110154601	BM observation well 3	8T-500
364344110151201	Kayenta PM2	8A-295

Withdrawals from the N Aquifer

Withdrawals from the N aquifer are separated into three categories—(1) industrial use from the confined part of the aquifer, (2) municipal use from the confined part of the aquifer, and (3) municipal use from the unconfined part of the aquifer (**table 1**, **fig. 3**). The industrial category includes eight wells at the well field of Peabody Western Coal Company in northern Black Mesa (**fig. 4**). The BIA, NTUA, and Hopi Tribe operate about 70 municipal wells. Withdrawals from the N aquifer were compiled primarily on the basis of metered data (tables 1 and 3).

Withdrawals from wells equipped with windmills are not measured in this monitoring program. About 270 windmills in the Black Mesa area withdraw water from the D and N aquifers, and estimated total withdrawals by the windmills are about 65 acre-ft/yr (HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., 1999). This amount is less than 1 percent of the total annual withdrawal from the N aquifer.

In 2000, the total ground-water withdrawal from the N aquifer was about 7,740 acre-ft (table 1), which is a 9 percent increase from the total withdrawal in 1999. Withdrawals for municipal use from the confined part of the aquifer totaled 1,610 acre-ft, which is a 13 percent increase from 1999. Withdrawals for municipal use from the unconfined part of the aquifer totaled 1,640 acre-ft, which is an 11 percent increase. Withdrawals for industrial use totaled 4,490 acre-ft, which is a 7 percent increase.

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

In the 1970s, industrial use was about 75 percent of the total withdrawal. With the increase in municipal use over the last 30 years, industrial use, as a percentage of total withdrawals, has declined to about 60 percent in the late 1990s and in 2000.

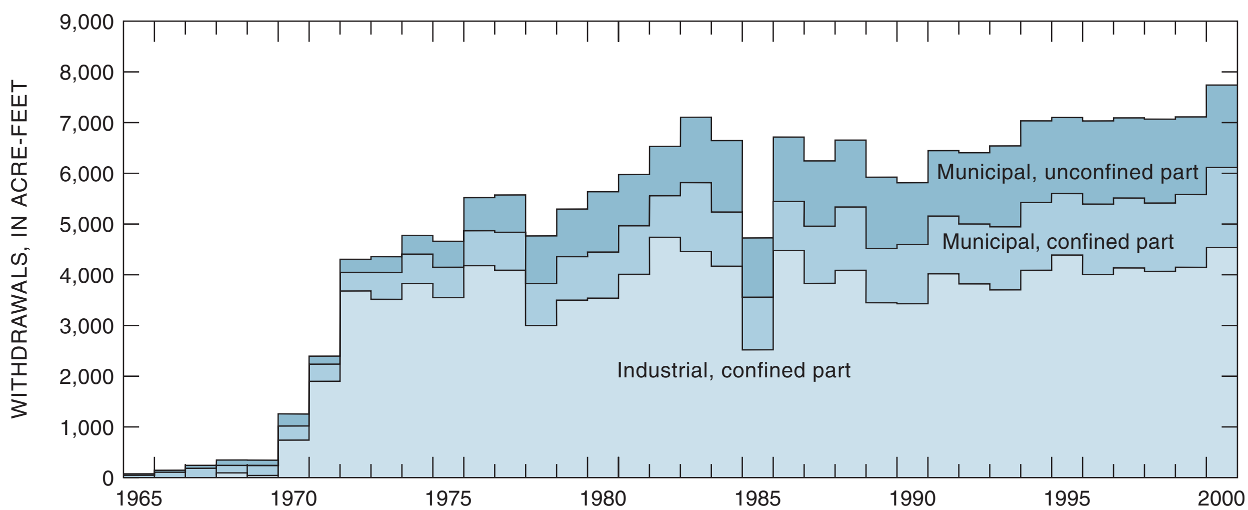


Figure 3. Withdrawals from the N aquifer, Black Mesa area, Arizona, 1965–2000.

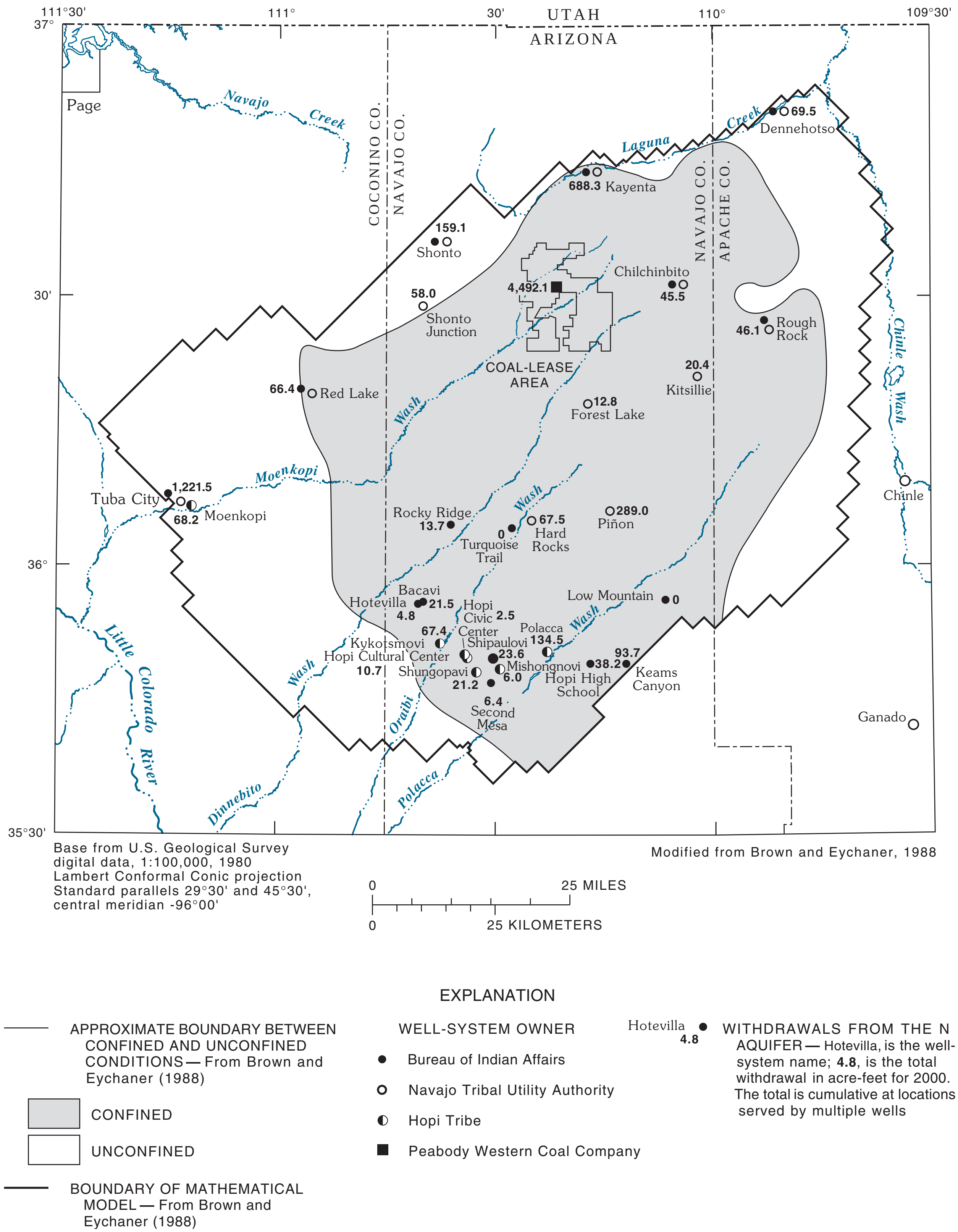


Figure 4. Locations of well systems monitored for withdrawals from the N aquifer, Black Mesa area, Arizona, 2000.

Table 3. Withdrawals from the N aquifer by well system, Black Mesa area, Arizona, 2000

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

Well system (one or more wells)	Owner	Source of data	Withdrawals	
			Confined aquifer	Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	7.8	
Dennehotso	BIA	USGS/BIA		35.1
Hopi High School	BIA	USGS/BIA	38.2	
Hotevilla	BIA	USGS/BIA	4.8	
Kayenta	BIA	USGS/BIA	76.3	
Keams Canyon	BIA	USGS/BIA	93.7	
Low Mountain	BIA	USGS/BIA	[1]0	
Piñon	BIA	USGS/BIA	[1]0	
Red Lake	BIA	USGS/BIA		8.0
Rocky Ridge	BIA	USGS/BIA	13.7	
Rough Rock	BIA	USGS/BIA	32.9	
Second Mesa	BIA	USGS/BIA	6.4	
Shonto	BIA	USGS/BIA		142.4
Tuba City	BIA	USGS/BIA		164.3
Turquoise Trail	BIA	BIA Roads	[1]0	
Chilchinbito	NTUA	NTUA	37.7	
Dennehotso	NTUA	NTUA		34.4
Forest Lake	NTUA	NTUA	12.8	
Hard Rock	NTUA	NTUA	67.5	
Kayenta	NTUA	NTUA	612.0	
Kitsillie	NTUA	NTUA	20.4	
Piñon	NTUA	NTUA	289.0	
Red Lake	NTUA	NTUA		58.4
Rough Rock	NTUA	NTUA	13.2	
Shonto	NTUA	NTUA		16.7
Shonto Junction	NTUA	NTUA		58.0
Tuba City	NTUA	NTUA		1,057.2
Mine Well Field	Peabody	Peabody	[2]4,492.1	
Bacavi	Hopi	USGS/Hopi	21.5	
Hopi Civic Center	Hopi	USGS/Hopi	2.5	
Hopi Cultural Center	Hopi	USGS/Hopi	10.7	
Kykotsmovi	Hopi	USGS/Hopi	67.4	
Mishongnovi	Hopi	USGS/Hopi	6.0	
Moenkopi	Hopi	USGS/Hopi		68.2
Polacca	Hopi	USGS/Hopi	[3]134.5	
Shipaulovi	Hopi	USGS/Hopi	23.6	
Shungopovi	Hopi	USGS/Hopi	21.2	

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

In an effort to improve and ensure the accuracy of ground-water withdrawal data, a quality-assurance program was begun in 1985 for withdrawal data from industrial and municipal wells completed in the N aquifer. Nearly all industrial and municipal wells in the study area are equipped with totalizing flowmeters to measure ground-water withdrawals. The flowmeters on the wells are tested about once every 5 years by measuring pumpage with a calibrated mechanical flowmeter and comparing the measured pumpage to the metered pumpage. For the purpose of this study, the allowable difference between the discharge measured by the permanent totalizing flowmeter and the test meter is 10 percent. No testing of flowmeters was done this past year.

Ground-Water Levels in the N Aquifer

Ground water in the N aquifer is under confined conditions in the central part of the study area and under unconfined or water-table conditions around the periphery (**fig. 5**). The ground water generally flows radially outward from recharge areas near Shonto to the southwest, south, southeast, and east (Lopes and Hoffman, 1997).

Ground-water levels are measured each year and compared with levels from previous years to determine changes over time. In 2001, water levels were measured in 33 wells that are used for observation, municipal supply, or stock supply (**table 4**). Six of the 33 wells are observation wells that were operated on a continuous basis; water levels were recorded daily. Water levels were measured manually twice a year in the six continuous-observation wells.

The wells used for water-level measurements are spread throughout the study area (fig. 5). Although all the wells are completed in the N aquifer, characteristics of the wells vary considerably. Construction dates range from 1934 to 1993, depths range from 107 to 3,535 ft, and depths to the top of the N aquifer range from 0 to 2,400 ft (**table 5**).

From winter 1999 to spring 2001 (about 16 months), water levels declined in 18 of 31 wells. Two wells measured in 2001 (3K-311 and Kykotsmovi PM3) are not used in the annual comparison because the previous measurement was made more than 4 years ago. The median water-level change in the 31 wells was -0.4 ft. Changes ranged from -10.8 ft in the Piñon PM6 well to +6.0 ft in the Keams Canyon PM2 well (table 4).

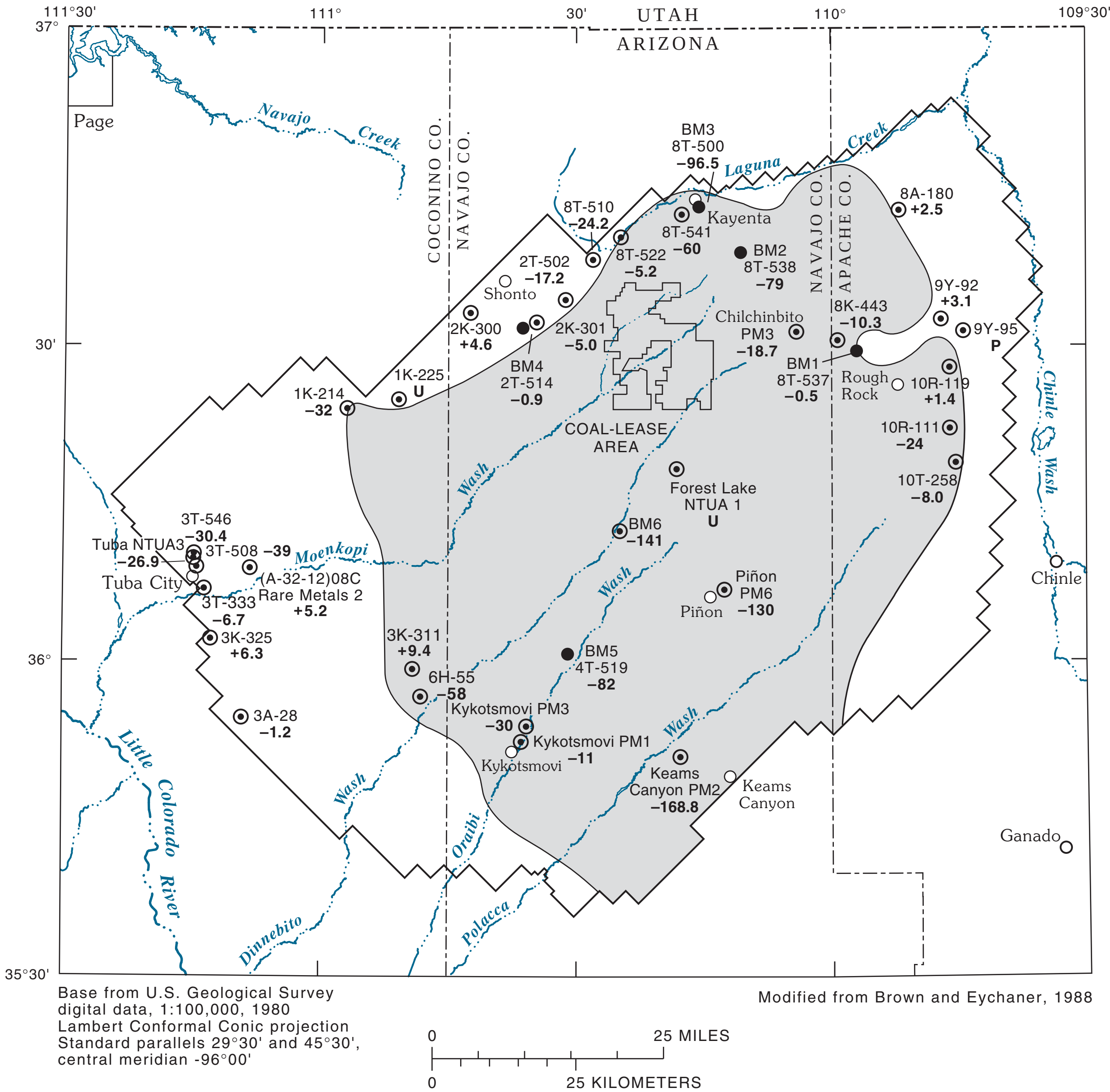
From winter 1999 to spring 2001, water levels declined in 10 of 15 wells in unconfined areas. The median change was -0.4 ft, and the changes ranged from -7.6 ft to +2.3 ft. In confined areas, water levels declined in 8 of 16 wells. The median change was -0.2 ft, and the changes ranged from -10.8 ft to +6.0 ft (table 4).

Median annual water-level changes for observations wells from 1983 to 2001 are shown in **figure 6**. Median annual changes before 1983 are not shown because there were insufficient water-level data to compute median values. Trends in the annual water-level changes from 1983 to 2001 were tested with a two-sided nonparametric Kendall's tau statistical test (Conover, 1980). There is a significant decreasing trend in the median annual water-level changes for wells in unconfined areas (p-value = 0.035), and the average annual median change was 0.2 ft. There is no significant trend in the water-level changes for wells in confined areas (p-value = 0.139), and the average annual median change was -1.8 ft.

From the prestress period (prior to 1965) to 2001, the median water-level change in 33 wells was -17.2 ft. Water levels in 15 unconfined wells had a median change of -1.2 ft and ranged from -39 ft to +6.3 ft (table 4). Water levels in 18 confined wells had a median change of -31.0 ft and ranged from -168.8 ft to +9.4 ft.

Hydrographs of water levels in wells in the annual observation-well network show the time trends of changes since about 1970 or 1980 (**fig. 7**). Water levels in wells in unconfined areas have changed only slightly. In contrast, water levels in wells in confined areas are more variable. In some wells, there were large declines (wells Piñon PM6 and Keams Canyon PM2), and in other wells there were small changes (wells 8T-522 and 10R-119).

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



EXPLANATION

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

CONFINED

UNCONFINED

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

6H-55 **−58** WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 6H-55, is Bureau of Indian Affairs site number; second entry, **−58**, is change in water level, in feet, between measurement made during the prestress period and measurement made during 2001. **U**, unable to measure. **P**, well was being pumped during site visit

BM2 8T-538 **−79** 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, **−79**, is change in water level, in feet, from simulated prestress period to 2001

Figure 5. Water-level changes in N-aquifer wells from the prestress period (prior to 1965) to 2001, Black Mesa area, Arizona.

Table 4. Water-level changes in wells completed in the N aquifer, Black Mesa area, Arizona, prestress period to 2001

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

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year, in feet[1] 1999–2000	2001	Water level, in feet below land surface, 2001	Prestress period water level[2] Feet below land surface	Date	Change in water level from prestress period to 2001, in feet
Unconfined area							
BM observation well 1[3]	8T-537	0.0	-0.3	374.5	374	([3])	-0.5
BM observation well 4[3]	2T-514	-1.0	+.4	216.9	[4]216	([3])	-.9
Cow Springs	1K-225	.0	([5])	([5])	60	07–04–54	([5])
Goldtooth	3A-28	([5])	[6]-.5	231.2	230.0	10–29–53	-1.2
Long House Valley	8T-510	-.9	-.7	123.6	99.4	08–22–67	-24.2
Northeast Rough Rock	8A-180	-.7	-.5	44.4	46.9	11–13–53	+2.5
Rough Rock	9Y-95	+.3	([7])	([7])	119.5	08–03–49	([7])
Do	9Y-92	-.5	-.4	165.7	168.8	12–13–52	+3.1
Shonto	2K-300	-.8	+.4	171.9	176.5	06–13–50	+4.6
Shonto Southeast	2K-301	-.4	-.3	288.9	283.9	12–10–52	-5.0
Do	2T-502	-.9	-7.6	423.0	405.8	08–22–67	-17.2
Tuba City	3T-333	-1.2	+2.3	29.7	23.0	12–02–55	-6.7
Do	3K-325	-.5	+.3	201.7	208	06–30–55	+6.3
Tuba City Rare Metals 2	---	.0	+.8	51.8	57	09–24–55	+5.2
Tuba NTUA 1	3T-508	-4.9	-.6	67.8	29	02–12–69	-39
Tuba NTUA 3	---	[6]-3.6	-1.0	61.1	34.2	11–08–71	-26.9
Tuba NTUA 4	3T-546	-.8	-3.4	64.1	33.7	08–06–71	-30.4
Confined area							
BM observation well 2[3]	8T-538	-1.3	-2.9	204.4	125	([3])	-79
BM observation well 3[3]	8T-500	+8.9	-7.0	151.5	[4]55.0	04–29–63	-96.5
BM observation well 5[3]	4T-519	-3.3	-1.9	406.0	324	([3])	-82
BM observation well 6[3]	---	[8]-4.3	[8]-4.4	838.0	[4]697	([3])	-141
Chilchinbito PM3	---	[6]+.8	-.5	424.0	405.3	09–25–65	-18.7
Forest Lake NTUA 1	4T-523	-4.8	([5])	([5])	1,096R	05–21–82	([5])
Howell Mesa	3K-311	([5])	([9])	453.6	463.0	11–03–53	+9.4
Howell Mesa	6H-55	[6]-1.0	+.2	270.0	212	07–08–54	-58
Kayenta West	8T-541	-1.6	-4.1	290.5	230	03–17–76	-60
Keams Canyon PM2	---	-4.5	+6.0	461.3	292.5	06–10–70	-168.8
Kykotsmovi PM1	---	-18.7	+2.3	230.6	220	05–20–67	-11
Kykotsmovi PM3	---	([5])	([9])	240.1	210	08–28–68	-30
Marsh Pass	8T-522	-.6	-1.7	130.7	125.5	02–07–72	-5.2
Piñon PM6	---	([5])	-10.8	873.6	743.6	05–28–70	-130.0
Rough Rock	10R-119	-0.8	+0.8	255.2	256.6	12–02–53	+1.4
Do	10T-258	-.5	+.3	309.0	301.0	04–14–60	-8.0
Do	10R-111	-4.0	+1.3	193.7	170	08–04–54	-24
Sweetwater Mesa	8K-443	-.4	+.3	539.7	529.4	09–26–67	-10.3
White Mesa Arch	1K-214	-.3	+.6	220.0	188	06–04–53	-32

[1]The dates of water-level measurements were changed from fall-winter (October 1999–February 2000) in the last monitoring report (1999) to spring (March-May 2001) in this report (2000–2001). This interval between measurements was approximately 16 months instead of the usual 12 months. Subsequent annual water-level measurements will be made in the spring.

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

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

[4]Prestress water levels for indicated wells were changed from previous Black Mesa monitoring reports to more accurately represent prestress conditions. The water level in BM3 was 77.1 feet in 1998 report and 60 feet in 1995–97 reports. The water levels were 217 feet in BM4 and 735.6 feet in BM6 in 1995–98 reports.

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

[6]Change in water level from last measurement 2 to 4 years earlier.

[7]2001 water level influenced by pumping.

[8]Water level of 836.7 feet reported in 1999 monitoring report was incorrect. Correct water level was 833.6 feet.

[9]Change in water level not shown because last measurement was more than 4 years ago.

Table 5. Well-construction characteristics, top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, Arizona, 2000–2001

Bureau of Indian Affairs site number, or common name	Date well was completed	Land- surface altitude, in feet	Well depth, in feet below land surface	Screened/open interval(s), in feet below land surface	Depth to top of N aquifer, in feet below land surface[1]	Type of data collected
8T-537 (BM observation well 1)	02–01–72	5,864	850	300–360;400–420; 500–520;600–620; 730–780	290	Water level
8T-538 (BM observation well 2)	01–29–72	5,656	1,338	470–1,338	452	Water level
8T-500 (BM observation well 3)	07–29–59	5,724	868	712–868	155	Water level
2T-514 (BM observation well 4)	02–15–72	6,320	400	250–400	160	Water level
4T-519 (BM observation well 5)	02–25–72	5,869	1,683	1,521–1,683	1,520	Water level
BM observation well 6	01–31–77	6,332	2,507	1,954–2,506	1,950	Water level
1K-214	05–26–50	5,771	356	168–356	250	Water level
1K-225	07–04–54	5,722	251	19–251	[2]10	Water level
2K-300	[3]06–00–50	6,264	300	260–300	0	Water level
2K-301	06–12–50	6,435	500	318–328; 378–500	[2]30	Water level
2T-502	08–10–59	6,670	523	12–523	[2]5	Water level
3A-28	04–19–35	5,381	358	([4])	60	Water level
3K-311	[3]11–00–34	5,855	745	380–395 605–745	615	Water level
3K-325	06–01–55	5,250	450	75-450	[2]30	Water level
3T-333	12–02–55	4,940	229	63–229	[2]4	Water level
3T-508 (Tuba City NTUA 1)	08–25–59	5,119	475	([4])	0	Water level, withdrawals
3T-546 (Tuba City NTUA 4)	[3]08–00–71	5,206	612	256–556	0	Water level, withdrawals
4T-523	10–01–80	6,654	2,674	1,870–1,910 2,070–2,210 2,250–2,674	([5])	Water level, water chemistry, withdrawals
6H-55	12–08–44	5,635	361	310–335	310	Water level
8A-180	01–20–39	5,200	107	60–107	[2]40	Water level
8A-295	[3]00–00–36	5,623	840	268–280 691–788	95	Water chemistry, withdrawals
8K-443	08–15–57	6,024	720	619–720	590	Water level
8T-510	02–11–63	6,262	314	130–314	[2]125	Water level
8T-522	[3]07–00–63	6,040	933	180–933	480	Water level
8T-541	03–17–76	5,885	890	740–890	700	Water level
9Y-92	01–02–39	5,615	300	154–300	[2]50	Water level
9Y-95	11–05–37	5,633	300	145–300	[2]68	Water level
10R-111	04–11–35	5,757	360	267–360	210	Water level
10R-119	01–09–35	5,775	360	(4)	310	Water level
10T-258	04–12–60	5,903	670	465–670	460	Water level
Chilchinbito PM3	09–25–65	5,950	1,600	1,140–1,570	1,136	Water level, withdrawals
Hotevilla PM1	06–00–57	6,357	1,757	1,500–1,750	1,450	Water chemistry withdrawals
Keams Canyon PM2	[3]05–00–70	5,809	1,106	906–1,106	900	Water level, withdrawals
Kitsillie NTUA 2	11–09–93	6,780	2,620	2,217–2,223 2,240–2,256 2,314–2,324 2,344–2,394 2,472–2,527	2,205	Water chemistry, withdrawals

See footnotes at end of table.

Table 5. Well-construction characteristics, top of N aquifer, and type of data collected for wells in monitoring program, Black Mesa area, Arizona, 2000–2001—Continued

Bureau of Indian Affairs site number, or common name	Date well was completed	Land- surface altitude, in feet	Well depth, in feet below land surface	Screened/open interval(s), in feet below land surface	Depth to top of N aquifer, in feet below land surface[1]	Type of data collected
Kykotsmovi PM1	02–20–67	5,657	995	655–675 890–990	880	Water level, withdrawals
Kykotsmovi PM2	10–14–77	5,717	1,160	950–1,160	890	Water chemistry, withdrawals
Kykotsmovi PM3	08–07–68	5,618	1,220	850–1,220	840	Water level, withdrawals
Peabody 4	[3]05–00–68	6,229	3,535	2,029–3,458	2,280	Water chemistry, withdrawals
Peabody 9	[3]00–00–83	6,385	3,510	2,332–3,505	2,400	Water chemistry, withdrawals
Piñon NTUA 1	02–25–80	6,336	2,350	1,860–2,350	1,850	Water chemistry withdrawals
Piñon PM6	[3]02–00–70	6,397	2,248	1,895–2,243	1,870	Water level, withdrawals
Red Lake PM1	[3]09–00–57	5,616	550	150–510	120	Water chemistry, withdrawals
Rocky Ridge PM3	03–09–76	5,995	1,805	1,639–1,805	1,595	Water chemistry, withdrawals
Rough Rock PM5	06–27–64	6,299	1,420	1,180–1,420	1,156	Water chemistry, withdrawals
Second Mesa PM2	[3]10–00–68	5,777	1,090	740–1,090	720	Water chemistry, withdrawals
Tuba City NTUA 3	[3]10–00–71	5,176	442	142–442	34	Water level, withdrawals
Tuba City Rare Metals 2	[3]09–00–55	5,108	705	100–705	[2]55	Water level

[1]Depth to top of N aquifer from Eychaner (1983) and Brown and Eychaner (1988).
[2]All material between land surface and top of the N aquifer is unconsolidated--soil, alluvium, or dune sand.
[3]00, indicates month or day is unknown.
[4]Screened and (or) open intervals are unknown.
[5]Top of N aquifer was not estimated.

