SIMULATION OF FIVE GROUND-WATER WITHDRAWAL PROJECTIONS FOR THE BLACK MESA AREA, NAVAJO AND HOPI INDIAN RESERVATIONS, ARIZONA

By James G. Brown and James H. Eychaner

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4000

Prepared in cooperation with the

U.S. OFFICE OF SURFACE MINING RECLAMATION AND ENFORCEMENT

Tucson, Arizona
February 1988

DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units, conversion factors for the inch-pound units used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
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 squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

Sea level: In this report "sea level" refers to the 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 of 1929."

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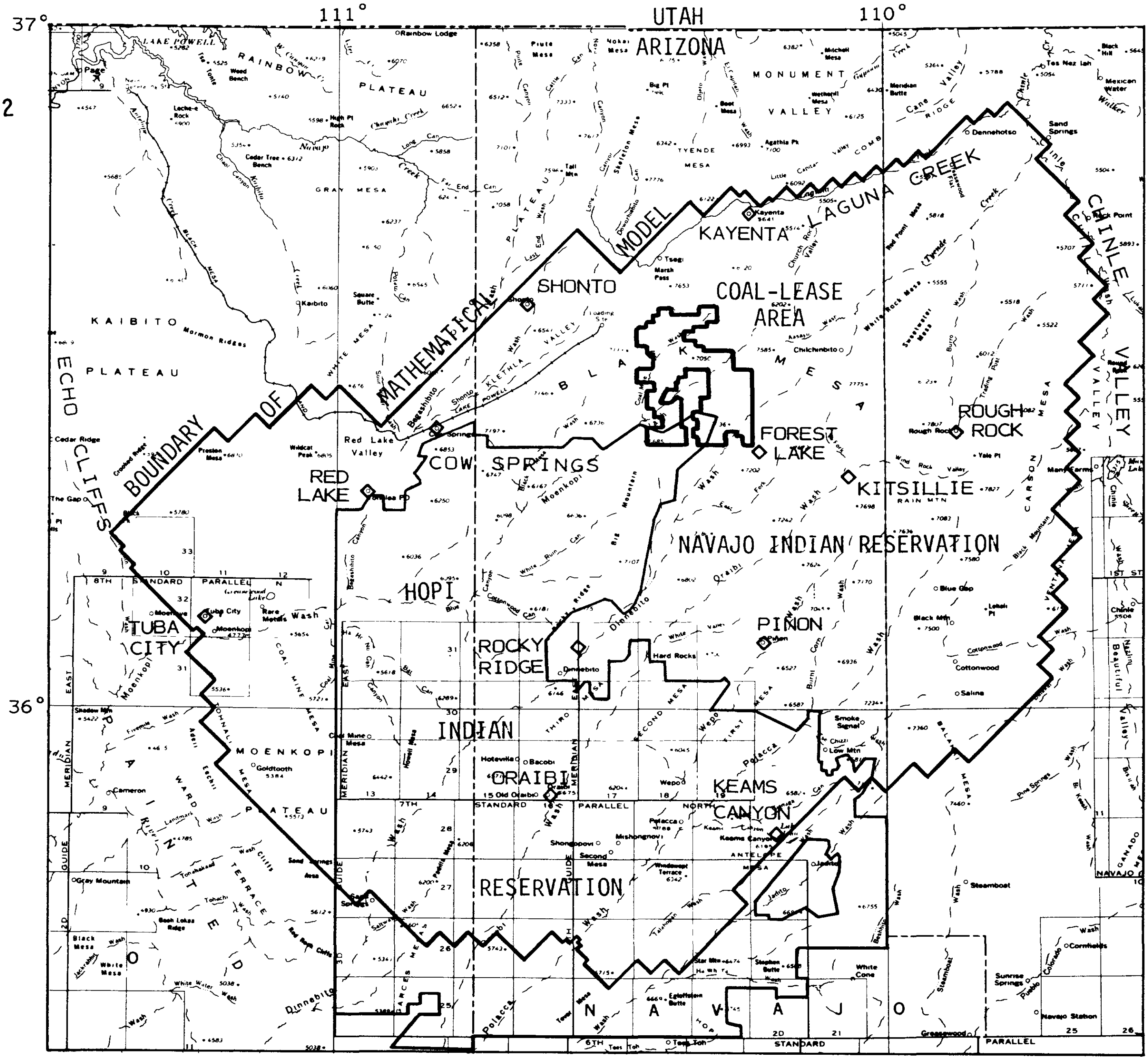
ABSTRACT

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. Water in the aquifer is under confined conditions in the central 3,300 square miles of the area. Maximum saturated thickness is about 1,050 feet. Annual ground-water withdrawals from 1972 through 1986 averaged 5,480 acre-feet and included 3,820 acre-feet used to operate a coal mine on Black Mesa. As a result, water levels have declined in a large part of the aquifer. The coal company has applied for a permanent permit under the Surface Mining Control and Reclamation Act of 1977.

An existing mathematical model of the aquifer in the Black Mesa area was converted to a newer model program and recalibrated by using revised estimates of selected aquifer parameters and a finer spatial grid. The model was used to simulate four ground-water withdrawal alternatives that combined the existing and proposed mining plans with projected constant or increasing pumpage for nearby communities. A fifth alternative combined increasing community pumpage with no mine withdrawals and was used as a basis for comparison. Simulated water levels for the year 2031 in the coal-lease area are projected to be 60 feet lower than in 1985 for the proposed mining plan combined with growing community pumpage and more than 100 feet lower than predevelopment water levels over an area of 1,660 square miles. Ground water would rise to within 100 feet of predevelopment levels less than 10 years after mine withdrawals cease. Withdrawals at the mine were a minor factor in determining simulated water levels at most communities in the study area. Water levels at Tuba City were not affected by mine pumpage in any projection.

INTRODUCTION

The N aquifer includes the Navajo Sandstone of Jurassic and Triassic(?) age and is the main source of water in the 5,400 mi² Black Mesa area in the Navajo and Hopi Indian Reservations in northeastern Arizona (fig. 1). Black Mesa itself is a prominent landmark within the area and covers about 2,000 mi². The mesa is bounded by cliffs as high as 2,000 ft 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



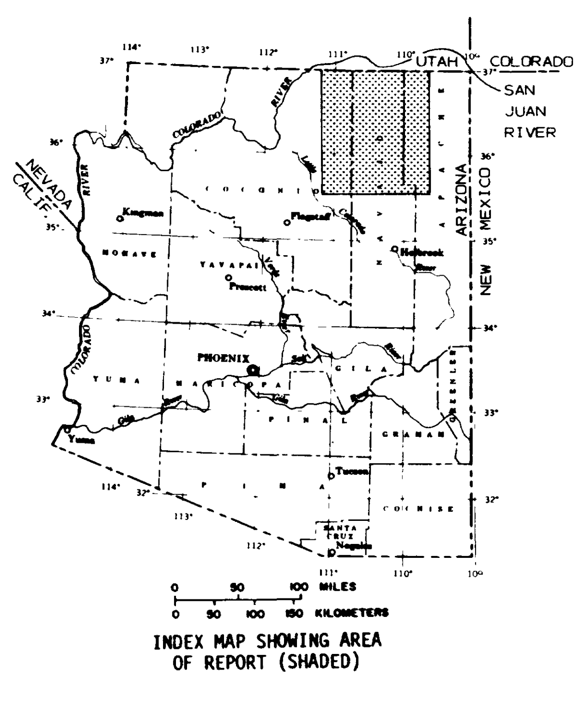


Figure 1.--Area of report.

mesa, a coal company operates a coal mine in a lease area of about 100 mi^2. From 1972 through 1986, the company pumped an average of 3,820 acre-ft/yr of water from the aquifer (Hill and Sottilare, 1987, p. 11). Annual withdrawals ranged from 2,520 to 4,740 acre-ft. 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 by the Navajo and Hopi Tribes for public supply increased from about 600 acre-ft in 1972 to 2,200 acre-ft in 1986. 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 U.S. Geological Survey has measured withdrawals and water-level changes in the area since 1971 and developed a mathematical model of the aquifer (Eychaner, 1983).

The coal company holds an interim permit under the Surface Mining Control and Reclamation Act of 1977 for its current mining plan. In 1986, the company applied to the U.S. Office of Surface Mining Reclamation and Enforcement (OSMRE) for a permanent permit under the act to cover mining until the year 2011. The new permit cannot be issued until the OSMRE assesses the cumulative hydrologic impact of all anticipated mining, including a proposal to mine additional coal and extend mining and associated ground-water withdrawals through 2031. As part of that assessment, the U.S. Geological Survey in cooperation with OSMRE began a study to simulate the effects of five future alternative withdrawals from the N aquifer.

Purpose and Scope

This report describes the results of a study to estimate the changes in ground-water levels and flow components that might occur from 1985 through 2051 by using several projected withdrawal alternatives. The selection of future withdrawal rates was based on the length of planned and proposed mining as well as two different projections of growth at the Indian communities. An existing finite-difference grid (Eychaner, 1983) was revised in order to provide greater detail near Kayenta, Tuba City, Keams Canyon, and Oraibi. On the new grid, the model nodes in those areas represent blocks of the aquifer no larger than 0.5 mi on a side.

The work initially was limited to that necessary to make the projections. The ground-water flow-model program by Trescott and others (1976) used in an earlier study would not run properly on the computer hardware now available; therefore a program by McDonald and Harbaugh (1984) was selected. The initial work involved converting from one model program and grid to another. During the conversion process, an error was discovered in the calculation of evapotranspiration in the previous flow model. For that reason, the scope of work was expanded to include recalibration of the model on a revised grid.

Relation to Previous Investigations

The geology and hydrology of the Black Mesa area have been described in many reports over the past several decades. The most comprehensive study of the area was by Cooley and others (1969), whose report includes extensive citations of the pertinent literature. The U.S. Geological Survey began a monitoring program in 1971 and has produced a series of progress reports, the most recent of which is by Hill and Sottilare (1987).

Eychaner (1983) developed a mathematical model of ground-water flow in the N aquifer on the basis of available information about the aquifer. The model was calibrated using observed ground-water withdrawals and water-level changes for 1965-79, and the effects of four possible courses of development from 1980 through 2014 were simulated. In 1985, the model was rerun with observed withdrawals for 1980-84 to check the continued agreement of observed and simulated water levels (Hill and Whetten, 1986, p. 6). The model developed by Eychaner (1983) will be called the 1983 model, and the recalibrated model described in this report will be called the 1988 model.

Approach

The objectives of the study were accomplished in three stages. First, data arrays from the 1983 model using the model program by Trescott and others (1976) were reformatted so that the model program by McDonald and Harbaugh (1984) could be used. Using the same discretizations of time and space, the model was run for 1965-84. A close match between the results and those of the 1985 update run (Hill and Whetten, 1986) confirmed that the new program provides equivalent results to the original. Second, the model grid was subdivided near Kayenta, Tuba City, Keams Canyon, Oraibi, and the coal-lease area to provide for greater detail in the simulated water levels. The refined discretization of space allowed streams, springs, and wells to be located more precisely. During rediscretization, an error was discovered in the rate used to calculate evapotranspiration in the 1983 model. In the third stage, the rate was corrected and the model recalibrated. After recalibration, five projection runs were made for 1985-2051 by using withdrawal rates estimated on the basis of information obtained from the Navajo and Hopi Tribes and the coal company.

GEOHYDROLOGIC SETTING

In the Black Mesa area (fig. 1), 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. The aquifer overlying the N aquifer is the D aquifer, which includes the Dakota Sandstone of Cretaceous age. Some water moves down from the D aquifer through confining layers and into the N aquifer. The N aquifer is generally the lowermost aquifer tapped by wells in the area, and withdrawals from it are many times larger than from overlying aquifers. The regional hydrogeology and description of the aquifers are presented in detail by Harshbarger and others (1957), Cooley and others (1969), and Eychaner (1983).

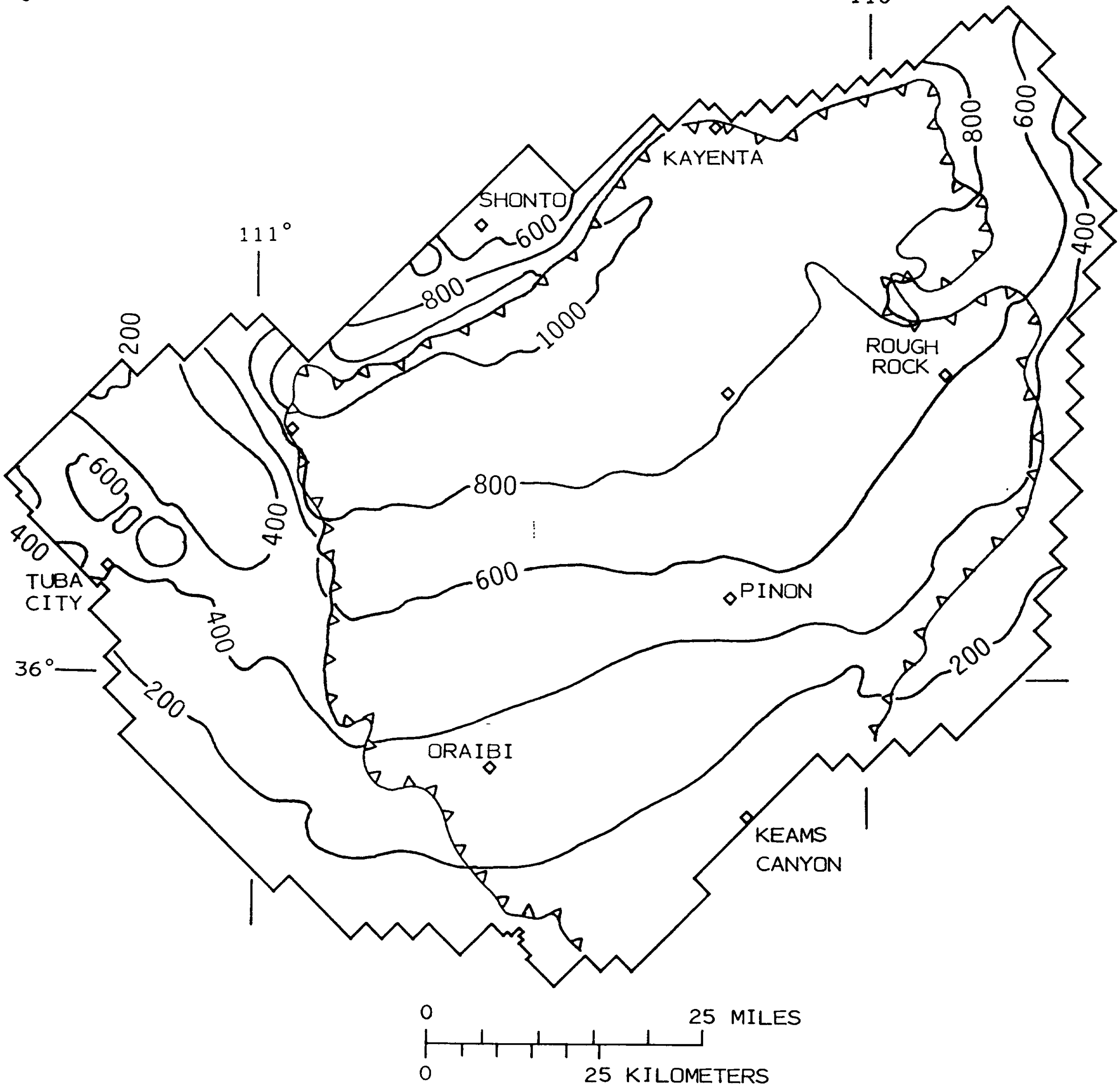
The N aquifer consists of the Navajo Sandstone of Jurassic and Triassic(?) age and, in the northeast part of the Black Mesa area, the underlying typical facies of the Kayenta Formation and Lukachukai Member of the Wingate Sandstone of Triassic age. The units consist of medium- to very fine-grained sandstone and generally are weakly cemented, well sorted, and crossbedded. In the Tuba City area, the silty facies of the Kayenta Formation consists of about 500 ft of interbedded sandstone and siltstone that underlie the Navajo Sandstone. The upper part of the silty facies resembles that of the typical facies (Harshbarger and others, 1957, p. 18) and probably is hydraulically connected with the Navajo Sandstone. Saturated thickness is about 1,050 ft south of Shonto, and the aquifer thins to extinction to the southeast (fig. 2). In the central 3,300 mi² of the study area, the rocks of the N aquifer dip steeply into a structural basin more than 1,500 ft deep. In the basin, younger rocks overlie the Navajo Sandstone, and water is under confined, or artesian, conditions (fig. 2). In most of the area outside the structural basin, erosion has removed the overlying units and exposed the aquifer. Ground water in this area is unconfined.

Boundaries of the study area generally approximate the areal extent of the N aquifer. The aquifer pinches out at the south boundary and is absent as a result of erosion northeast of Kayenta and at the east and southwest boundaries. The aquifer extends beyond the study area to the northwest, where a ground-water divide forms the boundary.

Average annual recharge to the N aquifer in the study area is about 13,000 acre-ft. This recharge occurs in areas totaling about 1,400 mi² where the aquifer is exposed. Much of the recharge occurs in an area of high precipitation near Shonto, from which water moves radially along lines of decreasing head. In 1964, before extensive development of the aquifer, the system was in equilibrium, or steady state. Water originating near Shonto moved southward and southeastward under Black Mesa, where it diverged to flow west toward Moenkopi Wash, east and northeast toward Laguna Creek and Chinle Wash, and south toward Oraibi (fig. 3). Southward thinning of the aquifer, however, limits ground-water flow to the Oraibi-Keams area and causes water levels in that area to be particularly sensitive to pumping. Water recharged on the Moenkopi Plateau west of Oraibi moved northwestward toward Moenkopi Wash.

Water discharges from the aquifer by evapotranspiration and by outflow to springs and streams in the area of unconfined ground water (fig. 4). Most of the outflow to streams occurs in Moenkopi Wash and Laguna Creek.

Withdrawals from the N aquifer were less than 100 acre-ft in 1965 and increased to a maximum of 7,100 acre-ft in 1983 (Hill and Sottilare, 1987, p. 11). Average withdrawals were 5,480 acre-ft/yr during 1972-86 and 6,290 acre-ft/yr during 1981-86. Withdrawals for the mine averaged 3,820 acre-ft/yr from 1972 through 1986 and 4,060 acre-ft/yr from 1981 through 1986. By 1985, water levels had declined more than 10 ft in most of the area of confined ground-water conditions. Previous model results indicate that water levels declined more than 100 ft in about 350 mi² under Black Mesa. Simulated outflow to streams, springs, and evapotranspiration decreased about 1 percent indicating that nearly all water withdrawn from wells came from ground-water storage. Withdrawals



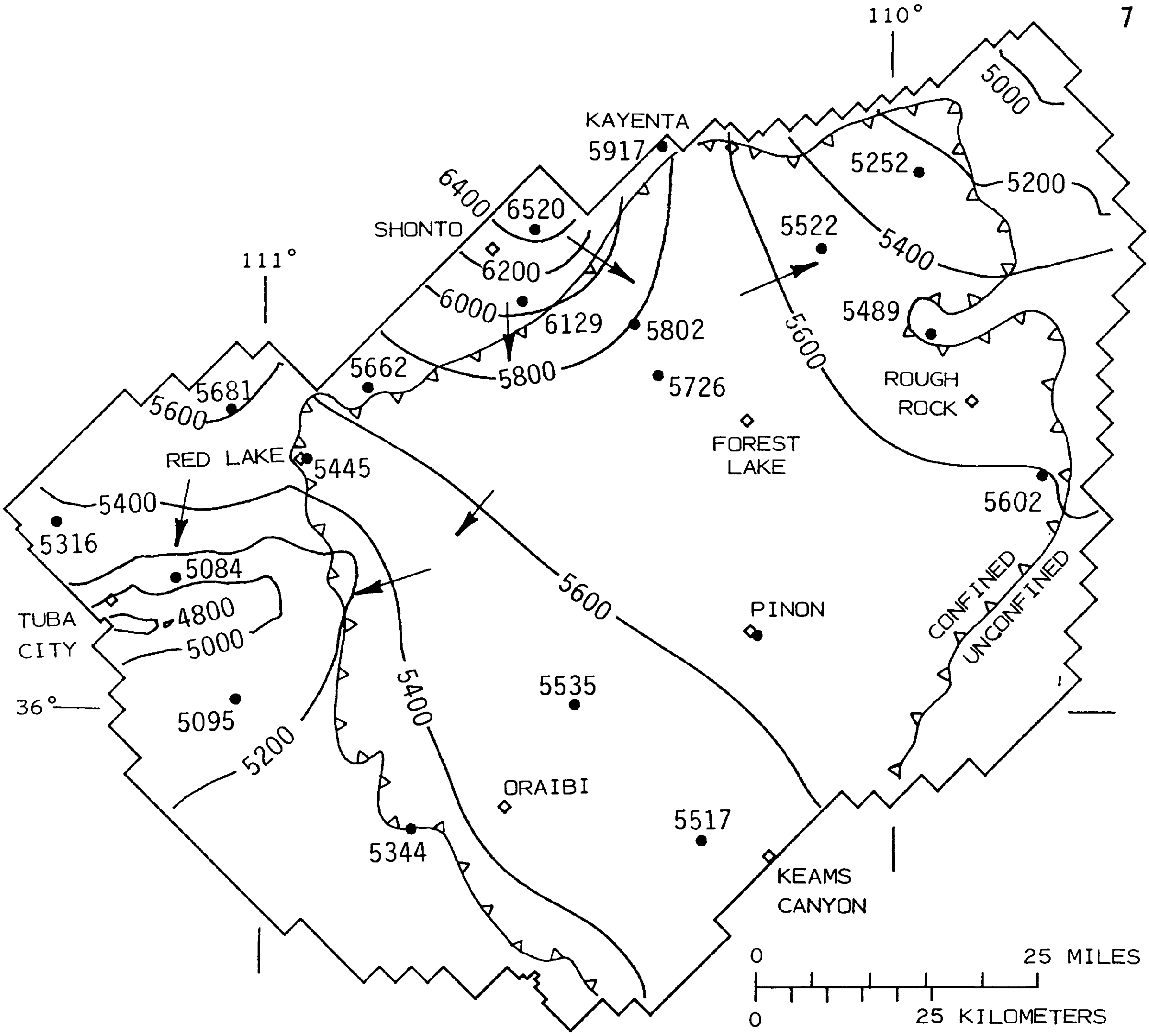
EXPLANATION

——200—— LINE OF EQUAL SATURATED THICKNESS—Shows approximate generalized saturated thickness. Interval 200 feet

APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS

BOUNDARY OF MATHEMATICAL MODEL

Figure 2.--Saturated thickness of the N aquifer.



