Projected water-level declines in the Ogallala aquifer in Lea County, New Mexico

By Douglas P. McAda

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CONVERSION FACTORS

Figures for measurements in this report are given in inch-pound units only. The following table contains factors for converting to metric units.

Multiply inch-pound units	By	To obtain metric units
foot	0.3048	meter
foot per day	0.3048	meter per day
foot squared per day	0.09290	meter squared per day
cubic foot	0.02832	cubic meter
cubic foot per second	0.02832	cubic meter per second
foot per mile	0.1894	meter per kilometer
inch	25.40	millimeter
inch per year	25.40	millimeter per year
mile	1.609	kilometer
square mile	2.590	square kilometer
acre	0.4047	hectare
acre-foot	0.001233	cubic hectometer
acre-foot per year	0.001233	cubic hectometer per year

PROJECTED WATER-LEVEL DECLINES IN THE OGALLALA AQUIFER IN LEA COUNTY, NEW MEXICO

BY DOUGLAS P. McADA

ABSTRACT

A two-dimensional digital ground-water flow model was constructed of the Ogallala aquifer in Lea County, New Mexico. Simulations of predevelopment steady-state and historical pumping conditions were used to adjust the model. Projections of water-level declines were made based on the condition of no additional development and the condition of a 0.44 percent annual increase in irrigation withdrawals to 1990 and a 0.88 percent annual increase in nonirrigation withdrawals to 2020. Based on no additional development, projected maximum water-level declines from 1980 were 31 feet in 2000 and 59 feet in 2020. The amount of recoverable water remaining in the aquifer as simulated by the model was 24.6 million acre-feet in 2000 and 22.4 million acre-feet in 2020, compared to an estimated 28 million acre-feet in 1980. With increased withdrawals, projected maximum declines were 33 feet in 2000 and 67 feet in 2020. As simulated by the model, 24.4 million acre-feet of recoverable water remained in 2000 and 21.8 million acre-feet remained in 2020.

The sensitivity of the model to variations in hydraulic conductivity, specific yield, and recharge was tested over their ranges of uncertainty. Projected water-level declines were most sensitive to specific yield. In response to changes in specific yield, declines varied by as much as 6.2 feet from the standard simulation to 2020 with no additional development.

INTRODUCTION

Water users on the High Plains in Lea County, New Mexico, rely primarily on the underlying Ogallala aquifer for their water supply. Irrigated agriculture supports most of the area's economy and uses the largest amount of water. All other uses, including industrial, municipal, and domestic, account for only about 30 percent of the total ground-water withdrawal.

Irrigation development in Lea County increased rapidly in the first decade after the Second World War. Withdrawal of ground water since that time has caused water levels in the aquifer to decline, significantly reducing saturated thickness in some areas. With continued ground-water withdrawal, the saturated thickness of the aquifer may be reduced to the point that it will become uneconomical for large quantities of water to be pumped for irrigation.

Purpose and Scope

Declining water levels in the Ogallala aquifer in Lea County, New Mexico, have caused increasing concern regarding the availability of ground water and the future of irrigated agriculture in the area. This study was done in cooperation with the New Mexico State Engineer Office to provide information to help planners and water users determine how much water is available for their use. The specific objectives of the study are to estimate the present quantity of water in the Ogallala aquifer in Lea County and to project future water-level declines based on anticipated water use.

A two-dimensional digital model (Trescott, Pinder, and Larson, 1976) was used to simulate the Ogallala aquifer in Lea County. Simulations of predevelopment conditions and the 1970 to 1973 historical pumping period were used to adjust the aquifer characteristics, within predetermined plausible ranges, in order to fit the model to the measured water levels. A third simulation, from 1970 to 1980, was used to check how the model would fit another set of measured water levels without adjusting the aquifer characteristics. Four projections of water-level declines from 1980 to the years 2000 and 2020 were made based on current withdrawal rates and projected increased withdrawal rates.

Location of the Study Area

The model described in this report covers approximately 2,400 square miles of the Southern High Plains in southeastern New Mexico (fig. 1). The area of interest covers most of the Lea County Underground Water Basin (New Mexico State Engineer, 1966) and includes the northern part of Lea County and small parts of Chaves and Eddy Counties. The area is bounded by the Mescalero Ridge escarpment on the west and south, the Texas State line on the east, and extends as far as the Roosevelt County line on the north.

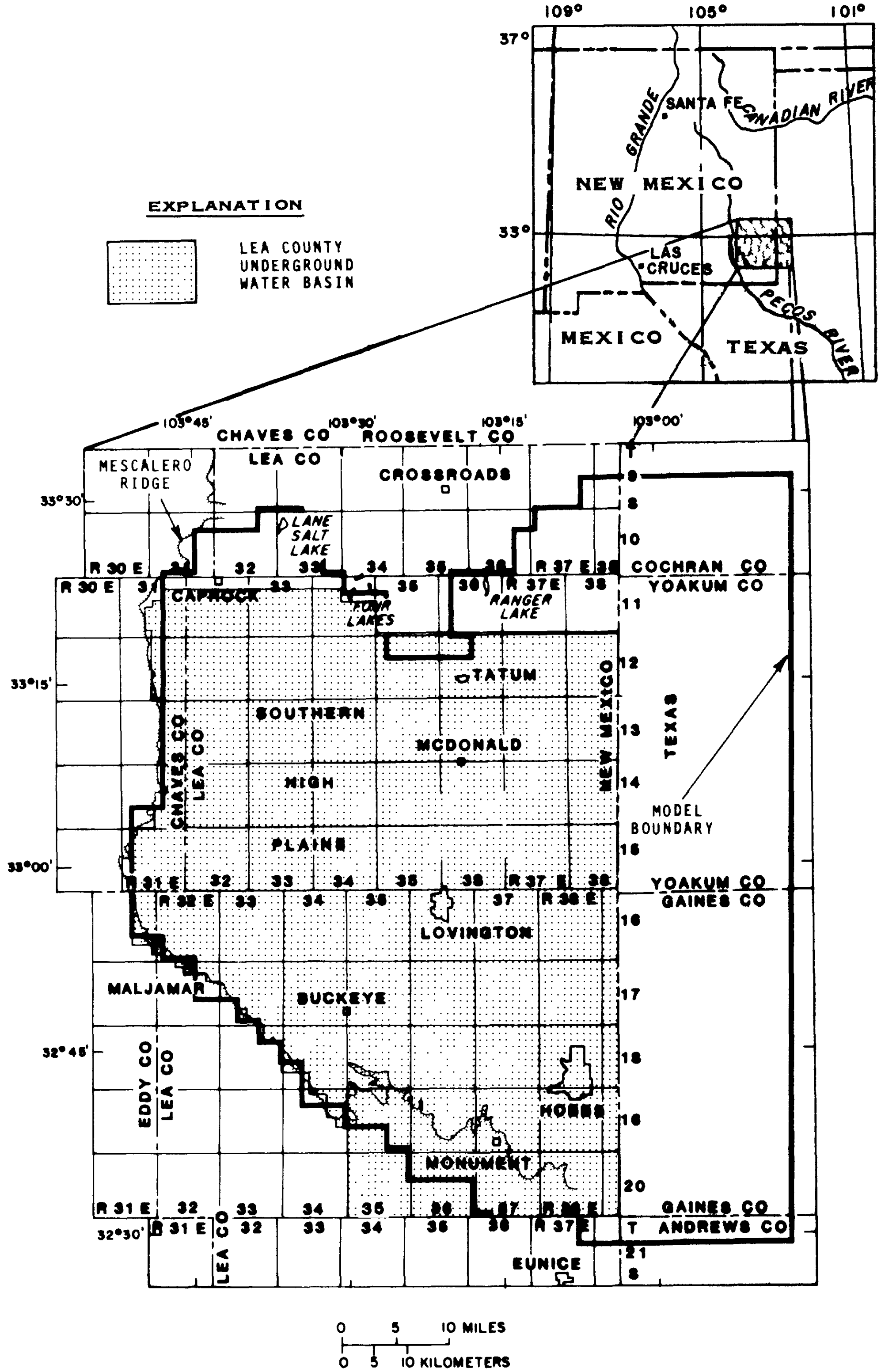


Figure 1.--Location of the modeled area.

General Geology

The Ogallala Formation of late Tertiary age is the principal aquifer of the High Plains in Lea County and is the focus of this report. Detailed descriptions of geology in the area have been reported in previous studies (Nye, 1930; Nicholson and Clebsch, 1961; Ash, 1963; Havens, 1966; Cronin, 1969).

The Ogallala Formation crops out over most of the High Plains area. It unconformably overlies the pre-Ogallala erosional surface developed on Cretaceous and Triassic rocks. The Ogallala Formation is erosionally truncated against the underlying Cretaceous and Triassic rocks in the northern and western part of Lea County and increases in thickness to about 350 feet along parts of the Mescalero Ridge (Ash, 1963). Variations in thickness are primarily due to irregularities in the pre-Ogallala erosional surface (Nye, 1930). The High Plains surface is relatively flat and slopes about 10 to 15 feet per mile to the east-southeast.

Ogallala sediments are primarily unconsolidated sand, silt, clay, and gravel. Sediments near the top of the formation are cemented by calcium carbonate to form a caliche cap rock that extends over most of the area. Cementation also is present within the formation but generally decreases with depth (Nye, 1932). Cementation becomes negligible at depths greater than 35 to 50 feet below the surface (Ash, 1963).

Quaternary alluvial deposits present in the southern part of the area near Monument are hydraulically connected to the Ogallala Formation (Nicholson and Clebsch, 1961). The alluvial sediments are primarily sand, silt, and clay. For the purpose of this report these deposits are included as part of the Ogallala aquifer.

Well-Numbering System

The system of numbering wells in this report is based on the common subdivisions in sectionized land. The well number, in addition to designating the well, locates it to the nearest 10-acre tract in the land net (fig. 2).

The well number consists of four parts separated by periods. The first part is the township number, the second part is the range number, and the third part is the section number. Since all the township blocks within Lea County are south of the base line and east of the principal meridian, the letters, S and E, indicating direction are omitted as well as the letter T for township and R for range. Hence, the number 14.35.25 is assigned to any well located in sec. 25, T. 14 S., R. 35 E.

The fourth part of the number consists of three digits which denote the particular 10-acre tract within the section in which the well is located. The method of numbering the tracts within a section is shown in figure 2. For this purpose the section is divided into four quarters, numbered 1, 2, 3, and 4, in the normal reading order, for the northwest, northeast, southwest, and southeast quarters, respectively. The first digit of the fourth part gives the quarter section, which is a tract of 160 acres. Each quarter is subdivided in the same manner so that the first and second digit together define the 40-acre tract. Finally, the 40-acre tract is divided into four 10-acre tracts, and the third digit denotes the 10-acre tract. Thus, well 14.35.25.241 in Lea County is located in the NW¼ of the SE¼ of the NE¼ of section 25, T. 14 S., R. 35 E.

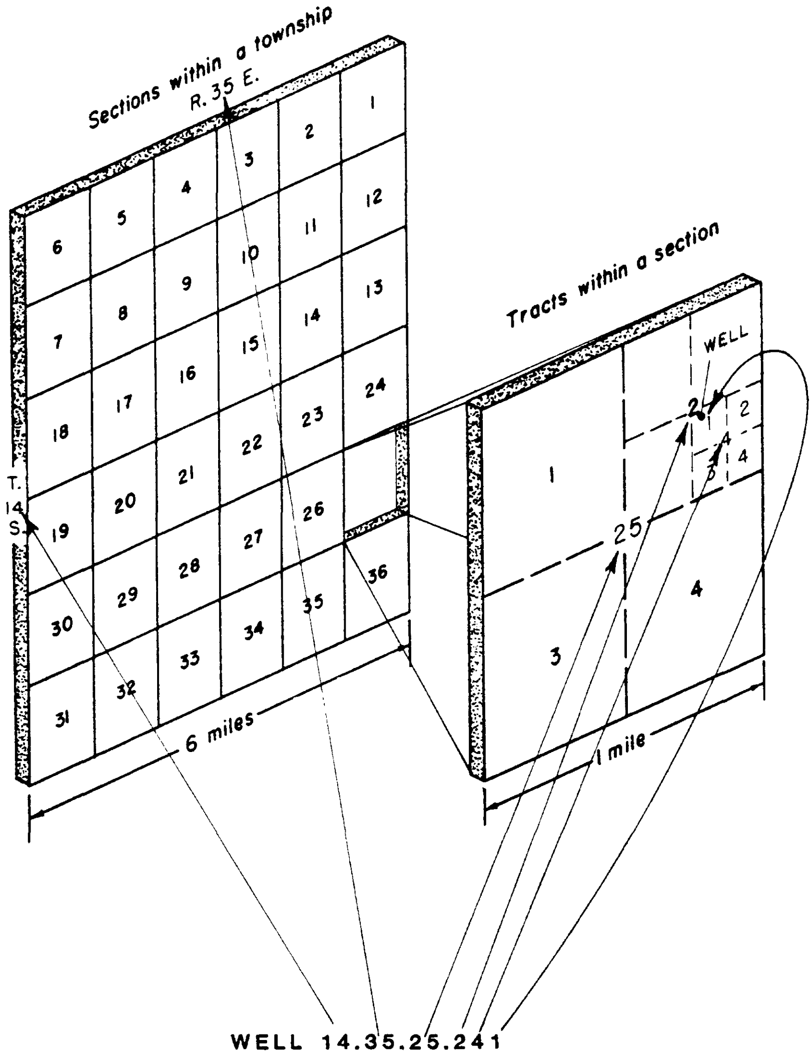


Figure 2.--System of numbering wells in New Mexico.

If a well cannot be located accurately within a 10-acre tract, a zero is used as the third digit of the fourth part of the well number, and if it cannot be located accurately within a 40-acre tract, zeros are used for both the second and third digits of the fourth part of the well number. If the well cannot be located more closely than the section, the fourth part of the well number is omitted.

Acknowledgments

This study was done in cooperation with the New Mexico State Engineer Office (SEO). The author wishes to thank Dale Berning, SEO Lea County Basin Supervisor, and Earl Sorensen, Chief of the SEO Data Acquisition Section, for providing pumpage data.

HYDROLOGY

Surface Water

Six perennial lakes are near the northern boundary of the modeled area (fig. 1). Lane Salt Lake is in T. 10 S., R. 33 E.; Four Lakes is a group of four small lakes in T. 11 S., R. 34 E.; and Ranger Lake is in T. 11 S., R. 36 E. All six lakes receive inflow from ground water and surface runoff (Ash, 1963).

Numerous shallow, closed depressions scattered over the area collect runoff during periods of heavy rain. Most of the water in these depressions infiltrates or is lost by evaporation within a few months, although a few depressions may contain water throughout the year.

In the western part of the area, where the depressions are most common, surface runoff drains to these depressions. To the east, however, depressions become less common and the predominant surface drainage is southeastward along shallow swales. There are no perennial streams in the area.

Ground-Water System

The Ogallala aquifer is unconfined in Lea County. The water table slopes about 12 feet per mile to the southeast. Depth to water ranges from less than 20 feet in the area of Four Lakes east of Caprock and near Monument, to more than 250 feet along Mescalero Ridge in T. 15 S., R. 31 E. Saturated thickness is minimal in the northern and western part of the area and increases to more than 200 feet in parts of the east-central section. Variation in saturated thickness occurs locally due to irregularities in the underlying bedrock surface.

Recharge to the aquifer occurs from precipitation falling on the High Plains surface. Most of the precipitation is lost by evapotranspiration, but a small amount percolates to the water table.

Discharge from the Ogallala aquifer in Lea County occurs through pumpage and subsurface flow. The general direction of ground-water flow in the aquifer is southeastward. The largest amount of natural ground-water discharge is the subsurface flow moving into Texas. A small amount of the ground water discharges through the Quaternary alluvium to the southern part of Lea County (Nicholson and Clebsch, 1961, p. 59).

Some of the ground water discharges through springs and seeps. Springs have been reported along Mescalero Ridge and near Monument (Ash, 1963; Nicholson and Clebsch, 1961; Theis, 1939). Springs also discharge into the perennial lakes at the north edge of the study area (Ash, 1963).

Relatively little ground water is lost by evapotranspiration. Some ground water discharged to the six perennial lakes is lost to evaporation. Native vegetation near the lakes and near springs and seeps where the water table is near the surface contribute to transpiration losses.

The Cretaceous and Triassic rocks underlying the aquifer form a relatively impermeable barrier that restricts the downward movement of ground water (Havens, 1966, p. 17). Therefore, a negligible amount of ground water is lost by leakage to underlying formations.

The amount of water stored in the Ogallala aquifer in Lea County can be estimated from the equation:

$$V = Apb$$

where

V is the amount of water in storage;
A is the surface area;
p is the average porosity of the aquifer; and
b is the average saturated thickness.

An average porosity of 35 percent was assumed for the aquifer materials (Theis, 1934, p. 133). The study area covers about 1,500,000 acres, and the average saturated thickness in 1980 was about 92 feet. On the basis of these assumptions, the total quantity of ground water stored in the Ogallala aquifer in Lea County was about 48 million acre-feet in 1980.

Not all the water stored in the aquifer is recoverable. Some water will remain in the formation, held by capillary forces after that part of the formation is drained by gravity. Based on an average specific yield of 0.20, an estimated 28 million acre-feet of water is theoretically recoverable from the aquifer if the saturated part was drained by gravity. However, in practice total drainage is not attainable.

MODEL DESCRIPTION

With certain assumptions, the movement of ground water may be expressed by differential equations (Pinder and Bredehoeft, 1968). Solving these differential equations analytically is rarely possible because of the complexity of hydrologic boundaries and the heterogeneity and anisotropy of aquifer materials. A digital ground-water flow model is used to solve the ground-water flow equations numerically with the aid of a computer. The model is a tool that may be used to help understand an aquifer system and to predict the response of an aquifer to certain stresses. Because of the assumptions and simplifications made during the formulation and solution of the mathematical equations, the model is only an approximation and simulated results should be interpreted carefully.

Model Development

Ground-water flow in the Ogallala aquifer in Lea County was assumed to be in two dimensions. The vertical component of flow was assumed to be negligible. By assuming the Cartesian coordinate axes, x and y, are aligned with principle components of hydraulic conductivity, ground-water flow in a water-table aquifer may be expressed by the following equation (Trescott, Pinder, and Larson, 1976, p. 2):

$$\frac{\partial}{\partial x}\left(K_x b \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y b \frac{\partial h}{\partial y}\right) = Sy \frac{\partial h}{\partial t} + W(x,y,t)$$

where

K_x, K_y are the hydraulic conductivities in the x and y directions (LT^{-1});
b is the saturated thickness of the aquifer (L);
h is the hydraulic head, or water-level altitude (L);
Sy is the specific yield of the aquifer (dimensionless);
W is the volume of water recharged or withdrawn per unit surface area of the aquifer per unit time (LT^{-1}); and
t is time (T).

The above two-dimensional flow equation can be approximated by replacing the derivatives with finite differences. The modeled area is divided into rectangular blocks. Aquifer properties in each block are assumed to be uniform. The hydraulic heads in the model are assumed to be at the center of each block (node). For a model with N blocks, N simultaneous equations are formulated with the hydraulic heads as unknowns. The finite-difference equations may then be solved simultaneously with the aid of a digital computer. The computer program used for this study was developed by Trescott, Pinder, and Larson (1976). The strongly implicit procedure was used as the algorithm to solve the finite-difference equations.

The modeled area was divided into a series of blocks with the rows oriented east-west and columns oriented north-south (fig. 3). In the majority of the study area, the blocks are 2 miles on a side. Near the margins and utside the study area the block size progressively increases by a factor of 1.5 to minimize computation cost by reducing the total number of blocks. Aquifer properties and initial values of water-level altitude were assigned to each block as model input.

The model is not intended to be used to simulate water levels at particular well sites. Given the size of the blocks, the simulated results can at best represent an average condition over the area of a block; therefore, simulated water levels may differ from those at actual well locations.

Boundary Conditions

Aquifer boundaries can be represented in the model in three ways: constant head, constant flux, or head-dependent flux. At a constant-head boundary, the hydraulic head is maintained at a specified level. At a constant-flux boundary, water is added or extracted independent of hydraulic head. A no-flow boundary is a specific constant-flux boundary where no water is added or extracted. Head-dependent-flux boundaries lose or gain water as a function of hydraulic head. The lateral boundaries used in this model are shown in figure 3.

An increase in altitude of subsurface Triassic-age rocks occurs at the western edge of the aquifer along Mescalero Ridge, causing the aquifer to be unsaturated. This is represented in the model by a no-flow boundary.

Unlike the relatively impermeable material that generally forms the lower boundary of the Ogallala aquifer in Lea County, the Cretaceous rocks to the north of the modeled area contain a larger amount of more permeable material, thus, allowing movement of ground water between the Cretaceous rocks and the Ogallala aquifer (Cooper, 1960, p. 12; Cronin, 1969, p. 4; Ash, 1963). At the north-central boundary of the model, from T. 10 S., R. 32 E. to T. 11 S., R. 36 E., the combined effects of discharge to the six perennial lakes and leakage to and from the Cretaceous rocks where the Ogallala Formation becomes unsaturated are represented by a constant-flux boundary. The flux rates were estimated based on hydraulic gradients and lake evaporation rates and were modified during the model calibration process. The resulting flow rates at the constant-flux boundary are shown in table 1. In the area near Ranger Lake, the Ogallala aquifer gains water from the Cretaceous rocks to the west and northwest. In addition, Cretaceous rocks crop out on the west side of Ranger Lake (Conover and Akin, 1942, p. 286), which may supply water directly to the lake. These gains may compensate for evaporation from the lake, giving a net positive flow to the Ogallala aquifer in that area.

The northern boundary to the east of T. 11 S., R. 36 E. is represented as a no-flow boundary. In that area, ground-water flow is generally parallel to the contact where the saturated Ogallala material is truncated against Cretaceous rocks (Cronin, 1969).

