Geohydrology and Effects of Water Use in the Black Mesa Area, Navajo and Hopi Indian Reservations, Arizona

United States Geological Survey Water-Supply Paper 2201

Prepared in cooperation with the Arizona Department of Water Resources

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By James H. Eychaner

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GLOSSARY

A number of terms used in the report are defined below. The definitions were adapted from Baldwin and McGuinness (1963), Lohman and others (1972), and U.S. Water Resources Council (1980).

Aquifer—A layer of rock or soil that carries a usable supply of water.

Artesian aquifer—See confined aquifer.

Confined aquifer—An aquifer that lies between layers of less permeable rock and in which ground water is confined under pressure. Static water levels in wells that penetrate a confined aquifer are higher than the top of the aquifer. Synonym: artesian aquifer. See also unconfined aquifer.

Discharge—The processes by which water leaves an aquifer.

Ground-water divide—A ridge in the water table or other potentiometric surface from which ground water moves away in both directions.

Ground-water model—Simulated representation of a ground-water system to aid definition of behavior and decisionmaking.

Head—The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point in an aquifer. In this report, datum used is National Geodetic Vertical Datum of 1929. See potentiometric surface.

Hydraulic conductivity—The rate at which water is transmitted through a unit cross-sectional area of an aquifer under a unit hydraulic gradient. Hydraulic conductivity describes the ability of the aquifer material to transmit water and may have substantially different values for horizontal and vertical flow through the same material.

Hydraulic gradient—The change in head per unit of distance in a given direction.

National Geodetic Vertical Datum of 1929 (NGVD of 1929)—A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

Potentiometric surface—An imaginary surface representing the static head of ground water, of which the water table is one type. The potentiometric surface for a confined aquifer is the level at which water would stand in wells that tap the aquifer.

Recharge—The processes of addition of water to the zone of saturated rock.

Specific yield—The volume of water that will drain by gravity from a unit volume of saturated material. Specific yield reflects storage in pores within the aquifer material and approximates the storage coefficient of an unconfined aquifer.

Storage—Water naturally detained in a ground-water reservoir, artificial impoundment of water in ground-water reservoirs, or the water so impounded.

Storage coefficient—The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. The storage coefficient of a confined aquifer reflects storage due to the pressure exerted on the water and rock. See also specific yield.

Transmissivity—The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity describes the ability of the entire thickness of an aquifer to transmit water and is the product of hydraulic conductivity and saturated thickness.

Unconfined aquifer—An aquifer in which only part of the permeable rock is saturated. Synonym: water-table aquifer. See also confined aquifer.

Water budget—An accounting of the inflow to, outflow from, and storage changes in an aquifer.

Water table—The surface in an unconfined aquifer below which the rocks are saturated with water. The water table is the level at which water stands in wells that penetrate the uppermost part of an unconfined aquifer. See potentiometric surface.

Water-table aquifer—See unconfined aquifer.

Conversion Factors

For readers who prefer to use the International System of Units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	*By*	*To obtain SI unit*
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Geohydrology and Effects of Water Use in the Black Mesa Area, Navajo and Hopi Indian Reservations, Arizona

By James H. Eychaner

Abstract

The N aquifer is the main source of water in the 5,400-square-mile Black Mesa area in the Navajo and Hopi Indian Reservations in northeastern Arizona. The N aquifer consists of the Navajo Sandstone and parts of the underlying Kayenta Formation and Wingate Sandstone of Jurassic and Triassic age. Maximum saturated thickness of the aquifer is about 1,050 feet in the northwestern part of the area, and the aquifer thins to extinction to the southeast. Water is under confined conditions in the central 3,300 square miles of the area. To the east, north, and west of Black Mesa, the aquifer is exposed at the surface, and water is unconfined. The aquifer was in equilibrium before about 1965. Recharge of about 13,000 acre-feet per year was balanced primarily by discharge near Moenkopi Wash and Laguna Creek and by evapotranspiration. At least 180 million acre-feet of water was in storage. The estimated average hydraulic conductivity of the aquifer is 0.65 foot per day. The confined storage coefficient is estimated to be about 0.0004 where the aquifer is thickest, and the estimated unconfined storage coefficient ranges from 0.10 to 0.15.

Ground-water withdrawals that averaged 5,300 acre-feet per year from 1976 to 1979 have caused water levels to decline in wells in the confined part of the aquifer. Withdrawals include an average of 3,700 acre-feet per year to supply a coal-slurry pipeline from a coal mine on Black Mesa. Six observation wells equipped with water-level recorders have been used to monitor aquifer response. The water level in one well 32 miles south of the mine declined 17 feet from 1972 through 1979 and 3.5 feet during 1979.

A mathematical model of the N aquifer was developed and calibrated for equilibrium and nonequilibrium conditions. The model was used in part to improve estimates of aquifer characteristics and the water budget, and it successfully reproduced the observed response of the aquifer through 1979. The model results indicate that about 95 percent of the 44,000 acre-feet of water pumped from 1965 to 1979 was withdrawn from storage, but the reduction amounted to less than 0.03 percent of total storage. Water-level declines through 1979 were estimated to be more than 100 feet in an area of 200 square miles. Four projections of future water-level changes were made using the model. The most probable projection indicates that water-level declines would exceed 100 feet in an area of 440 square miles by 2001. Most of the decline would be recovered within a few years if withdrawals at the mine ceased. By 1990, however, municipal-supply pumpage is expected to exceed pumpage at the mine, and this pumpage would continue to have significant impacts on water levels in the Black Mesa area.

INTRODUCTION

The N aquifer is the main source of water in the 5,400-mi^2 Black Mesa area in the Navajo and Hopi Indian Reservations in northeastern Arizona (fig. 1). Black Mesa is a prominent landmark, which covers about 2,000 mi^2. The mesa is bounded by cliffs as much as 2,000 ft high and 30 mi long on its north and northeast sides in the central part of the Navajo Indian Reservation and slopes southward into the northern part of the Hopi Indian Reservation. On the northern part of the mesa, Peabody Coal Co. operates a coal mine in a lease area of about 100 mi^2. Since 1970, the company has been pumping about 3,700 acre-ft/yr of water from the aquifer. Most of the water is used to transport coal as a slurry from the mine to a powerplant in southern Nevada. In addition, ground-water withdrawals for public supply increased from about 400 acre-ft in 1970 to 1,800 acre-ft in 1979. Because of the withdrawals, water levels in wells that tap the N aquifer have declined in a large part of the Black Mesa area. The Navajo and Hopi Indian Tribes have expressed three concerns: (1) how much of the water-level decline is a result of pumping at the mine, (2) what further declines may be expected over the life of the mine, and (3) what will be the long-term effects on the availability of water from the N aquifer for other uses?

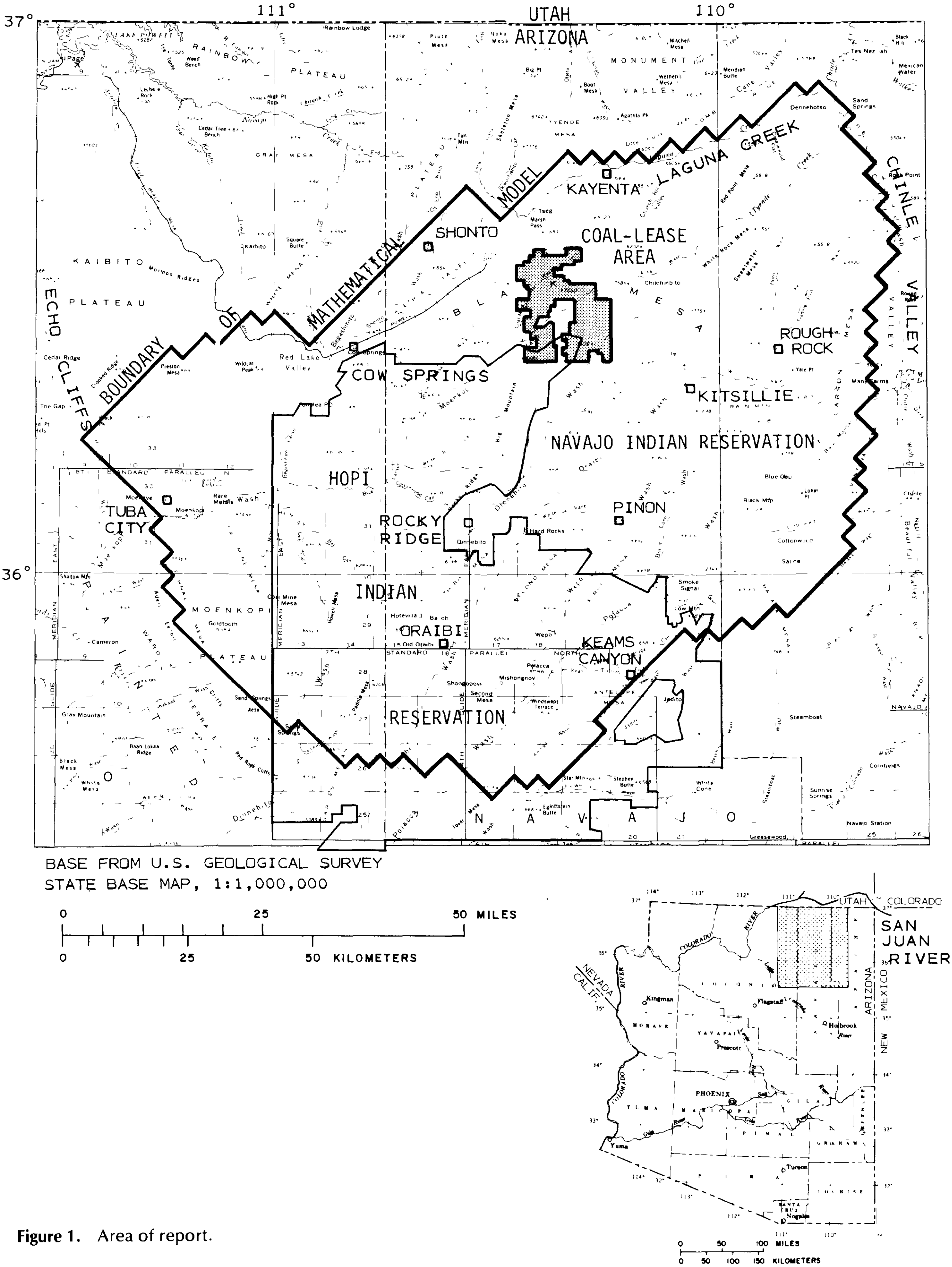


Figure 1. Area of report.

Purpose and Scope of the Study

The purpose of the study was to develop a mathematical model of the ground-water flow in the N aquifer in order to improve understanding of the aquifer and to compare the probable future effects of alternative management plans. The study integrated all available descriptive information about the aquifer, but extensive new data were not collected. A number of terms used in the report are defined in the glossary. This report covers one phase of a continuing program to monitor the N aquifer. The program is funded jointly by the U.S. Geological Survey and the Arizona Department of Water Resources. The cooperation and assistance of the Navajo Tribe, Hopi Tribe, U.S. Bureau of Indian Affairs, and Peabody Coal Co. are gratefully acknowledged.

Relation to Previous Investigations

The geology and hydrology of the Black Mesa area have been discussed in detail by many authors. Harshbarger and others (1957) and Cooley and others (1969) discussed the formations of principal interest in this study and gave extensive citations of the pertinent literature. Cooley and others (1969) included a complete geologic map. Levings and Farrar (1977a, b, c, d) and Farrar (1979, 1980) summarized the available data on ground-water conditions near Black Mesa. These map reports show the extent of each aquifer, distribution of water levels, direction of ground-water flow, areas where water is under confined or unconfined conditions, and chemical quality of water. Additional reports that present basic data or describe the geohydrology of the Black Mesa area are listed in the section entitled "Selected References."

Before the coal mining began, a time-drawdown analysis of a hypothetical single well was used to estimate the worst probable outcome after 30 years of pumping. The analysis indicated that water-level decline might reach 600 ft at 10 mi from the pumping center and 300 ft at 20 mi (W. T. Pecora, U.S. Geological Survey, written commun., 1966). In 1971 after the mining had begun, a mathematical model was used to estimate the most likely results of 30 years of pumping. That model computed 200 ft of water-level decline at 10 mi from the pumping center and 100 ft at 20 mi (L. A. Wood, U.S. Geological Survey, written commun., 1971). These analyses did not consider the effects of community pumping or the variation of aquifer characteristics in the area.

The Black Mesa monitoring program began in 1971. Water-level recorders were installed in six observation wells to measure water-level changes. Five of the six wells were drilled to collect additional geologic data. Annual water-level measurements were begun in six stock wells. Water meters were installed at selected municipal-supply wells to complement the meters that measure all water pumped at the coal mine. Because any changes in water quality were expected to appear first in the area of greatest stress, water samples for chemical analysis were collected periodically from the production wells at the mine. Using these methods, the program measured the stress applied to the aquifer and the response to that stress.

A progress report on the monitoring program points out the need for a detailed evaluation of the effects of withdrawals on water levels in wells serving communities near Black Mesa to distinguish the effects of pumping at the mine from the effects of community pumping (U.S. Geological Survey, 1978, p. 4). The hydraulic analysis in the present report, which addresses that need, is more detailed than those in previous studies and uses data on water-level declines that were not available earlier.

Methods of Investigation

A mathematical model was developed to simulate the flow of ground water in the N aquifer. The model was based on a computer program by Trescott and others (1976). The model program approximates the differential equation for nonsteady- state flow of water in an aquifer using a two-dimensional finite-difference equation. Application of the model program to the N aquifer requires estimates of inflow and outflow rates and of the hydraulic characteristics of the aquifer throughout the area. These characteristics include saturated thickness, hydraulic conductivity, storage coefficient, and water levels measured periodically. Initial estimates were made for each characteristic from field data. The model was used to improve the estimates in areas of uncertainty, and the resulting estimates collectively are considered to be more reliable than the initial ones. The model was used to simulate the effects of four possible courses of development from 1965 through 2014.