EXPLANATION

——— 5600 ——— LINE OF EQUAL SIMULATED WATER-LEVEL ALTITUDE—Contour interval 200 feet. Datum is sea level

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

● 6520 WELL IN WHICH DEPTH TO WATER WAS MEASURED—Measurement was made before 1965 or during assumed local equilibrium before 1972. Number, 6520, is altitude of water level in feet above sea level

→ GENERALIZED DIRECTION OF GROUND-WATER MOVEMENT

——— BOUNDARY OF MATHEMATICAL MODEL

Figure 3.--Simulated altitude of water levels, 1964.

have been small in comparison to the total of at least 180 million acre-ft of water estimated to be in storage in the N aquifer (Eychaner, 1983, p. 11), however, some of this water is probably not recoverable by wells.

The quantity of evapotranspiration in an area is a function of the interaction of air temperature, wind speed, solar radiation, and soil-water availability (Bouwer, 1978, p. 261). Maximum evapotranspiration occurs when the water table is at or near the land surface. As the depth to ground water increases, evapotranspiration decreases. Little direct evaporation of ground water occurs from below a depth of 6 ft (Bouwer, 1978, p. 299); below this depth evapotranspiration of ground water is almost entirely a result of plant transpiration. The quantity of water transpired by plants below this depth is controlled by several factors, including plant type, density, and depth to water. Some phreatophytes, such as tamarisk, may obtain water from depths exceeding 30 ft. Robinson (1958, p.22) found, however, that when depth to ground water exceeded 5 ft, even deep-rooted phreatophytes used much less water. Evapotranspiration in the study area was estimated to be negligible when depth to water was more than 10 ft.

Rates of evaporation from pans have been measured at 10 sites in northeastern Arizona and northwestern New Mexico (National Climatic Data Center, 1952-1986; and Michael Foley, hydrologist, Navajo Nation, written commun., 1987). The sites range from 3,900 to 8,200 ft above sea level and are from 43 to more than 150 mi from Black Mesa. In the study area, evapotranspiration from the N aquifer occurs mainly near Moenkopi Wash and Laguna Creek at altitudes between 4,800 and 5,600 ft. The Arizona pan-evaporation sites at Many Farms, Leupp, and Page are at altitudes of 4,270 to 5,310 ft and are thought to best represent conditions in the study area. Pan evaporation at the three sites ranged from 7.0 to 7.6 ft/yr and averaged 7.3 ft/yr. Actual evapotranspiration from lakes and reservoirs is about 70 percent of pan evaporation (Chow, 1964, p. 11-7) and is about equal to the maximum evapotranspiration from soils (Bouwer, 1978, p. 261). The maximum evapotranspiration rate in the study area was estimated to be 5.1 ft/yr.

SIMULATION OF FLOW

Before any model can be used to project future conditions, it must be shown to adequately represent past and present conditions. For most ground-water flow models, this calibration is accomplished by changing the values of hydrologic properties within the range of observed field values until computed heads and flow components match a group of field observations within acceptable tolerances. Eychaner (1983, p. 17) stated a series of assumptions on which the 1983 model was based. These assumptions also apply to the 1988 model. The present work was intended to be a conversion of the 1983 model to a more recently developed model program and a new spatial grid. The benchmark for accepting the conversion would have been that the new model duplicates results of the 1983 model.

During the conversion, however, an error was discovered in the 1983 model. Although Eychaner (1983) intended to use a maximum evapotranspiration rate of 3 ft/yr, a value of 0.03 ft/yr was used. The error was not detected during the previous study because the changes in other values remained within acceptable ranges. Although the 1983 model reasonably simulated water-level changes from 1965 to 1984 (Eychaner, 1983; Hill and Whetten, 1986), it would be improper to perpetuate a known error.

Data from the 1983 model were reformatted and rerun using the new model program, and the results were compared with the 1983 model. The 1988 model was then calibrated using the revised grid to develop a new set of estimated aquifer characteristics that are consistent with the field observations. Results from the 1988 model were compared with results from the 1983 model for steady-state conditions (before 1965) and for 1965-84 when withdrawals increased and water levels declined under Black Mesa. Because the results of program and grid conversion were used in the recalibration, they are included in the following discussion.

Model Programs

A computer program written by Trescott and others (1976) was used for the 1983 model and will be called the Trescott program. A computer program by McDonald and Harbaugh (1984) was used for the 1988 model and will be called the modular program. The Trescott and modular programs are similar in many respects. Both programs:

1. Solve the equation for ground-water flow throughout an aquifer using finite-difference approximations over an array of nodes centered in rectanular blocks that represent the aquifer.

2. Solve a set of finite-difference equations by using the strongly implicit procedure.

3. Vary transmissivity with saturated thickness as water levels change.

4. Account for storage due to pore drainage or compressibility and select the appropriate storage coefficient on the basis of water levels.

5. Can simulate water entering the aquifer at a specified recharge rate.

6. Represent evapotranspiration by an outflow rate proportional to the depth of the water table below land surface.

7. Simulate water entering or leaving the aquifer at rates proportional to the head difference between the aquifer and a river, or another aquifer.

8. Can simulate withdrawal from the aquifer by wells.

The programs also have differences. The Trescott program uses a two-dimensional approximation of the flow equation, which requires the assumption that aquifer characteristics are vertically uniform and that flow is nearly horizontal. The modular program uses a three-dimensional approximation and allows the thickness of one or several aquifers to be represented by several layers of blocks. For this study, data were entered into the modular program for a single layer only, with the effect of reducing the modular program to a two-dimensional approximation identical to that in the Trescott program.

The most important difference between the two programs is the manner in which flow from an overlying aquifer through a confining layer is simulated. Vertical flow from the overlying D aquifer into the N aquifer was simulated in the 1983 model by the head-dependent boundary function of the Trescott program, which accounts for changes in storage in the intervening confining layer as head in the N aquifer varies. This simulated inflow was 200 acre-ft/yr before 1965 and increased to 270 acre-ft/yr in one projection. The only way to account for confining-layer storage in the modular program is to simulate the confining unit and the D aquifer as separate layers. This approach was rejected because the estimated vertical flow from the D aquifer is a small part of the total flow into the N aquifer, a large number of nodes would be required, and much additional data and work would be needed. Instead, the general-head boundary option of the modular program was used. This option varies inflow as the head in the N aquifer varies, but ignores storage in the confining layer. Differences in simulated aquifer response caused by the use of the general head-boundary option rather than the Trescott head-dependent boundary function are discussed in a later section. Other differences between the Trescott and modular programs concern data entry and manipulation and do not affect model results.

In a simulation of steady-state conditions using the original model grid and the modular program, computed heads at all nodes were virtually identical with heads computed in the 1983 model. The largest difference at any node was 0.2 ft. The computed water budget from the modular program agreed with previous calculations within 0.1 percent for all equivalent budget items. The simulated water balance (total inflow minus total outflow) was less than 0.05 percent of inflow. This balance is a measure of computational precision and is similar to the balance obtained by the 1983 model using the Trescott program.

The first-stage modular model was tested next with pumpage data for 1965-84. A water balance comparable to that obtained from the Trescott program could only be achieved by modifying the modular program to perform all numerical operations in double precision. Simulated water-level declines from 1965 to 1984 for the converted model were within 0.2 ft of those obtained with the 1983 model where declines were less than 10 ft. The two models generally agreed within 1.0 ft where declines exceeded 100 ft; the maximum difference was 1.3 ft.

Heads simulated by the modular program were consistently lower because of the different treatment of inflow from the D aquifer. Simulated inflow with the Trescott program increased from 200 to 240 acre-ft/yr from 1965 to 1984 as the head difference across the confining layer increased. Inflow using the modular program only increased to 225 acre-ft/yr. The difference is the simulated effect of storage in the confining layer and results in slightly lower simulated water levels. Compared to total recharge of about 13,000 acre-ft/yr, however, the difference is insignificant.

The net quantity of water taken out of storage from 1965 to 1984 was 1.1 percent greater in the simulations using the modular program than in simulations using the Trescott program because the modular model cannot simulate storage from the overlying confining layer. All other water-budget components differed by less than 1.0 percent between simulations using the two programs. At this point, conversion to the modular program was considered successful. The modular version of the 1983 model was effectively identical to the original 1983 model.

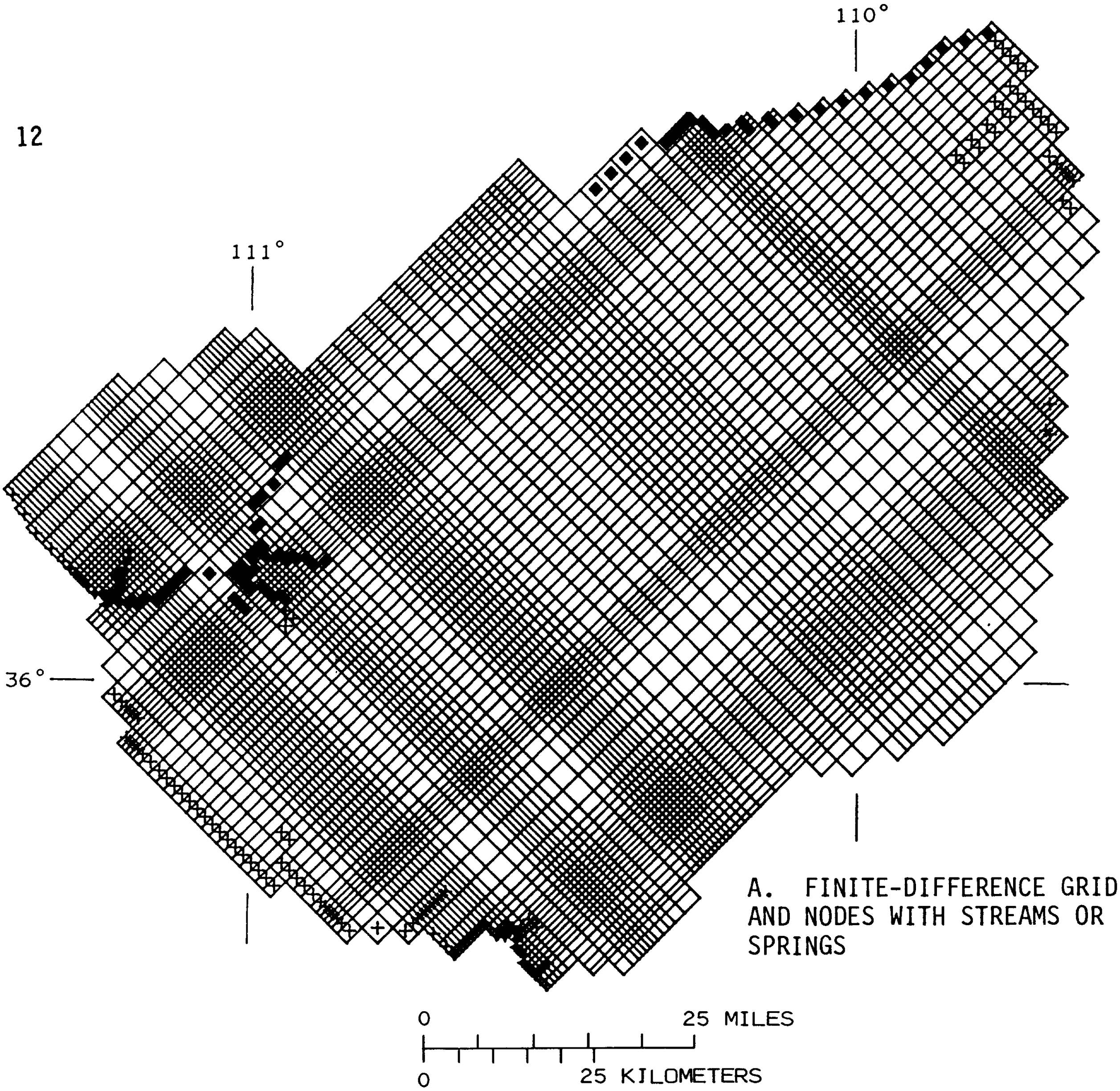
Calibration

Calibration of the model included estimating all aquifer characteristics and inflow or outflow rates at each node. Values of hydraulic characteristics from the 1983 model generally were used as initial estimates. The estimates then were adjusted as necessary within the range of observed field values until the best possible match was obtained between simulated and observed water levels and flow rates.

The finite-difference grid used in the 1983 model was revised to provide more detail near Kayenta, Tuba City, Keams Canyon, Oraibi, and the coal-lease area. Pumping history and management projections of future withdrawals indicate that stresses on the aquifer will be greatest in these areas. The grid used in the 1983 model and for runs comparing the Trescott and modular programs consisted of identical square blocks that were 4 mi^2 in area and will be called the old grid. Specifications for the new grid required blocks 0.5 mi on a side in some areas, but the original grid spacing was retained where possible. The new grid was designed so that each new block fell completely within a single block on the old grid. Redefining the grid in this manner facilitated both the data manipulations necessary for grid conversion and the comparisons of simulations with the old and new grids (fig. 4).

In areas where grid dimensions were decreased, input data were modified to more accurately represent land-surface altitude and the altitudes and locations of blocks representing rivers, springs, and wells (fig. 4). As a result, several subdivided blocks fell north of Laguna Creek and were excluded from the model. The model boundary was adjusted northwest and west of Tuba City and south of Oraibi to more accurately simulate the physical extent of the aquifer.

Where the altitude of the land or water surface was changed, the top altitude of the aquifer was checked and adjusted if necessary. The top of the N aquifer slopes steeply to the south and west in a broad arc from northwest of the coal-lease area to near Rough Rock. The transition from confined to unconfined flow conditions in this part of Black Mesa generally occurs where the aquifer dips into the structural basin and becomes overlain by confining material. To better simulate this area of changing flow conditions, the altitude of the top of the N aquifer was



EXPLANATION

BLOCK—Each block represents an area of the aquifer ranging from 0.25 to 4 square miles, which is represented in the model by a node at the center of each block

AREA IN WHICH INFLOW TO THE N AQUIFER WAS SIMULATED FOR:

Recharge of rainfall or snowmelt

Vertical leakage from upper confining layer

NODE AT WHICH OUTFLOW FROM THE N AQUIFER WAS SIMULATED FOR:

◆ Discharge to streams

\+ Discharge to springs

× Evapotranspiration

• MUNICIPAL OR INDUSTRIAL WELL

∘ WINDMILL

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

Figure 4.--Finite-difference grid and model-boundary conditions.

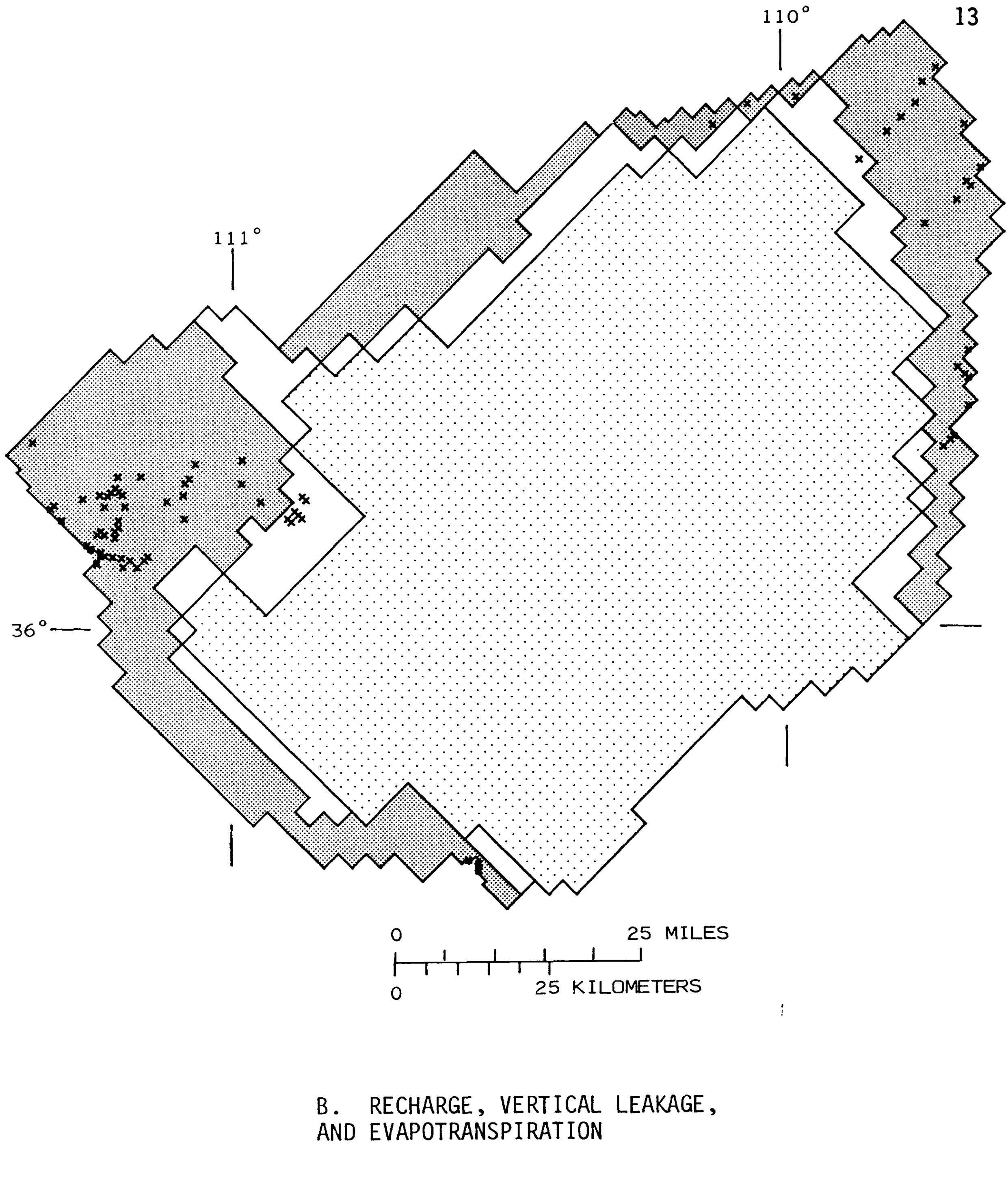


Figure 4.--Finite-difference grid and model-boundary conditions--Continued.