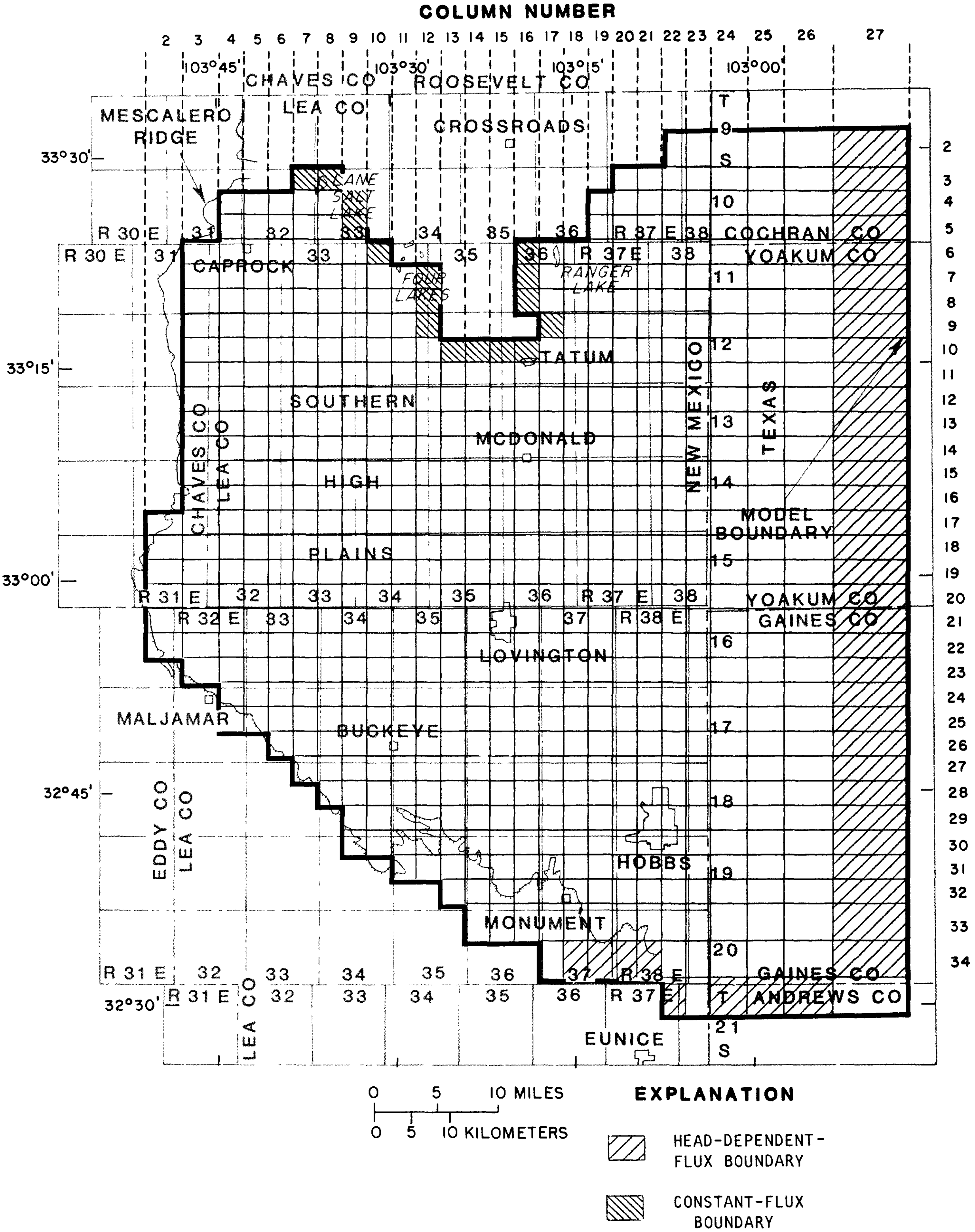


Figure 3.--Grid orientation and boundary conditions represented in the model.

Table 1. Constant-flux boundaries represented in the model

Location		Flow to (+) or from (-) aquifer, in cubic feet per second
Row	Column	
3	7	-0.2
3	8	- .2
4	9	- .3
5	9	- .3
6	10	- .3
7	12	- .3
8	12	- .3
9	12	- .3
10	13	.1
10	14	.1
10	15	.1
10	16	.1
6	16	.2
7	16	.2
8	16	.3
9	17	.2

It was impractical to extend the model to the physical boundary of the Ogallala aquifer to the east and southeast in Texas; therefore, an artificial boundary was used. The boundary was extended far enough so the effect of the boundary would be negligible in the area of interest, Lea County. The eastern model boundary is 17 miles east of the New Mexico-Texas State line (fig. 3). The effect of the boundary was tested by comparing simulated water levels of three transient simulations of the period 1970 to 1980, each using different boundary conditions. No-flow, constant-head, and head-dependent-flux boundaries were used. The greatest difference in simulated water levels at the model boundary in Texas among any of the three simulations was 15.6 feet at node 26, 27 (row 26, column 27). The greatest difference along column 24, 16 miles away from the model boundary, was 0.1 foot. All three simulations showed differences in simulated water levels of less than 0.1 foot in Lea County. Therefore, it was concluded that the artificial boundary would have an insignificant effect in the area of interest during the model projections. Head-dependent-flux boundaries were used in the model simulations to allow a decrease in discharge as water levels decline in the model projections.

In addition to lateral boundaries, upper and lower boundaries of the Ogallala aquifer must be defined. A negligible amount of leakage occurs between the Ogallala and the relatively impermeable material comprising the underlying formations. This boundary is modeled as having no flow. Recharge and evapotranspiration occur at the upper boundary of the Ogallala. These topics are discussed later in this report.

Aquifer Characteristics

Hydraulic conductivity and specific yield must be estimated for each model block. These characteristics vary spatially over the modeled area. The initial estimates of these characteristics were made using available data. If the simulated water levels differed from the measured water levels, the aquifer characteristics were modified within a plausible range by a trial and error procedure. The error associated with the model in relation to the uncertainty of the aquifer characteristics is addressed in the section on model sensitivity.

Hydraulic Conductivity

The ability of an aquifer to transmit water is described by hydraulic conductivity or transmissivity. The hydraulic conductivity is the volume of water that will flow through a unit area of an aquifer under a unit hydraulic gradient in unit time. Transmissivity is the hydraulic conductivity multiplied by the saturated thickness of the aquifer.

Transmissivity can be determined by conducting aquifer tests using wells that are open to the entire saturated thickness of an aquifer. An average hydraulic conductivity can then be calculated by dividing the determined transmissivity by the saturated thickness of the aquifer. Several aquifer tests have been conducted in the Southern High Plains of New Mexico and Texas. Theis (1934) calculated hydraulic conductivity to be 41 to 48 feet per day based on data from a test conducted near Hobbs by Nye (1932). Aquifer tests conducted near Amarillo, Texas, indicate values of between 21 and 25 feet per day (Moulder and Frazor, 1957). Cronin and Wells (1960) conducted a long-term aquifer test near Plainview, Texas, and estimated hydraulic conductivity to be between 13 and 23 feet per day. Hydraulic conductivity values in the Ogallala aquifer in the Southern High Plains of Texas of more than 200 feet per day were reported by Myers (1969).

The hydraulic conductivity of Ogallala sediments collected in and near Lea County by Theis (1934) was determined in the laboratory. Values ranged from 2 to 17 feet per day and averaged 8 feet per day.

Laboratory analysis of a recompacted sand sample from a Lovington well resulted in a hydraulic conductivity of 13 feet per day (Havens, 1966). Havens (1966) concluded that 43 feet per day is a reasonable estimate for the average hydraulic conductivity in the Ogallala aquifer in Lea County.

These site-specific values of hydraulic conductivity range from 2 to more than 200 feet per day. The plausible range of hydraulic conductivity in the model was assumed to be from 10 to 170 feet per day.

A method of estimating hydraulic conductivity from drillers' logs was used to obtain values to extrapolate over the modeled area. The method calculates a vertically weighted average by assigning hydraulic conductivity values to each saturated interval based on the lithologic descriptions (Lappala, 1978, p. 68). The values assigned to each interval were from a table reported by Lappala (1978, p. 70-71). Only logs from wells drilled through the entire formation were used in the determinations.

The distribution of hydraulic conductivity used in the model is shown in figure 4. The average hydraulic conductivity in the model for Lea County is 40 feet per day.

Specific Yield

In an unconfined aquifer, specific yield is the relative change in the volume of water in storage resulting from a change in water level. It is defined as the volume of water that will drain by gravity per unit surface area of the aquifer per unit decline in hydraulic head.

Values of specific yield for the Ogallala aquifer in the Southern High Plains of Texas have been calculated from aquifer tests. Moulder and Frazor (1957) obtained values of 0.09 to 0.16 from tests conducted near Amarillo, Texas. Values of 0.11 to 0.14 were obtained from aquifer tests conducted near Plainview, Texas (Cronin and Wells, 1960).

Laboratory determinations of specific yield have been made from Ogallala sediments collected in the Southern High Plains. Barnes and others (1949) determined the average specific yield of eight recompacted samples of Ogallala sand to be 0.29. They concluded that the specific yield of the undisturbed aquifer material would probably be between 0.15 and 0.20. Havens (1966) reported the specific yield of a recompacted sand sample from a Lovington well to be 0.38. The specific yield of samples collected in and near Lea County by Theis (1934) averaged 0.28 (Havens, 1966).

Alexander, Broadhurst, and White (1943) estimated specific yield for the areas near Plainview and Hereford, Texas, by dividing the net amount of water pumped from 1938 to 1943 by the volume of sediments dewatered. They found the specific yield to be between 0.14 and 0.15. By the same method Havens (1966, p. 24) calculated the average specific yield in Lea County to be 0.24 based on the period 1930 to 1955.

Site-specific values of specific yield ranged from 0.09 to more than 0.30. The plausible range of average specific yield in the model was assumed to be 0.10 to 0.28. The same weighted-average method discussed previously was used to estimate average specific yield from drillers' logs, based on values of specific yield summarized by Johnson (1967). These values were extrapolated over the modeled area.

The distribution of specific yield used in the model is shown in figure 5. The average specific yield in the model for Lea County is 0.20.

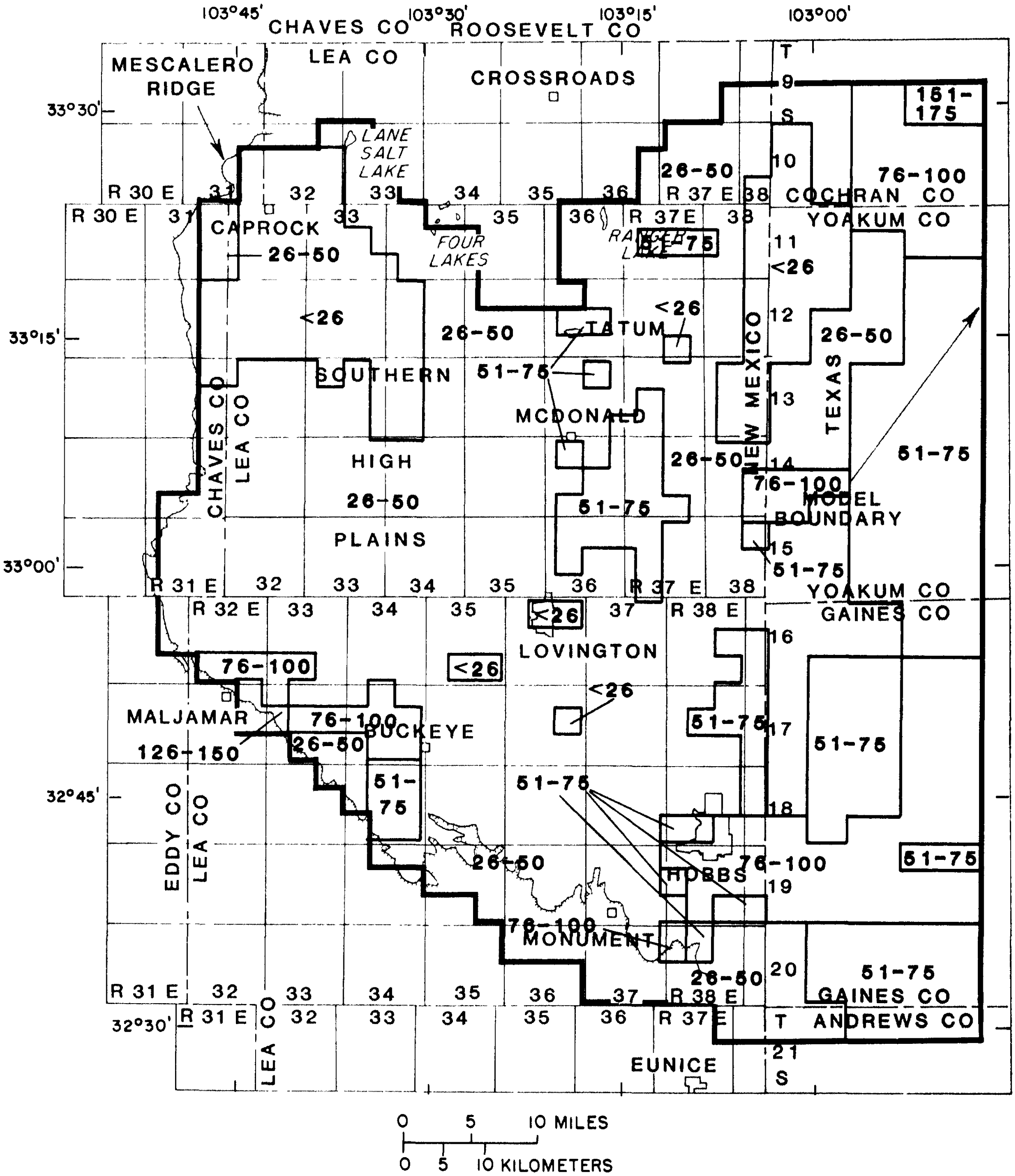


Figure 4.--Distribution of hydraulic conductivity in the model, in feet per day.

Recharge

Several investigators have estimated the amount of recharge to the Ogallala aquifer in the Southern High Plains in New Mexico and Texas (Theis, 1934 and 1937; White and others, 1946; Cronin, 1961; Havens, 1966). These estimates indicate the average recharge to be on the order of ¼ to ½ inch per year. This is considered to be the plausible range of areal recharge in the model.

The actual amount of recharge varies yearly due to variation in precipitation. No effort was made to vary the annual amount of recharge to the model. It was assumed that over a simulation period the average recharge would tend towards the long-term average.

A preliminary model using an equal amount of recharge over the entire area was rejected because the simulated water levels did not match the measured water levels. The problem could not be resolved by modifying the aquifer characteristics or by varying the average recharge rates.

Recharge is probably not uniform over the area. Downward movement of water is restricted by caliche underlying the surface. Percolation of water to the water table can occur where the caliche is fractured, soft, or absent. Absence or thinning of caliche has been observed in several of the closed depressions (Havens, 1966). Ash (1963) considers the most recharge to occur in areas where the depressions are most numerous and in areas covered by dune sand where rapid downward percolation of water can occur. Relatively little area on the High Plains in Lea County is covered by dune sand; however, a fairly large area is covered by depressions (Hunt, 1977). Havens (1966) outlines the area where depressions are most prevalent. By increasing recharge over this area, the contradiction between simulated and measured water levels was resolved. The distribution of annual recharge used in the model is shown in figure 6.

Evapotranspiration

In the area near Monument, the water table is close enough to the land surface in some places for water to be lost from the aquifer by evapotranspiration. To simulate this condition in the model, the evapotranspiration rate is assumed to be a linear function of the depth of the water table below land surface. At land surface, evapotranspiration attains a maximum rate. Below land surface, evapotranspiration was assumed to decrease linearly to a value of zero at 20 feet below land surface.

Average annual evaporation from shallow reservoirs is about 72 inches in the modeled area (Hale, Reiland, and Beverage, 1965). Evapotranspiration by crops is estimated to be on the order of 60 to 80 percent of evaporation from a free-water surface (Gray, 1973, p. 3.52). A smaller amount of water would probably be lost from natural vegetation. On the basis of the above discussion, 18 inches per year, one-fourth the average annual evaporation from a shallow reservoir, was used as the maximum evapotranspiration rate. This value produced reasonable model results and water budgets.

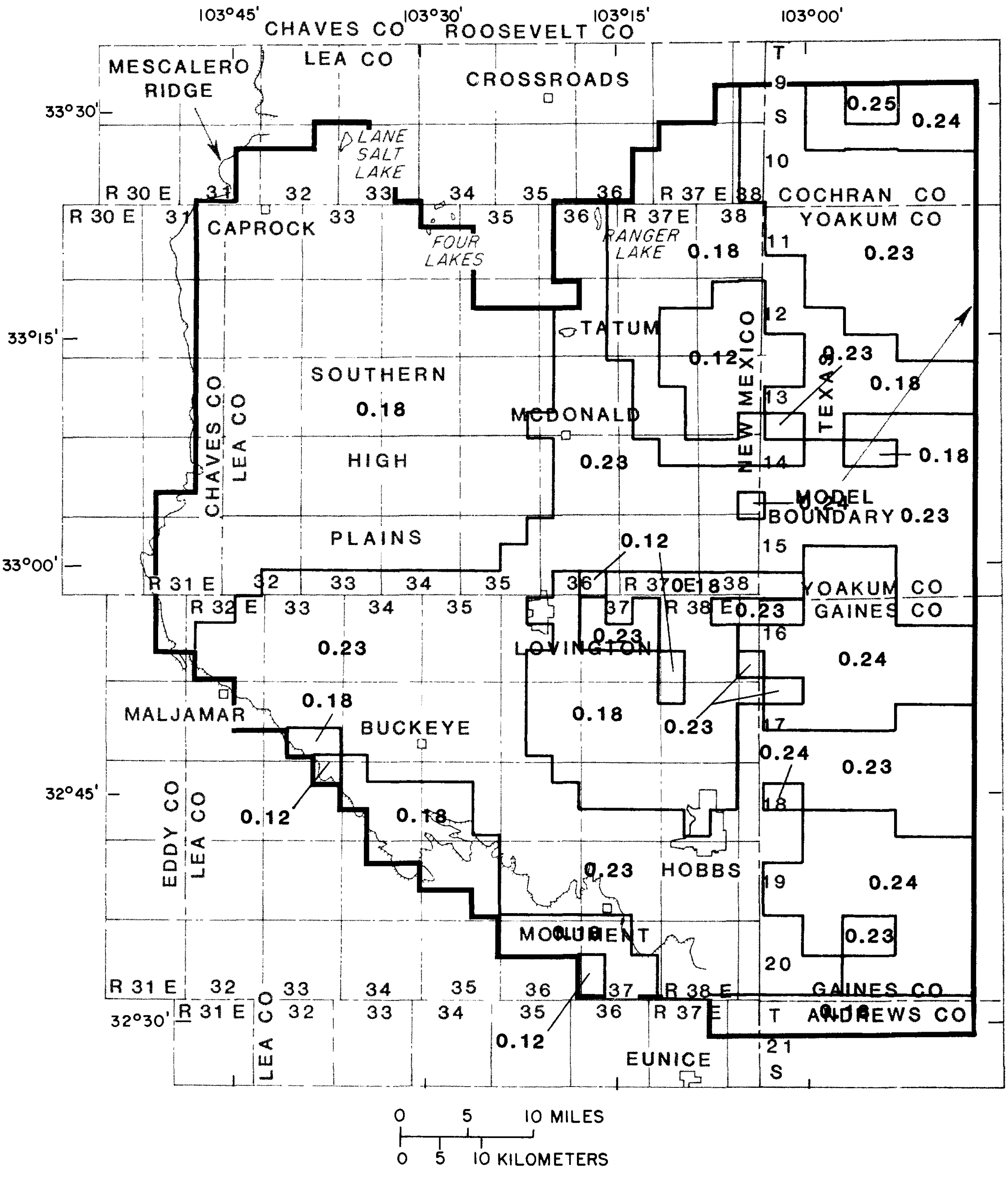


Figure 5.--Distribution of specific yield in the model.

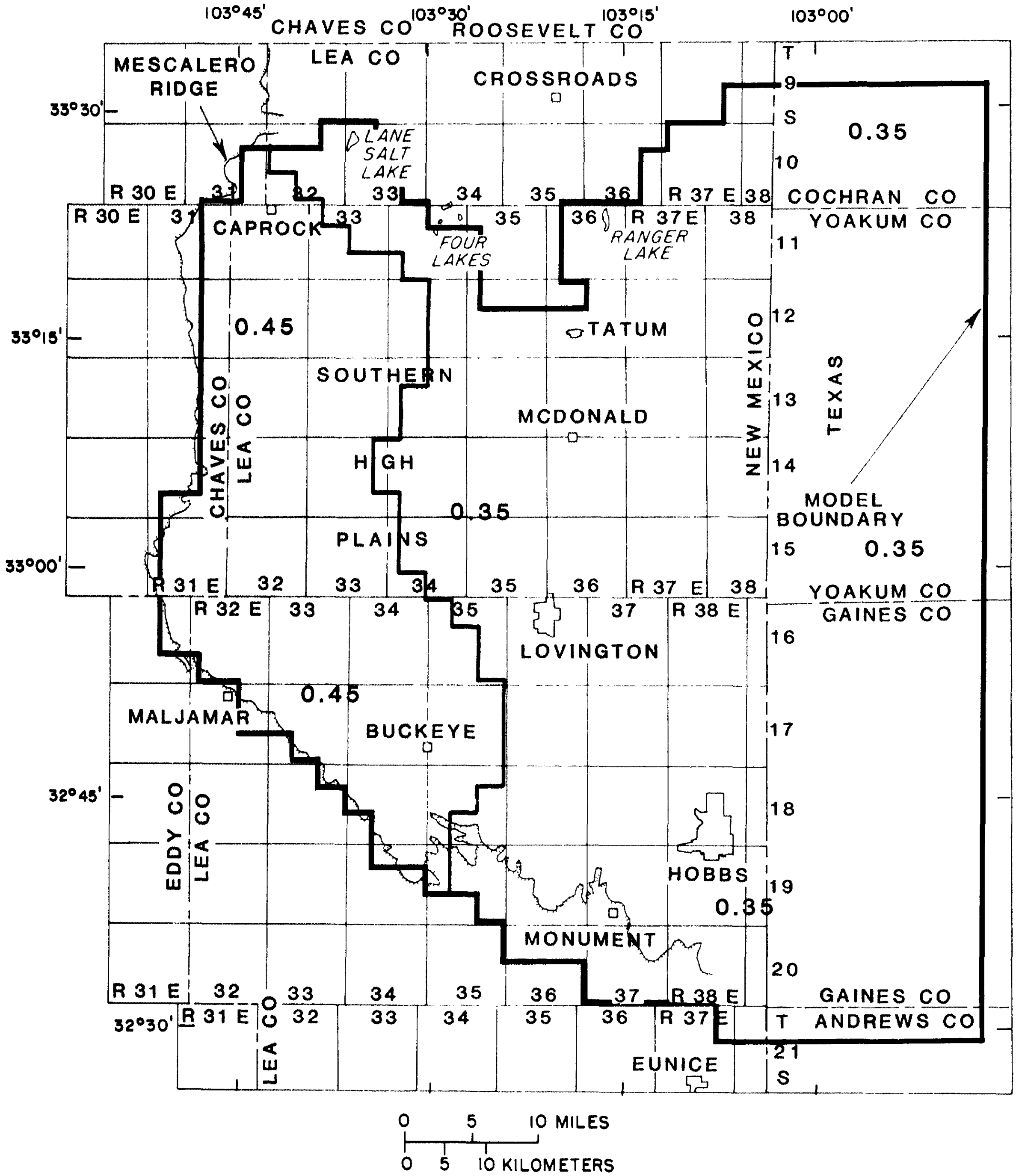


Figure 6.--Distribution of recharge in the model, in inches per year.

STEADY-STATE SIMULATION

The predevelopment steady-state condition of the aquifer was simulated by adjusting the recharge and aquifer characteristics within plausible ranges to find the best fit between the simulated and measured water levels. The solution to the steady-state simulation is independent of specific yield; therefore, only hydraulic conductivity and recharge were adjusted.

It was estimated that prior to 1940, total net pumpage from the Ogallala aquifer in Lea County was less than 9,000 acre-feet annually (Havens, 1966, p. 27). Therefore, it was assumed that water levels measured prior to 1940 would approximate the predevelopment conditions. In areas where little development has occurred, measurements taken during 1940-60 were used if earlier data were unavailable. Actual predevelopment water levels may have been somewhat higher than those stated; however, due to the block sizes used in the model such differences probably are insignificant. In blocks where actual water-level measurements were not available, simulated water levels were compared to values interpolated from predevelopment water-level contours. In blocks where actual measurements were available, the simulated water levels were compared to the measured values. Emphasis was given to the blocks with measured water levels in determining the fit of the model.

Model Adjustments

Preliminary models with uniform recharge and hydraulic conductivity distributions, no evapotranspiration, and no flow allowed between the Ogallala and Cretaceous rocks at the northern model boundary were rejected. Simulated water levels from these models were contradicted by measured water levels. In each case the contradiction could not be resolved by adjustments within plausible ranges.

The approach chosen to adjust the model was to adjust hydraulic conductivity by a judgmental trial and error procedure while holding the recharge distribution constant. If simulated water levels differed from measured water levels, recharge was modified and hydraulic conductivity was readjusted. This procedure was repeated until the simulated water levels were substantiated by measured water levels and hydraulic conductivity and recharge were consistent with data from previous investigations.