GEOHYDROLOGIC SETTING

In the Black Mesa area ground water is present in four main aquifers, each of which consists of one or more geologic formations. In parts of the area where more than one aquifer is present, the aquifers overlie one another and are separated by layers of less permeable rocks. In ascending order the aquifers are the C aquifer, N aquifer, D aquifer, and the Wepo and Toreva Formations of Cretaceous age (Levings and Farrar, 1977b, c). The N aquifer is the lowest unit considered because it is generally the lowermost aquifer tapped by wells in the area and no significant amount of water moves between the N and C aquifers. Stratigraphic relations for the Black Mesa area were presented by Cooley and others (1969, pl. 1).

Geologic Units

The N aquifer consists of the Navajo Sandstone of Jurassic and Triassic(?) age and, in the northern and eastern parts of the area, of the underlying Kayenta Formation and Lukachukai Member of the Wingate Sandstone of Triassic age (Levings and Farrar, 1977b, c). The units are medium to very fine grained sandstone, which generally is weakly cemented, well sorted, and crossbedded (Harshbarger and others, 1957, p. 10–22). In some parts of the area the units include thin beds of mudstone. In general, the rocks of the N aquifer are exposed at the surface around Black Mesa, but they dip steeply into a structural basin more than 1,500 ft deep under the mesa (fig. 2). The aquifer is more than 1,200 ft thick at Kaibito, which is a short distance northwest of the study area, and thins to extinction at the southeast boundary of the area.

The N aquifer is underlain throughout the area by more than 1,100 ft of low-permeability rocks of the Chinle and Moenkopi Formations of Triassic age (Repenning and others, 1969, p. 2). The units are mostly claystone, mudstone, siltstone, and silty sandstone and form a confining base under the N aquifer that prevents significant downward movement of water. In the southwestern part of the area the Kayenta Formation grades into a siltstone, mudstone, and sandstone sequence more than 650 ft thick (Harshbarger and others, 1957, p. 18–19) that forms the confining base of the aquifer. The Coconino Sandstone of Permian age and its lateral equivalent, the De Chelly Sandstone, underlie the Moenkopi Formation and are the main water-bearing units of the C aquifer (Cooley and others, 1969, p. 12–13).

The boundaries of the study area generally correspond to the physical limits of the N aquifer. To the west and southwest, the aquifer is absent beyond the Echo Cliffs and Moenkopi Plateau. In the south where the aquifer is not exposed at the surface, the rocks either were not deposited or were removed by ancient erosion. To the east, Chinle Wash has eroded through the entire aquifer. To the northeast along Comb Ridge, the rocks were folded upward and removed by erosion. Between Chinle Valley and Comb Ridge, a narrow neck of the aquifer connects with a part of the aquifer beyond the study area. To the north, the rocks are cut by canyons tributary to the Colorado and San Juan Rivers. In the northwest where the aquifer extends beyond the study area, the boundary is along a ground-water divide.

Potentiometric Surface and Movement of Water

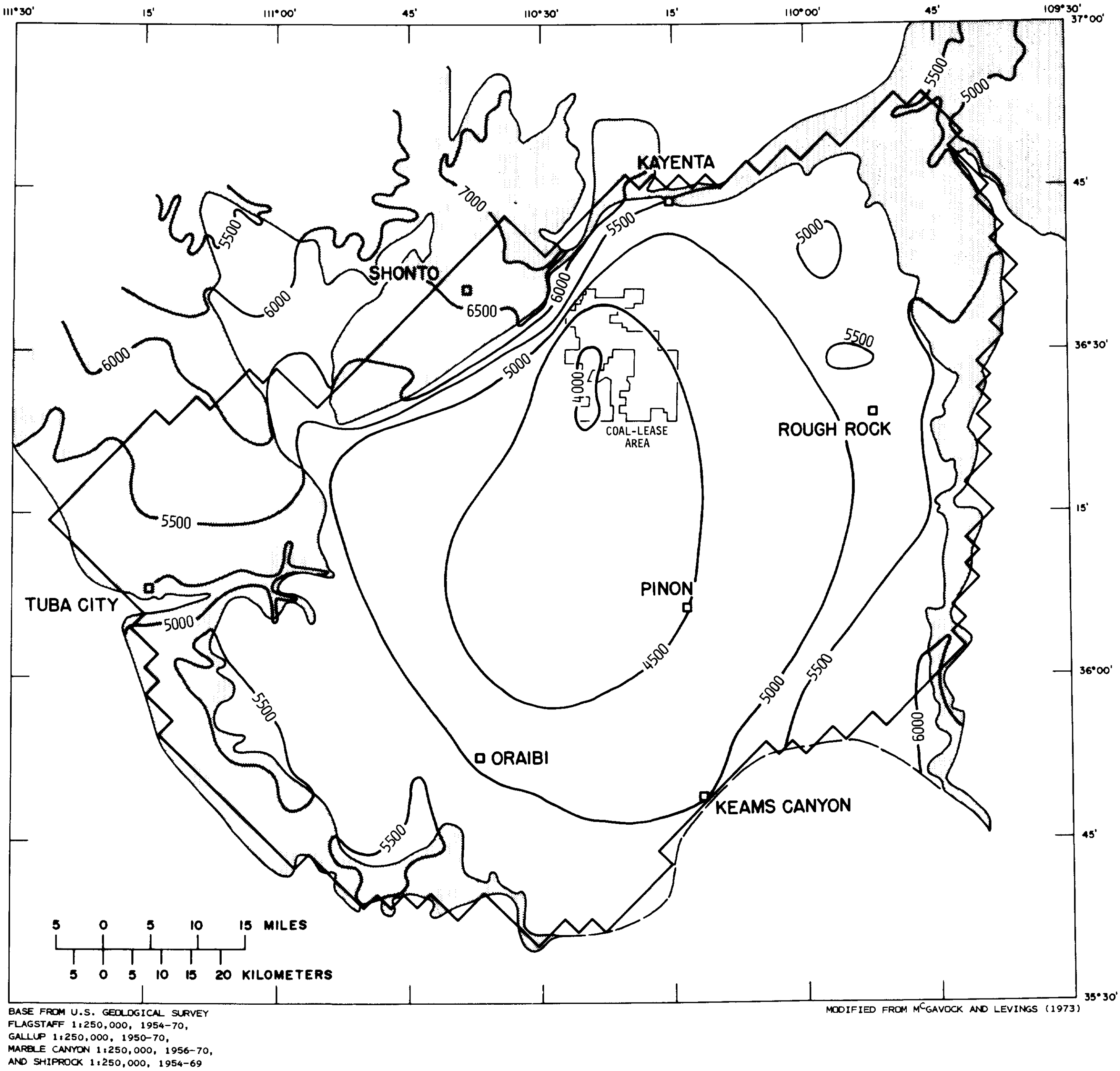
The approximate altitude of the potentiometric surface of the water in the N aquifer in 1964 is shown in figure 3. This altitude, which represents the head in the aquifer, is the altitude at which water would stand in a well that taps the aquifer but is not pumped. In 1964 the potentiometric surface was highest near Shonto and lowest along Moenkopi Wash and near the mouth of Laguna Creek. Until 1965, the potentiometric surface showed no general trend of change. Observation-well records show little seasonal or annual variation in head that is not related to pumping.

The potentiometric surface under much of Black Mesa is above the top of the aquifer (figs. 2 and 3). Therefore, the entire thickness of the aquifer is saturated and the water is under pressure; the water is said to be confined. Water in the N aquifer is under confined or artesian conditions in an area of about 3,300 mi^2. Water levels in that area are much more sensitive to pumping than those in the rest of the study area. The water level in a well that taps a confined aquifer will rise above the top of the aquifer to the potentiometric surface. Before 1965, the artesian rise was as much as 1,800 ft. In an area of 2,250 mi^2 the rise was more than 500 ft; however, water levels generally were still 500 to 1,500 ft below the land surface.

The potentiometric surface is below the top of the aquifer in the outcrop areas and around the fringe of Black Mesa. In these areas only part of the aquifer is saturated; the water is unconfined. The boundary between the areas of confined and unconfined conditions marks a line where head is equal to the elevation of the top of the aquifer.

Water in an aquifer flows in the direction of decreasing head. From the area near Shonto, water in the N aquifer in 1964 moved southward and southeastward under Black Mesa (fig. 3). The flow divided under the mesa, and part of the flow moved westward toward Moenkopi Wash and part moved eastward and northeastward toward Laguna Creek and Chinle Wash. The same general pattern of flow existed in 1980. Ground water flows toward the wells at the coal mine on Black Mesa, but hydraulic gradients 10 to 30 mi from the mine have changed only slightly.

The direction of ground-water movement indicates areas of inflow to and outflow from the aquifer. Recharge from precipitation enters the N aquifer in areas of outcrop near Shonto and in the southern part of Chinle Valley. Some water probably moves vertically from the overlying confining bed into the N aquifer under Black Mesa. Water from these sources is available to wells on Black Mesa. East and west of the mesa, additional recharge from precipitation enters the aquifer on other outcrops. The water recharged in these areas, however, generally is not available to wells on the mesa because the head is much less than the head under the mesa. Water in the N aquifer discharges mainly along Moenkopi Wash and Laguna Creek (fig. 3). Water also discharges to springs and seeps and to the alluvium along washes near the east, west, and southwest boundaries of the study area.



EXPLANATION

AREA OF OUTCROP OF N AQUIFER

—— 4500 —— STRUCTURE CONTOUR—Shows approximate altitude of top of N aquifer, generalized in areas of outcrop. Contour interval 500 feet. National Geodetic Vertical Datum of 1929

— — — — APPROXIMATE SOUTH LIMIT OF N AQUIFER

———— BOUNDARY OF MATHEMATICAL MODEL

Figure 2. Altitude of the top of the N aquifer and areas of outcrop.

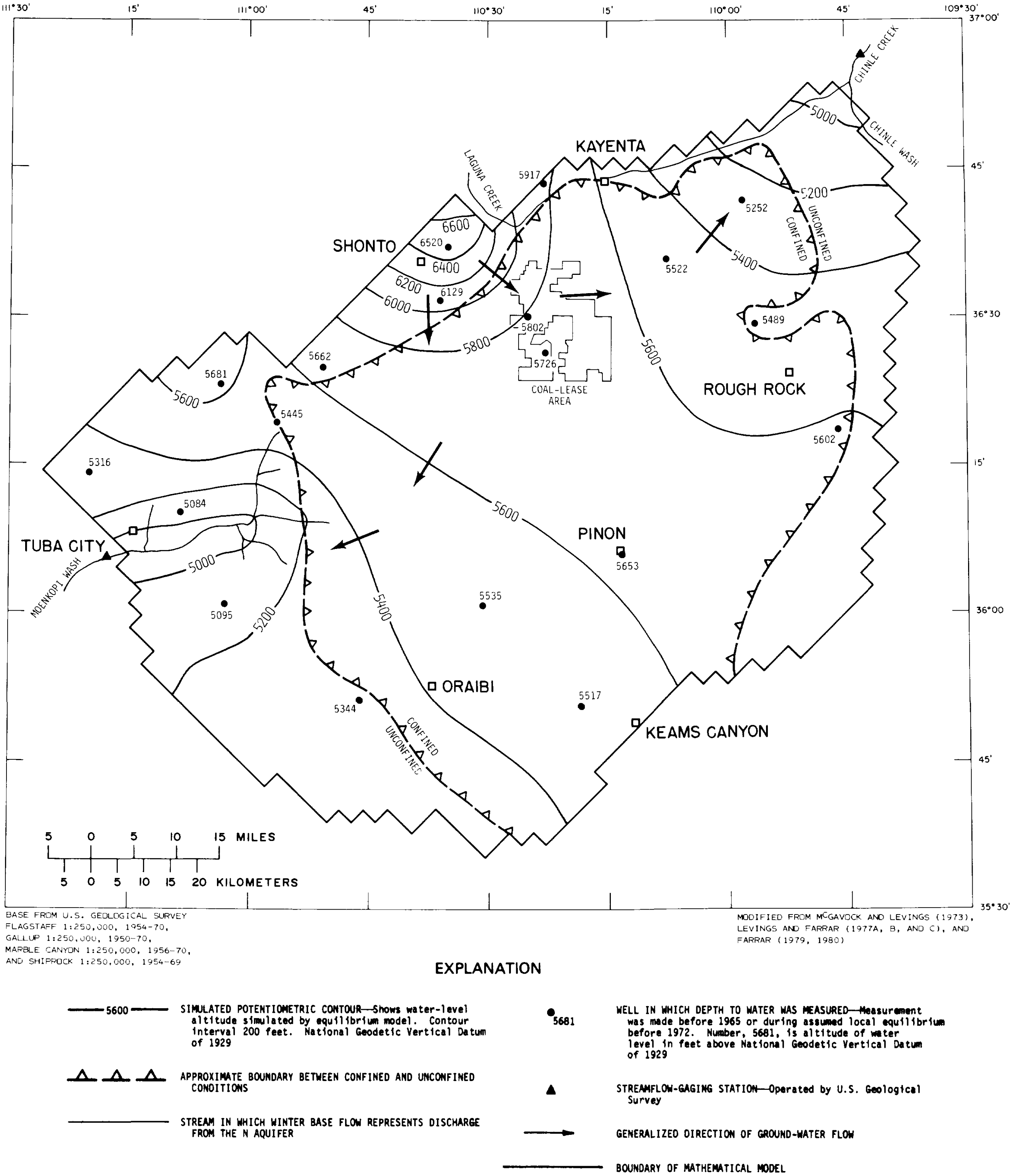


Figure 3. Altitude of water levels in wells that tap the N aquifer, 1964.

