DIGITAL SIMULATION OF GROUND-WATER FLOW IN THE HIGH PLAINS AQUIFER IN PARTS OF COLORADO, KANSAS, NEBRASKA, NEW MEXICO, OKLAHOMA, SOUTH DAKOTA, TEXAS, AND WYOMING

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1400-D

Digital Simulation of Ground-Water Flow in the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming

By RICHARD R. LUCKEY, EDWIN D. GUTENTAG, FREDERICK J. HEIMES, *and* JOHN B. WEEKS

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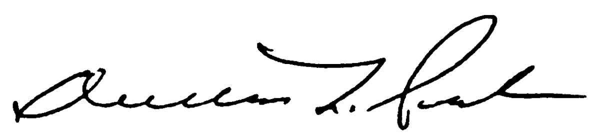
FOREWORD

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 after a Congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed, hydrologic system, and of any changes brought about by human activities, as well as to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and, where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and, thereafter, will continue in numerical sequence as the interpretive products of subsequent studies become available.



Dallas L. Peck
Director

PREFACE

The Regional Aquifer-System Analysis of the High Plains was conducted by U.S. Geological Survey personnel in each of the eight States in the High Plains—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. To provide assistance, technical support, and additional information, contracts were awarded to the Kansas Geological Survey, New Mexico Natural Resources Department, Oklahoma Water Resources Board, and Texas Department of Natural Resources. In addition, valuable information was provided by many other State and local agencies throughout the High Plains. Their contributions are an integral part of this investigation without which this report would not have been possible.

The U.S. Geological Survey coordinated its investigation of the High Plains aquifer with a concurrent study by the Economic Development Administration of the U.S. Department of Commerce. The Six-State High Plains- Ogallala Aquifer Area Study by the Ecomomic Development Administration was authorized by Congress in 1976. The study was charged with the responsibility of examining the feasibility of increasing water supplies to ensure the economic growth and vitality of the High Plains. Together, these two studies will provide a comprehensive evaluation of the High Plains aquifer and the potential impacts of declining ground-water supplies on the region. The Economic Development Administration study will develop and propose alternative strategies to alleviate or mitigate those impacts and the U.S. Geological Survey has provided hydrologic data and models needed to evaluate the effects of those strategies on the ground-water resource.

CONVERSION FACTORS

The following report uses inch-pound units as the primary system of measurement. The units commonly were abbreviated using the notations shown below in parentheses. Inch-pound units can be converted to metric units by multiplying by the factors given in the following list.

Multiply inch-pound unit	By	To obtain metric units
inch per year (in./yr)	2.540×10^{1}	millimeter per year
foot (ft)	3.048×10^{-1}	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	9.290×10^{-2}	square meter
acre	4.047×10^{-1}	hectare
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1.233×10^{-3}	cubic hectometer
acre-foot per year (acre-ft/yr)	1.233×10^{-3}	cubic hectometer per year
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second
gallon per minute (gal/min)	6.308×10^{-2}	liter per second
foot per day (ft/d)	3.048×10^{-1}	meter per day

National Geodetic Vertical Datum of 1929 (NGVD): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called *"Mean Sea Level."*

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By RICHARD R. LUCKEY, EDWIN D. GUTENTAG, FREDERICK J. HEIMES, and JOHN B. WEEKS

ABSTRACT

The flow system in the High Plains aquifer was simulated using a digital, finite-difference technique to solve the ground-water flow equation. The High Plains was divided into three parts—the southern High Plains, central High Plains, and northern High Plains—with each part simulated separately. A regular network of nodes spaced 10 miles apart in both the north-south and east-west directions was used. Predevelopment and development periods were simulated for each area of the High Plains. In the predevelopment simulations, hydraulic conductivity and recharge from precipitation were adjusted to best fit the simulated water levels with the observed water levels. In the development-period calibrations, which were from 20 to 40 years, return flow from pumpage and additional stresses caused by human activities were varied to obtain the best correspondence between observed and simulated water levels or water-level changes.

For the southern High Plains, the estimated predevelopment recharge ranged from 0.086 to 1.03 inches per year. The mean difference between the observed and simulated water levels was +0.22 foot with a standard deviation of 41.6 feet. The estimated predevelopment recharge in the central High Plains ranged from 0.056 to 0.84 inch per year. The mean difference between observed and simulated water levels was −0.28 foot. with a standard deviation of 38.5 feet. The estimated predevelopment recharge in the northern High Plains ranged from 0.075 to 1.52 inches per year. The mean difference between the observed and simulated water levels was +0.30 foot with a standard deviation of 55.2 feet.

Two development periods, 1940–60 and 1960–80, were used for calibration of the southern High Plains model. For each period the best correspondence between observed and simulated water levels was achieved when return flow was adjusted such that net withdrawal (total pumpage minus return flow) equaled 90 percent of the estimated irrigation requirement. During the 1960–80 period, an additional 2 inches of recharge were simulated on all irrigated land. The mean difference between observed and simulated water levels for the first simulation period (1940–60) was −0.22 foot. and the mean difference for the second simulation period (1960–80) was +0.28 foot. The simulated change in storage for the period 1940–60 was 19 percent less than the observed change in storage for the same period, whereas the simulated change in storage for the period 1960–80 was 2 percent more than the observed change in storage. The simulated change in storage for the entire development period (1940–80) was 7 percent less than the observed change in storage. The historical change in storage was estimated on the basis of water-level change in the area times the estimated specific yield of the aquifer.

Only one development period, 1950–80, was simulated for the central High Plains. The model was calibrated using water-level change instead of water level because the water level had not changed as much as it had in the southern High Plains. The best correspondence between observed and simulated water-level change was obtained when irrigation return flow was adjusted such that net withdrawal equaled 100 percent of the estimated irrigation requirement. On a volumetric basis, the simulated change was 9 percent less than the observed change; on an areal basis, the simulated change was 6 percent more than the observed change. The simulated change in storage of 54.9 million acre-feet compared favorably to the observed change in storage of 50.3 million acre-feet.

One development period, 1960–80, was simulated for the northern High Plains. The best correspondence between observed and simulated water-level change was achieved when net withdrawal equaled 100 percent of the estimated irrigation requirement. For the northern High Plains, other significant stresses occurred because of human activities. These additional stresses contributed 47.0 million acre-feet of water to the aquifer during the development period. This, coupled with ground-water irrigation return flow of 37.5 million acre-feet, in large part counterbalanced the 105.0 million acre-feet of water pumped between 1960 and 1980 in the northern High Plains. The simulated net decrease in storage was 15 million acre-feet and the observed decrease in storage was 6 million acre-feet. The 9 million acre-feet difference between observed and simulated decrease in storage was less than 9 percent of the volume pumped.

INTRODUCTION

The U.S. Geological Survey began a study of the High Plains regional aquifer in 1978 (Weeks, 1978) as part of the Survey's program of Regional Aquifer-System Analysis (RASA) (Bennett, 1979). Major objectives of the High Plains study were to: (1) Provide hydrologic information needed to evaluate the effects of continued ground-water development; (2) design and develop computer models to simulate the aquifer system; and (3) predict aquifer response to changes in ground-water deveolopment.

The High Plains aquifer underlies about 174,000 mi^2 of the central United States east of the Rocky Mountains in the southern part of the Great Plains. Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming are underlain by the High Plains aquifer (fig. 1). The High Plains aquifer is the shallowest and most abundant source of ground water in the region and the irrigated agricultural economy of the High Plains has depended on the aquifer for its growth and prosperity.

More than 20 percent of the irrigated land in the United States overlies the High Plains aquifer from which about 30 percent of the ground water used in the United States during 1980 was pumped. Throughout most of the High Plains, the rate of ground-water withdrawal greatly exceeds the rate of natural replenishment resulting in water-level declines in places. Consequently, many irrigators have experienced increased pumping costs and decreased well yields and are concerned about the future of irrigated farming on the High Plains.

PURPOSE AND SCOPE

The general purpose of the High Plains RASA was to provide the hydrologic information and analytical capability needed for effective management of the ground-water resource of the High Plains. This report describes the design and calibration of digital models of the High Plains aquifer. The models were constructed on the bases of the geologic and hydrologic conditions described by Gutentag and others (1984). Historical data on irrigation demand (Heimes and Luckey, 1982), water levels, and water-level changes (Luckey and others, 1981) were used to test or calibrate the models. The models provide water managers with a tool for evaluation of water-management alternatives.

HIGH PLAINS AQUIFER

The High Plains aquifer consists mainly of hydraulically connected geologic units of late Tertiary and Quaternary age. Late Tertiary units include part of the Brule Formation, the Arikaree Group (or Formation), and the Ogallala Formation. Quaternary deposits included in the aquifer consist of alluvial, dune-sand, and valley-fill deposits.

The Ogallala Formation, which underlies 134,000 mi^2, is the principal geologic unit in the High Plains aquifer. The Ogallala Formation consists of a heterogeneous sequence of clay, silt, sand, and gravel deposited by streams that flowed eastward from the ancestral Rocky Mountains. Within the Ogallala, zones cemented with calcium carbonate are resistant to weathering and form escarpments that typically mark the boundary of the High Plains.

The formations comprising the High Plains aquifer were deposited on an erosional surface that ranges in age from Permian to Tertiary. Faulting and salt dissolution also have affected the underlying surface that controls the thickness of the High Plains aquifer. In Wyoming, faults have displaced the underlying surface vertically as much as 1,000 ft, and, in South Dakota, a fault has caused about 500 ft of vertical displacement. Additional faulting and collapse are associated with salt dissolution. Permian salt deposits being dissolved by circulating ground water mainly occur south of the Arkansas River. Water from the units underlying the High Plains aquifer affects the quality of water in the aquifer and streams draining the High Plains in Kansas, Oklahoma, and Texas.

Water levels in the High Plains aquifer range from just below land surface to nearly 400 ft below land surface. The saturated thickness ranges from nearly zero to about 1,000 ft. Hydraulic conductivity (a measure of the aquifer's ability to transmit water) and specific yield (a measure of the aquifer's ability to store water) (Lohman, 1972, p. 6) of the aquifer depend on sediments that vary widely both areally and vertically. Hydraulic conductivity ranges from about 25 to 300 ft/d and averages 60 ft/d. Specific yield ranges from about 10 to 30 percent and averages 15 percent.

Ground water in the High Plains aquifer generally flows from west to east, at an average rate of about 1 ft/d. At this rate, a particle of water would take at least several thousand years to move from the western edge of the aquifer to the eastern edge of the aquifer. The ground water discharges naturally to streams and springs, and directly to the atmosphere by evapotranspiration where the water table is near land surface. Precipitation is the principal source of recharge to the High Plains aquifer. Estimated recharge rates range from 0.024 in./yr in part of Texas to 6 in./yr in part of Kansas (Gutentag and others, 1984, table 7). Typically, recharge estimates are greatest for areas with sandy soils. Refinement of these recharge estimates is one of the results of the model simulations.

During 1980, the High Plains aquifer contained about 3.25 billion acre-ft of drainable water. This is equivalent to about 80 percent of the volume of water contained in Lake Michigan. About 66 percent of the water in storage is in Nebraska, about 12 percent is in Texas, and about 10 percent is in Kansas. Colorado, Oklahoma, South Dakota, and Wyoming each have less than 4 percent of the water in storage. New Mexico, with about 1.5 percent, has the least volume of water in storage in the High Plains aquifer.

The quality of water in the High Plains aquifer generally is suitable for irrigation but, in many places, the water does not meet U.S. Environmental Protection Agency (1976, 1977) limits for some constituents for drinking water. Excessive concentrations of dissolved solids, fluoride, chloride, and sulfate occur in parts of the aquifer in all eight States (Krothe and others, 1982).

About 95 percent of all water pumped from the High Plains aquifer is used for irrigation. During 1980, more than 170,000 wells pumped an estimated 18 million acre-ft of water from the High Plains aquifer to irrigate 13 million acres (Heimes and Luckey, 1983, p. 34).

Large water-level declines have occurred in some areas of the aquifer. Water levels have declined more than 100 ft from predevelopment to 1980 in parts of Kansas, New Mexico, Oklahoma, and Texas in areas totaling 2,500 mi^2 (Luckey and others, 1981). Water levels have declined more than 50 ft in areas totaling 12,000 mi^2 and more than 10 ft in areas totaling 50,000 mi^2.

The volume of water in storage in the aquifer has decreased about 166 million acre-ft since ground-water development began (Gutentag and others, 1984, table 11). Most of the depletion has occurred in Kansas and Texas; about 114 million acre-ft have been depleted in Texas and 29 million acre-ft have been depleted in Kansas.

Water-level declines increase pumping lift, decrease well yields, and limit development of the ground-water resource. Well yields of more than 750 gal/min generally can be obtained throughout large areas of the High Plains. However, only wells yielding less than 250 gal/min can be constructed where the saturated thickness is thin near the edge of the aquifer or where water-level declines have greatly decreased the saturated thickness.

HIGH PLAINS AQUIFER FLOW MODELS

The High Plains is divided into three parts, as shown in figure 2. The southern High Plains is the part of the High Plains in Texas and New Mexico south or west of Amarillo, Tex. The central High Plains is the area north or east of Amarillo and south of approximately 39° latitude. The northern High Plains is the area north of approximately 39° latitude.

A narrow isthmus, approximately 12 mi wide, joins the southern and central High Plains in the vicinity of Amarillo, Tex. The isthmus joining the central and northern High Plains is about 32 mi wide and follows a bedrock high and a thin saturated section of the aquifer. Probably little exchange of water occurs between the northern and central High Plains or between the central and southern High Plains. Because of the narrow isthmuses joining the separate parts, constructing separate ground-water flow models for each part of the High Plains should not create significant errors.

The history of ground-water development in the High Plains was divided into two periods: the period prior to large-scale development of irrigation (predevelopment period) and the period of development of irrigation (development period). The development period was further subdivided as needed.

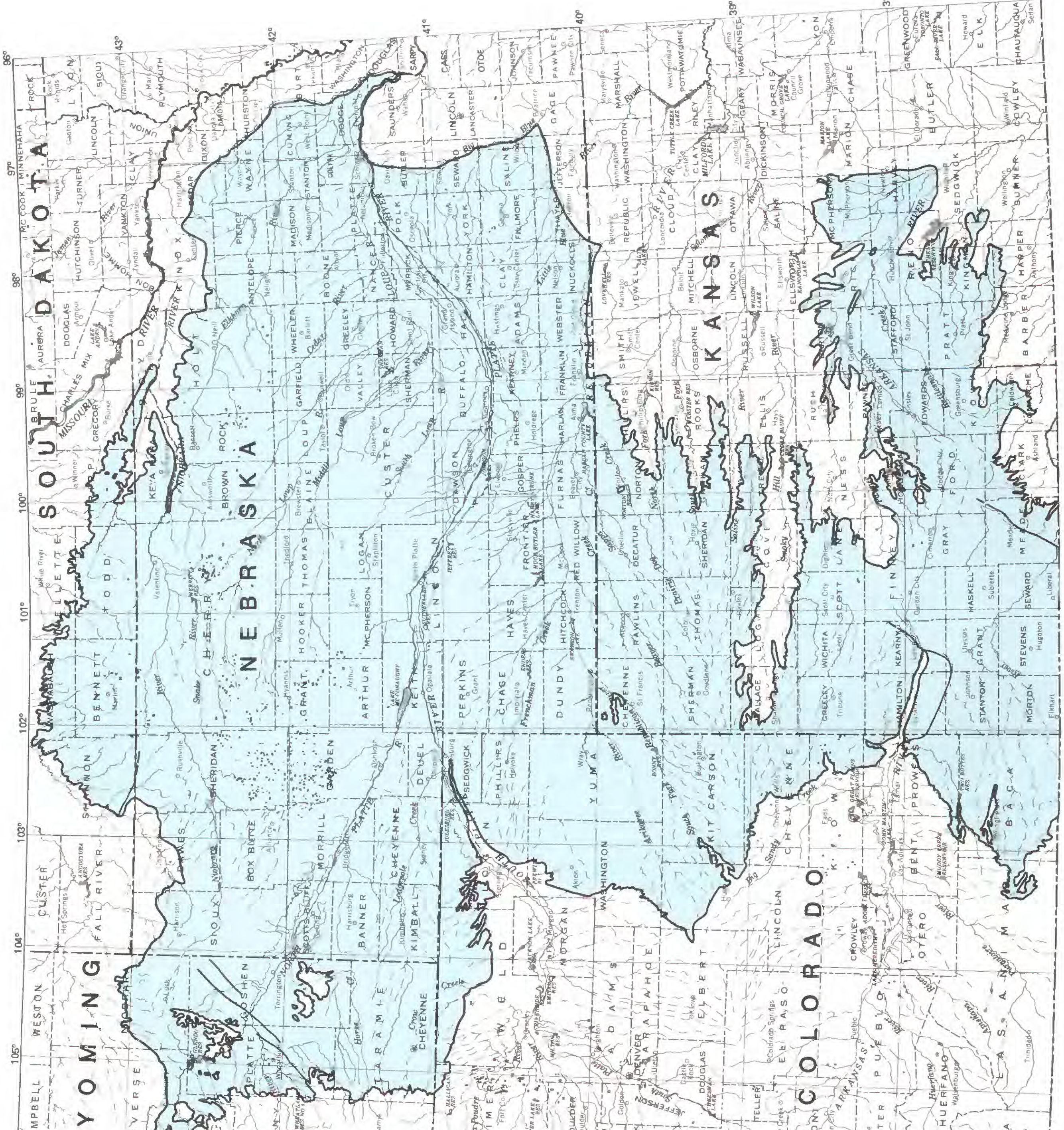
Four general categories of information are needed for model input: (1) Aquifer geometry; (2) boundary conditions; (3) aquifer parameters; and (4) aquifer stresses. In addition to these four categories, the development-period models require an initial water-table configuration. This was generated by the predevelopment-period models.