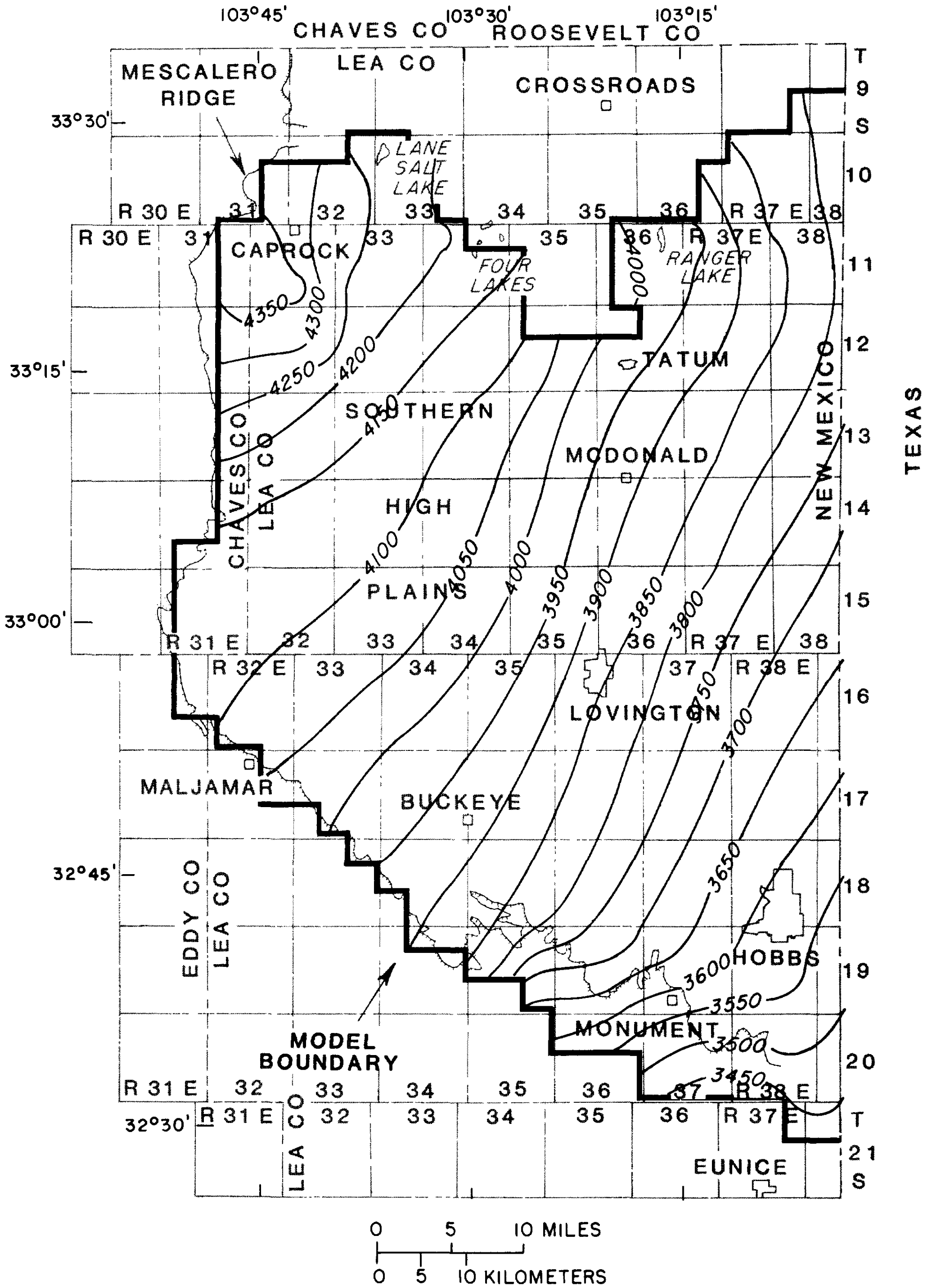
The accepted model is as described in the previous sections. The representation of the physical system in the model is substantiated by available data. However, the distributions of recharge and hydraulic conductivity used in the model probably do not constitute a unique solution. The error that might be introduced into the model due to the uncertainty of recharge and hydraulic conductivity is addressed in the section on model sensitivity.

Simulation Results

The simulated water-level distribution of the steady-state model is shown in figure 7. The error in the model was calculated as the measured minus the simulated water levels. The measured and simulated predevelopment water levels are listed in table 2. The mean difference between the measured water levels and those in the steady-state simulation is 1.9 feet, the mean absolute difference is 5.5 feet, and the maximum absolute difference within any model block is 17 feet.

The extent to which the model represents the predevelopment condition is shown in figure 8 by comparing the measured to the simulated water levels. Some variability between the measured and simulated water levels may be attributed to water levels being simulated at the node rather than at wells. Given an average hydraulic gradient of 12 feet per mile in a southeasterly direction, water levels could vary within a block 2 miles on each side by as much as 34 feet diagonally across the block. Some variability may be due to the model's inability to accurately represent the detailed heterogeneity of the aquifer. The frequency distribution of the differences between the measured and simulated steady-state water levels is shown in figure 9. The extent to which the simulated water levels match the measured water levels is considered acceptable.

The computed water budget of the steady-state simulation is shown in table 3. The budget includes the Texas part of the model and, therefore, is not representative of the inflow and outflow in Lea County alone. It shows the calculated evapotranspiration to be a relatively small part of the total discharge. The majority of discharge is through the head-dependent-flux nodes, which represent the underflow to Texas.



EXPLANATION

——3700—— WATER-LEVEL CONTOUR--Shows altitude of simulated steady-state water level. Interval 50 feet. Datum is sea level.

Figure 7.--Steady-state water levels simulated by the model.

Table 2. Measured predevelopment and simulated steady-state water-level altitudes for selected wells in Lea County, in feet above sea level

Well location	Location in model		Measured water level	Simulated water level	Water-level difference
	Row	Column			
11.33.25.442	8	9	4182	4193	-11
13.37. 9.111	12	19	3869	3866	3
13.35.19.211	13	12	4052	4052	1
13.36.33.321	14	16	3917	3918	-1
13.36.35.413	14	17	3889	3891	-2
14.36. 6.421	15	15	3839	3932	7
14.37.14.112	15	20	3799	3802	-4
14.36.21.111	16	16	3904	3895	9
14.37.20.412	16	19	3821	3817	4
14.38.28.121	16	22	3741	3739	3
14.35.33.433	17	13	3972	3980	-8
14.38.31.111	17	21	3748	3751	-3
15.36.14.131	18	17	3842	3850	-8
15.37.19.311	19	18	3807	3800	7
15.37.30.331	19	19	3785	3771	14
15.38.22.432	19	23	3689	3679	10
16.34. 1.221	21	10	4009	4009	0
16.36. 5.213	21	14	3894	3897	-3
16.38. 3.333	21	21	3703	3694	9
16.32.18.443	22	3	4095	4097	-2
16.34.20.233	23	8	4019	4012	7
16.36.27.133	23	15	3836	3837	-1
16.37.33.122	23	18	3757	3753	4
16.38.28.444	23	21	3678	3669	9
17.36. 3.333	24	15	3828	3829	-2
17.35.13.322	25	13	3876	3874	2
17.37.13.312	25	19	3699	3697	2
17.34.35.130	26	10	3930	3935	-5
17.35.24.223	26	13	3866	3862	4
17.36.27.131	26	15	3811	3809	2
17.38.27.133	26	21	3642	3630	12
18.35. 2.144	27	13	3848	3851	-3
18.38. 3.313	27	21	3628	3616	12
18.35.17.144	28	11	3876	3885	-9
18.35.13.144	28	13	3832	3837	-5

Table 2. Measured predevelopment and simulated steady-state water-level altitudes for selected wells in Lea County, in feet above sea level - Concluded

Well location	Location in model: Row	Location in model: Column	Measured water level	Simulated water level	Water-level difference
18.38.15.241	28	21	3610	3602	8
18.37.35.111	29	19	3655	3638	17
19.38. 2.122	30	22	3559	3561	-2
19.37.18.331	31	17	3650	3658	-8
19.38.19.344	32	20	3564	3558	6
20.37. 9.112	33	18	3523	3526	-3
20.36.24.442	34	17	3501	3492	9
21.37. 3.433	35	21	3395	3395	0

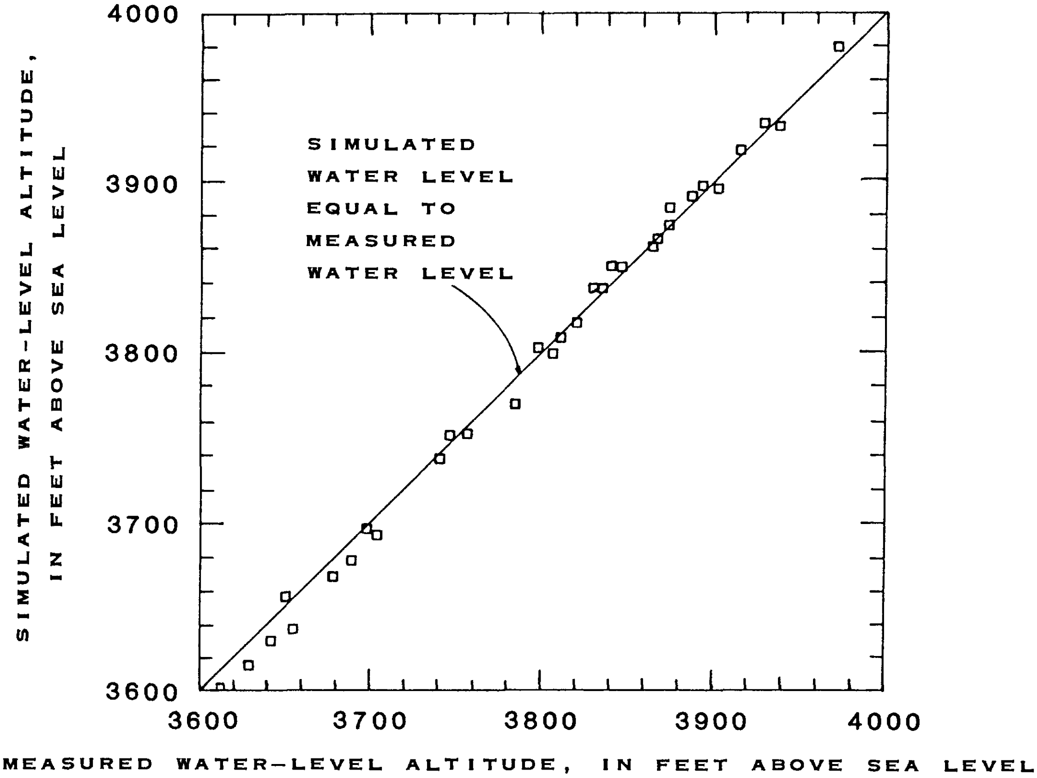


Figure 8.--Comparison between measured water levels for selected wells in Lea County and those simulated by the steady-state model.

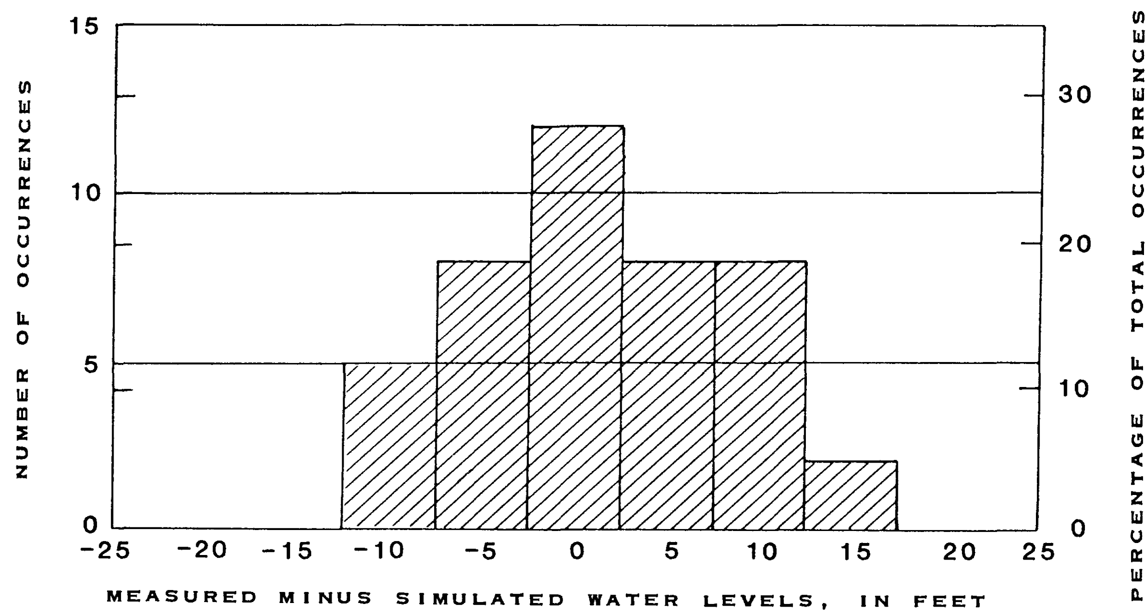


Figure 9.--Histogram of water-level differences during the steady-state simulation for model blocks in which measured values were available.

Table 3. Water budget for the predevelopment steady-state simulation

Description	Flow, in cubic feet per second
Sources	
Storage	0.00
Recharge	95.15
Constant flux	1.30
Total	96.45
Discharges	
Evapotranspiration	6.40
Constant flux	2.20
Head-dependent flux	87.85
Total	96.45
Discharges minus sources	0.00
Percent difference	0.00

TRANSIENT SIMULATIONS

Changes to the steady-state system have taken place because of ground-water being withdrawn from storage within the aquifer. A simulation of a historical pumping period during which ground-water withdrawals are known was used to adjust values of specific yield within the established plausible range. A simulation of another historical pumping period was used to check how the model would fit a second set of data without adjusting the aquifer characteristics.

It was believed that the withdrawal and water-level data after 1970 were most reliable and readily available; therefore, 1970 was used as the initial year in the transient simulations. The initial water levels for the transient simulations were the measured water levels in blocks where measurements were available. In blocks where no water-level measurements were available, the initial values were interpolated from 1970 water-level contours.

Comparison of the simulated and the measured water levels at the end of each transient simulation period was used to determine the fit of the model. Only wells with measured water levels at the beginning and end of a simulation period were used for comparison.

Water-level measurements in irrigation wells are usually taken in January, when pumping is at a minimum. Therefore, the transient simulations were done from January 1 of the beginning year to January 1 of the ending year.

Pumpage

Ground-water withdrawals from the Lea County Underground Water Basin are reported annually (New Mexico State Engineer Office, 1970-80). The withdrawal amounts are determined from meter readings and estimates of irrigated acreage. The New Mexico State Engineer Office estimates return flow from irrigation to be 1/6 of the withdrawal (Havens, 1966). Therefore, net irrigation withdrawal used in the model was estimated to be 5/6 of the irrigation pumpage. Pumpage for non-irrigation uses was not adjusted for return flow.

The amount of pumpage from specific irrigation wells in Lea County is not definitely known. Because individual wells irrigate relatively small areas in comparison with the size of a model block and because these wells are generally located near the areas they irrigate, it was assumed that all pumpage for the irrigated area within a model block occurred at the node of that block. The ground-water withdrawal for irrigation was distributed to each model block in proportion to the amount of irrigated acreage within the block. The model blocks representing the irrigated areas in Texas were assigned the same proportionate irrigation pumpage as in Lea County.

The primary irrigation season in Lea County is probably about 5 months long, starting sometime near the beginning of May (Blaney and Hanson, 1965). It was assumed in the model that pumping for irrigation began on May 1 and ended on October 1 each year and was uniformly distributed throughout this period. Pumping for nonirrigation uses was assumed to be uniformly distributed throughout each year.

Simulation of the 1970 to 1973 Pumping Period

Model Adjustments

The FORTRAN program of Trescott, Pinder, and Larson (1976) treats a node that goes dry (saturated thickness is zero) in one of two ways, depending on whether the node is nonpumping or pumping. A nonpumping node that goes dry becomes a no-flow node for the remainder of that simulation and flow to or from the node is prohibited. If a pumping node goes dry, the simulation is terminated. In order to avoid this termination, the FORTRAN program was modified.

The program modification allows a node to be pumped until the saturated thickness at the node decreases to specified minimum level, rather than zero. The saturated thickness at a node represents the estimated average saturated thickness over the area of an entire model block, which is unlikely to completely desaturate. Five feet was selected as the level of minimum saturated thickness. If the saturated thickness at a pumping node decreases to less than 5 feet, pumping at the node is stopped for the remainder of that pumping period but flow to and from the node continues. Pumping at the node is permitted at the beginning of the next pumping period if the saturated thickness has increased to more than 5 feet.

Hydraulic conductivity and recharge were adjusted during the steady-state simulations. They were held constant and only specific yield was adjusted in the 1970 to 1973 transient simulations.

The specific yield was adjusted by a judgmental trial and error procedure in an effort to minimize the difference between the measured and simulated 1973 water levels. Specific yield increased by a maximum of 0.03 from the initial estimates and was consistent with data from previous investigations. The final values of specific yield used in the model are shown in figure 5.

The distributions of hydraulic conductivity, recharge, and specific yield used in the model probably do not constitute a unique solution. The error that may be introduced into the model due to the uncertainty in each of these properties is addressed in the section on model sensitivity.

Simulation Results

The error in the fit of the transient model was defined as the difference between the measured and simulated 1973 water levels. The measured and simulated water-level altitudes are listed in table 4. The mean difference is 0.36 foot, the mean absolute difference is 7.1 feet, and the maximum absolute difference within any model block is 23 feet.

The relation between the measured and simulated water levels for selected wells is shown in figure 10. Some of the variability between the simulated and measured water levels may be attributed to water levels being simulated at the node, whereas the measured water levels can be located anywhere within the block. For example, wells 17.38.7.111 and 17.38.8.211 are represented in the model by the same node; however, the measured water levels in the wells differ by 29 feet.

The frequency distribution of the differences in water levels is shown in figure 11. The extent to which the simulated water levels match the measured water levels is considered acceptable.

The water budget for the simulation is shown in table 5. Most of the discharge, 78 percent, was by pumping. The major source of water, 73 percent, was from storage. The major natural discharge, underflow at the model boundary in Texas represented by the head-dependent-flux nodes, was 16 percent less than that calculated for predevelopment conditions (table 3). This decrease is primarily caused by a reduction in saturated thickness. A 1-percent reduction in recharge from the predevelopment simulation occurred because more nodes were unsaturated with the lower 1970 water levels. However, in reality, the unsaturated areas still would have received recharge.

Table 4. **Measured and simulated 1973 water-level altitudes for selected wells in Lea County, in feet above sea level**

Well location	Location in model		Measured water level	Simulated water level	Water-level difference
	Row	Column			
11.32.24.411	7	6	4254	4252	2
11.33.25.442	8	9	4183	4178	5
12.32. 3.433	9	5	4356	4356	0
12.34.11.421	9	11	4111	4121	-10
12.38. 4.132	9	22	3830	3830	0
12.33.28.211	10	7	4182	4192	-10
12.37.20.341	10	19	3905	3903	2
12.34.35.322	11	11	4099	4101	-2
13.37. 9.111	12	19	3864	3860	4
13.34.21.111	13	10	4094	4092	2
13.35.19.211	13	12	4050	4050	0
13.32.25.214	14	6	4154	4148	6
13.36.26.413	14	17	3861	3872	-11
13.37.28.413	14	19	3818	3824	-6
14.37. 5.211	14	19	3808	3824	-16
14.36. 9.111	15	16	3887	3890	-3
14.36. 2.113	15	17	3854	3856	-2
14.36.10.212	15	17	3859	3856	3
14.37. 7.311	15	18	3829	3828	1
14.37. 8.113	15	19	3812	3800	12
14.37.14.111	15	20	3752	3769	-17
14.35.23.313	16	14	3979	3956	23
14.36.21.111	16	16	3884	3879	5
14.37.19.111	16	18	3824	3818	6
14.37.16.421	16	19	3775	3783	-8
14.37.20.412	16	19	3783	3783	0
14.37.13.311	16	21	3738	3735	3
14.38.21.311	16	22	3724	3722	2
14.33.35.133	17	8	4091	4090	1
14.35.33.433	17	13	3968	3981	-13
14.35.25.241	17	15	3886	3903	-17
14.36.33.131	17	16	3864	3868	-4
14.37.27.311	17	20	3754	3750	4
14.38.31.111	17	21	3722	3733	-11
14.38.27.313	17	23	3702	3688	14

Table 4. Measured and simulated 1973 water-level altitudes for selected wells in Lea County, in feet above sea level - Continued

Well location	Location in model		Measured water level	Simulated water level	Water-level difference
	Row	Column			
15.36.17.111	18	16	3858	3855	3
15.36. 1.311	18	18	3814	3796	18
15.37. 7.111	18	18	3798	3796	2
15.37. 4.113	18	19	3774	3774	0
15.38.10.321	18	23	3691	3685	6
15.36.20.133	19	16	3853	3838	15
15.36.29.112	19	16	3845	3838	7
15.36.14.131	19	17	3824	3816	8
16.36.23.241	19	17	3801	3816	-15
15.37.19.311	19	18	3787	3786	1
15.37.29.111	19	19	3761	3755	6
15.37.20.221	19	19	3753	3755	-2
15.37.23.112	19	20	3742	3738	4
15.37.27.111	19	20	3731	3738	-7
15.38.22.432	19	23	3679	3676	3
15.36.28.113	20	16	3825	3825	0
15.36.34.111	20	17	3811	3796	15
15.37.31.132	20	18	3765	3764	1
15.37.33.311	20	19	3729	3735	-6
15.38.35.131	20	23	3661	3657	4
16.36. 5.124	21	14	3875	3875	0
16.37. 7.114	21	17	3803	3788	15
16.37. 2.211	21	18	3734	3754	-20
16.37.11.111	21	19	3726	3720	6
16.38. 3.333	21	21	3688	3687	1
16.35.13.112	22	13	3915	3916	-1
16.35.24.111	22	13	3915	3916	-1
16.37.14.211	22	19	3708	3713	-5
16.34.20.233	23	8	4016	4009	7
16.35.26.211	23	13	3922	3904	18
16.38.27.111	23	21	3653	3649	4
16.38.34.131	23	22	3618	3626	-8
16.39.29.233	23	23	3598	3604	-6
17.37.10.211	24	18	3711	3724	-13
17.37.12.113	24	19	3678	3692	-14

Table 4. **Measured and simulated 1973 water-level altitudes for selected wells in Lea County, in feet above sea level—Concluded**

Well location	Location in model: Row	Location in model: Column	Measured water level	Simulated water level	Water-level difference
17.38. 8.211	24	20	3651	3661	-10
17.38. 7.111	24	20	3680	3661	19
17.38. 2.311	24	22	3629	3613	16
17.33.13.341	25	7	3962	3970	-8
17.34.28.223	26	9	3917	3922	-5
17.34.35.130	26	10	3911	3920	-9
17.36.27.131	26	15	3806	3802	4
17.38.34.113	26	21	3614	3614	0
18.38. 3.313	27	21	3604	3600	4
18.35.17.144	28	11	3870	3872	-2
18.35.20.214	28	12	3861	3854	7
18.36.27.111	29	15	3768	3756	12
19.36.19.113	31	14	3688	3703	-15
19.37.32.241	32	18	3563	3571	-8
19.38.34.222	32	22	3543	3531	12

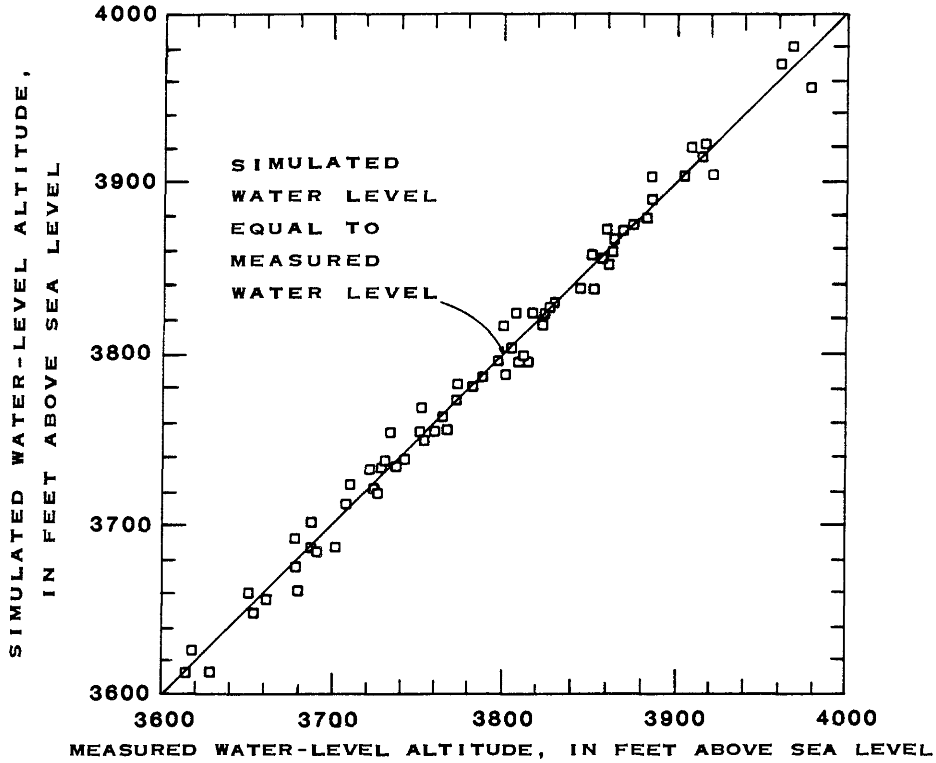


Figure 10.--Comparison between measured 1973 water levels for selected wells in Lea County and those simulated by the model.