Relation to Overlying Formations

In the structural basin under Black Mesa the N aquifer is overlain by the Carmel Formation and the medial silty member of the Entrada Sandstone of Jurassic age (Harshbarger and others, 1957, p. 33–38). The units act as an upper confining bed to the aquifer and impede the vertical movement of water. The units consist of 200 to 350 ft of siltstone and silty, very fine grained sandstone.

In most of the area the Carmel Formation includes sandstone layers less than 3 ft thick. The units are separated by the lower sandy member of the Entrada Sandstone, which is a very fine grained sandstone 50 to 300 ft thick that contains some silt. The contacts of the lower sandy member with the other two units are gradational, and the member yields small amounts of water to wells.

The D aquifer overlies the Entrada Sandstone on Black Mesa and extends southeastward beyond the limit of the N aquifer. In ascending order the D aquifer consists of the Cow Springs Sandstone and Morrison Formation of Jurassic age and the Dakota Sandstone of Cretaceous age (Levings and Farrar, 1977b, c). In 1964 the potentiometric surface of the water in the D aquifer was as much as 600 ft above that in the N aquifer. The concentration of dissolved solids in water from the D aquifer is about 7 times greater than that from the N aquifer, the concentration of chloride ion is 11 times greater, and the concentration of sulfate ion is 30 times greater. The D aquifer is the uppermost aquifer considered in this report because it is overlain by the Mancos Shale of Cretaceous age (O'Sullivan and others, 1972, p. 13–24). The Mancos Shale consists of 450 to 650 ft of claystone and mudstone and prevents significant vertical movement of water.

HYDRAULIC CHARACTERISTICS

The hydraulic characteristics of the N aquifer affect the rate at which water moves through the aquifer, the amount of water in storage, and the rate and areal extent of water-level declines caused by groundwater withdrawals. The saturated thickness, transmissivity, hydraulic conductivity, and storage coefficient of the aquifer and the vertical hydraulic conductivity and specific storage of the upper confining beds were estimated mainly from drill-hole and aquifer-test data.

Saturated Thickness

The saturated thickness of the N aquifer (fig. 4) was estimated mainly on the basis of drillers', stratigraphic, or geophysical logs of about 75 wells that completely penetrate the Navajo Sandstone and about 125 wells that partly penetrate it. Some logs of wells that partly or totally penetrate the Kayenta Formation and the Lukachukai Member of the Wingate Sandstone were also used. Harshbarger and others (1957, p. 10–22) provided additional useful information on regional trends in the total thickness of each unit on the basis of measured sections in outcrops. In areas of unconfined conditions, geologic structure as mapped by Cooley and others (1969, pl. 1) aided in the estimation.

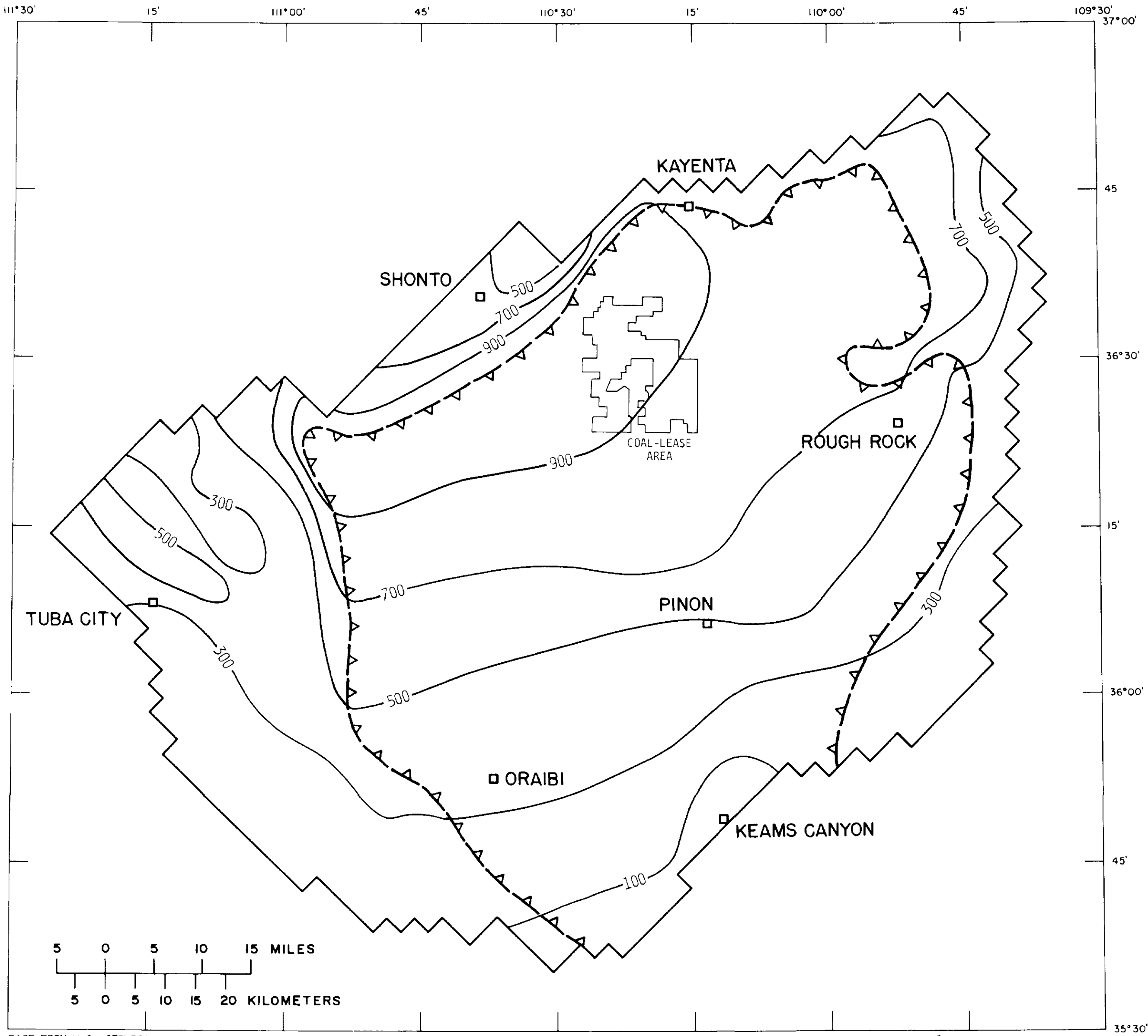
The saturated thickness of the N aquifer in the northeast half of the area includes the Navajo Sandstone, Kayenta Formation, and Lukachukai Member of the Wingate Sandstone (fig. 4). In the southwestern part of the area only the Navajo Sandstone is included. Because of a facies change (Harshbarger and others, 1957, p. 17–19), the Kayenta becomes the lower confining bed of the aquifer and isolates the Lukachukai in that area. In a central transition zone, part of the thickness of the lower two units is included. The saturated thickness of the N aquifer is greatest in the northwestern part of the area of confined conditions. The saturated thickness is about 1,050 ft near Shonto, and the aquifer thins to extinction to the southeast. Along the east and west boundaries of the aquifer, saturated thickness generally is between 100 and 400 ft.

Transmissivity and Hydraulic Conductivity

The transmissivity and horizontal hydraulic conductivity of the N aquifer were estimated from an aquifer-test analysis of water-level records for two observation wells during 6½ years of pumping at the Peabody well field. The observation wells, which are part of the ongoing monitoring program, are about 18 mi northeast and 32 mi south of the well field. The analysis must be considered approximate because the six pumping wells were used in various combinations, total pumping rate varied, and possible effects of vertical leakage or other pumping in the aquifer were ignored. The wells involved, however, span a large part of the area of confined conditions in the N aquifer. Estimated transmissivity was 700 ft^2/d, and estimated hydraulic conductivity, which was based on the average saturated thickness between the well field and the observation wells, was 1.1 to 1.4 ft/d. Short-term tests made when the eight wells were drilled produced estimates less than half the values computed from the long-term analysis.

More than 40 other short-term well and aquifer tests have been made in the area. Estimates of transmissivity ranged from 20 to 800 ft^2/d. The smaller values generally were in the southern part of the area where saturated thickness is less. Using total saturated thickness (fig. 4) to compute horizontal hydraulic conductivity gave estimates that ranged from 0.05 to 2.1 ft/d and averaged 0.65 ft/d. A regional trend to these values is not obvious, but the values may be slightly lower in the northeastern part of the area and under the northern part of Black Mesa. Estimates of transmissivity and hydraulic conductivity differed widely over short distances, and not all estimates were considered equally accurate. The differences in estimates may be due to regional differences in aquifer characteristics between sites; to local heterogeneities in the aquifer at the points sampled; or to incomplete or incorrect design, execution, or analysis of the tests.

Hood and Danielson (1979, p. 16–19) used core samples of the Navajo Sandstone to estimate hydraulic conductivity in an area about 100 mi north of Black Mesa.



BASE FROM U.S. GEOLOGICAL SURVEY
FLAGSTAFF 1:250,000, 1954-70,
GALLUP 1:250,000, 1950-70,
MARBLE CANYON 1:250,000, 1956-70,
AND SHIPROCK 1:250,000, 1954-69

MODIFIED FROM McGAVOCK AND LEVINGS (1973),
LEVINGS AND FARRAR (1977A, B, AND C), AND
FARRAR (1979, 1980)

EXPLANATION

——— 500 ——— APPROXIMATE LINE OF EQUAL SATURATED THICKNESS—Contour interval 200 feet

—△—△—△—△—△— APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS

———————— BOUNDARY OF MATHEMATICAL MODEL

Figure 4. Saturated thickness of the N aquifer.

While drilling test wells, they collected 16 short cores from depths of 830 to 2,350 ft below the land surface. The average horizontal hydraulic conductivity of the cores, as determined in the laboratory, was 0.55 ft/d. This value is similar to values derived from field tests in the Black Mesa area.

Vertical Hydraulic Conductivity of the Confining Beds

The vertical hydraulic conductivity of the Carmel Formation and the medial silty member of the Entrada Sandstone, which overlie the N aquifer, was estimated by the equation:

$$Q=KIA \qquad (1)$$

where

Q is discharge, in cubic feet per day;
K is hydraulic conductivity, in feet per day;
I is hydraulic gradient (dimensionless); and
A is the cross-sectional area of flow, in square feet.

Leakage through the units was estimated to be 200 acre-ft/yr (see section entitled "Water Budget"). The leakage occurs in an area of about 3,400 mi^2, in which the average thickness of the units is about 250 ft and the average head difference across the units is about 300 ft. Head differences greater than average occur in an area where the thickness is less than average. By using these values in equation 1, rearranging terms, and converting units, the vertical hydraulic conductivity of the upper confining beds was estimated to be 10^{-7} to 10^{-8} ft/d. The larger values apply in the southwestern part of the mesa where the Carmel Formation contains a higher proportion of sand (Harshbarger and others, 1957, p. 34). The values are not highly reliable, but they are consistent with results of other studies. Davis (1969, p. 69–71) stated that the vertical hydraulic conductivity of siltstone generally is less than 2.5×10^{-5} ft/d and cited one formation for which the value is 3.6×10^{-8} ft/d.

The geologic descriptions of the Chinle and Moenkopi Formations that underlie the N aquifer indicate that their vertical hydraulic conductivity is less than that of the upper confining beds. In this study the value was assumed to be effectively zero.

Storage Coefficient

The storage coefficient in areas of confined conditions can be estimated from aquifer tests or specific storage. Specific storage is the ratio of storage coefficient to saturated thickness and is a function of the compressibility and other physical properties of water and aquifer rock (Freeze and Cherry, 1979, p. 58–59).

Analyses of long-term records for two observation wells and four short-term aquifer tests produced estimates of storage coefficient between 0.00022 and 0.0008 and estimates of specific storage between 2.5×10^{-7} and 1.3×10^{-6} ft^{-1}. Using an assumed value for the compressibility of the rock, specific storage was estimated to be 2.5×10^{-7} ft^{-1}. Because both methods gave similar values for specific storage, the confined storage coefficient of the N aquifer was estimated throughout the study area by multiplying the saturated thickness by 4×10^{-7} ft^{-1}. The estimate of the confined storage coefficient was about 0.0004 under the northern part of Black Mesa, and the estimates decreased to the southeast.

The storage coefficient in areas of unconfined conditions was estimated to range from 0.10 to 0.15. Cooley and others (1969, p. 45–49) reported that laboratory determinations of the specific yield of weathered cores of material from the N aquifer ranged from 0.18 to 0.29. Because the samples were disturbed and weathering and leaching of soluble material from the samples probably increased their specific yield, lower values were used for the unconfined storage coefficient in this study.

The specific storage of the upper confining beds was estimated to be 10^{-7} ft^{-1}, which is slightly less than the estimate for the aquifer. This value was used in simulation of leakage from the confining beds.

WATER BUDGET

The water budget of an aquifer accounts for all inflows, outflows, and changes in ground-water storage. The sum of all inflows less the sum of all outflows equals the change in storage. If inflow equals outflow, the change in storage is zero and the aquifer is in equilibrium or steady state. Equilibrium is reflected by the absence of long-term trends of changing water levels, as was the case in the N aquifer before about 1965. If inflow does not equal outflow, the aquifer is in nonequilibrium or transient state, and the change in storage is reflected in changing water levels. Between 1965 and 1979, withdrawal of water from the N aquifer increased sufficiently to cause water levels to decline in wells that tap the artesian part of the aquifer. These declines indicate nonequilibrium.

A complete water budget of the N aquifer in the Black Mesa area cannot be calculated from available field data. The components of the budget that have been calculated are discussed in this section. The remaining components were estimated during calibration of the mathematical model. A water-budget table derived from the model is included in the section entitled "Calibration."

Inflow

The primary inflow to the aquifer is recharge of rainfall and snowmelt on outcrops. A small amount of inflow probably occurs as leakage from the upper confining beds.