Aquifer geometry defines vertical and areal extent of the aquifer. This requires the configuration of the base and the areal extent of the aquifer. The position of the water table, which is simulated by the model, defines the upper limit of the aquifer.

Boundary conditions of the model define the conditions at the limit of the aquifer. The limit of the aquifer could be the bottom of the aquifer where exchange of water with another aquifer may take place, the lateral edge of the aquifer where water may enter or leave the system, or the top of the aquifer where the aquifer may interact with streams or lakes. Boundary conditions at the lateral edge of the aquifer generally are specified as a constant water level, a constant slope of the water table, or no flow across the boundary. In the High Plains models, the boundary at the bottom of the aquifer was modeled as a no flow boundary. At some nodes where the aquifer was in hydraulic connection with streams, boundary conditions were specified at the top of the aquifer.

Undoubtedly, some exchange of water takes place between the High Plains aquifer and other aquifers, particularly the aquifers in the Lower Cretaceous and the Triassic and Jurassic units. Estimates were made of the quantities and direction of this exchange and were tested by the model. The simulations indicated that the model was insensitive to this exchange because the volume estimated was small. Hence, the interaction between the High Plains aquifer and the underlying aquifers was assumed to be negligible, and the base of the High Plains aquifer was simulated as an impermeable boundary.

Aquifer parameters—hydraulic conductivity and specific yield—describe the physical properties of the


SOUTH DAKOTA
NEBRASKA
KANSAS
COLORADO
WYOMING

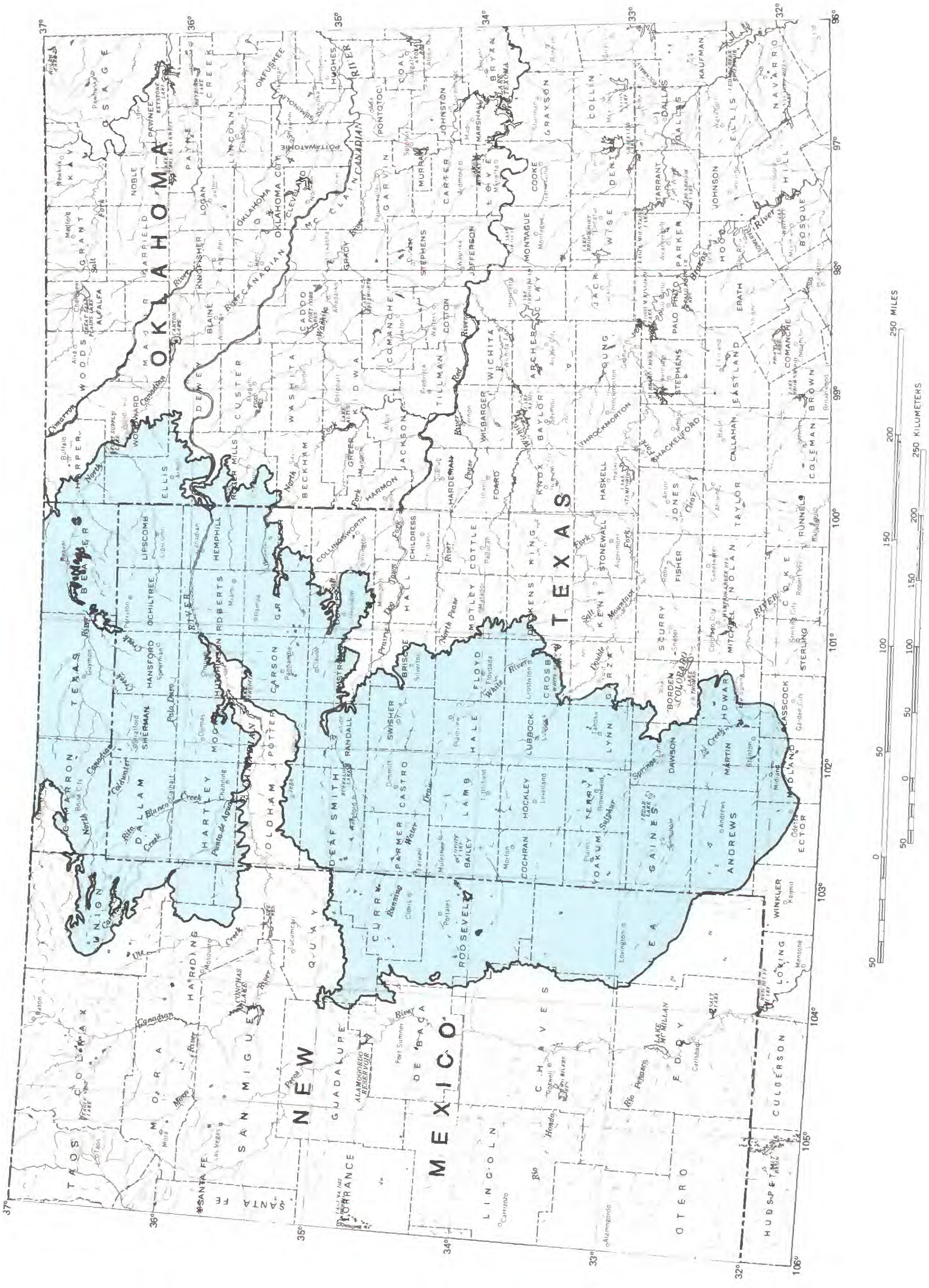


FIGURE 1.—Location of High Plains aquifer.

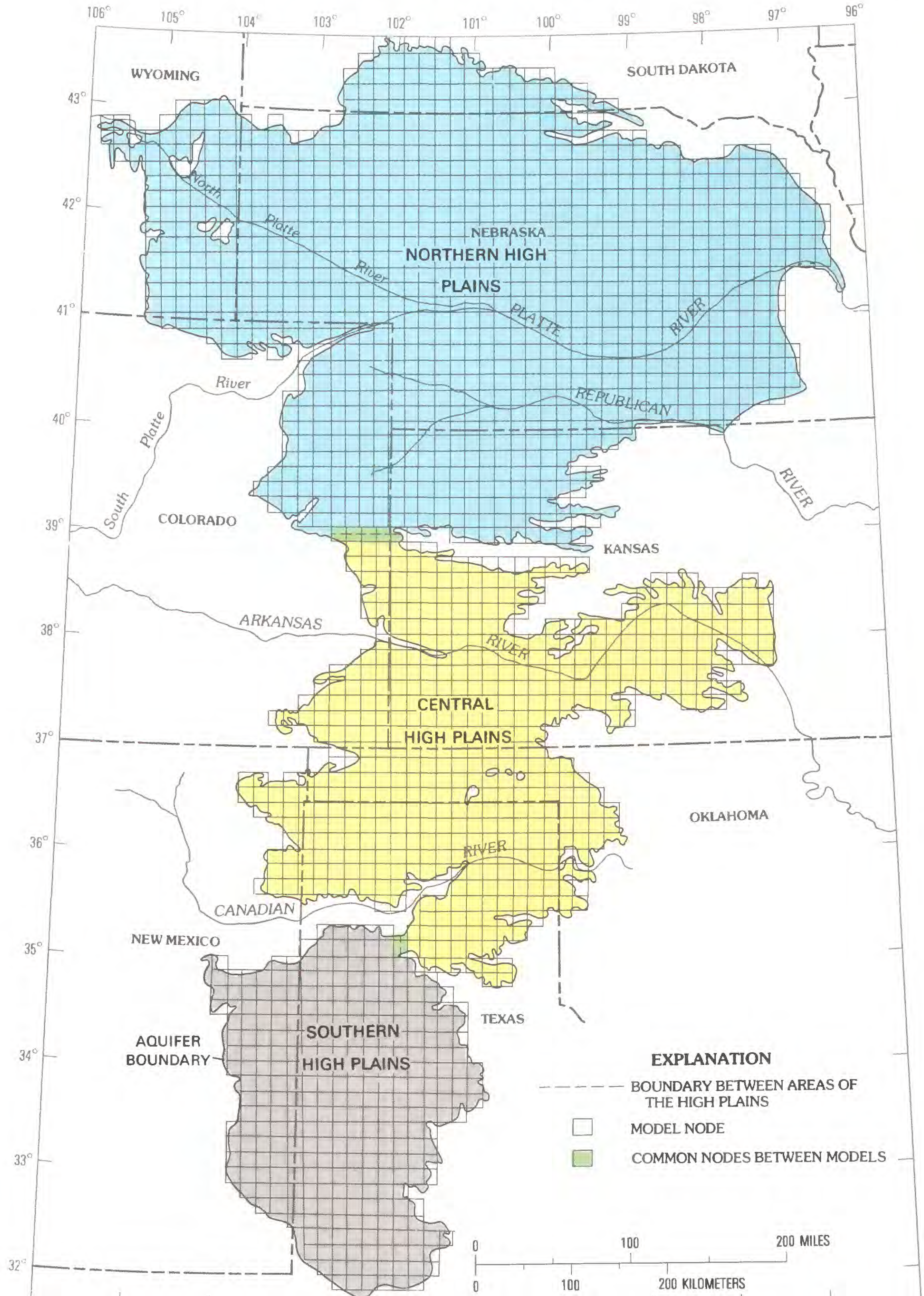


FIGURE 2.—Division of the High Plains and grids for the models.

aquifer. Before irrigation development, the aquifer was in a state of equilibrium with no significant change in storage taking place. Therefore, the parameter specific yield was not needed for the predevelopment-period model. However, both parameters were needed for the development-period model.

Aquifer stress is defined as any addition or withdrawal of water from the aquifer that is not accounted for in the boundary conditions. In the predevelopment period, the aquifer system was in a state of dynamic equilibrium with recharge from precipitation equal to discharge to streams and across the eastern study boundary. Hence, the predevelopment-period model requires a description of the predevelopment recharge. However, as the aquifer was being developed, additional recharge occurred because of irrigation infiltration and canal and reservoir leakage and the rate of recharge from precipitation on dryland agriculture land.

The ground-water flow model calculates water levels, base flow to rivers, flow across the study boundaries, and change of water in storage. The simulated results were compared with historical data. Statistics were used to analyze the difference between the simulated and observed water levels and water-level changes. These statistics include the mean, standard deviation, and extremes of the water-level differences.

The flow of ground water in a heterogeneous and anisotropic unconfined aquifer may be expressed by the following partial differential equation (Trescott, 1975, p. 3):

$$\frac{\partial}{\partial x}\left(K_{xx}b\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}b\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}b\frac{\partial h}{\partial z}\right)=S\frac{\partial h}{\partial t}+bW(x, y, z, t) \quad (1)$$

where

x, y, and z	are space coordinates,
K_{xx}, K_{yy}, and K_{zz}	are hydraulic conductivities in the x, y, and z directions,
b	is saturated thickness,
h	is water level,
S	is specific yield,
t	is time coordinate, and
W	is stress (source-sink) term.

To solve equation 1, which is a function of aquifer parameters and stresses, boundary conditions and initial conditions need to be specified. Boundary conditions include either the water level or the flow at the boundary. Initial conditions include the water level throughout the area at the beginning of the simulation period.

Equation 1 describes the flow of ground water in three dimensions; that is, in both the vertical and horizontal directions. On a local scale, particularly near recharge or discharge areas, both horizontal and vertical components of ground-water flow occur in the High Plains aquifer. However, on a regional scale, the horizontal-flow components are so much larger than the vertical-flow components that the vertical-flow components may be neglected without inducing significant errors. Hence, the regional flow of ground water in the High Plains aquifer was modeled as two-dimensional flow.

Gutentag and Weeks (1981) analyzed several thousand lithologic logs from wells in the High Plains aquifer to develop a statistical relationship between aquifer parameters and saturated thickness. They concluded that no consistent pattern of sediment distribution occurs on a regional scale (e.g., no regional basal gravel) and, hence, that vertically averaged aquifer parameters may be used as a single value representing the physical property of the aquifer material. Using vertically averaged parameters and assuming two-dimensional ground-water flow, equation 1 can be rewritten as:

$$\frac{\partial}{\partial x}\left(K_{xx}b\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}b\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+bW(x, y, z, t) \quad (2)$$

Two basic techiques—finite-element and finite-difference—usually are used to approximate equation 2. In this study the finite-difference technique was used. To approximate the flow equation by the finite-difference technique, the derivatives in equation 2 are replaced with finite-difference approximations (Trescott and others, 1976, p. 2) as shown below.

$$\frac{1}{\Delta x_j}\left\{\left[b_{i,j}K_{xx(i,j+1/2)}\frac{(h_{i,j+1,k}-h_{i,j,k})}{\Delta x_{j+1/2}}\right]-\left[b_{i,j}K_{xx(i,j-1/2)}\frac{(h_{i,j,k}-h_{i,j-1,k})}{\Delta x_{j-1/2}}\right]\right\}+\frac{1}{\Delta y_i}\left\{\left[b_{i,j}K_{yy(i+1/2,j)}\frac{(h_{i+1,j,k}-h_{i,j,k})}{\Delta y_{j+1/2}}\right]-\left[b_{i,j}K_{xx(i-1/2,j)}\frac{(h_{i,j,k}-h_{i-1,j,k})}{\Delta y_{i-1/2}}\right]\right\}=S_{i,j}\frac{h_{i,j,k}-h_{i,j,k-1}}{\Delta t}+b_{i,j}W_{i,j,k} \quad (3)$$

where

Δx, Δy, and Δt	represent the grid spacing in the space and time coordinates,
i, j, and k	represent the i^{th} row, j^{th} column, and k^{th} time, and other symbols are the same as for equation 1.

Equation 3 is written for each node in the discretized network and all of the finite-difference equations are solved simultaneously by computer using either a strongly implicit or a direct solution numerical technique. The numerical technique is used to solve equation 3 for water levels at each node through an iterative process which compares water levels simulated at the present iteration with those simulated at the previous iteration. If the absolute water-level differences between the two adjacent iterations reaches a value less than the predescribed value (the closure error), then the iteration process stops and a solution of equation 3 is obtained. The computer program used was virtually the one described by Trescott and others (1976) and modified by Larson (1978). A few minor modifications were made.

One modification allows more control over the iteration parameters which are used to accelerate the solution technique. This control was necessary for the High Plains models because of the coarse grid and the rapid change in aquifer parameters and thickness between the adjacent nodes. The additional control over the iteration parameters sometimes allowed the High Plains simulation program to reach a solution when the original Trescott and Larson simulation program would fail to reach a solution. The range that transmissivity (the product of hydraulic conductivity and saturated thickness) can vary between iterations (solutions of equation 3) also was limited in the High Plains simulation program. This change was necessary for the same reason that more control was given over the iteration parameters.

Constant-gradient boundary conditions (constant slope of the water table) for a water-table aquifer were added to the simulation program. At each iteration the flow at each constant-gradient node was recalculated and added explicitly into the equation.