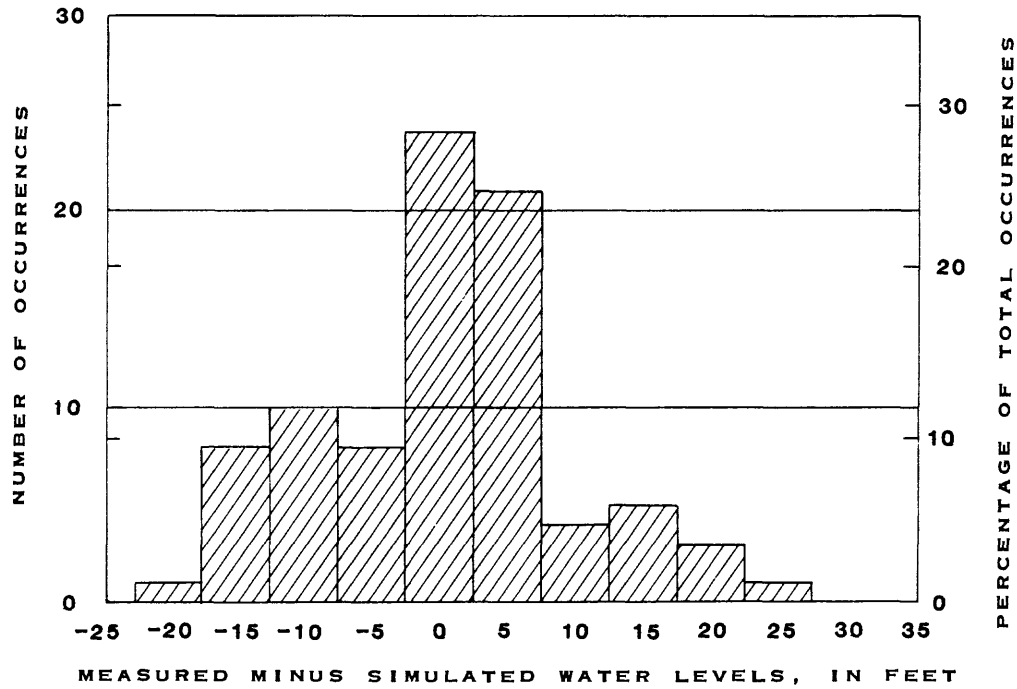


Figure 11.--Histogram of water-level differences in the simulation of 1973 water levels for model blocks in which measured values were available.

Table 5. Water budget for the simulation of the 1970 to 1973 period

Description	Cumulative water budget, in acre-feet	Average flow for the last year in the simulation, in cubic feet per second
Sources		
Storage	549,175	236.36
Recharge	204,202	93.93
Constant flux	2,826	1.30
Total	756,203	331.59
Discharges		
Pumping	590,852	254.74
Evapotranspiration	1,967	1.31
Constant flux	4,783	2.20
Head-dependent flux	159,957	73.48
Total	757,559	331.73
Discharges minus sources	1,356	0.14
Percent difference	0.18	0.04

Simulation of the 1970 to 1980 Pumping Period

A continuation of the transient simulation was done to the year 1980 to check how the model would match a second set of measured water levels. This simulation was done without adjusting the aquifer characteristics in the model.

A comparison of the simulated and measured water levels was made by matching the water-level contours (fig. 12). Some interpretation was involved in contouring; therefore, the comparison should be considered to be general. Over most of the modeled area, the contours of the simulated water levels differ from those of the measured water levels by less than one-half contour interval.

The 1980 measured water levels and those simulated by the model are listed in table 6. The mean difference between the measured and simulated water levels is 0.57 foot, the mean absolute difference is 9.1 feet, and the maximum absolute difference within any model block is 29 feet.

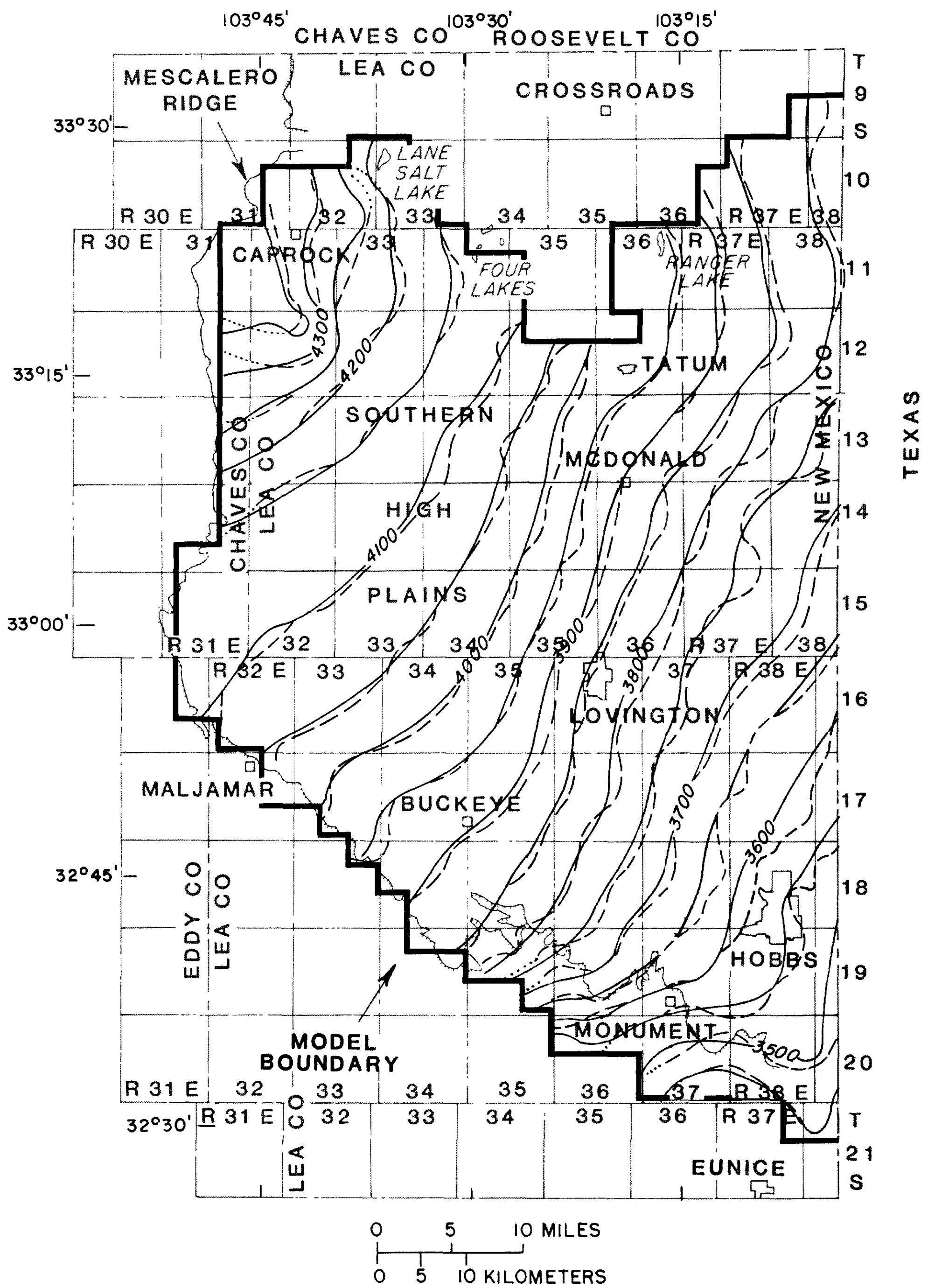
The relationship between simulated water levels and the measured water levels in selected wells is shown in figure 13. Again some of the variability may be explained by water levels being simulated at the nodes rather than at wells. The maximum absolute difference is only slightly more than the difference between measured water levels in wells 17.38.8.211 and 17.38.7.111 (table 6), which are located in the same model block.

Hydrographs of measured and simulated water-level changes from 1970 to 1980 for nine representative wells in Lea County are shown in figure 14. Relatively small declines occurred in the northern, northwestern, and extreme southeastern part of Lea County (fig. 14A through E). In the east-central part of the area (fig. 14F through H) and in the southwest near Buckeye (fig. 14I), declines were greater because of greater ground-water withdrawals.

The frequency of occurrence of the water-level differences during the 1980 transient simulation is shown in figure 15. The extent to which the simulated water levels match the 1980 measured water levels is considered to be acceptable.

The simulated water budget is shown in table 7. Outflow from the model through head-dependent-flux nodes decreased by 1.1 percent from the 1973 rate. Simulated evapotranspiration increased from 1.31 cubic feet per second in 1973 to 2.27 cubic feet per second in 1980. This increase corresponds with an increase in measured water levels in the area near Monument during 1970-80.

The 1980 saturated thickness of the Ogallala aquifer in Lea County as simulated by the model is shown in figure 16. Twenty-eight percent of the area had less than 50 feet of saturation, while 14 percent had more than 150 feet of saturation. Four percent of the area had less than 10 feet of saturation.



EXPLANATION

4000 SIMULATED WATER-LEVEL CONTOUR--Shows altitude of simulated 1980 water level. Interval 50 feet. Datum is sea level.

4000 WATER-LEVEL CONTOUR--Shows altitude of 1980 water level. Dotted where approximately located. Interval 50 feet. Datum is sea level.

Figure 12.--Comparison of 1980 measured water levels and those simulated by the model.

Table 6. Measured and simulated 1980 water-level altitudes for selected wells in Lea County, in feet above sea level

Well location	Location in model		Measured water level	Simulated water level	Water-level difference
	Row	Column			
11.32.24.411	7	6	4255	4248	7
11.33.25.442	8	9	4183	4175	8
12.32. 3.433	9	5	4355	4353	2
12.34.11.421	9	11	4111	4121	-10
12.38. 4.132	9	22	3830	3829	1
12.37.20.341	10	19	3905	3902	3
12.34.35.322	11	11	4100	4100	0
13.35. 2.111	11	14	4006	4010	-4
13.37. 4.243	12	19	3857	3854	3
13.37. 9.111	12	19	3863	3854	9
13.34.21.111	13	10	4093	4087	6
13.35.19.211	13	12	4050	4048	2
13.32.25.214	14	6	4155	4147	8
13.36.26.413	14	17	3853	3867	-14
13.37.28.413	14	19	3810	3819	-9
14.37. 5.211	14	19	3802	3819	-17
14.36. 9.111	15	16	3880	3884	-4
14.36. 2.113	15	17	3845	3849	-4
14.36.10.212	15	17	3850	3849	1
14.37. 7.311	15	18	3820	3822	-2
14.37. 8.113	15	19	3807	3795	12
14.37.14.111	15	20	3744	3765	-21
14.38. 7.113	15	21	3728	3742	-14
14.35.23.313	16	14	3978	3949	29
14.36.21.111	16	16	3881	3874	7
14.37.19.111	16	18	3820	3811	9
14.37.16.421	16	19	3770	3778	-8
14.37.20.412	16	19	3777	3778	-1
14.37.13.311	16	21	3726	3730	-4
14.38.21.311	16	22	3715	3715	0
14.33.35.133	17	8	4091	4091	0
14.35.33.433	17	13	3968	3980	-12
14.35.25.241	17	15	3882	3900	-18
14.36.33.131	17	16	3862	3865	-3
14.37.31.333	17	18	3794	3804	-10

Table 6. Measured and simulated 1980 water-level altitudes for selected wells in Lea County, in feet above sea level - Continued

Well location	Location in model		Measured water level	Simulated water level	Water-level difference
	Row	Column			
14.37.27.311	17	20	3747	3743	4
14.38.31.111	17	21	3716	3726	-10
14.38.27.313	17	23	3692	3681	11
15.36.17.111	18	16	3854	3848	6
15.36. 1.311	18	18	3814	3788	26
15.37. 7.111	18	18	3793	3788	5
15.37. 4.113	18	19	3766	3764	2
15.38.10.321	18	23	3680	3677	3
15.36.20.133	19	16	3849	3829	20
15.36.29.112	19	16	3841	3829	12
15.36.14.131	19	17	3819	3806	13
16.36.23.241	19	17	3798	3806	-8
15.37.19.311	19	18	3782	3778	4
15.37.29.111	19	19	3755	3749	6
15.37.20.221	19	19	3746	3749	-3
15.37.23.112	19	20	3734	3728	6
15.37.27.111	19	20	3717	3728	-11
15.38.22.432	19	23	3670	3668	2
15.36.28.113	20	16	3825	3816	9
15.36.34.111	20	17	3808	3786	22
15.37.31.132	20	18	3760	3758	2
15.37.33.311	20	19	3722	3730	-8
15.38.35.131	20	23	3652	3650	2
16.36. 5.124	21	14	3874	3874	0
16.37. 7.114	21	17	3793	3780	13
16.37. 2.211	21	18	3729	3750	-21
16.37.11.111	21	19	3720	3715	5
16.38. 3.333	21	21	3683	3679	4
16.35.13.112	22	13	3918	3910	8
16.35.24.111	22	13	3913	3910	3
16.37.14.211	22	19	3705	3708	-3
16.34.20.233	23	8	4014	4004	10
16.35.26.211	23	13	3917	3900	17
16.38.27.111	23	21	3637	3638	-1
16.38.34.131	23	22	3602	3617	-15

Table 6. Measured and simulated 1980 water-level altitudes for selected wells in Lea County, in feet above sea level - Concluded

Well location	Location in model: Row	Location in model: Column	Measured water level	Simulated water level	Water-level difference
16.39.29.233	23	23	3584	3597	-13
17.37.10.211	24	18	3699	3721	-22
17.37.12.113	24	19	3671	3687	-16
17.38. 8.211	24	20	3642	3653	-11
17.38. 7.111	24	20	3670	3653	17
17.38. 2.311	24	22	3616	3603	13
17.33.13.341	25	7	3951	3968	-17
17.34.28.223	26	9	3903	3915	-12
17.34.35.130	26	10	3895	3912	-17
17.36.27.131	26	15	3804	3801	3
17.37.34.111	26	18	3673	3692	-19
17.38.34.113	26	21	3604	3602	2
17.38.31.311	27	20	3636	3613	23
18.38. 3.313	27	21	3592	3588	4
18.35.17.144	28	11	3869	3869	0
18.35.20.214	28	12	3860	3848	12
18.36.27.111	29	15	3765	3749	16
19.36.19.113	31	14	3687	3708	-21
19.38.34.222	32	22	3543	3529	14

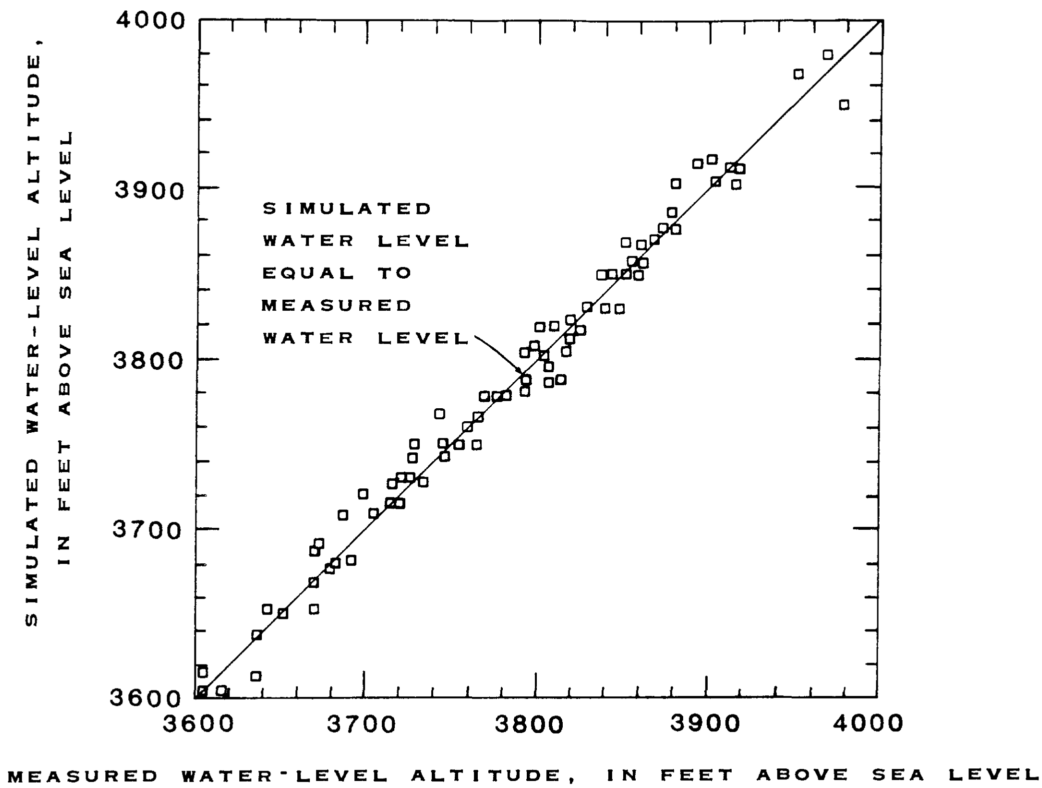


Figure 13.--Comparison between measured 1980 water levels for selected wells in Lea County and those simulated by model.

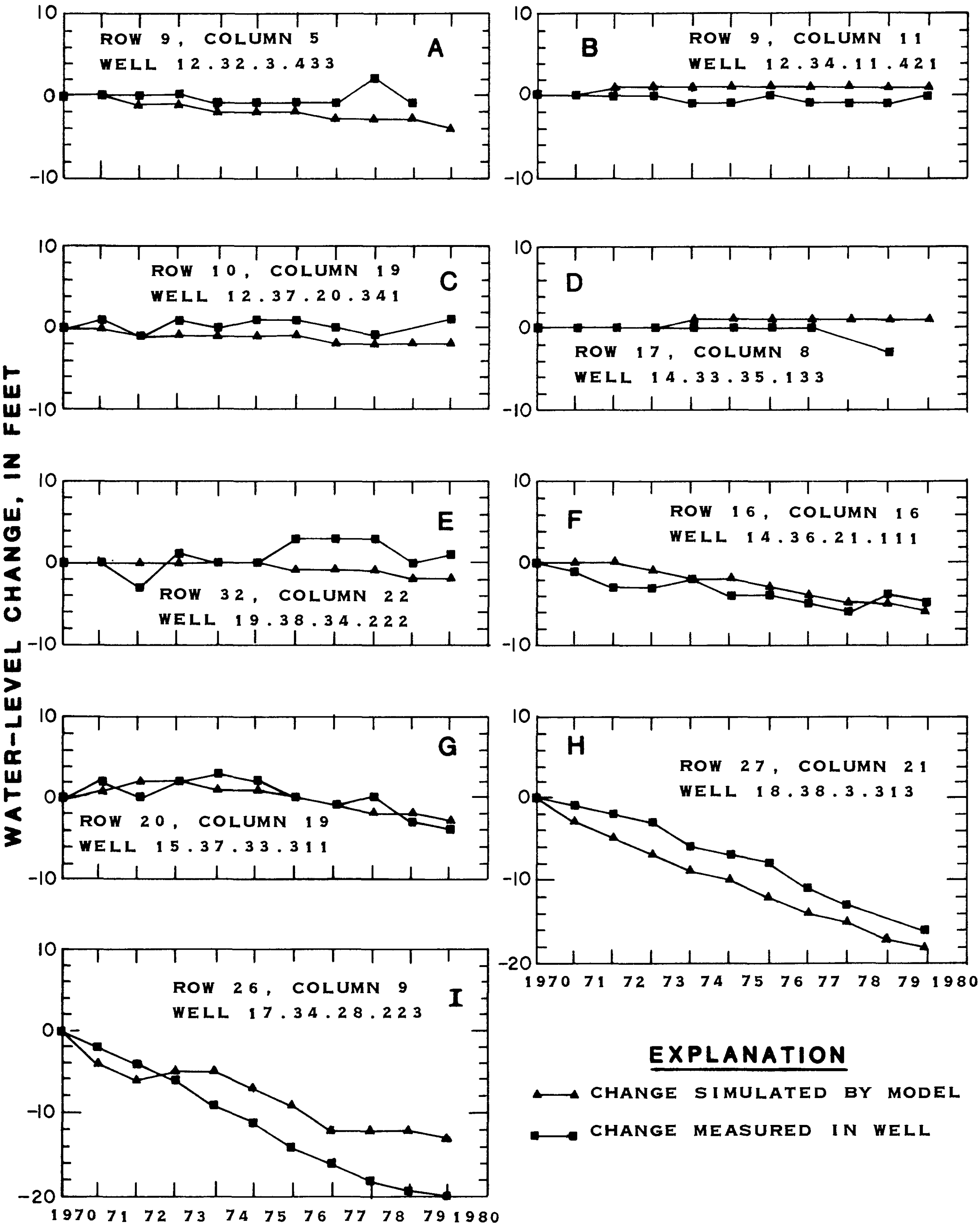


Figure 14.--Comparison between water-level changes (1970-80) measured in selected wells and simulated in the corresponding model blocks.