Recharge

Rainfall and snowmelt recharge the N aquifer throughout the 1,400 mi^2 where the aquifer is exposed at the surface. Average annual precipitation in most outcrop areas is less than 12 in., but north of Black Mesa near Shonto it is as much as 18 in. (Cooley and others, 1969, pl. 4). About 3 percent of the precipitation near Shonto and about 1 percent in the other outcrop areas were assumed to become recharge. Estimated average annual recharge was 13,000 acre-ft. Although the area near Shonto is only about 15 percent of the outcrop, the area was estimated to produce more than one-third of the recharge.

Leakage

Some water may enter the N aquifer from the upper confining beds. The driving force for such flow is present because the head in the overlying D aquifer in 1964 averaged about 300 ft higher than that in the N aquifer. Geologic descriptions of the confining beds suggest that they could transmit water downward. Differences in the chemical composition of the waters of the two aquifers, however, indicate that the amount of flow must be small. The concentrations of sulfate, chloride, and dissolved solids are much greater in the D aquifer. Unless a chemical process decreases the concentrations in transit, water from the N aquifer in areas affected by leakage should have greater concentrations than water from unaffected areas.

Chemical reduction is the only process likely to cause depletion of sulfate between the D and N aquifers. The rocks between the aquifers are red or white, which suggests an oxidizing environment where reduction would not be expected. Therefore, the sulfate concentration in the water from the D aquifer is unlikely to decrease in transit. If all sulfate in the water from the N aquifer came from the D aquifer, the ratio of concentrations would equal the ratio of water volumes from each source. The sulfate concentration in water from the N aquifer in the Black Mesa area generally is less than 20 milligrams per liter (mg/L); however, the average sulfate concentration in water from the D aquifer is 600 mg/L. Therefore, not more than 3 percent of the water in the N aquifer is derived from vertical leakage, and at least 97 percent comes from recharge. Similar though less pronounced differences exist for chloride and dissolved solids. Thus, not more than 400 acre-ft/yr—3 percent of 13,000 acre-ft/yr—could have moved between the aquifers before stress was applied to the system. This value is probably too large because some sulfate is present in water from the N aquifer in outcrop areas where leakage could not occur and because not all water recharged from precipitation moves through the area of overlap. The rate of leakage between the aquifers was estimated to be 200 acre-ft/yr before stress.

Any increase in the leakage rate due to pumping from the N aquifer should appear first as an increase in the dissolved-solids concentration in water from the Peabody wells, because the head decline in the aquifer is greatest in that area. Water samples for chemical analysis have been collected from the wells in most years since 1968. As of 1980, no changes have been observed.

Outflow

Outflow from the N aquifer occurs as surface discharge to streams and springs, evaporation and transpiration, subsurface seepage into alluvium along stream channels, underflow in a small area near the mouth of Laguna Creek, and withdrawals. Because the head in the N aquifer is greater than that in the underlying C aquifer, water may leak downward from the N aquifer. The lower confining beds are much less permeable than the upper ones; therefore, downward leakage probably is much smaller than leakage from above. Downward leakage was assumed to be negligible.

Surface Flow

Most outflow from the N aquifer appears as surface flow in Moenkopi Wash and Laguna Creek (fig. 3) and as springs near the boundaries of the aquifer (Davis and others, 1963). The streams are dry during the summer because of high evapotranspiration losses along the channels. Winter base flow is less affected and was used to estimate the equilibrium discharge of the N aquifer near the streams. During water years 1926–41, winter base flow at the Moenkopi Wash near Tuba gaging station was about 5.3 ft^3/s, which is equivalent to about 3,800 acre-ft for a full year. During 1965–78, winter base flow at the Chinle Creek near Mexican Water gaging station, which is 5 mi downstream from the mouth of Laguna Creek, was about 4 ft^3/s or 2,900 acre-ft/yr. Part of the flow, however, may have come from Chinle Wash above Laguna Creek. Discharge of springs measured in the summer along the east, west, and south boundaries of the area totaled about 0.6 ft^3/s or 430 acre-ft/yr (Davis and others, 1963).

Evapotranspiration and Seepage

Discharge from the N aquifer by evapotranspiration occurs where the water table is near the land surface. Seepage of water from the aquifer into saturated alluvium occurs along Moenkopi Wash, Laguna Creek, and normally dry washes that flow toward the south and east boundaries of the area. Evaporation from bare soil may be a significant part of evapotranspiration in some areas, particularly near Tuba City. Evapotranspiration and outflow to alluvium tend to occur in the same areas; water that moves into the alluvium may later be discharged from it by evapotranspiration. Total outflow by evapotranspiration and seepage was estimated to be 6,000 acre-ft in 1964.

Underflow

Outflow from the study area occurs as underflow near the mouth of Laguna Creek. Water in the aquifer moves northeastward across the study-area boundry and joins water moving northwestward in a part of the aquifer outside the study area to form a northward flow along Chinle Creek. Underflow was estimated in a cross section 9 mi wide with an average saturated thickness of about 600 ft. The hydraulic gradient was estimated from field data to be 15 ft/mi and the hydraulic conductivity 0.65 ft/d. From equation 1, underflow was estimated to be 53,000 ft^3/d or 440 acre-ft/yr.

Withdrawals

Before about 1950, development of the N aquifer was slight and consisted of collection works at springs, dug wells a few tens of feet deep, and a few drilled wells equipped with windmills. Beginning about 1950, many deep holes were drilled and equipped with windmills to provide water for domestic and stock uses throughout the reservations. In 1964 total withdrawal by the wells was estimated to be about 100 acre-ft. Because the withdrawal was spread over a large area, it was assumed to be zero in this study.

As towns grew and schools were built in the Black Mesa area, water-supply systems pumping ground water were built to serve them. Withdrawals by the systems were assumed to be an insignificant part of the outflow from the aquifer before 1965. Water use has been increasing most rapidly at Kayenta, which is in the area of confined conditions, and at Tuba City where the water is unconfined. Since 1970, the annual increase in water use has been about 45 acre-ft at Kayenta and about 120 acre-ft at Tuba City. Table 1 shows the amount of water withdrawn for 1965–79.

The greatest withdrawal from the aquifer has been an average of 3,700 acre-ft/yr since 1971 from the area of confined conditions by Peabody Coal Co. (table 1). During 1967 and 1968, Peabody drilled five production wells into the N aquifer in the northern part of Black Mesa. Final lease agreements to permit 30 years of mining were signed in 1970 and 1971, and mining and slurry operations began in 1970. Two additional production wells were drilled in 1972 and 1980. The seven wells obtain water mainly from the N aquifer, although they are also

Table 1. Withdrawals from the N aquifer, 1965–79

Year	Withdrawal, in acre-feet		
	Industrial[1]	Nonindustrial[2]	
		Confined[3]	Unconfined[4]
1965	0	50	20
1966	0	110	30
1967	0	120	50
1968	95	150	100
1969	43	200	100
1970	740	280	150
1971	1,900	340	150
1972	3,680	370	250
1973	3,520	530	300
1974	3,830	580	362
1975	3,550	600	508
1976	4,180	690	645
1977	4,090	750	726
1978	3,000	830	930
1979	3,500	860	930

[1]Metered pumpage by Peabody Coal Co. at their mine on Black Mesa, which is in the area of confined conditions.

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

[3]Includes metered pumpage at Kayenta and estimated pumpage at Chilchinbito, Rough Rock, Pinon, Keams Canyon, and Oraibi.

[4]Includes estimated pumpage at Tuba City, 1965-73, and metered pumpage, 1974-79.

perforated in the lower sandy member of the Entrada Sandstone. The wells do not obtain water from the Wepo or Toreva Formations or the D aquifer, and they do not penetrate the C aquifer. Separate accounting of production from the Entrada has not been made but is probably only a small fraction of the total. All pumpage at the mine is metered.

Storage

Storage in an aquifer is due primarily to the volume of saturated pore space in the aquifer, which varies with head in areas of unconfined conditions. In areas of confined conditions an additional, smaller amount of storage is due to expansion of the pores and compression of water under pressure, which also varies with head. A minimum estimate of the amount of water in storage may be obtained by multiplying the specific yield by the volume of saturated material in the entire aquifer. Using 0.10 for specific yield, storage in the N aquifer in 1964 was at least 180 million acre-ft. The additional storage due to pressure in the area of confined conditions was about 420,000 acre-ft. Total storage in the aquifer was about 14,000 times the annual inflow.

Because both components of storage are functions of head, a change in head is equivalent to a change in storage. Water-level changes in wells indicate changes in storage.

Of the six observation wells used in the monitoring program, water levels have declined in all four in the area of confined conditions, but through 1979, water levels had not declined in the two wells in unconfined areas (figs. 5 and 6). By 1970, the water level in well BM3, which is near Kayenta, had declined at least 23 ft from the level during 1959–63. The water levels in wells BM2 and BM5, which are 18 mi northeast and 32 mi south of the mine, respectively, began declining in late 1972. The decline from 1972 through 1979 was 18 ft in BM2 and 17 ft in BM5; during 1979, the declines were 4.5 and 3.5 ft. The water level in well BM6 has been declining steadily since the well was drilled in 1977; during 1979, the decline was about 6 ft.

Annual water-level measurements in six wells equipped with windmills show the same pattern of decline in the area of confined conditions and absence of decline in unconfined areas. Water levels in two of the wells in an area of unconfined conditions between Shonto and Kayenta rose 2 to 4 ft from 1972 to January 1980. Intermittent measurements showed that in most of the area of confined conditions water levels declined more than 10 ft from equilibrium to 1979. The largest decline measured where water is unconfined was 7 ft in one well near Tuba City. No water-level changes attributable to pumping from the N aquifer have been measured in wells that tap other aquifers in the study area.

Water pumped from a well comes first from the water in storage near the well. Depending on the aquifer, the withdrawal may induce recharge of water previously unable to enter the aquifer or may reduce discharge from the aquifer. In the N aquifer the greatest withdrawal is in the area of confined conditions. Recharge occurs in areas of unconfined conditions at some distance from the pumping. Because the amount of precipitation is small, little excess water is available to increase recharge. Discharge also occurs mainly in areas of unconfined conditions far from the pumping center. Therefore, little opportunity is available to induce recharge or reduce discharge. Reduction of storage accounts for nearly all water withdrawn from the N aquifer from 1965 through 1979, but the total withdrawal was less than 0.03 percent of total storage.

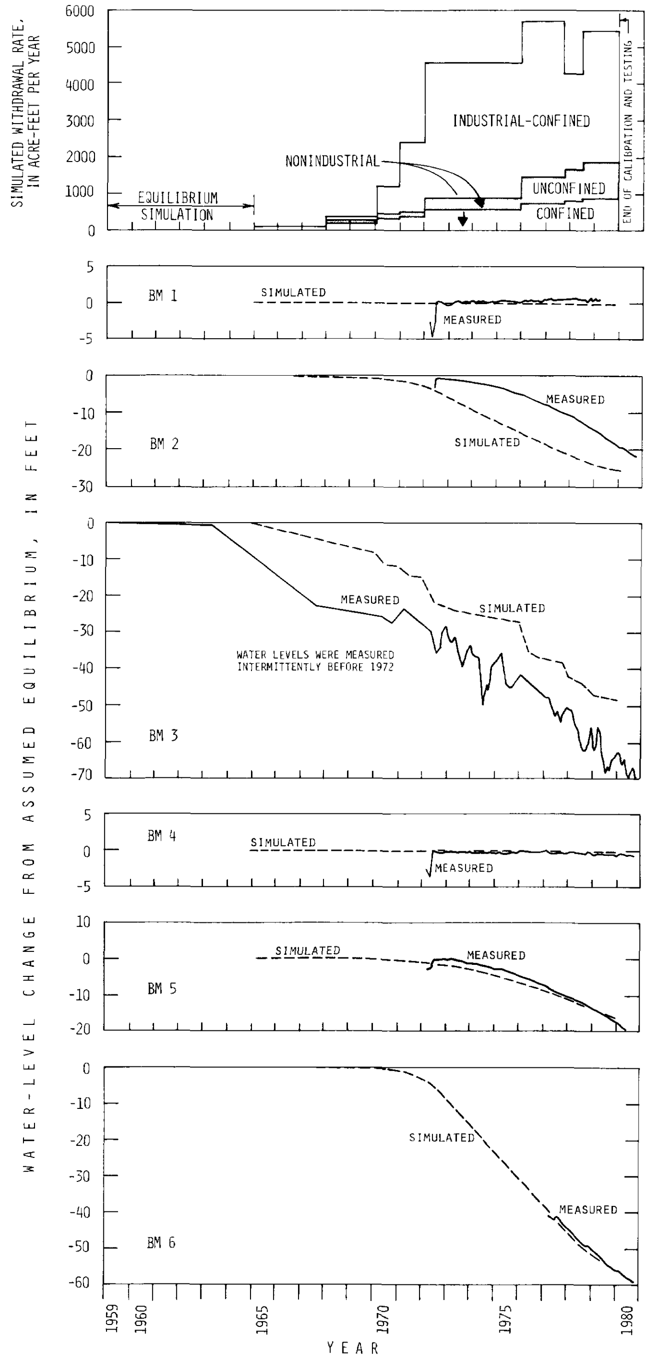
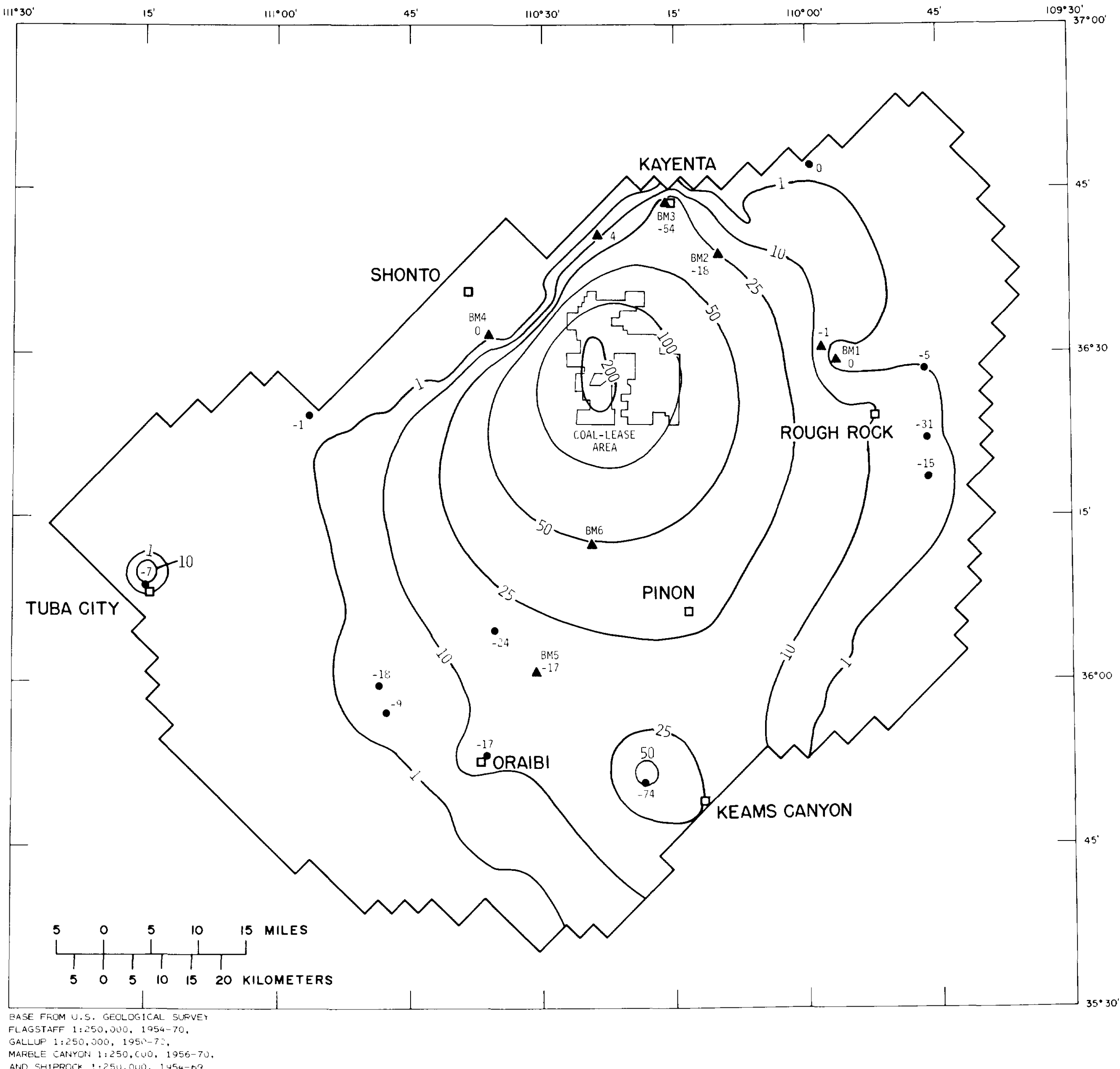