A number of other changes altered the way the data were entered into the program and the way the results were summarized by the program. An alternative method of entering the pumpage data was necessary because of the extremely large number of wells in the High Plains. The pumpage was defined either on a well-by-well basis or as a matrix. A more detailed summary of boundary conditions was given by the simulation program, including the simulated flow into and out of each boundary node. This supplemented the mass-balance or water-budget information calculated by the original Trescott and Larson program. A routine was added to calculate statistics for the simulated water-level changes or for the difference between the observed and the simulated water levels. This statistical information was used to evaluate the results of each simulation.

The simulation program allows a variable rectangular grid in both the x and y directions. However, for the High Plains models, a uniform regular network of nodes was used (fig. 2). The nodes in each of the models were 10 mi apart in both north-south and east-west directions. The southern High Plains models had 26 rows and 20 columns and 303 active nodes. The central High Plains models had 32 rows and 37 columns and 513 active nodes. One common node existed between the southern and central High Plains models. The water level of this node was fixed in the central High Plains models to be identical to that simulated in the southern High Plains models. The northern High Plains models had 35 rows and 51 columns and 943 active nodes. Five nodes were common between the central and northern models. The water levels at these five common nodes were fixed in the northern High Plains models to be identical to those simulated in the central High Plains models.

PREDEVELOPMENT-PERIOD MODELS

Prior to extensive agricultural development on the High Plains, the ground-water system was in a state of dynamic equilibrium with long-term recharge balanced by discharge along the eastern boundary and in the river valleys that intercepted the water table. The rate and location of recharge and discharge were to be determined during the calibration of the predevelopment-period models. Gutentag and others (1984, table 7) compiled various estimates of recharge for the High Plains and the values ranged from a minimum of 0.024 in./yr to a maximum of 6.0 in./yr. The broad range and dissimilarity of the estimated recharge rate indicated that recharge was virtually an unknown quantity throughout much of the High Plains. One of the objectives of the predevelopment-period model calibration was to refine the estimates of the recharge rate.

The predevelopment-period models calculate a predevelopment water-table configuration by integrating data for the altitude of the base of the aquifer, hydraulic conductivity, and predevelopment recharge rate. The altitude and geology of the base of the aquifer were obtained from Weeks and Gutentag (1981) and the altitude of the base was not altered during calibration. The geology was used as a guide to places where the High Plains aquifer might exchange water with underlying aquifers.

The initial estimates of hydraulic conductivity were obtained from a map that was used to prepare the map presented by Gutentag and others (1984, fig. 10). The hydraulic conductivity was one of the two model inputs that was altered during the predevelopment-period calibration. The location and extent of these modifications are described in the model-calibration sections.

The predevelopment recharge rates were estimated during the calibration. The method used to distribute recharge varied by area and also is discussed in later sections.

The calculated predevelopment water-table configuration was compared to a map of the predevelopment water table that was constructed using early water-level measurements from hundreds of wells. The accuracy of the map varied considerably from area to area depending on the density and distribution of water-level data, but the map was a good representation of the predevelopment water table except in areas where the saturated thickness was thin and data were sparse. The comparison of observed and simulated water tables was part of the calibration process for the predevelopment-period models. The predevelopment-period models also calculated the discharge across the eastern boundary of the High Plains aquifer and the base flow to streams that drain the aquifer. The models were calibrated in part by matching the calculated discharge with the observed or estimated discharge from the aquifer.

DEVELOPMENT-PERIOD MODELS

The development period in the High Plains began when substantial ground-water development occurred. The development period began in the 1940's in the southern High Plains, in the 1950's in the central High Plains, and in the 1960's or later in much of the northern High Plains. Models of the development period required all of the information from the predevelopment-period models plus data on specific yield of the aquifer and additional stress imposed on the aquifer since development began. All of the data, as refined during the predevelopment-period model calibration, were used in the development-period models.

The specific yield of the aquifer was obtained from a map presented in Gutentag and others (1984, fig. 11). This map was constructed by analyzing numerous lithologic logs, and the specific yield was not altered during the development-period calibration.

Additional stress on the aquifer during the development period consisted of pumpage, return flow to the aquifer from irrigation, and additional recharge caused by human activities. Pumpage was the largest stress on the aquifer, but return flow and additional recharge also were significant in some areas.

Pumpage was calculated using the method outlined by Heimes and Luckey (1982). Irrigated acreage and composite crop demand are given in that report for cells of dimension 10 minutes of latitude by 10 minutes of longitude (10-minute cells) at 5-year intervals for 1949 to 1978. The product of irrigated acreage and composite crop demand yields an irrigation requirement. An irrigation efficiency factor (crop demand divided by application) for these years is all that was needed to estimate total pumpage from irrigation requirement for each 10-minute cell. Numerous estimates of the irrigation efficiency factor are available. Most estimates range from about 40 percent to 80 percent of application with efficiency improving with time. The following irrigation efficiency factors were used to generate pumpage estimates for the indicated years for the High Plains:

Year	Southern High Plains	Central High Plains	Northern High Plains
1949	55 percent	45 percent	---
1954	55 percent	45 percent	---
1959	55 percent	45 percent	45 percent
1964	60 percent	60 percent	60 percent
1969	65 percent	60 percent	60 percent
1974	70 percent	70 percent	70 percent
1978	70 percent	70 percent	70 percent

Total pumpage for the 7 years in the above table was used to calculate an average pumpage for a 5-year period for each 10-minute cell for 1940–80. For 1940–50, a backward projection was made based on the rate of increase of irrigation in the major areas irrigated between 1940 and 1950. For 1950–80, an interpolation between years was used. The 5-year average pumpage for each period was calculated as follows:

1940–44: 0.18×(1949 pumpage)
1945–49: 0.7×(1949 pumpage)
1950–54: 0.4×(1949 pumpage)+0.6×(1954 pumpage)
1955–59: 0.4×(1954 pumpage)+0.6×(1959 pumpage)
1960–64: 0.4×(1959 pumpage)+0.6×(1964 pumpage)
1965–69: 0.4×(1964 pumpage)+0.6×(1969 pumpage)
1970–74: 0.4×(1969 pumpage)+0.6×(1974 pumpage)
1975–79: 0.5×(1974 pumpage)+0.5×(1978 pumpage)

Return flow to the aquifer from irrigation was the principal unknown variable during the development-period simulations. Return flow was assumed to be a function of the difference between total pumpage and irrigation requirement. The manner in which return flow was varied is discussed in the model calibration sections. A change in recharge due to human activities was the other component that was varied during the development-period calibrations.

SOUTHERN HIGH PLAINS MODEL CALIBRATION

The southern High Plains consists of about 29,000 mi^2 in New Mexico and Texas. The area includes most of the High Plains south of the Canadian River. This was the first area of the High Plains that was extensively developed for irrigation, with some development beginning in the late 1930's. A predevelopment period and two development period calibrations were done for the southern High Plains flow models. The predevelopment-period model was calibrated by matching observed and simulated predevelopment water levels and the development-period model was calibrated by matching observed and simulated water levels for 1960 and 1980. Parts of the southern High Plains have been modeled by Knowles and others (1982) and McAda (1984).

PREDEVELOPMENT-PERIOD CALIBRATION

In the predevelopment-period model, hydraulic conductivity and recharge from precipitation were adjusted. Estimates of recharge for the High Plains of Texas and New Mexico range from a minimum of 0.024 in./yr to a maximum of 1.0 in./yr (Gutentag and others, 1984, table 7). White and others (1940) estimated the ground-water discharge along 75 mi of the eastern boundary to be about 160 gal/min per mi and the discharge by evapotranspiration from shallow water-table areas to be about one-half that rate. Therefore, the total discharge was estimated to be 240 gal/min per mi.

The discharge along the eastern boundary was simulated by specifying constant heads along the boundary; the flow across the boundary was then simulated by the model. Discharge to streams and from shallow water-table areas was not specified explicity because many of these areas are close to the eastern boundary and were included in the boundary nodes. Other boundaries were specified as no-flow boundaries.

A hydraulic-conductivity map was constructed prior to model calibration. The minimum contour value was 15 ft/d and the maximum contour value was 300 ft/d. Mean values for each model node were determined from the map and the values ranged from 10 to 280 ft/d.

The discharge across the eastern boundary was estimated using Darcy's law on the bases of the predevelopment water-table and hydraulic conductivity maps. Darcy's law indicated an outflow of about 250 ft^3/s for the entire 370 mi of the eastern boundary or an average of 300 gal/min per mi. This is equivalent to a long-term average recharge throughout the entire area of 0.11 in./yr.

A simulation with the above hydraulic conductivity map and the mean recharge of 0.11 in./yr resulted in simulated water levels significantly lower than observed water levels in the northern part of the southern High Plains and somewhat higher than the observed water levels in the southern part. A decrease of hydraulic conductivity and recharge by 50 percent resulted in a similar pattern. Using a constant hydraulic conductivity for all nodes of 40 ft/d, which was the mean value, somewhat decreases the differences between the observed and simulated water-levels but the simulated water levels still were not satisfactory.

Most of the large differences between the observed and simulated water levels occurred in the areas with large estimates of hydraulic conductivity. A series of simulations in which the largest estimates of hydraulic conductivity were decreased indicated that the difference between the observed and the simulated water levels were minimized when all hydraulic conductivity estimates of more than 50 ft/d were decreased using the following formula:

$$K_f=50+(K_i-50)\frac{(160-50)}{(300-50)} \quad (4)$$

where

K_i is initial hydraulic conductivity, and
K_f is final hydraulic conductivity to be used in the model.

Equation 4 effectively decreased a hydraulic-conductivity estimate of 300 ft/d to 160 ft/d while leaving a hydraulic-conductivity estimate of 50 ft/d or less unchanged. A number of well logs in areas with large estimates of hydraulic conductivity were reevaluated and the decrease in hydraulic-conductivity estimates appeared reasonable. With this decrease, the hydraulic conductivity for the model nodes ranged from 10 to 150 ft/d.

The revised hydraulic-conductivity distribution corresponds to that presented by Gutentag and others (1984, fig. 10). The simulated discharge along the eastern boundary using the revised hydraulic-conductivity estimates was 210 ft^3/s or 250 gal/min per mi. This is similar to White and others' (1940, p. 10–11) estimate of about 240 gal/min per mi for discharge from shallow water-table areas plus discharge along the boundary for a 75-mi length.

A discharge rate of 210 ft^3/s means that the long-term average recharge for the entire 29,000 mi^2 area would be approximately 0.095 in./yr. Because no information was available on the distribution of recharge, possible recharge distributions were tested by the model. Assigning every node the average recharge rate resulted in an unsatisfactory correspondence between observed and simulated predevelopment water levels. An assumed recharge distribution based on soil type also resulted in an unsatisfactory result. Several simulations that varied recharge according to variations in precipitation and potential evapotranspiration indicated that the recharge rate in the northern part of the southern High Plains had to be more than three times the rate in the southern part and the recharge rate does not vary from west to east, so neither mean annual precipitation nor evapotranspiration probably was the controlling factor for recharge.

Finch and Wright (1970) described the Running Water Draw–White River lineaments in the northern part of the southern High Plains as a zone of structural weakness and possible faulting that might be an appropriate site for recharge through the caliche caprock. This zone was at and south of Running Water Draw and the White River. Simulating greater recharge rates in this area, as shown in figure 3, resulted in the best correspondence between observed and simulated predevelopment water levels. The total recharge for this simulation was 270 ft^3/s or an average of about 0.13 in./yr which was greater than the 0.095 in./yr described previously. This average recharge rate of 0.13 in./yr and the recharge distribution shown in figure 3 were used for the final simulations. The statistical values of the final simulation results are: (1) The mean difference between the simulated and observed water levels at the 303 nodes was +0.22 ft; (2) the standard deviation was 41.6 ft; (3) the mean of the absolute values of the differences was 31.9 ft; and (4) the extreme values of the differences were −113 ft and +99 ft.

The observed and simulated predevelopment water tables are shown in figure 4. In general, a satisfactory correspondence exists between the observed and simulated water levels but certain differences are notable. In the southeast and east-central part of the area, the simulated water level is generally above the observed water level. This indicates that either the predevelopment recharge was even less than 0.086 in./yr or some discharge was not accounted for. The latter is a more likely explanation. In the southwest part of the area and in the extreme northern part, the simulated water level generally is below the observed water level. This indicates that either the predevelopment recharge was greater than the rate estimated or that the hydraulic conductivity actually is less than estimated. No physical evidence indicates that either the recharge estimate should be increased or the hydraulic conductivity estimate should be decreased; therefore, no further adjustment was made.

A second, totally different, approach to simulating the predevelopment water levels was tested. This approach was based on the premise that, due to a cooler or wetter climate and greater recharge, the water table was probably at or near the land surface at various times in the geologic past and, during warmer and dryer episodes, the aquifer received no recharge and the water table slowly declined as the aquifer drained. The most recent lengthly period of more effective precipitation in the southern High Plains, called the Lubbock subpluvial (Wendorf, 1970), occurred about 10,000 years ago and at that time the water table could have been near land surface. A 10,000-year simulation with the initial position of the water-table at land surface, no recharge, uniform specific yield of 0.15, and constant water levels along the eastern boundary (set equal to predevelopment water levels) indicated that the aquifer would be virtually drained in a few thousand years. The approximate time that the water table would take to decline from land surface to the predevelopment position if the area received no recharge is shown in figure 5. This analysis indicated that the above premise of no recent recharge is untenable and that significant recharge has occurred, at least at irregular intervals, during the recent past.

DEVELOPMENT-PERIOD CALIBRATION

The development period of the southern High Plains was divided into two periods: 1940–60 and 1960–80. By 1940, only relatively small areas of the aquifer had been significantly disturbed. The development-period models were calibrated by matching observed and simulated water levels for 1960 and 1980.

Additional stresses on the aquifer since 1940 consisted of pumpage, return flow to the aquifer from irrigation infiltration, and additional recharge from precipitation due to change of soil characteristics by cultivation that did not occur during the predevelopment period. Pumpage was the largest additional stress on the system, but return flow and additional recharge also were significant. Pumpage for irrigation was more than 97 percent of the pumpage for all uses, so pumpage for other uses was neglected in the southern High Plains model.