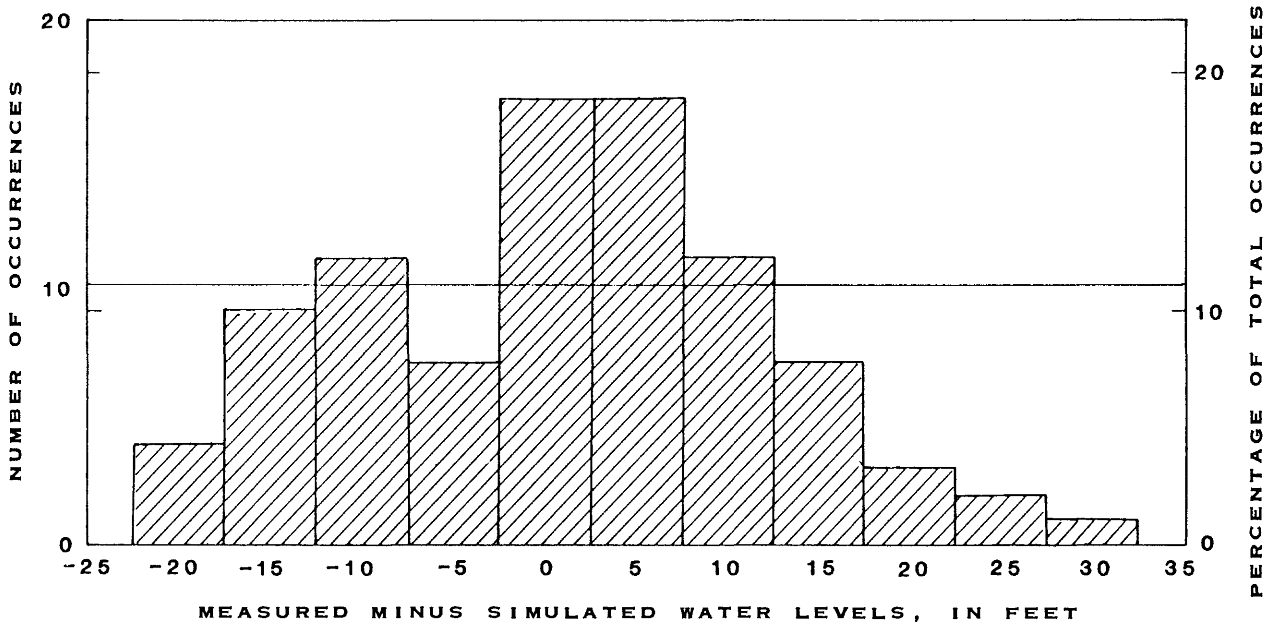


Figure 15.--Histogram of water-level differences in the simulation of 1980 water levels for model blocks in which measured values were available.

Table 7. Water budget for the simulation of the 1970 to 1980 period

Description	Cumulative water budget, in acre-feet	Average flow for the last year in the simulation, in cubic feet per second
Sources		
Storage	1,819,809	230.89
Recharge	680,426	93.93
Constant flux	9,417	1.30
Total	2,509,652	326.12
Discharges		
Pumping	1,955,670	249.22
Evapotranspiration	12,796	2.27
Constant flux	15,936	2.20
Head-dependent flux	530,335	72.68
Total	2,514,737	326.37
Discharges minus sources	5,085	0.25
Percent difference	0.20	0.08

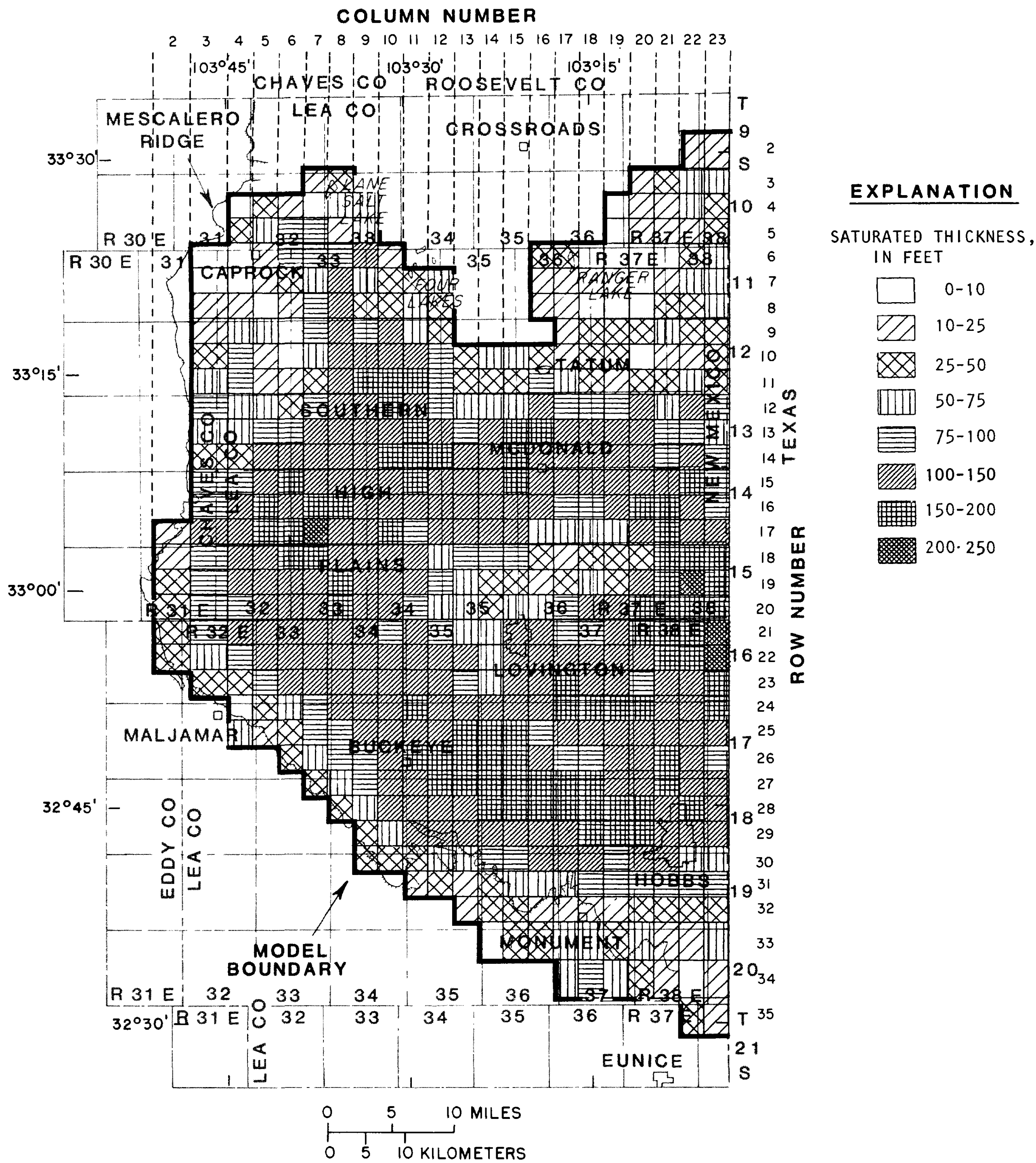


Figure 16.--Saturated thickness in 1980 simulated by the model.

SIMULATED RESPONSE TO PROJECTED WITHDRAWALS

The response of the Ogallala aquifer in Lea County to future withdrawals was simulated to the years 2000 and 2020 using the simulated 1980 water levels as the initial condition. Two scenarios were simulated.

The first scenario assumes no additional development. The projected withdrawals were the average annual withdrawals over the 10-year period from 1970 to 1980. The average withdrawals as represented in the model are listed in table 8.

In the second scenario, nonirrigation withdrawals were calculated from the increase in withdrawals for nonirrigation uses estimated by Lansford and others (1974). They estimated that with no water constraint, nonirrigation withdrawals would be an average of 55 percent greater in 2020 than in 1970. The average yearly increase, 0.88 percent, was used to annually increase the 1970-80 average nonirrigation withdrawals. Lansford (1982) estimated irrigated cropland in Lea County to increase 5.9 percent from 1977 to 1990 and then remain constant to 2020. The average yearly increase, 0.44 percent, was used to annually increase the 1970-80 average irrigation withdrawal to 1990. Irrigation withdrawal was then kept constant to 2020. Since ground water in many areas in Lea County has been fully appropriated and the annual ground-water withdrawal is less than the maximum allowable, it was assumed that the relative distribution of withdrawals in these simulations did not change from that used in the historical simulations.

It is unlikely that actual future ground-water withdrawal will match either of the scenarios. However, it is believed that withdrawals will be in the range of the simulated conditions. If this is the case, these simulations may give some indication of the water-level declines that could be expected.

Table 8. Average withdrawals from 1970 to 1980 as represented in the model

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location Row	Location Column	Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
4	23	2.00	-
5	9	-	0.11
5	23	1.73	-
6	9	1.81	-
6	16	0.04	-
7	6	1.38	0.01
7	7	0.41	-
7	8	0.46	-
7	9	0.80	-
7	11	1.74	-
7	12	0.98	-
7	16	0.04	-
7	20	0.24	-
8	6	1.08	-
8	7	0.62	-
8	9	0.22	0.12
8	12	0.61	-
8	16	0.06	-
9	17	0.04	-
9	18	0.27	-
9	22	0.28	-
10	10	0.46	-
10	12	0.34	-
10	13	0.02	-
10	14	0.15	-
10	15	0.84	-
10	16	0.14	0.11
10	19	0.42	-
10	20	0.39	-
11	3	-	0.02
11	8	0.27	-
11	11	0.38	0.02
11	15	0.86	-
11	16	0.67	0.11
11	22	0.50	-

Table 8. Average withdrawals from 1970 to 1980 as represented in the model - Continued

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location: Row	Location: Column	Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
12	9	0.54	-
12	10	1.44	-
12	11	0.55	-
12	12	0.24	-
12	13	0.54	-
12	14	2.75	-
12	15	2.55	-
12	16	0.95	-
12	19	1.82	-
12	20	0.70	-
12	21	4.36	-
12	22	1.14	-
12	23	1.88	-
13	4	-	0.03
13	10	2.45	-
13	11	1.46	-
13	12	0.71	-
13	13	0.71	-
13	14	0.22	-
13	15	0.57	-
13	16	0.86	-
13	18	1.63	-
13	19	0.88	-
13	21	1.99	-
13	22	0.81	-
13	23	3.69	-
14	4	-	0.03
14	10	0.59	-
14	11	0.98	-
14	12	0.16	-
14	13	0.44	-
14	14	1.89	-
14	15	1.48	-
14	16	4.19	-
14	17	3.24	-

Table 8. Average withdrawals from 1970 to 1980 as represented in the model - Continued

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location			
Row	Column	Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
14	18	2.28	-
14	19	1.72	-
14	20	2.31	-
14	21	1.94	-
14	23	1.16	-
15	12	0.17	-
15	13	0.25	-
15	15	0.69	-
15	16	2.49	-
15	17	5.19	-
15	18	4.05	-
15	19	2.87	-
15	20	1.85	-
15	21	3.58	-
15	22	0.42	-
15	23	1.36	-
16	3	-	0.01
16	13	0.88	-
16	14	2.43	-
16	15	0.45	-
16	16	1.97	-
16	17	1.64	0.02
16	18	1.84	-
16	19	3.23	-
16	20	5.61	-
16	21	3.76	-
16	22	2.09	-
16	23	1.32	-
17	2	-	0.01
17	8	-	0.22
17	12	1.15	-
17	14	0.24	-
17	15	1.28	-
17	16	1.22	-
17	17	3.25	-

Table 8. Average withdrawals from 1970 to 1980 as represented in the model - Continued

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location		Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
Row	Column		
17	18	0.64	-
17	19	3.15	-
17	20	1.61	-
17	21	1.91	-
17	22	0.93	-
17	23	3.39	-
18	4	-	0.18
18	5	-	0.18
18	11	0.57	-
18	12	0.24	-
18	14	0.79	-
18	15	1.25	-
18	16	4.30	-
18	17	1.12	-
18	18	3.28	-
18	19	2.02	-
18	20	0.46	0.17
18	21	-	0.08
18	22	0.50	-
18	23	2.41	-
19	5	-	0.93
19	12	0.19	-
19	13	-	0.64
19	16	4.03	-
19	17	2.02	-
19	18	0.77	-
19	19	1.27	-
19	20	1.46	-
19	23	1.19	-
20	2	-	0.08
20	3	-	0.02
20	4	-	1.46
20	5	-	0.49
20	6	-	0.37
20	10	0.10	-

Table 8. Average withdrawals from 1970 to 1980 as represented in the model - Continued

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location		Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
Row	Column		
20	12	0.23	-
20	13	0.27	0.37
20	14	0.86	0.37
20	15	1.59	-
20	16	2.88	-
20	17	2.05	-
20	18	0.48	-
20	19	2.65	-
20	20	2.04	-
20	23	0.53	-
21	2	-	0.06
21	4	-	0.07
21	10	0.11	-
21	11	0.08	-
21	12	0.08	-
21	13	0.23	-
21	14	1.83	-
21	15	0.73	0.81
21	16	1.33	0.35
21	17	1.13	-
21	18	0.42	-
21	19	5.20	-
21	20	1.56	-
21	21	0.84	-
21	22	0.62	-
21	23	0.59	-
22	8	-	0.59
22	9	-	0.51
22	10	0.40	-
22	11	0.16	-
22	12	0.49	-
22	13	1.43	-
22	14	2.76	0.21
22	15	1.54	-
22	16	2.89	-

Table 8. **Average withdrawals from 1970 to 1980 as represented in the model - Continued**

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location			
Row	Column	Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
22	17	0.68	-
22	19	2.52	-
22	20	0.88	-
22	21	1.21	-
22	22	1.18	-
22	23	2.26	-
23	4	-	0.96
23	6	-	1.35
23	8	-	0.59
23	13	1.29	-
23	14	0.23	-
23	15	0.16	-
23	16	0.06	0.88
23	17	-	1.02
23	19	1.17	-
23	20	2.45	-
23	21	3.92	-
23	22	2.83	-
23	23	3.50	-
24	4	-	0.11
24	5	-	0.31
24	6	-	0.71
24	7	-	1.11
24	13	-	0.14
24	14	0.36	-
24	15	0.21	-
24	16	1.45	0.39
24	17	1.26	-
24	18	0.62	-
24	19	0.58	0.02
24	20	2.37	-
24	21	4.90	-
24	22	2.52	-
25	7	-	1.83
25	10	-	0.61

Table 8. Average withdrawals from 1970 to 1980 as represented in the model - Continued

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location: Row	Location: Column	Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
25	14	0.08	-
25	15	0.16	-
25	16	0.10	-
25	19	2.34	-
25	20	2.61	-
25	21	1.79	-
25	22	2.54	-
25	23	1.92	-
26	8	-	0.95
26	9	-	6.27
26	10	-	0.95
26	11	-	0.74
26	12	-	0.10
26	15	0.48	-
26	16	0.07	-
26	18	0.22	-
26	19	3.99	-
26	20	1.78	-
26	21	1.46	-
26	22	2.62	-
26	23	5.78	-
27	7	-	0.01
27	8	-	0.18
27	10	-	0.94
27	11	-	0.36
27	12	-	0.40
27	13	0.25	0.40
27	14	-	0.57
27	15	2.40	-
27	16	0.11	-
27	17	0.18	-
27	18	0.80	-
27	19	0.72	1.13
27	20	2.53	-
27	21	0.97	-

Table 8. Average withdrawals from 1970 to 1980 as represented in the model - Continued

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location Row	Location Column	Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
27	22	3.92	0.08
27	23	3.14	-
28	9	-	0.02
28	10	-	1.12
28	11	-	0.56
28	12	-	0.46
28	14	-	0.57
28	15	-	0.57
28	16	-	0.57
28	17	0.25	-
28	19	-	0.02
28	20	-	2.16
28	21	2.68	2.10
28	22	1.23	-
28	23	0.64	-
29	13	-	0.04
29	14	-	0.57
29	15	0.13	0.57
29	16	-	2.55
29	17	0.81	0.02
29	18	0.31	-
29	19	0.28	-
29	20	0.65	-
29	21	-	2.14
29	22	-	2.10
29	23	1.42	-
30	11	0.14	-
30	13	-	0.05
30	15	-	0.43
30	16	-	1.24
30	17	0.03	0.64
30	18	0.50	-
30	19	-	1.85
30	20	0.33	-
30	21	0.07	-

Table 8. Average withdrawals from 1970 to 1980 as represented in the model - Concluded

[1/ Irrigation withdrawal in the model occurs for only 5 months of each year.]

Location		Irrigation withdrawals, in cubic feet per second 1/	Nonirrigation withdrawals, in cubic feet per second
Row	Column		
30	22	0.72	0.25
30	23	0.94	-
31	14	0.41	-
31	17	-	0.77
31	18	-	0.13
31	20	0.28	-
31	21	0.19	0.01
31	22	1.39	-
31	23	0.31	-
32	13	0.22	-
32	14	0.72	-
32	16	-	0.75
32	17	0.07	0.01
32	18	0.43	-
32	20	0.65	-
32	21	0.91	-
32	22	1.01	-
32	23	0.89	-
33	14	0.24	-
33	16	-	0.12
33	17	0.06	0.01
33	18	0.46	-
33	20	0.69	0.12
33	21	0.21	-
33	22	1.43	-
33	23	0.41	-
35	21	0.19	-

Simulated Response with No Additional Development

The simulated decline in water levels in 2000, after 20 years of pumping at the 1970-80 average rate, is shown in figure 17. The maximum decline of 31 feet occurred near the Texas State line northeast of Hobbs at node 26,23. Declines greater than 20 feet occurred over a large area north of Hobbs and east and northeast of Lovington in areas of extensive irrigation.

The simulated saturated thickness in 2000 is shown in figure 18. Thirty-two percent of the modeled area in Lea County had less than 50 feet of saturation. More than 150 feet of saturation occurred in eight percent of the area. Six percent of the area had less than 10 feet of saturation in 2000 compared to four percent in 1980. The saturated thickness in nodes 8,6 (southeast of Caprock) and 19,16 (northeast of Lovington) was reduced by pumping to less than 5 feet.

The amount of water remaining in the aquifer that could be recovered if the entire saturated thickness could be drained by gravity can be calculated from the specific yield and the simulated saturated thickness. In the simulation of no additional development, 24.6 million acre-feet of recoverable water remained in the aquifer in Lea County in 2000.

The water budget for the simulation to 2000 is shown in table 9. The total pumping rate in the model declined by 0.79 percent over the simulation period because pumping was stopped in the two nodes in which saturated thickness fell below 5 feet. The reduction in the head-dependent flux by 4.1 percent primarily resulted from the lowering of water levels, which decreased saturated thickness. The decrease in the rate of withdrawal from storage was a direct result of the decrease in discharge. The increase in the rate of evapotranspiration resulted from a rise in water levels in the area near Monument, the same area where a rise in water levels was measured during 1970 to 1980.

The simulated decline in the water surface in 2020, after 40 years of pumping with no additional development, is shown in figure 19. Declines of more than 50 feet occurred north of Hobbs. The maximum decline of 59 feet occurred in node 26,23 northeast of Hobbs.

The simulated saturated thickness in 2020 is shown in figure 20. Thirty-six percent of the modeled area in Lea County had less than 50 feet of saturation, and six percent of the area had more than 150 feet of saturation. Eight percent of the area had less than 10 feet of saturation. Fourteen nodes were pumped to less than 5 feet of saturation. The amount of water remaining in the aquifer in Lea County that could be recovered if the entire saturated thickness could be drained by gravity was 22.4 million acre-feet in 2020.

The water budget for the simulation to 2020 is shown in table 10. Saturated thickness in 14 pumping nodes fell to less than 5 feet, causing pumping to be stopped in those nodes. The total pumping rate in 2020 was 3.0 percent less than in 2000 and 3.7 percent less than in 1980 (table 9). Flow at head-dependent-flux nodes in 2020 was 5.9 percent less than in 2000 and 9.8 percent less than in 1980 (table 9).

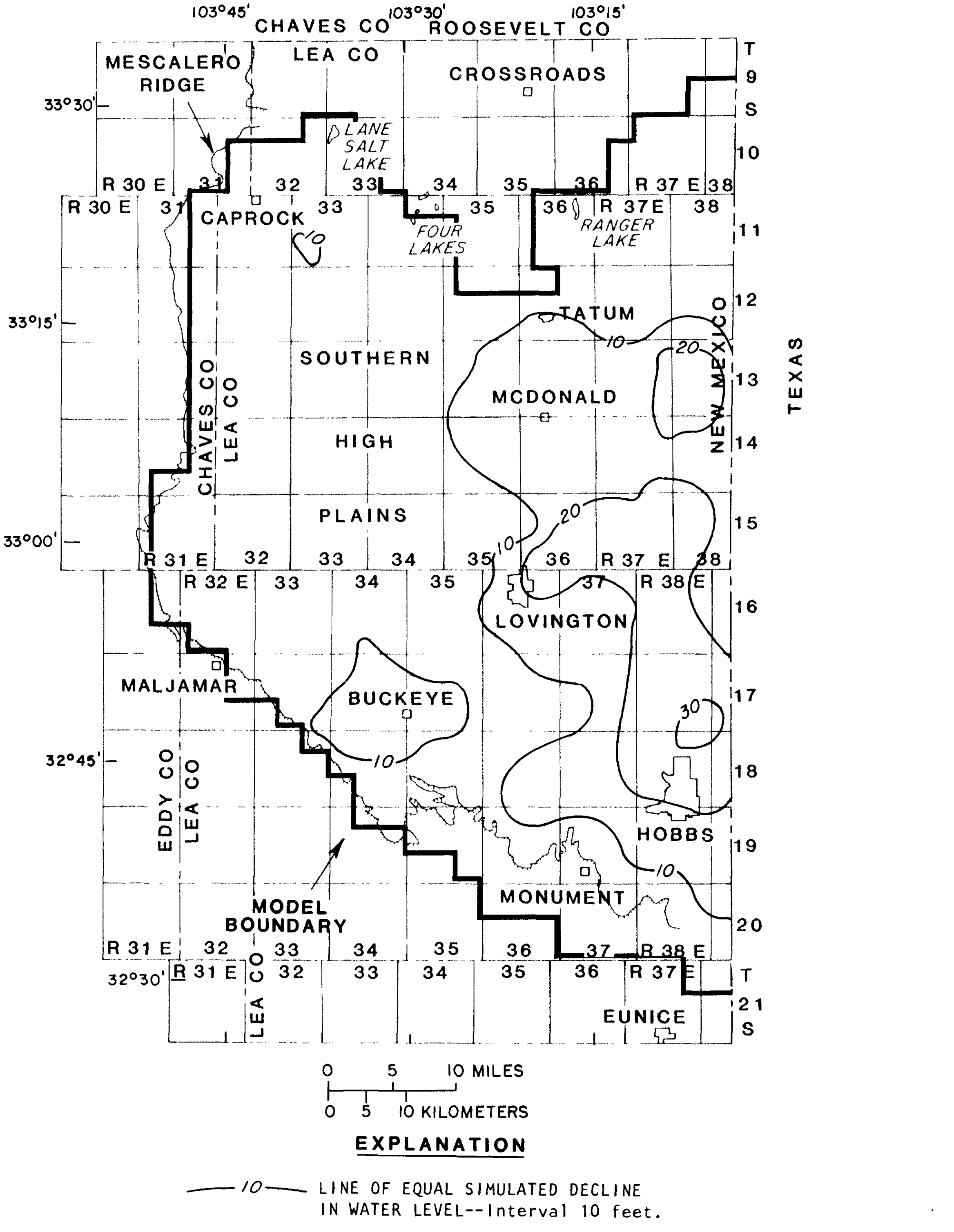


Figure 17.--Simulated decline in water levels (1980-2000) assuming 1970-80 average pumping rates.