Figure 5. Simulated ground-water withdrawals and measured and simulated water-level changes for observation wells, 1959–80.

SIMULATION OF FLOW

A simulation model is a group of mathematical equations that describe the flow of water through an aquifer in relation to aquifer characteristics, the amount of water in storage, and rates of inflow and outflow. Use of a simulation model can help improve understanding of the aquifer system. The model can help improve estimates of the water budget and regional aquifer characteristics by making them consistent and by testing the reasonableness of estimates in areas of sparse data. A calibrated model, one for which all the estimates are acceptable, can be used to compare the future effects of management alternatives for the development of the aquifer.



EXPLANATION

—50— LINE OF EQUAL SIMULATED WATER-LEVEL DECLINE—Shows simulated decline from January 1965, date of assumed general equilibrium, through December 1979. Contour interval, in feet, is variable

▲ BM5 -17 WELL IN WHICH DEPTH TO WATER WAS MEASURED AT LEAST ANNUALLY—Identifier, BM5, indicates observation well equipped with water-level recorder as part of monitoring program. Number, -17, is difference, in feet, between water-level measurements during assumed local equilibrium 1965-72 and about December 1979. Number is not shown for observation well drilled in 1977

● -9 WELL IN WHICH DEPTH TO WATER WAS MEASURED INTERMITTENTLY—Number, -9, is difference, in feet, between water-level measurements during assumed local equilibrium 1953-70 and about 1979

——— BOUNDARY OF MATHEMATICAL MODEL

Figure 6. Measured and simulated water-level changes, 1965–79.

Computer Program

Several generalized computer programs have been written to solve the simulation equations. A model program by Trescott and others (1976) was used in this study. Because aquifer characteristics are not uniform, the aquifer was divided into rectangular blocks in which the characteristics were assumed to be uniform. The model program uses a node at the center of each block to represent all characteristics of the block. The program solves for the head and flow at each node by using a two-dimensional, finite-difference approximation to the partial differential equation for ground-water flow. Various processes of inflow and outflow at a block are described by additional equations. The analytic equations and their finite-difference approximations are described in the model program documentation (Trescott and others, 1976, p. 1–26). No changes were made to the documented solution methods.

In estimating leakage to or from an overlying aquifer, the model program limits the effective head in the aquifer to the greater of the actual head or the top of the aquifer. For a confined aquifer that receives inflow by leakage, this limit is appropriate. For the Black Mesa area, the same function was used to simulate discharge from the aquifer to streams and springs in areas of unconfined conditions, where head was above the streams and springs but below the top of the aquifer. In those areas, use of the limit caused several difficulties, which included incorrect selection of confined instead of unconfined storage coefficient and incorrect computation of leakage or transmissivity. Therefore, the limit was removed from the model program for this study. Discharge was simulated in proportion to the difference between the elevation of the stream or spring and the head in the aquifer. This change caused no problems in the confined part of the aquifer, because in no simulation of past or future water levels would the elevation of the top of the aquifer have been properly substituted for head. The revised program may not be directly applicable to other aquifers.

Input to the model program includes data that describe the physical area and thickness of the aquifer, the array of blocks used in computations, and initial estimates of head in each block. In general, these data were not changed during calibration. Other required data describe the water budget and the hydraulic characteristics of the aquifer and upper confining beds. These data were modified within reasonable limits during calibration.

The locations of the blocks used to simulate the N aquifer are shown in figure 7. Each block is a square with 2 mi to a side. The grid lies approximately northeast to southwest. Only those blocks for which computations were made are shown. The block size was selected as a reasonable compromise between the available data and the detail desired in the results.

Because the simulation equations are solved using average conditions over each block, the results probably will not reflect conditions that change in an area smaller than one block. In contrast, conditions that are uniform over several blocks generally will be represented adequately. Therefore, simulated heads in the area of confined conditions should be reliable. The water level in a pumping well that occupies 1 ft^2, however, will not agree with the simulated head in a 4-square-mile block. The simulated head can be adjusted to estimate the pumping level, but the adjustment may be large.

The boundaries of the model grid match the physical boundaries of the N aquifer in all but two areas (fig. 2). In the northwest the boundary was selected to approximate a ground-water divide that extends from near Shonto to the Echo Cliffs northwest of Tuba City. South of the divide, water in the N aquifer moves toward Moenkopi Wash; north of the divide, water moves toward the Colorado River. No water flows across the divide, and no simulated change in head was sufficient to move it. In the northeastern part of the area near the mouth of Laguna Creek, an arbitrary boundary was placed at a narrow neck in the aquifer. Underflow through the neck out of the study area was estimated.

Calibration

Calibration of the simulation model involves estimating all aquifer characteristics and inflow or outflow rates at each node. Although many measurements or computations have been made of water levels in wells, aquifer thickness, and transmissivity, data are not available for most nodes. Some data may be incorrect or be subject to multiple interpretations. Therefore, an initial estimate of each characteristic was made, and the model was used to compute the water level at each node. Disagreement between a measured water level in a well and the computed water level for the node is to be expected because the value for the node represents a much larger area. A large disagreement, however, indicated that estimated aquifer characteristics or flow rates were wrong. New estimates, which were within the range of values observed in the field, were made and tested by recomputing the water levels. This process was repeated until computed water levels were acceptably close to measured values. The calibration was done in two phases; one phase was for equilibrium conditions and one for nonequilibrium conditions.

Equilibrium

The model was calibrated initially for equilibrium conditions. The N aquifer was assumed to be in equilibrium before 1965. Computed water levels in the equilibrium calibration were tested against water levels measured as late as 1972 in areas not affected by pumping.

Discharge to streams and springs and seepage to alluvium were simulated by a leakage function that varies the discharge as head in the aquifer varies. Evapotranspiration was simulated by a function that reduces the discharge as the depth to water below the land surface increases. Recharge from precipitation was simulated as a constant rate at each node where the aquifer crops out. Inflow by leakage from the upper confining bed was simulated in the area where the D aquifer is present. The factors that control inflow and outflow were adjusted during the equilibrium calibration. Figure 7 shows the location of all nodes for which inflow or outflow was simulated, and table 2 summarizes the model water budget developed in this phase.

During equilibrium calibration, hydraulic conductivity was also adjusted. An average value of 0.65 ft/d was used over large areas, and adjustments were limited to the range from 0.32 to 0.97 ft/d. The transmissivity of the aquifer derived from this adjustment is shown in figure 8. Maximum transmissivity of the aquifer was thus estimated to be about 1,000 ft^2/d in the area of greatest saturated thickness, which is between Tuba City and Shonto. Simulated transmissivity ranged from about 300 to 800 ft^2/d in the area where the long-term aquifer-test analysis gave a value of 700 ft^2/d.

The simulated potentiometric surface derived from equilibrium calibration and water levels in wells measured during local equilibrium are shown in figure 3. The average difference between the initial estimate and the simulated value of head at each node was about 18 ft. Measured water levels generally were within 50 ft of simulated levels or about one-fourth of the contour interval used.

Nonequilibrium

Further calibration was done for the period of nonequilibrium from 1965 through September 1977, and the model was tested using data through 1979. During the calibration period, increasing amounts of ground water were withdrawn from the aquifer. In this phase the head values developed in the equilibrium calibration were used as input data so that changes in head caused by withdrawals could be examined independently of changes due to inaccuracies in the equilibrium calibration. The model program divides time into discrete "pumping periods" during which average values are used for pumpage, evapotranspiration, and other processes, although they actually vary daily or hourly. Six pumping periods were used in nonequilibrium calibration. The periods selected and the average rates used were assumed to be reasonable approximations of actual conditions. Withdrawal from the aquifer was simulated as a constant rate during each period at each node with a pumping well. Withdrawals by windmills are small and were not included. Figure 7 shows the locations of nodes at which pumping was simulated.

Nonequilibrium calibration involved adjusting aquifer characteristics, primarily the storage coefficient, to match computed rates of water-level decline with measured ones. Figure 5 shows simulated withdrawal rates and measured and simulated water-level changes in the six observation wells in the monitoring program. The well locations are shown in figure 6. Simulated declines were in good agreement with measured values for all wells except BM2. That well agreed more closely with the simulated decline in the next node northeast of the well. The well is near a monocline where the rocks dip steeply to the west and near the boundary between confined and unconfined conditions in the aquifer. The difference between measured and simulated response may be due to imprecision in defining the distance to the area of unconfined conditions, to locally significant vertical flow components in the aquifer, or to other errors in the estimated aquifer characteristics.

Although observation wells BM1 and BM2 are about the same distance from the Peabody well field, measured and simulated water levels declined during this period in BM2 but not in BM1. Well BM1 is in a small area of unconfined conditions related to local geologic structure, and the storage coefficient is 0.1. Near BM1, 10 acre- ft of water would be produced by a head decline of 0.16 ft over an area of 1 mi^2. BM2 is in the area of confined conditions, and the storage coefficient is about 0.00035. The production of 10 acre-ft of water near BM2 would require head to decline 45 ft over 1 mi^2. Thus, the increase in storage coefficient in moving from confined to unconfined conditions greatly restricts decline caused by distant pumping.

After the model was calibrated through September 1977, it was tested by entering pumping rates for the period through 1979. The model reasonably reproduced measured hydrographs during this period without further adjustment, including the hydrograph of observation well BM6, which was drilled in 1977 (fig. 5). Figure 6 shows simulated and measured water-level declines to the end of 1979 throughout the Black Mesa area. The declines are limited almost entirely to the area of confined conditions (compare figure 3 with figure 6). Decline exceeds 10 ft in an area of about 2,300 mi^2 and exceeds 100 ft in about 200 mi^2. The largest declines are around the Peabody well field, but other pumping centers are evident at Kayenta and Oraibi and near Keams Canyon and Tuba City. The declines diminish in a short distance northwest of the mine because unconfined water is nearby. South of the mine where the aquifer becomes thin, the declines diminish gradually. Municipal pumping has added to the decline in this area, but simulated pumping rates were mainly estimates, which may be in error. Although measured declines in stock wells on the southeast and southwest sides of the mesa are greater than simulated values, in most of the Black Mesa area the agreement between simulated and measured water-level changes is good.