The following estimates of total pumpage for irrigation were made:

1940–44:	0.5 million acre-ft/yr
1945–49:	2.1 million acre-ft/yr
1950–54:	4.6 million acre-ft/yr
1955–59:	6.3 million acre-ft/yr
1960–64:	7.0 million acre-ft/yr
1965–69:	6.7 million acre-ft/yr
1970–74:	6.4 million acre-ft/yr
1975–79:	6.2 million acre-ft/yr

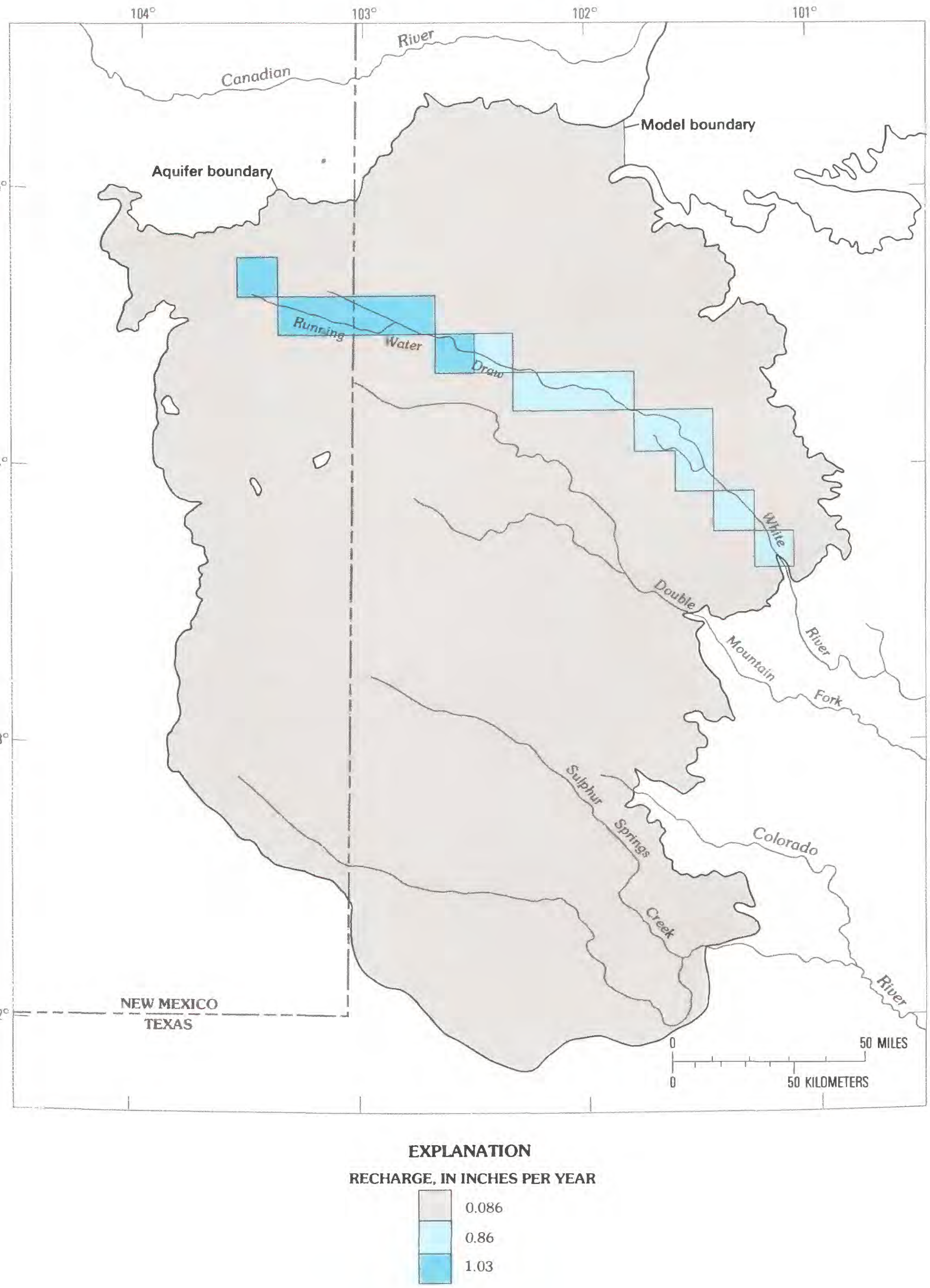
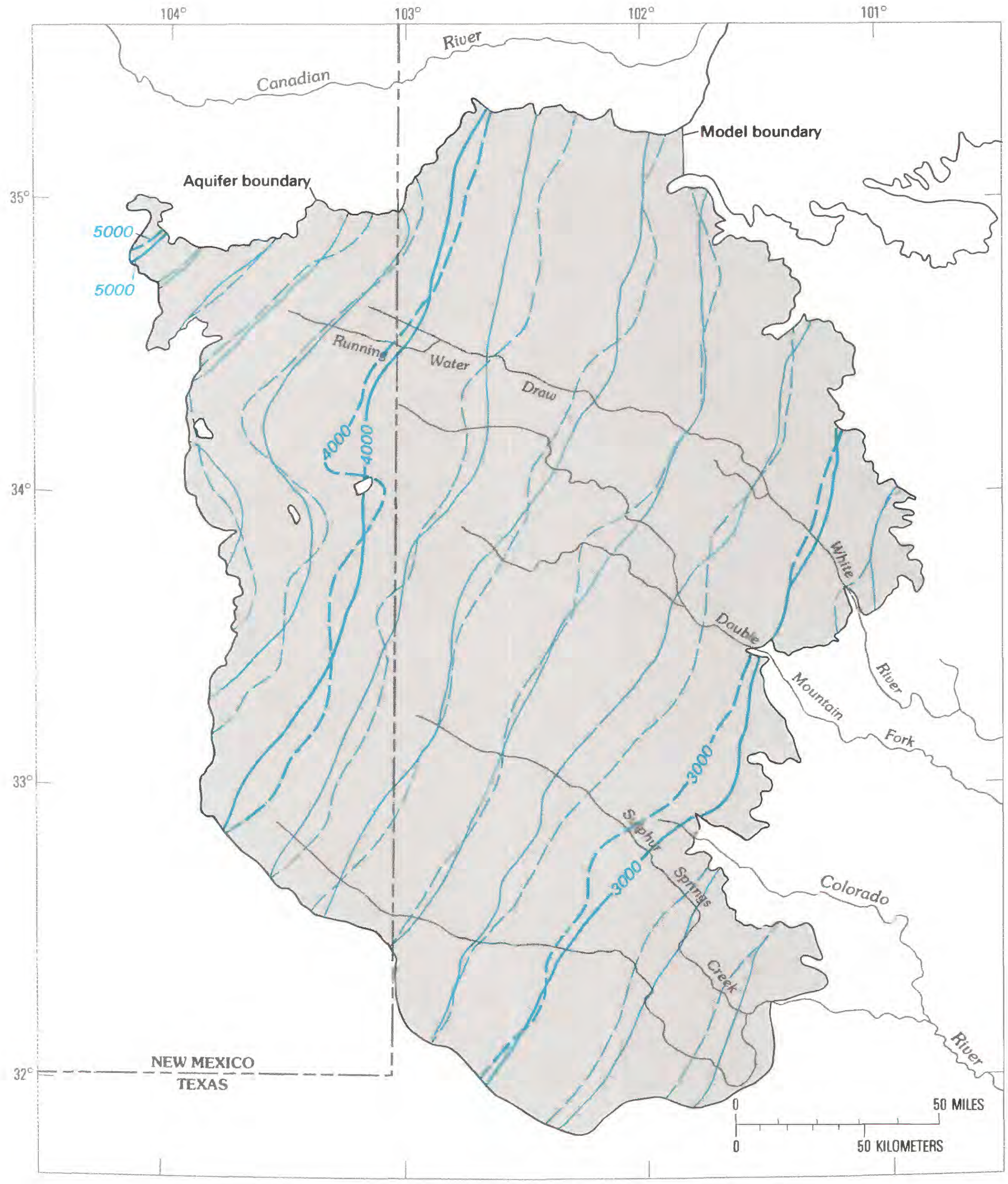


FIGURE 3.—Estimated predevelopment, long-term average recharge rates for the southern High Plains.



EXPLANATION

WATER LEVEL CONTOUR — Contour interval 200 feet. National Geodetic Vertical Datum of 1929

--3000-- Observed

—3000— Simulated

FIGURE 4.—Observed and simulated predevelopment water level for the southern High Plains.

EXPLANATION

•950 LOCATION AND TIME OF DECLINE IN YEARS

FIGURE 5.—Simulated time required for water level in the southern High Plains to decline from land surface to predevelopment position assuming no recharge.

About 200 million acre-ft of water have been pumped from the aquifer since 1940. These estimates are 15–20 percent more than those reported by the Texas Department of Water Resources (1981). The above estimates probably are greater because of the implicit assumption that the irrigators try to get maximum yields from their crops. In water-short areas such as the southern High Plains, irrigators may apply only a fraction of the

TABLE 1.—*Water budget for 1940–60 development-period calibration of the southern High Plains flow model*

[units are in millions of acre-feet]

Budget item	Net withdrawal equal to 73 percent of irrigation requirement	Net withdrawal equal to 90 percent of irrigation requirement	Net withdrawal equal to 100 percent of irrigation requirement
Outflows:			
Total pumpage	70.34	70.20	69.92
Boundary outflow	2.46	2.40	2.37
Total	72.80	72.60	72.29
Inflows:			
Return flow from irrigation	42.20	35.10	31.47
Recharge from precipitation	3.19	3.19	3.19
Total	45.39	38.29	34.66
Change in storage:	–27.41	–34.31	–37.63

irrigation requirements and accept less than maximum yield (P. L. Rettman, U.S. Geological Survey, oral commun., 1982).

Several simulations for 1940–60 were made with the return flow to the aquifer from irrigation being the component that was changed between simulations. Total pumpage changed slightly between simulations because pumpage was curtailed at one node near the boundary at different times as the node became virtually unsaturated. Major components of the water budget for three simulations are summarized in table 1.

The minimum mean residual between observed and simulated water levels for 1960 was obtained for a return flow of 50 percent of the applied irrigation water or net withdrawal (total pumpage minus return flow) equal to approximately 90 percent of the irrigation requirement. The mean difference between the observed and simulated water levels was −0.22 ft with a standard deviation of 27.2 ft. The simulated decrease in storage of 34.3 million acre-ft was 19 percent less than the observed change in storage of 42.2 million acre-ft. The observed and simulated water levels for 1960 are shown in figure 6. The simulated water-level contours follow the observed water-level contours fairly closely with the simulated water-level contours usually being smoother.

For 1960–80, total ground-water pumpage in the southern High Plains was nearly twice as large as during the previous 20 years. For this period, the return flow to the aquifer from irrigation was again the principal component that was changed between simulations. Total pumpage changed slightly between simulations because pumping was curtailed at some nodes which became virtually unsaturated. Major water-budget components for two simulations are summarized in table 2.

The minimum mean residual between observed and simulated water levels was again obtained for net withdrawal equal to 90 percent of the irrigation requirement. However, because a better irrigation efficiency was assumed for this period, the return flow to the

TABLE 2.—*Water budget for 1960–80 development-period calibration of the southern High Plains flow model*

[units are in millions of acre-feet]

Budget item	Net withdrawal equal to 90 percent of irrigation requirement	Net withdrawal equal to 110 percent of irrigation requirement
Outflows:		
Total pumpage	139.35	137.42
Boundary outflow	1.71	1.58
Total	141.06	139.00
Inflows:		
Return flow from irrigation	58.55	40.03
Recharge from precipitation on agricultural land	23.34	23.06
Recharge from precipitation on rangeland and along streams	3.19	3.19
Total	85.08	66.28
Change in storage:	–55.98	–72.72

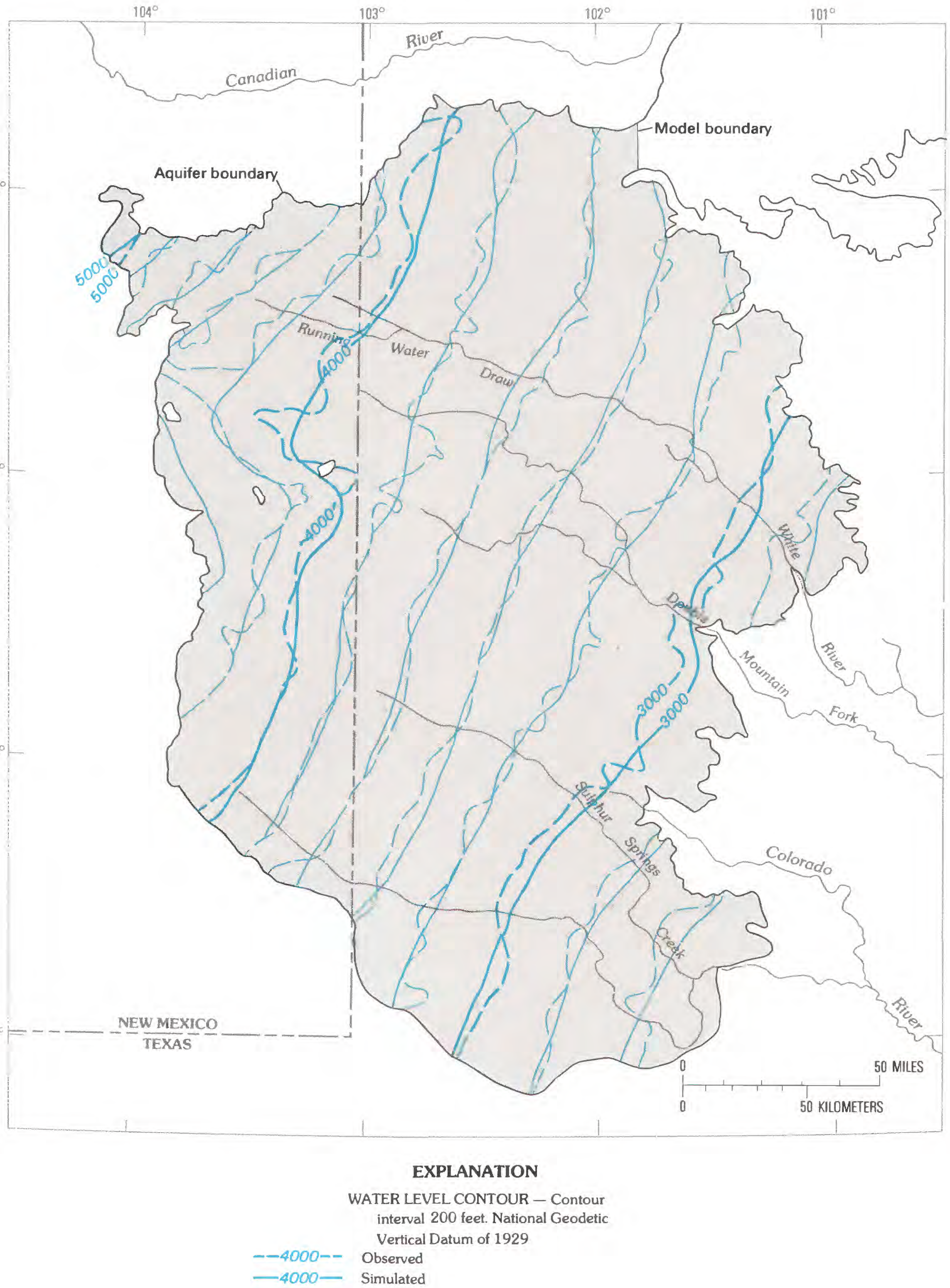
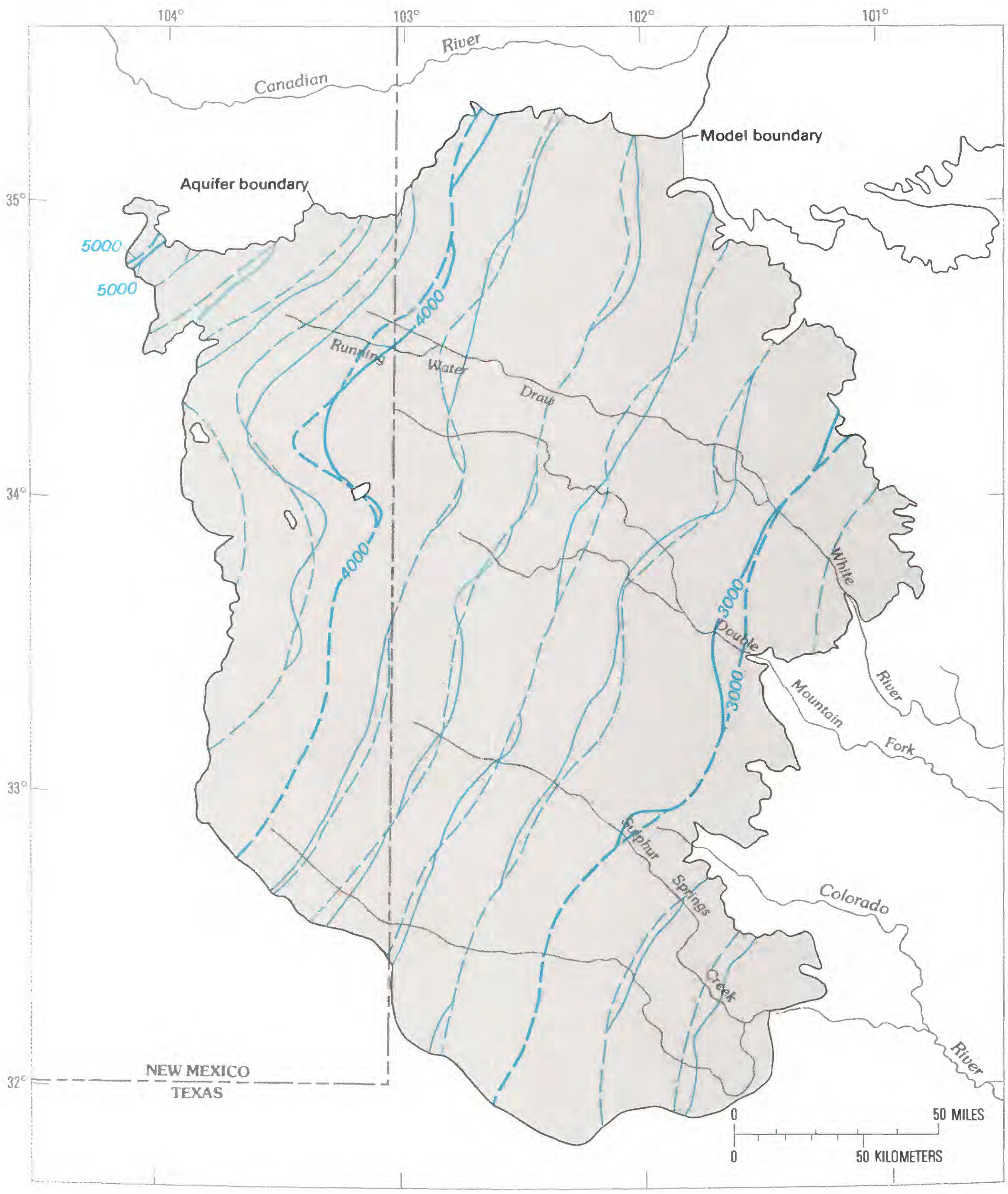


FIGURE 6.—Observed and simulated 1960 water level for the southern High Plains.