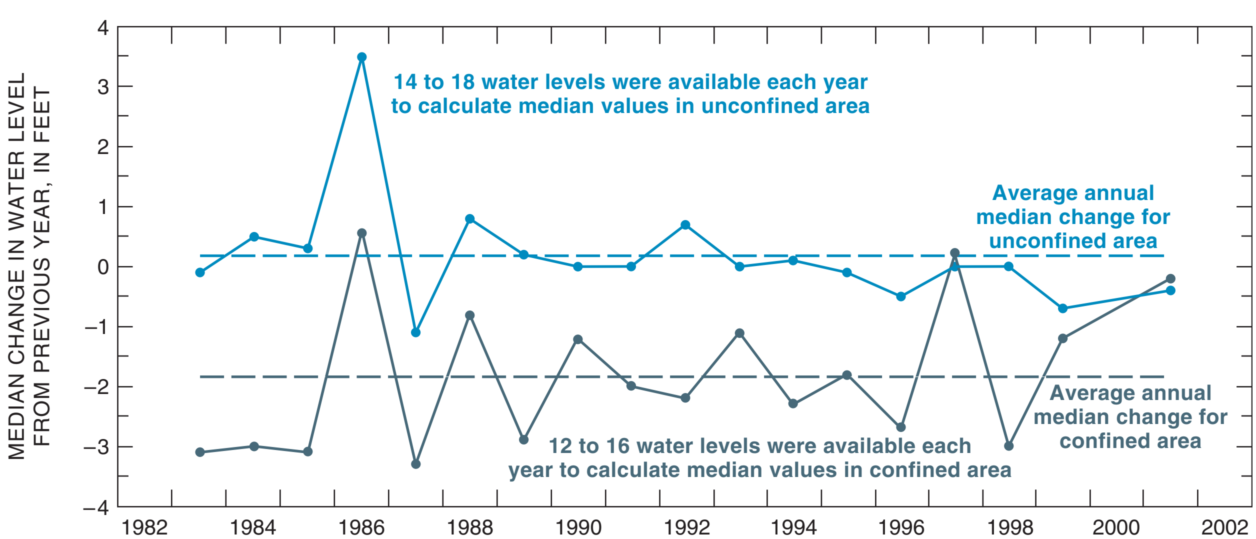


Figure 6. Annual water-level changes for observation wells completed in the N aquifer, Black Mesa area, Arizona, 1983–2001.

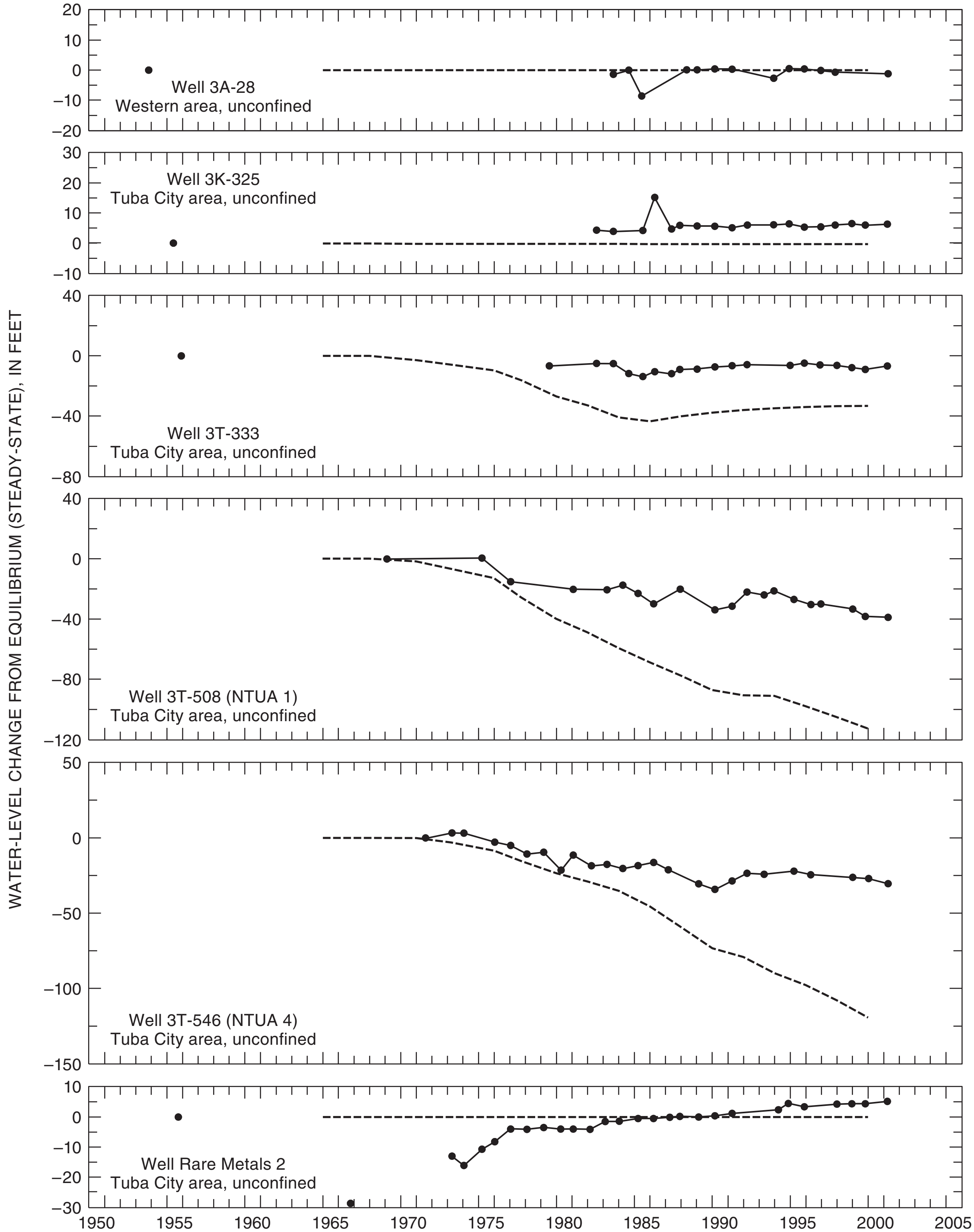
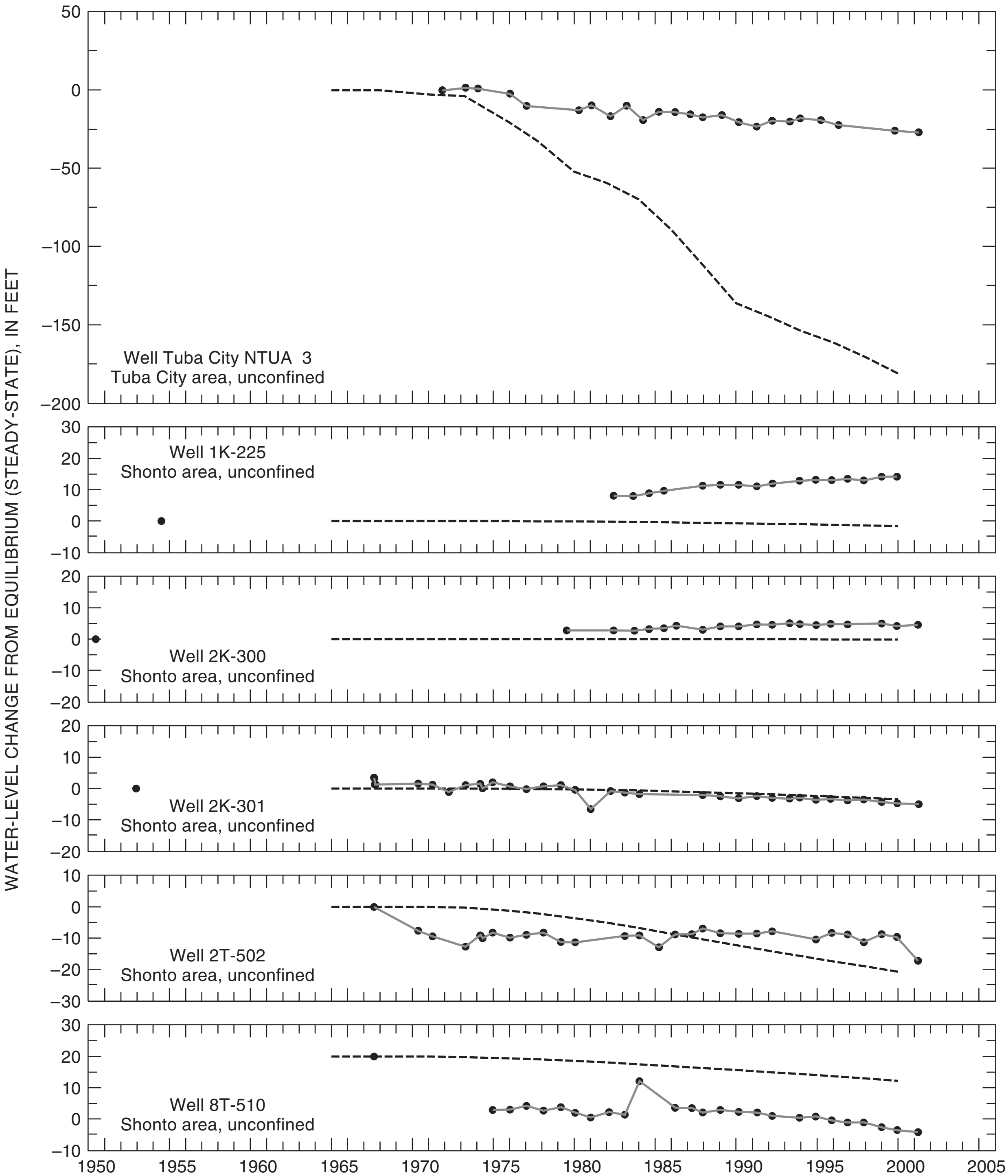


Figure 7. Observed water-level changes, 1950–2001 (circles and solid line), and simulated water-level changes, 1965–99 (dashed line), for annual observation-well network, Black Mesa area, Arizona.



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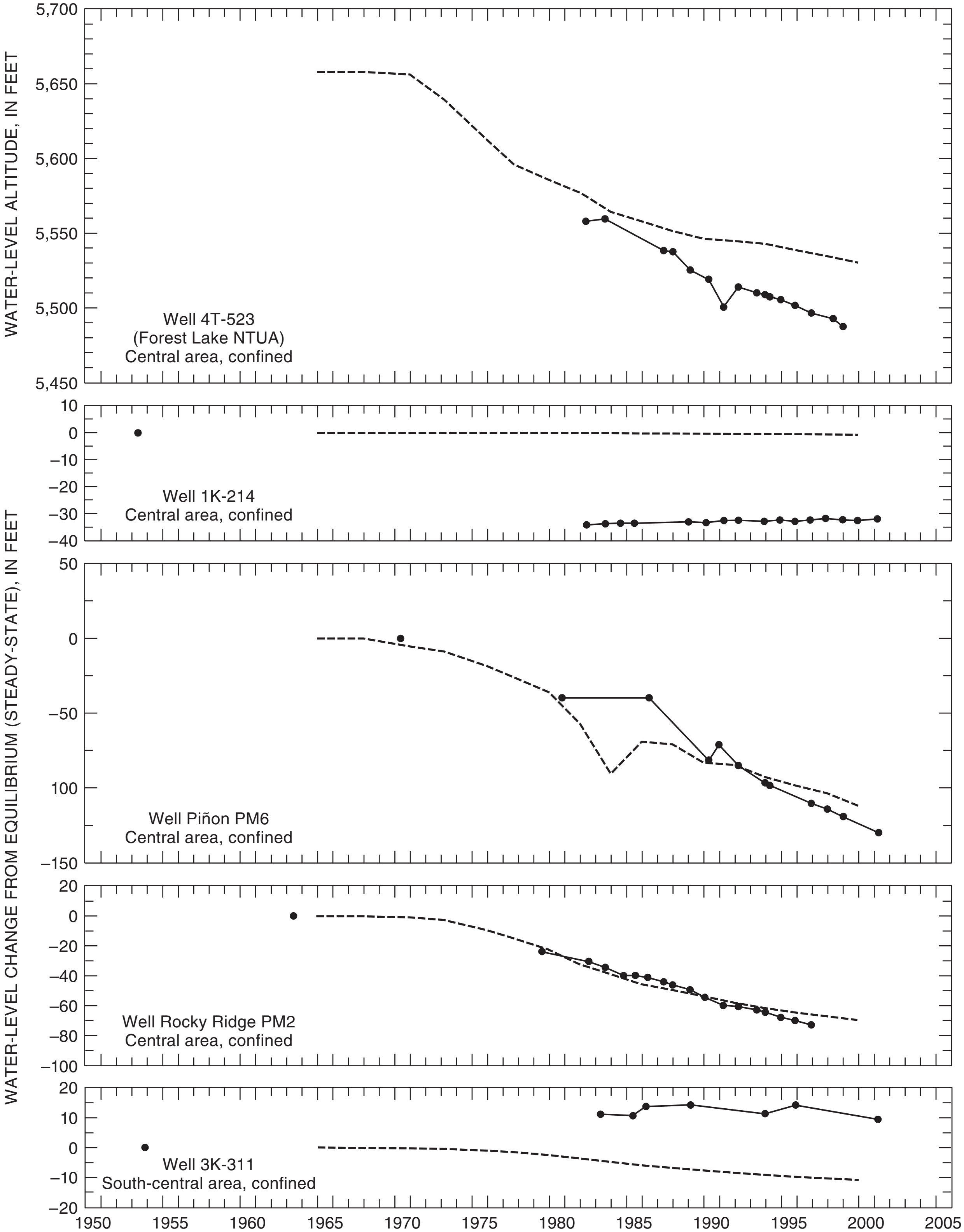

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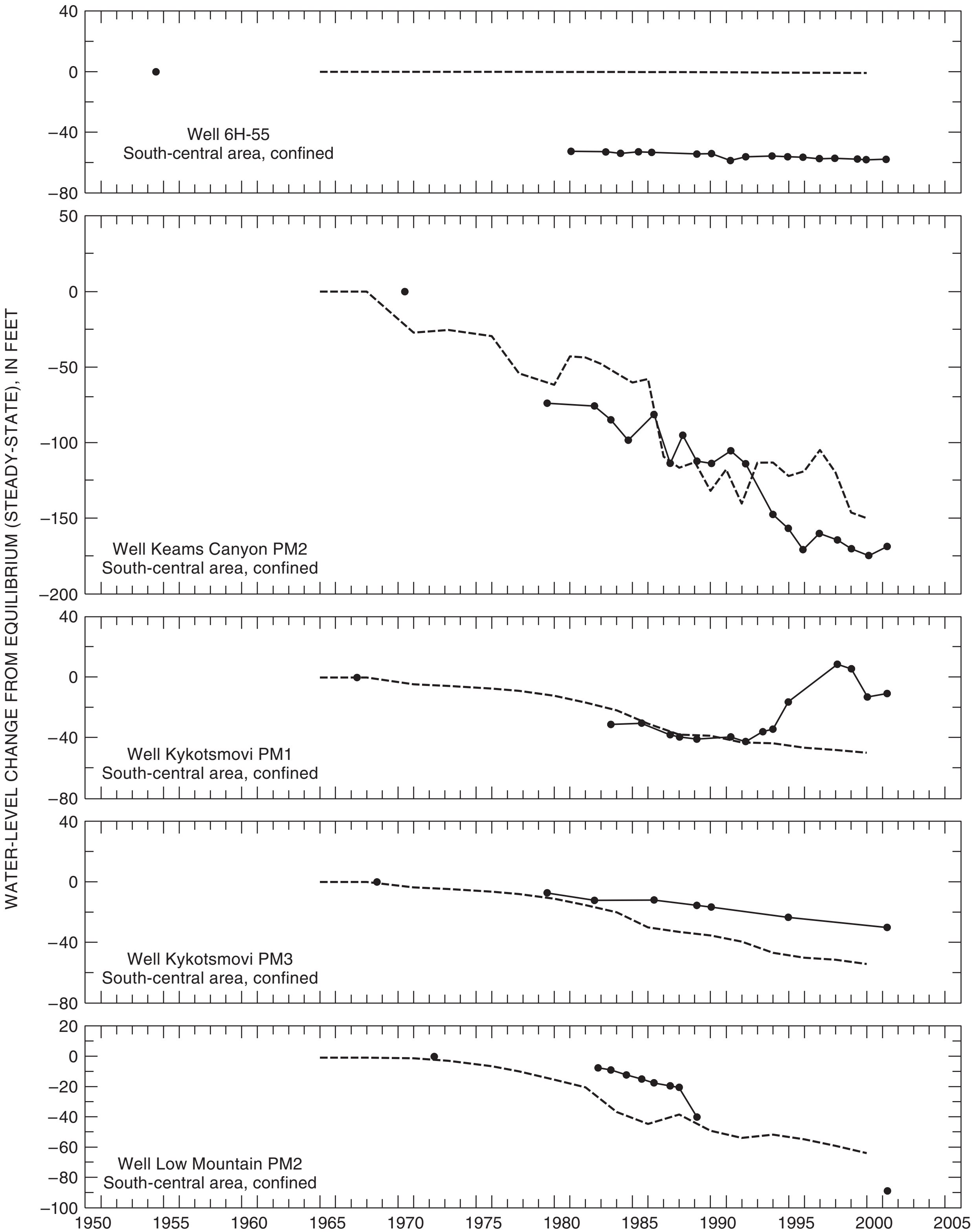

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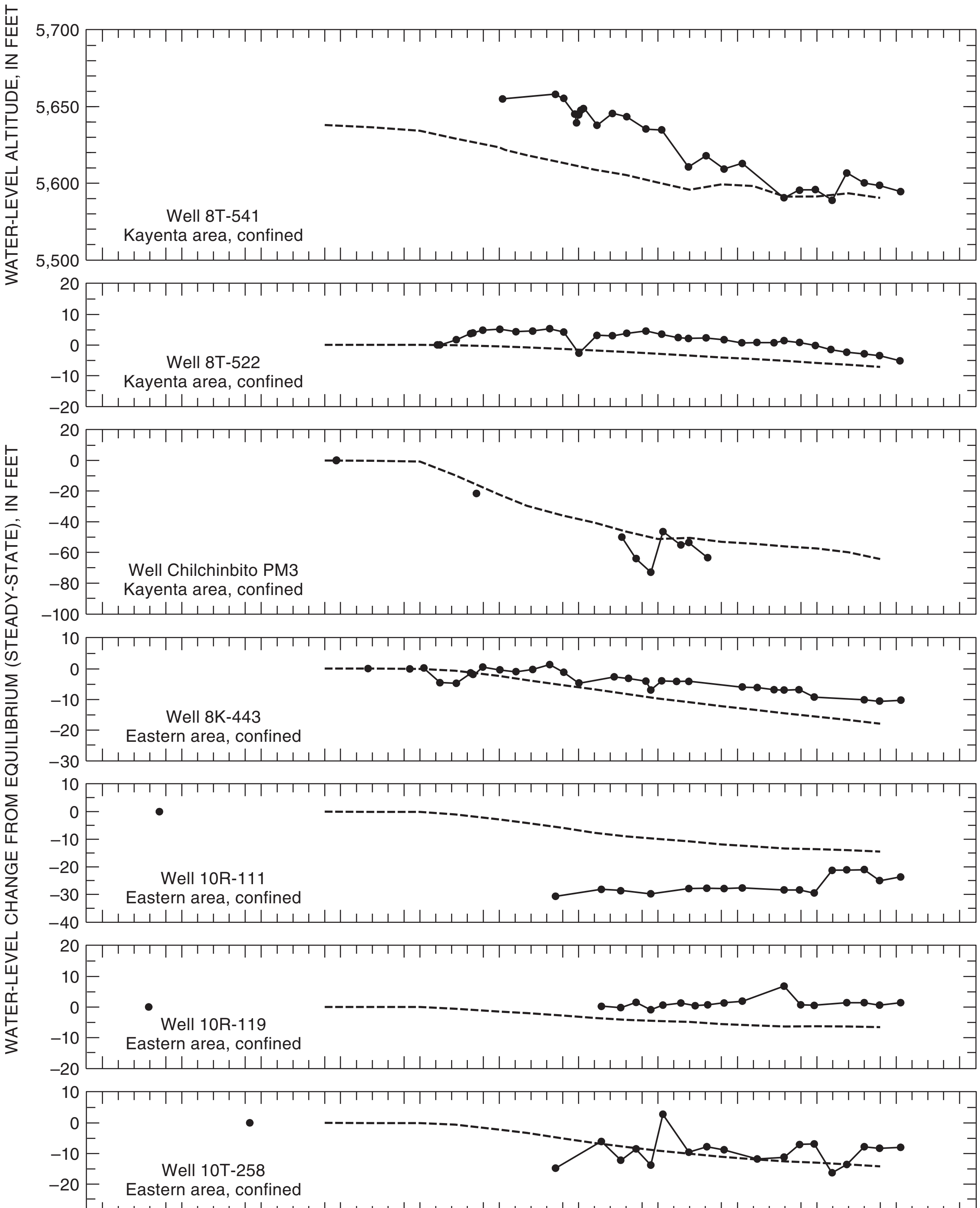

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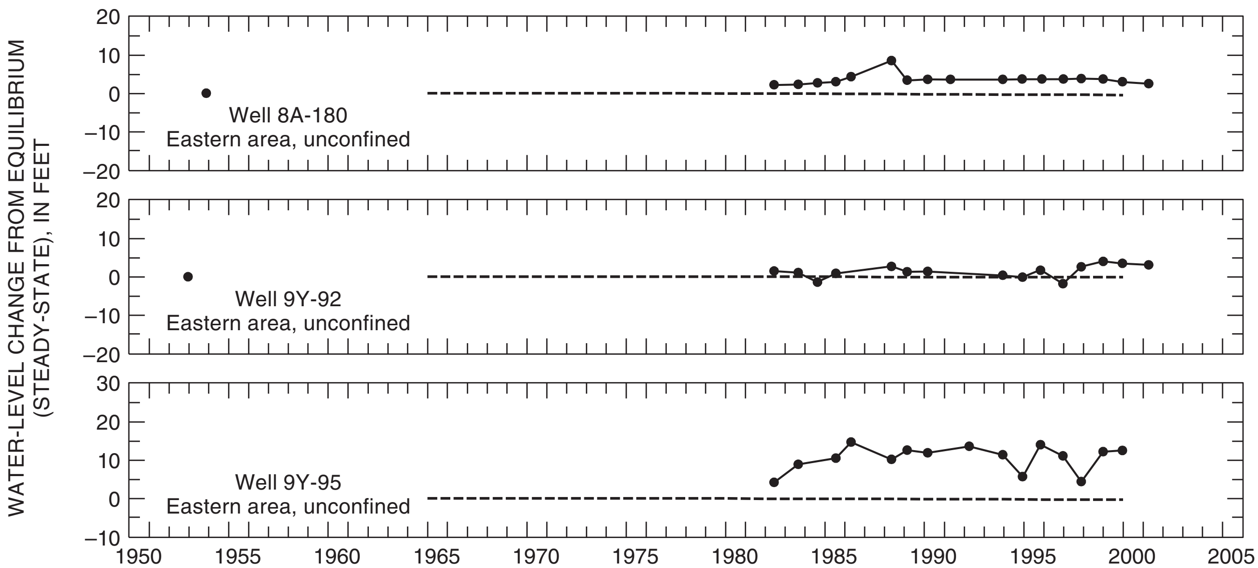

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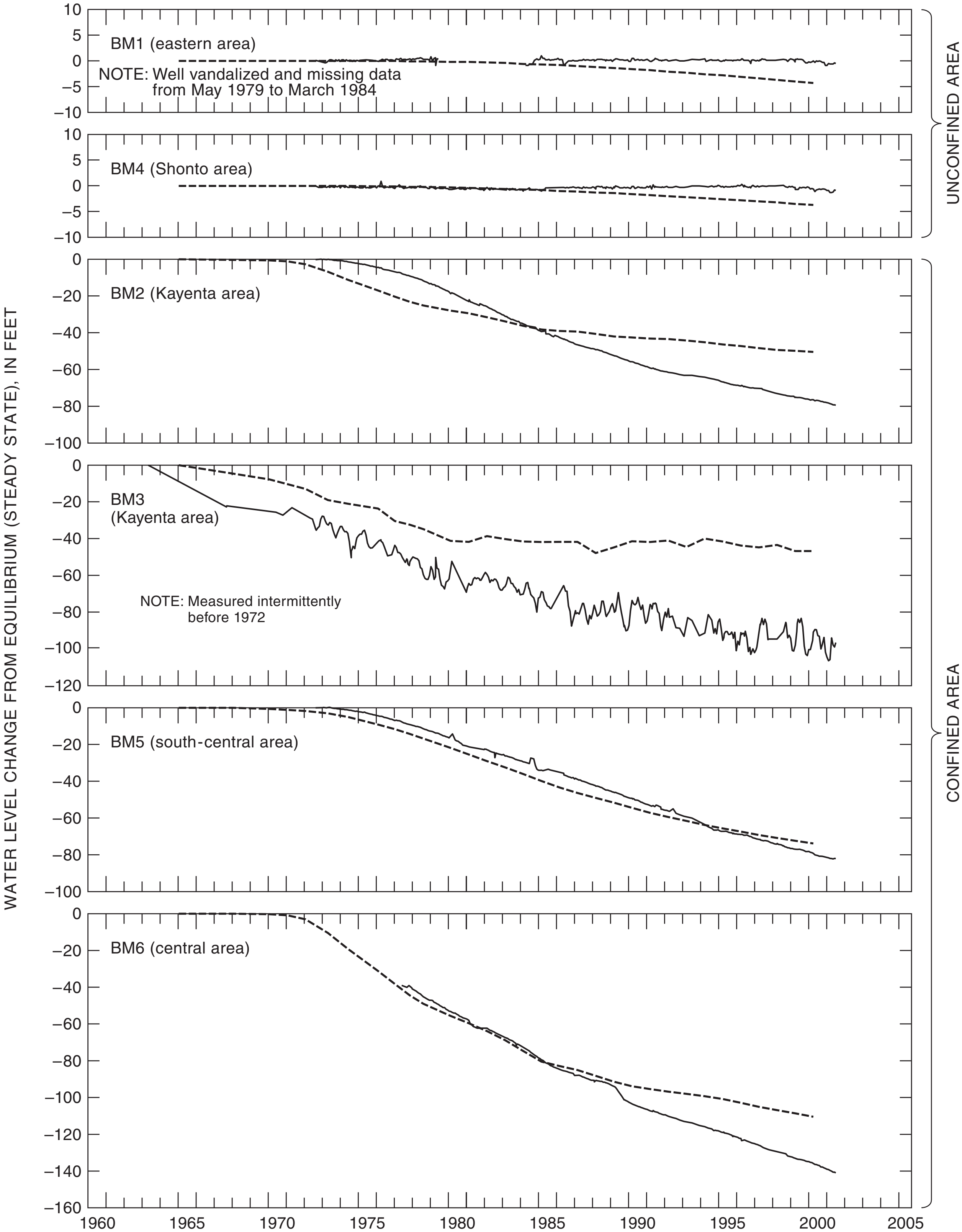

Figure 8. Observed water-level changes in continuous-record observation wells, BM1–BM6, 1963–2001 (solid line), and simulated water-level changes 1965–99 (dashed line), Black Mesa area, Arizona.

Spring Discharge from the N Aquifer

Ground water in the N aquifer discharges from many springs around the margins of the Black Mesa area. Discharge from selected springs is measured annually and compared to discharge from previous years to determine changes in spring discharge over time. In March–June 2001, discharge was measured at four springs (table 6). Three springs are on the west or southwest side of the Black Mesa area and one is on the northeast side (**fig. 9**). The discharge from these four springs represents only a small fraction of the total spring discharge from the N aquifer.

In 2001, measured discharges were 0.2 gal/min from Burro Spring, 26.8 gal/min from the unnamed spring near Dennehotso, 13.7 gal/min from Moenkopi School Spring, and 37 gal/min from Pasture Canyon Spring. Compared to spring discharges in 1999, discharges decreased by 33 percent for Burro Spring, increased by 81 percent for the unnamed spring near Dennehotso, increased by 3 percent for Moenkopi School Spring, and decreased by 5 percent for Pasture Canyon Spring. The discharge measured at all four springs represents only part of the total discharge from the springs. Because of separate seeps and problematic measuring conditions, it would be difficult to measure the total discharge at those sites.