The maximum decline simulated for a 4-square-mile block was about 220 ft near the mine. In that block, however, the decline near the pumping well was estimated by the model to be about 400 ft. Assuming 75 percent well efficiency, drawdown in the well would be about 530 ft. Total pumping lift, which is the sum of drawdown

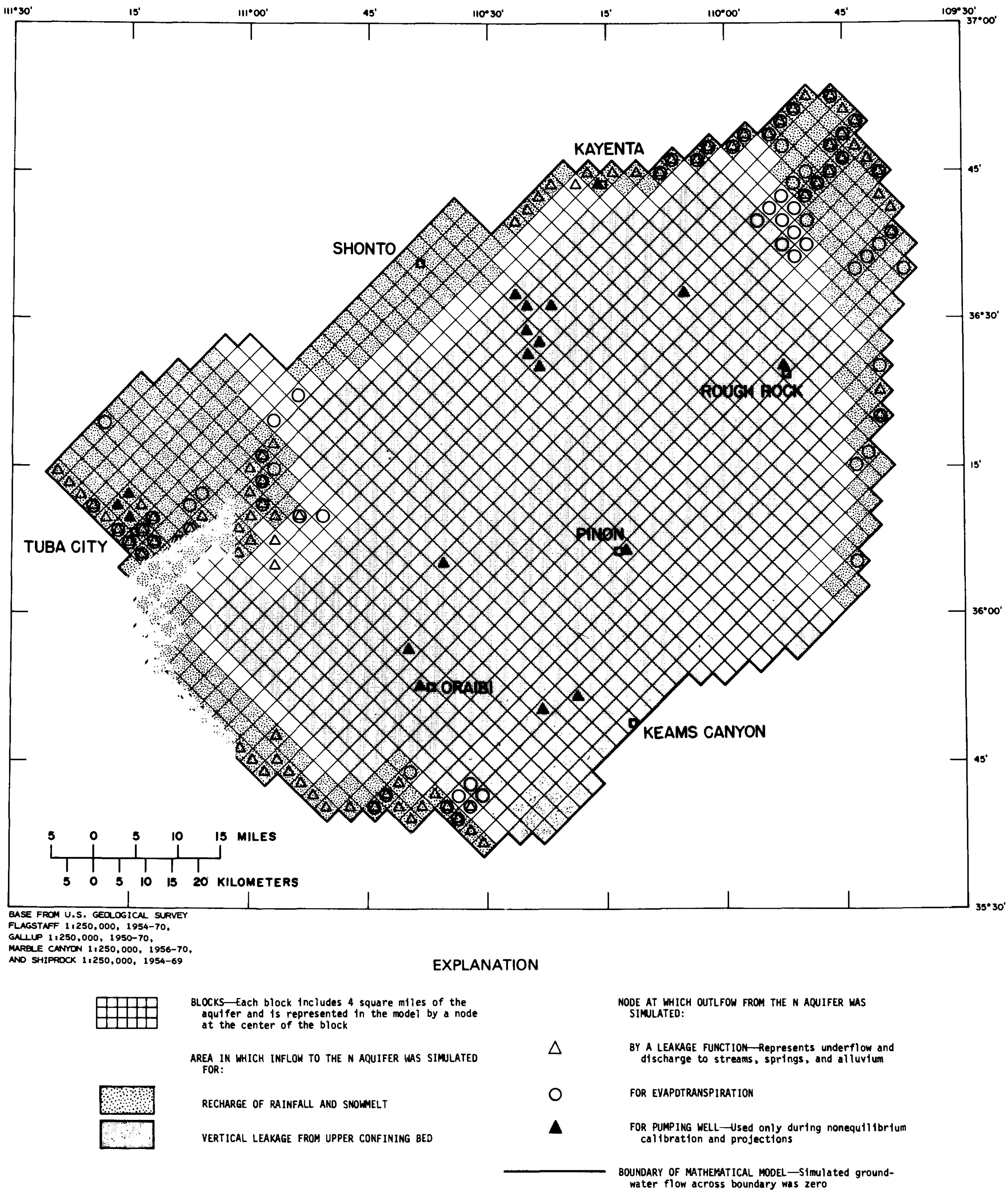


Figure 7. Finite-difference grid and boundary conditions used in mathematical model.

and depth to water during equilibrium, would be about 1,200 ft.

The water budget for 1979 developed from the nonequilibrium calibration is summarized in table 2. For 1979, simulated reduction in storage accounted for more than 95 percent of withdrawals. From 1965 through 1979,

Table 2. Simulated water budget of the N aquifer in 1964 and 1979

[Values, in acre-feet, are not intended to imply accuracy to the precision shown]

	1964		1979	
Inflow:				
Recharge from infiltration of rainfall and snowmelt				
Near Shonto	4,830		4,830	
West of Black Mesa	4,480		4,480	
East of Black Mesa	3,620		3,620	
Total		12,930		12,930
Vertical leakage from the upper confining bed		200		240
Total inflow		13,130		13,170
Outflow:				
To streams, springs, and alluvium				
Near Moenkopi Wash	5,500		5,490	
Near Laguna Creek	2,500		2,410	
In other areas	1,700		1,700	
Total		9,700		9,600
Underflow near mouth of Laguna Creek		450		450
Evapotranspiration		2,980		2,940
Withdrawals[1]				
Industrial (confined)	0		3,590	
Nonindustrial (confined)	0		850	
Nonindustrial (unconfined)	0		1,010	
Total		0		5,450
Total outflow		13,130		18,440
Change in storage (inflow minus outflow)		0		-5,270

[1]Does not include withdrawals from wells equipped with windmills, which were assumed to be negligible. In 1964, does not include withdrawals of small municipal systems, which were assumed to be negligible. Values for 1979 do not agree with those given in table 1 because this table is based on pumping periods not equivalent to the calendar-year basis of table 1.

simulated reduction in storage was also more than 95 percent of the 44,000 acre-ft withdrawn, but total storage in the aquifer decreased less than 0.03 percent. Simulated outflow near Laguna Creek decreased 4 percent from 1964 to 1979, primarily because of municipal pumpage at Kayenta. Also, small reductions in evapotranspiration and outflow near Moenkopi Wash and a small increase in vertical leakage were simulated.

Limitations and Use of the Model

The model reasonably reproduced the behavior of the N aquifer by using a number of assumptions. Vertical components of flow were assumed to have little enough regional significance to justify use of a single-layer, two-dimensional model. The mathematical assumptions in the model program were accepted for use in the model. Only geologic units that were assumed to be hydraulically significant were included in the simulation. The calibrated input data were assumed to describe accurately the water budget and hydraulic characteristics of the aquifer.

One way to evaluate the accuracy of the estimated aquifer characteristics is to examine the sensitivity of the results to other input values. The calibrated model includes estimates at every node, but they are not unique. Other combinations of estimates that are consistent with field observations could be selected that would simulate the N aquifer equally well. A 10-percent increase in transmissivity throughout the model caused simulated equilibrium head to decline about 13 ft and reduced simulated decline from 1965 through 1979 by about 5 percent. Reducing recharge by 10 percent caused equilibrium head to decline about 18 ft but made no change in simulated declines from 1965 through 1979. Reducing the leakage from the upper confining beds to zero caused equilibrium head to decline an average of 7 ft but had little effect on simulated declines through 1979. Changing the storage coefficient did not change the equilibrium head but changed the rate of decline due to stress. Increasing the confined storage coefficient by 50 percent reduced average decline through 1979 by 23 percent; however, decreasing it 50 percent increased the decline 66 percent. Changing the unconfined storage coefficient had little effect because most of the declines have occurred in areas of confined conditions. The value of 0.1 that was used is a minimum estimate. If the true value is higher, future head declines in areas of unconfined conditions would be less than those projected using this model.

Additional field data could help verify or correct some of the assumptions. The most important continuing monitoring effort concerns pumpage. Water use by communities is increasing, and several new community water systems have been established on Black Mesa since the late 1970's. Community water use probably will exceed pumpage at the Peabody mine by about 1990. Pumping from the area of confined conditions affects water levels in all other wells in that area in a short time. Therefore, accurate pumpage data are essential. Also, monitoring of water levels in observation wells will help check the accuracy of model calibration.

Several new activities would provide useful data to test the model. Periodic discharge measurements of selected springs and of Laguna Creek east of Kayenta would be helpful. Every 3 to 5 years, water-level measurements in 20 to 50 wells selected in light of model projections would be valuable to test and improve the calibration. An additional observation well near the Peabody mine equipped to monitor head at several points distributed vertically in the system would be useful. Well-designed aquifer tests could provide a check on the magnitude and variation of transmissivity and storage coefficient. If new wells are drilled, data would be obtained on the total thickness of the geologic units, and core samples could be taken for laboratory analyses to determine the specific yield of the aquifer and the vertical hydraulic conductivity of the confining beds.

These activities would provide additional descriptive data about the aquifer and its response to stress. Accurate data are the necessary foundation of reliable simulation modeling.

The calibrated model can be used to project future conditions in the N aquifer and to compare the effects

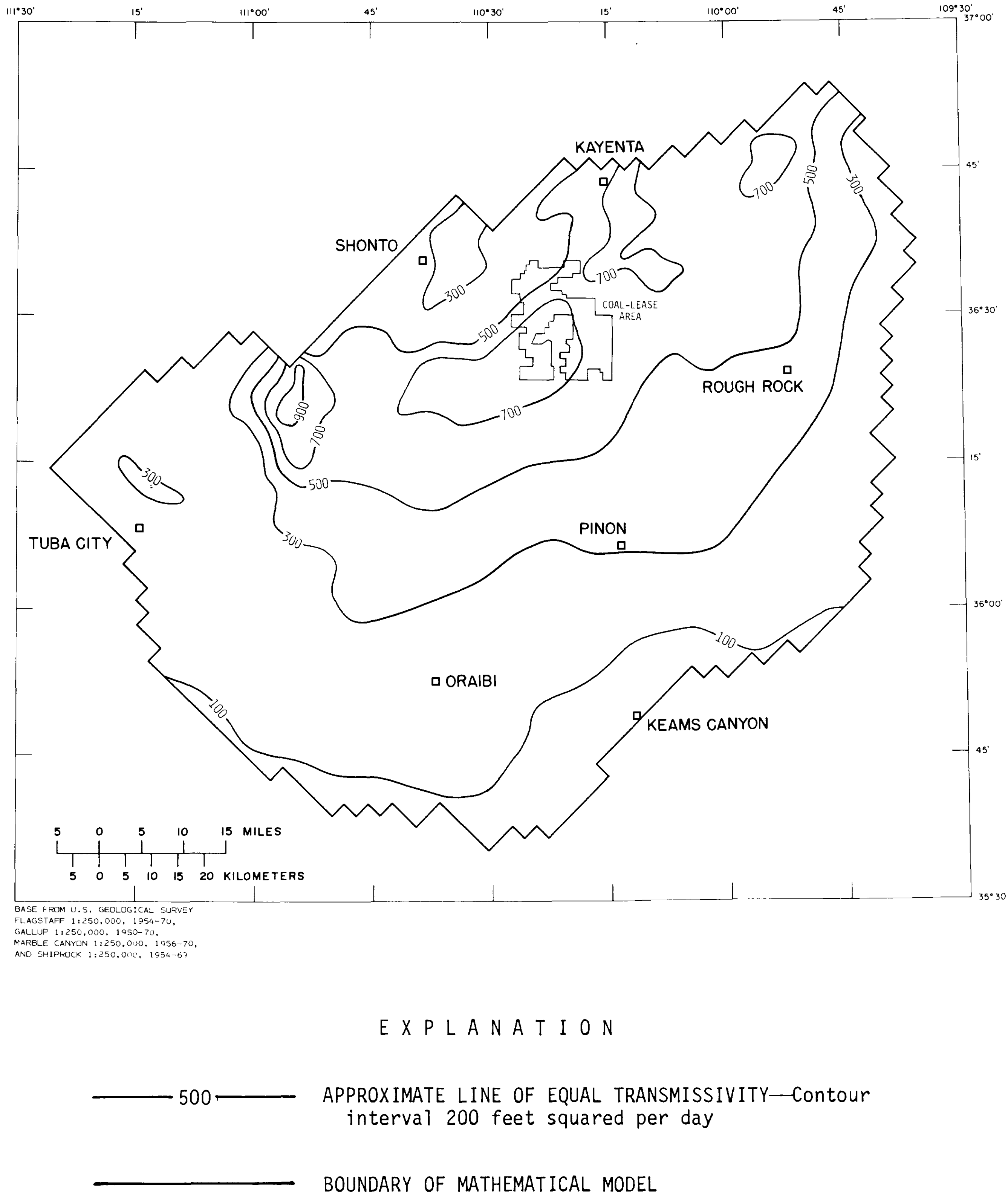


Figure 8. Transmissivity used in equilibrium simulation.

of alternative development plans. The model can provide a basis for more detailed studies of smaller areas within the aquifer and can be used to guide future data-collection activities. The model program, calibrated input data, and model output are on file in the offices of the U.S. Geological Survey, Tucson, Arizona.

The accuracy of any projection is limited by the accuracy of the estimated aquifer characteristics and the estimated future pumpage. The relative magnitude of past and future pumpage is also important. This model of the N aquifer has been tested against 9 years of stress during which pumpage averaged 35 percent of the annual inflow to the aquifer. However, inflow and outflow that were not accounted for in the simulation may be occurring. Greater future stresses, therefore, may cause unanticipated responses by the aquifer. If any of these effects becomes evident in the future, the model should be recalibrated to include them.

PROJECTED EFFECTS OF FUTURE WITHDRAWALS

Because the model was successful in simulating conditions in the N aquifer from 1965 through 1979, it was assumed that the model could make reasonable estimates of the water levels that would result from future pumping from the aquifer. Four projections were made of future pumping rates and the resulting water-level changes. Because the existing coal leases expire in 2001, the projections were carried through 2014 to estimate the remaining effects of mining in the years after it ends. Simulated pumping was mainly from the area of confined conditions under Black Mesa. Larger pumping rates would be possible with less regional head decline if the pumping were distributed in areas of unconfined conditions.

Projections are most useful as comparisons rather than exact estimates of future water levels. The simulated water-level changes discussed in this section represent average conditions over 4-square-mile blocks. Simulated water levels do not represent water levels in pumping wells.