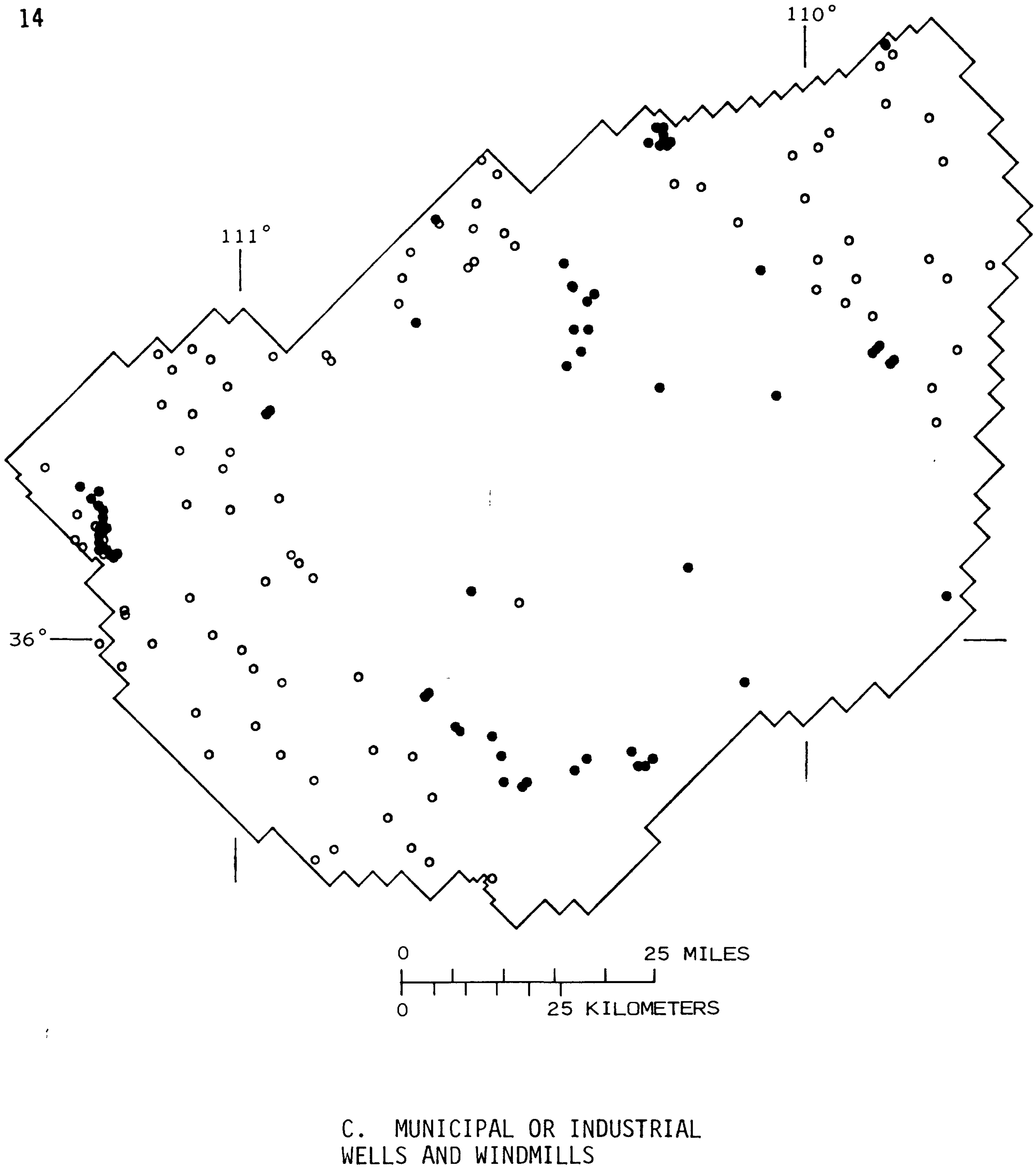


Figure 4.--Finite-difference grid and model-boundary conditions--Continued.

checked and revised where necessary. The altitude of the aquifer bottom was adjusted near Tuba City and includes as much as 200 ft of the uppermost Kayenta Formation, which consists of interbedded sandstone and siltstones and intertongues with the lowest part of the Navajo Sandstone.

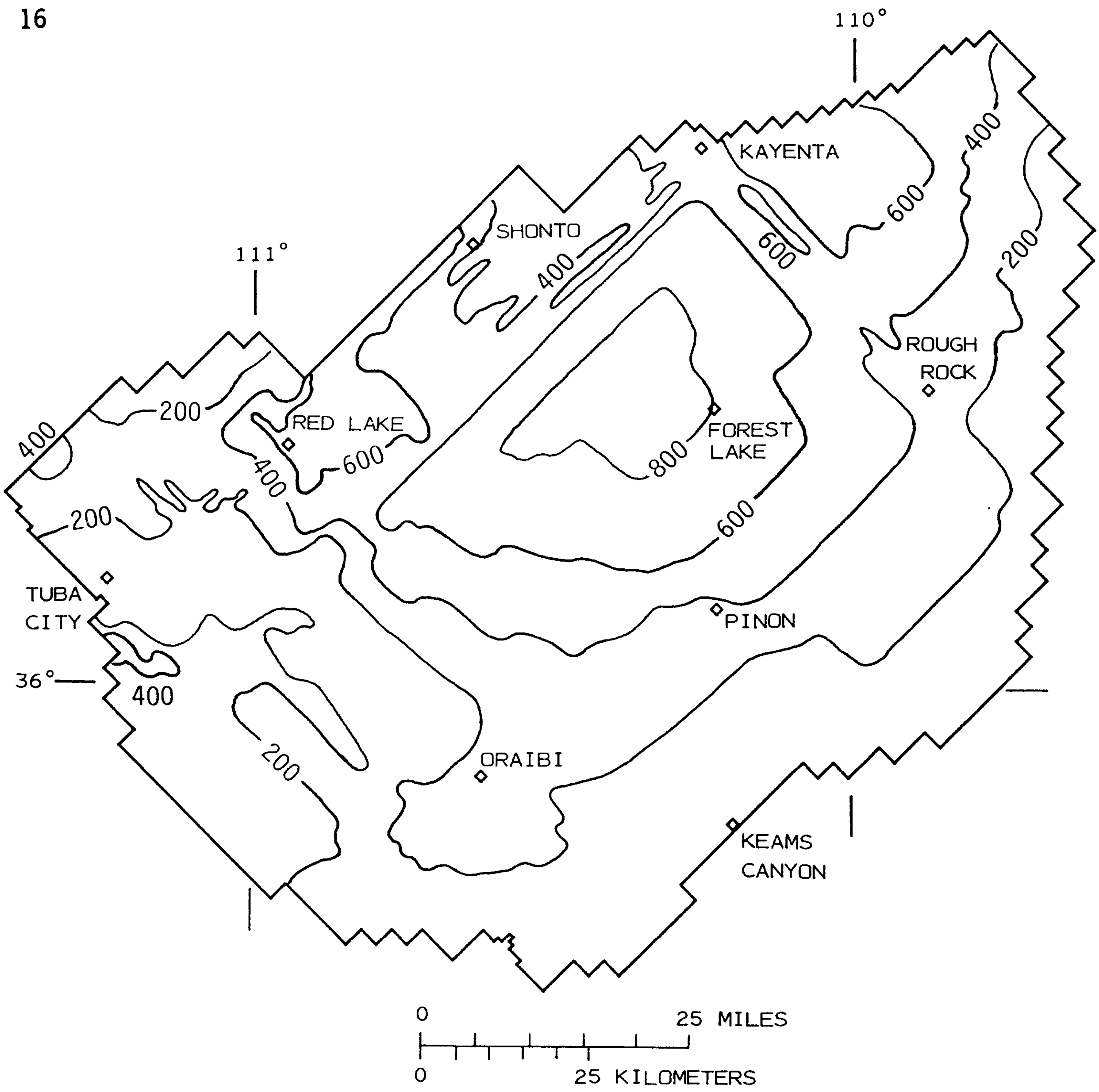
Equilibrium conditions.--The model was calibrated initially for equilibrium conditions. The N aquifer was assumed to be in equilibrium before 1965 (Eychaner, 1983). For much of the model area, computed water levels in the equilibrium calibration were compared with water levels measured in 1965 or earlier. Water levels measured as late as 1972 were used in areas not affected by pumping.

Input data from the 1983 model generally were used as initial estimates of aquifer properties. River and drain conductances were adjusted at several nodes to achieve a reasonable match of both inflow and head in the immediate area. Recharge to the N aquifer was increased by 4 percent to maintain a better conceptual balance between inflow and outflow. A maximum evapotranspiration rate of 5.1 ft/yr was used in the model. The water-table depth at which evapotranspiration ceases was adjusted during equilibrium calibration; the best overall results were achieved using 10 ft.

Using the hydraulic-conductivity values from the 1983 model yielded unsatisfactory results, so they were completely recalibrated. Estimates of hydraulic conductivity based on field data averaged 0.65 ft/d and ranged from 0.05 to 2.1 ft/d; values of 0.32 to 0.97 ft/d were used in the 1983 model (Eychaner, 1983, p. 7, 15). Starting with a constant 0.65 ft/d throughout the area, a distribution of hydraulic conductivity was developed that ranged from 0.1 to 1.8 ft/d in a slightly different pattern from that of the 1983 model. In most of the model area, calibrated hydraulic-conductivity values were between 0.5 and 0.9 ft/d. The values were smallest in the Tuba City area and largest east of Echo Cliffs along the west edge of the model area. Calibrated hydraulic conductivity differs by less than 50 percent between the two models in about 85 percent of the study area.

Transmissivity is equal to hydraulic conductivity multiplied by saturated thickness and reflects the rate at which water may move through the aquifer. Simulated transmissivity ranged from more than 800 ft^2/d in the coal-lease area where the aquifer is thickest and hydraulic-conductivity values are relatively large to less than 200 ft^2/d along the thin southern margin of the aquifer. Transmissivity is less than 200 ft^2/d near Tuba City where hydraulic conductivity is smallest (fig. 5).

Simulated equilibrium water levels for 123 wells generally were closer to observed levels in the 1988 model than in the 1983 model (table 1). After rediscretization and recalibration, the average of the absolute values of the differences decreased from about 28 ft to 21 ft, and the square root of the average squared differences decreased from about 35 to 29 ft. Simulated water levels for the 1988 model were within 50 ft of observed water levels for 110 of 123 wells, thus the probability is about 90 percent that a specific simulated water level would be within 50 ft of the level in a corresponding well. This improved match between simulated and observed water levels is largely the result of



EXPLANATION

—— 200 —— LINE OF EQUAL TRANSMISSIVITY—Shows approximate generalized transmissivity distribution used in equilibrium simulation. Interval 200 feet squared per day

———— BOUNDARY OF MATHEMATICAL MODEL

Figure 5.--Transmissivity used in equilibrium simulation.

Table 1.--Differences between observed and simulated water levels for equilibrium conditions

	1983 model	1988 model
Mean difference, in feet...........	0.7	-1.1
Mean absolute difference, in feet..	27.8	21.4
Root mean squared difference, in feet............................	35.4	28.9
Percentage of wells in which observed and simulated water levels were within 50 feet..........................	82	89

rediscretization. In areas where node sizes were decreased, simulated water levels represented the average condition over a smaller block and made possible a more precise approximation of the observed water-level distribution.

Many of the simulated water budget items differed from those of the 1983 model. Evapotranspiration for equilibrium conditions in the 1983 model was 3,000 acre-ft/yr. In the 1988 model, evapotranspiration was 6,600 acre-ft/yr (table 2), which is only 10 percent more than the value of 6,000 acre-ft/yr estimated by Eychaner (1983). For the most part, the increase in simulated evapotranspiration was balanced by reduced outflow to rivers and springs, which decreased from 9,640 acre-ft/yr in the 1983 model to 7,030 acre-ft/yr. This value closely approximates the estimate of 7,170 acre-ft/yr for discharge to rivers and springs by Eychaner (1983, p. 10).

Nonequilibrium conditions.--The final step in calibrating the model was to simulate the period from 1965 through 1984 when water levels were changing in response to pumping. The confined- and unconfined-storage coefficents from the 1983 model were used in the 1988 model without adjustment.

Municipal well locations were checked using data supplied by OSMRE, who also provided locations and estimated withdrawal rates for windmills that pump from the N aquifer. After cross checking with data in U.S. Geological Survey files, withdrawals for 98 windmills not otherwise represented in the model were included for a total withdrawal of about 23 acre-ft/yr. Withdrawals by windmills were simulated as a constant rate beginning in 1965. Because of the addition of windmills, the simulated quantity of water withdrawn by wells in the 1988 model was slightly larger than that in the 1983 model. Municipal and industrial pumpage was the same for both models.

Simulated water-level changes from 1965 to 1984 using the 1988 model generally agree with water-level changes observed in six

Table 2.--Simulated water budget of the N aquifer, 1964 and 1984

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

	1964		1984	
Inflow				
Recharge from infiltration of rainfall and snowmelt.......		13,380		13,380
Vertical leakage from upper confining bed...............		180		210
Total inflow..................		13,560		13,590
Outflow				
To streams, springs, and alluvium:				
Near Moenkopi Wash..........	3,170		3,170	
Near Laguna Creek...........	2,440		2,230	
In other areas	1,250		1,220	
Subtotal....................		6,860		6,620
Underflow near mouth of:				
Laguna Creek................		150		150
Evapotranspiration..........		6,550		6,370
Withdrawals				
Industrial..................	0		4,100	
Nondustrial.................	0		2,130	
Windmills	0		26	
Subtotal....................		0		6,260
Total outflow................		13,560		19,400
Change in storage (inflow minus outflow)........		0		-5,810

continuous-record observation wells (figs. 6 and 7) and are nearly identical to water-level declines simulated in the 1983 model. Wells BM5 and BM6 are in the area in which ground water is confined, and the simulated and measured water levels are within 5 ft and 1 ft, respectively. The 1983 model simulates small declines at wells BM1 and BM4, which are in the area of unconfined ground water. Observed water levels in these wells have either not changed or have risen slightly. In well BM4, the rise probably relates to increased recharge since 1981.

At well BM2, ground water is confined, but the boundary between confined and unconfined ground water is about 5 mi northeast of the well. Observed water levels at BM2 declined less rapidly than simulated water levels from 1965 to 1978. The slope of the simulated declines decreases after about 1978, probably because the larger simulated storage coefficient in the unconfined ground-water area restricts the rate of growth of the area of decline. The flattening of the observed hydrograph in 1983 may be due to the nearby confined-unconfined boundary or to a decrease in pumpage at the mine following 18 months of greater than normal withdrawals. The simulated hydrograph is insensitive to annual changes in pumping at the mine, which ranged from 2,520 to 4,740 acre-ft/yr between 1972 and 1986 (Hill and Sottilare, 1987, p. 11). Since 1983, the observed and simulated hydrographs are in close agreement.

The inconsistencies between observed and simulated water levels for well BM3 at Kayenta mostly occurred before 1970. Since then, the trends are generally parallel. The decline of observed and simulated water levels slowed in 1981 when a new well field south of Kayenta replaced some wells closer to BM3. Simulated water levels for well BM3 are very sensitive to the location and rate of pumpage within the Kayenta well fields.

From 1965 through 1984, simulated outflow to streams, springs, and evapotranspiration decreased 3 percent (table 2). Flow through the confining layer increased 15 percent, but this increase amounted to only 28 acre-ft/yr, which is less than 1 percent of the total inflow to the N aquifer.

Water levels have declined throughout the 3,300 mi^2 area of confined ground-water conditions (fig. 3). The 1983 model simulated declines of more than 10 ft from 1965 through 1984 in 2,760 mi^2 and declines exceeding 100 ft in 344 mi^2. The 1988 model simulates more than 10 ft of decline in 2,810 mi^2 and more than 100 ft in 309 mi^2 (fig. 7). In both simulations, maximum drawdown occurred in the Peabody well field. The maximum simulated drawdown was 249 ft in the 1983 model and 243 ft in the 1988 model. Pumpage through 1984, however, had little effect on ground-water flow directions more than a few miles from the lease area (fig. 8).

Pumping at the mine and throughout the area of confined ground water had no effect on simulated water levels at Tuba City, Shonto, and Dennehotso through 1984. Ground water in the N aquifer in these areas is unconfined; the lack of confinement prevents distant pumping from causing rapid water-level changes. The nearest point to Tuba City at which simulated decline caused by pumping in the area of confined conditions exceeded 1 ft was 19 mi to the east in late 1984 (fig. 7), about 0.5 mi closer than 5 years earlier.

MODEL SENSITIVITY AND PREDICTIVE LIMITATIONS

Model-sensitivity analysis is one way of determining relative reliability and recognizing the limitations in the predictive adequacy of a model. Although the 1988 model reasonably reproduced observed water-level changes in six observation wells, the solution is not unique. Equally close agreement to the observed heads was reached by the 1983 model using different evapotranspiration rates balanced by different aquifer characteristics. Other combinations that are consistent with field observations could be selected that would simulate the N aquifer equally well.

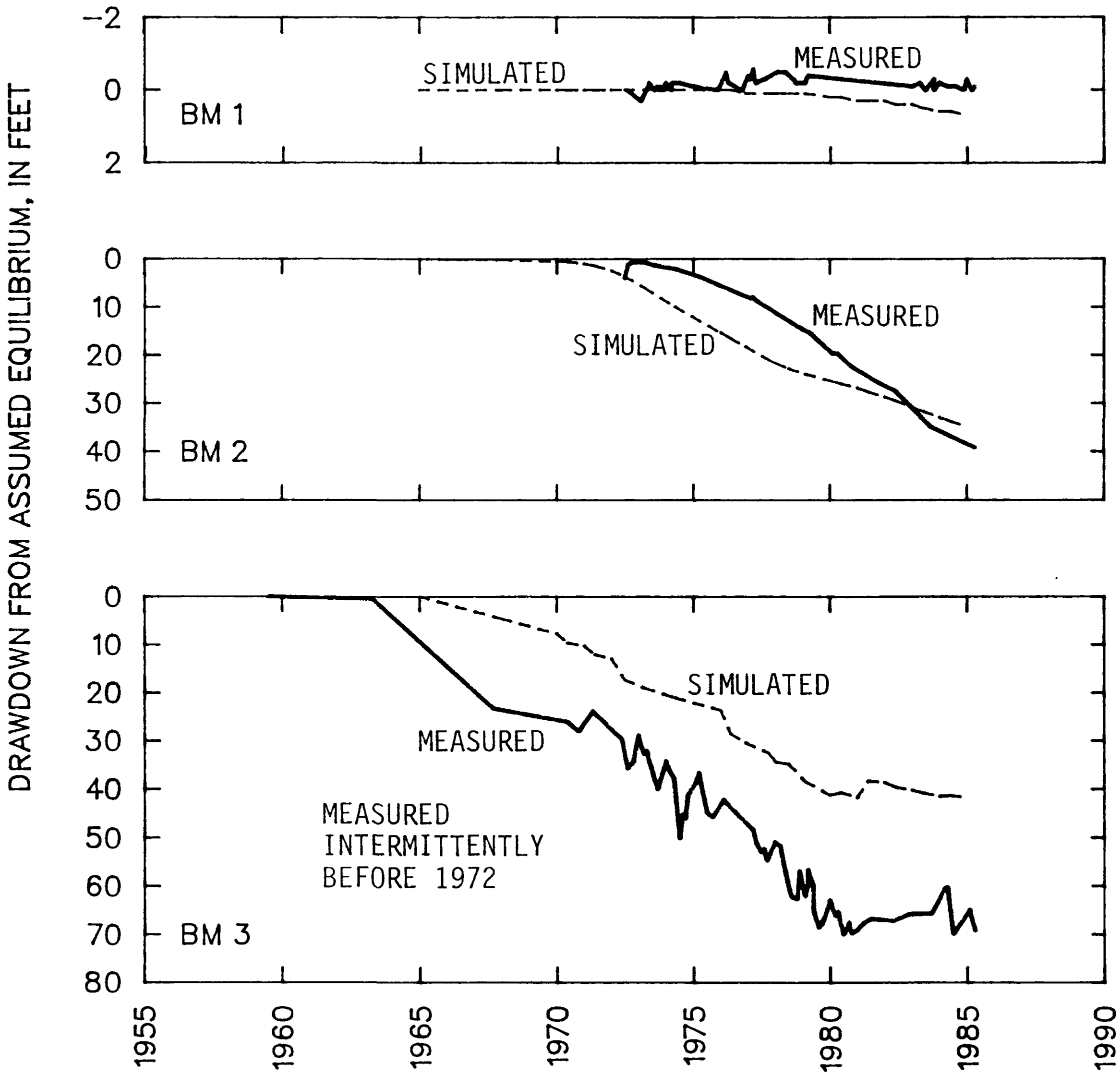


Figure 6.--Measured and simulated water-level changes for observaton wells, 1959-85. (See figure 7 for well locations.)