Table 6. Discharge measurements of selected springs, Black Mesa area, Arizona, 1952–2001

U.S. Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Burro Spring			
6M-31	Navajo Sandstone	12–15–89	0.4
		12–13–90	.4
		03–18–93	.3
		12–08–94	.2
		12–17–96	.4
		12–30–97	.2
		12–08–98	.3
		12–07–99	.3
		04–02–01	.2
Unnamed spring near Dennehotso			
8A-224	Navajo Sandstone	10–06–54	[3]1
		06–27–84	[3]2
		11–17–87	[3]5
		03–26–92	16
		10–22–93	14.4
		12–05–95	17
		12–19–96	15.7
		12–31–97	25.6
		12–14–98	21.0
		12–15–99	14.8
		03–14–01	26.8
Moenkopi School Spring			
3GS-77-6	Navajo Sandstone[1]	05–16–52	40
		04–22–87	[2]16
		11–29–88	[2]12.5
		02–21–91	[2]13.5
		04–07–93	[2]14.6
		12–07–94	[2]12.9
		12–04–95	[2]12.1
		12-16-96	[2]10
		12–17–97	[2]13.1
		12–08–98	[2]12.0
		12–13–99	[2]13.3
		03–12–01	[2]13.7
Pasture Canyon Spring			
3A-5	Navajo Sandstone, alluvium	11–18–88	[4]211
		03–24–92	[4]233
		10–12–93	[4]211
		12–04–95	[5]38
		12–16–96	[5]38
		12–17–97	[5]40
		12–10–98	[5]39
		12–21–99	[5]39
		06–12–01	[5]37

[1]Tongue in the Kayenta Formation.

[2]Discharge measured at water-quality sampling site and at different point than the measurement in 1952. Discharge does not represent total discharge from the Moenkopi School Spring system.

[3]Discharge measured at different point than later measurements and does not represent total discharge from unnamed spring near Dennehotso.

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

[5]Discharge measured at water-quality sampling point about 20 feet below upper spring on west side of canyon. Discharge does not represent total discharge from Pasture Canyon Spring.

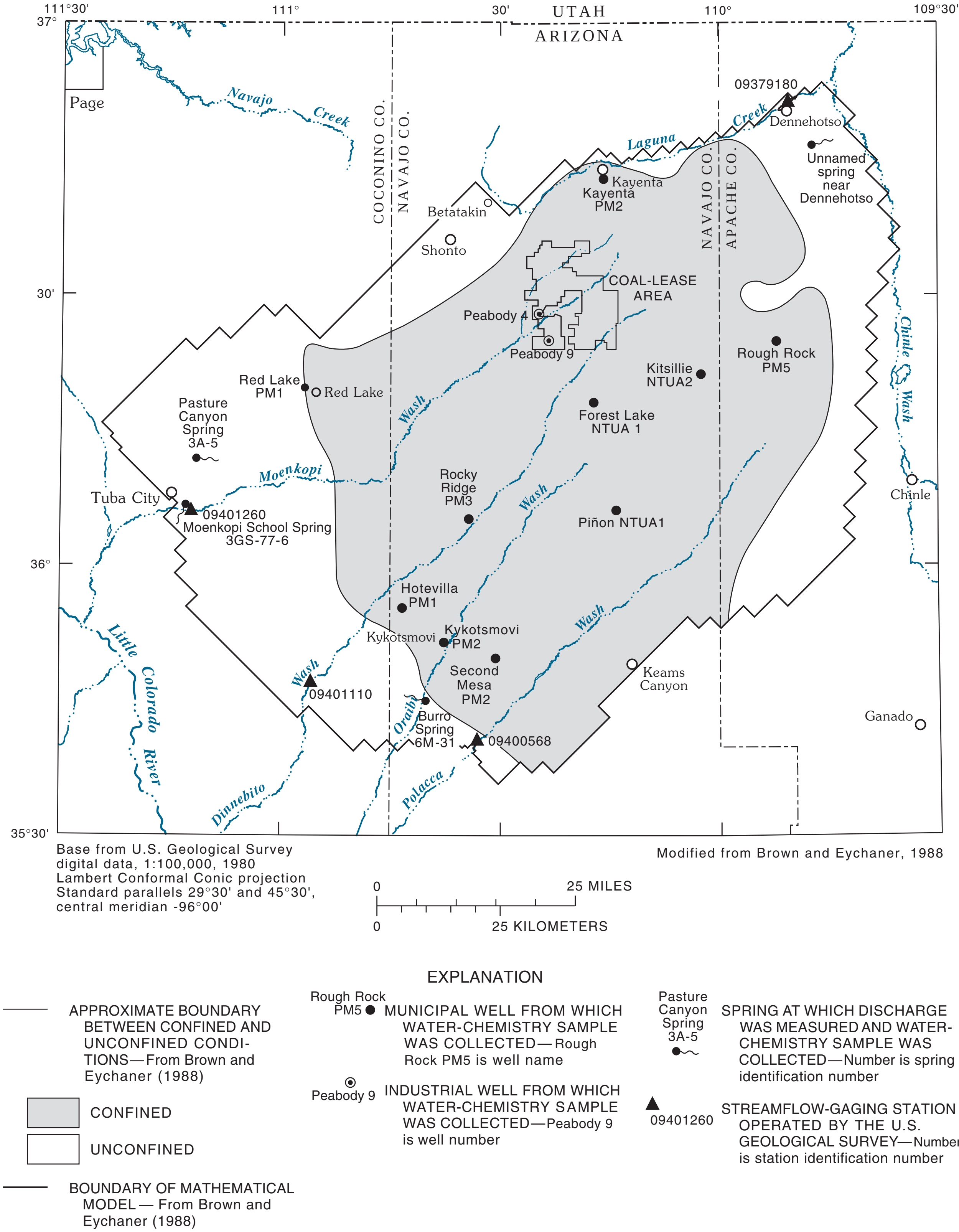

Figure 9. Surface-water and water-chemistry data-collection sites, Black Mesa area, Arizona, 2000–2001.

Long-term changes in spring discharge can be evaluated for the entire record at Burro Spring but can be evaluated only for parts of the records for the other three springs because discharge measuring points changed during the periods of record (**table 6**). Consistent measuring points are available for 1992–2001 at the unnamed spring near Dennehotso, for 1987–2001 at Moenkopi School Spring, and for 1995–2001 at Pasture Canyon Spring. For the consistent periods of record at Burro Spring, the unnamed spring near Dennehotso, and Moenkopi School Spring, there are no significant trends in the discharge; all p-values from a Kendall's tau statistical test are greater than 0.05. A statistical test was not done for Pasture Canyon Spring because its record is too short (six discharge measurements).

Surface-Water Discharge

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

Data on surface-water discharge have been collected continuously at selected streams each year of the monitoring program. The discharge data provide useful information about ground-water discharge and about runoff from rainfall and snowmelt. In this study, the total discharge in streams is roughly separated into ground-water discharge and runoff so that the temporal trends in ground-water discharge can be monitored.

In 2000, continuous-record discharge data were collected at four streamflow-gaging stations (tables 7–10). The gaging stations and their starting dates of operation are: Moenkopi Wash in July 1976, Laguna Creek in July 1996, Dinnebito Wash in June 1993, and Polacca Wash in April 1994 (**fig. 9**, **table 11**).

The annual average discharges for the four gaging stations vary considerably during their periods of record (fig. 10). The records for Laguna Creek, Dinnebito Wash, and Polacca Wash are too short to discern any trends. There is no significant trend in the annual average discharges for Moenkopi Wash from 1977 to 2000; a Kendall's tau statistical test resulted in a p-value of 0.172.

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

The median flow for November, December, January, and February is an index of ground-water discharge rather than an absolute estimate of discharge. A more rigorous and accurate estimate would include detailed evaluations of streamflow hydrographs, flows into and out of bank storage, gain and loss of streamflow as it moves down the stream channel, and interaction of ground water in the N aquifer with ground water in the shallow alluvial aquifers in the stream valleys. The median winter flow, however, is useful as a consistent index for evaluating possible time trends in ground-water discharge.

In the 2000 water year (October 1 to September 30), median flows for November, December, January, and February were 2.2 ft^3/s for Moenkopi Wash, 1.6 ft^3/s for Laguna Creek, 0.32 ft^3/s for Dinnebito Wash, and 0.17 ft^3/s for Polacca Wash. There is no significant trend in the median winter flows for Moenkopi Wash from 1977 to 2000; a Kendall's tau statistical test resulted in a p-value of 0.819. The records for the other three streams are too short for a statistical analysis of trends. The median winter flows for Dinnebito Wash and Polacca Wash, however, appear to have decreased during the last 6 years. This decrease in flows may be related to less-than-average precipitation and ground-water recharge during the last 6 years. Annual precipitation at Betatakin, about 15 miles west of Kayenta, has been less than average for 4 of the last 6 years (**figure 10**).

Table 7. Discharge data, Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 2000

[---, no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2000
DAILY MEAN VALUES

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	[1]1.9	[1]3.3	3.7	7.4	1.1	0.0	0.0	0.0	0.0	[1]35	[1]23	0.92
2	[1]1.8	[1]3.2	4.0	2.8	1.2	.0	.0	.0	.0	[1]9.8	[1]4.3	1.1
3	[1]1.8	[1]3.2	3.7	2.2	1.2	.0	.0	.0	.0	[1]1.5	1.4	1.2
4	[1]1.8	3.1	4.0	2.7	1.0	.0	.0	.0	.0	.45	2.8	1.2
5	[1]1.8	3.0	4.3	.86	.84	.0	.0	.0	.0	.62	.80	1.1
6	[1]1.8	3.2	4.7	.52	.72	.0	.0	.0	.0	.09	.34	1.1
7	[1]1.8	3.3	5.3	1.1	.71	.0	.0	.0	.0	.04	.10	.99
8	[1]1.8	2.6	5.9	.50	.66	.0	.0	.0	35	.03	.04	1.2
9	[1]1.8	3.0	4.9	1.0	.65	.0	.0	.0	22	108	.06	1.1
10	[1]1.8	3.1	4.4	.98	.70	.0	.0	.0	1.6	[1]5.0	.05	1.3
11	[1]1.8	3.0	3.9	1.5	.40	.0	.0	.0	.0	[1]3.2	.10	1.0
12	[1]1.8	3.1	3.5	1.9	.36	.0	.0	.0	.0	[1].60	.11	.87
13	[1]1.8	3.0	3.7	1.8	.46	.0	.0	.0	.0	.15	.09	.58
14	[1]1.8	2.7	3.9	1.7	.56	.0	.0	18	.0	.10	.20	.41
15	[1]2.5	2.7	4.2	1.7	.69	.0	.0	5.9	.0	.12	.28	.38
16	[1]3.5	2.6	3.8	1.7	.46	.0	.0	.03	.0	.27	.18	[1].46
17	4.2	6.5	3.4	1.6	.25	.0	.0	.0	.0	.38	.49	[1].44
18	4.3	6.4	2.9	1.6	.29	.0	.0	.0	.0	.40	.42	[1].53
19	4.0	4.0	2.7	1.6	.47	.0	.0	.0	.0	.56	[1].50	[1].53
20	3.8	4.1	3.1	1.6	.86	.0	.0	.0	.0	.58	[1].60	[1].70
21	3.7	4.2	4.1	1.6	.61	.0	.0	.0	.0	.63	[1].90	[1].73
22	3.7	5.3	4.5	1.5	.49	.0	.0	.0	.0	[1]134	[1].90	[1].75
23	2.5	5.4	6.0	1.6	.39	.0	.0	.0	.0	[1]31	[1].92	[1].78
24	2.8	5.5	4.3	1.6	.29	.0	.0	.12	.0	[1]15	1.0	[1].78
25	3.0	5.1	3.6	1.5	.11	.0	.0	1.3	.0	[1]7.6	[1]1.1	[1].75
26	3.6	5.1	3.0	1.5	.0	.0	.0	.0	.0	[1]10	[1]1.4	[1].88
27	3.4	5.7	2.3	1.4	.0	.0	.0	[1]7.5	.0	2.8	1.4	[1].88
28	3.4	4.6	3.9	1.3	.0	.0	.0	[1]17	.0	[1]23	1.3	[1].78
29	[1]3.4	3.2	13	1.1	.0	.0	.0	[1]19	.0	[1]19	1.4	[1].85
30	[1]3.4	---	7.8	1.1	.0	.0	.0	[1]9.7	436	[1]6.3	1.3	[1].80
31	[1]3.3	---	28	---	.0	---	.0	.01	---	[1]152	---	[1].78
TOTAL	83.8	113.2	160.5	50.96	15.47	0.0	0.0	78.56	494.6	568.22	47.48	25.87
MEAN	2.7	3.9	5.2	1.7	.50	0.0	0.0	2.5	16.5	18.3	1.58	0.83
MAX	4.3	6.5	28	7.4	1.2	0.0	0.0	19	436	152	23	1.3
MIN	1.8	2.6	2.3	0.5	0.0	0.0	0.0	0.0	0.0	0.03	0.04	.38
AC-FT	166	225	318	101	31	0.0	0.0	156	981	1,130	94	51

CALENDAR YEAR 2000 TOTAL 1,638.66 MEAN 4.49 MAXIMUM 436 MINIMUM 0.0 ACRE-FT 3,250

[1]Estimated.

Table 8. Discharge data, Laguna Creek at Dennehotso, Arizona (09379180), calendar year 2000

[---, no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2000 DAILY MEAN VALUES												
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
1	[1]3.0	[1]5.6	1.1	0.69	0.0	0.0	0.0	0.0	[1]0.0	[1]0.04	[1]16	[1]2.8
2	[1]3.1	[1]2.5	1.5	.42	.0	.0	.0	.0	[1].0	[1].0	[1]16	[1]6.0
3	[1]1.1	[1]2.5	1.6	.41	.0	.0	.0	.0	[1].0	[1].0	11	[1]4.0
4	[1]1.1	6.7	1.5	.41	.0	.0	.0	.0	.0	.0	6.7	1.3
5	[1]1.1	7.5	1.5	1.7	.0	.0	.0	.0	.0	.0	6.1	1.4
6	[1]1.5	6.1	1.5	1.7	.0	.0	.0	.0	.0	.0	5.2	2.6
7	.38	5.3	2.0	1.1	.0	.0	.0	.0	.0	.0	4.6	2.2
8	.11	4.8	1.9	.40	.0	.0	.0	.0	.0	.0	3.4	2.9
9	.07	4.9	1.5	.33	.0	.0	.0	.0	.0	.0	1.9	[1]2.0
10	.08	4.7	1.2	.24	.0	.0	.0	.0	.0	22	2.9	[1]1.6
11	.10	4.9	.64	.13	.0	.0	.0	.0	.0	7.8	[1]2.8	[1]1.3
12	[1].50	4.8	.45	.08	.0	.0	.0	.0	.0	1.6	[1]3.0	1.4
13	[1]1.0	4.4	.60	.03	.0	.0	.0	.0	.0	.60	1.3	1.4
14	[1]1.3	3.8	.56	.0	.0	.0	.0	.0	.0	.24	[1]2.0	1.3
15	[1]3.0	3.2	.55	.0	.0	.0	.0	.0	.0	.29	[1]4.5	3.3
16	[1]2.5	2.7	.48	.0	.0	.0	.0	.0	.0	.36	2.2	[1]1.6
17	5.7	2.5	.38	.0	.0	.0	.0	.0	.0	.51	[1]2.7	[1].60
18	[1]5.0	1.3	.35	.0	.0	.0	.0	.0	.0	.65	[1]2.0	[1].70
19	11	4.3	.30	.0	.0	.0	.0	.0	.0	.61	1.4	[1].70
20	[1]12	2.4	.37	.0	.0	.0	.0	.0	.0	.62	[1]1.5	[1].70
21	13	1.8	.86	.0	.0	.0	.0	.0	.0	.65	[1]1.5	[1]1.3
22	10	1.6	1.3	.0	.0	.0	.0	.0	.0	4.0	[1]2.6	[1].70
23	12	1.4	2.6	.0	.0	.0	.0	.0	.0	651	[1]6.0	[1].70
24	8.6	1.3	1.4	.0	.0	.0	.0	.0	.0	114	[1]7.0	[1].70
25	7.3	.46	[1]2.0	.0	.0	.0	.0	[1].0	.0	19	[1]7.0	[1]2.5
26	7.9	.08	[1]3.0	.0	.0	.0	.0	[1]3.3	.0	8.8	[1]3.0	[1]1.5
27	11	.06	[1]1.0	.0	.0	.0	.0	10	.0	6.1	[1]3.5	1.8
28	[1]5.0	2.9	[1]2.0	.0	.0	.0	.0	3.0	.0	5.2	[1]4.7	1.6
29	[1]3.3	1.2	[1]1.0	.0	.0	.0	.0	34	.0	6.4	[1]7.3	1.1
30	[1]1.0	---	[1].60	.0	.0	.0	.0	17	[1]1.4	[1]8.4	[1]4.0	1.6
31	[1].20	---	.65	---	.0	---	.0	[1].46	---	9.9	---	[1]2.5
TOTAL	132.94	95.70	36.39	7.64	0.0	0.0	0.0	67.76	1.40	868.77	143.8	55.80
MEAN	4.3	3.3	1.2	.25	0.0	0.0	0.0	2.2	.05	28.0	4.8	1.8
MAX	13	7.5	3.0	1.7	0.0	0.0	0.0	34	1.4	651	16	6.0
MIN	.07	.06	.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.60
AC-FT	264	190	72	15	0.0	0.0	0.0	134	2.8	1,720	285	111

CALENDAR YEAR 2000 TOTAL 1,410.20 MEAN 3.86 MAXIMUM 651 MINIMUM 0.0 ACRE-FT 2,797

[1]Estimated.

Table 9. Discharge data, Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 2000

[---, no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2000 DAILY MEAN VALUES												
Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	0.36	0.32	0.40	0.41	0.27	0.26	0.23	0.12	0.57	0.21	3.2	0.34
2	.34	.32	.46	.38	.28	.25	.22	.13	.23	.20	.58	.36
3	.29	.33	.39	.36	.28	.25	.20	.11	.66	.21	.26	.34
4	.29	.36	.38	.36	.28	.27	.18	.11	.22	.27	.33	.33
5	.32	.33	.42	.35	.24	.26	.18	.12	.13	.25	.30	.36
6	.30	.19	.40	.32	.24	.26	.19	.12	.14	.24	.22	.34
7	.29	.19	.46	.30	.23	.25	.20	.12	.18	.24	.23	.37
8	.30	.20	.34	.33	.24	.23	.20	.42	.15	.22	.24	.40
9	.32	.55	.56	.32	.27	.22	.22	.54	.13	.23	.27	.37
10	.35	.32	.38	.32	.26	.22	.26	.18	.12	.26	.28	.37
11	.37	.32	.38	.35	.19	.22	.21	.15	.12	.23	.44	.35
12	.37	.29	.43	.36	.18	.22	.20	.22	.12	.24	.33	.37
13	.37	.30	.42	.35	.21	.21	.20	.16	.12	.26	.26	.38
14	.38	.32	.42	.29	.27	.20	.20	.13	.12	.28	.30	.35
15	.38	.32	.40	.30	.24	.20	.21	.13	.12	.27	.30	.33
16	.41	.33	.37	.29	.19	.19	.20	.14	.12	.28	.28	.32
17	.41	.37	.38	.26	.19	.19	.19	.14	.12	.30	.26	.33
18	.39	.35	.36	.29	.26	.19	.16	.15	.11	.31	.26	.27
19	.41	.35	.39	.32	.30	.19	.15	7.9	.11	.30	.25	.28
20	.38	.38	.42	.32	.27	.19	.15	.44	.12	.31	.30	.30
21	.36	.34	.58	.29	.26	.18	.13	.25	.11	.33	.33	.35
22	.36	.40	.81	.27	.26	.18	.13	.74	.09	2.9	.36	.36
23	.32	.38	.82	.28	.25	.18	.13	.41	.09	18	.35	.37
24	.27	.34	.45	.28	.22	.18	.13	.24	.11	91	.33	.38
25	.27	.35	.40	.29	.21	.26	.12	.14	.12	14	.32	.43
26	.39	.36	.38	.30	.24	.42	.11	.64	.16	3.5	.30	.38
27	.40	.36	.38	.29	.28	.23	.11	17	.37	2.2	.34	.31
28	.33	.33	.68	.26	.27	.25	.11	3.5	.19	38	.34	.32
29	.33	.36	.45	.23	.20	.26	.11	11	.16	14	.33	.33
30	.35	---	.46	.24	.25	.26	.12	18	.16	4.4	.34	.34
31	.37	---	.40	---	.24	---	.12	2.7	---	40	---	.33
TOTAL	10.78	9.66	13.97	9.31	7.57	6.87	5.27	66.15	5.27	233.44	12.23	10.76
MEAN	0.35	0.33	0.45	0.31	0.24	0.23	0.17	2.13	0.18	7.53	0.41	0.35
MAX	0.41	0.55	0.82	0.41	0.30	0.42	0.26	18	0.66	91	3.2	.43
MIN	0.27	0.19	0.34	0.23	0.18	0.18	0.11	0.11	0.09	0.20	.22	.27
AC-FT	21	19	28	18	15	14	10	131	10	463	24	21
CALENDAR YEAR: 2000 TOTAL 391.28 MEAN 1.07 MAXIMUM 91 MINIMUM 0.09 ACRE-FT 776												

Table 10. Discharge data, Polacca Wash near Second Mesa, Arizona (09400568), calendar year 2000

[---, no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 2000
DAILY MEAN VALUES

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	0.22	0.20	0.21	0.78	0.12	0.07	0.02	0.01	0.03	0.01	4.5	0.06
2	.22	.21	.27	.30	.13	.08	.02	.02	.01	.01	1.3	.06
3	.16	.22	.21	.22	.12	.08	.02	.02	.01	.01	.52	.06
4	.13	.22	.22	.21	.12	.09	.01	.01	.01	.04	.30	.06
5	.16	.22	.41	.21	.10	.06	.01	.0	.01	.02	.21	.07
6	.15	.21	.39	.18	.10	.02	.02	.0	.01	.01	.16	.06
7	.12	.21	.69	.18	.09	.03	.02	.0	.02	.01	.13	.06
8	.13	.21	.29	.18	.09	.02	.02	.0	.02	.01	.12	.06
9	.15	.23	.24	.17	.10	.02	.05	.0	.02	.01	.12	.06
10	.21	.20	.21	.18	.09	.02	16	.0	.01	85	.11	.06
11	.21	.21	.18	.18	.07	.02	.46	.0	.01	9.7	.11	.05
12	.24	.21	.20	.19	.08	.02	.06	.01	.01	53	.10	.06
13	.24	.21	.21	.18	.10	.02	.04	.01	.01	1.7	.10	.06
14	.23	.21	.20	.16	.10	.02	.03	.01	.01	.35	.09	.04
15	.23	.21	.21	.17	.09	.02	.02	.07	.01	.08	.09	.05
16	.24	.20	.17	.17	.09	.02	.02	.06	.01	.06	.09	.04
17	.25	.28	.15	.16	.07	.02	.02	.02	.01	.05	.09	.06
18	.24	.22	.13	.16	.10	.03	.02	.70	.01	.04	.07	.05
19	.22	.22	.13	.16	.11	.03	.01	.31	.01	.03	.07	.05
20	.23	.23	.51	.17	.09	.03	.01	.03	.01	.02	.07	[1].05
21	.22	.21	.34	.17	.09	.02	.0	.02	.01	.02	.08	.05
22	.21	.24	.69	.17	.08	.02	.0	.03	.0	47	.08	.06
23	.21	.23	.34	.17	.08	.03	.0	.02	.0	25	.07	.07
24	.22	.22	.26	.16	.07	.03	.0	.03	.0	365	.07	.07
25	.23	.20	.24	.16	.07	.03	.0	.07	.01	286	.07	[1].07
26	.30	.21	.22	.16	.08	.02	.0	102	.01	142	.06	[1].07
27	.21	.20	.22	.15	.08	.02	.0	2.0	.03	6.0	.07	.07
28	.20	.19	.47	.13	.08	.03	.0	.62	.01	11	.07	.07
29	.20	.20	.28	.12	.07	.02	.0	100	.01	12	.06	.07
30	.24	---	.78	.12	.07	.02	.0	9.4	.01	1.7	.06	.07
31	.21	---	1.1	---	.07	---	.0	.28	---	5.0	---	.06
TOTAL	6.43	6.23	10.17	5.82	2.80	0.96	16.88	215.75	0.34	1,050.88	9.04	1.85
MEAN	0.21	0.21	0.33	0.19	0.09	0.03	0.54	7.0	0.01	33.9	0.30	0.06
MAX	0.30	0.28	1.1	0.78	0.13	0.09	16	102	0.03	365	4.5	.07
MIN	0.12	0.19	0.13	0.12	0.07	0.02	0.0	0.0	0.0	0.01	.06	.04
AC-FT	13	12	20	12	5.6	1.9	33	428	0.7	2,080	18	3.7
CALENDAR YEAR 2000 TOTAL 1,327.15 MEAN 3.64 MAXIMUM 365 MINIMUM 0.0 ACRE-FT 2,632												

[1]Estimated.

Table 11. Date that data collection began and drainage areas for streamflow-gaging stations, Black Mesa area, Arizona

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

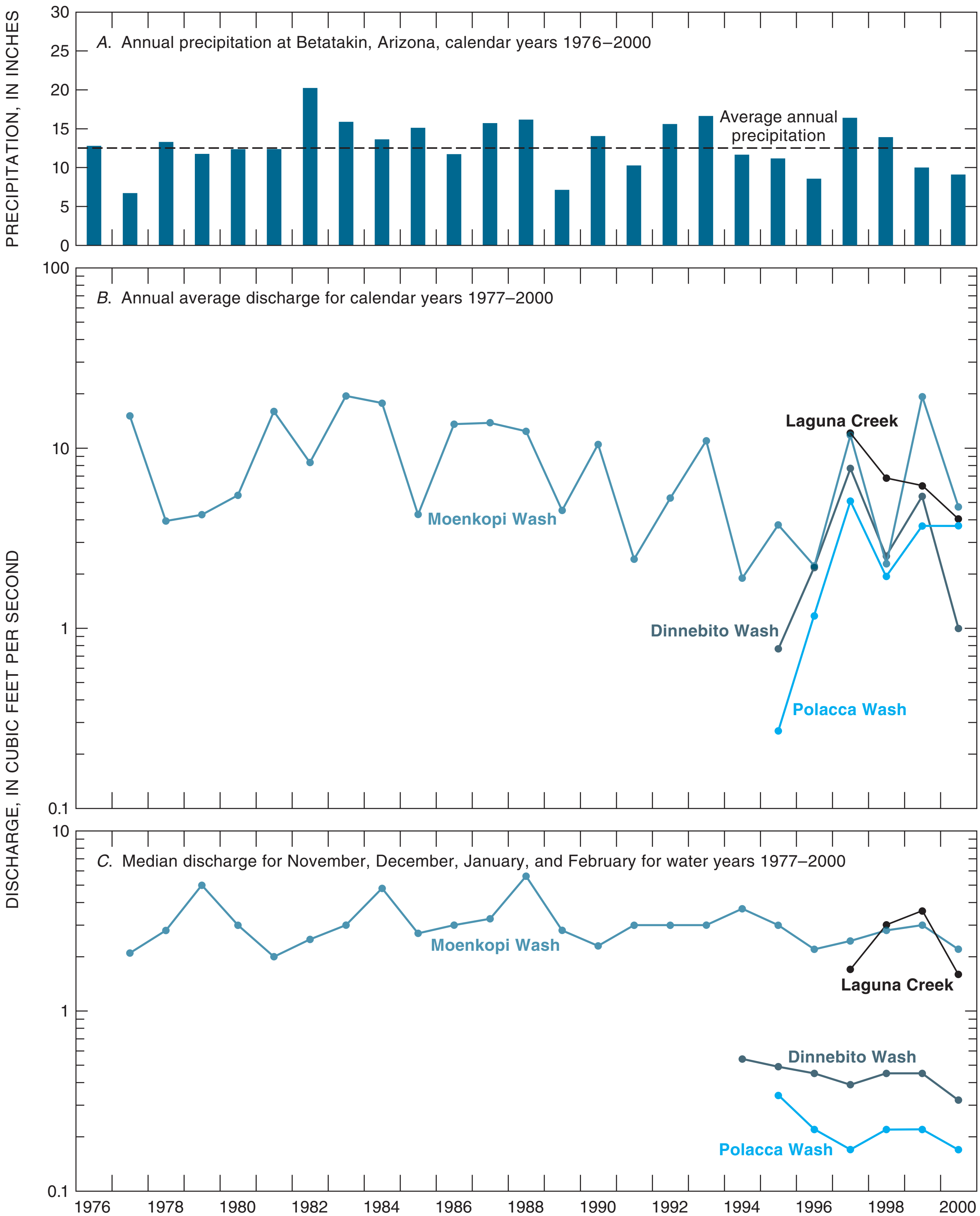

Figure 10. Annual precipitation at Betatakin, Arizona, and streamflow characteristics at Moenkopi Wash (09401260), Laguna Creek (09379180), Dinnebito Wash (09401110), and Polacca Wash (09400568), Black Mesa area, Arizona. *A*, Annual average precipitation at Betatakin, Arizona, calendar years 1976–2000 (National Weather Service). *B*, Annual average discharge for calendar years 1977–2000. *C*, Median discharge for November, December, January, and February for water years 1977–2000.