EXPLANATION

WATER LEVEL CONTOUR — Contour interval 200 feet. National Geodetic Vertical Datum of 1929

- - 4000 - - Observed

— 4000 — Simulated

FIGURE 7.—Observed and simulated 1980 water level for the southern High Plains.

aquifer was a smaller percentage of total pumpage than during 1940–60. The simulated return flow ranged from 46 percent of total pumpage during the early part of the period to 37 percent during the later part. The mean difference between observed and simulated water levels in 1980 shown in figure 7 was +0.28 ft with a standard deviation of 25.8 ft. The simulated change in storage of 56.0 million acre-ft was 2 percent larger than the observed change in storage of 54.9 million acre-ft. Most of the major differences between observed and simulated water levels occur away from the major pumping centers except for one area in the vicinity of Double Mountain Fork in Texas (the 3,000-ft contour in figure 7). In this area, the simulated 1980 water level is considerably below the observed water level. This probably is due to overestimating the total pumpage in water-short areas. This area is one of the most water-short areas of the High Plains.

In the 1960–80 simulations, additional recharge to the aquifer was added on all cropland. Cropland includes both irrigated land (fig. 8) and dryland (fig. 9). Mapped irrigated and dryland acreage were available only for 1978 (G. P. Thelin and F. J. Heimes, U.S. Geological Survey, written commun., 1984). These two maps were used under the assumption that the total cropland had not significantly changed since 1960 even though irrigated land has been converted to dryland and dryland to irrigated land. In various simulations, additional recharge ranging from 0 to 3.5 in./yr was applied uniformly to all cropland. The simulated water levels were compared to the observed water levels, particularly in the areas that were predominantly dryland. The simulated water levels most closely matched the observed water levels when the additional recharge was 2 in./yr. This recharge represents an addition of water to the aquifer of about 1 million acre-ft per year over the 19 million acres of the southern High Plains or about 0.6 in./yr if it were evenly distributed throughout the modeled area.

Tommy Knowles, Texas Department of Water Resources (oral commun., 1982), noted that in 1970 playas were full of water and water was standing in fields in a broad area of the southern High Plains, and between 1970 and 1980, water levels rose 0.5 to 1.0 ft per year in this area. Based on Knowles' observations, an alternate way to simulate the additional recharge would be to double the recharge rate and only apply it to the last one-half of the simulation period (1970–80). This procedure would have produced almost identical results to the procedure that was used. The additional recharge was necessary and appropriate for the 1960–80 simulation; however, it would not be appropriate to include it when using the model to make future evaluations because the additional recharge probably was the result of an unusual circumstance that occurs only infrequently.

Simulated discharge across the eastern boundary decreased significantly during this calibration period. The simulated boundary outflow was 270 ft^3/s during the predevelopment simulation, decreased to an average of 165 ft^3/s by 1960, and decreased further to an average of 118 ft^3/s by 1980 as a result of development. If flow along the boundary were uniform, the simulated outflow decreased from about 340 gal/min per mi prior to development to about 150 gal/min per mi by 1980. Both boundary outflow and the decrease in this flow were greatest in the northern one-half of the modeled area.

The generalized predevelopment to 1980 water-level change is shown in figure 10 and the simulated water-level change for the same period is shown in figure 11. The observed change map was not available prior to model calibration and, hence, was not used in calibration. Even though the change maps were not used in calibration, they are shown here to make this section comparable with later sections. In the northern one-half of the southern High Plains the two maps are similar but in the southern one-half significant differences exist between the two maps. The differences between the water-level change maps could have been reduced if the additional recharge simulated between 1960 and 1980 would have been increased in the southern one-half of the area. However, if this were done, the difference between the observed and simulated 1980 water levels would have been increased.

For the development-period simulations, only the difference between total pumpage and return flow from irrigation is needed because the two items were subtracted from each other in the stress term of the flow equation (equation 1). In the 1940–80 calibrations, total pumpage was estimated as 210 million acre-ft and return flow from pumpage was estimated as 94 million acre-ft. The difference is a net withdrawal of 116 million acre-ft. Although the calibrations indicated that net withdrawal must be close to 116 million acre-ft for the 40 years, quite possibly, total pumpage and return flow were both considerably less. The relationship between total pumpage and return flow becomes more important when using the models to evaluate future development. Decreasing total pumpage in the future may not decrease the net withdrawal significantly but may only decrease the return flow to the aquifer.

CENTRAL HIGH PLAINS MODEL CALIBRATION

The central High Plains consists of about 48,500 mi^2 in Colorado, Kansas, New Mexico, Oklahoma, and Texas. This area is mostly between the Canadian River in Texas and the Smoky Hill River in Kansas. The aquifer in the central High Plains was developed for irrigation later than in the southern High Plains with some development beginning by the 1950's. Two model calibrations were made—one simulating the system prior to irrigation development and the other simulating the system after irrigation development. The predevelopment-period calibration consisted of matching observed and simulated water levels and the development-period calibration consisted of matching observed and simulated water-level changes. Parts of the central High Plains have been modeled by Lindner–Lunsford and Borman (1984), Dunlap and others (1984), Cobb and others (1983), Havens and Christensen (1983), Knowles and others (1982), Morton (1980), Dunlap and others (1980), and Kapple and others (1977). In 1984, model studies were being conducted by the U.S. Geological Survey in western Kansas.

PREDEVELOPMENT-PERIOD CALIBRATION

For the predevelopment-period calibration, hydraulic conductivity and recharge from precipitation were adjusted. Estimates of recharge for the central High Plains range from a minimum of 0.05 in./yr to a maximum of 6.0 in./yr (Gutentag and others, 1984, table 7). These estimates were adjusted during model calibration. Prior to development, the aquifer was in a state of equilibrium and, therefore, the amount of recharge was in balance with the discharge along the eastern boundary and along numerous river valleys. The nodes along the eastern boundary were treated as constant-head nodes and the nodes along the principal river valleys were treated as river nodes to simulate the interaction of the streams with the aquifer (fig. 12). The primary difference between the constant-head nodes and the river nodes is that the simulated hydraulic head in the aquifer can change at the river nodes. The head in the aquifer at the river nodes controls the simulated exchange of water between the aquifer and the river. The hydraulic conductivity of the river bed was assumed to be the same as that of the aquifer and, hence, did not limit the rate of leakage. The simulated head in the aquifer cannot change at a constant head node and it is the gradient to the constant-head node that controls the flow of water from the aquifer at the node.

The initial estimates of hydraulic conductivity for the central High Plains (Gutentag and others, 1984, fig. 10) ranged from about 10 to 300 ft/d. Average values determined for each node ranged from 12 to 209 ft/d with a mean of 61 ft/d. During simulation, it was necessary to significantly decrease many of the hydraulic conductivity estimates to achieve the best match of the observed and simulated water levels. Hydraulic conductivities adopted from Gutentag and others (1984, fig. 10) are shown in figure 13 and the modified hydraulic-conductivity estimates as a result of model calibrations are shown in figure 14. The modified hydraulic-conductivity estimates range from 12 to 189 ft/d with a mean of 50 ft/d.

The areas where the hydraulic-conductivity estimates were modified correspond to the areas where the base of aquifer surface has been significantly altered by salt dissolution and sinkhole formation in the underlying Permian rocks. Sinkholes and other collapse structures are found in a broad area from northern Texas to central Kansas (Gutentag and others, 1984, p. 17). They were formed prior to, during, and after the deposition of the High Plains aquifer. The broad area where saturated thickness is more than 200 feet between the Smoky Hill and Canadian Rivers (Weeks and Gutentag, 1981) probably is a result of coalescing collapse features. Well yields in this area are consistent with the hydraulic conductivities indicated by Gutentag and others (1984). However, the regional flow simulated by models indicates significantly less hydraulic conductivity in this area.

A similar discrepancy between regional and local aquifer parameters was noted by Emmett and others (1978, p. 31) in a dolomite aquifer in Missouri. In a heterogeneous aquifer, the hydraulic parameters are scale dependent. On a small scale, local values are the important factor in the parameter value. However, on a large scale, the parameter value is a harmonic average of local extremes. Salt dissolution and sinkhole formation in the central High Plains cause extreme local variation in hydraulic conductivity because of disturbed and chaotic bedding combined with extreme changes in lateral lithologies. These extreme local variations exaggerate the scale dependence of the hydraulic conductivity.

Identical model results could have been obtained, using the hydraulic conductivity estimates without revision and changing the saturated thickness, by redefin-

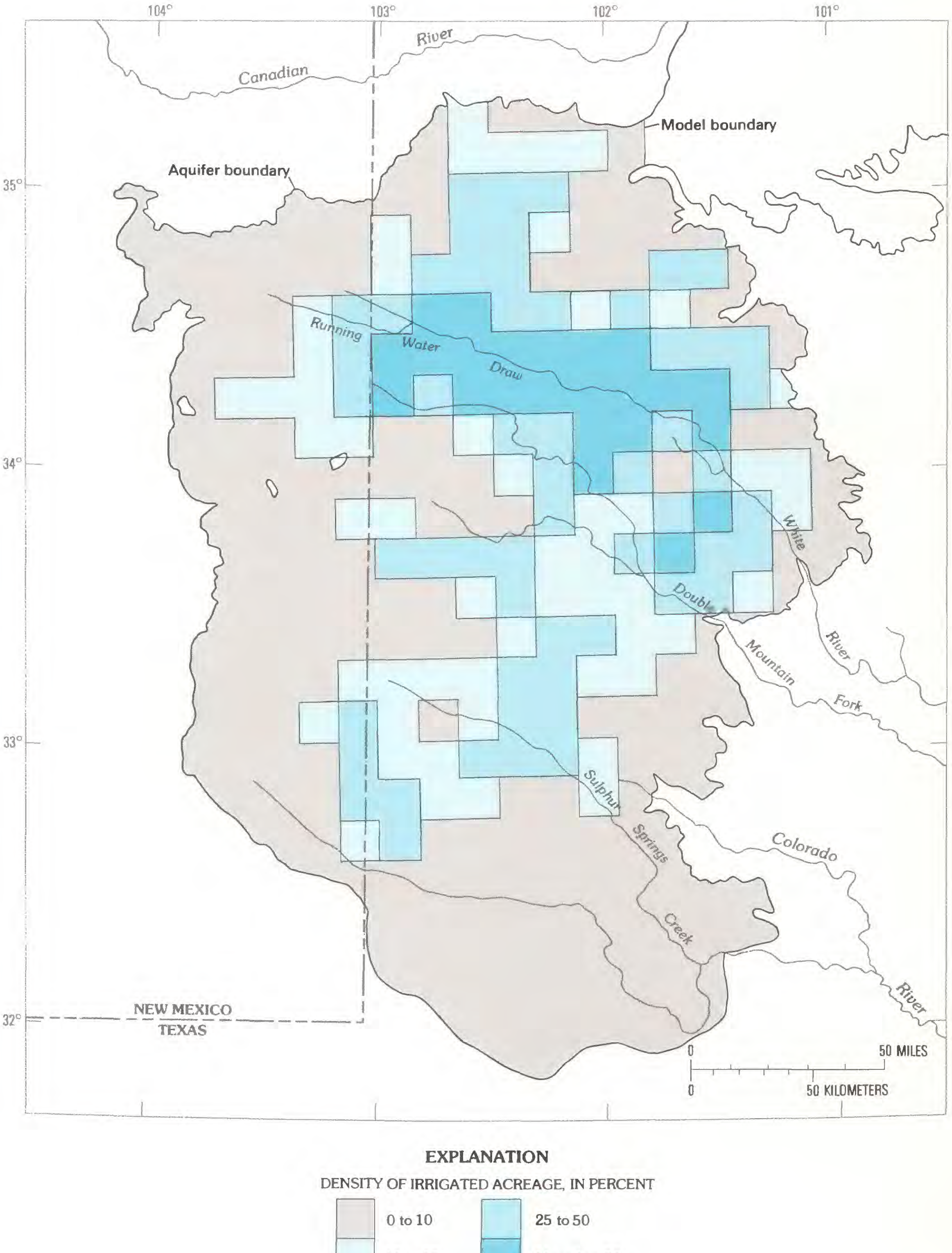


FIGURE 8.—Irrigated acreage in the southern High Plains during 1978.

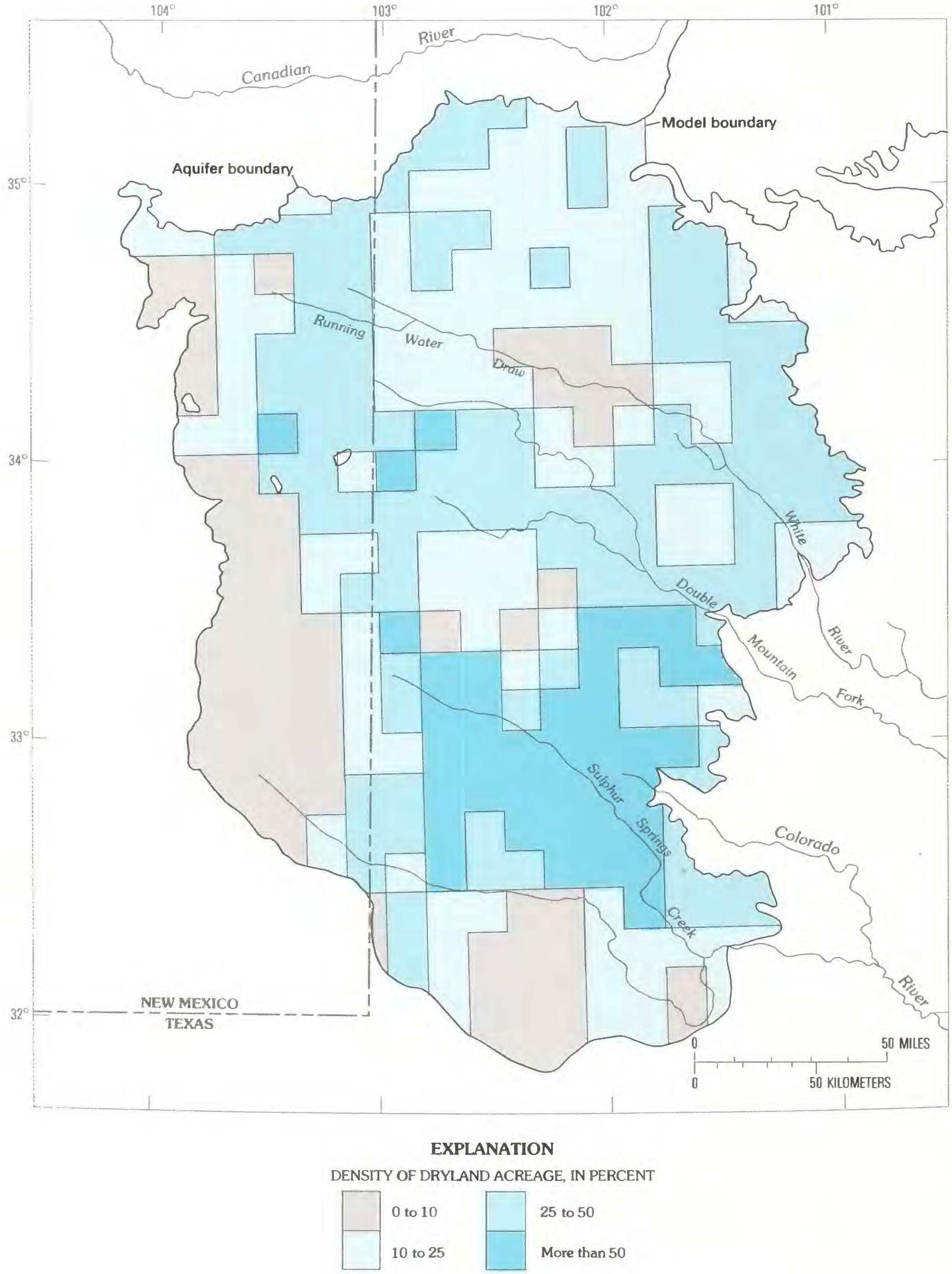


FIGURE 9.—Dryland acreage in the southern High Plains during 1978.