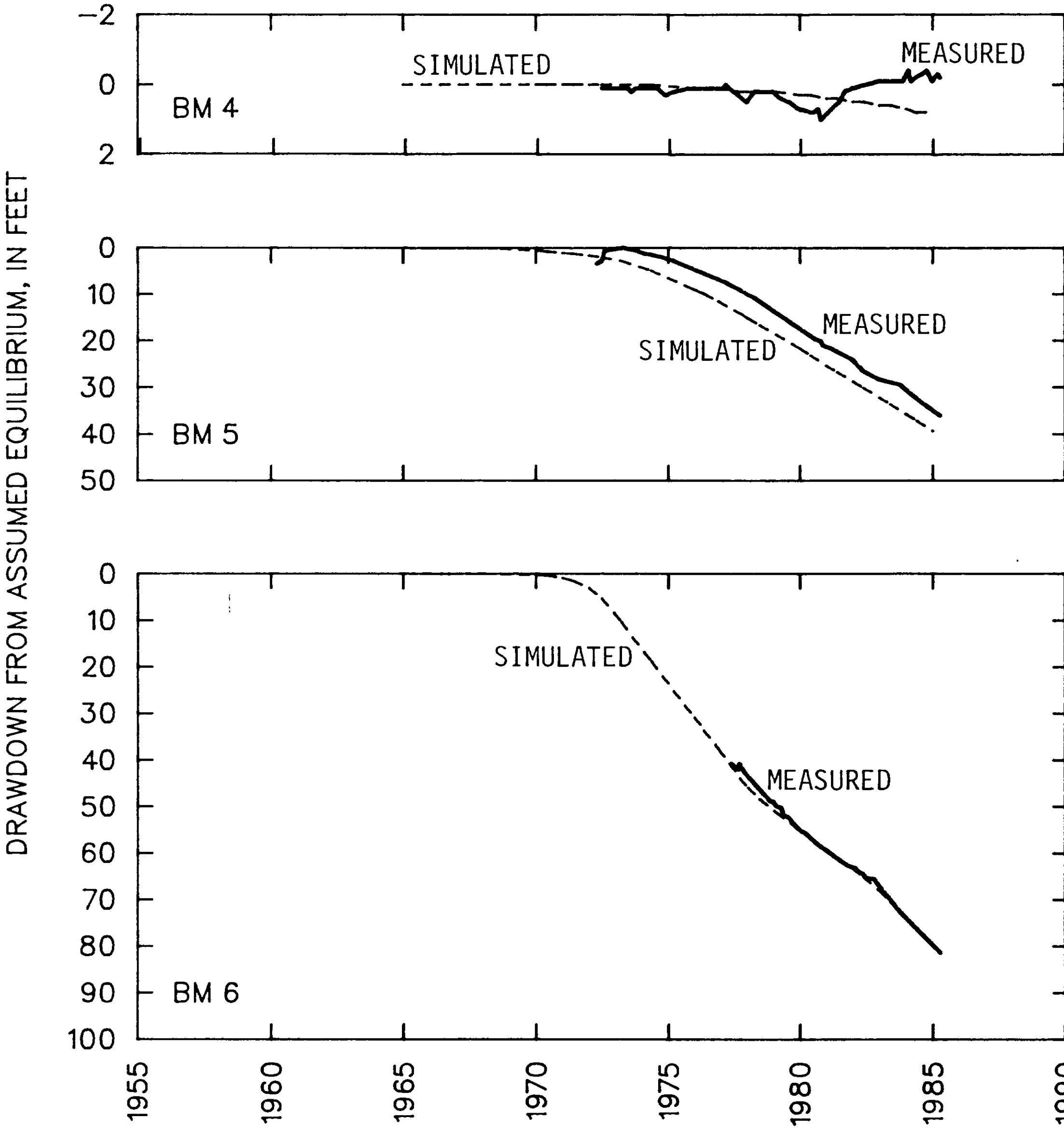
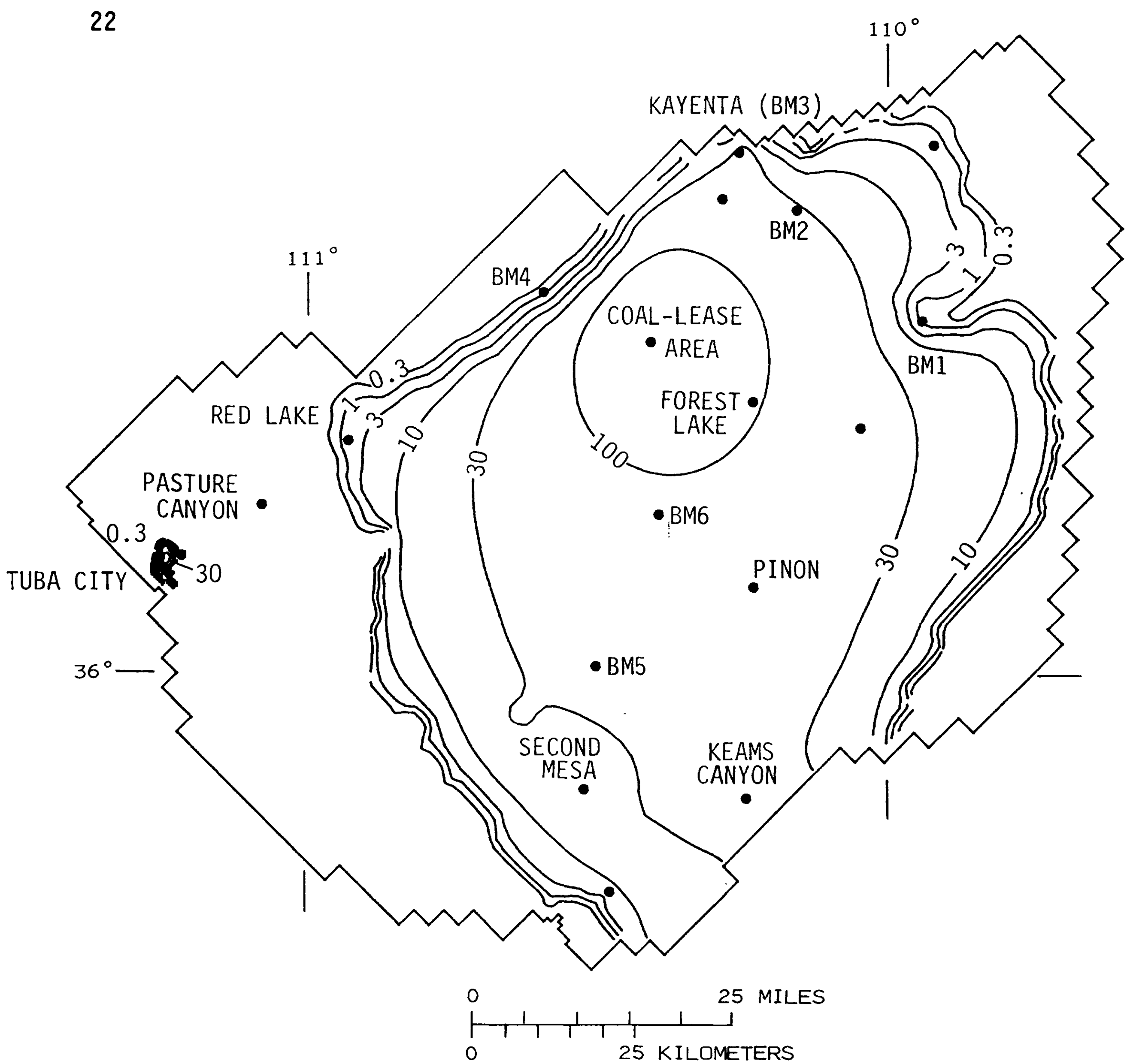


Figure 6.--Measured and simulated water-level changes for observation wells, 1959-85--Continued.



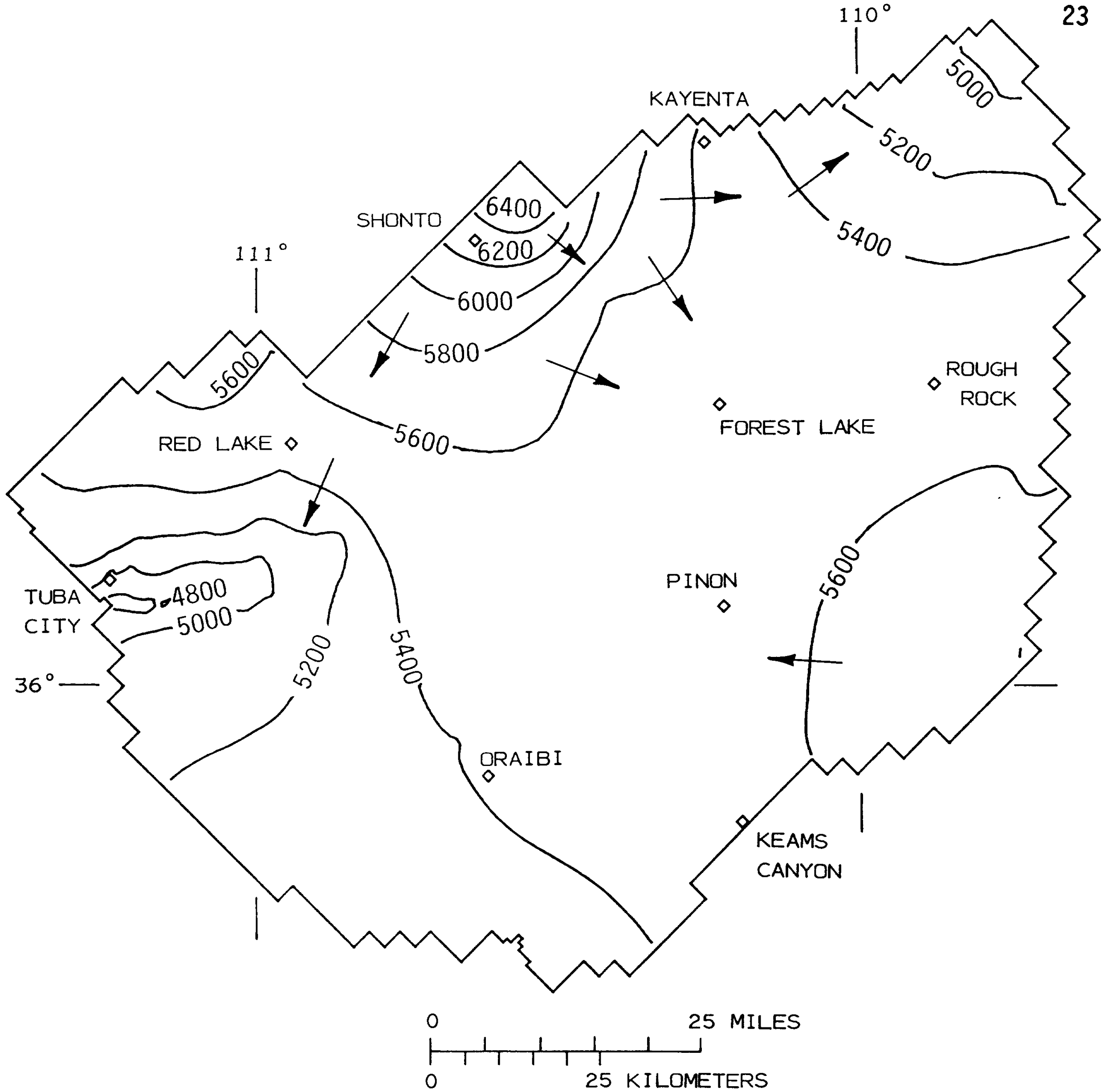
EXPLANATION

——30—— LINE OF EQUAL SIMULATED WATER-LEVEL DECLINE—Interval, in feet, is variable. (Total simulated ground-water pumpage for 1965-1984 was 74,000 acre-feet)

• BM6 NODE AT WHICH SIMULATED GROUND-WATER LEVELS ARE SHOWN ON HYDROGRAPH

———— BOUNDARY OF MATHEMATICAL MODEL

Figure 7.--Simulated water-level declines, 1965-84.



EXPLANATION

——5400—— LINE OF EQUAL SIMULATED WATER-LEVEL ALTITUDE—Contour interval 200 feet. Datum is sea level

——► GENERALIZED DIRECTION OF GROUND-WATER FLOW

——— BOUNDARY OF MATHEMATICAL MODEL

Figure 8.--Simulated altitude of water levels, 1984.

Sensitivity analyses are performed by systematically changing the values of model-input components in the calibrated model and observing the effects on simulated heads, drawdowns, and water-budget components. The range in values over which a component is varied is a function of the relative uncertainty of that component. If the effect on model results is great, the reliability of the predictive simulations may be questionable. If the effect is small, more confidence can be placed on the predictive simulations. Sensitivity analysis of the new model was performed by systematically varying transmissivity, areal recharge, vertical leakage, storage coefficients, and evapotranspiration within reasonable limits and observing the effects on model results.

A 10-percent increase in transmissivity throughout the model caused simulated equilibrium head to decline an average of 17 ft and decreased simulated decline from 1965 through 1984 by about 5 percent. Decreasing the recharge by 10 percent caused equilibrium head to decline an average of 20 ft but caused no change in simulated declines from 1965 through 1984. Decreasing the leakage from the upper confining beds to zero caused equilibrium heads to decline about 7 ft but had little effect on simulated declines through 1984. Changing the storage coefficient resulted in a change in the rate of water-level decline. Increasing the confined storage coefficient by 50 percent decreased average decline by 21 percent. Decreasing it 50 percent, however, increased the decline 30 percent and caused the area in which declines exceeded 100 ft to extend about 5 mi farther south than is shown in figure 7. Increasing the unconfined storage coefficient by 20 percent to 0.12 had little effect on average drawdown over the entire model area through 1984 but decreased the drawdown by a few feet near pumping centers in the areas of unconfined ground water.

Increasing the maximum evapotranspiration to equal the average annual pan evaporation caused simulated equilibrium heads to decline an average of less than 0.1 ft over the entire model and less than 0.3 ft in water-table areas where evapotranspiration occurs. Simulated declines from 1965 through 1984 were not affected. Decreasing the evapotranspiration by 40 percent caused equilibrium heads to rise 0.1 ft but had little effect on declines through 1984. Increasing the depth at which simulated evapotranspiration ceased to 15 ft caused equilibrium heads to decline an average of 2 ft throughout the model and 2 to 5 ft near Tuba City, Kayenta, and in the large area of unconfined ground water east of Black Mesa. Increasing this variable had no effect in simulated declines through 1984. In summary, the sensitivity analyses indicated that only variations in the value of confined storage coefficients significantly affected water-level declines.

The predictive accuracy of any model is related to the accuracy of the estimates of aquifer parameters used and predictions of future pumpage. During the 1965-84 calibration period, maximum annual withdrawals were about 50 percent of annual recharge. If future withdrawals were much greater, unanticipated responses in the aquifer that would require additional refinement of the model may occur.

As with the 1983 model, the focus of the 1988 model was to determine the impact of withdrawals at the mine on ground-water conditions at the Indian communities. These regional models cannot adequately represent the local geology and simulate hydrologic processes in detail. For example, the simulated impacts of competing water users near Tuba City may be inaccurate because of vertical variations in hydraulic properties of the N aquifer, local variations in streamflow characteristics, and inadequate knowledge of the pumping rates in individual wells.

SIMULATED EFFECTS OF FUTURE WITHDRAWALS

Because the 1988 model was successful in simulating conditions in the N aquifer from 1965 through 1984, it was assumed that the model could be used to make reasonable estimates of water levels that would result from future pumping from the aquifer. Five projections of water-level changes were made using pumping alternatives specified by the OSMRE. Simulated pumping was mainly in the area of confined ground-water conditions under Black Mesa. The simulated water-level changes represent average conditions over the area of each model block and do not represent water levels in pumping wells. The simulated water levels should not be expected to be closer than 50 ft to the actual water level in any block. Simulated values of future water-budget components are only as accurate as the estimates of aquifer parameters. For these reasons, projection results are better used to compare effects of different development plans rather than estimate actual future water levels and water-budget components. The simulated results will be discussed first for each pumping alternative and then for selected areas of the N aquifer. The later discussions will emphasize comparisons between projections.

Pumping Alternatives

The five pumping alternatives and their effects will be called projections A through E. The pumping rates and locations used in the projections were based on information from the Navajo and Hopi Tribes and the coal company. Projections A and B represent the existing mining plan; C and D represent possible pumpage under the proposed lease (fig. 9 and table 3). All four projections set future mine pumpage at 4,400 acre-ft/yr, which is approximately equal to the average during 1982-84 and about 34 percent of the estimated recharge to the aquifer. In projections A and B, pumping for the mine would be reduced to 1,100 acre-ft/yr after 2006 and to zero after 2011. Under the proposed lease, withdrawals would cease after 2031. Projection E terminates pumping for the mine in 1985 and provides a basis for comparison with projections A-D. All five projections were continued through 2051, which is 20 years past the end of withdrawals under the proposed lease, to examine the residual effects of the pumping during that period.

The mining options were combined with two alternatives of future pumping for the Indian communities. In projections A and C, tribal pumpage was held constant at 2,130 acre-ft/yr; in projections B, D, and E the pumpage was increased 2.5 percent per year simulated in 5-year steps (fig. 9). Estimates of future community withdrawals were made on the basis of recent pumping trends and expected future growth. By 2051,

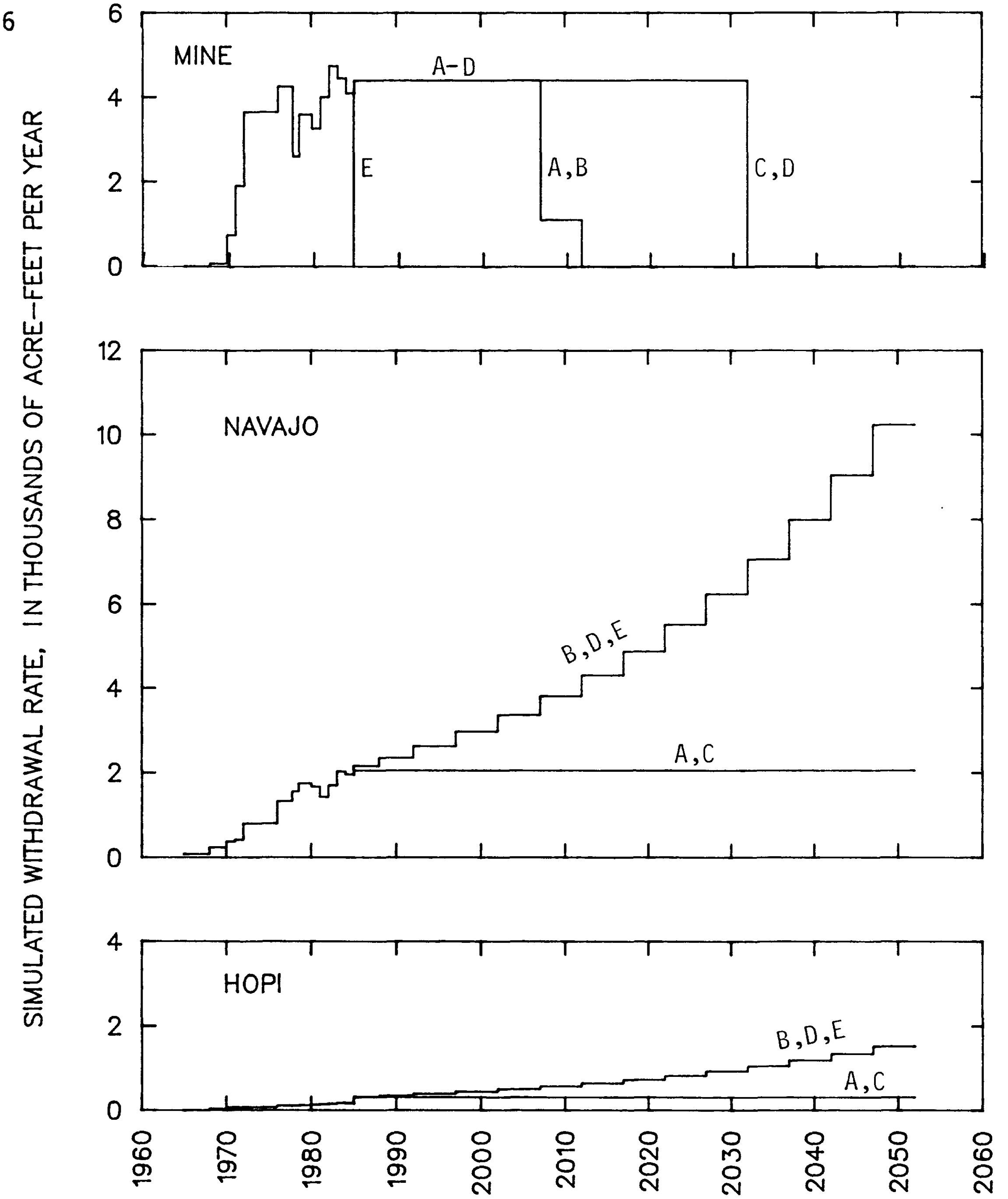


Figure 9.--Simulated withdrawals from the N aquifer, 1965-2051, for projections A, B, C, D, and E.