Water Chemistry

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

Water from Wells Completed in the N Aquifer

In 2001, water samples were collected from 12 wells completed in the N aquifer. Eleven of the wells are in confined parts of the aquifer, and one well (Red Lake PM1) is on the boundary between the confined and unconfined parts (**fig. 9**).

The primary types of water in the N aquifer are calcium bicarbonate and sodium bicarbonate. Calcium bicarbonate water generally is in the recharge areas of the northern and northwestern parts of the Black Mesa area, and sodium bicarbonate water is in the area that is downgradient to the south and east; this distribution was found in the water samples collected from the 12 wells in 2001. Samples from Kayenta PM2 in the north and from Red Lake PM1 in the northwest were calcium bicarbonate water, and samples from the other 10 wells were sodium bicarbonate water (**figs. 11** and **12**).

Dissolved-solids concentrations in water from the 12 wells ranged from 102 mg/L at Red Lake PM1 to 628 mg/L at Rough Rock PM5 (**table 12**, fig. 12). Two wells had appreciably higher concentrations of dissolved solids and chloride than the other 10 wells; Forest Lake NTUA 1 had a dissolved-solids concentration of 398 mg/L and a chloride concentration of 50 mg/L, and Rough Rock PM5 had a dissolved-solids concentration of 628 mg/L and a chloride concentration of 120 mg/L. Concentrations of dissolved solids in water samples from the other 10 wells ranged from 102 to 352 mg/L, and concentrations of chloride ranged from 1.3 to 7.1 mg/L. The areal distribution of dissolved solids generally was similar to the distribution of water types. Lower concentrations of dissolved solids are in the recharge areas of the north and northwest, and higher concentrations of dissolved solids are in areas to the south and east (fig. 12).

Trends in water chemistry over time were evaluated in water samples from 10 wells with data since about the mid-1980s or early 1990s (**table 13**, **fig. 13**). A Kendall's tau statistical test was made to determine if there are significant trends in the water-chemistry data from 7 wells with 8 or more years of data (Forest Lake NTUA 1, Hotevilla PM1, Kayenta PM2, Kykotsmovi PM2, Peabody 4, Rocky Ridge PM3, and Rough Rock PM5). For the 3 wells with insufficient data for statistical tests (Peabody 9, Red Lake PM1, and Second Mesa PM2), there does not appear to be any trends in the concentrations of dissolved solids, chloride, and sulfate (table 13). There are no significant trends in concentrations of dissolved solids, chloride, and sulfate in water samples from 6 of the 7 statistically tested wells (p-values were greater than 0.05). The concentration of one tested constituent (dissolved solids) in samples from Rocky Ridge PM3 significantly increased from 1990 to 2001 (p-value = 0.036).

The chemistry of water samples from the Forest Lake NTUA 1 well has varied considerably between 1982 and 2001 (table 13, fig. 13). This variation may be from insufficient purging of this deep well (2,674 ft) that has multiple well screens throughout an interval of about 800 ft from the lowest to highest screen (**table 5**).

Analyzed constituents from the 12 well samples were compared to U.S. Environmental Protection Agency (USEPA) Primary and Secondary Drinking-Water Regulations (U.S. Environmental Protection Agency, 2002). Maximum Contaminant Levels (MCLs), which are the primary regulations, are legally enforceable standards that apply to public water systems. MCLs protect drinking-water quality by limiting the levels of specific contaminants that can adversely affect public health. Secondary Maximum Contaminant Levels (SMCLs) provide guidelines for the control of contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. The USEPA recommends SMCLs for public water systems; however, compliance with these SMCLs is not mandatory.

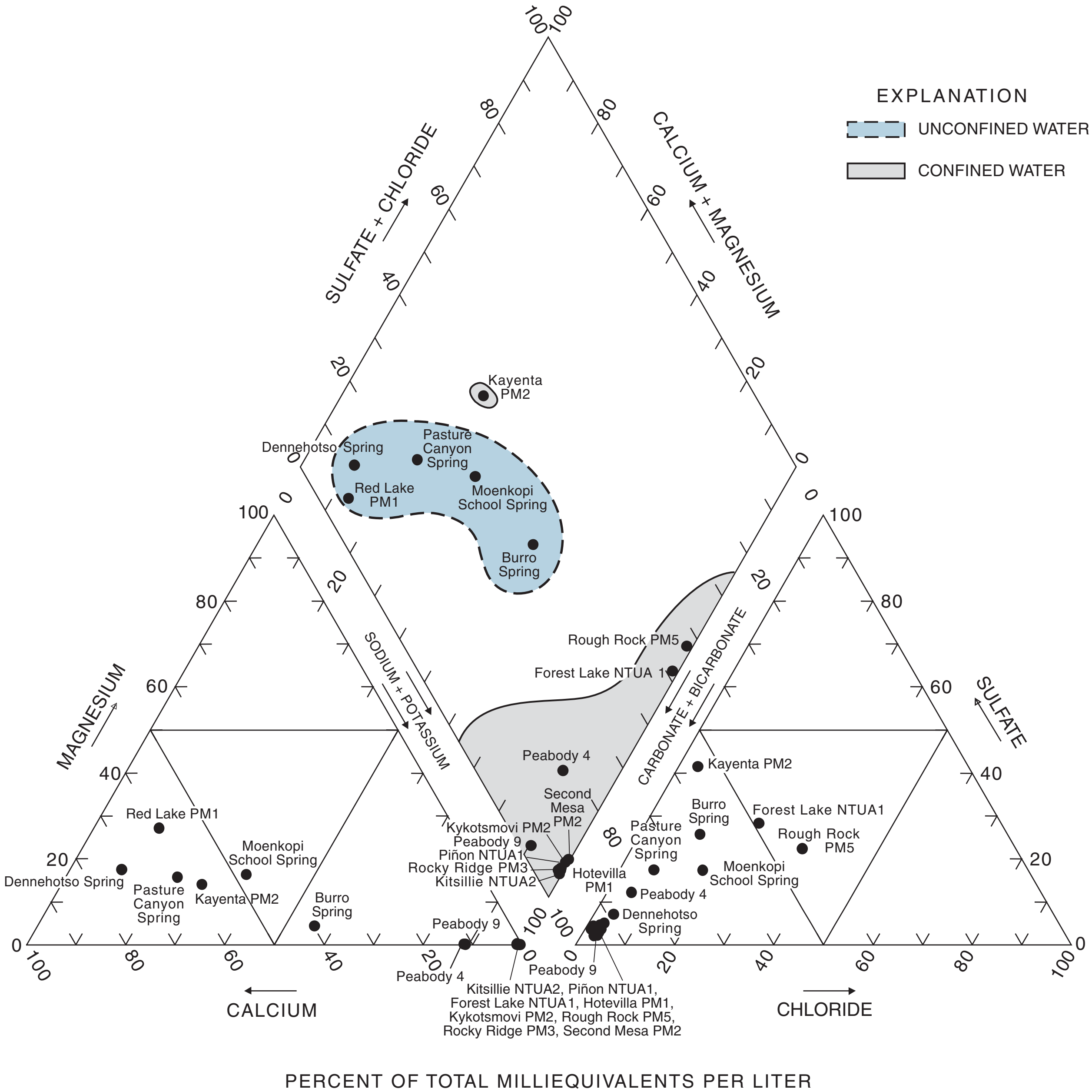

Figure 11. Relative chemical compositions of ground water from the N aquifer, Black Mesa area, Arizona, 2001.

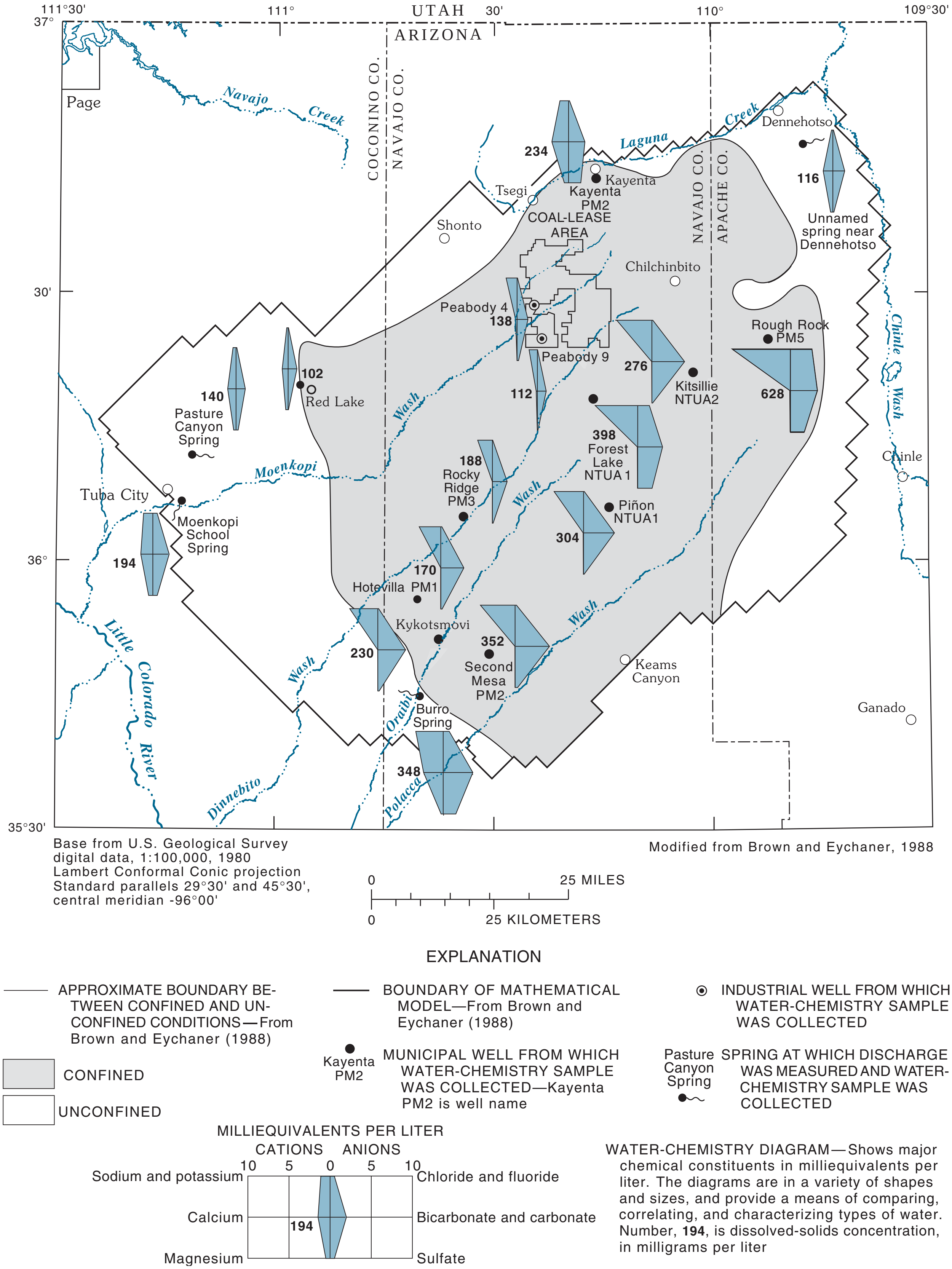

Figure 12. Water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, Arizona, 2001.

Table 12. Physical properties and chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 2001

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

Common well name	U.S. Geological Survey identification number	Date of sample	Temperature, field (°C)	Specific conductance, field (μS/cm)	pH, field (units)
Forest Lake NTUA1	361737110180301	04-03-01	28.5	584	9.2
Hotevilla PM1	355518110400301	06-11-01	26.1	267	9.6
Kayenta PM2	364344110151201	03-13-01	15.7	331	7.9
Kitsillie NTUA 2	362043110030501	04-03-01	11.5	409	9.6
Kykotsmovi PM2	355215110375001	04-06-01	22.4	339	9.6
Peabody 4	362647110243501	03-15-01	31.3	181	9.0
Peabody 9	362333110250001	03-15-01	31.5	88	8.8
Piñon NTUA1	360527110122501	04-04-01	26.3	473	9.8
Red Lake PM1	361933110565001	03-12-01	16.5	132	8.1
Rocky Ridge PM3	360422110353501	04-04-01	26.1	160	9.5
Rough Rock PM5	362418109514601	03-13-01	21.1	980	8.8
Second Mesa PM2	354749110300101	06-11-01	20.4	597	9.6

Common well name	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen NO_2+NO_3 dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
Forest Lake NTUA1	147	0.43	<0.02	1.1	0.10
Hotevilla PM1	137	1.0	.02	.65	.01
Kayenta PM2	100	.95	<.02	41	6.1
Kitsillie NTUA 2	197	1.4	<.02	.55	.02
Kykotsmovi PM2	171	1.2	.03	.49	.01
Peabody 4	89	.97	<.02	4.6	.03
Peabody 9	71	.73	<.02	3.6	.03
Piñon NTUA 1	252	1.3	<.02	.49	.01
Red Lake PM1	73	1.2	<.02	18	5.0
Rocky Ridge PM3	118	1.3	.02	.40	.01
Rough Rock PM5	218	1.0	<.02	1.9	.25
Second Mesa PM2	280	<.05	<.02	.42	.02

Table 12. Physical properties and chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 2001—Continued

Common well name	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)
Forest Lake NTUA1	121	0.70	50	84	1.0
Hotevilla PM1	63	.40	1.4	5.2	[1].1
Kayenta PM2	23	1.1	5.0	73	.2
Kitsillie NTUA 2	99	.50	5.0	4.5	1.6
Kykotsmovi PM2	79	.40	3.5	8.2	.2
Peabody 4	41	.60	4.0	13	.2
Peabody 9	30	.50	1.8	2.7	.2
Piñon NTUA 1	110	.30	4.9	5.5	.2
Red Lake PM1	4.6	1.9	1.8	2.2	.2
Rocky Ridge PM3	55	.40	1.3	5.4	[1].1
Rough Rock PM5	215	1.2	120	110	1.9
Second Mesa PM2	130	.40	7.1	15	.3

Common well name	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (μg/L as As)	Boron, dissolved (μg/L as B)	Iron, dissolved (μg/L as Fe)	Dissolved solids, residue at 180°C, (mg/L)
Forest Lake NTUA1	18	2.1	248	80	398
Hotevilla PM1	23	3.2	22	<10	170
Kayenta PM2	15	1.5	24	<10	234
Kitsillie NTUA 2	25	3.8	42	10	276
Kykotsmovi PM2	23	4.9	30	<10	230
Peabody 4	21	2.7	23	<10	138
Peabody 9	19	2.8	17	<10	112
Piñon NTUA 1	26	4.2	61	<10	304
Red Lake PM1	10	.4	20	<10	102
Rocky Ridge PM3	20	2.7	18	<10	188
Rough Rock PM5	12	45	383	[1]10	628
Second Mesa PM2	21	17	93	<10	352

[1]Estimated value.

Table 13. Specific conductance and concentrations of selected chemical constituents in water from industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1968–2001

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

Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Forest Lake NTUA 1				
1982	470	---	11	67
1990	375	226	8.2	38
1991	[1]350	183	10	24
1993	693	352	35	88
1994	[1]734	430	56	100
1995	470	274	13	60
1995	1,030	626	86	160
1995	488	316	16	71
1996	684	368	44	79
1997	[1]1,140	714	78	250
1998	489	350	37	71
1999	380	259	16	49
2001	584	398	50	84
Hotevilla PM1				
1990	290	192	1.6	5
1991	[1]304	208	.7	5.4
1993	305	180	1.2	5.5
1994	[1]307	166	1.4	4.8
1995	282	196	1.4	3.7
1996	328	186	1.3	5.3
1997	[1]307	185	1.5	5.2
2001	267	170	1.4	5.2
Kayenta PM2				
1982	360	([2])	4.5	58
1983	375	([2])	5.9	60
1984	[1]370	209	4.2	51
1986	300	181	8.2	30
1988	358	235	3.8	74
1992	383	210	5.6	78
1993	374	232	3.7	78
1994	[1]371	236	4.2	77
1995	371	250	4.2	72
1996	370	238	3.8	76
1997	379	230	3.9	77
1998	349	236	3.7	71
1999	364	236	4.0	72
2001	331	234	5.0	73
Kitsillie NTUA 2				
1997	[1]524	269	3.6	4.3
1998	379	270	3.8	4.1
1999	454	274	4.0	4.1
2001	409	276	5.0	4.5
Kykotsmovi PM2				
1988	368	212	3.2	8.6
1990	355	255	3.2	9.0
1991	[1]374	203	4.4	7.9
1992	363	212	3.3	8.4
1994	[1]365	212	3.6	8.5
1995	368	224	3.1	6.2
1996	365	224	3.3	8.5
1997	[1]379	222	3.0	8.0
1998	348	223	3.3	7.3
1999	317	221	3.5	7.9
2001	339	230	3.5	8.2
Peabody 4				
1974	200	140	3.8	13
1975	220	144	3.4	13
1976	240	138	2.9	19
1979	220	---	3.9	19
1980	230	139	4.3	13
1986	205	---	4.2	12
1987	194	135	[3]5.0	13
1992	224	125	4.3	12
1993	214	124	[3]3.0	12
1996	214	140	3.8	12
1997	[1]203	139	3.5	12
1999	216	142	4.0	13
2001	181	138	4.0	13
Peabody 9				
1986	181	---	3.1	4.9
1987	148	102	2.8	4.1
1990	158	106	1.6	3.0
1991	155	83	2.7	3.1
1993	157	94	1.6	2.9
1994	---	---	1.7	---
1995	154	122	1.6	1.6
1998	109	109	1.7	2.5
2001	88	112	1.8	2.7
Piñon NTUA 1				
1998	460	304	4.6	4.7
2001	473	304	4.9	5.5
Red Lake PM1				
1992	164	87	2.6	1.9
1993	156	84	1.6	2.1
1995	157	92	1.6	2.0

See footnotes at end of table.

Table 13. Specific conductance and concentrations of selected chemical constituents in water from industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1968–2001—Continued

Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Red Lake PM1—Continued				
1997	[1]156	96	3.2	1.7
1999	153	91	1.6	2.1
2001	132	102	1.8	2.2
Rocky Ridge PM3				
1976	270	---	5.3	3.8
1982	255	---	1.4	6.0
1990	222	126	1.5	6.0
1991	240	164	.7	6.8
1993	254	146	1.3	5.5
1994	248	152	1.4	5.5
1995	242	166	1.3	4.0
1996	256	156	2.0	5.8
1997	238	159	2.5	5.0
1998	222	164	3.2	5.0
2001	160	188	1.3	5.4
Rough Rock PM5				
1983	1,090	([2])	130	110
1984	[1]1,100	613	130	99
1986	1,010	633	140	120
Rough Rock PM5—Continued				
1988	1,120	624	130	[3]110
1991	[1]1,210	574	130	110
1993	1,040	614	130	110
1994	[1]1,070	626	130	110
1995	1,110	648	140	110
1996	1,100	634	130	110
1997	[1]1,060	628	130	110
1998	894	637	130	110
1999	1,050	630	130	110
2001	980	628	120	110
Second Mesa PM2				
1968	670	---	14	35
1990	590	364	6.5	16
1991	[1]595	292	10	15
1993	630	350	7.5	15
1994	[1]605	342	7.6	15
1995	610	357	7.2	14
1997	[1]646	356	7.1	14
2001	597	352	7.1	15

[1]Value is different in Black Mesa monitoring reports for 1999 and earlier years. The earlier reports showed values determined by laboratory analysis.
[2]Value is different in Black Mesa monitoring reports for 1999 and earlier years. The earlier reports showed values determined by the sum of constituents.
[3]Value is different in Black Mesa monitoring reports for 1999 and earlier years. The earlier reports applied a different rounding definition.

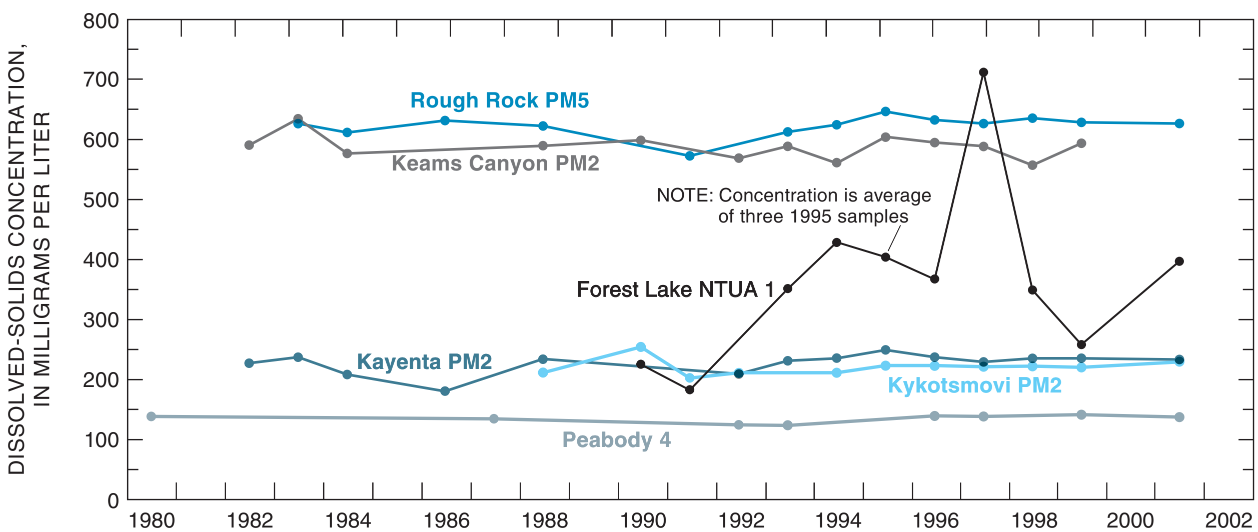

Figure 13. Dissolved-solids concentrations in water from wells Forest Lake NTUA 1, Kayenta PM2, Keams Canyon PM2, Kykotsmovi PM2, Rough Rock PM5, and Peabody 4, Black Mesa area, Arizona, 1980–2001.

The concentrations of most of the analyzed constituents from the 12 well samples were below MCLs and SMCLs. The pH level, however, exceeded the upper SMCL (8.5 units) in samples from 10 of the 12 wells. One other SMCL was exceeded; the sample from Rough Rock PM5 had a dissolved-solids concentration of 628 mg/L (the SMCL is 500 mg/L). Samples from two wells had arsenic concentrations that exceeded the MCL of 10 μg/L. Arsenic concentrations were 45 μg/L in the sample from Rough Rock PM5 and 17 μg/L in the sample from Second Mesa PM2.

Water from Springs that Discharge from the N Aquifer

In 2001, water samples were collected from four springs in the unconfined part of the N aquifer (**fig. 9**). Water samples from three of the springs—Pasture Canyon Spring, Moenkopi School Spring, and the unnamed spring near Dennehotso—were a calcium bicarbonate type and had low dissolved-solids concentrations (116 to 194 mg/L). The water sample from the fourth spring, Burro Spring, was a sodium bicarbonate type and had a much higher dissolved-solids concentration of 348 mg/L (**table 14**, **fig. 12**). Concentrations of all the analyzed constituents in samples from the four springs were below current USEPA MCLs and SMCLs (U.S. Environmental Protection Agency, 2002).

From the late 1980s to 2001, there are no significant trends in the concentrations of dissolved solids, chloride, and sulfate in water samples from Burro Spring, the unnamed spring near Dennehotso, and Pasture Canyon Spring (**table 15**); p-values from a Kendall's tau statistical test were greater than 0.05. From 1987 to 2001, concentrations of chloride and sulfate significantly increased in water samples from Moenkopi School Spring and concentrations of dissolved solids did not significantly change; the Kendall's tau p-values were 0.003 for chloride, 0.022 for sulfate, and 0.119 for dissolved solids.

PERFORMANCE AND SENSITIVITY OF THE 1988 USGS NUMERICAL MODEL OF THE N AQUIFER

Introduction

In the early 1980s, the U.S. Geological Survey developed a two-dimensional numerical model of the N aquifer in the Black Mesa area (Eychaner, 1983). A few years later, the model was updated and recalibrated by converting it to a new computer program and a finer spatial grid, and by revising estimates of selected aquifer properties (Brown and Eychaner, 1988). The 1988 model has been used to estimate the effects of industrial and municipal withdrawals on the N aquifer. Important effects include changes in water levels and changes in ground-water discharge to streams and springs.

This section describes results of an analysis of the performance and sensitivity of the 1988 USGS model of the N aquifer. The 1988 USGS model was constructed with data and information available in 1984. The performance analysis was done to determine how well the model has simulated 15 years of new water-level observation data (1985–99) and some additional and revised data before 1985. Numerical models of ground-water systems are constructed on the basis of available information and data, and if new data or information become available, testing the model's performance against that data will result in an increased understanding of the model and the ground-water system (Konikow and Bredehoeft, 1992). The sensitivity analysis was done to determine relations among the model parameters, observation data, and simulated values. Results of the performance and sensitivity analysis provide information that can be used to guide a data-collection plan and a study for updating and improving the model.

Objectives of this study were to (1) evaluate the performance of the model, (2) evaluate the sensitivity of the model, (3) determine potential revisions to improve the model on the basis of current data and information, and (4) determine potential new data and studies to improve the model. It was beyond the scope of the study to (1) recalibrate the model using trial-and-error or parameter-estimation techniques, (2) evaluate alternative conceptual models, or (3) evaluate the reliability and technical correctness of the model boundaries, hydraulic properties, and water budget.

Two previous studies evaluated the 1988 USGS model of the N aquifer. Papadopolus and Associates, Inc. (1993) evaluated the model by examining the quality of the input data and technical correctness of the model. Waterstone Environmental Hydrology and Engineering, Inc. (1995) used the parameter estimation model MODFLOWP (Hill, 1992) to evaluate the reliability and statistical uncertainty of the model parameters and input data through 1993. The limited scope of this study was to analyze model performance through 1999 and to determine sensitivity relations that provide information for updating and improving the model.