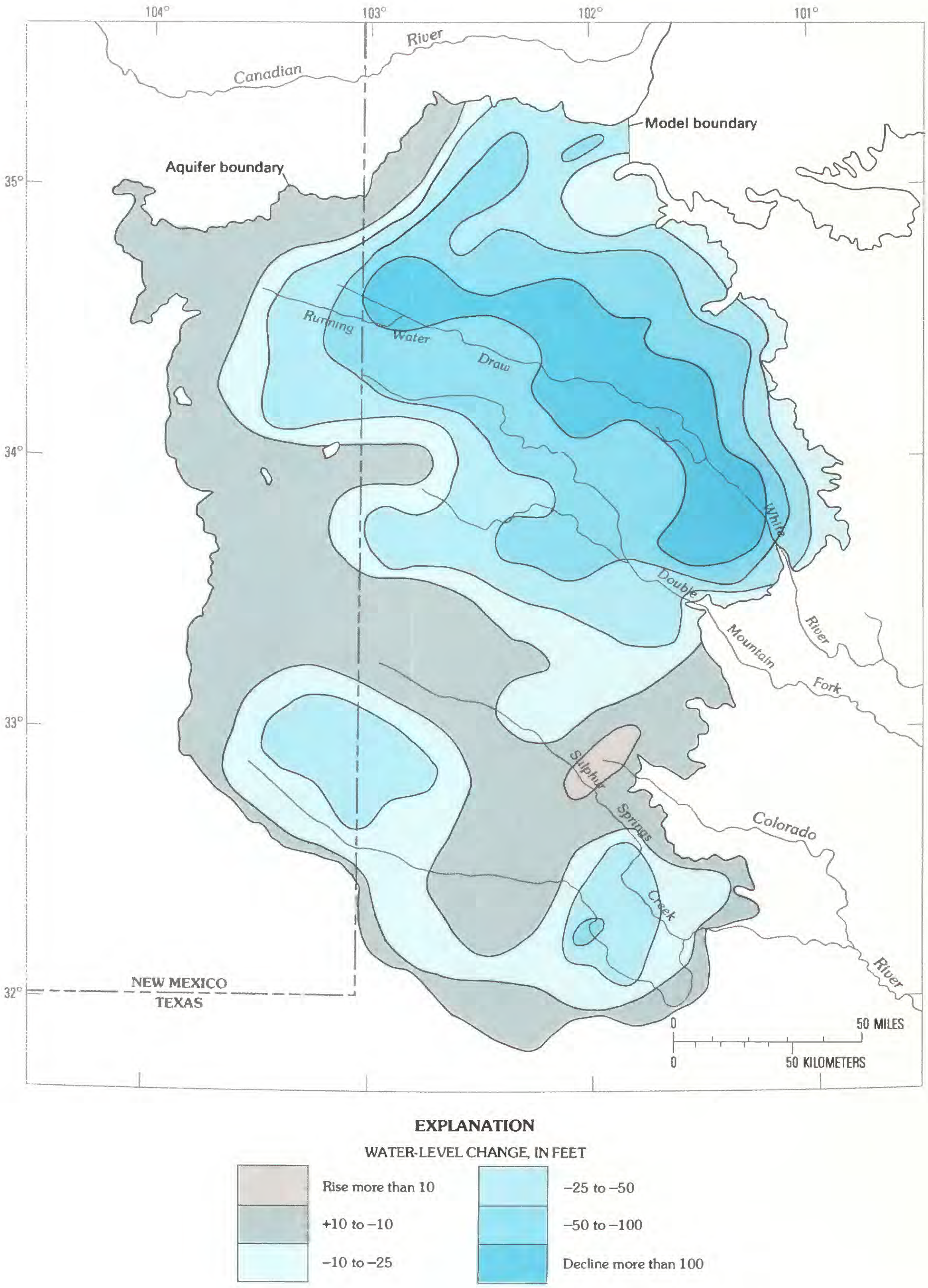


FIGURE 10.—Generalized observed predevelopment to 1980 water-level change for the southern High Plains.

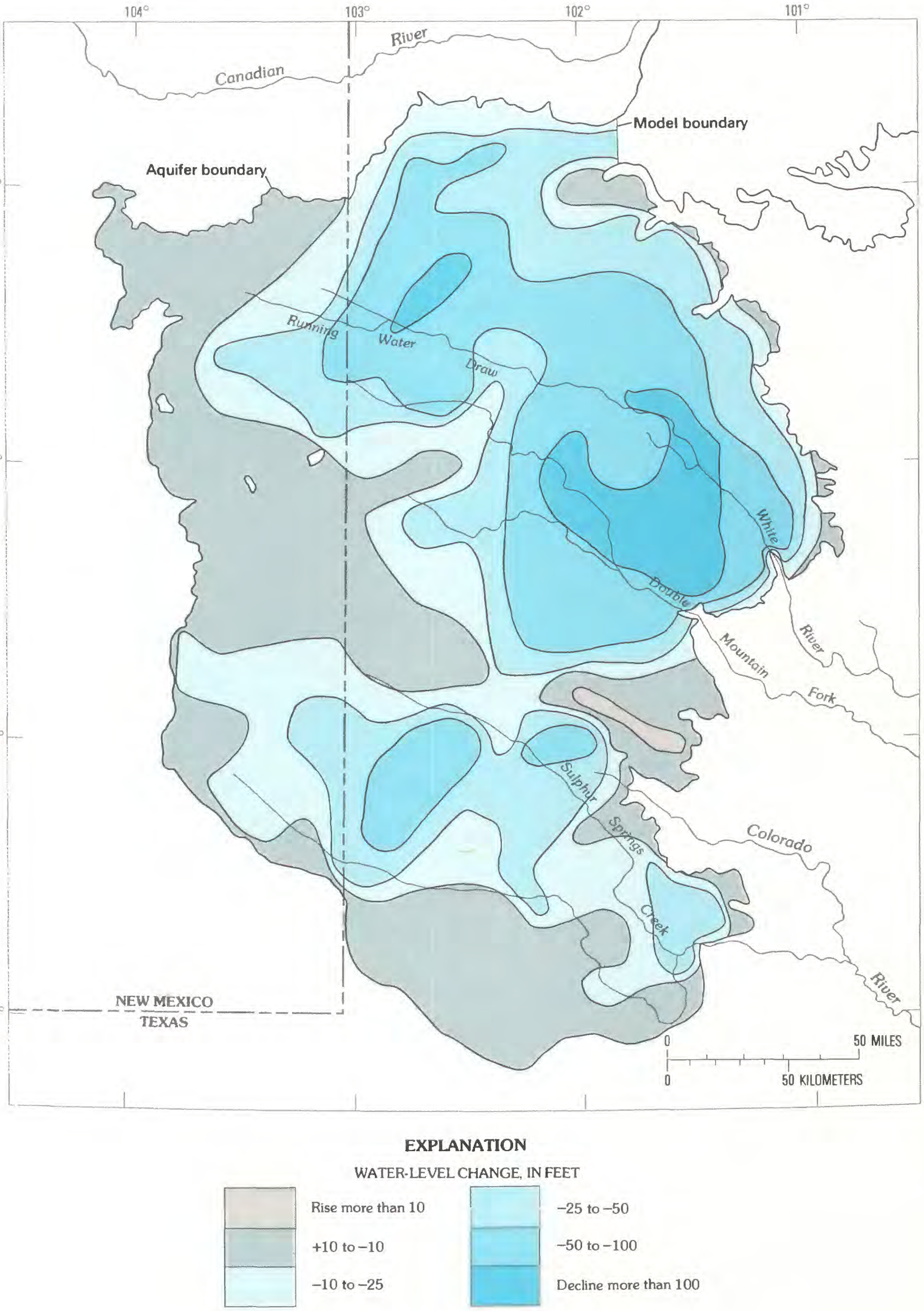


FIGURE 11.—Simulated predevelopment to 1980 water-level change for the southern High Plains.

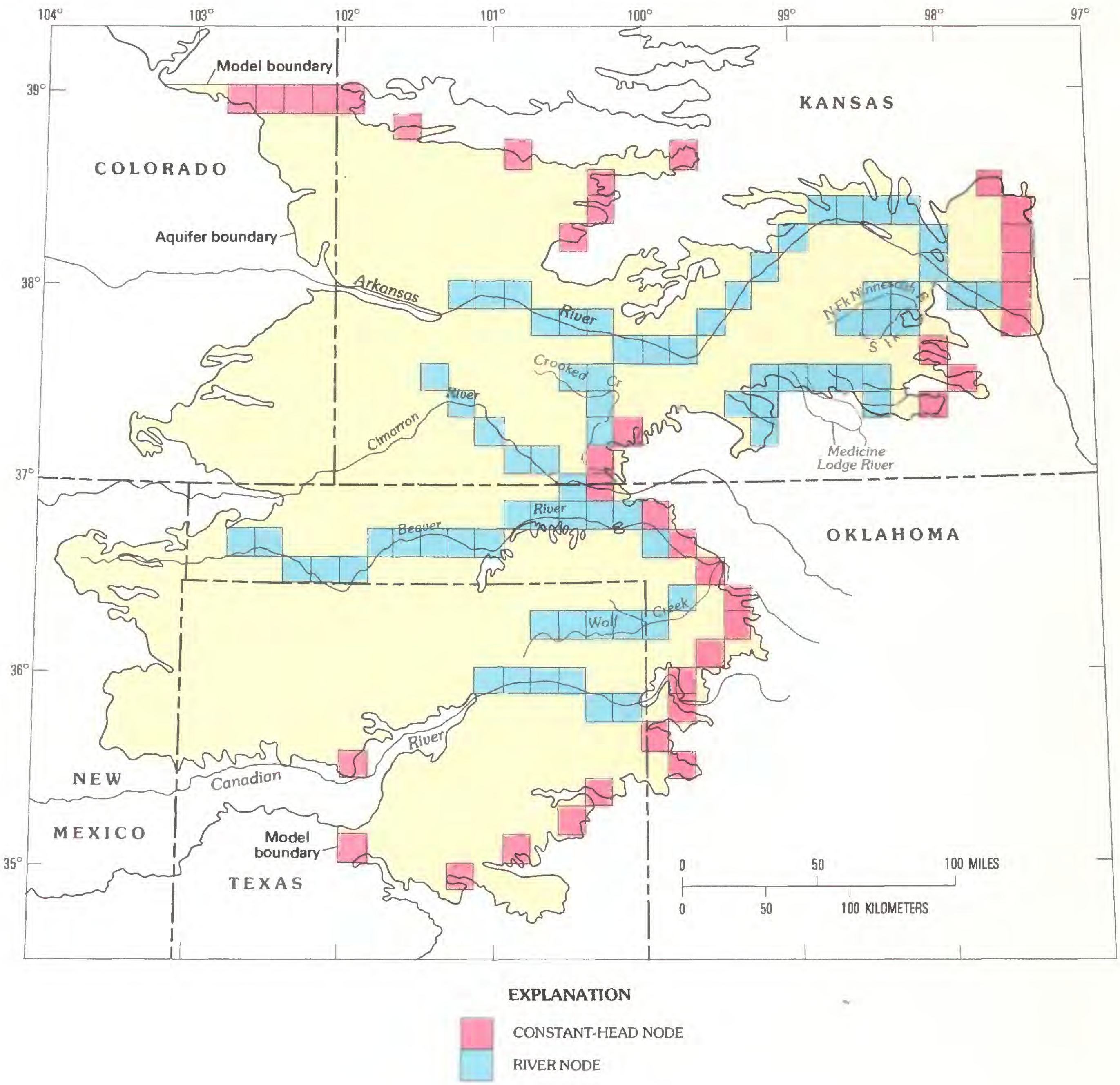


FIGURE 12.—Boundary conditions for the models of the central High Plains.

ing the location of the base of the aquifer. Although the map by Weeks and Gutentag (1981) is a good representation of the physical base of the Tertiary sediments, the effective base of the flow system might be significantly above the base of the sediments in the broad area of coalesced collapse features. Preliminary calculations tend to discount this effect, but further study is necessary to answer these questions.

Recharge from precipitation was the other parameter that was adjusted during the predevelopment-period calibration. Different recharge distributions were evaluated and the best correspondence between the observed and simulated water levels occurred when the recharge distribution was related to soil type. This is different from that found for the southern High Plains. Generalized soils for the central High Plains are shown

TABLE 3.—*Summary of simulated outflow from the central High Plains predevelopment-period model*

[Streams located on Figure 12]

Outflow element (rivers include tributaries)	Outflow, in cubic feet per second
Canadian River	67
Wolf Creek	23
Beaver River	78
Cimarron River	106
Crooked Creek	27
Arkansas River	81
North Fork Ninnescah	38
South Fork Ninnescah	41
Medicine Lodge River	4
Boundary outflow, south of Canadian River	18
Boundary outflow, between Canadian and Arkansas River	27
Boundary outflow, north of the Arkansas River	33
Total	543

in figure 15. Sandy soils are expected to be more conducive to recharge for two reasons: (1) Sandy soils are more permeable and (2) they have smaller water-holding capacity. These factors allow precipitation to more readily percolate below the root zone and ultimately become recharge to the aquifer. Topography also can be a major factor in the distribution of recharge. Recharge is much more likely to occur in dune areas with a poorly developed drainage pattern than in areas with a well-developed drainage pattern.

The recharge distribution that resulted in the predevelopment calibration for the central High Plains is shown in figure 16. The sand-dune areas have the maximum recharge rate with a long-term average of 0.84 in./yr or 15 times greater than the minimum value. The small zone of sand in the southwest part of the area has an estimated recharge rate of 0.39 in./yr. The large zone of sandy loams in the northeastern part of the area was assigned a recharge rate of 0.28 in./yr. The smaller areas of sand-loam soils were lumped with the silt-loam and the clay-loam soils because the simulations did not indicate that these areas received significantly more recharge. The clay and sandy loams in the extreme southern part of the model were assigned recharge rates of 0.11 in./yr. The minimum value, 0.056 in./yr, occurred over the remainder of the clay-, silt-, and sandy-loam soils. The overall mean long-term predevelopment recharge rate for the central High Plains was estimated to be 0.14 in./yr. This recharge rate is close to the mean predevelopment recharge rate estimated for the southern High Plains (0.13 in./yr).

The total predevelopment recharge from precipitation to this area was estimated to be 522 ft^3/s. Another 21 ft^3/s flowed into the central High Plains from the southern and northern High Plains. The rivers that originate to the west of the High Plains, particularly the Cimarron River, probably contribute some recharge to the aquifer. However, this component of recharge was difficult to detect because of the coarse grid used in this model; this recharge was included as part of the recharge from precipitation assumed in the sand-dune areas.

The total inflow of 543 ft^3/s was balanced by an equivalent quantity of outflow. This outflow consisted of discharge to rivers and seepage across the boundaries of the aquifer. A summary of the outflow is given in table 3.

The long-term ground-water contribution to rivers is difficult to evaluate, but estimates are available for some rivers. Fader and Stullken (1978, p. 11) estimated base flow to the North and South Fork Ninnescah River as 38 and 94 ft^3/s; the model simulated 38 and 41 ft^3/s, respectively. Gutentag and others (1981, p. 43) measured the base flow of the Cimarron River as about 60 ft^3/s at the Kansas-Oklahoma State line. The flow computed by the model at the same place was 80 ft^3/s. Winter flow records for 1896–1908 for the Arkansas River indicate a ground-water contribution to the river between Garden City and Hutchinson, Kans., of about 80 ft^3/s. The model simulated 71 ft^3/s for the same reach. Winter flow records for 1938–50 for the Canadian River between Armarillo and Canadian, Texas, indicate a ground-water contribution of about 45 ft^3/s; the model simulated 56 ft^3/s. Flow records for the same period indicate that the Beaver River and Wolf Creek each received about 30 ft^3/s from the High Plains aquifer. The model indicated a gain of 78 ft^3/s for the Beaver River and 23 ft^3/s for Wolf Creek.

The simulated seepage across the eastern boundary was very small, averaging less than 0.2 ft^3/s per mi. This was somewhat less than the estimated flow across the eastern boundary of the southern High Plains, but it is probably reasonable.