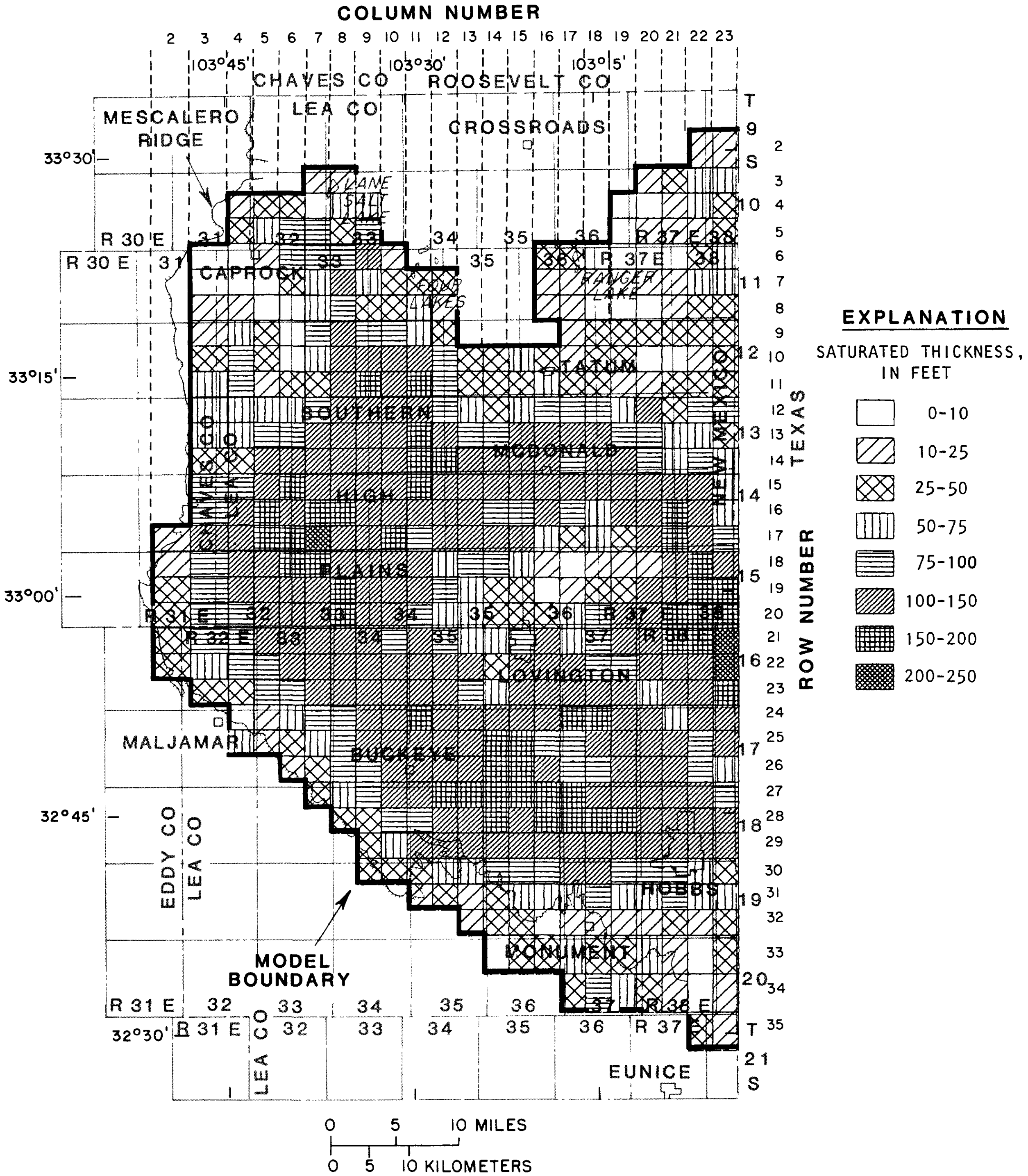
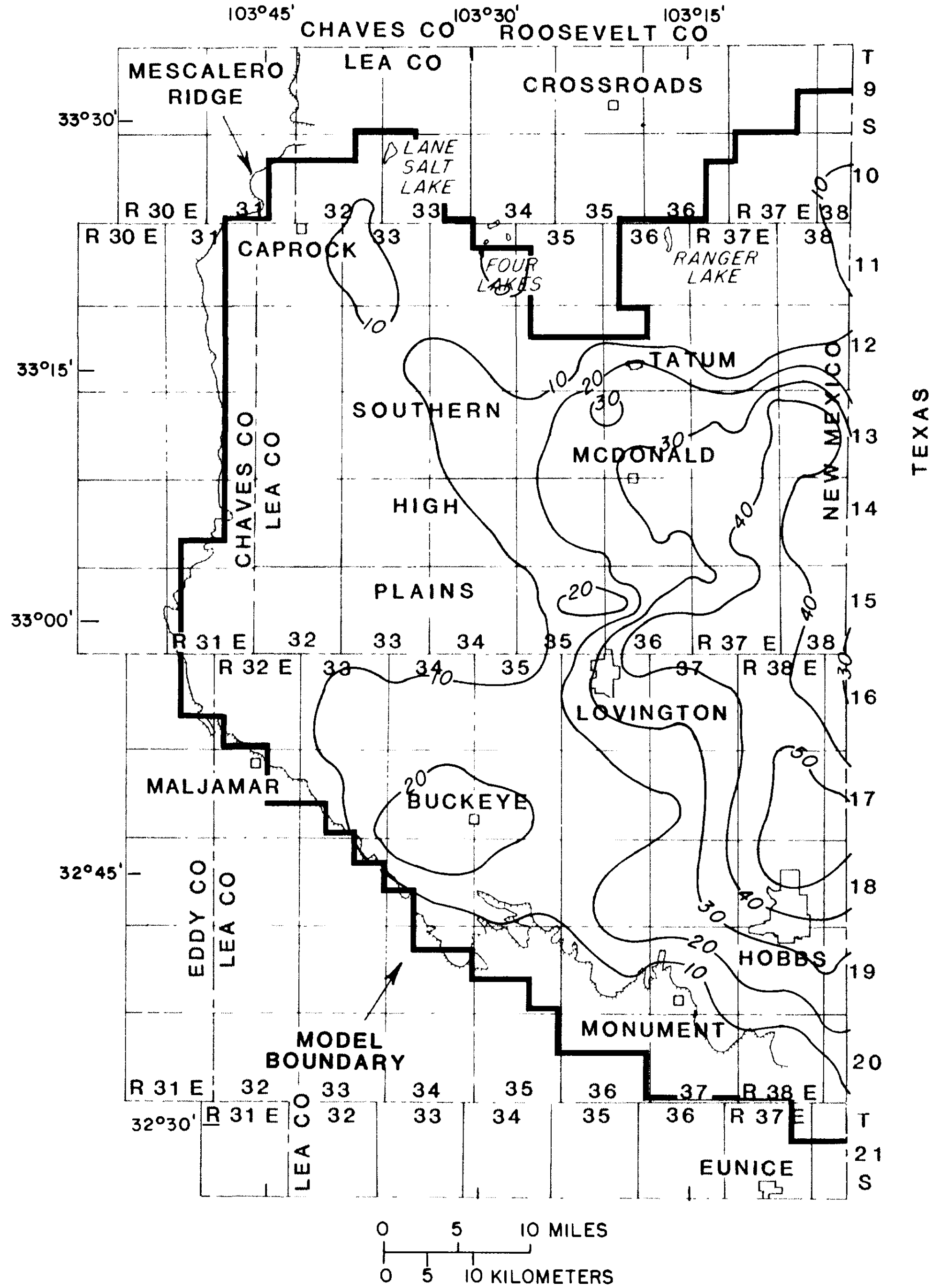


Figure 18.--Saturated thickness in 2000 simulated by the model assuming 1970-80 average pumping rates.

Table 9. Water budget for the 1980 to 2000 simulation assuming 1970 to 1980 average pumping rates

Description	Cumulative water budget, in acre-feet	Average flow for the first year in the simulation, in cubic feet per second	Average flow for the last year in the simulation, in cubic feet per second
Sources			
Storage	3,609,924	251.68	246.85
Recharge	1,360,108	93.93	93.93
Constant flux	18,823	1.30	1.30
Total	4,988,855	346.91	342.08
Discharges			
Pumping	3,899,361	270.11	267.97
Evapotranspiration	37,785	2.35	2.64
Constant flux	31,855	2.20	2.20
Head-dependent flux	1,029,775	72.50	69.51
Total	4,998,776	347.16	342.32
Discharges minus sources	9,921	0.25	0.24
Percent difference	0.20	0.07	0.07



EXPLANATION

30 LINE OF EQUAL SIMULATED DECLINE IN WATER LEVEL--Interval 10 feet.

Figure 19.--Simulated decline in water levels (1980-2020) assuming 1970-80 average pumping rates.

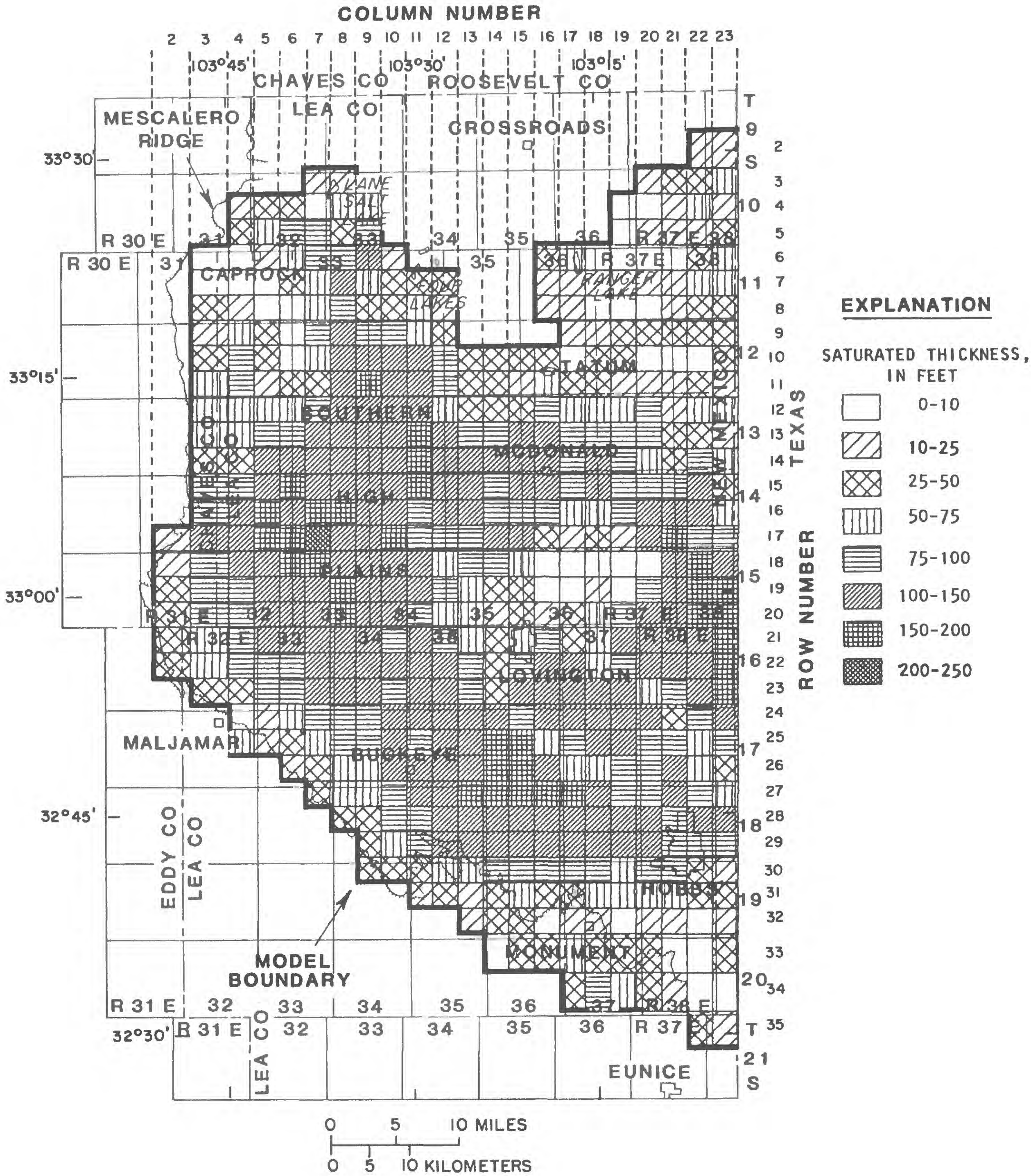


Figure 20.--Saturated thickness in 2020 simulated by the model assuming 1970-80 average pumping rates.

Table 10. Water budget for the 1980 to 2020 simulation assuming 1970 to 1980 average pumping rates

Description	Cumulative water budget, in acre-feet	Average flow for the last year in the simulation, in cubic feet per second
Sources		
Storage	7,102,062	234.70
Recharge	2,720,215	93.93
Constant flux	37,646	1.30
Total	9,859,923	329.93
Discharges		
Pumping	7,734,310	260.01
Evapotranspiration	74,700	2.31
Constant flux	63,709	2.20
Head-dependent flux	2,005,922	65.43
Total discharge	9,878,641	329.95
Discharges minus sources	18,718	0.02
Percent difference	0.19	0.01

Simulated Response with Increased Development

The simulated decline in the water surface in 2000, after 20 years of pumping with the previously stated increases in pumpage, is shown in figure 21. The maximum decline of 33 feet occurred near Hobbs in nodes 26,23 and 28,21.

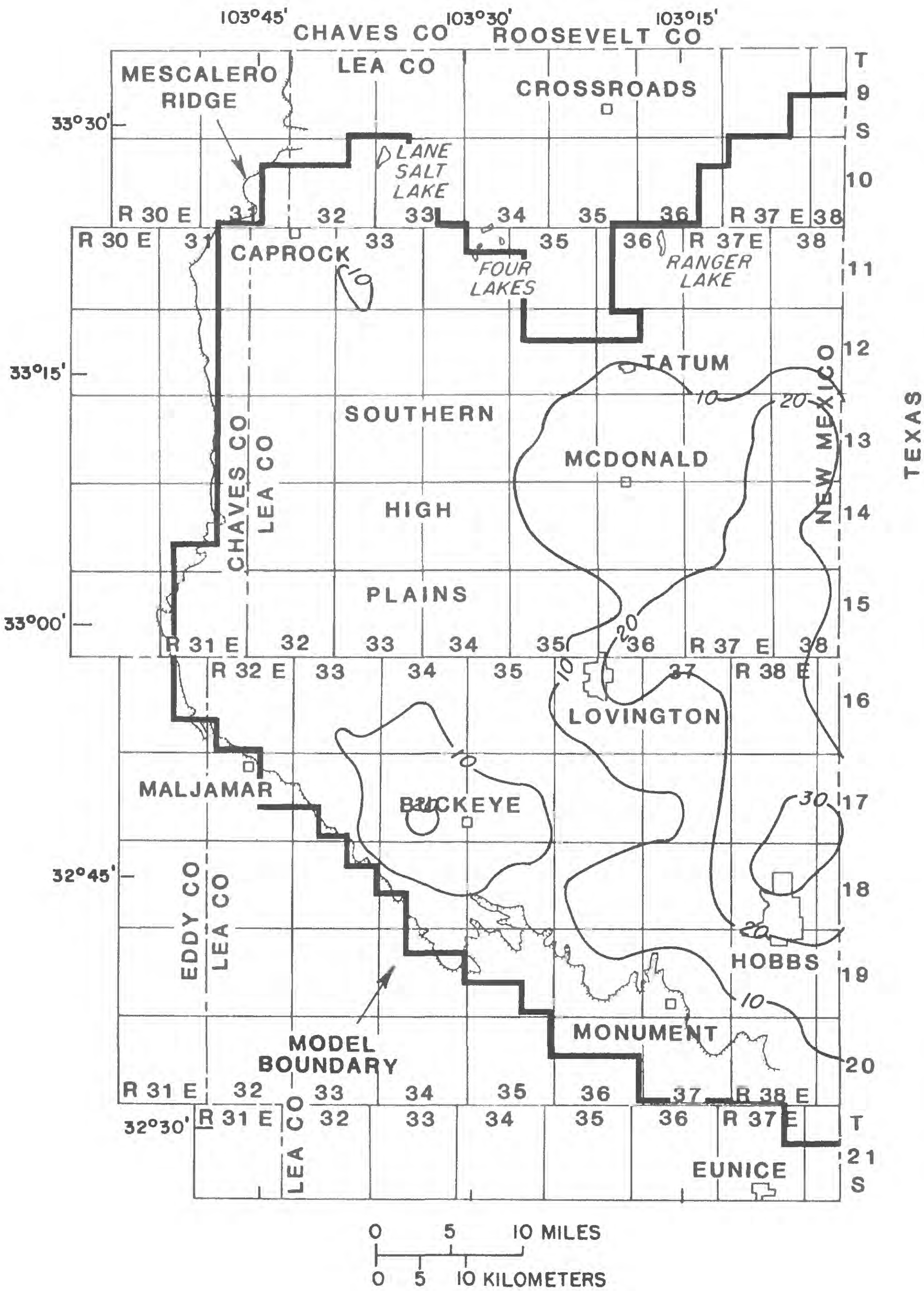
The simulated saturated thickness in 2000 is shown in figure 22. Thirty-two percent of the area had less than 50 feet of saturation, and eight percent had more than 150 feet. Six percent of the modeled area in Lea County had less than 10 feet of saturation. Nodes 8,6; 19,16; and 32,16 were pumped to less than 5 feet of saturation. The amount of water remaining in the aquifer in Lea County that could be recovered if the entire saturated thickness could be drained by gravity was 24.4 million acre-feet.

The water budget for the simulation to 2000 is shown in table 11. The average pumping rate at the end of the simulation was reduced by 2.67 cubic feet per second from the specified rate because pumping was stopped in three nodes where saturated thickness fell to less than 5 feet. The total amount of water pumped in this simulation was 6.1 percent greater than that pumped under the simulation with no additional development (table 9). Very little of this increase, 0.25 percent, was balanced by a decrease in evapotranspiration or head-dependent flux. Essentially all of the increased pumpage was withdrawn from storage.

The simulated decline in water levels in 2020, after 40 years of pumping with the previously stated increases in pumpage, is shown in figure 23. The maximum decline of 67 feet occurred in node 28,21 near Hobbs. Declines of more than 50 feet occurred west of Buckeye, northeast of Lovington, near the Texas State line in T. 13 S., R. 38 E., and over a large area north of Hobbs.

The simulated saturated thickness in 2020 is shown in figure 24. Thirty-six percent of the area had less than 50 feet of saturation, and five percent had more than 150 feet. Eight percent of the modeled area in Lea County had less than 10 feet of saturation. Seventeen nodes were pumped to less than 5 feet of saturation. The amount of water remaining in the aquifer in Lea County that could be recovered if the entire saturated thickness could be drained by gravity was 21.8 million acre-feet.

The water budget for the simulation to 2020 is shown in table 12. The average pumping rate at the end of the simulation was reduced by 15.7 cubic feet per second from the specified rate because pumping was stopped in 17 nodes where saturated thickness fell to less than 5 feet. The pumping rate was reduced to slightly less than the rate for the year 2000 (table 11). The total amount of water pumped in the simulation was 8.5 percent greater than that pumped under the simulation with no additional development (table 10). Again, all but a small amount of this increased pumpage was withdrawn from storage.



EXPLANATION

—20— LINE OF EQUAL SIMULATED DECLINE IN WATER LEVEL--Interval 10 feet.

Figure 21.--Simulated decline in water levels (1980-2000) assuming a 0.44 percent annual increase in irrigation withdrawals to 1990 and a 0.88 percent annual increase in nonirrigation withdrawals to 2020.

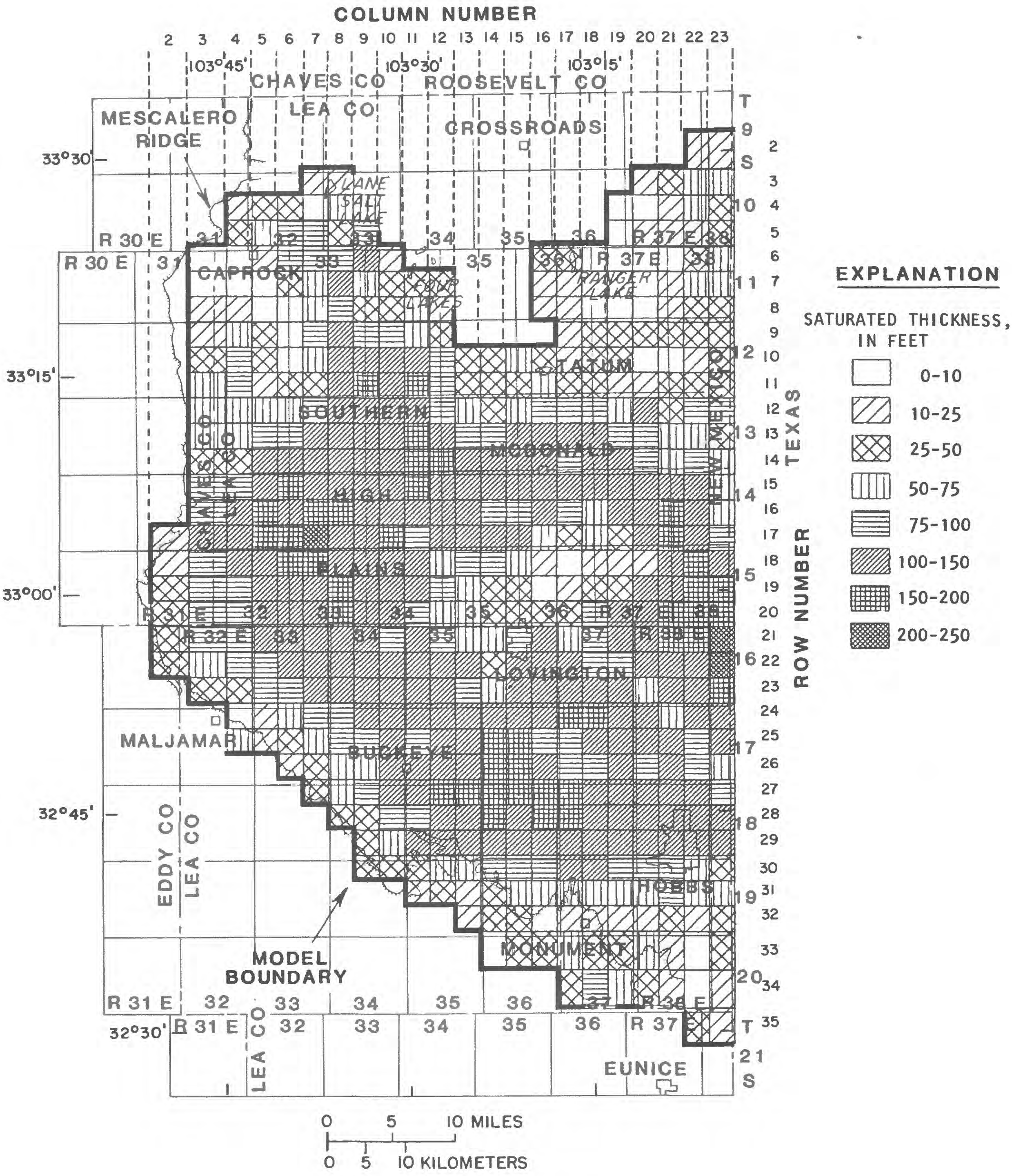
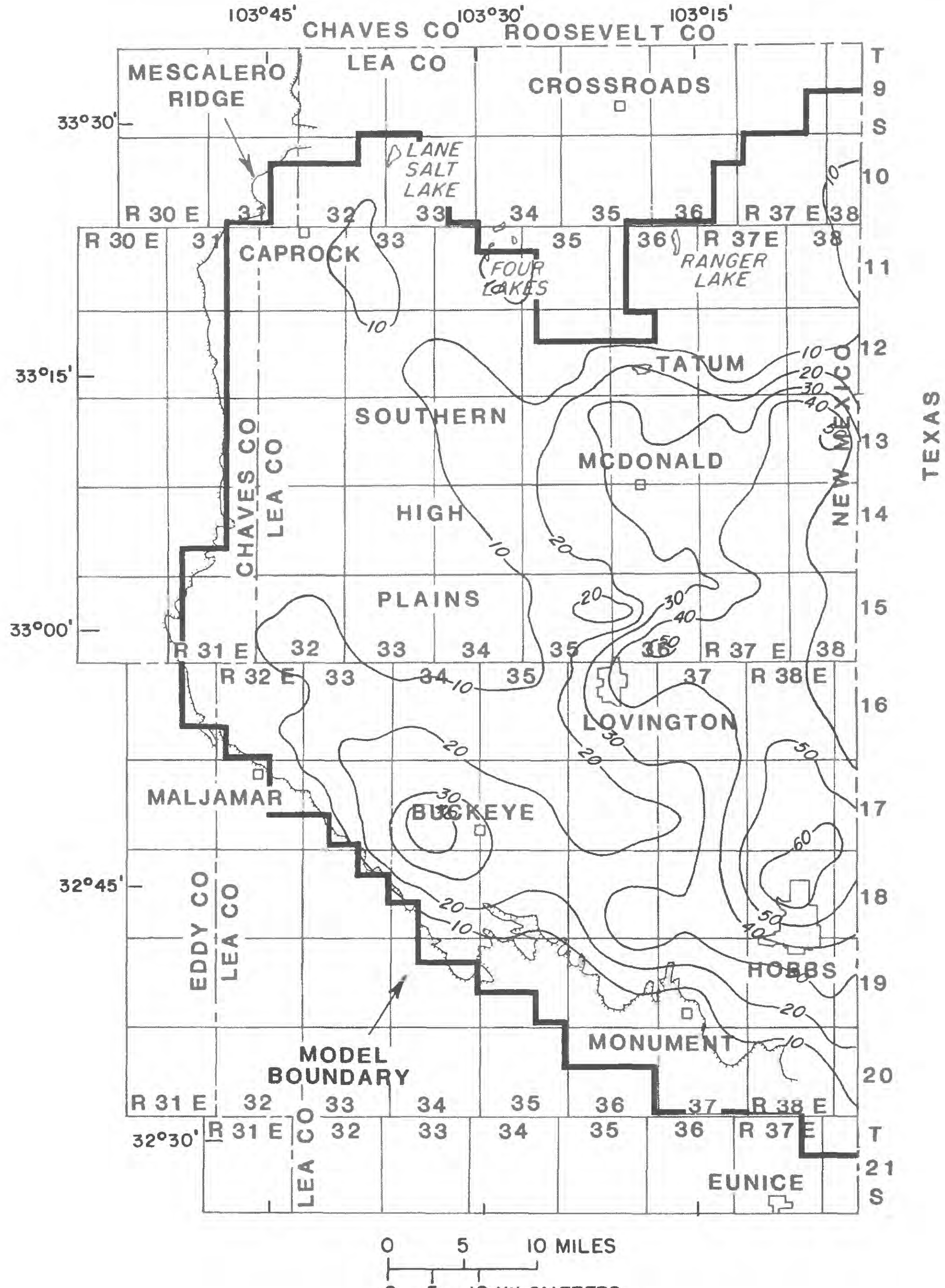


Figure 22.--Saturated thickness in 2000 simulated by the model assuming a 0.44 percent annual increase in irrigation withdrawals to 1990 and a 0.88 percent annual increase in nonirrigation withdrawals to 2020.