Table 14. Physical properties and chemical analyses of water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 2001

[°C, degree Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than. Dashes indicate no data]

Spring name	Bureau of Indian Affairs site number	U.S. Geological Survey identification number	Date of sample	Temperature (°C)	Specific conductance, field (µS/cm)	pH (field) (units)
Burro Spring	6M-31	354156110413701	04-02-01	22.0	480	8.5
Unnamed spring near Dennehotso	8A-224	364656109425400	03-14-01	11.0	176	8.3
Moenkopi School Spring	3GS–77–6	360632111131101	03-12-01	16.6	313	7.5
Pasture Canyon Spring	3A-5	361021111115901	06-12-01	16.5	236	7.6

Spring name	Alkalinity, field, dissolved (mg/L as $CaCO_3$)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Hardness (mg/L as $CaCO_3$)	Hardness, non carbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)
Burro Spring	170	0.13	<0.02	130	---	46
Unnamed spring near Dennehotso	78	1.5	.02	78	---	25
Moenkopi School Spring	104	2.4	<.02	99	---	30
Pasture Canyon Spring	75	4.4	<.02	85	---	27

Spring name	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)
Burro Spring	3.1	74	0.4	24	68	0.4
Unnamed spring near Dennehotso	3.7	4.2	1.0	2.6	6.0	.2
Moenkopi School Spring	6.2	26	1.3	18	26	.2
Pasture Canyon Spring	4.2	11	1.2	5.1	17	.2

Spring name	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Burro Spring	13	0.7	75	<10	348
Unnamed spring near Dennehotso	12	2.5	18	<10	116
Moenkopi School Spring	13	2.5	44	<10	194
Pasture Canyon Spring	9.4	1.7	25	<10	140

Table 15. Specific conductance and concentrations of selected chemical constituents in water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 1948–2001

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

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Burro Spring				
1989	485	308	22	59
1990	[1]545	347	23	65
1993	595	368	30	85
1994	[1]597	368	26	80
1996	525	324	23	62
1997	[1]511	332	26	75
1998	504	346	25	70
1999	545	346	25	69
2001	480	348	24	68
Unnamed spring near Dennehotso				
1984	195	112	2.8	7.1
1987	178	[2]109	3.4	7.5
1992	178	108	3.6	7.3
1993	184	100	3.2	8
1995	184	124	2.6	5.7
1996	189	112	2.8	8.2
1997	[1]170	98	2.4	6.1
1998	179	116	2.4	5.4
1999	184	110	2.8	6.3
2001	176	116	2.6	6.0
Moenkopi School Spring				
1952	222	---	6	---
1987	270	161	12	19
1988	270	155	12	19
1991	297	157	14	20
1993	313	204	17	27
1994	305	182	17	23
1995	314	206	18	22
1996	332	196	19	26
1997	[1]305	185	18	24
1998	296	188	18	24
1999	305	192	19	26
2001	313	194	18	26
Pasture Canyon Spring				
1948	[1]227	([2])	5	13
1982	240	---	5.1	18
1986	257	---	5.4	19
1988	232	146	5.3	18
1992	235	168	7.1	17
1993	242	134	5.3	17
1995	235	152	4.8	14
1996	238	130	4.7	15
1997	232	143	5.3	17
1998	232	147	5.1	16
1999	235	142	5.1	14
2001	236	140	5.1	17

[1]Value is different in Black Mesa monitoring reports for 1999 and earlier years. Earlier reports showed values from laboratory analysis.
[2]Value is different in Black Mesa monitoring reports for 1999 and earlier years. Earlier reports showed values determined by the sum of constituents.

The two-dimensional 1988 USGS model was constructed using the MODFLOW program (McDonald and Harbaugh, 1984). The center of the model area is simulated as confined and the outside margins are simulated as unconfined (**fig. 5**). All lateral boundaries are no-flow boundaries, except for a narrow neck in the northeast, which is simulated as outflow. Recharge from precipitation is simulated as specified flux on N-aquifer outcrop areas around the margins of the model (**fig. 14**). Downward leakage from the D aquifer is simulated with the general head boundary (fig. 14). Ground-water discharge is simulated with the river, drain, and evapotranspiration boundaries (**fig. 15**). The lower boundary is assumed to be no-flow. The distributions of two of the most important hydraulic properties of the model—hydraulic conductivity and transmissivity—are shown in **figures 16** and **17**. Detailed information about the natural aquifer system and the model representation of the system were reported by Eychaner (1983) and Brown and Eychaner (1988).

Approach

The performance of the model was determined by evaluating the match between simulated and observed data for steady-state (before 1965) and transient (1965 to 1999) simulations. The 1988 USGS model included data through 1984, so withdrawal data from 1985 to 1999 were added to run the model from steady state to 1999. The amounts of annual ground-water withdrawals used in the model from 1965 to 1999 are shown in **table 1** and **figure 3**. No changes were made to the calibrated boundaries or parameter values of the 1988 model.

The 1988 model was calibrated using 123 steady-state heads, water-level changes in 6 continuous observation wells, and estimated ground-water discharge to 3 streams (**table 16**). This study analyzed the model using 126 steady-state heads, 331 water levels measured in 38 wells from 1965 to 1999, and estimated ground-water discharge to 3 streams and 1 group of springs (table 16 and **fig. 18**).

In addition to the new data from 1985 to 1999, a few changes were made to the observation data used in the 1988 model. In 1994, a differential-global-positioning-system (DGPS) survey determined new latitude, longitude, and land-surface altitude at 43 wells. The new DGPS data resulted in changes to the steady-state heads at those 43 wells and changes to the model cells for 12 wells. The maximum change in steady-state head was 25 ft; 95 percent of the changes were less than an absolute value of 15 ft, and 74 percent of the changes were less than an absolute value of 10 ft. There was no large areal bias in the changes in heads. Because of these changes in heads and cell locations, the statistics of steady-state model performance for this analysis are slightly different than the statistics for the 1988 model. The overall interpretation, however, was not changed.

New estimates of ground-water discharges also were made for this study. Discharge to Moenkopi Wash was estimated to be 3.1 ft^3/s. The discharge was assumed to equal the average of the median winter streamflows during water years 1977–2000 at Moenkopi Wash at Moenkopi, Arizona (09401260; **fig. 10**c). Water years 1977–2000 are during a period of ground-water withdrawals in the Black Mesa area (fig. 3). The median winter flows calculated from the gaging-station record, however, are assumed to represent steady-state ground-water discharge because (1) there appears to be no appreciable water-level declines in the unconfined area of the N aquifer that discharges to Moenkopi Wash (fig. 5), (2) the Peabody Western Coal Company withdrawal wells are about 40 miles from the nearest point of ground-water discharge to Moenkopi Wash (**fig. 4**), and (3) there is no significant trend in the median winter flows from 1977 to 2000.

The 1988 model used a different value for discharge to Moenkopi Wash. Eychaner (1983, p. 10) estimated a base flow of 5.3 ft^3/s from streamflow records during water years 1926–41 at Moenkopi Wash near Tuba, Arizona. The new estimate of discharge to Moenkopi Wash was made because the streamflow data from the gaging station used in this study are more representative of N-aquifer discharge than the data from the gaging station used by Eychaner (1983). The station used in this study is about 1.5 mile inside (east) of the model boundary (**fig. 9**), and the station used by Eychaner (1983) was about 5.5 miles outside (west) of the model boundary. Base flow at the gaging station used by Eychaner (1983) includes some discharge from ground water below the N aquifer and some discharge from springs in the Tuba City area.

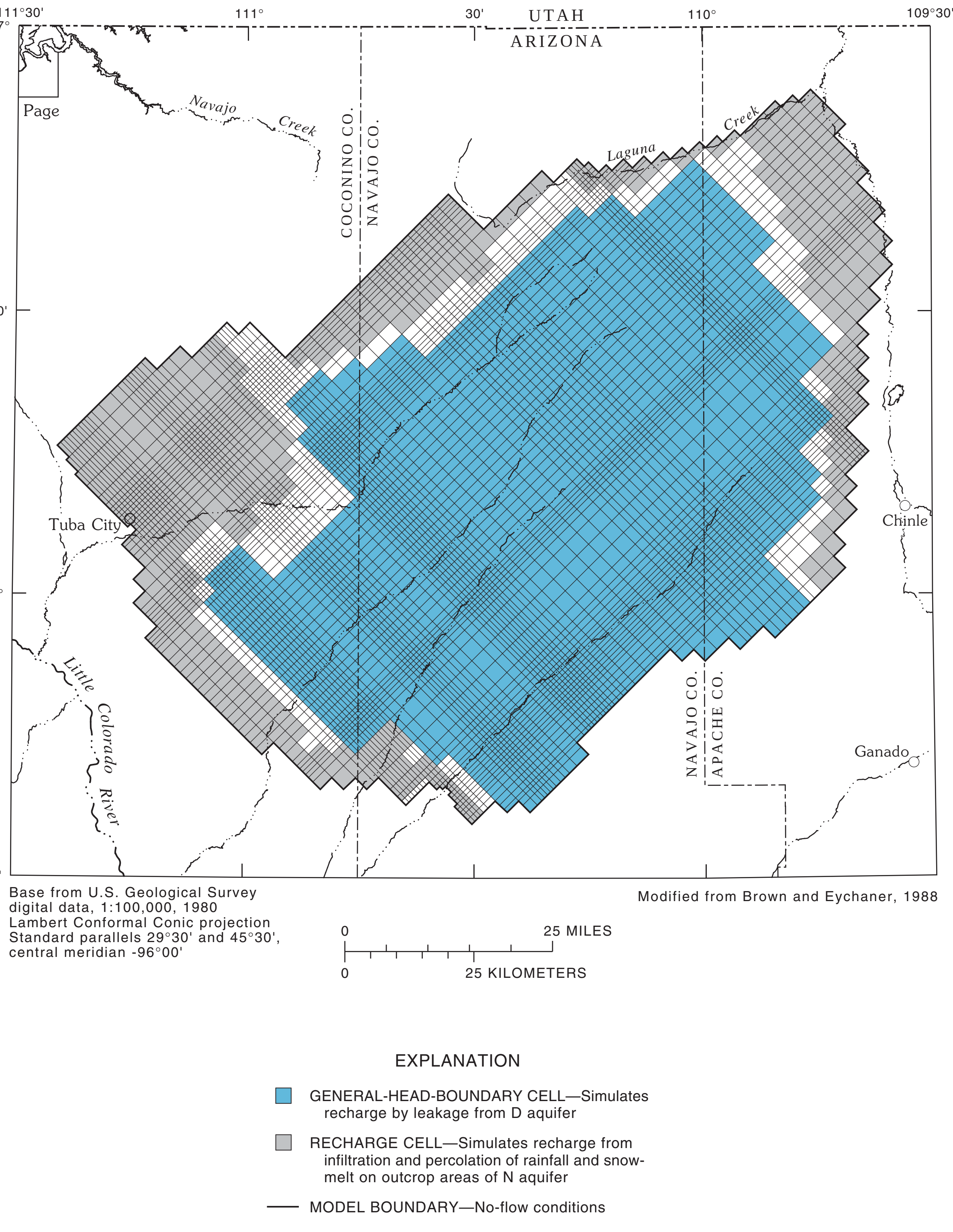

Figure 14. Grid for 1988 USGS model of the N aquifer (Brown and Eychaner, 1988) and boundary conditions used to simulate ground-water recharge, Black Mesa area, Arizona.

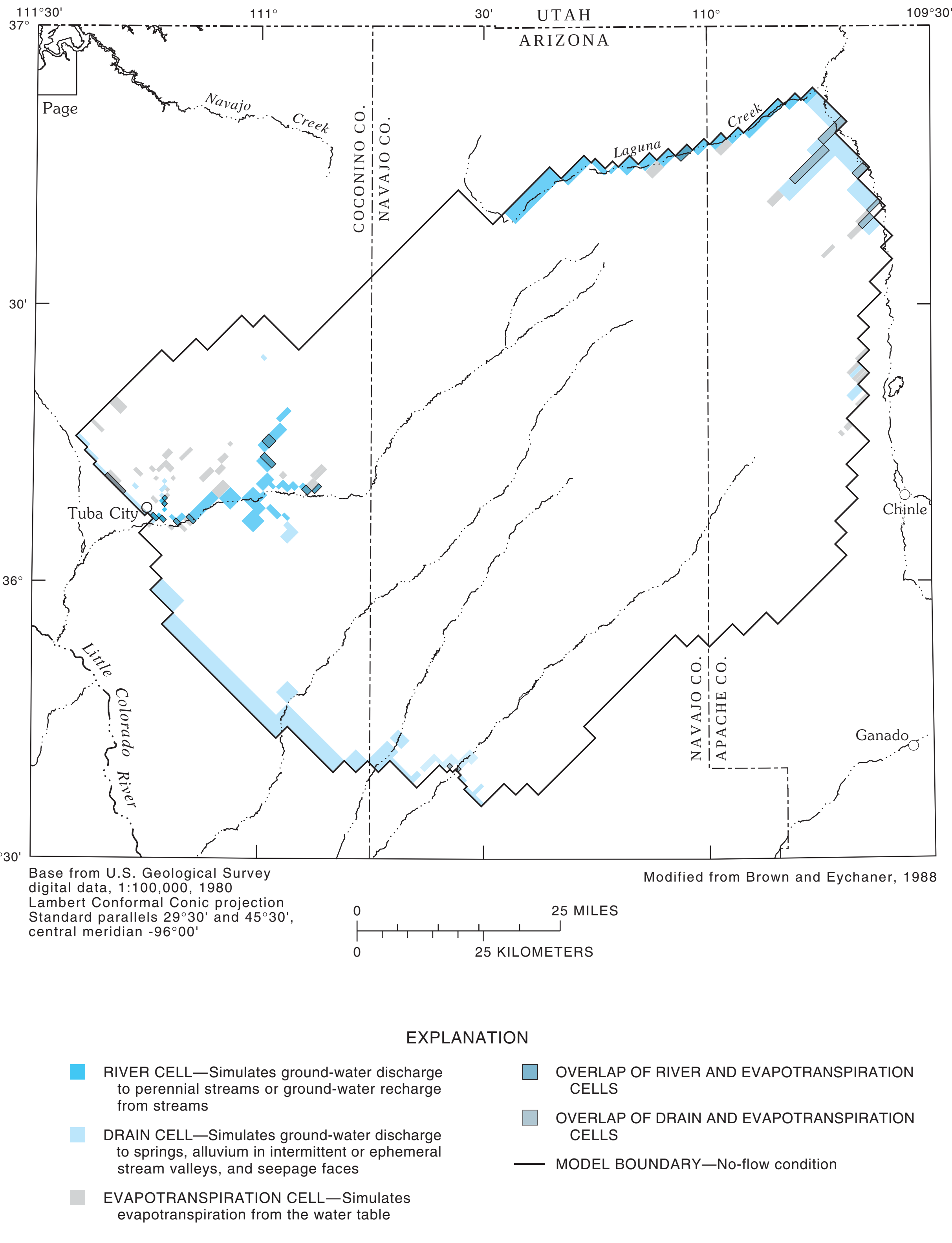

Figure 15. Boundary of 1988 USGS model of the N aquifer (Brown and Eychaner, 1988) and boundary conditions used to simulate ground-water discharge, Black Mesa area, Arizona.

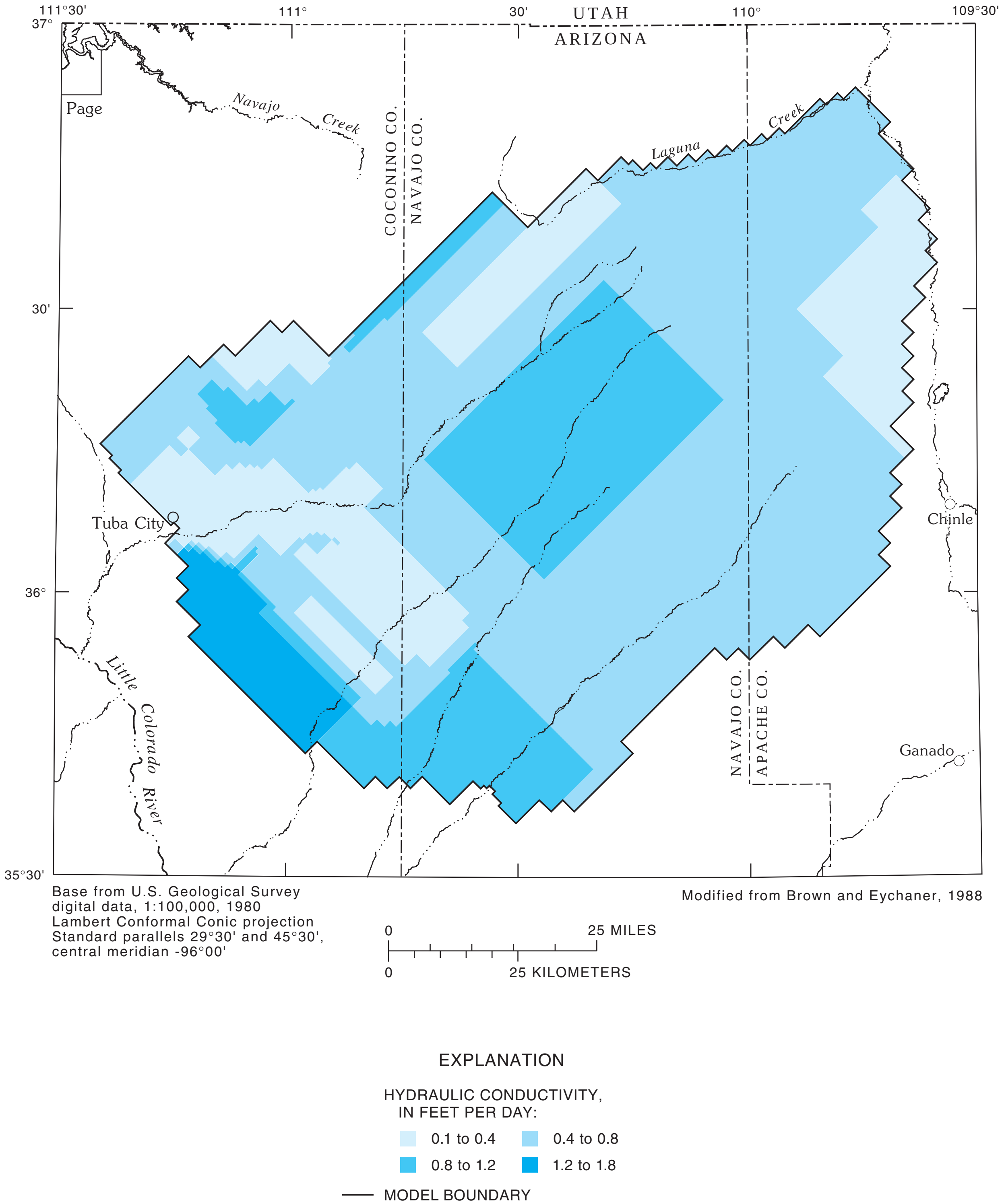

Figure 16. Distribution of hydraulic conductivity used in the 1988 USGS model of the N aquifer (Brown and Eychaner, 1988), Black Mesa area, Arizona.

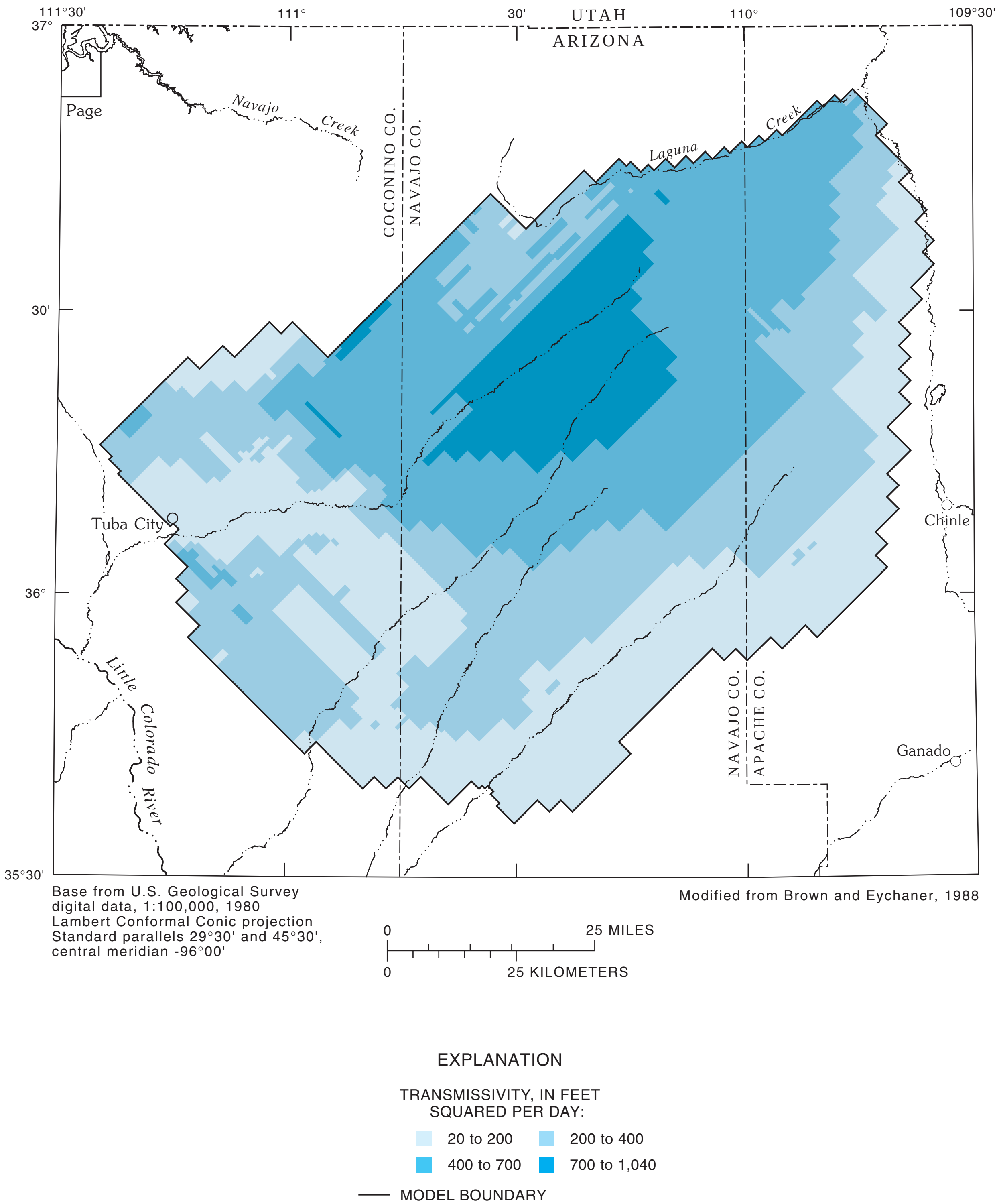

Figure 17. Distribution of transmissivity used in the 1988 USGS model of the N aquifer (Brown and Eychaner, 1988), Black Mesa area, Arizona.

Table 16. Observation data used in the 1988 USGS model of the N aquifer and in the analysis of the 1988 model for this report, Black Mesa area, Arizona

[1988 USGS model by Brown and Eychaner (1988)]

Type of observation	Observations used in 1988 model		Observations used in analysis of model for this report	
	Number	Time period in model	Number	Time period in model
Steady-state heads	123 heads in 123 wells	[1]Steady state	126 heads in 126 wells	[1]Steady state
Changes in heads	[2]Changes in heads in 6 wells	1965–84	331 changes in heads in 38 wells	1965–99
Flows (ground-water discharge)	Flows in: Laguna Creek and Chinle Wash Moenkopi Wash	Steady state and 1965–84	Flows in: Laguna Creek and Chinle Wash Moenkopi Wash Moenkopi School Spring and Pasture Canyon Spring	[3]Steady state and 1965–99
Withdrawals	Withdrawals from 4 wells in 1965 and 57 wells in 1984	1965–84	Withdrawals from 4 wells in 1965 and 73 wells in 1999	1965–99

[1]Steady state is before 1965, actual period of observations is 1945 to 1972. Observations during 1965–72 are in areas not affected by withdrawals.

[2]Changes in heads at the six continuous observation wells were primarily used for evaluation of model performance, and an unknown number of other changes in heads were evaluated

[3]Actual period of data used for independent estimates (observations) of flows is variable, see pages 41 and 46 of text.

An initial estimate of a combined ground-water discharge to Laguna Creek and Chinle Wash was 4.0 ft^3/s (Eychaner, 1983, p. 10). Discharge to Chinle Wash was assumed to be 25 percent of the total flow (1.0 ft^3/s) and this discharge was decreased by 20 percent (0.2 ft^3/s) because there is some ground-water discharge to Chinle Wash from aquifers outside this study area. The final estimate for total discharge to Laguna Creek and Chinle Wash was, therefore, 3.8 ft^3/s. Discharges to two springs near Tuba City were estimated from measured flows. A discharge of 210 gal/m (0.47 ft^3/s) to Pasture Canyon Spring was estimated from a measured flow in 1948 (S.C. Brown and L.C. Halpenny, U.S. Geological Survey, written commun., 1948). A discharge of 40 gal/m (0.09 ft^3/s) to Moenkopi School Spring was estimated from a measured flow in 1952 (**table 6**). For the analysis of model performance, discharges to Moenkopi School Spring and Pasture Canyon Spring were combined into one observation. The cells representing these springs are adjacent to each other (**figs. 9** and **15**).

Sensitivity of the 1988 USGS model was analyzed using techniques and indices available in the MODFLOWP inverse modeling program (Hill, 1992). The model was run from steady state (before 1965) to 1999, and sensitivities and correlations were calculated for parameters and the new observation data set. The purpose of this sensitivity analysis was to evaluate the calibrated parameters and boundaries of the 1988 USGS model; so MODFLOWP was used with the parameter-estimation option and was forced to converge at the 1988 parameter values (Hill, 1992).

All the model boundaries and parameter values in the 1988 USGS model were used in the MODFLOWP application except for one change. The 1988 USGS model used the convertible-layer option for simulations in MODFLOW where cells can convert back and forth between unconfined and confined conditions (McDonald and Harbaugh, 1984). Part of the N aquifer in the Black Mesa area is confined and part is unconfined. The MODFLOWP program used in this analysis could not perform this process; it could only accommodate all confined or all unconfined simulations. For this analysis, therefore, transmissivity was used for the entire model area. The unconfined cells in the 1988 USGS model were assigned the unconfined storage coefficient and the confined cells were assigned the confined storage coefficient.

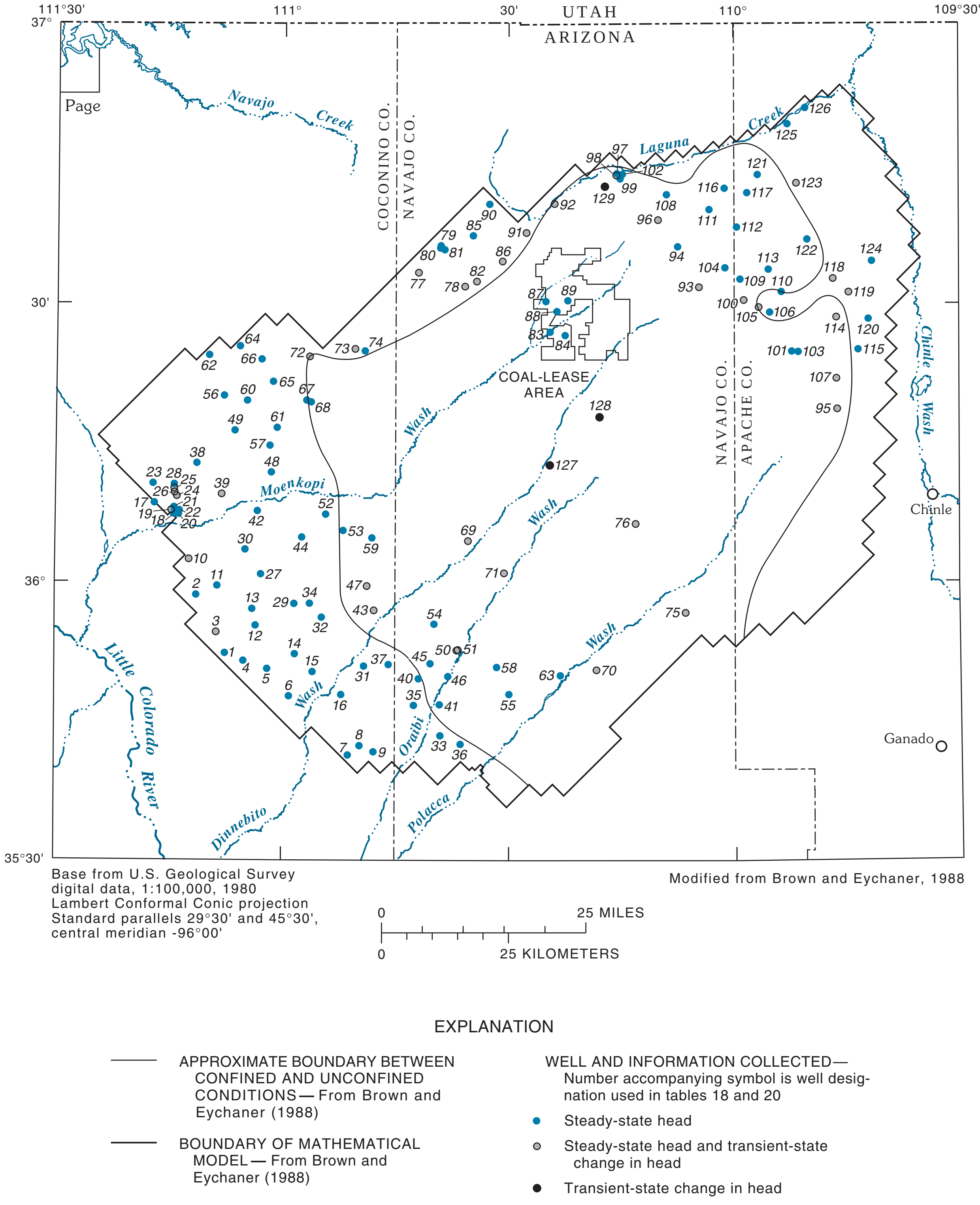

Figure 18. Locations of observation wells used in the performance and sensitivity analysis of the 1988 USGS model of the N aquifer (Brown and Eychaner, 1988), Black Mesa area, Arizona.