Table 3.--Simulated total withdrawal and decrease in storage

Years	Simulated total withdrawal, in thousands of acre-feet, for projection				
	A	B	C	D	E
1965-1984	74	74	74	74	74
1984-2006	149	166	149	166	70
2007-2031	64	148	169	253	142
2032-2051	47	197	47	197	197
Total	334	585	439	690	483

Years	Simulated decrease in storage, in thousands of acre-feet, for projection				
	A	B	C	D	E
1965-1984	72	72	72	72	72
1985-2006	133	150	133	150	57
2007-2031	41	117	141	218	118
2032-2051	27	164	22	159	168
Total	273	503	368	599	415

however, compounded annual increases of 2.5 percent would make community withdrawals more than three times the 1984 rate or about 92 percent of estimated recharge (fig. 10). As pumpage for the communities increases and water levels decline in existing wells, new wells are drilled. For projections B, D, and E with increasing community pumping, withdrawals were assigned to additional model blocks as needed in the Tuba City area to prevent excessive simulated declines. About 55 percent of the projected withdrawals by the Navajo Tribe are in the area of unconfined conditions and 45 percent in the area of confined conditions on and near Black Mesa. Nearly all of the withdrawals by the Hopi tribe are from the area of confined conditions.

Projection A.--The first pumping alternative represents the present mining plan and constant withdrawals for Indian communities. In that plan, withdrawals for the mine will decrease by 75 percent after 2006 and will stop after 2011. Water levels under projection A would decline about 40 ft from 1985 through 2006 in the coal-lease area and by lesser amounts to the north, east, and west. Water levels in the lease area would rise about 150 ft during the 5 years of reduced pumping and would continue to rise after mine pumping stopped. Water levels would decline by more than 30 ft from 1985 through 2006 in an area of 1,300 mi²

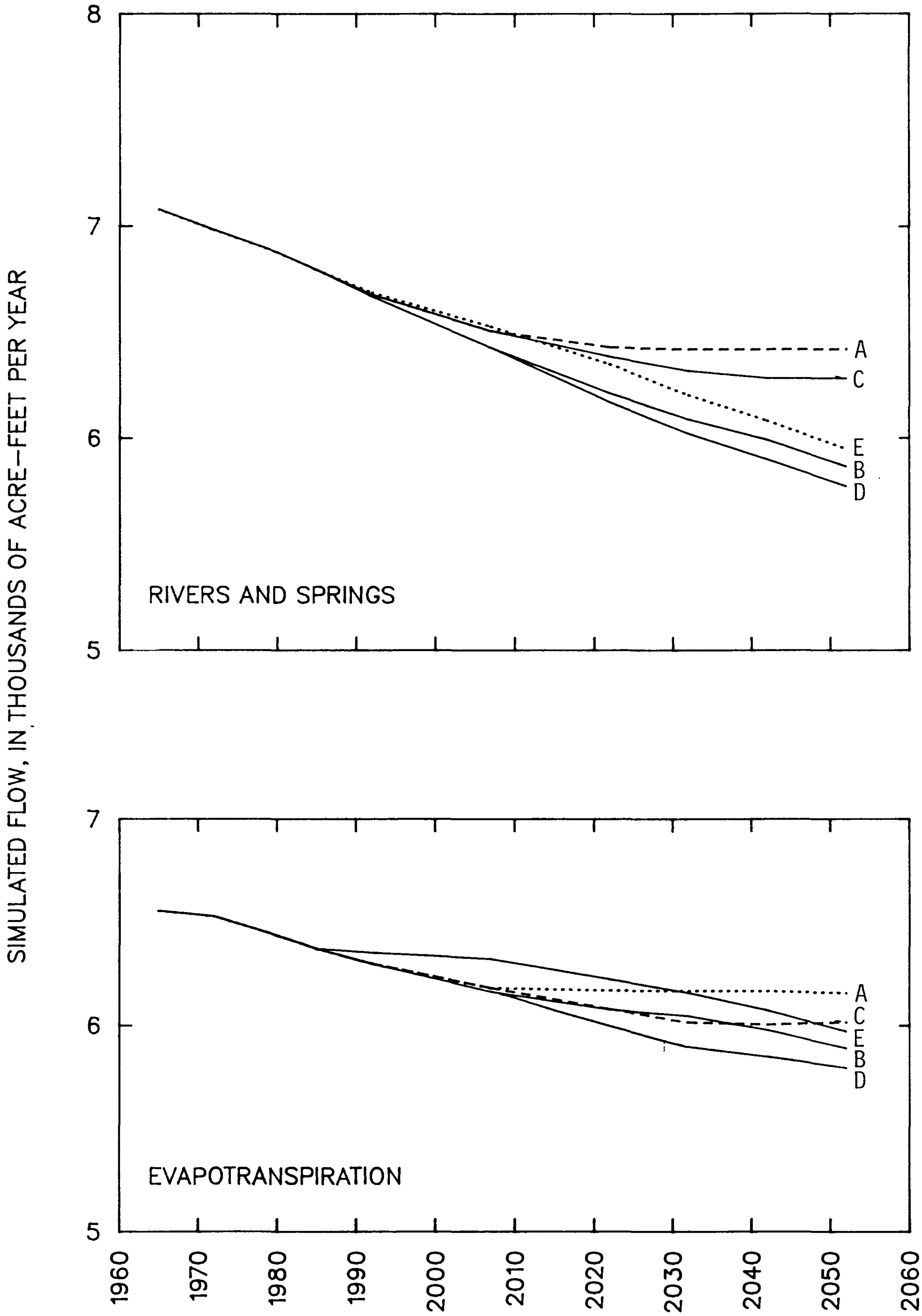


Figure 10.--Simulated components of the water budget, 1965-2051, for projections A, B, C, D, and E.

extending from the coal-lease area to the Hopi communities and in a small area of about 4 mi^2 centered around Tuba City (fig. 11).

In projection A, about 149,000 acre-ft of water would be withdrawn between 1985 and 2006, of which 65 percent would be for the mine (table 3). Decreased storage of water in the aquifer would account for 89 percent of the withdrawal and the rest would be balanced by a reduction in discharge to streams, springs, and evapotranspiration (fig. 10) and by increased leakage from the D aquifer. Total outflow to streams and springs in 2006 would be 8 percent less than in 1964 and 4 percent less than in 1984. The effects of the various projections on outflows to individual streams will be discussed in a later section. Evapotranspiration would be 3 percent less than in 1984 and 6 percent less than in 1964. Leakage would be about 234 acre-ft in 2006 compared to 184 acre-ft in 1964 and 212 acre-ft in 1984.

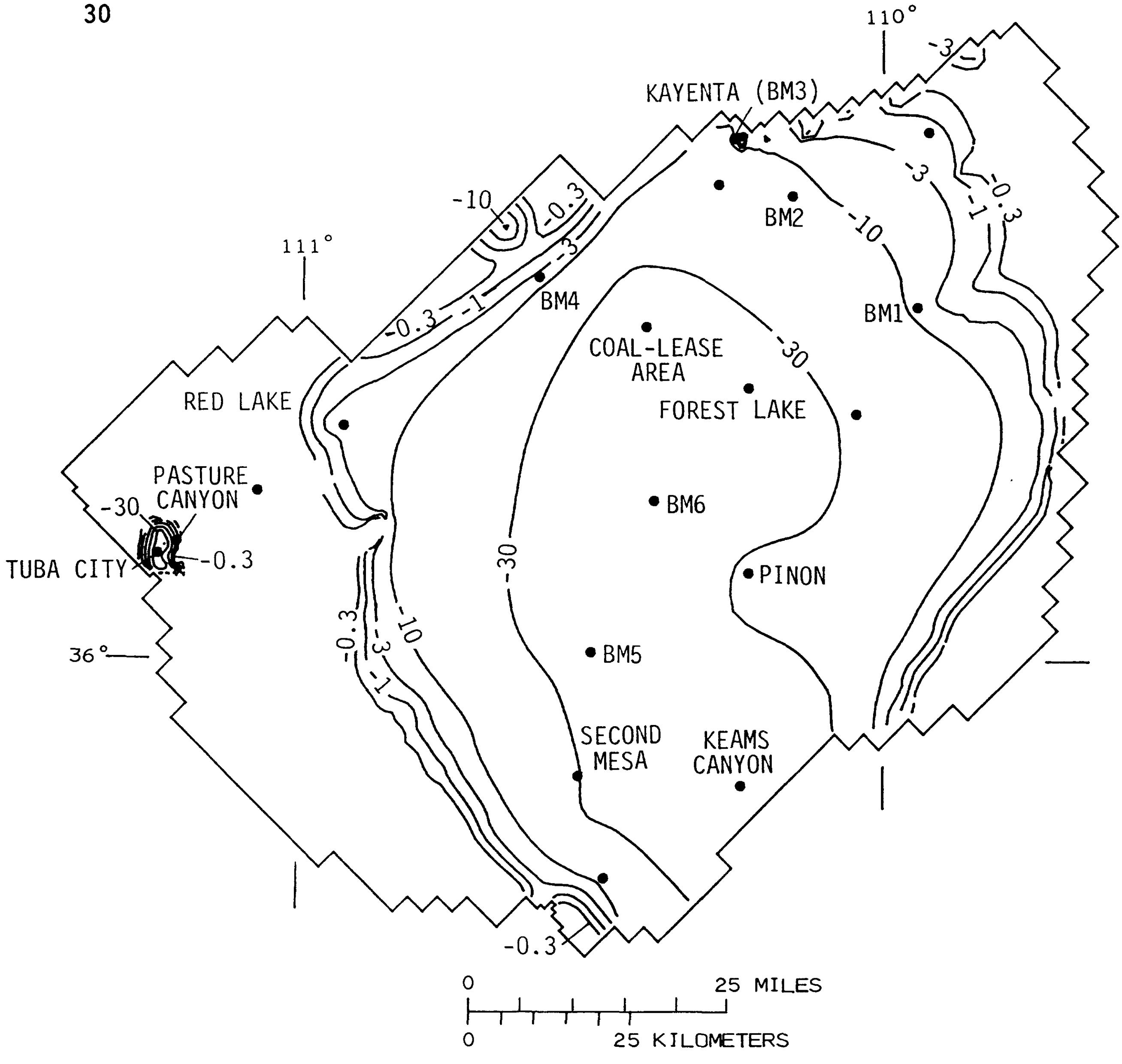
From 2007 through 2051, about 112,000 acre-ft of water would be withdrawn from the N aquifer, about 61 percent of which would come from storage. Discharge to streams and springs and by evapotranspiration would decrease less than 1 percent during this period. Inflow from the D aquifer would decrease to about 203 acre-ft/yr as water levels rise near the coal-lease area. Reduction in total storage in the N aquifer from 1985 through 2051 would be about 0.15 percent.

Projection B.--The second pumping alternative combines the present mining plan with increasing withdrawals for communities. Simulated water levels in the coal-lease area would be similar to those simulated under projection A, but the declines would be greater near all the communities. By 2006, simulated water levels would be more than 30 ft lower than in 1984 in an area of 1,680 mi^2 extending from the lease area to the Hopi communities (fig. 12). Simulated water levels would decline more than 100 ft in an area of 18 mi^2 near the Hopi communities.

As in projection A, the simulated water budget for projection B indicates that the water withdrawn from the aquifer would be taken mainly from storage. From 1985 through 2006, 166,000 acre-ft of water would be pumped from the N aquifer, of which 90 percent would come from storage (table 3). Outflow to springs and streams and by evapotranspiration would be reduced about 4 percent (fig. 10), and inflow from the D aquifer would rise to 240 acre-ft/yr.

Water levels near the mine would rise more than 100 ft above 1985 levels in an area of 137 mi^2 in the 40 years following cessation of mine pumping. The area of water-level decline exceeding 100 ft would increase to about 330 mi^2 around the Hopi communities, including an area of about 8 mi^2 where declines would exceed 300 ft. At Tuba City, declines exceeding 100 ft would occur in an area of less than 10 mi^2.

From 2007 through 2051, 345,000 acre-ft of water would be withdrawn from the N aquifer, which is twice that of projection A. Decreased ground water in storage would account for 81 percent of the withdrawals, which is 20 percent more than projection A for the same period. Outflow tosprings and streams in projection B would decline by 7 percent during this time. Leakage from the D aquifer would increase



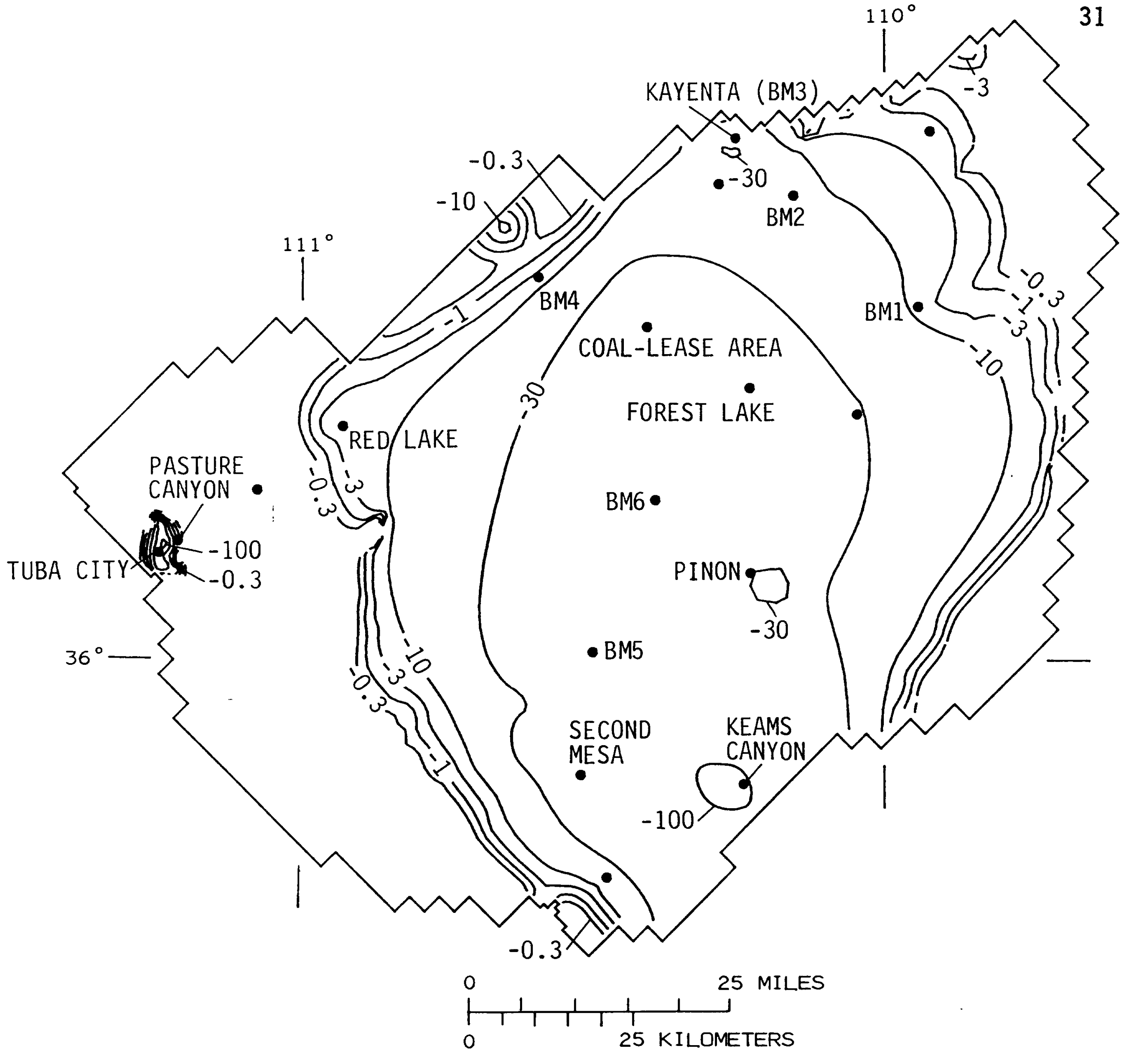
EXPLANATION

—— -30 —— LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE—Interval, in feet, is variable. (Total simulated ground-water pumpage for 1985-2006 was 149,000 acre-feet)

• BM6 NODE AT WHICH SIMULATED GROUND-WATER LEVELS ARE SHOWN ON HYDROGRAPH

———— BOUNDARY OF MATHEMATICAL MODEL

Figure 11.--Simulated water-level changes for projection A, 1985-2006.



EXPLANATION

—— -30 —— LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE—Interval, in feet, is variable. (Total simulated ground-water pumpage for 1985-2006 was 166,000 acre-feet)

● BM6 NODE AT WHICH SIMULATED GROUND-WATER LEVELS ARE SHOWN ON HYDROGRAPH

———— BOUNDARY OF MATHEMATICAL MODEL

Figure 12.--Simulated water-level changes for projection B, 1985-2006.

slightly to 243 acre-ft/yr despite the absence of pumping at the mine because of the higher conductance of the confining bed in the area of continuing water-level declines near Oraibi (Eychaner, 1983, p. 9).

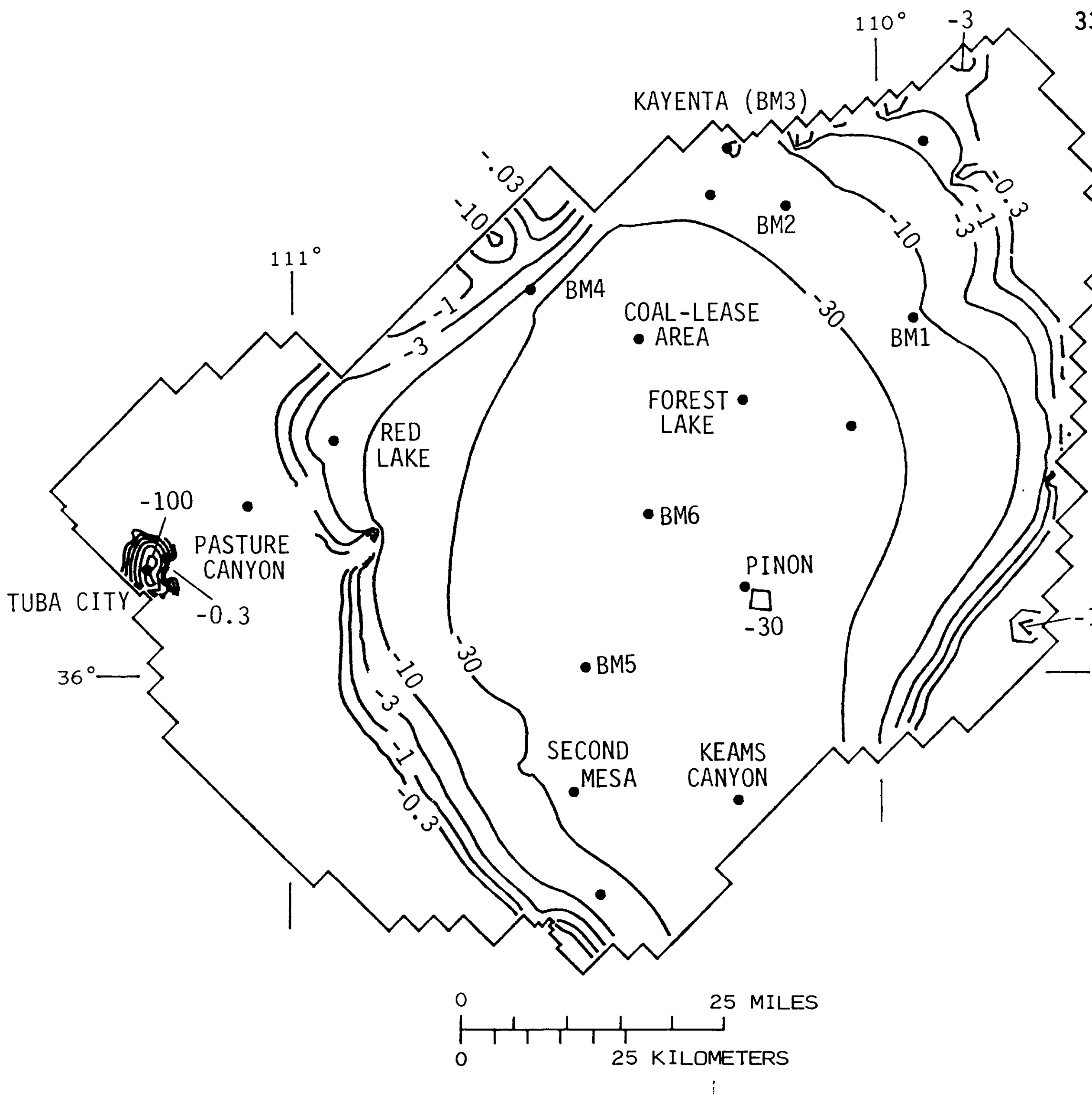
Projection C.--Projection C simulates the effects of the proposed lease and constant withdrawals for the Indian communities. Under that lease, pumping at the mine would continue through 2031, 20 years longer than under the present plan. Simulated water levels would decline about 50 ft from 1985 through 2031 near the mine and more than 30 ft in an area of 1,980 mi^2 that extends from the coal-lease area southward to Oraibi and Keams Canyon (fig. 13). Water levels in the lease area would rise about 250 ft in the 20 years following cessation of mine pumping, and the area of 30-ft decline from 1985 levels would shrink to 145 mi^2 around Keams Canyon. By 2052, simulated water levels throughout the area of confined conditions would be less than 30 ft lower for projection C than for projection A.