Table 11. Water budget for the 1980 to 2000 simulation assuming a 0.44 percent annual increase in irrigation withdrawals to 1990 and a 0.88 percent annual increase in nonirrigation withdrawals to 2020.

Description	Cumulative water budget, in acre-feet	Average flow for the first year in the simulation, in cubic feet per second	Average flow for the last year in the simulation, in cubic feet per second
Sources			
Storage	3,845,194	256.34	269.98
Recharge	1,360,108	93.93	93.93
Constant flux	18,823	1.30	1.30
Total	5,224,125	351.57	365.21
Discharges			
Pumping	4,135,304	274.66	291.17
Evapotranspiration	37,367	2.35	2.56
Constant flux	31,855	2.20	2.20
Head-dependent flux	1,029,596	72.50	69.44
Total	5,234,122	351.71	365.37
Discharges minus sources	9,997	0.14	0.16
Percent difference	0.19	0.04	0.04



EXPLANATION

—10— LINE OF EQUAL SIMULATED DECLINE IN WATER LEVEL--Interval 10 feet.

Figure 23.--Simulated decline in water levels (1980-2020) assuming a 0.44 percent annual increase in irrigation withdrawals to 1990 and a 0.88 percent annual increase in nonirrigation withdrawals to 2020.

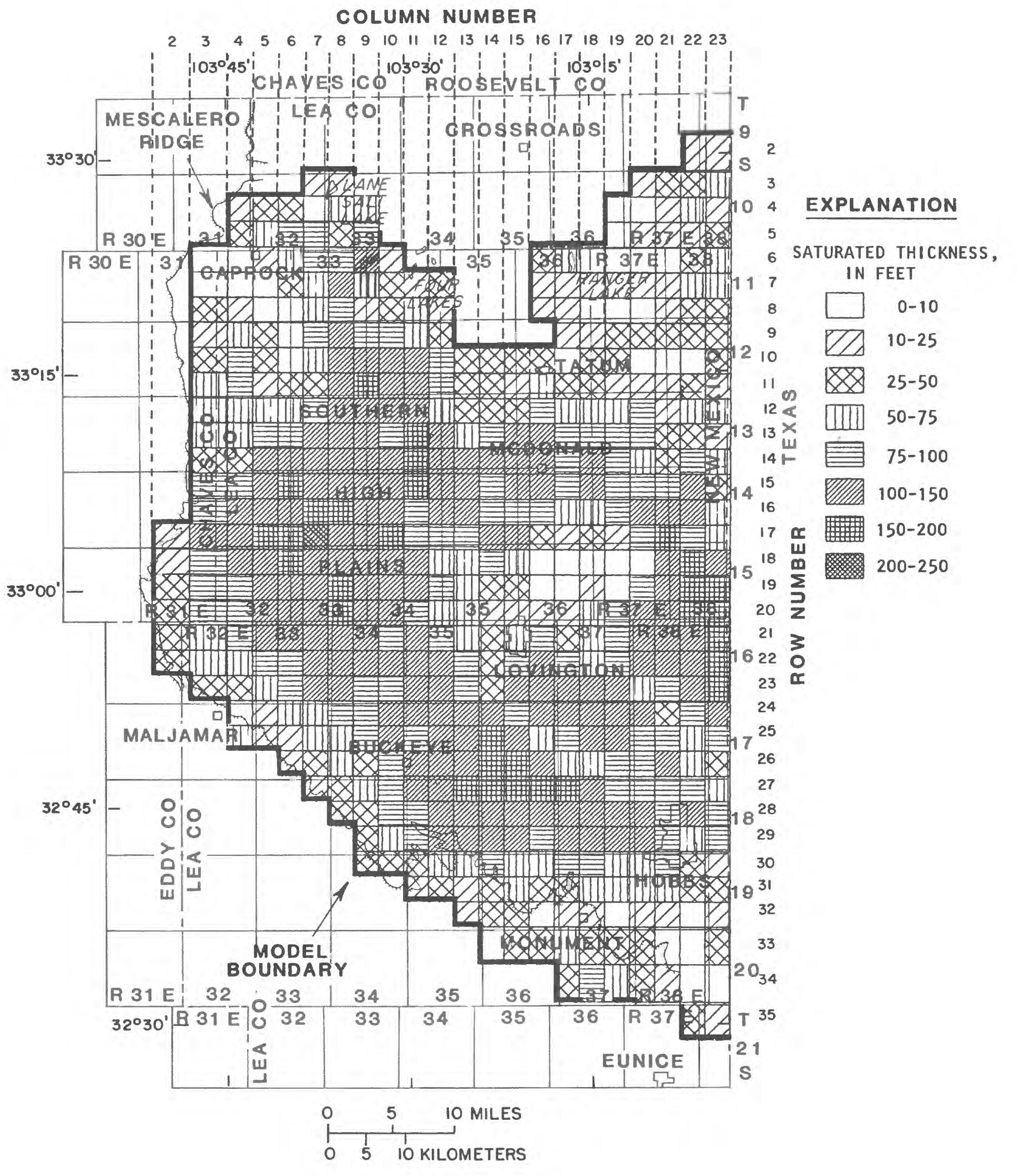


Figure 24.--Saturated thickness in 2020 simulated by the model assuming a 0.44 percent annual increase in irrigation withdrawals to 1990 and a 0.88 percent annual increase in nonirrigation withdrawals to 2020.

Table 12. Water budget for the 1980 to 2020 simulation assuming a 0.44 percent annual increase in irrigation withdrawals to 1990 and a 0.88 percent annual increase in nonirrigation withdrawals to 2020.

Description	Cumulative water budget, in acre-feet	Average flow for the last year in the simulation, in cubic feet per second
Sources		
Storage	7,754,715	265.10
Recharge	2,720,215	93.93
Constant flux	37,646	1.30
Total	10,512,576	360.33
Discharges		
Pumping	8,392,001	291.05
Evapotranspiration	72,046	2.06
Constant flux	63,709	2.20
Head-dependent flux	2,004,160	65.21
Total discharge	10,531,916	360.52
Discharges minus sources	19,340	0.19
Percent difference	0.18	0.05

MODEL SENSITIVITY

Modeled responses of the Ogallala aquifer to projected stresses must be viewed with consideration of how close the mathematical description of the model represents the actual system. A major assumption is that the recharge and aquifer characteristics in the model are similar to those in the Ogallala aquifer. As noted previously, these characteristics are not known with certainty. Therefore, the sensitivity of the model to variations in hydraulic conductivity, specific yield, and recharge was tested.

The sensitivity of the model to each characteristic was tested by varying that characteristic while holding the others constant. Each characteristic was varied so that the maximum and minimum values were near the bounds of the plausible range. This procedure produces a subjective measure of the uncertainty of the simulated response in relation to the uncertainty of values assigned to each characteristic.

Model sensitivity was tested for the simulated steady-state and transient conditions. The transient condition was tested using the simulation from 1980 to 2020 with no additional development.

Hydraulic Conductivity

The hydraulic conductivity used in the simulations described in the previous sections averaged 40 feet per day and ranged from 16 to 155 feet per day. The sensitivity of the model to hydraulic conductivity was tested using a uniform 10-percent increase and decrease in hydraulic conductivity. The maximum and minimum values used in the sensitivity tests approximate the plausible range of hydraulic conductivity.

Simulated Steady-State Response

Minor changes in the water levels occurred during the steady-state simulations due to the changes in hydraulic conductivity. Comparison of measured water levels with those simulated with 10 percent greater and 10 percent smaller hydraulic conductivity is shown in figure 25. This figure may be compared with the standard simulation shown in figure 8. With greater hydraulic conductivity, simulated water levels for nodes with measured values averaged 12.6 feet lower than in the standard simulation. The simulation with smaller hydraulic conductivity produced water levels that averaged 10.4 feet higher than those in the standard simulation.

In the simulation with larger hydraulic conductivity, the maximum change in water levels from the standard simulation was an increase of 51.9 feet at node 9,3. The water-level rise resulted from adjacent nodes going dry, which restricted outflow from the node. In the simulation with smaller hydraulic conductivity, the maximum change in water levels from the standard simulation was an increase of 17.3 feet at node 8,6. The maximum changes for both simulations occurred in an area where little data were available on hydraulic conductivity.

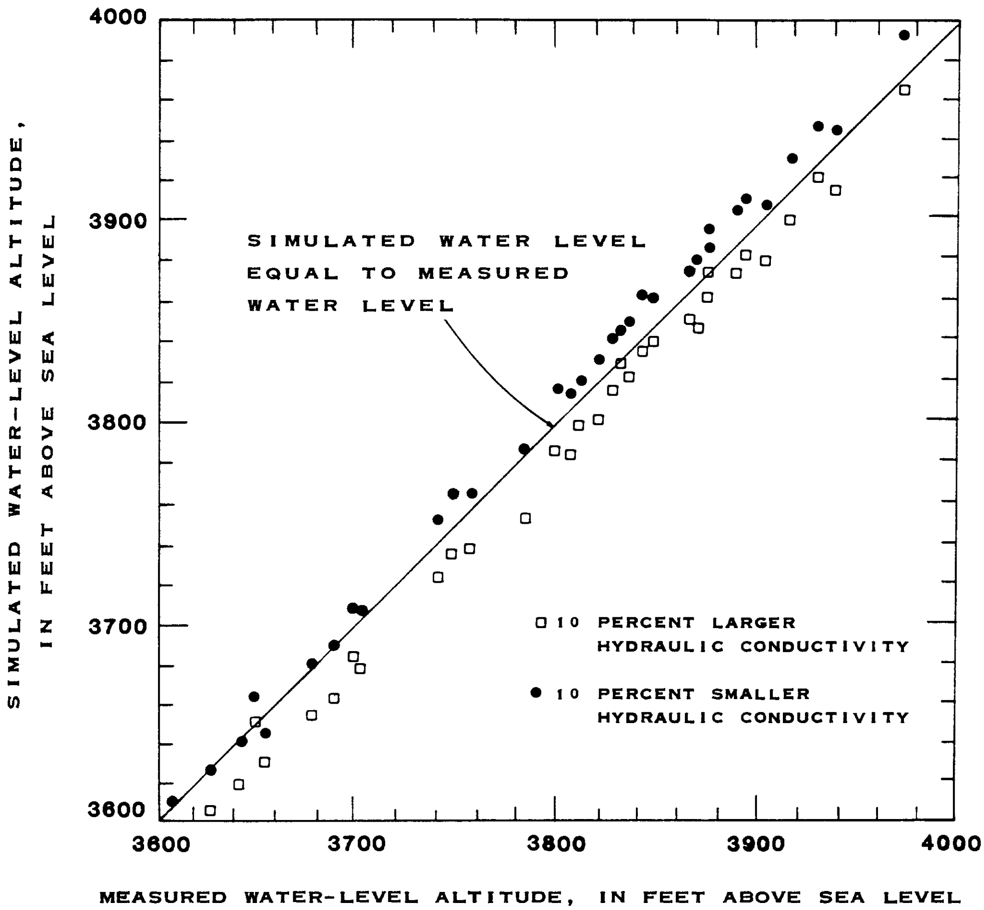


Figure 25.--Comparison between measured water levels for selected wells in Lea County and those simulated by assuming 10 percent larger and and 10 percent smaller hydraulic conductivity.

Minor changes in the simulated water budget resulted from adjusting hydraulic conductivity. The decrease in water levels using the greater hydraulic conductivity resulted in a 17-percent decrease in evapotranspiration compared to the standard simulation (table 3). The total recharge in the model was reduced by 2.0 percent because more nodes went dry and the head-dependent flux was reduced by 0.90 percent. The simulation with smaller hydraulic conductivity resulted in a 13-percent increase in evapotranspiration and a 0.81-percent decrease in head-dependent flux compared to the standard simulation. An increase in total recharge of 0.14 percent resulted from fewer nodes going dry.

Simulated Transient Response

Small changes in water levels occurred during the transient simulations due to variation in hydraulic conductivity. An increase in hydraulic conductivity resulted in smaller water-level declines than that obtained from the standard simulation in areas with large withdrawals relative to adjacent areas. Nodes in the areas away from the large withdrawals had greater water-level declines. With decreased hydraulic conductivity, areas with large withdrawals had greater declines and areas away from the large withdrawals had smaller declines. This response results from the increased ability of the aquifer with greater hydraulic conductivity to transmit water to pumping areas, and the decreased ability with smaller hydraulic conductivity.

At the end of the 1980 to 2020 simulation, changes in hydraulic conductivity caused less than 1 foot of change in water levels from those of the standard simulation at seven of the nine nodes shown in figure 14. Compared to the standard simulation for water levels at node 9,5, larger hydraulic conductivity resulted in an additional decline of 1.7 feet, and smaller hydraulic conductivity resulted in a decline that was 1.8 feet smaller (fig. 26A). At node 26,9, the larger conductivity caused a decline that was 2.4 feet smaller, and the smaller conductivity resulted in an additional 2.9 feet of decline (fig. 26B).

The maximum water-level declines at a single node were 57.5 feet for the simulation with larger hydraulic conductivity, 59.9 feet for the simulation with smaller hydraulic conductivity, and 58.8 feet for the standard simulation. In the simulation with larger hydraulic conductivity, the maximum change from the standard simulation was a 4.4-foot smaller decline at node 18,16. In the simulation with smaller hydraulic conductivity, the maximum change from the standard simulation was an additional decline of 4.4 feet at node 13,23.

Minor changes in the water budget of the standard simulation (table 10) resulted from adjusting hydraulic conductivity. With increased hydraulic conductivity, withdrawal from storage increased 0.43 percent, evapotranspiration increased 7.3 percent, and head-dependent flux increased 1.2 percent compared to the standard simulation. With decreased hydraulic conductivity, withdrawal from storage decreased 0.46 percent, evapotranspiration decreased 7.6 percent, and head-dependent flux decreased 1.2 percent compared to the standard simulation. In both simulations, pumping varied from the standard simulation by less than 0.1 percent.

The 10-percent increase or decrease in hydraulic conductivity resulted in less than a 3-percent change in projected water-level declines. Thus, the uncertainty of hydraulic conductivity within its plausible range is not critical. Therefore, the projected water levels were considered to be relatively insensitive to hydraulic conductivity.

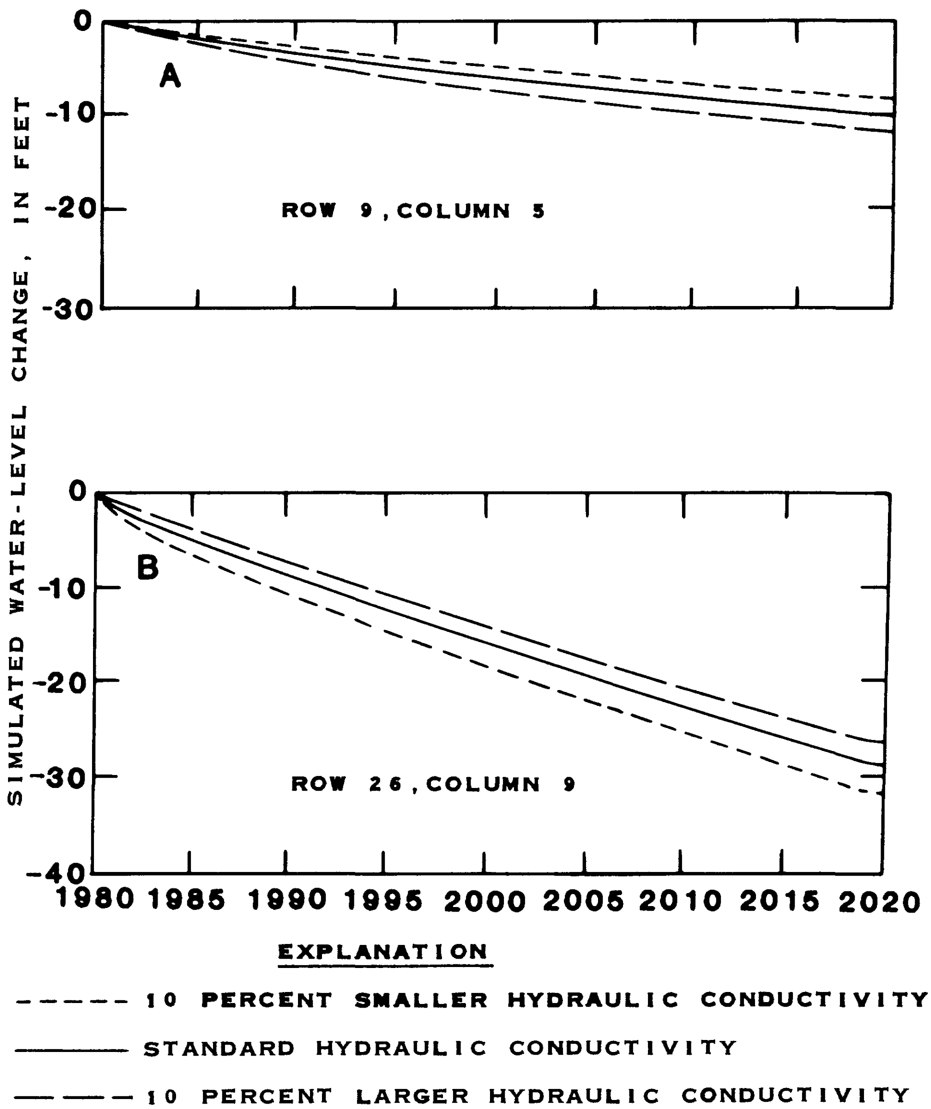


Figure 26.--Sensitivity of change in water level at selected nodes to variations in hydraulic conductivity.

Specific Yield

The specific yield used in the simulations described in the previous sections averaged 0.20 and ranged from 0.12 to 0.25. The sensitivity of the model to specific yield was tested using a uniform 10-percent increase and decrease in specific yield. The maximum and minimum values used in the sensitivity tests approximate the plausible range of specific yield.

The steady-state simulation is independent of specific yield. Therefore, the sensitivity of the model to specific yield was tested only for the transient simulations.

The simulated transient response of the model is affected by adjustments in specific yield. Specific yield represents the ratio of the volume of water taken from storage to the total volume of saturated sediments that have drained by gravity. By decreasing specific yield, greater water-level declines occur due to a greater amount of sediments being drained to produce an equal amount of water withdrawn.

At the end of the simulations with changes in specific yield, four of the nine nodes shown in figure 14 deviated less than 1 foot from the water levels of the standard simulation. All of these nodes had 10 feet or less decline in the standard simulation. The sensitivity to specific yield at the other five locations is shown in figures 27 and 28. The degree of variation from the standard simulation generally increases with greater water-level declines. The sharp change in the rate of water-level decline for the simulation with small specific yield between 2015 and 2020 (fig. 28B) is due to the saturated thickness in node 32,22 falling to less than 5 feet and pumping being stopped.

The maximum water-level decline in the Lea County part of the model was 53.8 feet for the simulation with large specific yield, 64.5 feet for the simulation with small specific yield, and 58.8 feet for the standard simulation. The greatest deviation from the standard simulation in water-level decline for any node in the model was 4.8 feet less decline at node 26,23 (large specific yield) and 6.2 feet more decline at node 12,21 (small specific yield).

Little change to the simulated water budget (table 10) occurred because of variation in specific yield. With the increased specific yield, withdrawal from storage increased 0.32 percent, evapotranspiration increased 0.79 percent, head-dependent flux increased 0.47 percent, and pumping increased 0.19 percent compared to the standard simulation. With decreased specific yield, withdrawal from storage decreased 0.41 percent, evapotranspiration decreased 1.2 percent, head-dependent flux decreased 0.57 percent, and pumping decreased 0.24 percent compared to the standard simulation.

The 10-percent increase or decrease in specific yield, which approximated its plausible range, resulted in about a 10-percent change in projected water-level declines. Therefore, the projected water levels were sensitive to specific yield.