The pumping rates used in the projections to simulate withdrawal at the coal mine and other withdrawal in areas of confined and unconfined conditions are shown in figure 9. Projection 1 used pumping rates that were considered most likely on the basis of pumpage increases during the calibration period. Projections 2 and 3 used pumping rates that estimated the lowest and highest probable withdrawals, respectively. Projection 4 simulated what might have happened if the coal mine had never begun operating; the projection allowed all other withdrawals to increase as in projection 1. The difference between the results of projections 1 and 4 is an estimate of the effect of pumping at the Peabody mine. The differences between projections 1, 2, and 3 show the possible range of effects caused by other pumping from the aquifer. The pumping rates shown in figure 9 were distributed among a number of assumed pumping locations. If future pumping in fact is distributed differently, the results would differ from those given in this section.

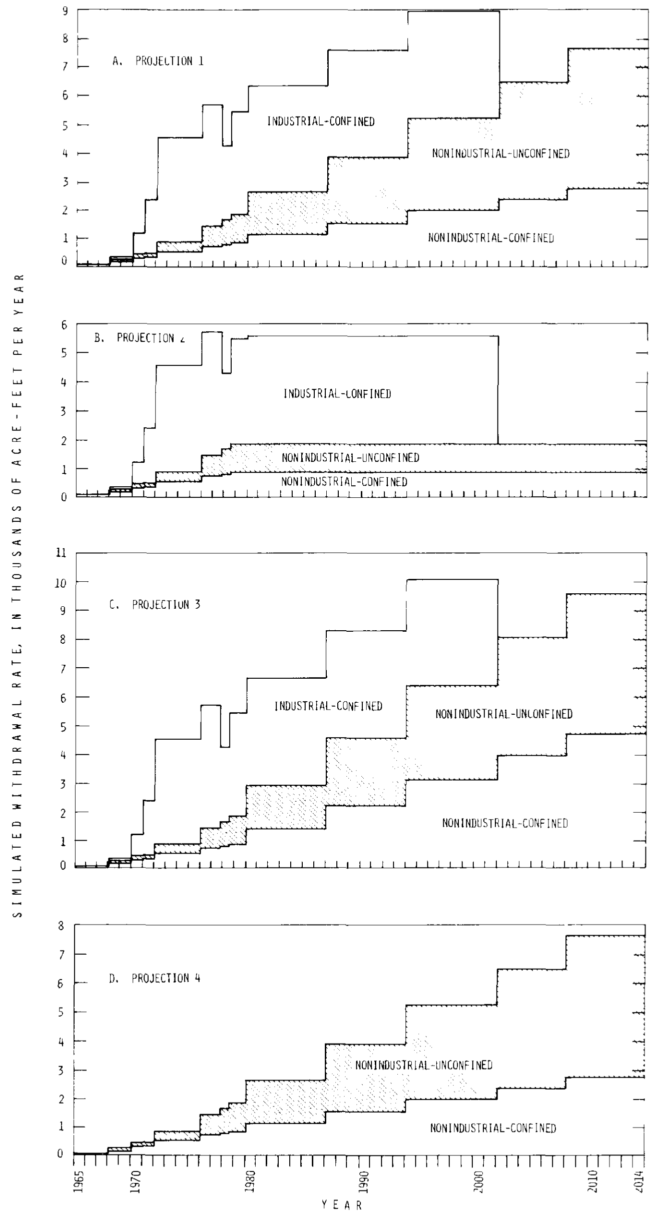
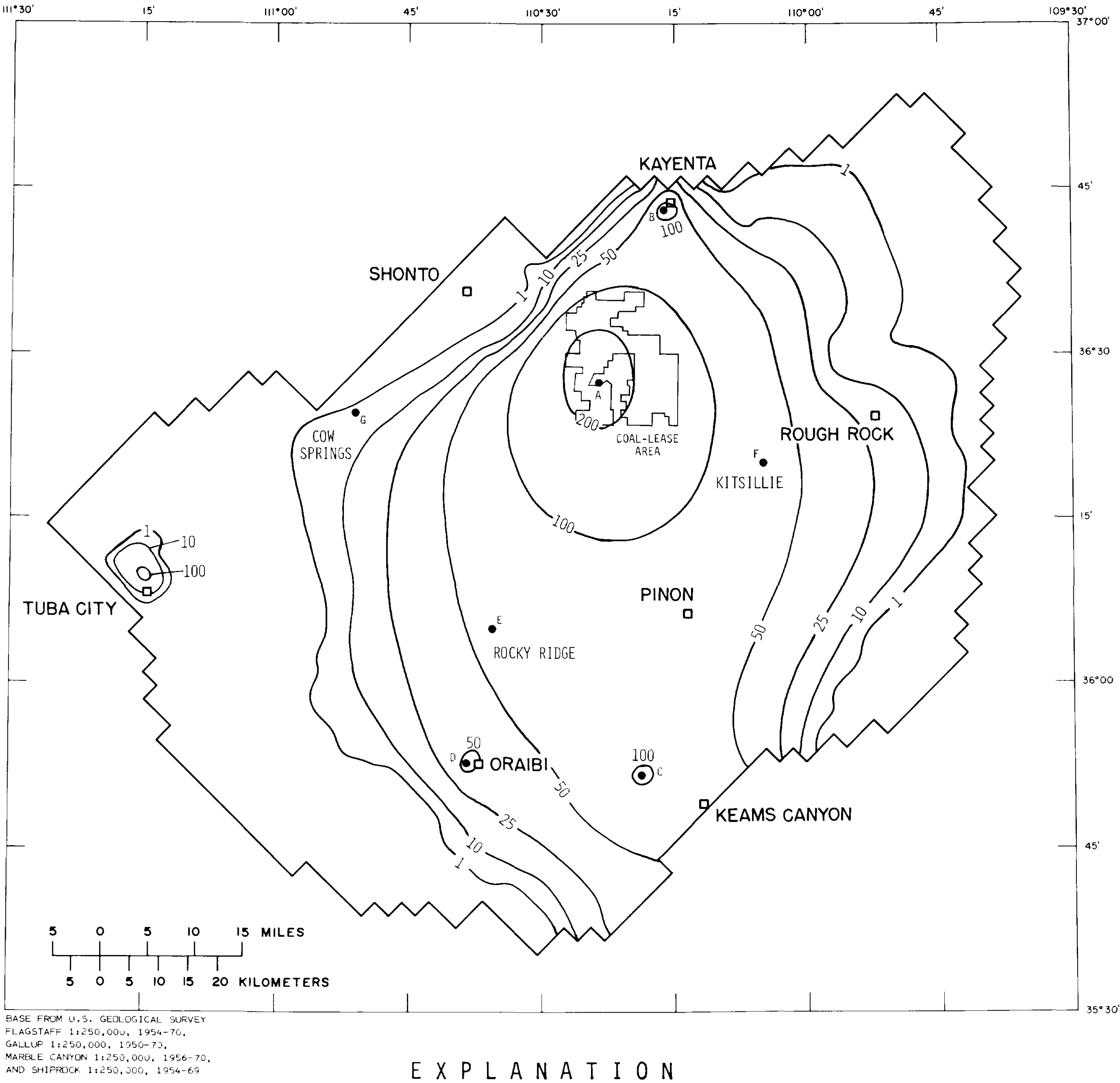


Figure 9. Simulated ground-water withdrawals, 1965–2014.

Projection 1—Most Likely Increase in Pumpage

Projection 1 combined continued pumping at the Peabody mine with continued increases in all other pumping (fig. 9A). Future pumpage at the mine was estimated as 3,700 acre-ft/yr, which is the past average rate, through 2001. Pumping at the mine was assumed to cease after 2001. Future pumpage by communities was estimated on the basis of increases during the calibration period. This nonindustrial pumpage was estimated to exceed 5,100 acre-ft in 2001.

Simulated water-level declines for projection 1 in 2001 are shown in figure 10. Projection 1 simulated more



EXPLANATION

——— 50 ——— LINE OF EQUAL SIMULATED WATER-LEVEL DECLINE—Contour interval, in feet, is variable

•A NODE FOR WHICH A SIMULATED HYDROGRAPH WAS DRAWN—Letter is that used on hydrograph

———— BOUNDARY OF MATHEMATICAL MODEL

Figure 10. Simulated water-level declines, 1965–2001, for projection 1.

than 25 ft of decline in most of the area of confined conditions (fig. 3) and more than 100 ft in an area of 440 mi^2 near the mine. In contrast, in 1979 (fig. 6) more than 10 ft of decline was estimated in most of the area of confined conditions and more than 50 ft in 580 mi^2 near the mine. The maximum decline simulated for a 4-square-mile block near the mine was about 220 ft in 1979 and 260 ft in 2001. More than 80 percent of the expected maximum decline already has occurred. Simulated decline in 2001 is apparent around other pumping centers near Kayenta and Keams Canyon. Although simulated pumpage at Tuba City was greater than that at Kayenta, decline of more than 10 ft was simulated in only three blocks near Tuba City because the water is unconfined in that area. The projection indicates that most water withdrawn at the mine during the period 1980–2001 will come from storage in the areas of unconfined conditions that surround Black Mesa.

Simulated water-level declines for projection 1 in 2014, which is 13 years after the assumed end of pumping at the mine, are shown in figure 11. Simulated water levels were substantially higher than those for 2001. The projection simulated 10 to 50 ft of residual decline under most of the mesa, but more than 140 ft of decline was simulated at pumping centers near Kayenta and Keams Canyon. Near Tuba City, the maximum decline simulated in a block was about 160 ft, but in most other areas of unconfined conditions declines probably will be less than 1 ft. As the large projected declines under Black Mesa diminish, storage in the area of confined conditions would increase and water would move from storage in surrounding areas. Declines in the surrounding areas would be almost too small to measure because the unconfined storage coefficient is much greater than the confined storage coefficient.

Hydrographs of water-level changes simulated by projection 1 for seven points in the aquifer are shown in figure 12. Locations of the points, labeled A–G, are shown in figures 10 and 11. Because withdrawals are simulated as a constant rate during each pumping period, simulated declines sometimes appear as a series of steps, such as shown in figure 12B. Figures 12A and F show the recovery of water levels that would occur under projection 1 after 2001 in the area of confined conditions. At Kayenta and Oraibi, which are also in the area of confined conditions, the assumed increase in community pumpage would offset any recovery due to the cessation of pumping at the mine (figs. 12B and D). At Cow Springs, water-level decline would be small and would change slowly because the aquifer is unconfined (fig. 12G).

The water budget of the aquifer in 2001 and 2014 as simulated by projection 1 is shown in table 3. From 1965 through 2001, about 210,000 acre-ft of water would be withdrawn, of which 94 percent would be from storage. Total storage would decrease about 0.1 percent from 1965 to 2001. The rest of the withdrawal would be accounted for by reduction of discharge to streams and springs, reduction of evapotranspiration, and increased leakage from the upper confining bed. By this estimate, discharge from the N aquifer to streams and springs would be about 5 percent less in 2001 than that in 1964; most of the reduction would occur along Laguna Creek near Kayenta. Evapotranspiration would be about 5 percent less than that in 1964. Leakage would increase 30 percent but would amount to only 260 acre-ft/yr. The increased leakage would not cause significant head declines in other aquifers.

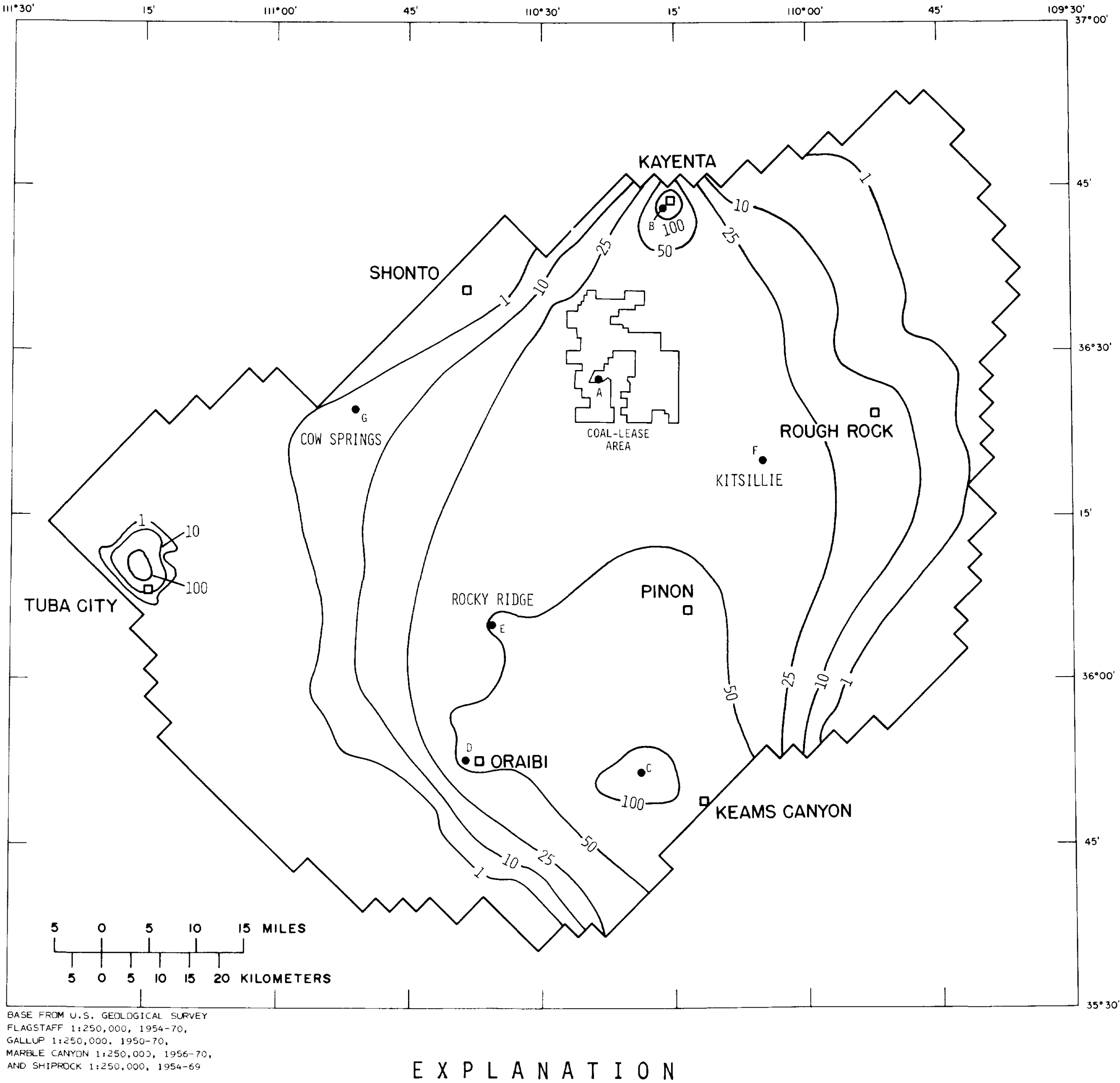
In 2014, storage would continue to contribute more than 85 percent of the water pumped. Discharge to streams and springs and by evapotranspiration would decrease about 6 percent from 1964, and leakage from the upper confining bed would be about 240 acre-ft. Although the projected decline of natural discharge is small, discharge rates are unlikely to return to those before 1965 in the foreseeable future. Despite the large changes in water levels during the 50 years simulated, only about 0.1 percent of the water in storage in the N aquifer would be withdrawn.