Transmissivity was calculated from the hydraulic conductivity and top and bottom altitudes of the N aquifer in confined areas, and from the hydraulic conductivity, water-table altitude, and bottom altitude of the N aquifer in unconfined areas.

To determine if the change made for MODFLOWP was reasonable for this analysis, the MODFLOWP model with transmissivity and the MODFLOW model with a convertible layer were run through 1999 and the results were compared. The simulated steady-state heads and budget components were within 0.1 percent, and simulated transient-state budget components were within 1 percent for all stress periods. Most of the simulated changes in heads in 1999 were within 1 ft for both models. The only area with appreciable differences in head changes was the unconfined area near Tuba City. Several of the cells with pumped wells had negative head changes between 5 and 10 ft greater in the MODFLOW convertible model than in the MODFLOWP transmissivity model. Some nearby cells also had head changes that were different by 1 to 5 ft in the two models. These differences in simulated changes in heads had no effect on the results of the performance analysis in this report because the performance analysis used the MODFLOW convertible model.

The differences in the MODFLOW convertible model and MODFLOWP transmissivity model had a small effect on the sensitivity analysis. The magnitudes of sensitivities and parameter correlation coefficients are determined by the model boundaries, parameter values, and observations. The differences in the two models had no effect on the sensitivity analysis of steady-state conditions because the boundaries, parameter values, and observations are exactly the same in both models. There was a small effect on the sensitivity analysis of transient conditions because the MODFLOW convertible model used slightly smaller transmissivity values in the Tuba City area in the later years of the transient simulation. The parts of the magnitudes of sensitivities and parameter correlation coefficients that are determined by the observations used in the model would be no different between the MODFLOW convertible model and the MODFLOWP transmissivity model because the same observations are used in both models and the sensitivities and correlation coefficients are independent of model fit (Hill, 1998, p. 15 and 38).

MODFLOWP requires weights to be assigned to all observations. The weights are based on estimated measurement errors of the observations. Consequences of the weighting are that (1) relatively accurate measurements are weighted more heavily than relatively inaccurate measurements in a regression analysis, (2) different types of observations with different units can be summed and combined in a regression analysis, and (3) different types of observations can be combined into composite sensitivities that are used to evaluate the model. It was beyond the scope of this study to perform a regression analysis, but composite sensitivities were analyzed.

For this study, measurement errors were assigned to steady-state heads, transient changes in heads, and flows. Errors for heads were based on estimated errors in land-surface altitudes and estimated errors in the actual measurement of depth to water in a well. The measurement-error statistics were estimated using guidelines presented in Hill (1998, p. 45–49). Information or assumptions used to estimate the errors were: (1) measurements of depths to water by the USGS were assumed to be accurate to within 0.2 ft, (2) measurements of depths to water reported from a driller were assumed to be accurate to within 1.2 ft, (3) all topographic maps were assumed to have a 20-ft contour interval, (4) land-surface altitudes determined from DGPS data were assumed to be accurate to within 0.5 ft, and (5) a 90-percent confidence interval was used in equations presented in Hill (1998, p. 45–49).

Steady-state heads could have one of four errors. Heads measured by the USGS had (1) a standard deviation of 6.18 ft for wells with land-surface altitudes determined from a map or (2) a standard deviation of 0.42 ft for wells with altitudes determined from DGPS data. Heads reported from a driller had (3) a standard deviation of 6.79 ft for wells with altitudes from a map or (4) a standard deviation of 1.03 ft for wells with altitudes from DGPS data. Changes in heads from initial heads measured by the USGS had a standard deviation of 0.17 ft, and changes in heads from initial heads reported from a driller had a standard deviation of 0.74 ft.

The ground-water discharge estimated for Moenkopi Wash (3.1 ft^3/s) was assigned a measurement error equal to the standard deviation of the median winter flows in the streamflow record. The standard deviation of 0.91 ft^3/s converts to a coefficient of variation (COV) of 29 percent. A similar method was used to estimate the measurement error of the 3.8 ft^3/s discharge to Laguna Creek and Chinle Wash. Median winter flows were calculated for the streamflow record during water years 1965–2000 at Chinle Creek near Mexican Water, Arizona (09379200). Station 09379200 is about 5 miles downstream of the confluence of Laguna Creek and Chinle Wash. The average of 27 median winter flows was 4.1 ft^3/s and the standard deviation was 1.51 ft^3/s (COV of 38 percent). Nine of the median winter flows were removed from the analysis because the median flows were obviously influenced by sustained winter runoff of rainfall or snowmelt. There was no trend in the median winter flows during 1965–2000. The COV of 38 percent was used for the measurement error for the 3.8 ft^3/s value resulting in a standard deviation of 1.44 ft^3/s. There were no long-term measurement data for discharge to Pasture Canyon Spring and Moenkopi School Spring, so the estimated discharge of 0.56 ft^3/s was assigned a measurement error equal to a COV of 30 percent, which is between the measurement errors estimated for Moenkopi Wash and for Laguna Creek and Chinle Wash.

The sensitivity of the 1988 USGS model was analyzed using sensitivities and parameter correlation coefficients calculated by MODFLOWP. Sensitivities show the relations among model parameters, observation data, and simulated values. Correlation coefficients show the strength of association between pairs of parameters. Seven parameters were analyzed: (1) transmissivity, (2) recharge, (3) storage coefficient, (4) river-boundary conductance, (5) drain-boundary conductance, (6) general-head-boundary conductance, and (7) maximum evapotranspiration rate. Locations and distributions of these parameters are shown in figures 14–17. Information about how these parameters were estimated and defined is in Eychaner (1983) and Brown and Eychaner (1988). Three types of sensitivities were calculated for this analysis.

Dimensionless scaled sensitivities were calculated for observations, and they are made dimensionless by a weighting factor, which accounts for the measurement error of the observation. These sensitivities indicate the importance of different observations to the estimation of a single parameter or the importance of different parameters to the calculation of a simulated value (Hill, 1998).

Composite scaled sensitivities were calculated for each parameter using the dimensionless scaled sensitivities for observations, and they indicate the total amount of information provided by the observations for the estimation of each parameter. Composite scaled sensitivities reflect how well the parameters are defined by the available observations and indicate how well the parameters would be estimated by an inverse model. Generally, a parameter with a large composite scaled sensitivity can be estimated with a small confidence interval relative to a parameter with a smaller composite scaled sensitivity (Hill, 1998).

One-percent scaled sensitivities were calculated for the entire model grid and they are approximately equal to the amount that a simulated value would change if the parameter value increased by one percent. One-percent scaled sensitivities have the same units as the simulated values. For this study, one-percent sensitivities were calculated for steady-state heads and for changes in head from steady state (before 1965) to 1999. A map of this sensitivity for a parameter can be used to compare the areal distribution of sensitivities for that parameter and to identify where additional observations would be most important to the estimation of that parameter (Hill, 1998).

Correlations between parameters are important because they are indicators of the uniqueness of a model. If a pair of parameters has a large correlation coefficient, the model is not unique and several models could be developed with different values for those parameters and still have similar fits to the observation data. The most common example of a pair of parameters with a large correlation coefficient is transmissivity and recharge.

Because the simulated values of a numerical ground-water model are nonlinear with respect to many estimated parameters, the results of this sensitivity analysis are only applicable to the model boundaries and parameter values of the 1988 USGS model and the observations used in this analysis. Using a different set of model boundaries, parameter values, or observations could provide different results, but the major characteristics of the results would likely be similar (Anderman and Hill, 1997, p. 28).

The last part of this study was to determine potential revisions to improve the model that could be done on the basis of current data and information, and to determine potential new data and studies that could improve the model. Results of the analysis of performance and sensitivity were compared with current data and information to accomplish these objectives.

Performance of Model

The overall performance of the model for steady-state conditions is reasonable for residuals of heads (difference between observed and simulated heads); the mean residual is 5.3 ft, median residual is -0.2 ft, root mean square error of residuals is 35 ft, and 80 percent of the absolute values of residuals are less than 38 ft (**tables 17** and **18**). There is a small overall positive bias (**fig. 19**) and a small positive areal bias in the Shonto, west-central, and Tuba City areas (**fig. 20**). Positive bias is where simulated heads are consistently lower than observed heads. The Shonto area is the principal recharge area with the highest steady-state heads of the model area. The Tuba City area is the principal discharge area of the western part of the model area (fig. 20).

Simulated steady-state flows do not agree well with two of the three observed (estimated) flows (**table 19**). Simulated flow in Moenkopi Wash is 40 percent larger than the observed flow, and simulated flow for Moenkopi School Spring and Pasture Canyon Spring is 38 percent less than the observed flow. Simulated flow is within 2 percent of observed flow in Laguna Creek and Chinle Wash. This comparison between simulated and observed (estimated) flows, however, is only a rough approximation of performance because the accuracy of the observed flow values is uncertain.

The overall performance of the model for transient conditions is fair for residuals of changes in head (difference between observed and simulated changes in head); the mean residual for changes in head from steady state to 1999 is 4.3 ft, median residual is 3.6 ft, root mean square error of residuals is 40 ft, and 80 percent of the absolute values of residuals are less than 31 ft (tables 17 and 20; figs. 7, 8, and 19). The model performance is biased in two areas. In the Tuba City area where the aquifer is unconfined, simulated changes in head are much more negative than observed changes in head (**fig. 21**); all six residuals are positive and three of the six residuals are between 75 and 155 ft. In the confined area of the aquifer (fig. 21), observed changes in head are more negative than simulated changes in head; 12 of the 17 residuals are negative and 8 of the residuals are between -57 and -20 ft. The model performance could not be evaluated for changes in flows because there are no independent estimates or observations of changes in flows from 1965 to 1999.

Residuals for changes in head increase in magnitude as the time of simulation increases (**fig. 22**). This relation is not surprising because the model was calibrated with data only through 1984. This relation also points out the need to periodically evaluate the performance of a ground-water model as new observation data become available.

Sensitivity of Model

The sensitivity of the model was evaluated using calculated sensitivities for parameters, observations, and simulated values, and correlations between parameters. Evaluated parameters were storage coefficient, transmissivity, recharge, maximum evapotranspiration rate, river-boundary conductance, drain-boundary conductance, and general-head-boundary conductance. Evaluated observations and simulated values were steady-state heads, changes in heads, and flows (ground-water discharge).

The combined observations (steady-state heads, transient changes in heads, and flows) contain substantial information about storage coefficient, transmissivity, and recharge; moderate information about conductance for river, drain, and general-head boundaries; and little information about maximum evapotranspiration rate (**fig. 23**). Stated from another perspective, the combined observations are most sensitive to storage coefficient, transmissivity, and recharge, moderately sensitive to boundary conductances, and least sensitive to evapotranspiration.

Steady-state heads are most sensitive to transmissivity and recharge; moderately sensitive to conductance for river, drain, and general-head boundaries; and least sensitive to maximum evapotranspiration rate. Transient changes in heads are most sensitive to storage coefficient and transmissivity; moderately sensitive to recharge, river conductance, and general-head-boundary conductance; and least sensitive to drain conductance and maximum evapotranspiration rate.

The flow observations are less sensitive to parameters than the steady-state head and transient change-in-head observations. Composite scaled sensitivities for flow observations range from 0.01 to 1.9 and composite scaled sensitivities for heads and changes in heads range from 0.02 to 310. Flow observations are most sensitive to transmissivity, recharge, river conductance, and drain conductance; moderately sensitive to storage coefficient; and least sensitive to maximum evapotranspiration rate and general-head-boundary conductance (fig. 23).

Table 17. Summary of residuals for steady-state heads and changes in heads from steady state to 1999, Black Mesa area, Arizona

[residual equals observed value minus simulated value]

Type of observation	Number of observations	Mean residual, in feet	Median residual, in feet	Root mean square error of residuals, in feet	80th percentile of absolute value of residuals, in feet
Steady-state head	126	5.3	-0.2	34.9	38
Change in head from steady state to 1999	33	4.3	3.6	39.7	31

Table 18. Observed heads, simulated heads, and head residuals for steady-state simulation, Black Mesa area, Arizona

[Map number from figure 18; head residual equals observed head minus simulated head]

Map number	USGS site identification number	Bureau of Indian Affairs site number, or common name	Observed head, in feet above sea level	Simulated head, in feet above sea level	Head residual, in feet
1	355213111073601	3T-504	5,170	5,204	-34
2	355828111112701	3K-326	5,064	5,123	-59
3	355428111084601	3A-28	5,151	5,179	-28
4	355123111050901	3A-151	5,209	5,230	-21
5	355032111015901	3K-328	5,237	5,248	-11
6	3547341110590501	3A-153	5,240	5,281	-41
7	354116110511601	5T-500	5,280	5,286	-6
8	354218110494501	6K-310N	5,316	5,311	5
9	354137110475401	6H-79	5,328	5,314	14
10	360217111122601	3K-325	5,042	5,052	-10
11	355927111084101	3A-27	5,065	5,114	-49
12	355512111033301	3T-540	5,201	5,198	3
13	355658111040201	3A-149	5,197	5,169	28
14	355209110582301	3M-175	5,241	5,256	-15
15	355013110560001	3K-320	5,256	5,279	-23
16	354746110521001	6K-300	5,297	5,301	-4
17	360819111170301	Grey Hills 2	5,132	5,085	47
18	360734111144801	3T-333	4,917	4,884	33
19	360708111142901	Kerley TP	4,852	4,830	22
20	360708111134901	3GS-77-5	4,785	4,763	22
21	360751111142601	3T-322-1	4,938	4,902	36
22	360731111134401	3T-507	4,872	4,855	17
23	361025111171401	3T-545	5,257	5,271	-14
24	360904111140201	3T-508 (Tuba City NTUA1)	5,090	5,005	85
25	360953111142401	3T-546 (Tuba City NTUA4)	5,172	5,131	41
26	360924111142201	Tuba City NTUA 3	5,142	5,083	59
27	360042111025301	3K-312	5,095	5,122	-27

Table 18. Observed heads, simulated heads, and head residuals for steady-state simulation, Black Mesa area, Arizona—Continued

Map number	USGS site identification number	Bureau of Indian Affairs site number, or common name	Observed head, in feet above sea level	Simulated head, in feet above sea level	Head residual, in feet
28	361018111142401	Tuba City NTUA 5	5,205	5,184	21
29	355733110582801	3M-176	5,238	5,192	46
30	360322111045801	3K-329	5,035	5,058	-23
31	355003110473801	6-3-ED3	5,331	5,325	6
32	355615110551001	3K-332	5,274	5,253	21
33	354322110390601	6-2B6	5,346	5,364	-18
34	355734110562401	3T-500A	5,245	5,226	19
35	354637110423701	6-3-504	5,344	5,370	-26
36	354227110362701	6K-304	5,345	5,357	-12
37	355102110455701	6K-322	5,351	5,355	-4
38	361237111112701	3T-528	5,234	5,240	-6
39	360918111080701	Rare Metals 2	5,051	5,024	27
40	354928110415701	6K-310	5,378	5,378	0
41	354642110391201	6K-2C-1	5,361	5,384	-23
42	360729111032201	3T-541	4,939	4,951	-12
43	355648110475501	6H-55	5,423	5,320	103
44	360441110572801	3K-330	5,084	5,091	-7
45	355107110402601	6-3-S03	5,395	5,401	-6
46	354944110380401	6M-52	5,395	5,405	-10
47	355924110485001	3K-311	5,392	5,314	78
48	361139111013401	3K-323	5,158	5,091	67
49	361608111062501	3K-324	5,408	5,436	-28
50	355230110365801	Kykotsmovi PM 1	5,437	5,430	7
51	355236110364501	Kykotsmovi PM 3	5,408	5,430	-22
52	360708110541901	3K-345	5,144	5,117	27
53	360526110520001	3M-156	5,285	5,228	57
54	355518110400301	Hotvilla PM 1	5,414	5,433	-19
55	354749110300101	Second Mesa PM 2	5,401	5,428	-27
56	361954111075201	3K-313	5,540	5,532	8
57	361432111014701	3T-518	5,347	5,337	10
58	355041110313701	Hopi Cultural Center	5,429	5,443	-14
59	360437110481001	3K-344	5,409	5,363	46
60	361922111044801	1T-520	5,545	5,529	16
61	361627111005001	1K-216	5,418	5,407	11
62	362414111095301	1K-204	5,646	5,638	8
63	354950110231501	Polacca PM 4	5,493	5,483	10
64	362512111054801	1K-222	5,645	5,681	-36
65	362124111012001	1K-226	5,515	5,549	-34
66	362348111025401	1T-522	5,679	5,650	29

Table 18. Observed heads, simulated heads, and head residuals for steady-state simulation, Black Mesa area, Arizona—Continued

Map number	USGS site identification number	Bureau of Indian Affairs site number, or common name	Observed head, in feet above sea level	Simulated head, in feet above sea level	Head residual, in feet
67	361933110565001	Red Lake PM 1	5,496	5,497	-1
68	361913110561901	1K-228	5,445	5,485	-40
69	360418110352701	Rocky Ridge PM 2	5,553	5,537	16
70	355023110182701	Keams Canyon PM 2	5,517	5,515	2
71	360055110304001	BM Observation Well 5	5,545	5,541	4
72	362406110563201	1K-214	5,583	5,588	-5
73	362456110503001	1K-225	5,662	5,671	-9
74	362443110491101	1P-511	5,670	5,666	4
75	355638110064001	Low Mountain PM 2	5,572	5,619	-47
76	360614110130801	Piñon PM 6	5,653	5,625	28
77	363309110420501	2K-300	6,088	6,092	-4
78	363143110355001	BM Observation Well 4	6,129	6,081	48
79	363604110390801	Shonto PM 4	6,249	6,288	-39
80	363558110392501	Shonto PM 2	6,256	6,284	-28
81	363538110383601	2T-505	6,232	6,276	-44
82	363213110342001	2K-301	6,151	6,119	32
83	362647110243501	Peabody 4	5,738	5,751	-13
84	362625110223701	Peabody 3	5,726	5,728	-2
85	363709110345001	2K-324	6,520	6,446	74
86	363423110305501	2T-502	6,264	6,120	144
87	363005110250901	Peabody 2	5,802	5,802	0
88	362901110234101	Peabody 5	5,771	5,763	8
89	363007110221201	Peabody 6	5,751	5,760	-9
90	364032110324101	Betatakin Natl Monument	6,695	6,587	108
91	363727110274501	8T-510	6,163	6,105	58
92	364034110240001	8T-522	5,915	5,940	-25
93	363137110044702	Chilchinbito PM 3	5,545	5,537	8
94	363558110073701	8T-419	5,522	5,513	9
95	361832109462701	10T-258	5,602	5,601	1
96	363850110100801	BM Observation Well 2	5,531	5,517	14
97	364350110154001	8P-450	5,601	5,607	-6
98	364338110154601	BM Observation Well 3	5,669	5,597	72
99	364322110152001	Kayenta USPH1	5,605	5,586	19
100	363013109584901	8K-443	5,494	5,501	-7
101	362443109522801	10K-221	5,542	5,549	-7
102	364344110151201	8A-295 (Kayenta PM 2)	5,582	5,586	-4
103	362438109513401	Rough Rock PM 6	5,525	5,546	-21
104	363342110011901	8A-121	5,460	5,470	-10
105	362936109564101	BM Observation Well 1	5,490	5,497	-7

Table 18. Observed heads, simulated heads, and head residuals for steady-state simulation, Black Mesa area, Arizona—Continued

Map number	USGS site identification number	Bureau of Indian Affairs site number, or common name	Observed head, in feet above sea level	Simulated head, in feet above sea level	Head residual, in feet
106	362854109552201	8K-435	5,502	5,503	-1
107	362149109463301	10R-111	5,587	5,584	3
108	364134110090501	8A-138	5,428	5,456	-28
109	363228109591901	8T-528	5,530	5,459	71
110	363107109534901	8A-273A	5,447	5,458	-11
111	363957110032401	8A-136	5,395	5,357	38
112	363805109594501	8K-1	5,278	5,366	-88
113	363332109553301	8K-430	5,403	5,402	1
114	362823109463101	10R-119	5,518	5,533	-15
115	362455109433801	10K-235	5,587	5,567	20
116	364215110012201	8K-420	5,289	5,308	-19
117	364146109582201	8K-421	5,252	5,269	-17
118	363232109465601	9Y-92	5,446	5,444	2
119	363103109445201	9Y-95	5,514	5,502	12
120	362812109421601	10R-174	5,595	5,565	30
121	364343109565701	8K-431	5,185	5,218	-33
122	363646109502201	8A-179	5,310	5,312	-2
123	364248109514601	8A-180	5,153	5,151	2
124	363426109414601	9K-215	5,470	5,436	34
125	364908109525301	8T-505	5,047	5,038	9
126	365045109504001	8K-521	4,997	5,018	-21

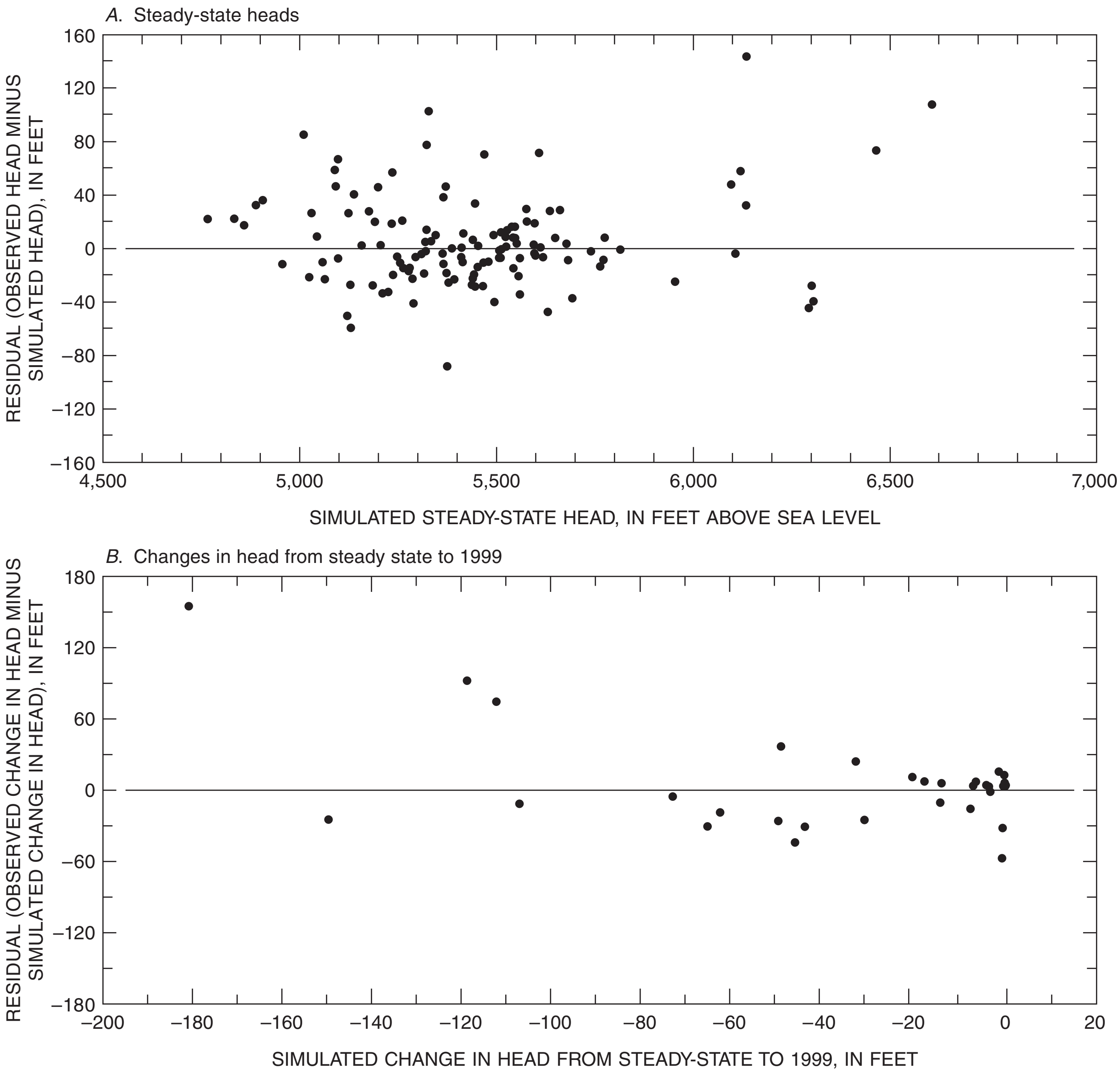

Figure 19. Relations between residuals and simulated values, Black Mesa area, Arizona. *A*, Steady-state heads. *B*, Changes in head from steady state to 1999.

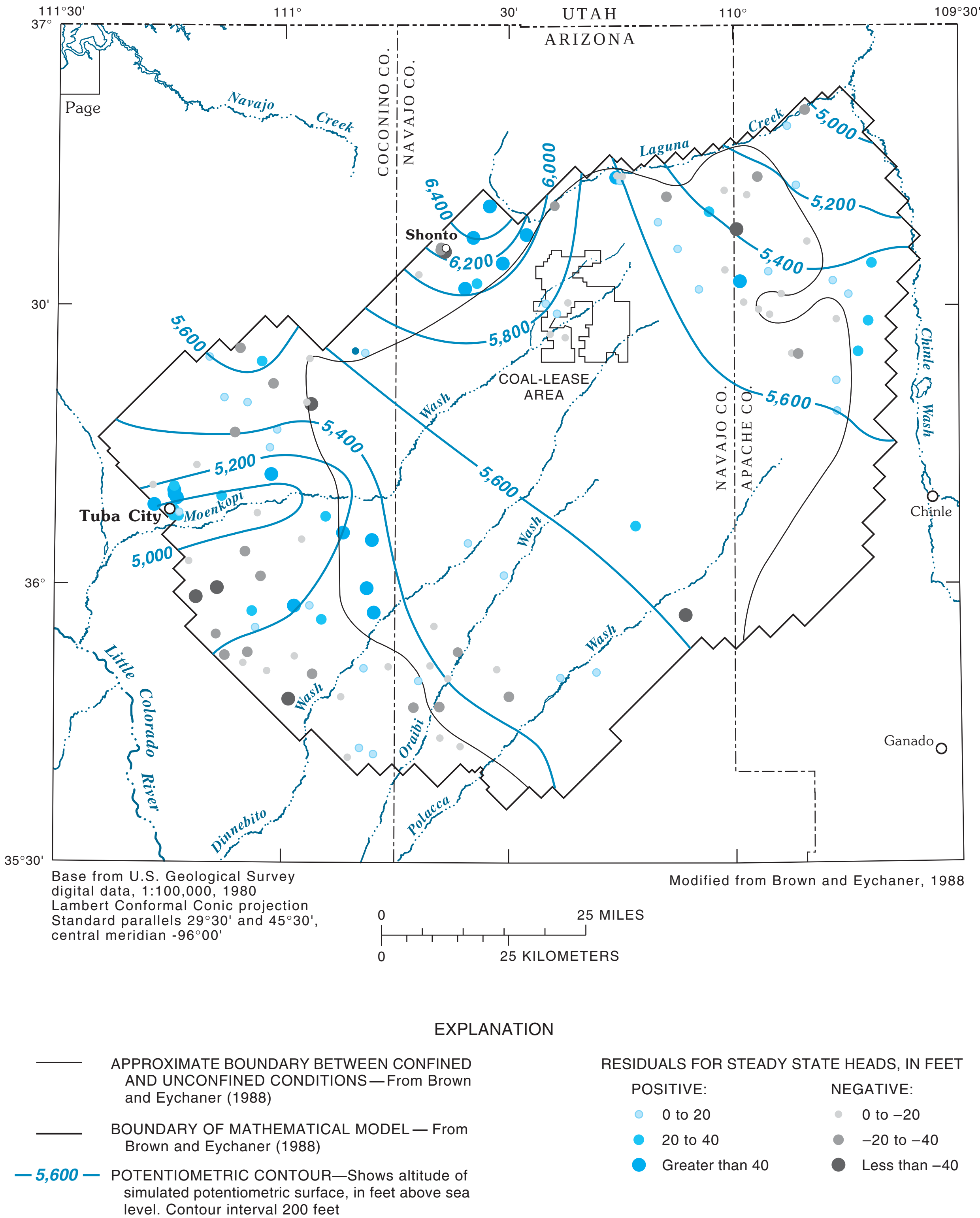

Figure 20. Residuals for steady-state heads and simulated steady-state potentiometric surface, Black Mesa area, Arizona.