About 81 percent of the simulated withdrawals in projection C would be balanced by a decrease in storage (table 3). Streamflow and evapotranspiration rates would decrease 7 percent between 1985 and 2051 (fig. 10). Maximum leakage from the D aquifer would be 241 acre-ft in 2031, but it would remain a minor contributor of flow into the N aquifer.

Projection D.--Combining the proposed lease with increasing withdrawals for communities would put more stress on the aquifer than any other specified alternative. In 2032 under projection D, simulated water levels would be more than 100 ft below 1964 levels in an area of 1,660 mi^2 under Black Mesa (fig. 14). Simulated water levels in the coal-lease area would decline about 60 ft from 1985 through 2031. These declines would alter the head distribution such that by 2032 some of the water that would have flowed toward an area of discharge during equilibrium conditions (fig. 3) would be diverted toward the mine (fig 15). In the 20 years after mine pumping stops, water levels in the coal-lease area would rise as much as 300 ft. Near Oraibi, simulated water levels would decline more than 100 ft in an area of 260 mi^2 from 1985 through 2031 (fig. 16). By 2052, the area of 100-ft decline would increase to 390 mi^2 and declines of over 300 ft would occur in an area of 11 mi^2 (fig. 17).

From 1985 through 2031, withdrawals would be 419,000 acre-ft in projection D; the simulated decrease in storage would be 88 percent of the withdrawals (table 3). Simulated evapotranspiration would decrease 7 percent, and outflow to springs and streams would decrease 11 percent. Inflow from the D aquifer would increase to 261 acre-ft/yr (fig. 10). From 2032 through 2051, 81 percent of withdrawals would come from storage. Simulated evapotranspiration would decline 2 percent and flow to streams and springs would decline 4 percent. From 1965 through 2051, evapotranspiration would decline 12 percent, and flow to springs and streams would decrease 18 percent.

Projection E.--As a basis of comparison, the fifth alternative would eliminate all pumping at the mine and increase withdrawals by communities 2.5 percent per year. Water levels near the lease area would begin to rise immediately. Water levels would rise more than 100 ft above 1984 levels in an area of 208 mi^2 by 2007, but water levels in the lease



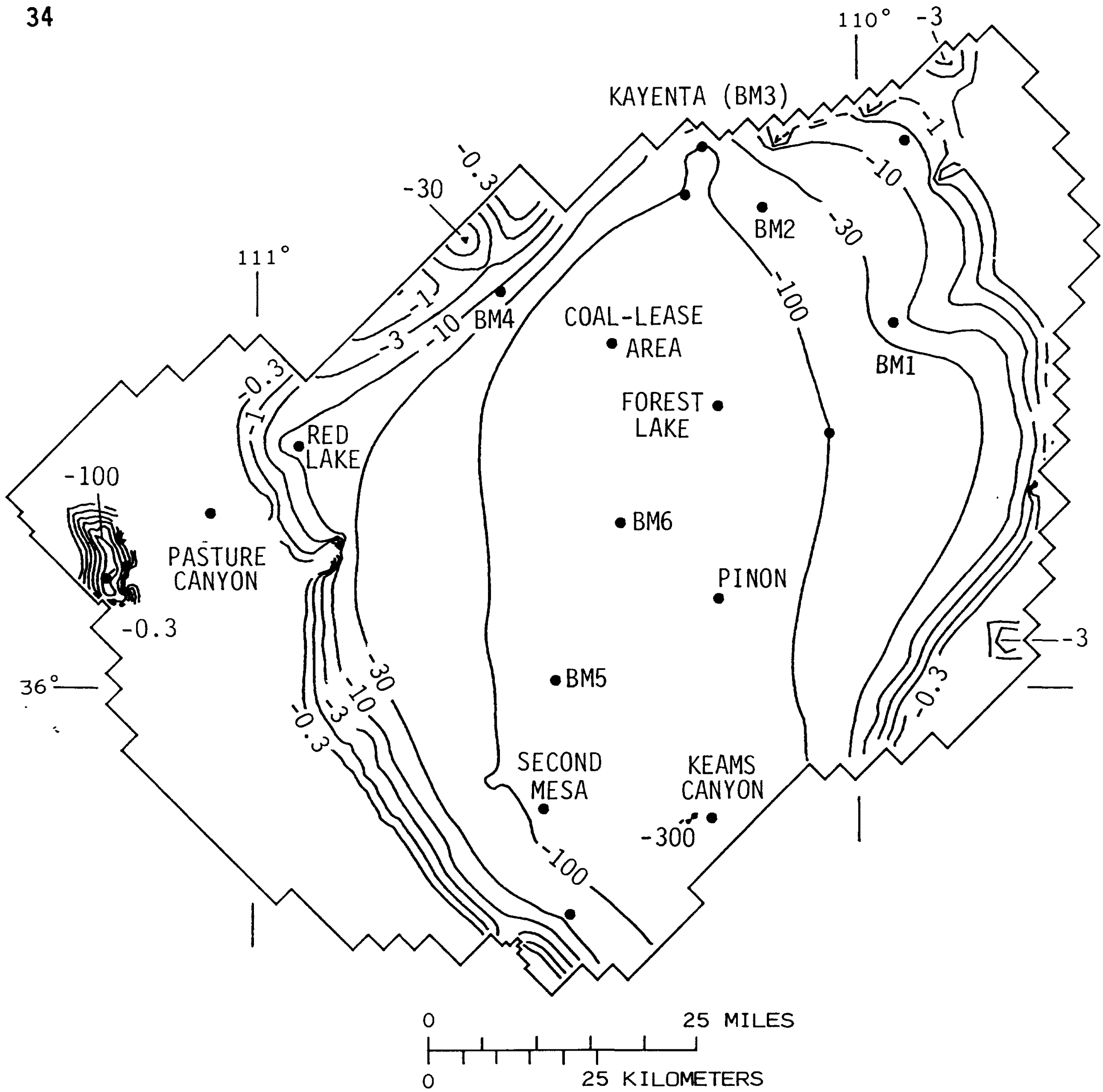
EXPLANATION

-30 — LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE—Interval, in feet, is variable. (Total simulated ground-water pumpage for 1985-2031 was 318,000 acre-feet)

• BM6 — NODE AT WHICH SIMULATED GROUND-WATER LEVELS ARE SHOWN ON HYDROGRAPH

——— BOUNDARY OF MATHEMATICAL MODEL

Figure 13.--Simulated water-level changes for projection C, 1985-2031.



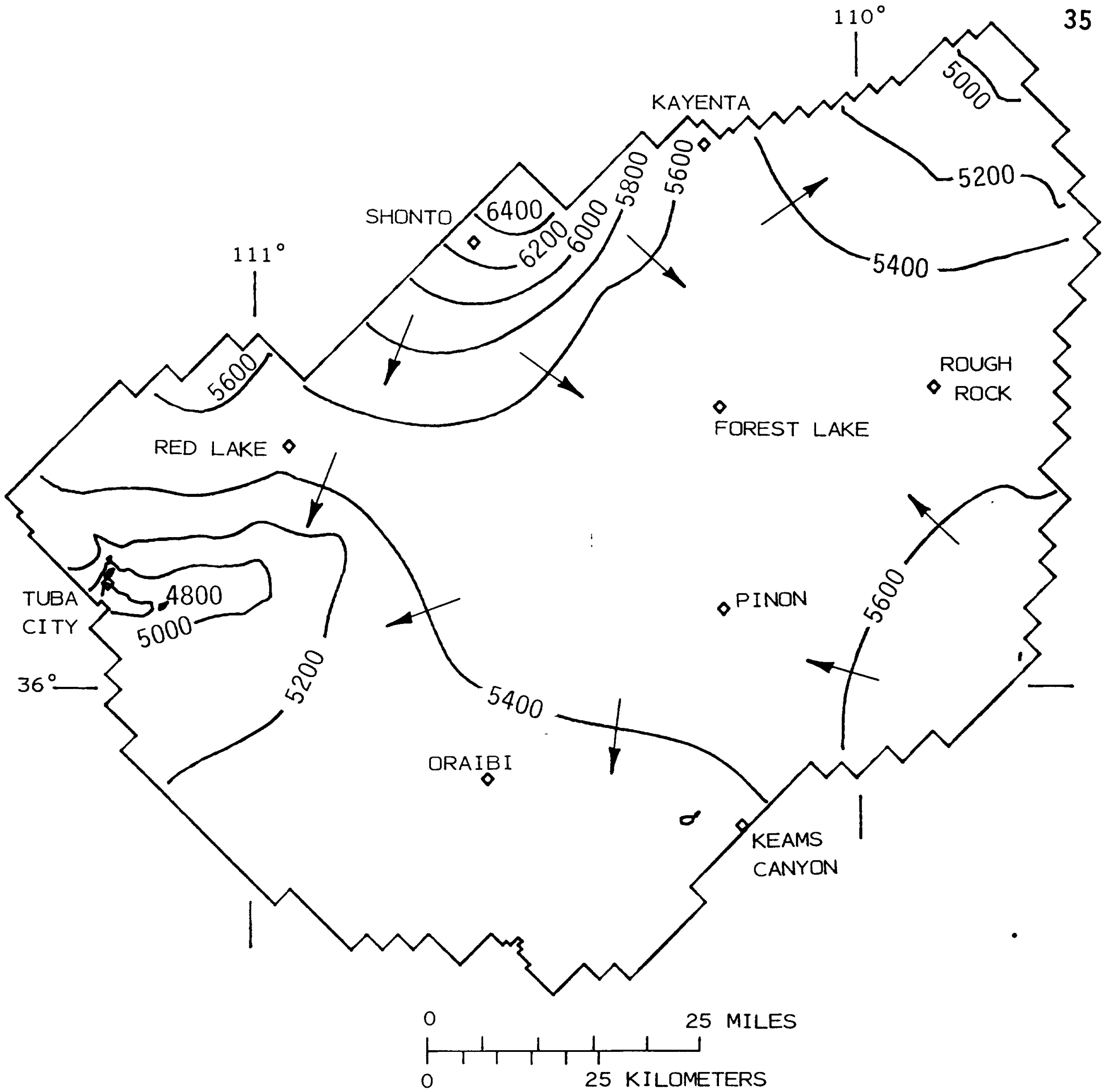
EXPLANATION

——— -30 ——— LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE—Interval, in feet, is variable. (Total simulated ground-water pumpage for 1965-2031 was 493,000 acre-feet)

•BM6 NODE AT WHICH SIMULATED GROUND-WATER LEVELS ARE SHOWN ON HYDROGRAPH

——————— BOUNDARY OF MATHEMATICAL MODEL

Figure 14.--Simulated water-level changes for projection D, 1965-2031.



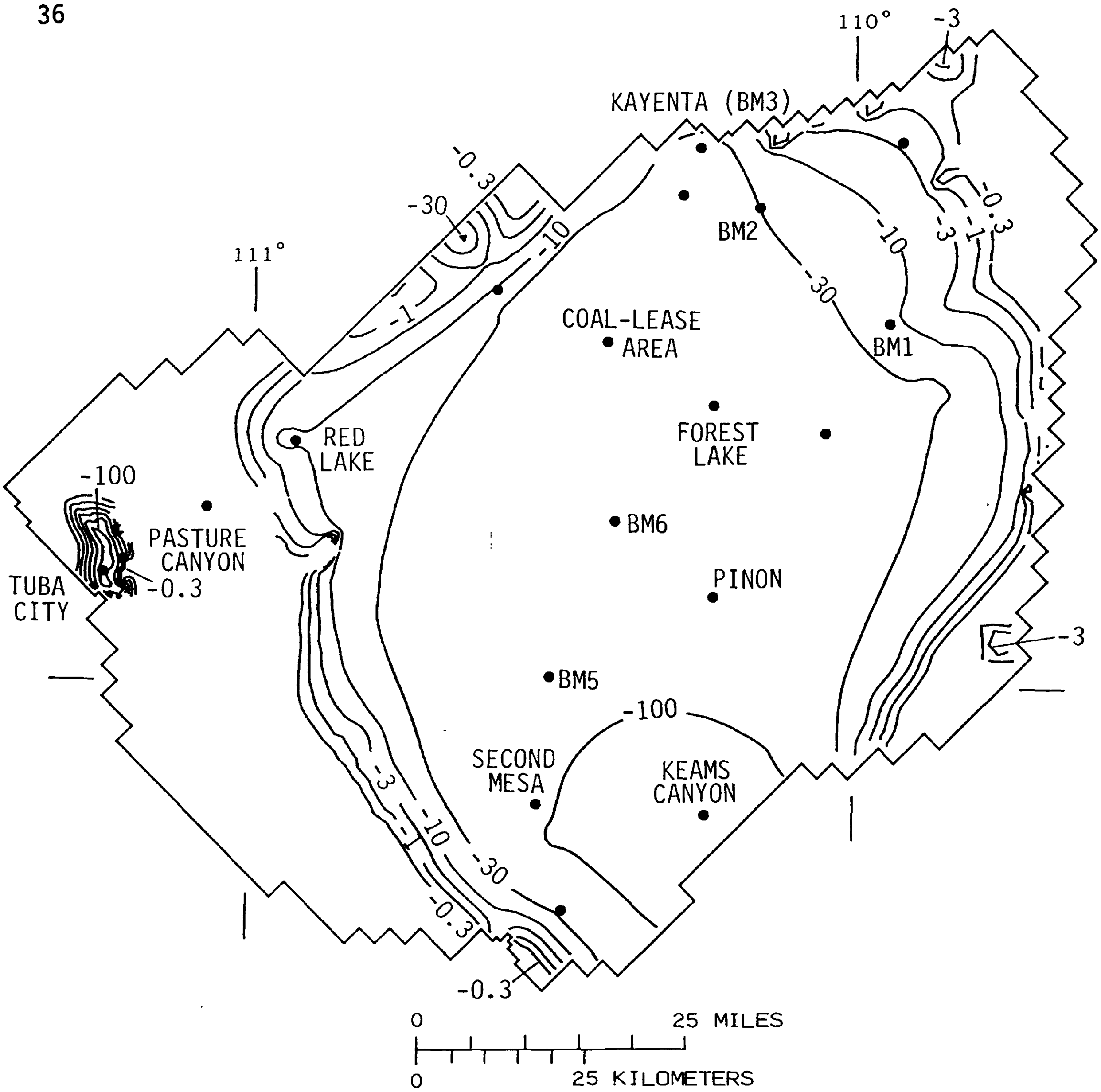
EXPLANATION

——5600—— LINE OF EQUAL SIMULATED WATER-LEVEL ALTITUDE—Contour interval 200 feet. Datum is sea level

⟶ GENERALIZED DIRECTION OF GROUND-WATER MOVEMENT

——— BOUNDARY OF MATHEMATICAL MODEL

Figure 15.--Simulated altitude of water levels for projection D, 2031.



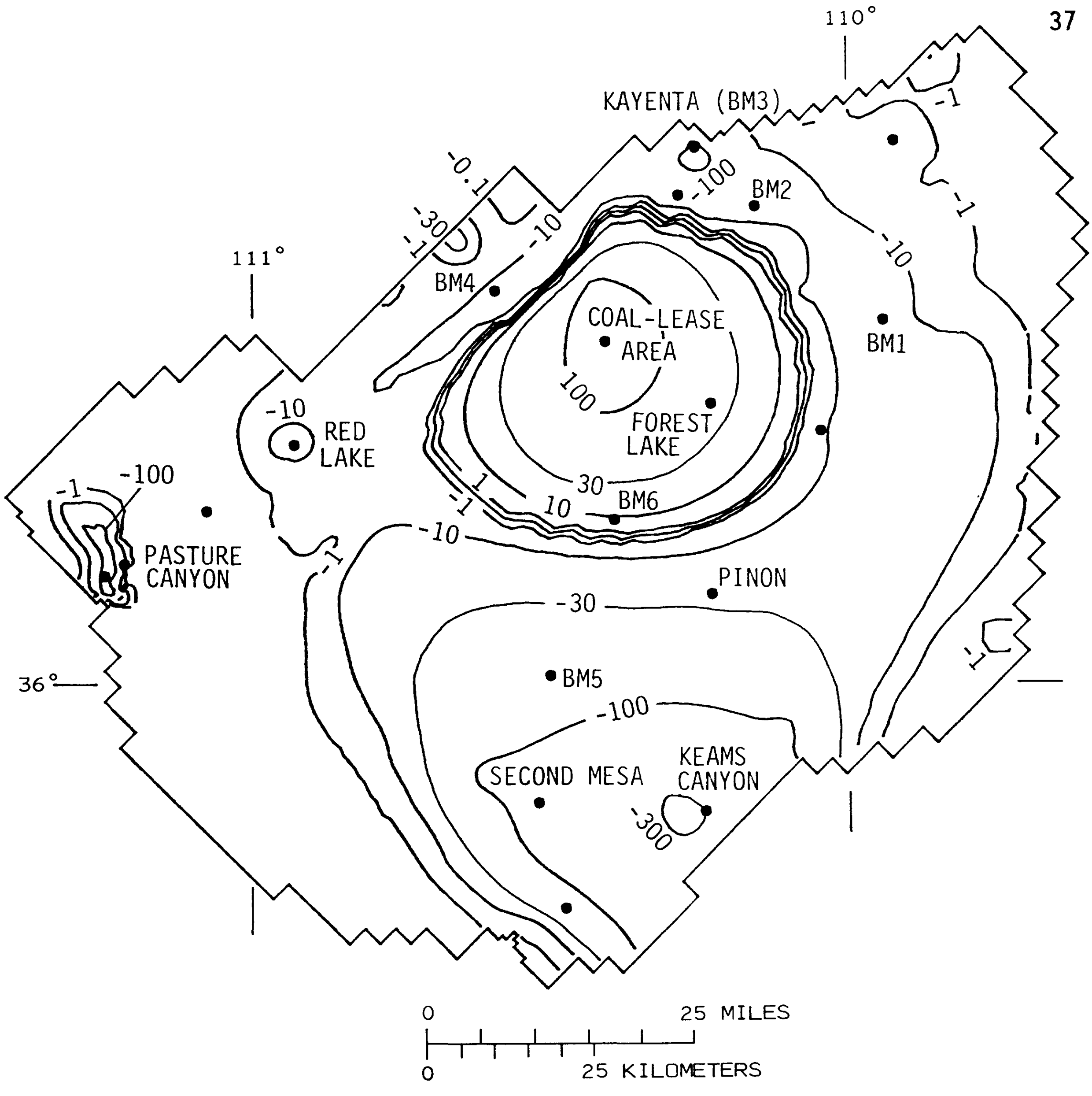
EXPLANATION

—— -30 —— LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE—Interval, in feet, is variable. (Total simulated ground-water pumpage for 1985-2031 was 419,000 acre-feet)

• BM6 NODE AT WHICH SIMULATED GROUND-WATER LEVELS ARE SHOWN ON HYDROGRAPH

———— BOUNDARY OF MATHEMATICAL MODEL

Figure 16.--Simulated water-level changes for projection D, 1985-2031.



EXPLANATION

——30—— LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE—Interval, in feet, is variable. (Total simulated ground-water pumpage for 1985-2051 was 616,000 acre-feet)

•BM6 NODE AT WHICH SIMULATED GROUND-WATER LEVELS ARE SHOWN ON HYDROGRAPH

———— BOUNDARY OF MATHEMATICAL MODEL

Figure 17.--Simulated water-level changes for projection D, 1985-2051.

area would begin to decline after 2019 as community pumping north and south of the mine increased. The area of 100-ft rise would decrease slightly to 199 mi^2 by 2032 and to 163 mi^2 by 2052 (fig. 18). Pumping for the Hopi communities would cause water-level declines from 1985 through 2051 to exceed 100 ft in an area of 306 mi^2. By 2052, water levels for projection E throughout most of the area of confined conditions would be less than 30 ft higher than for projection D in which withdrawals for the coal mine continue 47 years longer. North of the lease area, however, water levels for projection E will be more than 30 ft higher than in projection D in a area of 31 mi^2. Near Tuba City, however, projections B, D, and E are identical.