Projection 2—No Increase in Pumpage

Projection 2 assumed that future pumpage would be equal to pumpage in 1980, which is the lowest probable withdrawal. Future water-level declines are unlikely to be less than those simulated by projection 2. Withdrawals were estimated as 3,700 acre-ft/yr from 1980 through 2001 at the Peabody mine and 1,870 acre-ft/yr from 1980 through 2014 for all other users (fig. 9B).

Simulated water-level declines for projection 2 were similar to those for projection 1 near the Peabody well field (fig. 12A), in areas of confined conditions with little community pumping (fig. 12F), and in areas of unconfined conditions (fig. 12G). In contrast, simulated declines for projection 2 were substantially less in areas of confined conditions where community pumpage has increased rapidly (figs. 12B and D). Figures 12C and E represent an intermediate condition of sites at which significant decline is due to pumping at the mine and also local pumping.

The simulated water budget for projection 2 indicates that most water withdrawn would come from storage (table 3). Simulated outflow to streams, springs, and alluvium decreased less in projection 2 than in projection 1.



EXPLANATION

——50—— LINE OF EQUAL SIMULATED WATER-LEVEL DECLINE—Contour interval, in feet, is variable

•A NODE FOR WHICH A SIMULATED HYDROGRAPH WAS DRAWN—Letter is that used on hydrograph

—— BOUNDARY OF MATHEMATICAL MODEL

Figure 11. Simulated water-level declines, 1965–2014, for projection 1.

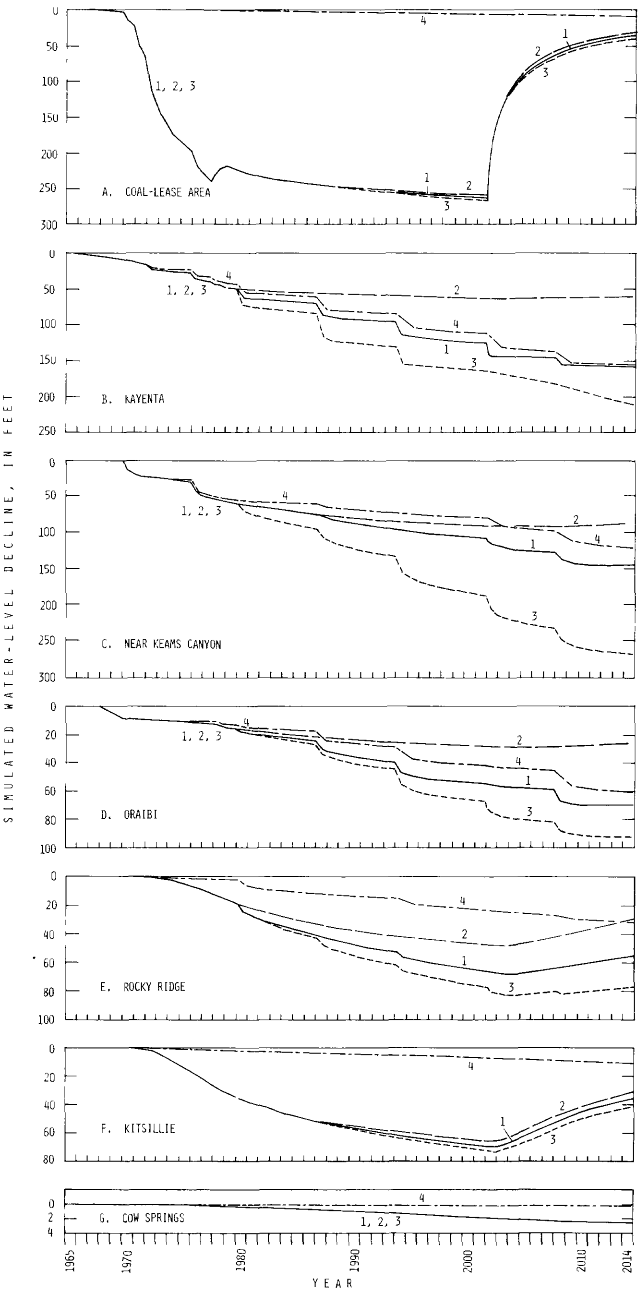


Figure 12. Simulated water-level changes, 1965–2014, for projections 1, 2, 3, and 4.

Projection 3—Maximum Probable Increase in Pumpage

Projection 3 assumed that withdrawal from the aquifer in the area of confined conditions would increase at twice the present (1980) rate. Future withdrawals probably will be less than the assumed withdrawals. Withdrawals at the mine were estimated as 3,700 acre-ft/yr through 2001 (fig. 9C). Other simulated withdrawals totaled 6,370 acre-ft in 2001 and 9,580 acre-ft in 2014. Simulated pumpage increases at Tuba City were the same as those in projection 1. Future water-level declines in the area of confined conditions are unlikely to be greater than those simulated by projection 3.

Increasing the assumed pumping rates above those used in projection 1 had little effect on simulated declines near the mine and in areas of unconfined conditions (figs. 12A, F, and G). The increased pumping caused a larger increase in simulated declines at Kayenta, Oraibi, and Rocky Ridge (figs. 12B, D, and E). The greatest simulated change was near Keams Canyon (fig. 12C). Because the saturated thickness and transmissivity of the aquifer are low in that area (figs. 4 and 8), a large hydraulic gradient would be needed to draw water toward a well at the rate simulated, which was 150 acre-ft for 2001 and 230 acre-ft for 2014.

As in the other projections, most of the withdrawal was balanced by a simulated reduction in storage (table 3). Projected outflow to streams, springs, and alluvium in 2001 was 6 percent less than in 1964, and in 2014 it was 9 percent less. Simulated evapotranspiration declined about 6 percent by 2014, and leakage from the upper confining beds reached a maximum that was simulated as 270 acre-ft for 2001. Even the maximum leakage rate would not cause significant head declines in other aquifers.

Projection 4—No Pumpage for Mining

Projection 4 was identical to projection 1 except that all pumping at the mine was excluded (fig. 9D). The difference in the results of this hypothetical projection and projection 1 is the simulated effect of pumping at the mine. In the coal-lease area and areas of unconfined conditions, nearly all the simulated water-level declines were caused by pumping at the mine (figs. 12A and G). At Rocky Ridge and Kitsillie in the central part of Black Mesa, most of the declines were related to the mine (figs. 12E and F). In areas with large community pumping, little of the simulated decline was caused by mine pumping (figs. 12B, C, and D). At Kayenta, over 85 percent of the simulated decline was caused by pumping for the community (fig. 12B).

For 2001, simulated outflow to streams, springs, and alluvium was 480 acre-ft less than in 1964 under projection 1 and 330 acre-ft less under projection 4 (tables 2 and 3). Therefore, two-thirds of the expected decrease would be caused by community pumping. Simulated evapotranspiration decreased and simulated leakage increased under both projections; about two-thirds of these changes would be caused by pumping at the mine.

Table 3. Simulated water budgets of the N aquifer in 2001 and 2014

[Values, in acre-feet, are not intended to imply accuracy to the precision shown. Projection numbers are explained in text]

	Projection 1		Projection 2		Projection 3		Projection 4	
	2001	2014	2001	2014	2001	2014	2001	2014
Inflow:								
Recharge from infiltration of rainfall and snowmelt	12,930	12,930	12,930	12,930	12,930	12,930	12,930	12,930
Leakage from the upper confining bed	260	240	250	220	270	250	220	220
Total inflow	13,190	13,170	13,180	13,150	13,200	13,180	13,150	13,150
Outflow:								
To streams, springs, and alluvium	9,220	9,010	9,370	9,310	9,120	8,860	9,370	9,150
Underflow near mouth of Laguna Creek	450	450	450	450	450	450	450	450
Evapotranspiration	2,840	2,810	2,860	2,850	2,820	2,790	2,930	2,880
Withdrawals	8,940	7,640	5,570	1,870	10,080	9,580	5,230	7,640
Total outflow	21,450	19,910	18,250	14,480	22,470	21,680	17,980	20,120
Change in storage (inflow minus outflow)	-8,260	-6,740	-5,070	-1,330	-9,270	-8,500	-4,830	-6,970

SUMMARY AND CONCLUSIONS

Increasing withdrawal of water from the N aquifer in the Black Mesa area has caused water levels in some wells to decline. The N aquifer includes the Navajo Sandstone and parts of the underlying Kayenta Formation and Wingate Sandstone. The aquifer is exposed at the surface in about 1,400 mi^2 near the boundaries of the 5,400-square-mile study area. Saturated thickness ranges from about 1,050 ft in the northwestern part of the area to zero in the southeastern part. Hydraulic conductivity was estimated to average 0.65 ft/d, and maximum transmissivity was estimated to be about 1,000 ft^2/d.

Water in the N aquifer is under confined conditions in an area of 3,300 mi^2 under Black Mesa, and water levels in that part of the aquifer are much more sensitive to withdrawals than those in the rest of the study area. The estimated confined storage coefficient varies with saturated thickness and reaches a maximum of about 0.0004 under the northern part of Black Mesa. Unconfined storage coefficient was estimated to range from 0.10 to 0.15. The production of 10 acre-ft of water from 1 mi^2 of the aquifer, therefore, would require a water-level decline of less than 0.16 ft under unconfined conditions but at least 39 ft under confined conditions.

Annual recharge to the aquifer was estimated to be about 13,000 acre-ft, and at least 180 million acre-ft of water is in storage. The aquifer discharges mainly along Moenkopi Wash and Laguna Creek, which flow continuously in the winter. Withdrawal from the aquifer increased from negligible levels before 1965 to about 5,300 acre-ft in 1979. Peabody Coal Co., which operates a coal mine on Black Mesa and supplies a coal–slurry pipeline, withdrew an average of 3,700 acre-ft/yr from 1974 through 1979.

On the basis of these data, a mathematical model of the N aquifer was developed that simulated water levels during equilibrium—before 1965—and measured changes in water levels during the period 1965–79 with reasonable accuracy. The simulation model is capable of projecting the effects of future withdrawals from the aquifer to compare the effects of alternative management plans. The model can provide a basis for more detailed studies of smaller areas within the aquifer and can be used to guide future data-collection activities.

The model was calibrated for a period when withdrawals averaged 35 percent of inflow. Greater future stresses, however, may cause unanticipated responses by the aquifer. Long-term projections that include large increases in pumping should be used with caution.

Accurate data on future pumping are necessary to maintain the calibration of the model. Simulated water-level changes are sensitive to pumping rates, and recalibrating the model using inaccurate rates can introduce serious errors.

Four projections were made of water-level changes in the N aquifer from 1965 to 2014. The effects of three possible future pumping schemes were compared with the changes that would have occurred if withdrawal at the coal mine never had begun. The projections assumed that withdrawal at the mine would stop in 2001 at the end of existing coal leases. In the most probable projection, more than 90 percent of all withdrawals through 2001 would come from water in storage, and discharge to streams and springs and by evapotranspiration would decrease by less than 10 percent. By 2014, most of the water-level declines near the mine would have recovered, and most of the reduction in storage would have been distributed as water-level declines of less than 1 ft in areas of unconfined conditions. Increased community pumping near Kayenta and Keams Canyon would have caused new centers of decline by 2014. Large water-level changes were simulated for the 50 years analyzed; however, only about 0.1 percent of the water in the N aquifer would be withdrawn.

Concern was expressed that head declines in the N aquifer might cause increased leakage of poor-quality water from overlying formations. Annual water- quality samples were collected from wells at the coal mine where stress is greatest. No changes in water quality have been detected through 1980. Leakage simulated by the model has increased slightly and is projected to continue increasing as long as pumping increases. Even the greatest simulated leakage rate, however, would cause little change in water quality.

No water-level changes attributable to pumping from the N aquifer have been measured in wells that tap other aquifers in the study area. The projected changes in leakage into the N aquifer would not cause significant water-level declines in other aquifers.

The simulated water-level changes represent regional effects only and are not equivalent to changes in pumping wells. The total lift in a pumping well includes the depth to water before 1965, any regional water-level change, and well losses and local drawdown caused by pumping the well. In the area of confined conditions the depth to water in 1965 generally was 500 to 1,500 ft. Projected regional declines were less than 200 ft in most of the area. Well losses and local drawdown depend on the pumping rate and generally are 50 to 500 ft in the Black Mesa area.

In some aquifers, wells must be deepened when water levels decline. In the N aquifer, deepening would be unnecessary. Where the water is unconfined, projected declines are small. Where water is confined, the water levels in wells in 1965 generally were more than 500 ft above the top of the aquifer. Projected regional declines would not lower water levels below the top of the aquifer. Pump settings, however, might need to be lowered in some wells.

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