Table 19. Summary of residuals for observed (estimated) and simulated flows, Black Mesa area, Arizona

[Residual for steady-state flow equals observed flow minus simulated flow; ft^3/s, cubic feet per second]

Stream or springs	Observed (estimated) steady-state flow, in ft^3/s	Simulated steady-state flow, in ft^3/s	Residual for steady-state flow, in ft^3/s	Weighted residual for steady-state flow, in ft^3/s	Simulated change in flow from steady state to 1999, in ft^3/s
Moenkopi Wash	3.10	4.38	-1.28	-1.40	-0.02
Laguna Creek and Chinle Wash	3.80	3.87	-0.07	-.05	-.59
Moenkopi School Spring and Pasture Canyon Spring	.56	.21	.35	1.98	-.02

Table 20. Observed and simulated changes in head from steady state to 1999, and residuals for changes in head, Black Mesa area, Arizona

[Map number from figure 18; residual for change in head equals observed change in head minus simulated change in head]

Map number	USGS site identification number	Bureau of Indian Affairs site number, or common name	Observed change in head from steady state to 1999, in feet	Simulated change in head from steady state to 1999, in feet	Residual for change in head, in feet
10	360217111122601	3K-325	6.0	-0.2	6.2
18	360734111144801	3T-333	-9.0	-33.2	24.2
24	360904111140201	3T-508 (Tuba City NTUA 1)	-38.2	-112.9	74.7
25	360953111142401	3T-546 (Tuba City NTUA 4)	-27.0	-119.4	92.4
26	360924111142201	Tuba City NTUA 3	-25.9	-181.1	155.2
39	360918111080701	Rare Metals 2	4.4	0.0	4.4
43	355648110475501	6H-55	-58.2	-0.8	-57.4
50	355230110365801	Kykotsmovi PM 1	-12.9	-49.8	36.9
70	355023110182701	Keams Canyon PM 2	-174.8	-150.1	-24.7
71	360055110304001	BM Observation Well 5	-79.2	-73.8	-5.4
72	362406110563201	1K-214	-32.6	-0.7	-31.9
73	362456110503001	1K-225	[1]14.2	[1]-1.5	15.7
75	355638110064001	Low Mountain PM 2	-82.0	-63.3	-18.7
76	360614110130801	Piñon PM 6	[1]-119.2	[1]-107.8	-11.4
77	363309110420501	2K-300	4.2	-0.1	4.3
78	363143110355001	BM Observation Well 4	-0.6	-3.7	3.1
82	363213110342001	2K-301	-4.7	-3.4	-1.3
86	363423110305501	2T-502	-9.6	-20.7	11.1
91	363727110274501	8T-510	-23.5	-7.8	-15.7
92	364034110240001	8T-522	-3.5	-7.2	3.7
95	361832109462701	10T-258	-8.3	-14.2	5.9
96	363850110100801	BM Observation Well 2	-76.4	-50.4	-26.0
98	364338110154601	BM Observation Well 3	-90.8	-46.7	-44.1
100	363013109584901	8K-443	-10.6	-18.0	7.4
105	362936109564101	BM Observation Well 1	0.0	-4.3	4.3
107	362149109463301	10R-111	-25.0	-14.5	-10.5
114	362823109463101	10R-119	0.6	-6.6	7.2
118	363232109465601	9Y-92	3.5	-0.1	3.6
119	363103109445201	9Y-95	12.5	-0.3	12.8
123	364248109514601	8A-180	3.0	-0.5	3.5
127	361225110240701	BM Observation well 6	[2]-96.7	[2]-66.1	-30.6
128	361737110180301	Forest Lake NTUA 1	[3]-75.3	[3]-44.5	-30.8
129	364226110171701	8T-541	[4]-56.4	[4]-31.3	-25.1

[1]Most recent heads are for 1998 instead of 1999.
[2]Changes in head are for 1977 to 1999.
[3]Changes in head are for 1982 to 1999.
[4]Changes in head are for 1976 to 1999.

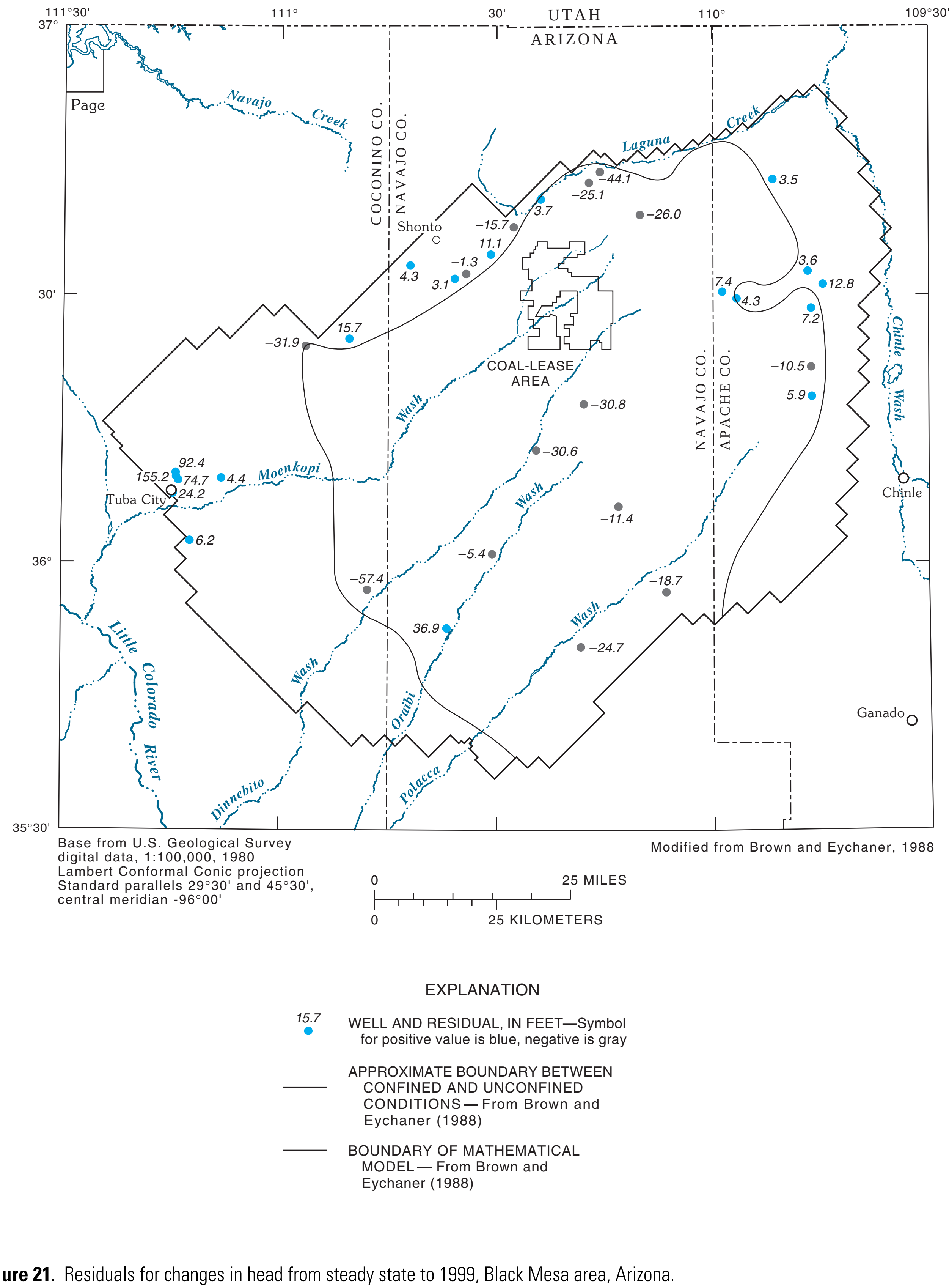

Figure 21. Residuals for changes in head from steady state to 1999, Black Mesa area, Arizona.

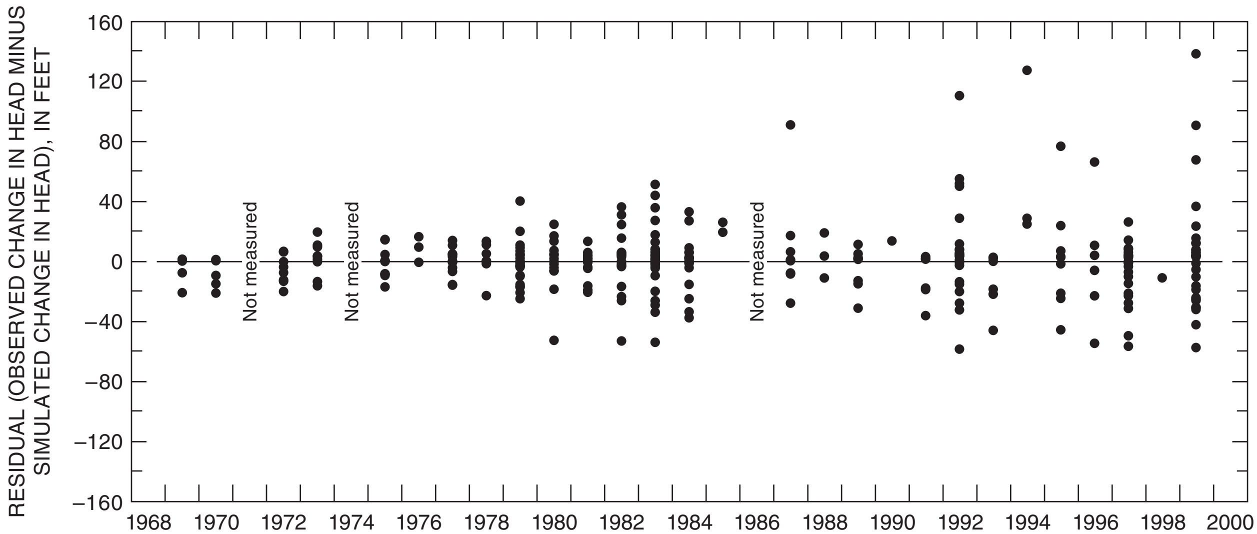

Figure 22. Relation between residuals for changes in heads and year of simulation, Black Mesa area, Arizona.

Composite scaled sensitivities can indicate whether there is enough information in the available observation data to estimate parameters using inverse modeling or traditional calibration techniques (Hill, 1998, p. 38–39). The model sensitivities indicate that there probably is enough information in the available observation data to estimate storage coefficient, transmissivity, and recharge. There might be enough information in the data to estimate conductance of river, drain, and general-head boundaries, and there probably is not enough information in the data to estimate the maximum evapotranspiration rate. It must be emphasized that these statements are only applicable to the 1988 model construction and 1999 observation data set, and that other factors are involved in the success of estimating parameters.

Another statistic that needs to be evaluated to determine whether there is enough information in the available observation data to estimate parameters is the correlation between parameters. Correlations were calculated for the steady-state simulation with only head data and with head and flow data (table 21). Almost all parameter pairs have correlations near 1.0 in the simulation with only head data. This indicates a problem with uniqueness; many models with different parameter values could be developed with similar fits to the head data. Adding flow data improved the correlations for all parameter pairs; however, many pairs still had correlations greater than 0.99, and the correlation between transmissivity and recharge remained near 1.0. Steady-state heads and flows, therefore, still do not provide enough information to develop a unique model. Linearly coordinated changes in values of transmissivity and recharge could result in similar model fits to the observation data. A possible reason for the small decrease in the correlation between transmissivity and recharge when flow data are included is that only about 40 percent of the total ground-water discharge was estimated and used as flow observations in the model. The total of the estimated flows was 7.5 ft^3/s, and the total steady-state outflow was 18.7 ft^3/s. Thus, 60 percent of the discharge was not estimated and is not used as a constraint on the model.

Parameter correlations were calculated for the combined steady-state and transient simulations with (1) steady-state heads and transient changes in heads, and with (2) the same head data and flows (table 22). For both sets of observation data, all correlations are small or moderate; the largest correlation coefficient is 0.82 for transmissivity and recharge.

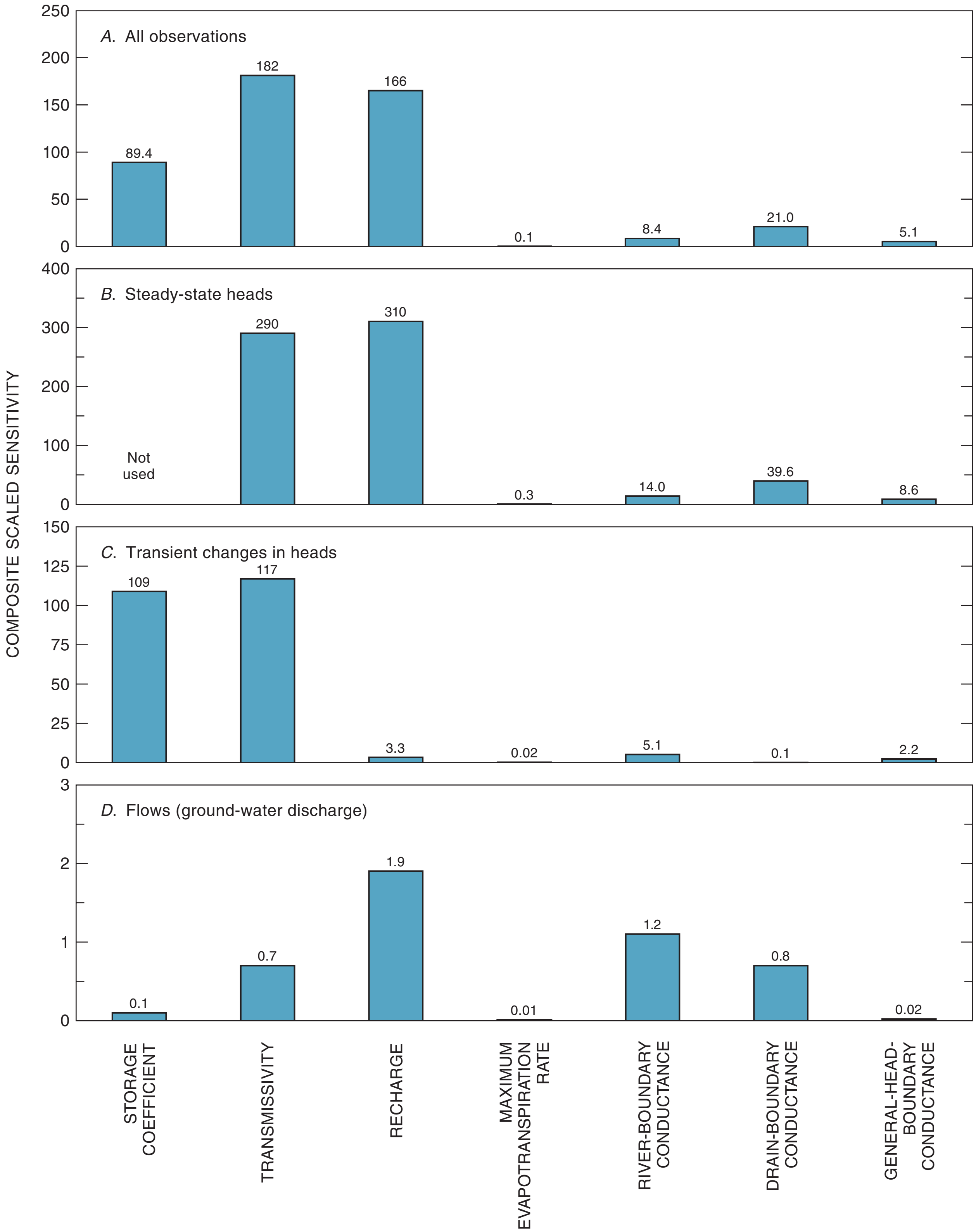

Figure 23. Composite scaled sensitivities for model parameters. *A*, Based on all observations. *B*, Based on steady-state heads. *C*, Based on transient changes in heads. *D*, Based on flows (ground-water discharge).

Table 21. Correlation matrices for parameters in steady-state simulations, Black Mesa area, Arizona

A. Correlations computed with steady-state heads

Parameter	Transmissivity	Recharge	Maximum evapotrans-piration rate	River-boundary conductance	Drain-boundary conductance	General-head-boundary conductance
Transmissivity	1.0000					
Recharge	1.0000	1.0000				
Maximum evapotranspiration rate	.9999	.9999	1.0000			
River-boundary conductance	1.0000	1.0000	.9999	1.0000		
Drain-boundary conductance	1.0000	1.0000	.9999	1.0000	1.0000	
General-head-boundary conductance	1.0000	1.0000	.9999	1.0000	1.0000	1.0000

B. Correlations computed with steady-state heads and flows

Parameter	Transmissivity	Recharge	Maximum evapotrans-piration rate	River-boundary conductance	Drain-boundary conductance	General-head-boundary conductance
Transmissivity	1.0000					
Recharge	.9999	1.0000				
Maximum evapotranspiration rate	.2271	.2277	1.0000			
River-boundary conductance	.9973	.9974	.1867	1.0000		
Drain-boundary conductance	.9998	.9998	.2293	.9968	1.0000	
General-head-boundary conductance	.9923	.9922	.2892	.9887	.9932	1.0000

Table 22. Correlation matrices for parameters in steady-state and transient simulations, Black Mesa area, Arizona

A. Correlations computed with steady-state heads and changes in heads

Parameter	Storage coefficient	Transmissivity	Recharge	Maximum evapotrans-piration rate	River-boundary conductance	Drain-boundary conductance	General-head-boundary conductance
Storage coefficient	1.0000						
Transmissivity	-.5124	1.0000					
Recharge	-.4379	.8211	1.0000				
Maximum evapotranspiration rate	-.1158	-.1123	.1316	1.0000			
River-boundary conductance	.0501	-.1572	-.0536	-.3860	1.0000		
Drain-boundary conductance	-.1331	.1263	.0974	-.0322	-.1864	1.0000	
General-head-boundary conductance	-.0852	-.3272	-.3500	.5031	.0029	.2939	1.0000

B. Correlations computed with steady-state heads, changes in heads, and flows

Parameter	Storage coefficient	Transmissivity	Recharge	Maximum evapotrans-piration rate	River-boundary conductance	Drain-boundary conductance	General-head-boundary conductance
Storage coefficient	1.0000						
Transmissivity	-.5125	1.0000					
Recharge	-.4378	.8211	1.0000				
Maximum evapotranspiration rate	-.1157	-.1124	.1316	1.0000			
River-boundary conductance	.0499	-.1576	-.0536	-.3839	1.0000		
Drain-boundary conductance	-.1331	.1263	.0974	-.0324	-.1863	1.0000	
General-head-boundary conductance	-.0851	-.3272	-.3502	.5028	.0041	.2939	1.0000

From a first look at the parameter correlations calculated using all the observation data (steady-state heads, transient changes in heads, and flows), it would appear that there is no longer a problem of uniqueness of the model because all correlations are small or moderate; however, this analysis is too limited to make this conclusion. No regression analysis or calibration was performed in this study to actually test this conclusion. Parameter sensitivities and correlations are only indicators of the relations between parameters and observation data; there are many more factors involved in determining if observation data are sufficient to accurately estimate parameters and to calibrate a model. Waterstone Environmental Hydrology and Engineering, Inc. (1995) performed a thorough sensitivity analysis of the 1988 USGS model that included using MODFLOWP and a regression analysis to estimate parameters and to calibrate the model. They found a strong correlation between recharge and hydraulic conductivity, and thus transmissivity, using steady-state heads and transient changes in heads through 1993, and they could not simultaneously estimate conductivity and recharge.

The areal distribution of parameter sensitivity is shown in the one-percent sensitivity maps that were calculated for steady-state heads and for changes in head from steady state to 1999. Areas with the largest one-percent sensitivity for a selected parameter have the most information for estimating that parameter, and areas with the smallest sensitivity have the least information. Thus, new data collection to improve estimates of a parameter would likely be the most efficient and effective in the areas with the largest one-percent scaled sensitivity.

Maps of one-percent scaled sensitivity of steady-state heads are shown for the four parameters with the largest composite scaled sensitivity—transmissivity, recharge, river conductance, and drain conductance (**fig. 24**). The two most important steady-state parameters, transmissivity and recharge, have similar geographic patterns, except the calculated sensitivities have opposite signs. Sensitivities for transmissivity are negative and sensitivities for recharge are positive. Both maps have large values in the principal recharge area near Shonto and the smallest values on the west and northeast sides. Sensitivities for river conductance are largest near Moenkopi Wash near some river cells (**fig. 15**) and smallest away from the river cells. Sensitivities for drain conductance are largest on the southwest side of the model near some drain cells (fig. 15) and smallest away from the drain cells.

Maps of one-percent scaled sensitivity of transient changes in head from steady state to 1999 are shown for the four parameters with the largest composite scaled sensitivity—transmissivity, storage coefficient, recharge, and river conductance (**fig. 25**). Sensitivities for transmissivity are largest in the area of largest withdrawals and largest changes in head—the Peabody well field (**figs. 4** and **5**). Most sensitivities for transmissivity change sign from confined to unconfined areas. Sensitivities for storage coefficient are largest in the confined south-central and central parts of the model area. They are also large for a few cells in the Tuba City area. Sensitivities for recharge and river conductance generally are small; the largest sensitivities are in the Kayenta area because cells representing recharge and river conductance are nearby (figs. 14 and 15) and there have been appreciable ground-water withdrawals and changes in heads in that area (figs. 4 and 5).

The importance of different wells to the transient simulation was evaluated by ranking the wells according to the dimensionless scaled sensitivity calculated for the observations of changes in heads from steady state to 1999. The 10 highest ranked wells are shown for the two most important parameters in the transient simulation–transmissivity and storage coefficient (**table 23**). A well that has an observation with a large dimensionless scaled sensitivity for a selected parameter provides more information about the parameter than a well with a smaller dimensionless scaled sensitivity. Thus, continued collection of head data at the wells listed in table 23 would likely be efficient and productive for improving the estimates of transmissivity and storage coefficient.

The changes in heads from steady state to 1999 in the four continuous observation wells in confined areas (BM observation wells 2, 3, 5, and 6) generally have large dimensionless scaled sensitivities for transmissivity and storage coefficient and thus contain substantial information about those parameters (table 23). The changes in heads from steady state to 1999 in some municipal wells also have large dimensionless scaled sensitivities, so these wells also are important to the estimation of transmissivity and storage coefficient and to a calibration of the model (table 23).

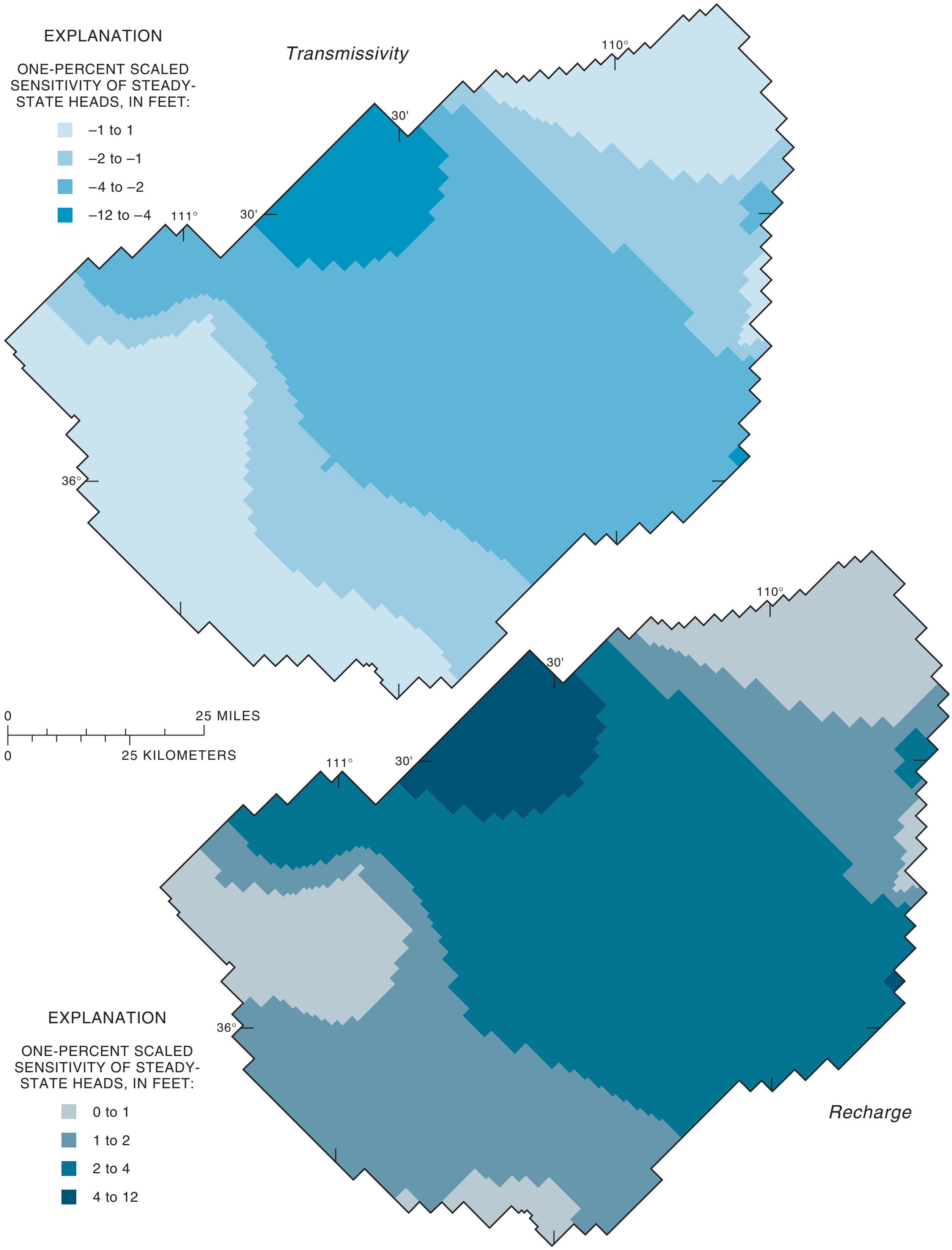

Figure 24. One-percent scaled sensitivity of steady-state heads for transmissivity, recharge, river conductance, and drain conductance, Black Mesa area, Arizona.