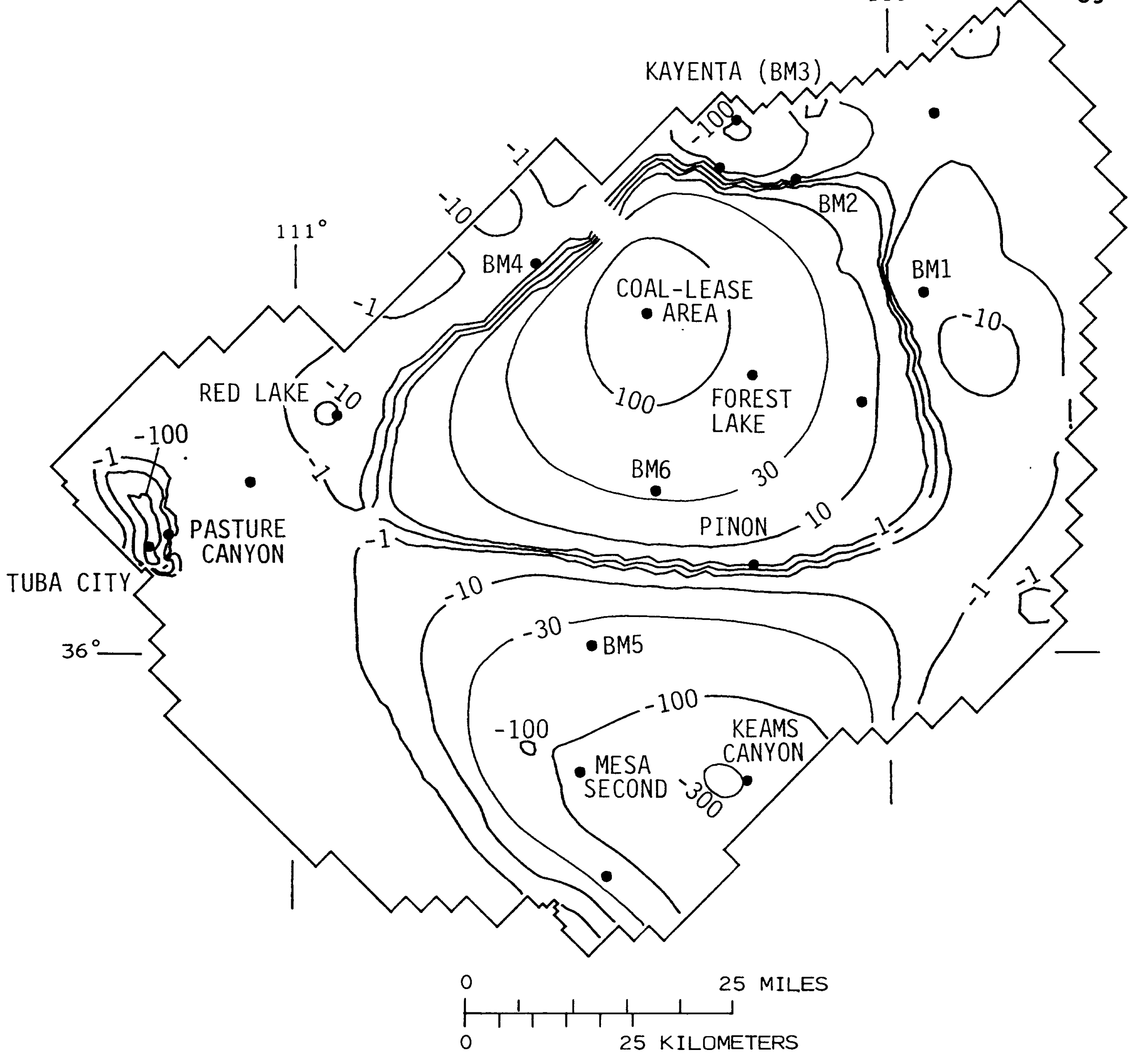
About 84 percent of simulated withdrawals for projection E would be balanced by a decrease in storage (table 3). Simulated outflows to streams and springs would decrease about 4 percent by 2007, another 5 percent by 2032, and 4 percent more by 2052 (fig. 10). Simulated evapotranspiration would decrease 1 percent by 2007, another 3 percent by 2032, and 3 percent more by 2052. Because of higher simulated heads under most of Black Mesa, inflow from the D aquifer would increase more slowly than under projections B and D and would reach 239 acre-ft in 2051.

Local Effects of Future Withdrawals

Simulation results may also be examined by comparing the water levels and budget components that would result from each projection in selected areas of the aquifer. The relative effects of mine and community pumping on water levels in different areas vary and are a function of pumping distribution and local hydrogeologic conditions.

Coal-lease area.--Pumping at the mine is the dominant factor influencing water levels near the coal-lease area (fig. 19). Within the lease area, more than 75 percent of the maximum decline simulated in any projection occurred before 1985. Differences in community pumping would change the simulated water levels less than 30 ft. Water-level declines from 1985 through 2031 under projection D, which has the greatest total withdrawal, would be about 60 ft.

Simulated water levels in the coal-lease area are characterized by a rapid recovery after mine withdrawals are stopped, regardless of whether community pumpage is constant or increasing. These recoveries are to be expected under confined conditions where water-level changes are the result of changes in pore pressure in the aquifer rather than filling or draining of pores, as is the case with unconfined conditions. In addition, the higher transmissivity of the N aquifer at the mine (fig. 5) and proximity to the recharge area at Shonto (fig. 4) contribute to rapid post-mining water-level recoveries. Under projection E, which includes only increasing community pumping, water levels would recover to within 50 ft of 1964 levels after just 6 years. For the other four projections, water levels would recover to within 100 ft of 1964 levels less than 10 years after mine withdrawals cease, and, in projections with constant community pumping, will recover to within 50 ft of simulated equilibrium



EXPLANATION

——— -30 ——— LINE OF EQUAL SIMULATED WATER-LEVEL CHANGE—Interval, in feet, is variable. (Total simulated ground-water pumpage for 1985-2051 was 409,000 acre-feet)

• BM6 NODE AT WHICH SIMULATED GROUND-WATER LEVELS ARE SHOWN ON HYDROGRAPH

——————— BOUNDARY OF MATHEMATICAL MODEL

Figure 18.--Simulated water-level changes for projection E, 1985-2051.

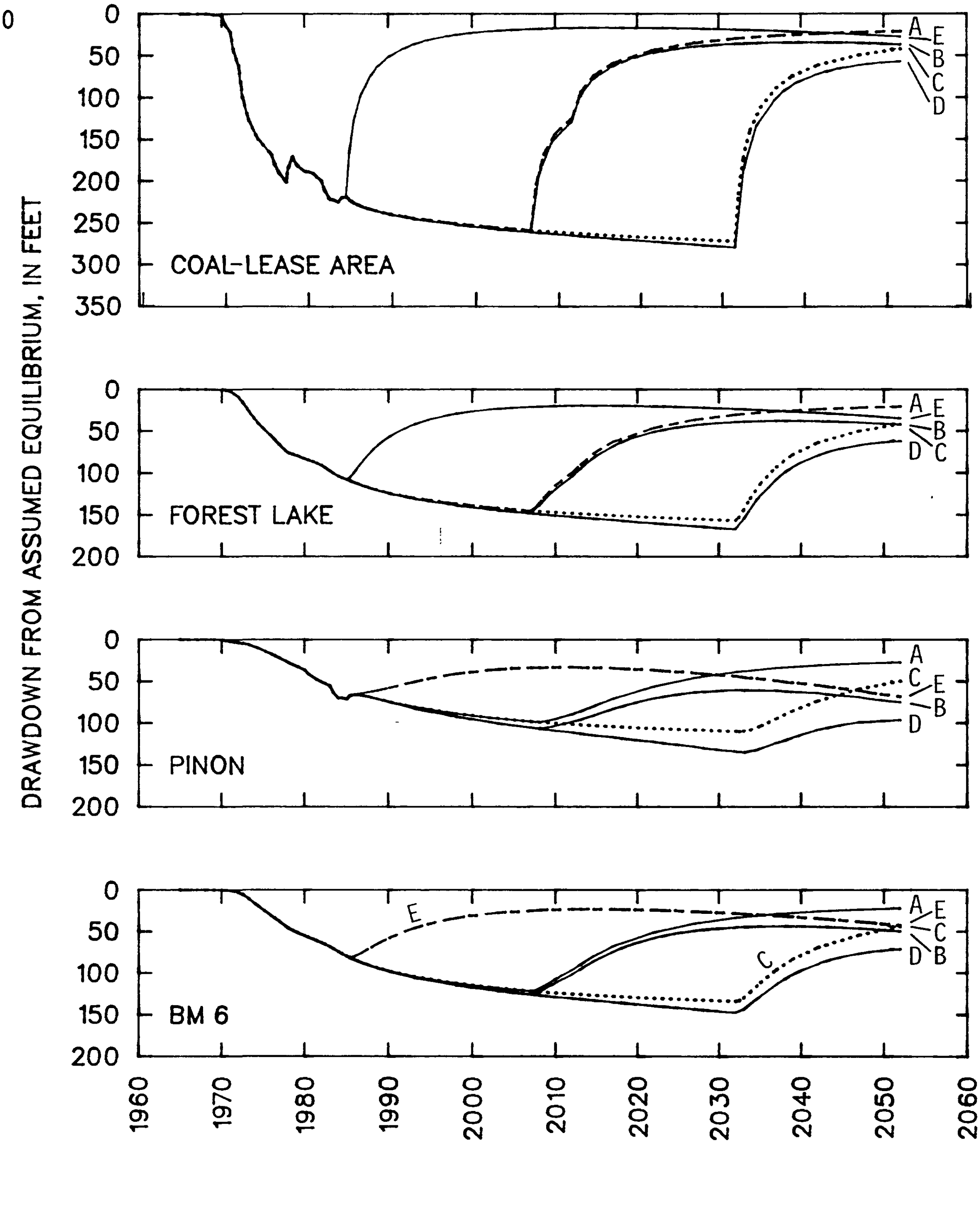


Figure 19.--Simulated water-level changes near the coal-lease area, 1965-2051, for projections A, B, C, D, and E.

water levels in less than 15 years. In projection B, increasing community pumping will cause water levels to begin declining again about 30 years after mine pumping ceases; in projection D, water levels will continue to rise through 2051.

Simulated drawdown from equilibrium is less at Forest Lake than in the lease area, but mine withdrawals remain the dominant factor (fig. 19). About half the maximum simulated decline in any projection occurred before the well at Forest Lake was completed in December 1980; the maximum simulated decline after 1980 is about 85 ft. Simulated decline during 1981-84 was 25 ft. Under projection A, the simulated water level would decline about 37 ft between 1985 and 2007; under projection C, extended mine pumping would add another 12 ft of decline. Increasing community pumpage would add 3 ft of decline through 2006 and about 11 ft through 2031. In every projection, the simulated water level at Forest Lake would rise above the 1980 level within 10 years after pumping at the mine ceases, and the level in 2052 would be more than 60 ft higher in projection A, which has the smallest total withdrawal. The simulated water level at Forest Lake would begin to decline again about 33 years after mine pumping stops in projections B and E.

Farther from the mine at Pinon and observation well BM6, water levels would be affected by pumping both at the mine and the Hopi communities. The effect of mine withdrawals can be seen by comparing projections B and D with projection E on figure 19. At Pinon, the simulated water level for projection E is as much as 72 ft higher than projection B and 90 ft higher than projection D. The simulated differences caused by mine withdrawals are larger at BM6, which is closer to the mine. Projections A and B, like C and D, differ in the amount of water withdrawn for communities, and simulated water-level differences are similar between each pair. The water level at Pinon in projection A would be 7 ft higher than in projection B in 2007, 22 ft higher in 2032, and 48 ft higher in 2052. The differences caused by increasing community pumpage would be smaller at BM6 because that site is more than 10 mi from any community well.

Kayenta area.--Simulated water-level changes near Kayenta are affected most by pumping at the community (fig. 20). Under projection E with no mine pumping after 1984, water-level declines would be 49 ft by 2007 and 86 ft by 2032. The present mine plan would add 9 ft of decline by 2007 and 5 ft of decline by 2032. The proposed mine plan would cause an additional 8 ft of decline through 2031, on the basis of a comparison of projections B and D. The maximum water-level decline from equilibrium in Kayenta would be 147 ft under projection D in 2051; 11 ft of this decline would be a result of pumping at the mine. In contrast, water levels for projections A and B, which differ only in the rate of pumping for communities, would differ by 14 ft in 2006 and 100 ft in 2051. Under projections A and C, water levels at Kayenta would rise less than 5 ft in the 20 years after withdrawals stop at the mine.

South and southeast of Kayenta simulated water levels are affected both by mine and community pumping (fig. 20). Water levels would rise after pumping stops at the mine but would decline again 10 to 20 years later if community pumping continued to increase.

In addition to water-level changes, which largely represent changes in the quantity of water in storage, withdrawals can reduce outflow from the N aquifer. Outflow from the aquifer includes winter base flow in streams. Total flow in a stream would be larger during periods of runoff from rainfall or snowmelt and could be smaller during hot periods when evapotranspiration is high. The flow of Laguna Creek is most affected because it is close to the pumping centers at Kayenta and the mine (fig. 21). As with simulated water-level changes at Kayenta, simulated outflow to Laguna Creek is affected most by community pumping. The difference between outflows under different pumping rates at Kayenta (projections A and B) is larger than under different pumping durations at the coal mine (projections D and E). Outflow to Laguna Creek would decrease about 21 percent from 1965 to 2052 under projection A and about 46 percent under projection D.

Tuba City area.--Simulated water-level changes near Tuba City are due entirely to local municipal pumping (fig. 22). Changes for nodes in Tuba City depend only on which alternative of withdrawal for the communities is represented. If pumpage for Tuba City and Moenkopi were static (projections A and C), the water level at Tuba City would decline about 125 ft from 1985 through 2051. If withdrawals increased 2.5 percent per year (projections B, D, and E), the decline would be about 19 ft greater. Declines in Pasture Canyon would not exceed 2 ft in any projection. As with outflow to the Pasture Canyon springs, however, reliable estimates of these water levels depend on the details of location and pumping rate for individual wells.

Simulated water levels do not change in any projection for a point midway between Tuba City and Red Lake (fig. 22). The wide band of the aquifer under unconfined conditions in that area prevents any effect of pumping near Black Mesa from reaching the Tuba City area. By 1985, the nearest point at which pumping at the mine caused simulated water levels to decline more than 1 ft was about 19 mi east of Tuba City (fig. 7). That distance would decrease to about 15 mi by 2052 under projection D, which includes the longest duration of pumping for the mine.

At Red Lake, simulated water levels would decline less than 17 ft in all projections (fig. 22). Red Lake is near the edge of the artesian part of the aquifer, and water levels there respond both to pumpage at the mine and for the community. Simulated water levels would be about 3 ft lower in 2031 under the proposed lease than under the present mining plan. The simulated decline of about 1 ft in 1985 resulted from pumpage at Red Lake that was not included in the 1983 model.

Simulated outflow from the N aquifer to Moenkopi Wash west of Black Mesa would decrease by 1 to 2 percent between 1965 and 2051 under the five projections (fig. 21). Community pumping would have slightly more effect on outflows to Moenkopi Wash than would varying the duration of pumping at the mine.

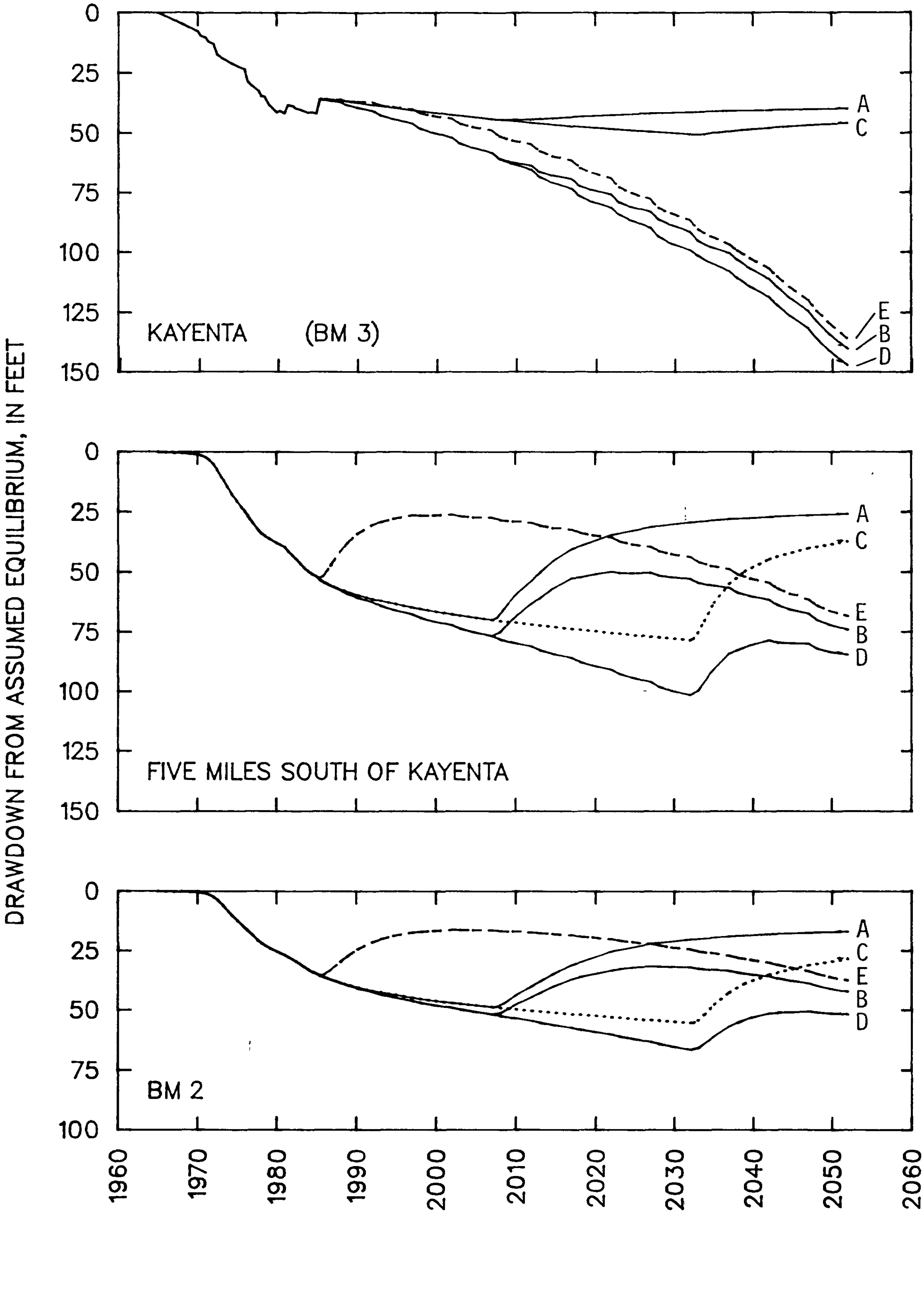


Figure 20.--Simulated water-level changes near Kayenta, 1965-2051, for projections A, B, C, D, and E.

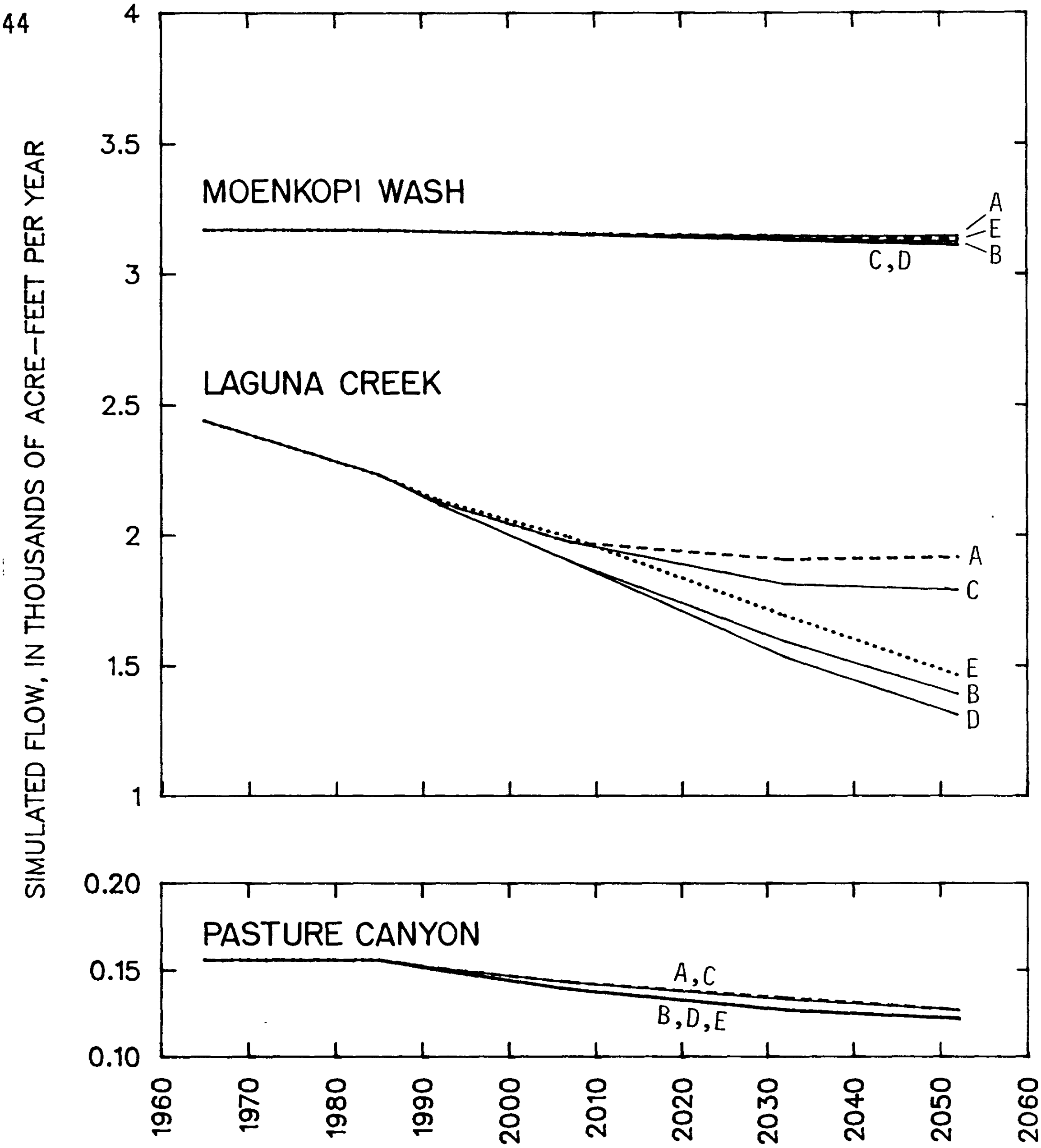


Figure 21.--Simulated discharge from the N aquifer to Moenkopi Wash, Laguna Creek, and Pasture Canyon, 1965-2051, for projections A, B, C, D, and E.