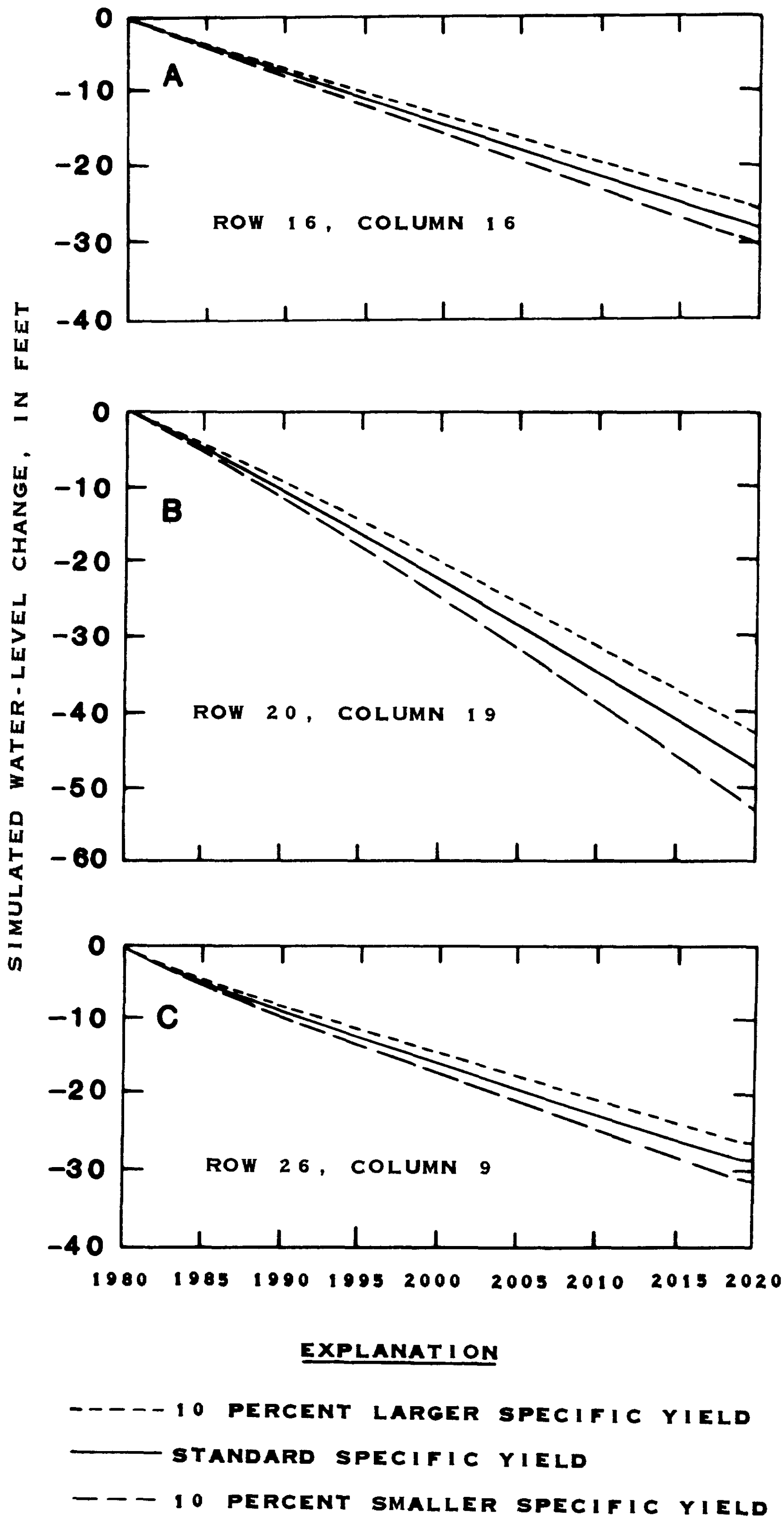


Figure 27.--Sensitivity of change in water level at nodes 16,16; 20,19; and 26,9 to variations in specific yield.

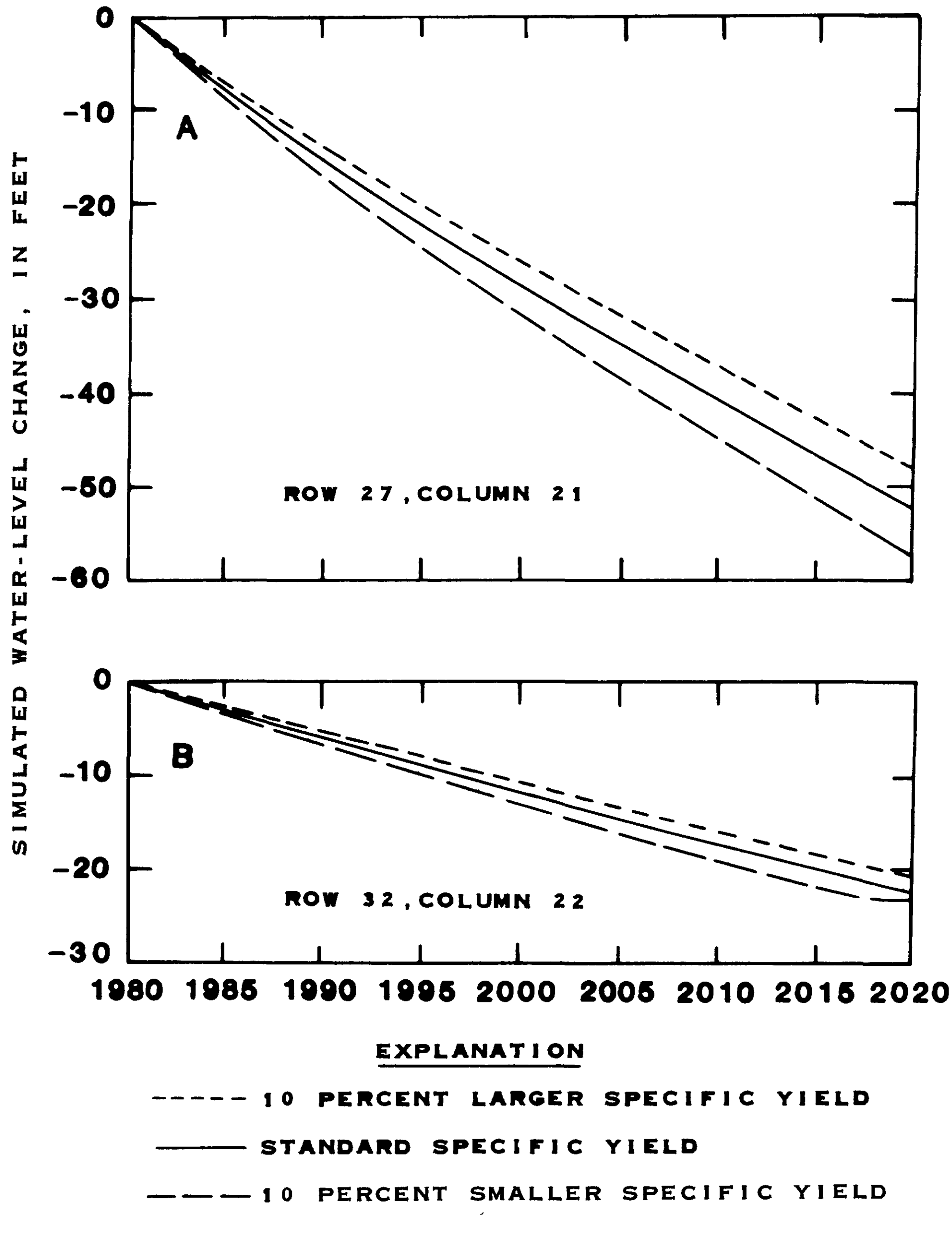


Figure 28.--Sensitivity of change in water level at nodes 27,21 and 32,22 to variations in specific yield.

Recharge

The recharge used in the simulations described in the previous sections averaged 0.38 inch per year over the model's area. The sensitivity of the model to recharge was tested by simulations with a 20-percent increase and decrease in recharge.

Simulated Steady-State Response

Changes in the simulated steady-state water levels resulted from variations in recharge. A comparison of measured water levels with those simulated using 20 percent greater and 20 percent smaller recharge is shown in figure 29. With greater recharge, simulated water levels for nodes with measured values averaged 20.7 feet higher than in the standard simulation (fig. 8). With smaller recharge, simulated water levels averaged 44.0 feet lower than in the standard simulation (fig. 8). Fewer points are shown for smaller recharge because several nodes went dry before steady state was attained. The maximum difference in water level in the simulation with greater recharge was 33.6 feet higher than the standard simulation at node 3,8. The maximum difference in the simulation with smaller recharge was 113 feet lower than the standard simulation at node 20,18.

An adjustment in the simulated water budget because of changes in recharge was necessary to achieve steady state. The 20-percent increase in recharge resulted in an 18 percent greater head-dependent-flux outflow and a 56 percent greater evapotranspiration rate than in the standard simulation (table 3). The 20-percent reduction in recharge caused an overall reduction in total recharge of 46 percent because 240 nodes went dry before steady state was attained, a 43-percent decrease in head-dependent flux, and an 83-percent decrease in evapotranspiration.

The response of the steady-state model to reduced recharge may be more extreme than the physical system's response. Dry nodes in the model exclude any inflow or outflow, thereby allowing no recharge. This is unrepresentative of the physical system. However, the simulation does show that the steady-state system was sensitive to reduced recharge.

Simulated Transient Response

Small changes in the simulated transient response occurred because of variation in recharge. An increase in recharge resulted in smaller water-level declines than in the standard simulation, and a decrease resulted in greater water-level declines.

At the end of the simulations with changes in recharge, two of the nine nodes shown in figure 14 had less than 1 foot of variation in water level from the standard simulation. The sensitivity to recharge at the other seven locations is shown in figures 30 and 31.

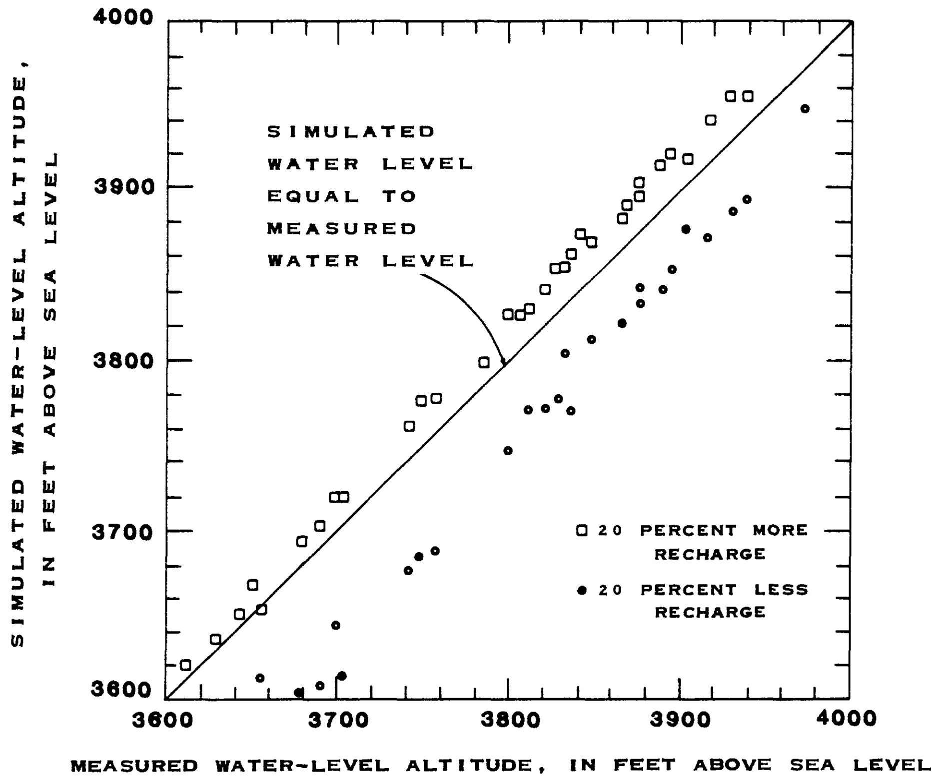


Figure 29.--Comparison between measured water levels for selected wells in Lea County and those simulated by assuming 20 percent more and 20 percent less recharge.

The maximum water-level decline in the model was 57.3 feet for the simulation with more recharge, 59.9 feet for the simulation with less recharge, and 58.8 feet for the standard simulation. The greatest deviation from the standard simulation in water-level decline for any node in the model occurred at node 12,21. The water-level decline was 3.3 feet smaller in the simulation with more recharge and 3.5 feet greater in the simulation with less recharge.

Changes in the simulated water budget resulted from adjustments in recharge. The 20-percent increase in recharge from the standard simulation resulted in a 7.2-percent decrease in withdrawal from storage, a 6.6-percent increase in evapotranspiration, a 0.76-percent increase in head-dependent flux, and a 0.12-percent increase in pumpage (table 10). The 20-percent decrease in recharge resulted in a 7.2-percent increase in withdrawal from storage, a 6.6-percent decrease in evapotranspiration, a 0.76-percent decrease in head-dependent flux, and a 0.13-percent decrease in pumpage.

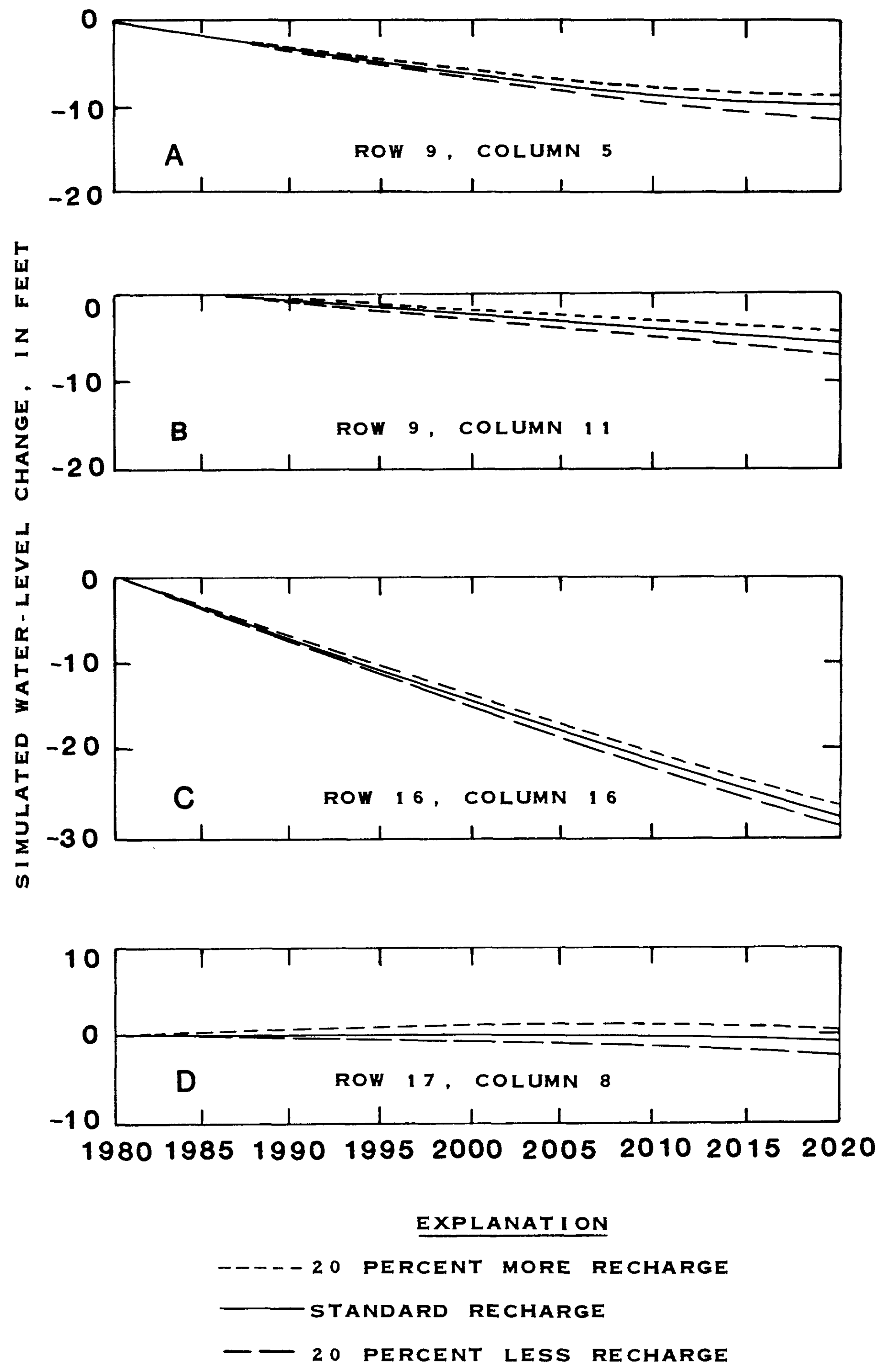


Figure 30.--Sensitivity of change in water level at nodes 9,5; 9,11; 16,16; and 17,8 to variations in recharge.

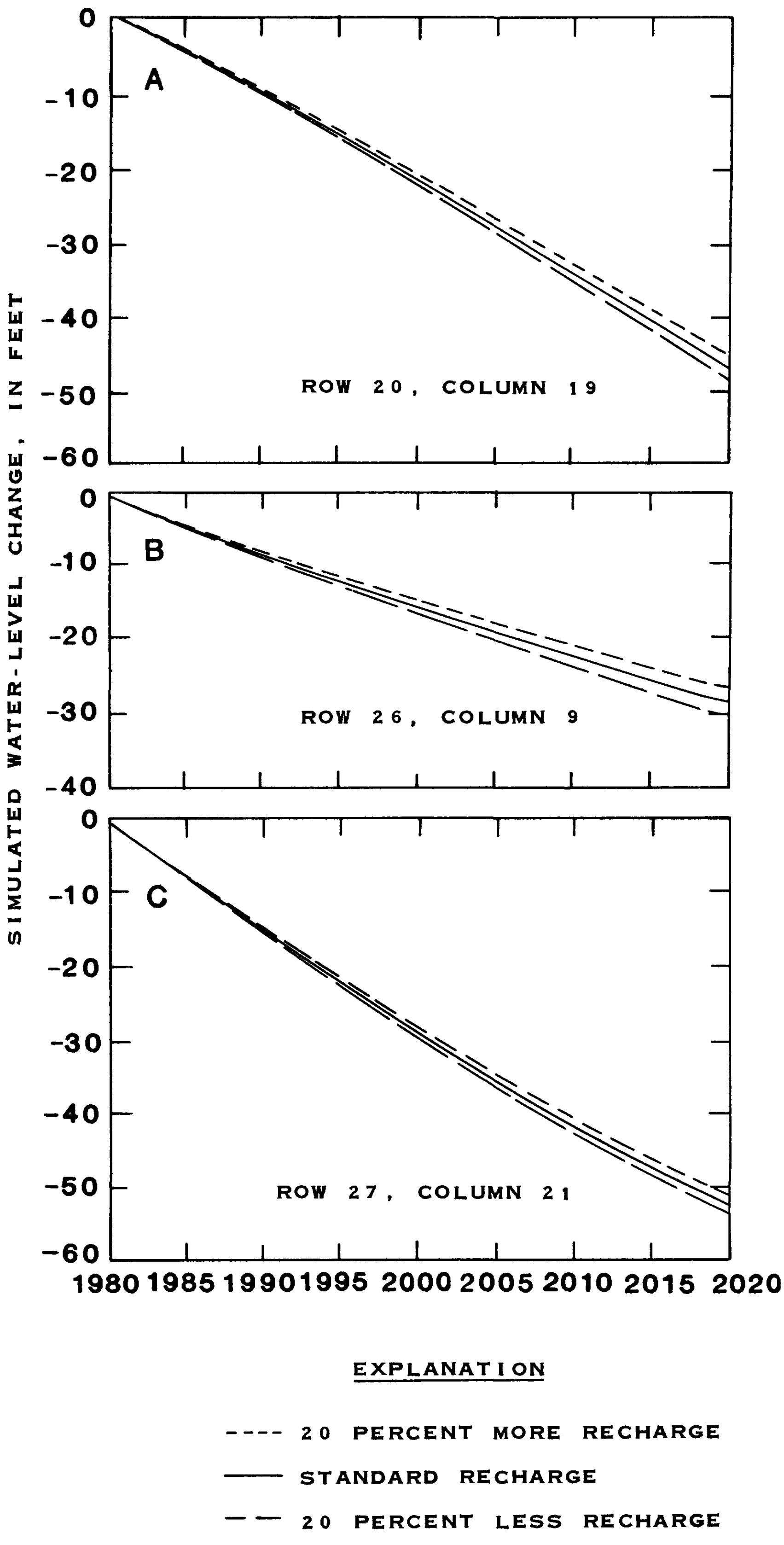


Figure 31.--Sensitivity of change in water level at nodes 20,19; 26,9; and 27,21 to variations in recharge.

The changes in recharge resulted in less than a 3-percent change in maximum projected water-level declines and less than 4 feet of change in projected decline at any node. Thus, the uncertainty of recharge within its plausible range of values was not critical. Therefore, the projected water levels were considered to be relatively insensitive to recharge.

Uncertainty in Projected Response

A subjective measure of the uncertainty of the modeled response in relation to the uncertainty in values of hydraulic conductivity, specific yield, and recharge was evaluated by the described sensitivity tests. Each characteristic was varied in the model so that the values approximately covered its plausible range in the modeled area.

The projected maximum water-level declines are shown in table 13. Simulated water-level declines were most sensitive to changes in specific yield; the maximum decline varied 9 to 10 percent from the 58.8 feet projected in the standard simulation. Variations in hydraulic conductivity and recharge resulted in less than a 3-percent change in maximum decline. The maximum deviation in water levels from the standard simulation at any node in the model is shown in table 14.

Table 13. Projected maximum decline in water level (in feet) in 2020, assuming 1970 to 1980 average pumping rates

[Maximum decline in standard simulation was 58.8 feet]

Characteristic varied	Large value	Small value
Hydraulic conductivity (±10 percent)	57.5	59.9
Specific yield (±10 percent)	53.8	64.5
Recharge (±20 percent)	57.3	59.9

Table 14. Maximum deviation in projected water-level altitude (in feet) in 2020, assuming 1970 to 1980 average pumping rates

Characteristic varied	Large value	Small value
Hydraulic conductivity (±10 percent)	4.4	- 4.4 *
Specific yield (±10 percent)	4.8	- 6.2
Recharge (±20 percent)	3.3	- 3.5

* Altitudes lower than the standard simulation are indicated by a minus sign.

SUMMARY

A two-dimensional digital ground-water flow model was constructed for the Ogallala aquifer in Lea County, New Mexico. Values of recharge, hydraulic conductivity, and specific yield were adjusted within their plausible range of uncertainty to find the best fit between the simulated and measured water levels of the predevelopment steady-state condition and the 1970 to 1973 pumping period. The average hydraulic conductivity used in the model was 40 feet per day, the average specific yield was 0.20, and the average annual recharge was 0.38 inch. The 1970 to 1980 pumping period was also simulated. The mean error associated with the steady-state simulation, calculated as the difference between the measured and simulated water levels, was 1.9 feet, and the mean absolute difference was 5.5 feet. The mean difference for the 1970 to 1980 simulation was 0.57 foot, and the mean absolute difference was 9.1 feet. The simulation of water levels by the model is considered to be acceptable.

Projections of water-level declines for future pumping scenarios were made on the basis of (1) no additional development, and (2) increased withdrawals. The second scenario consisted of a 0.88 percent annual increase in the 1970-80 average nonirrigation withdrawal to 2020 and a 0.44 percent annual increase in the 1970-80 average irrigation withdrawal to 1990.

With no additional development, the maximum water-level decline from 1980 water levels was 31 feet in 2000 and 59 feet in 2020. The amount of water remaining in the aquifer that could be recovered if the entire saturated thickness could be drained by gravity was 24.6 million acre-feet in 2000 and 22.4 million acre-feet in 2020 compared to an estimated 28 million acre-feet in 1980.

With increased withdrawals, maximum declines from 1980 water levels were 33 feet in 2000 and 67 feet in 2020. The amount of water remaining in the aquifer that could be recovered if the entire saturated thickness could be drained by gravity was 24.4 million acre-feet in 2000 and 21.8 million acre-feet in 2020.

The sensitivity tests indicated that water-level decline was most sensitive to specific yield. With no additional development, maximum simulated water-level declines in 2020 varied from the standard simulation by about 10 percent as a result of a 10-percent increase or decrease in specific yield. The maximum deviation in water level from the standard simulation for any node in the model was 6.2 feet as a result of changes in specific yield. Changes in the values of recharge and hydraulic conductivity resulted in less than a 3-percent change in maximum decline.

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