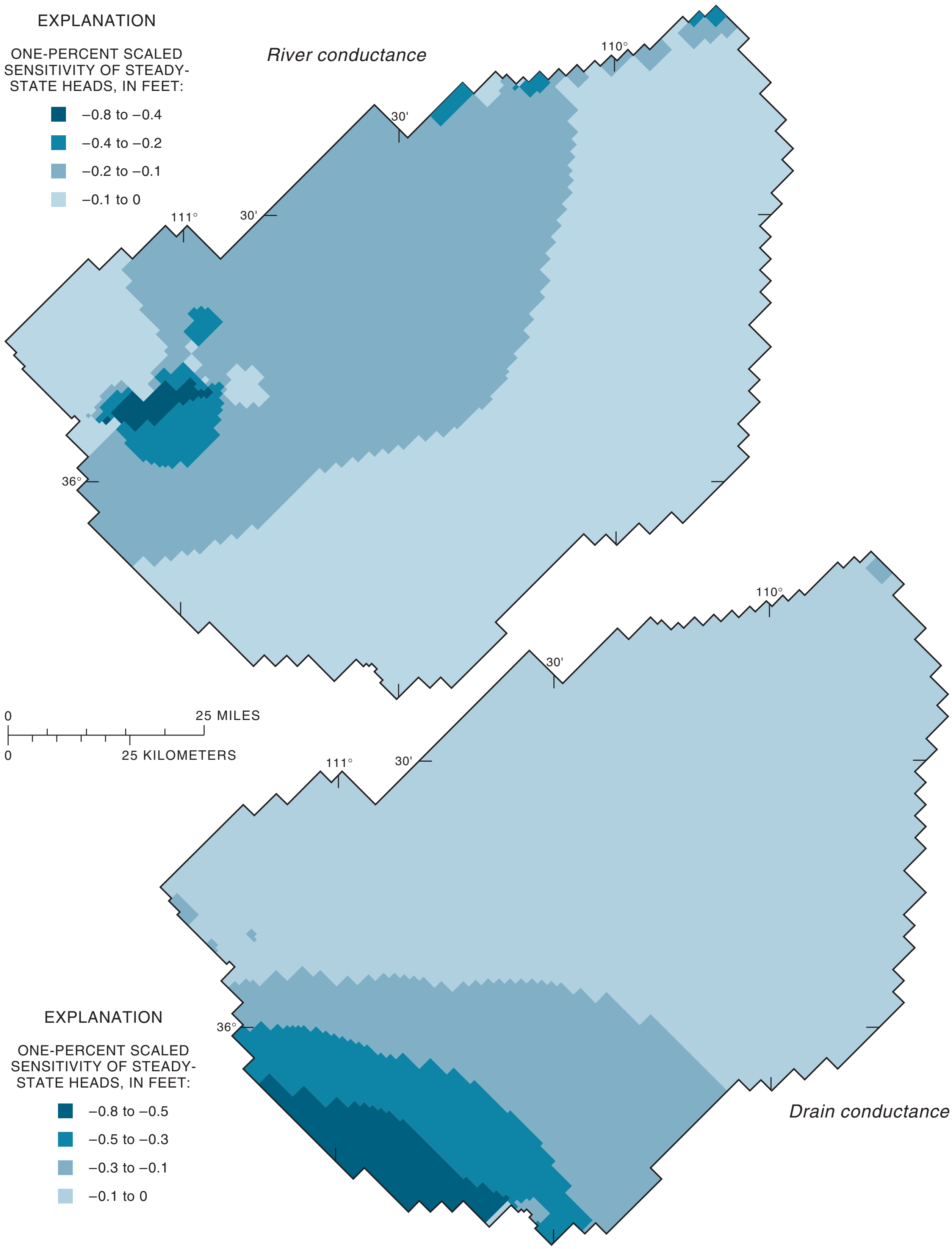

Figure 24. Continued.

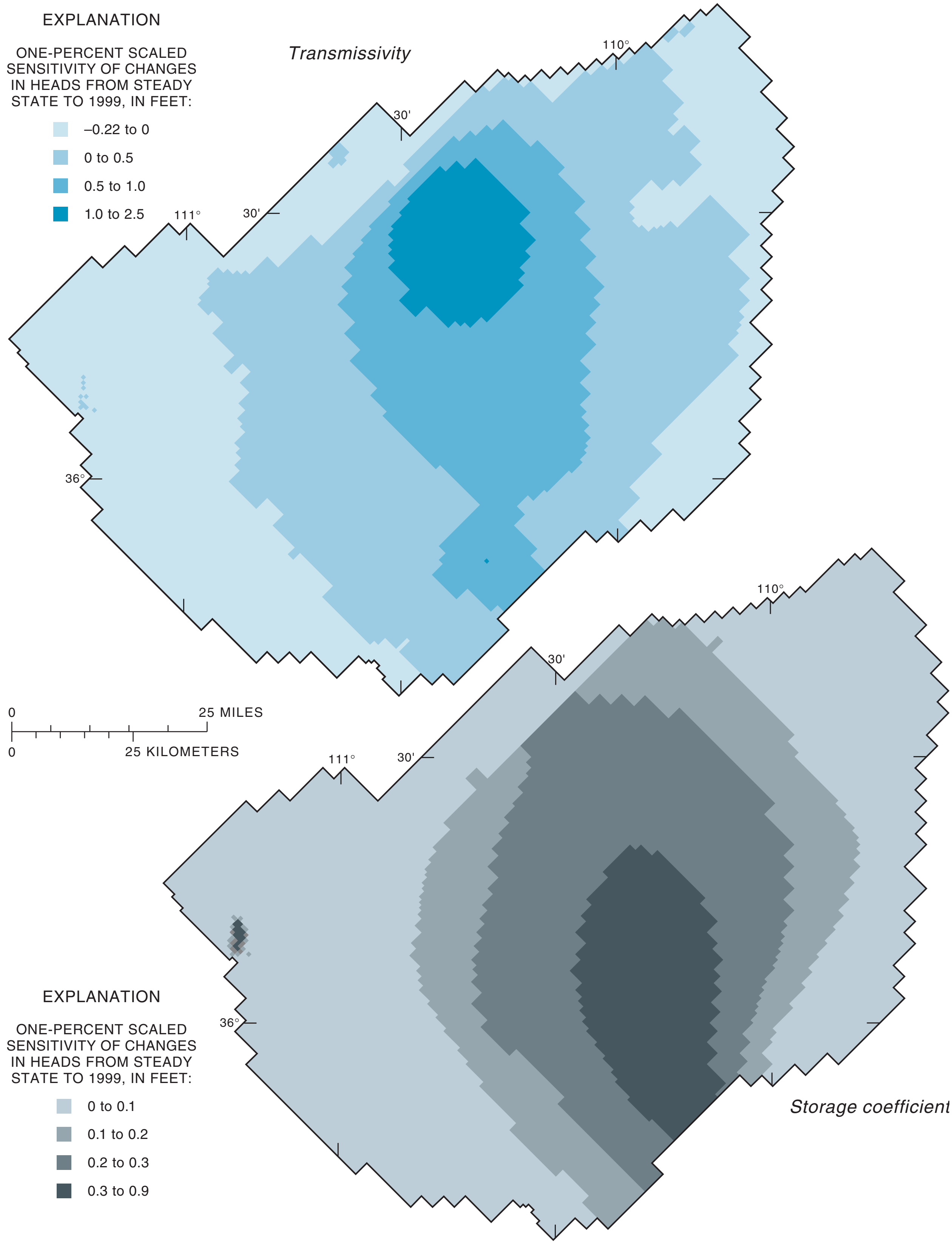

Figure 25. One-percent scaled sensitivity of changes in head from steady state to 1999 for transmissivity, storage coefficient, recharge, and river conductance, Black Mesa area, Arizona.

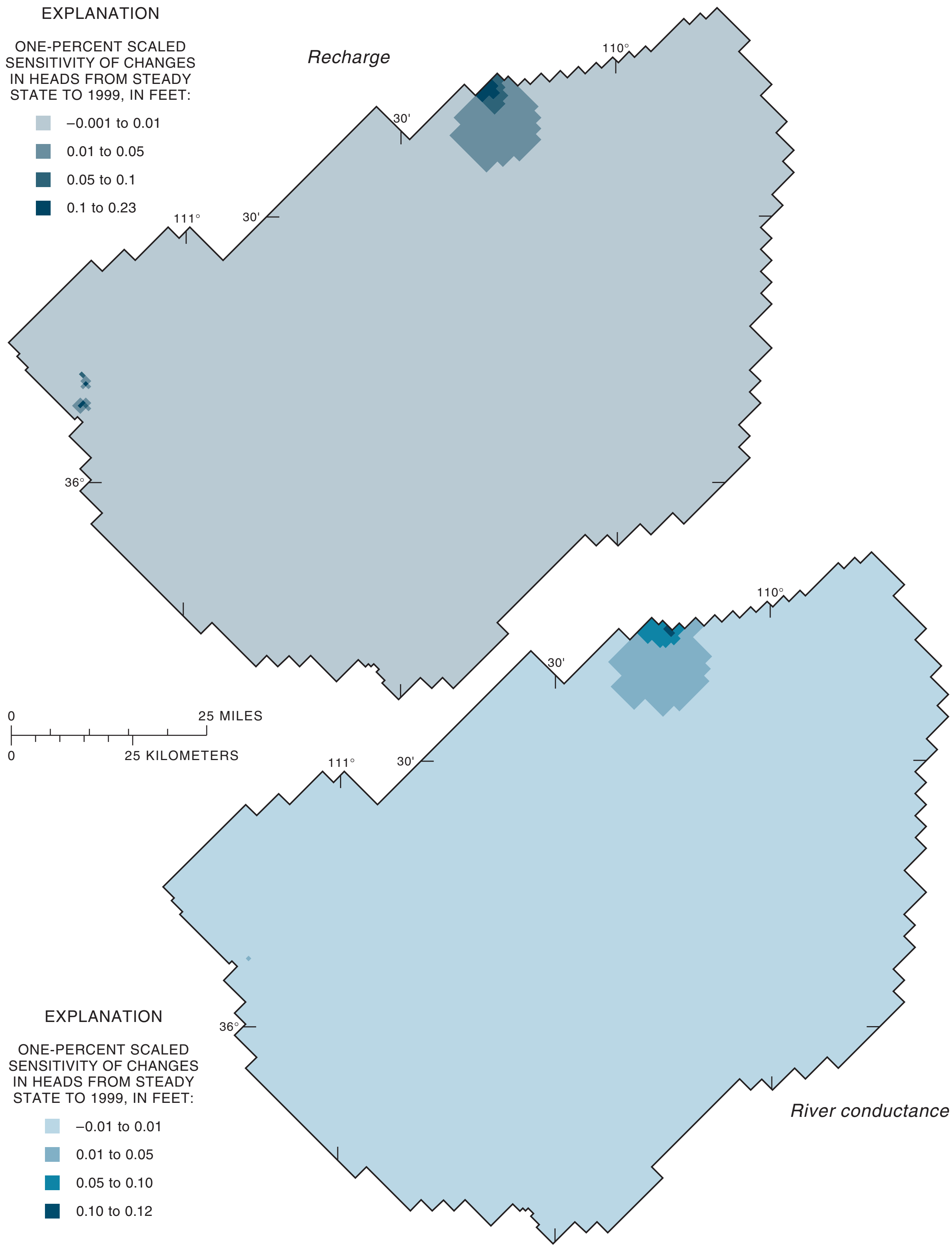

Figure 25. Continued.

Table 23. The most important wells in terms of sensitivity of changes in heads from steady state to 1999, for transmissivity and storage coefficient, Black Mesa area, Arizona

[Dimensionless scaled sensitivity indicates the importance of each observation to the estimation of a single parameter or the importance of each parameter to the calculation of a simulated value]

Well name	Simulated change in head from steady state to 1999, in feet	Dimensionless scaled sensitivity (dss) of change in head from steady state to 1999, and rank in magnitude of dss for indicated parameter			
		Transmissivity	Rank	Storage	Rank
Keams Canyon PM 2	-150	688	1	181	4
Tuba City NTUA 3	-181	455	2	514	1
BM observation well 6	-111	430	3	-47	15
Forest Lake NTUA 1	-128	317	4	-60	11
BM observation well 5	-74	260	5	163	5
3T-508 (Tuba City NTUA 1)	-113	254	6	371	3
3T-546 (Tuba City NTUA 4)	-119	215	7	478	2
BM observation well 2	-50	208	8	83	9
BM observation well 3	-47	153	9	71	10
Piñon PM6	-112	99	10	45	16
2T-502	-21	-16	22	144	6
3T-333	-33	62	11	131	7
8K-443	-18	22	18	83	8

There is a strong correlation between simulated changes in heads from steady state to 1999 and dimensionless scaled sensitivities for transmissivity [significance level (α) is less than 0.01] and a weak correlation between simulated changes in heads and sensitivities for storage coefficient [significance level (α) is greater than 0.05; table 23; Sokal and Rohlf, 1973]. The correlation coefficients (r) are -0.80 for changes in heads and transmissivity, and -0.42 for changes in heads and storage coefficient. These correlation relations also were seen in the maps of one-percent scaled sensitivity for those parameters.

Potential Revisions, New Data, and Studies to Improve the Model

The 1988 USGS model of the N aquifer can be improved by making revisions on the basis of current data and information, and by collecting and analyzing new data. Residual statistics, model sensitivities, and parameter correlations from the analysis in this report and results of previous studies were used to determine the potential revisions, and to determine the potential new data and analyses.

Revisions Based on Current Data and Information

Current data and information could be used to improve the 1988 USGS model. The 1988 model was constructed with data and information available in 1984. New withdrawal and water-level data from the USGS Black Mesa monitoring program could be used to update the model. Several new geochemical studies (HSIGeoTrans, Inc., 1993; Lopes and Hoffmann, 1997; Zhu and others, 1998; Zhu, 2000; Margot Truini, hydrologist, U.S. Geological Survey, written commun., 2002) and a new three-dimensional ground-water model (HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc., 1999) could be used to update and refine the conceptual and numerical model of the N aquifer.

The 1988 USGS model also could be improved by updating it to new simulation methods, such as MODFLOW-2000 (Harbaugh and others, 2000; Hill and others, 2000). The parameter estimation package of MODFLOW-2000 could be used to test different hypotheses about the flow system, to provide more efficient and objective methods of calibration, and to provide quantitative assessments of model uncertainty. The MODPATH program (Pollock, 1994) could be used to facilitate calibration by comparing simulated time of travel with estimates of ground-water ages reported by Lopes and Hoffmann (1997).

Several hypotheses about the ground-water flow system could be tested during the development of a new model. The hypothesis testing would result in a simulation analysis that more accurately describes the knowledge of the system and uncertainties. Parts of the conceptual model used as a basis for the 1988 USGS model have been disputed or questioned by new data or studies (Lopes and Hoffmann, 1997; HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc., 1999; and Zhu, 2000). Components of the flow system that need to be investigated include the amount and distribution of recharge, the amount of leakage from overlying formations, the effects of fractures and folds on hydraulic properties, and the lower boundary of the N aquifer; one alternative concept is that the Wingate Sandstone is intimately connected and can be considered a part of the N aquifer.

This study identified specific parts of the 1988 USGS model that need improvement. The areal distribution of hydraulic conductivity (**fig. 16**) could be simplified because it may be more detailed than is justified by field data. There were no obvious regional trends in more than 40 single-well tests or aquifer tests used by Eychaner (1983). Little new data are available on hydraulic properties, but current modeling philosophy emphasizes that areal distributions of hydraulic properties should only be as complex as is justified by field data (Hill, 1998). The boundary that simulates evapotranspiration in the 1988 model has little influence on heads or changes in heads (**fig. 23**), and thus the maximum evapotranspiration rate of that boundary is difficult to calibrate. Other methods of simulating evapotranspiration, such as the drain boundary, need to be investigated. The southwest boundary of the 1988 model simulates discharge through drains; an alternative boundary might be no-flow because there are few known springs in that area. The strong correlation between transmissivity and recharge needs to be decreased to make the model more unique. One possible approach would be to use ground-water ages estimated by Lopes and Hoffmann (1997) as advective-transport target data in calibration. The lateral boundary of the N aquifer in the Kayenta area needs to be moved slightly to the north to match new geologic data (HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc., 1999).

New 10-meter digital-elevation data can be used to improve estimates of land-surface altitudes for the entire model area. These altitudes would improve the model by providing more accurate estimates of water-surface altitudes for river and drain boundaries and more accurate estimates of evapotranspiration extinction depth.

The 1988 USGS model could be improved with more accurate estimates of ground-water discharge. Discharge estimates could be refined with a detailed analysis of continuous streamflow records for several streams in the study area. Records for Moenkopi Wash are available from 1976 to the current time (2002), records for Chinle Creek are available from 1965 to the current time, and records for Laguna Creek, Dinnebito Wash, Polacca Wash, Oraibi Wash, and Jeddito Wash are available from the mid-1990s to the current time.

The 1988 USGS model could be improved by modifying boundaries and parameters to obtain a better fit to available observation data. This study identified several areas where the model is performing poorly. There is a small overall bias in simulated steady-state heads, a poor fit to most of the estimated flows, and a poor fit to transient changes in heads in some areas. Small adjustments to recharge, hydraulic conductivity, or transmissivity could correct the bias in simulated steady-state heads. The accuracy of the flows estimated in this study is uncertain, so more studies are needed to refine estimates of recharge or discharge before much effort is put into matching the model to the current discharge estimates. Adjustments to transmissivity or storage coefficient could improve the match to observed changes in heads.

New Data and Studies

The 1988 USGS model could be improved by collecting and analyzing new data. New data or information can be grouped into two categories: (1) observations for use in a model and (2) data and interpretive studies. Observations are a certain kind of data that are used to calibrate a model, to assess performance, and to estimate parameters in inverse modeling. Examples of observations are hydraulic heads, flows, or estimates of advective transport. Data and interpretive studies are used to estimate the model boundaries, internal hydraulic properties, and water budget. Examples of data are geophysical data, lithologic data, geochemical data, and precipitation. Examples of interpretive studies are geologic studies that define physical boundaries of an aquifer, water-budget studies that estimate recharge, or aquifer tests that estimate transmissivity and storage.

Results of this study indicate that observations of steady-state heads, changes in heads, and flows provide important information for improving the model. New observations of steady-state heads are not possible in most of the model area because withdrawals have created transient-state conditions. Heads in the Shonto area, however, have remained fairly stable during the last 30 years (**figs. 5** and **7**), so new observations of heads in that area could be considered close to steady state, and they would provide information about recharge and transmissivity (**figs. 23** and **24**). Observations of changes in heads would be most beneficial in the areas of most stress, including near the Peabody well field, most of the confined area, and near Tuba City. These change-in-head observations provide the most information for estimating transmissivity and storage coefficient (fig. 23). Observations or estimates of ground-water discharge also are needed for improving the model. These discharges can be used for calibration targets, constraining information for the water-budget magnitude, assessing changes in discharge over time, and decreasing the correlation between recharge and transmissivity.

New data and interpretive studies are needed to improve the understanding of all components of the N aquifer. A general order of priority for components of the N aquifer, listed in order of importance and level of uncertainty, is: (1) ground-water recharge from precipitation, (2) recharge by leakage from the D aquifer, (3) ground-water discharge, (4) hydraulic conductivity, (5) storage coefficient, (6) hydraulic characteristics of the Carmel confining unit, (7) characteristics of the lower boundary, (8) vertical head gradients and vertical flow within the entire ground-water system between the Mancos Shale and Chinle Formation, (9) changes in ground-water discharge over time, and (10) extent of lateral and altitude of upper boundaries.

Ground-water recharge from precipitation has a strong influence on steady-state heads and ground-water discharge (fig. 23). In addition, recharge is strongly correlated to transmissivity and thus is an important factor in the uniqueness of a ground-water model of the N aquifer. Possible studies that could improve the understanding of recharge include studies of daily water budgets of watersheds, environmental tracers, or geophysical data. An additional benefit of recharge studies might be to determine if bare soil or bare-rock outcrops are areas of net recharge or net discharge.

Recent geochemical data (Lopes and Hoffmann, 1997) and the recent three-dimensional ground-water model (HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc., 1999) indicate that recharge by leakage from the D aquifer could be appreciable. Possible studies or new data that could improve the understanding of leakage include studies of geochemical data, geophysical data, and water-level and hydraulic-property data from new wells that could be completed in and near the Carmel confining unit.

Ground-water discharge data are important to constrain ground-water models, and discharge estimates also help to decrease the correlation coefficient between recharge and transmissivity. The understanding of discharge could be improved with a comprehensive inventory of springs in the model area, studies of environmental tracers, studies of evapotranspiration from cliff faces, and detailed studies of hydraulic gradients, water temperatures, and hydraulic characteristics at sites of stream/aquifer interactions.

Transmissivity (or hydraulic conductivity) of the N aquifer strongly influences steady-state heads and transient changes in heads, and storage coefficient strongly influences transient changes in heads (fig. 23). Aquifer tests, geophysical studies, and analyses of core samples and lithology from existing and new wells could improve the understanding of transmissivity, hydraulic conductivity, and storage coefficient.

Characteristics of the Carmel confining unit influence the amount and timing of leakage from the D to the N aquifer. Geophysical studies, aquifer tests, and analyses of core samples and lithology from existing and new wells could improve the understanding of the Carmel confining unit.

Characteristics of the lower boundary of the N aquifer are important. The altitude of the lower boundary influences the magnitude of transmissivity and the amount of available storage in the aquifer. Geophysical studies could be used to better estimate the altitude of the boundary. The formations that are included in the N aquifer are important. The recent three-dimensional ground-water model (HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc., 1999) includes most of the Wingate Sandstone, and the 1988 USGS model includes only a small part of the Wingate Sandstone. Studies of water-level data, geophysical data, and lithology from wells could provide information to determine if the Wingate Sandstone should be included in the N aquifer.

The N aquifer is more than one geologic formation and it is part of a larger ground-water system between the Mancos Shale and Chinle Formation (**fig. 2**). It is, therefore, important to understand the vertical head gradients and the amount of vertical flow within the N aquifer and in the entire ground-water system. Water-level and geochemical data from existing wells and from new vertically nested wells could improve the understanding of vertical gradients and vertical flow.

One of the possible effects of ground-water withdrawals is a decrease in ground-water discharge over time. New data and studies are needed to independently determine if discharges have changed or will change in the future. Data and studies also are needed to distinguish between the changes caused by natural fluctuations in recharge and changes caused by withdrawals. Continuous measurements of discharge to springs and streams, and measurements of factors affecting recharge, such as precipitation, evapotranspiration, and runoff, could improve the understanding of changes in discharge over time.

The lateral and upper boundaries of the N aquifer influence the total water budget and flow conditions near the boundaries. Existing surficial geologic mapping and lithologic data in wells are sufficient to define the physical extent (lateral boundary) and the altitude of the upper boundary. Head data from existing and new wells in the northwestern part of the study area could be used to refine the location of the ground-water divide that is used as a no-flow boundary in the 1988 USGS model.

SUMMARY

The N aquifer is the major source of water for industrial and municipal users in the Black Mesa area of northeastern Arizona. Availability of water is an important issue in the Black Mesa area because of continued industrial and municipal use, a growing population, and precipitation of about 6 to 14 in/yr.

This report presents results of ground-water, surface-water, and water-chemistry monitoring in the Black Mesa area from January 2000 to June 2001. The monitoring data for 2000–2001 are compared with data for 1999 and with historical data from the 1950s to the present. This report also presents results of an analysis of the performance and sensitivity of a numerical model of the N aquifer developed by the USGS in 1988. The performance analysis was done to determine how well the model has simulated water-level observation data collected since the model was constructed. The sensitivity analysis was done to determine relations among the model parameters, observation data, and simulated values. The performance and sensitivity analysis is also a logical first step for updating and improving the 1988 model.

In 2000, total ground-water withdrawals were 7,740 acre-ft, industrial use was 4,490 acre-ft, and municipal use was 3,250 acre-ft. From 1999 to 2000, total withdrawals increased by 9 percent, municipal use increased by 12 percent, and industrial use increased by 7 percent. During the past 10 years, total withdrawals and municipal and industrial use increased at an average rate of about 3 percent per year.

From 1999 to 2001, ground-water levels declined in 18 of 31 wells. The median water-level change for the 31 wells was -0.4 ft, and changes ranged from -10.8 ft to +6.0 ft. In unconfined areas of the N aquifer, water levels declined in 10 of 15 wells, and the median change was -0.4 ft. In confined areas, water levels declined in 8 of 16 wells, and the median change was -0.2 ft.

For wells in confined areas of the N aquifer, there is a significant decreasing trend in the median annual water-level changes from 1983 to 2001, and the average annual median change was +0.2 ft. For wells in confined areas, there is no significant trend in the median annual water-level changes, and the average annual median change was –1.8 ft.

From the prestress period (prior to 1965) to 2001, water levels in 33 wells changed by a median of -17.2 ft. Water levels in the 15 wells in the unconfined part of the N aquifer had a median change of -1.2 ft, and the changes ranged from -39 ft to +6.3 ft. Water levels in the 18 wells in the confined part of the aquifer had a median change of -31.0 ft, and the changes ranged from -168.8 ft to +9.4 ft.

Discharges were measured annually at four springs in 1999 and 2001. Burro Spring had a 33 percent decrease in discharge, the unnamed spring near Dennehotso had an 81-percent increase, Moenkopi School Spring had a 3-percent increase, and Pasture Canyon Spring had a 5-percent decrease. For about the past 10 years, discharges did not significantly change in Burro Spring, the unnamed spring near Dennehotso,

and Moenkopi School Spring. The record of discharge from a consistent measuring point for Pasture Canyon Spring is too short for a statistical analysis of trends.

The annual average discharges at the four streamflow-gaging stations vary considerably during their periods of record. Continuous records of surface-water discharge have been collected from July 1976 to 2000 at Moenkopi Wash, July 1996 to 2000 at Laguna Creek, June 1993 to 2000 at Dinnebito Wash, and April 1994 to 2000 at Polacca Wash.

The records for Laguna Creek, Dinnebito Wash, and Polacca Wash are too short for a statistical analysis of trends. There is no significant trend in the annual average discharges for Moenkopi Wash from 1977 to 2000. Median flows for November, December, January, and February of each water year are used as an index of ground-water discharge to those streams. There is no significant trend in the median winter flows for Moenkopi Wash from 1977 to 2000. The records for the other three streams are too short for a statistical analysis of trends. The median winter flows for Dinnebito Wash and Polacca Wash, however, appear to have decreased during the last 6 years. There is no apparent trend in the median winter flows for Laguna Creek since 1997.

In 2001, water samples were collected from 12 wells and analyzed for selected chemical constituents. Dissolved-solids concentrations ranged from 102 to 628 mg/L, and samples from 8 of the wells had dissolved-solids concentrations less than 300 mg/L. From about the mid-1980s or early 1990s to 2001, there are no significant trends in the concentrations of dissolved solids, chloride, and sulfate in water samples from 6 of the 7 wells with sufficient years of record for a statistical test. The concentration of one tested constituent (dissolved solids) in samples from Rocky Ridge PM3 significantly increased from 1990 to 2001.

Dissolved-solids concentrations in water samples from the unnamed spring near Dennehotso, Pasture Canyon Spring, and Moenkopi School Spring ranged from 116 to 194 mg/L, and dissolved-solids concentration in the water sample from Burro Spring was 348 mg/L. From the late 1980s to 2001, there are no significant tends in the concentrations of dissolved solids, chloride, and sulfate in water samples from Burro Spring, the unnamed spring near Dennehotso, and Pasture Canyon Spring. From 1987 to 2001, concentrations of chloride and sulfate significantly increased in water samples from Moenkopi School Spring and concentrations of dissolved solids did not significantly change.

The performance and sensitivity of the 1988 USGS numerical model of the N aquifer were analyzed. The overall performance of the model for steady-state conditions is reasonable for residuals of heads (difference between observed and simulated steady-state heads). The mean residual for steady-state heads is 5.3 ft, median residual is -0.2 ft, root mean square error of residuals is 35 ft, and 80 percent of the absolute values of residuals are less than 38 ft. There is a small overall positive bias and a small positive areal bias in the Shonto, west-central, and Tuba City areas. Positive bias is where simulated heads are consistently lower than observed heads. Simulated flows are about 40 percent different than estimated flows at 2 of 3 discharge areas simulated in the model; however, this comparison is only a rough approximation of performance because the accuracy of the estimated flows is uncertain.

The overall performance of the model for transient conditions is fair for residuals of changes in head (difference between observed and simulated changes in head); the mean residual for changes in head from steady state to 1999 is 4.3 ft, median residual is 3.6 ft, root mean square error of residuals is 40 ft, and 80 percent of the absolute values of residuals are less than 31 ft. The model is biased in two areas. In the Tuba City area, simulated changes in head are much more negative than observed changes in head; all six residuals are positive and three residuals are between 75 and 155 ft. In the confined area of the N aquifer, observed changes in head are more negative than simulated changes in head; 12 of the 17 residuals are negative and 8 residuals are between -57 and -20 ft.

Analysis of model sensitivity indicates that recharge, transmissivity, and storage coefficient are the most important parameters for estimating heads, changes in heads, and flows. A strong correlation between recharge and transmissivity and a lack of independent and reliable estimates of recharge, transmissivity, and discharge create a uniqueness problem in model calibration. Several models could be constructed and calibrated with different values of recharge or transmissivity and still have similar fits to the observation data. The amount of simulated evapotranspiration is uncertain because available observation data are insensitive to the maximum evapotranspiration parameter in the model and there are no independent estimates of evapotranspiration.

Information from recent data and studies and more advanced modeling techniques could be used to develop a more representative and less uncertain model. The most useful objectives of future data collection and studies would be to obtain better estimates of recharge, discharge, transmissivity, and storage coefficient. Additional observation data (heads, changes in heads, and flows) would be the most useful in the recharge area near Shonto, discharge areas of Moenkopi Wash and Laguna Creek, and areas of most stress (withdrawals), such as Kayenta and the central, south-central, and Tuba City areas.

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