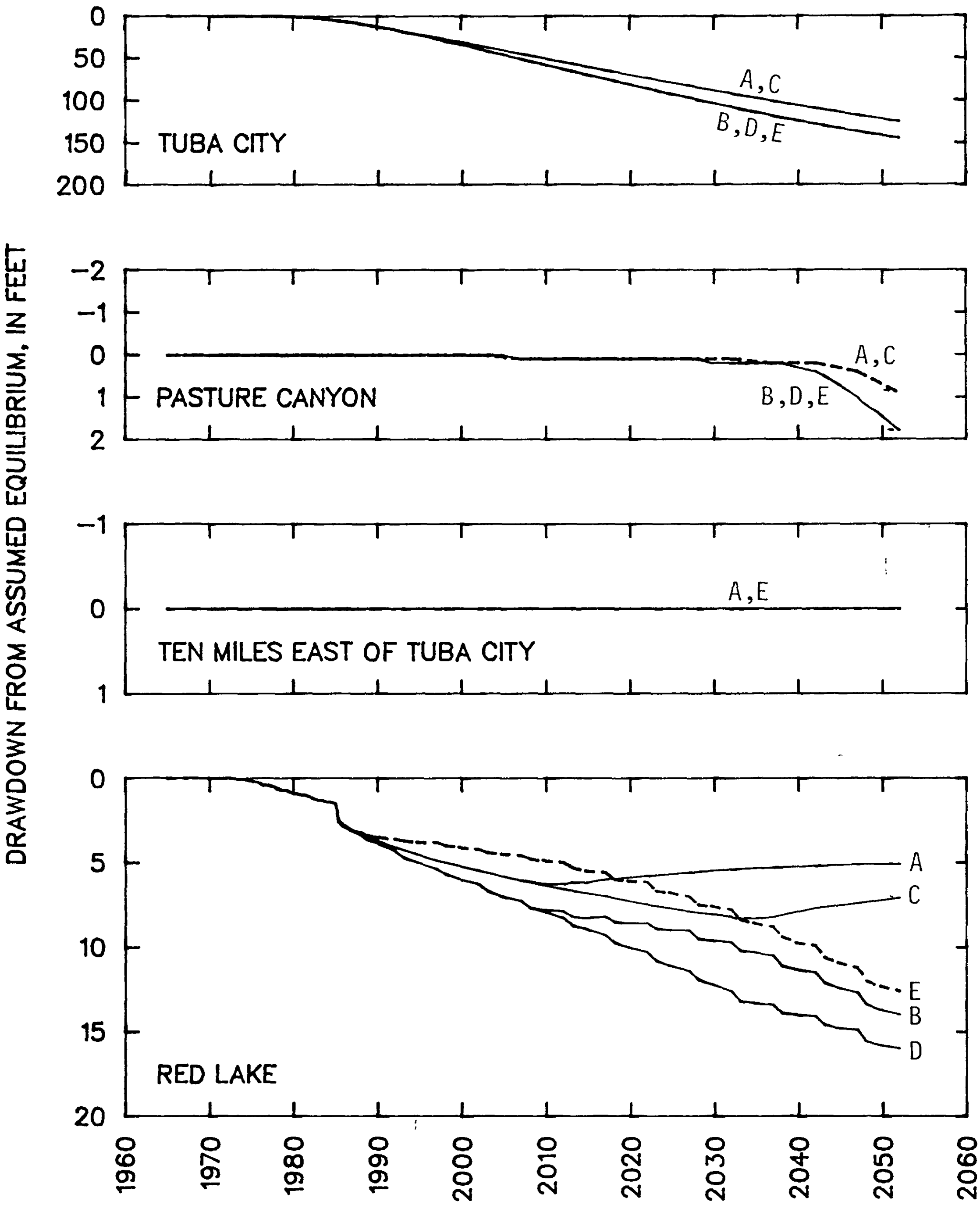


Figure 22.--Simulated water-level changes near Tuba City, 1965-2051, for projections A, B, C, D, and E.

Outflow from the aquifer to the springs in Pasture Canyon would decrease about 19 percent under projections A and C and about 22 percent under projections B, D, and E by 2052 (fig. 21). These numbers should be used with caution, however, because the model does not adequately represent important details of the local geology. The model uses a single layer of blocks to represent the N aquifer, even though the N aquifer as simulated in the Tuba City area includes 100 to 200 ft of interbedded sandstone and siltstone of the intertonguing and underlying Kayenta Formation. Reliable estimation of changes in flow of the Pasture Canyon springs would require detailed study and modeling of that local area.

Hopi area.--Near the Hopi communities, simulated water-level declines are caused largely by community pumping and to a lesser degree by pumping at the mine. The Hopi communities are more than 50 mi from the major source of recharge near Shonto (fig. 4). This, plus the fact that the N aquifer is relatively thin in this area (fig. 2) causes water levels to be sensitive to pumping. Simulated water-level declines would exceed 100 ft in an area of 95 mi^2 by 2032 and 300 mi^2 by 2052 under projection E. The proposed lease would increase this area by 170 mi^2 through 2031 and by 94 mi^2 through 2051.

At Keams Canyon, simulated water levels would decline about 55 ft under the proposed lease from 1985 to 2052 if community pumpage were constant and more than 300 ft if community withdrawals increased through time (fig. 23). At Second Mesa, simulated water levels would decline about 25 ft from 1985 to 2052 if community pumpage were constant and about 125 ft if it were increasing. On the basis of a comparison of projections D and E, pumping at the mine through 2031 would cause about 27 ft of the decline at Second Mesa and about 47 ft at Keams Canyon. Six miles south of Second Mesa, the relative impacts of mine and community pumpage are similar, although simulated water-level declines would not exceed 75 ft in any projection (fig. 23).

Simulated water levels in observation well BM5 are influenced by both mine and community pumping (fig. 23). The simulated water level declined 39 ft by 1985. The water level would decline 41 ft more by 2007 because of the mine before rising 49 ft by 2052 under the present mining plan if accompanied by constant community pumpage. The water level would be 49 ft lower in 2032 under the proposed lease than the present plan and 19 ft lower in 2052. The simulated water level would be 9 ft lower by 2007 if community withdrawals increase than if they remain constant and 57 ft lower by 2052.

Less-developed areas.--Simulated water levels at the margins of the area of confined conditions would decline 5 to 25 ft during the 67 years of each projection. The exact value would be governed largely by total withdrawals in the projection and by the distance to an area of unconfined conditions (fig. 24). Simulated water levels in observation well BM4, in a water-table area northwest of the mine, would be affected most by the duration of pumping at the mine. Observation well BM1 is in a small area of unconfined conditions largely surrounded by confined conditions, and simulated water-level declines would be larger. Water levels 20 mi east of Kayenta and about 35 mi from the mine would

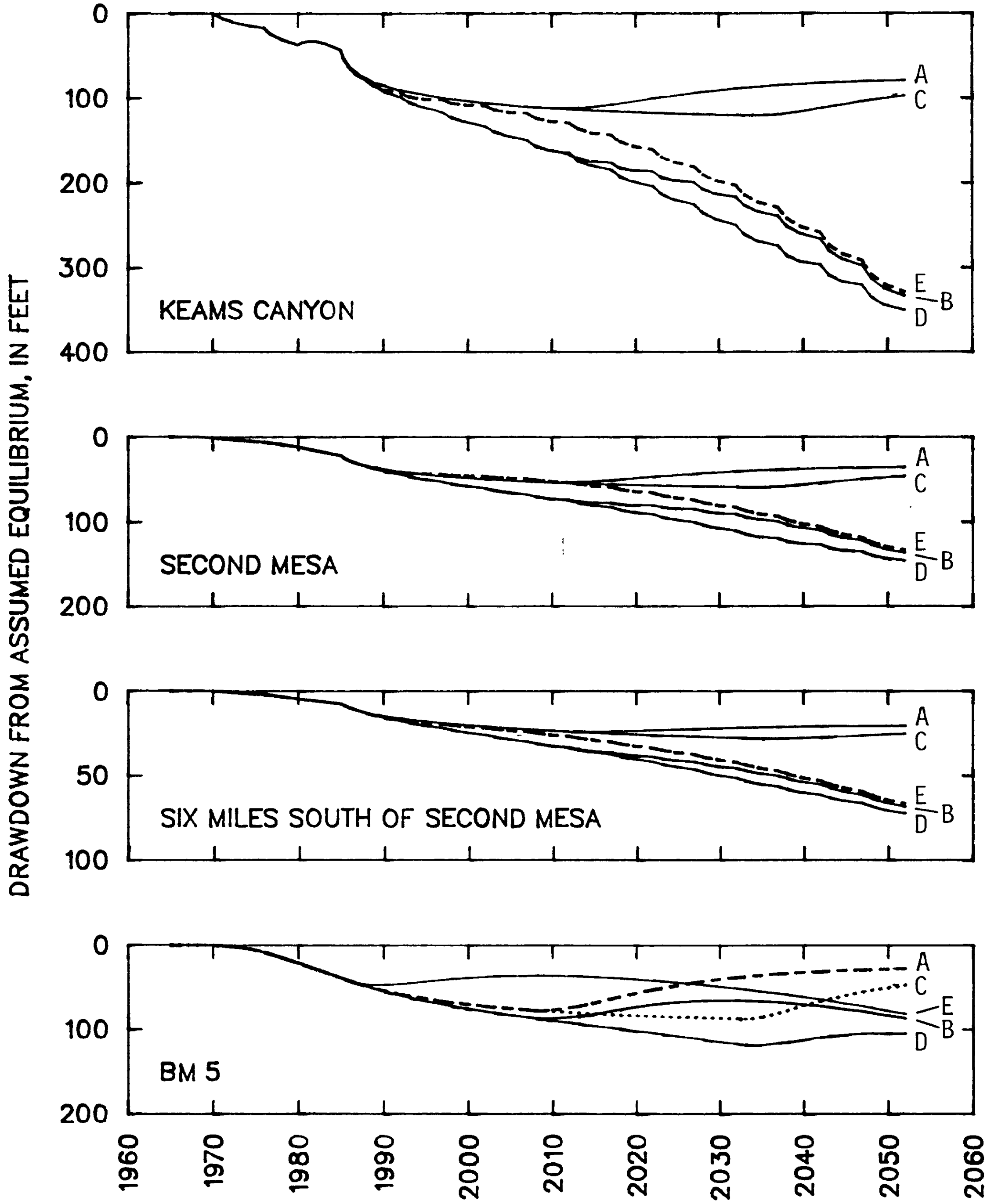


Figure 23.--Simulated water-level changes near the Hopi communities, 1965-2051, for projections A, B, C, D, and E.

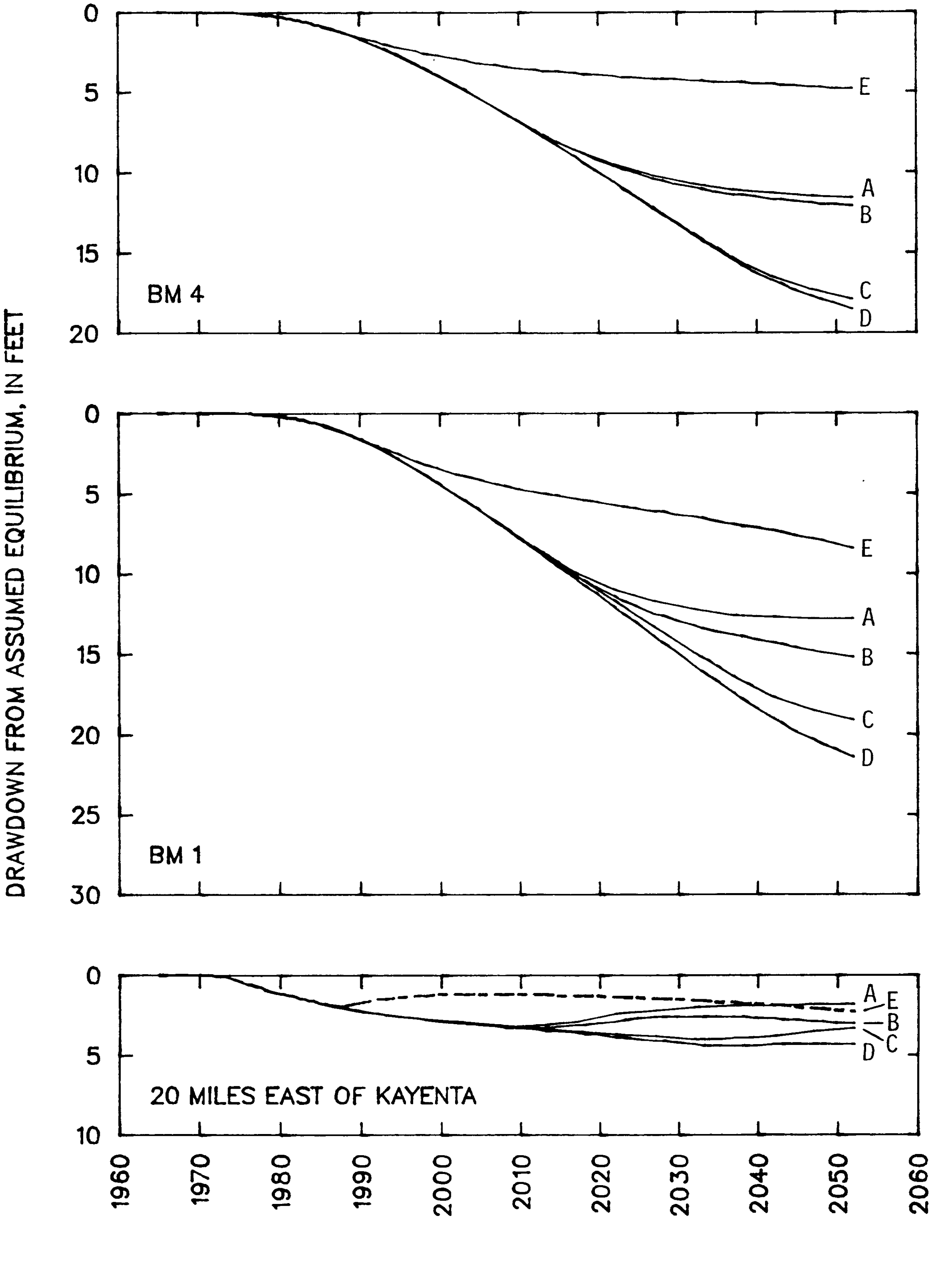


Figure 24.--Simulated water-level changes at the margins of confined conditions, 1965-2051, for projections A, B, C, D, and E.

decline slowly by a maximum of 5 ft. Simulated water levels would change little or not at all in areas of unconfined conditions more than about 5 mi from the area of confined conditions or a large community.

SUMMARY AND CONCLUSIONS

Increasing withdrawal of water from the N aquifer in the Black Mesa area since 1972 has caused water levels in some wells to decline. The aquifer is exposed on the surface in about 1,400 mi^2 near the boundaries of the 5,400 mi^2 study area, and saturated thickness is as much as 1,050 ft. Water in the N aquifer is under confined conditions in an area of 3,400 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. In the area of confined conditions, water-level changes reflect changes in pore pressure rather than drainage of the pores themselves. In previous studies, annual recharge to the aquifer was estimated to be about 13,000 acre-ft. At least 180 million acre-ft of water is in storage. The aquifer discharges mainly along Moenkopi Wash and Laguna Creek.

Withdrawals from the N aquifer were less than 100 acre-ft/yr in 1965 and increased to a maximum of 7,100 acre-ft/yr in 1983. A coal company, which operates a coal mine on Black Mesa and supplies a coal-slurry pipeline, withdrew an average of 4,060 acre-ft/yr from 1981 through 1986. The company has applied for a permit to mine through 2011 and proposed a new lease that would extend its withdrawals through 2031. As part of the evaluation of the permit application, the U.S. Geological Survey, in cooperation with OSMRE, simulated the effects of planned and potential future withdrawals from the aquifer.

A mathematical model of the N aquifer developed by Eychaner (1983) was converted to a newer model program and a finer spatial grid and recalibrated using revised estimates of aquifer parameters. The 1988 model simulated water levels during equilibrium—before 1965—and measured changes from 1965 through 1984 with reasonable accuracy. Ground-water pumpage totaling 74,000 acre-ft during this period caused observed water levels to decline steadily in the area of confined conditions. In areas of unconfined flow, declines exceeding 1 ft occurred mainly within 5 mi of pumping centers. Simulated declines exceeded 100 ft by 1985 in an area of 310 mi^2. Simulated water levels had about one chance in ten of being more than 50 ft different from actual levels before 1965, and the accuracy of projected water levels is uncertain. Future withdrawals that greatly exceed the amounts withdrawn through 1984 may cause unanticipated responses in the aquifer. Long-term projections that include large increases in pumpage should be used with caution.

Five projections of water-level changes in the N aquifer from 1985 through 2051 in response to hypothetical pumping rates were made. Four of the projections represent withdrawals under the existing mining plan and proposed lease in combination with pumpage for the Indian communities that either remains constant or increases by 2.5 percent per year. The fifth projection terminates pumpage for the mine immediately to provide a basis for comparison.

The maximum simulated water-level decline in the coal-lease area would be about 60 ft greater than the 1985 level. The maximum decline for the proposed mining plan would be about 30 ft more than for the present plan. Simulated water levels in all projections would rise to within 100 ft of 1964 levels in less than 10 years after mine withdrawals cease.

About half the maximum simulated decline from the 1964 level at Forest Lake occurred before the well was completed in December 1980. The maximum simulated decline after 1985 would be about 60 ft for the proposed lease combined with increasing community withdrawals. Maximum declines under the present plan would be about 12 ft less. In every projection, the simulated water level would rise above the 1980 level within 10 years after pumpage for the mine ceases.

Simulated water levels at Kayenta would be 11 ft lower in 2051 following implementation of the proposed lease than if the mine ceased pumping in 1985. Most of the simulated decline at Kayenta is due to pumpage for the community.

Simulated water levels near Tuba City and simulated outflow to springs in Pasture Canyon have not been and would not be affected by pumping at the mine. Increasing withdrawals for the local community would cause simulated declines of about 144 ft at Tuba City and about 2 ft at Pasture Canyon from 1985 through 2051. These numbers should be used with caution, however, because the model does not adequately represent important details of the local geology.

Near the Hopi communities, water-level declines are largely controlled by community pumpage. At Keams Canyon, maximum declines of more than 300 ft would occur between 1985 and 2052 by increasing community pumpage even if the mine were shut down in 1985. Pumping at the mine would cause about 47 ft of additional decline through 2031. Water levels near the Hopi communities are particularly sensitive to pumping rates because less ground water moved through that area before 1965 than in other parts of the aquifer. Increasing community withdrawals would cause 100 ft of simulated decline over an area of 300 mi^2; proposed mine pumpage would increase this area by 94 mi^2.

Simulated water levels at the margins of the area of confined conditions would decline 5 to 25 ft during the 67 years of each projection, with the exact value governed largely by total withdrawals in the projection and by the distance to an area of unconfined conditions. In areas of unconfined conditions more than about 5 mi from the area of confined conditions or a large community, simulated water levels would not change.

Although the results of this study should be reliable within the limits stated earlier, it is clear that more accurate simulation of present and future water levels and flow components in the N aquifer requires more than simply adding nodes to the grid. A more accurate simulation of ground water within the Navajo and Hopi Indian Reservations might be possible by using two levels of models. A general model could represent the entire N aquifer plus the overlying D aquifer to provide boundary conditions for detailed models of small parts of the aquifer that have particular problems. A better model would also require field investigations of geology, water levels, natural discharge, and withdrawals, because accurate data are the necessary basis for accurate modeling.

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