The observed and simulated predevelopment water levels were quite similar throughout most of the central High Plains (fig. 17). The mean difference between the observed and simulated water levels at 513 nodes was −0.28 ft with a standard deviation of 38.5 ft. At 98 percent of the nodes, the simulated water level was within 100 ft of the observed water level. Most of the major discrepancies were in areas of sparse water-level data. The major difference was in Texas on the north side of the Canadian River. To properly simulate the observed water levels in this area, recharge would have to be increased considerably, but analysis gave no indi-

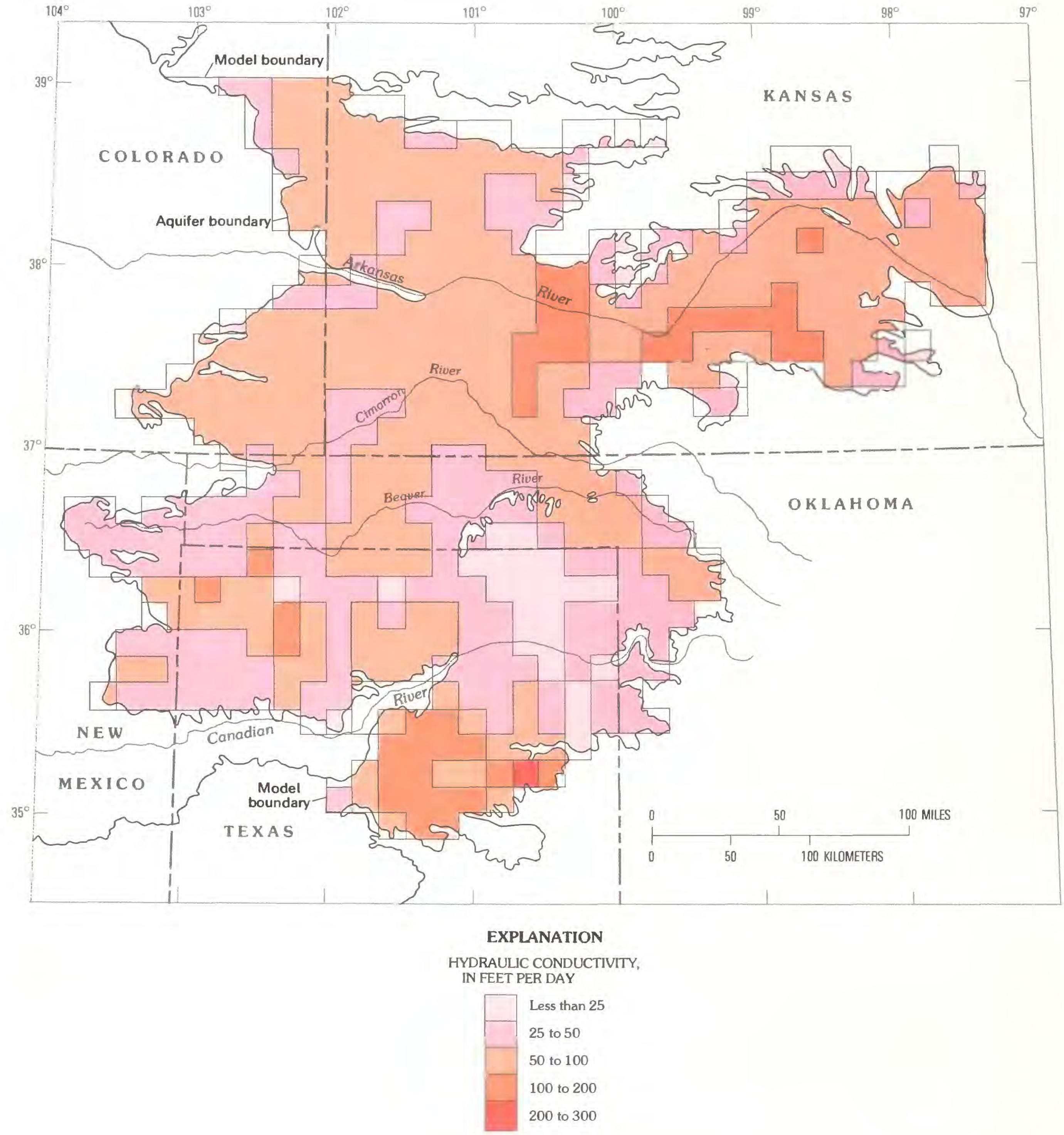


FIGURE 13.—Hydraulic-conductivity estimates for the central High Plains adapted from Gutentag and others (1984).

cation that this area should receive more recharge than other areas of similar soil type. Therefore, no more recharge was added to the model in this area. A smaller area of discrepancy was south of the Canadian River where the model indicated that too much recharge was being simulated. Other minor differences were throughout the area, but in general the correspondence between the observed and simulated water levels is good.

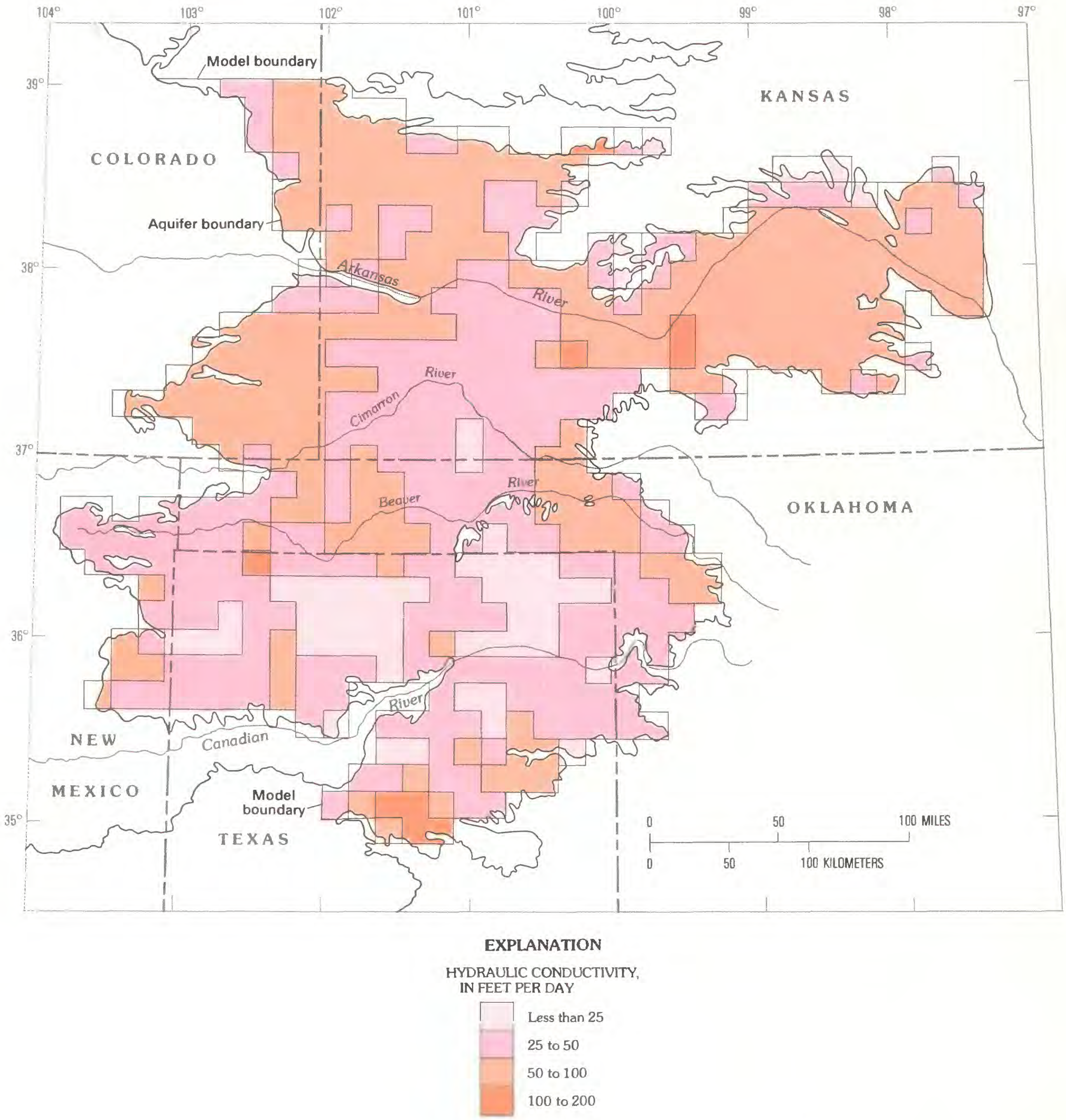


FIGURE 14.—Revised hydraulic-conductivity estimates for the central High Plains.

DEVELOPMENT-PERIOD CALIBRATION

Two development calibration periods were used in the southern High Plains because of the long history of development. However, the central High Plains has a shorter history of development and, hence, only one development period, 1950–80, was simulated. By 1950, only relatively small areas had been significantly dis-

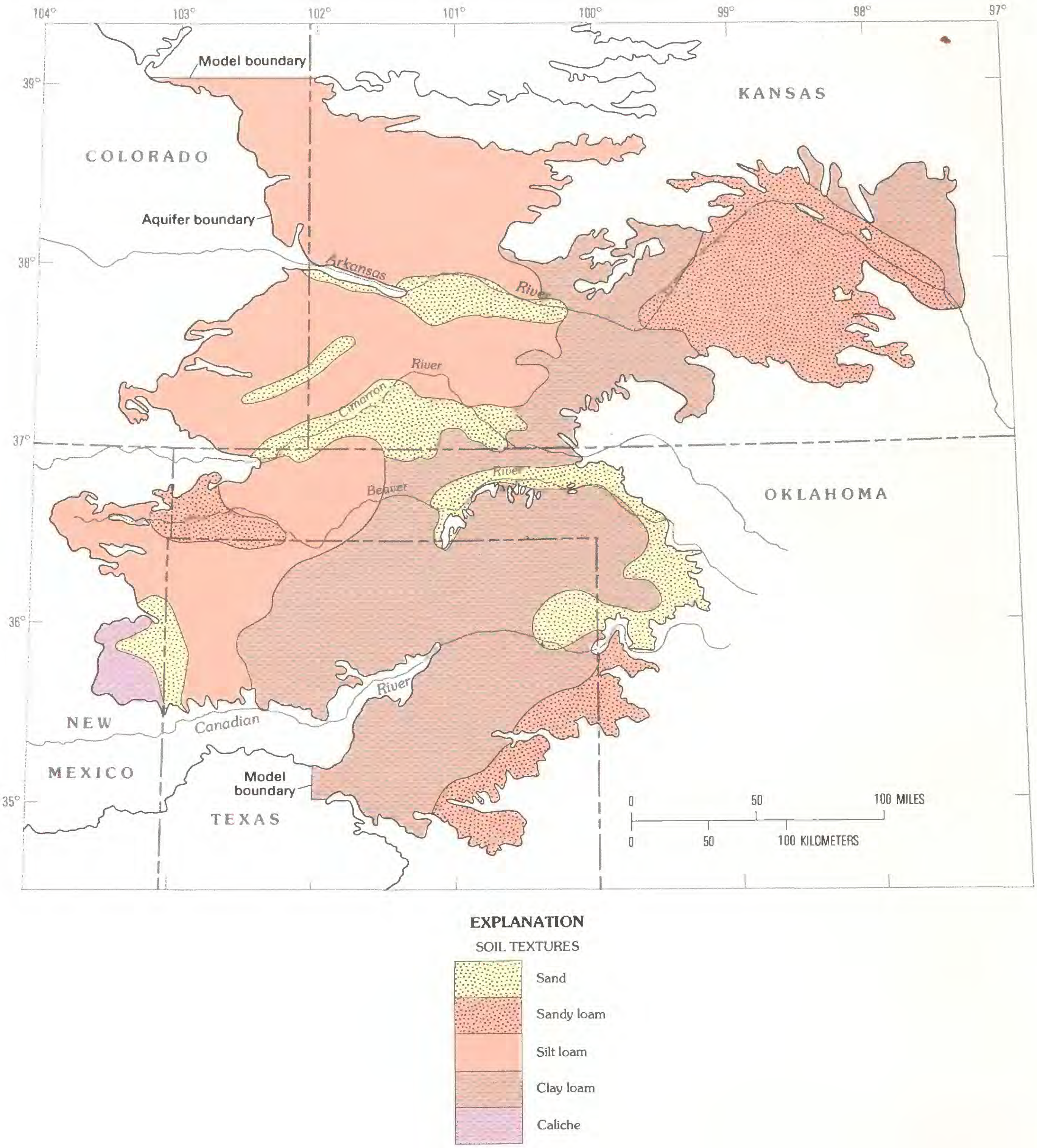


FIGURE 15.—Generalized soil types of the central High Plains.

turbed from predevelopment conditions, and the simulated predevelopment water levels were used as the initial water levels for the development-period simulation.

Throughout a substantial part of the central and northern High Plains, the water levels have changed much less than 50 ft since development began so to comparing water-level contours was difficult. The mod-

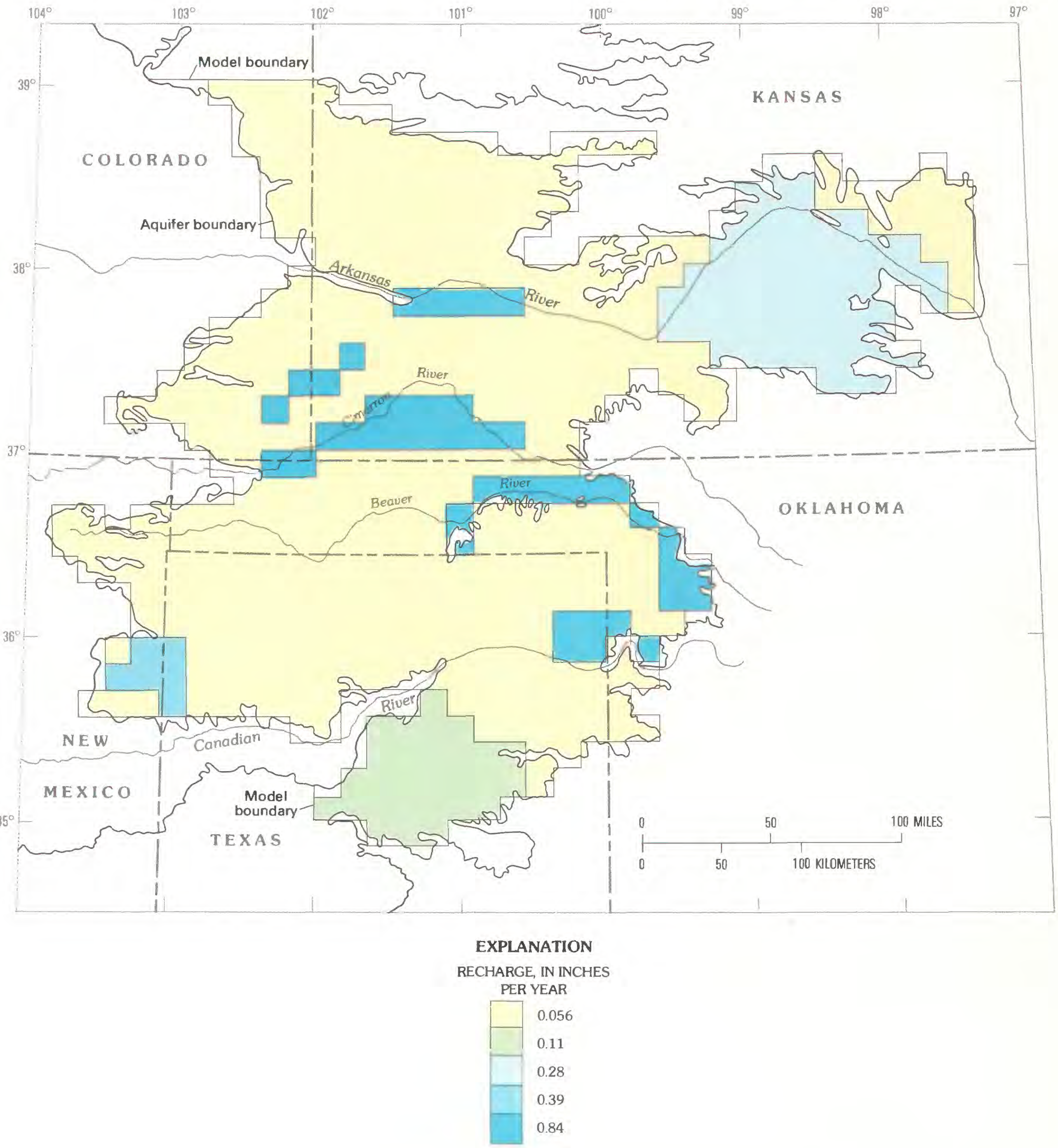


FIGURE 16.—Estimated predevelopment, long-term average recharge rates for the central High Plains.

els, therefore, were calibrated by adjusting the input data to obtain a reasonable match between observed and simulated water-level changes. Areas and volumes of water-level change were compared.

Pumpage for the central High Plains was divided into three categories: (1) Pumpage for irrigation; (2) pumpage for municipal and industrial use; and (3) pumpage for stock and domestic use. The last category was insig-

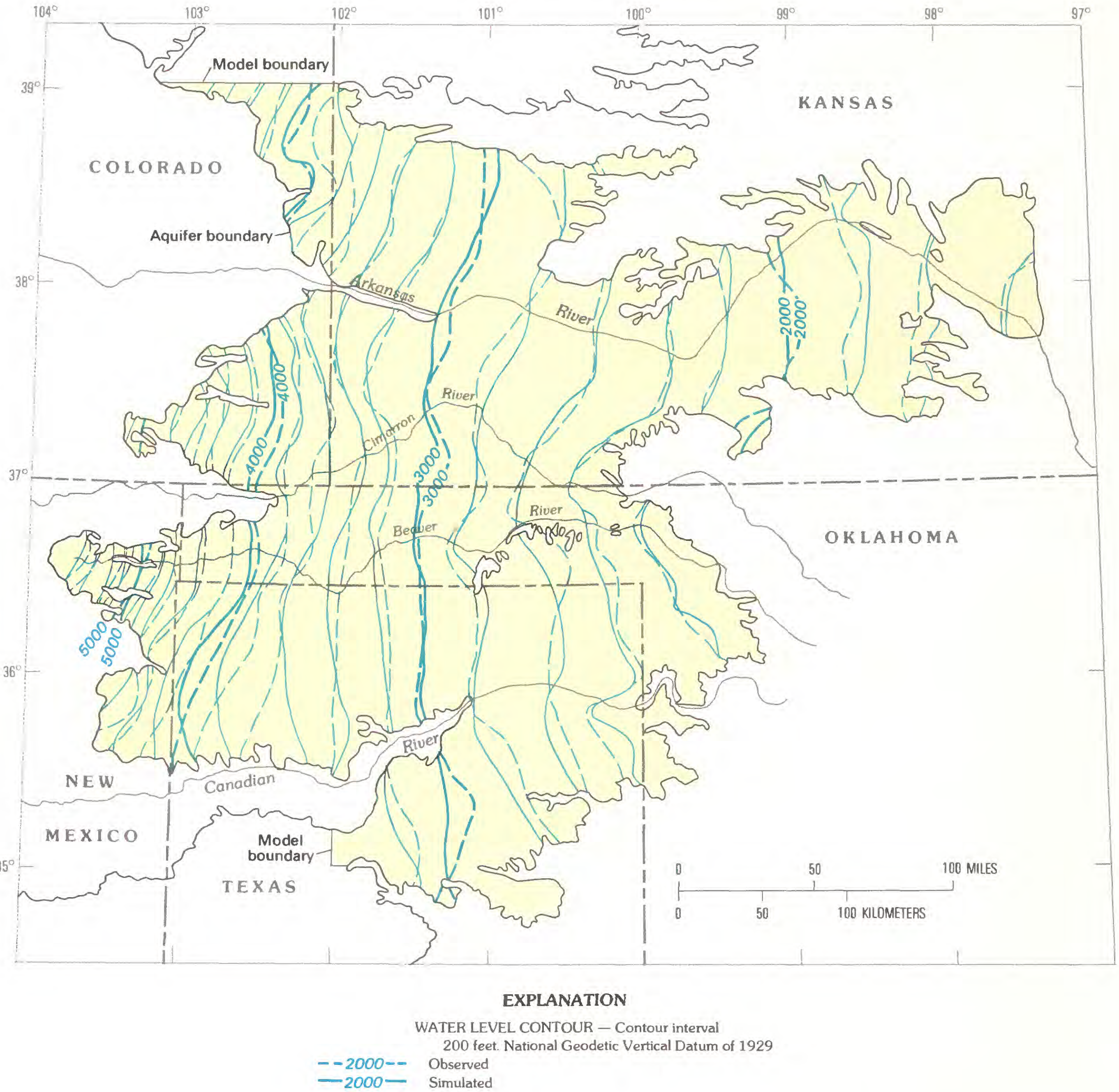


FIGURE 17.—Observed and simulated predevelopment water level for the central High Plains.

nificant compared to the other two categories and was ignored. Municipal and industrial pumpage, which was only a few percent of the total pumpage, was estimated from data from various State agencies and from published population figures. The pumpage estimates for the central High Plains are given in table 4 which indicates that approximately 94 million acre-ft of water had been pumped from the aquifer in the central High Plains from 1950 to 1980. This is about one-half the total pumped from the southern High Plains.

A generalized observed water-level change map (fig. 18) was constructed from the water-level change map presented by Luckey and others (1981) by estimating the average change at each 100 mi^2 node, and then con-

TABLE 4.—*Pumpage in the central High Plains, 1950 to 1980, by State*

State	Pumpage, in thousands of acre-feet per year							
	Municipal and industrial		Irrigation					
	1950–64	1965–79	1950–54	1955–59	1960–64	1965–69	1970–74	1975–79
Colorado	0.4	0.8	6	19	40	60	79	92
Kansas	62	124	447	279	1,363	1,812	2,418	3,127
New Mexico	—	—	5	8	11	35	46	43
Oklahoma	11	21	43	113	195	422	537	572
Texas	16	33	136	459	847	1,352	1,517	1,571
Total	89.4	178.8	637	1,578	2,456	3,681	4,597	5,405

touring these estimated changes. The water-level change map of Luckey and others (1981) was reinterpreted and modified in northern Texas near and north of the Canadian River. Water-level changes for each simulation were contoured and the resulting map was compared with the generalized, observed change map.

Return flow to the aquifer from irrigation was adjusted among simulations. Because return flow was assumed to reach the aquifer within the 5-year pumping period, changing return flow was exactly equivalent to changing net withdrawal (total pumpage minus return flow). Return flow was assumed to be a function of the difference between total pumpage and irrigation requirement. Simulated water-level changes when return flow was equal to 100 percent of this difference (net withdrawal equal to irrigation requirement) are shown in figure 19. For this simulation, the return flow ranged from 55 percent of total pumpage early in the development period to 30 percent later and averaged 43 percent. This return flow appears large, but, as in the southern High Plains development-period model, only the difference between total pumpage and return flow was important and both may be considerably overestimated whereas the difference remains correct. The extent of the area of significant water-level declines (greater than 10 ft) was similar between the observed and simulated water-level change maps but the area of decreases in excess of 50 ft was much larger on the observed change map.

In a second simulation, net withdrawal was assumed to be 130 percent of irrigation requirement. For this case, return flow ranged from 42 percent of total pumpage early in the development period to 9 percent later and averaged 17 percent. The water-level change for this simulation is shown in figure 20. Although no simulated water-level decline exceeds 100 ft, one node (100 mi^2) had an average decline of 96 ft. The area where simulated water-level declines exceed 50 ft is much larger in this simulation than in the previous simulation.

A summary of the results of these two simulations is given in table 5. Data in the table indicate both the areal extent of the declines and the volume of aquifer material dewatered. The total volume of aquifer material dewatered was chosen as a comparison factor rather than volume of water removed because the measurement of the volume of aquifer dewatered does not require knowledge of the specific yield of the aquifer.

For the areas where the observed water-level declines exceed 50 ft, the second simulation (net withdrawal equals 130 percent of irrigation requirement) fits the observed water-level declines better, but, overall, the first simulation (net withdrawal equals 100 percent of irrigation requirement) provides a better result. On a volumetric basis, the water-level declines for the first simulation were 9 percent less than the observed water-level declines. On an areal basis, the water-level declines for the first simulation were 6 percent greater than the observed declines. For the first simulation, the simulated change in storage was 54.9 million acre-ft; the observed change in storage was 50.3 million acre-ft.

The differences between the observed and simulated water-level change maps are believed to be primarily due to errors in the distribution of pumpage. Pumpage was estimated based on data presented by Heimes and Luckey (1982). Although these data were presented for 10-minute cells, the irrigated-acreage data originally came from county-level census data. The acreage was then distributed to the 10-minute cells within each county as described in that report. The 10-minute cells did not correspond to the 100-mi^2 nodes used in the model, so the pumpage data had to be redistributed from the 10-minute cells to the model nodes. Both pro-

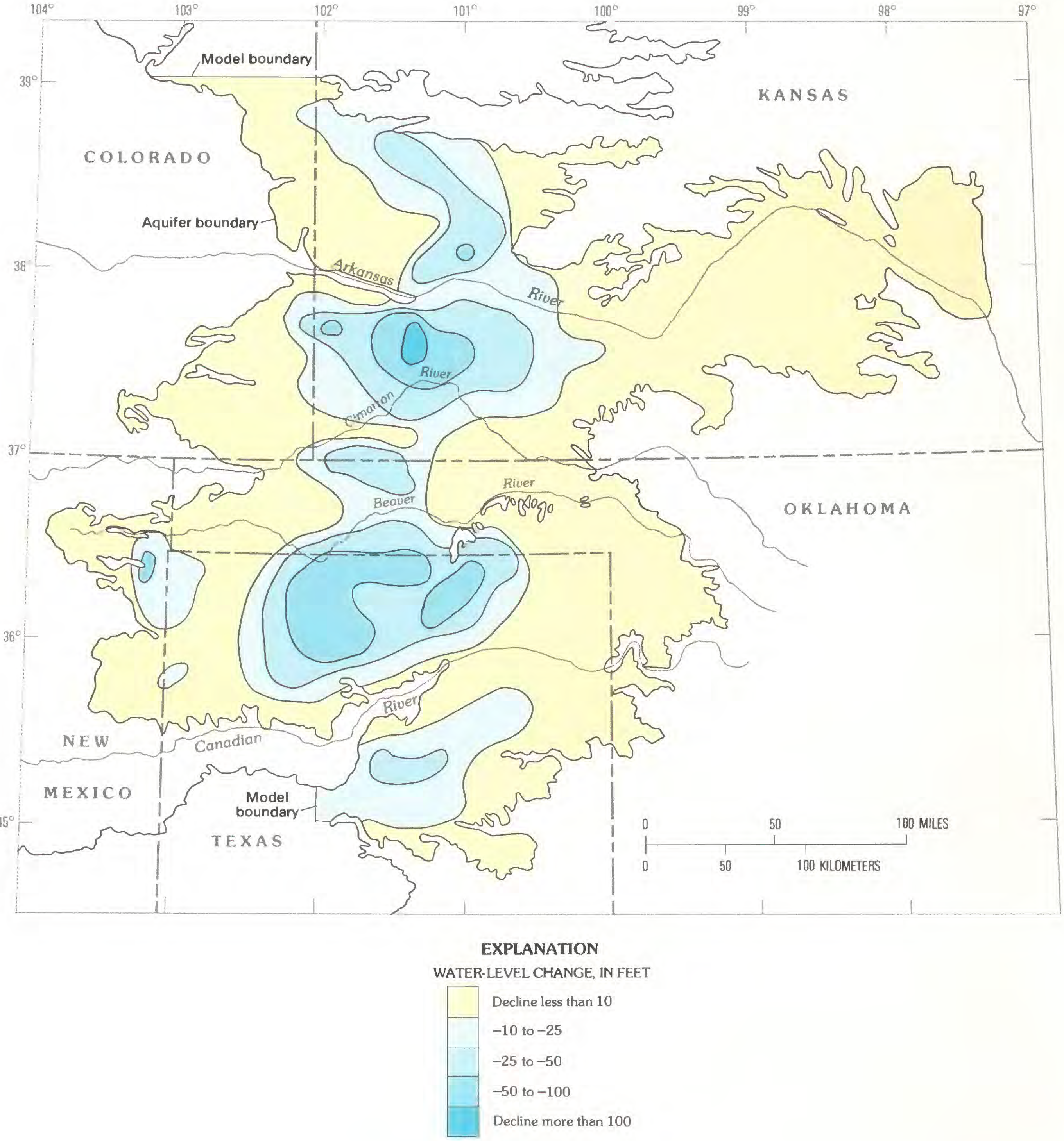


FIGURE 18.—Generalized, observed predevelopment to 1980 water-level change for the central High Plains.

cesses, allocating county data to 10-minute cells and redistributing 10-minute data to 100-mi^2 model nodes, tend to spread the pumpage throughout a somewhat broader area than where it actually occurred. Additionally, the model assumes that the pumpage occurred uniformly throughout the node; this tends to spread the effects of pumpage even further. This spreading of the pumpage probably was a less serious problem in the southern High Plains because that area has been densely developed throughout broad areas for a long time.

TABLE 5.—*Comparison of observed and simulated water-level declines, 1950 to 1980, for the central High Plains*

Water-level decline, in feet	Volume of aquifer material dewatered, in millions of acre-feet			Area of water-level decline, in square miles		
	Observed declines	Simulated declines		Observed declines	Simulated declines	
		Net withdrawal of 100 percent of irrigation requirement	Net withdrawal of 130 percent of irrigation requirement		Net withdrawal of 100 percent of irrigation requirement	Net withdrawal of 130 percent of irrigation requirement
More than 10......	339	306	450	15,200	16,100	23,300
More than 25......	257	215	298	7,900	8,000	9,700
More than 50......	124	47	130	2,400	1,000	2,700
More than 100.....	11	0	0	100	0	0
10 to 25	82	91	152	7,300	8,100	13,600
25 to 50	133	168	168	5,500	7,000	7,000
50 to 100.........	113	47	130	2,300	1,000	2,700

Spreading of the pumpage causes the simulated water-level declines to be more extensive but less severe in local areas.

NORTHERN HIGH PLAINS MODEL CALIBRATION

The northern High Plains consists of about 96,500 mi^2 of the High Plains in Colorado, Kansas, Nebraska, South Dakota, and Wyoming. This area generally is north of the Smoky Hill River. The northern High Plains flow model includes all of the northern High Plains except a small part in the northwest corner which was not included because the geology in this region is too complex for the scale of the model. The northern High Plains was the last area of the High Plains to be developed for irrigation, with development generally starting after 1960. By 1980, a large part of this area was still virtually undeveloped. Two separate calibrations were made, one simulating the system prior to development and the other simulating the system after development. However, because of the lack of development in the northern High Plains, the second calibration is limited. The first calibration consisted of matching observed and simulated predevelopment water levels and comparing observed and simulated predevelopment base flow to major rivers. The second calibration consisted of matching observed and simulated water-level changes.

Small areas of the northern High Plains have been modeled by a number of investigators. Lindner-Lunsford and Borman (1984) and Reddell (1967) modeled the northern High Plains in Colorado. Kapple and others (1976) and Luckey and Hofstra (1973a and 1973b) modeled parts of the High Plains in Colorado. Lappala and others (1979) modeled a substantial part of Nebraska, and smaller areas of Nebraska were modeled by Pettijohn and Chen (1984), Cady and Ginsberg (1979), Lappala (1978), Huntoon (1974), and Emery (1966). The High Plains in South Dakota has been modeled by Kolm and Case (1983), and the High Plains in Wyoming has been modeled by Crist (1975, 1977, and 1980) and Hoxie (1977 and 1979). In 1984, model studies were being conducted by the U.S. Geological Survey in western Kansas.

PREDEVELOPMENT-PERIOD CALIBRATION

In the predevelopment-period model hydraulic conductivity and recharge from precipitation were adjusted. Estimates of recharge for the northern High Plains ranged from a minimum of 0.17 in./yr to a maximum of 5.0 in./yr (Gutentag and others, 1984, table 7). Ground-water recharge in the northern High Plains aquifer ultimately discharges along the boundaries, along river valleys, and in areas where the water level is close to land surface. The nodes along the boundary were treated as constant-head nodes and the nodes along the principal river valleys were treated as river nodes (fig. 21). The discharge to areas where the water level is close to land surface, such as lakes and wet meadows in the sandhills, was not handled directly in the model. Instead, this discharge was subtracted from total recharge for the node; hence, the modeled recharge at each node represents the net recharge (total recharge minus total discharge) for the node.

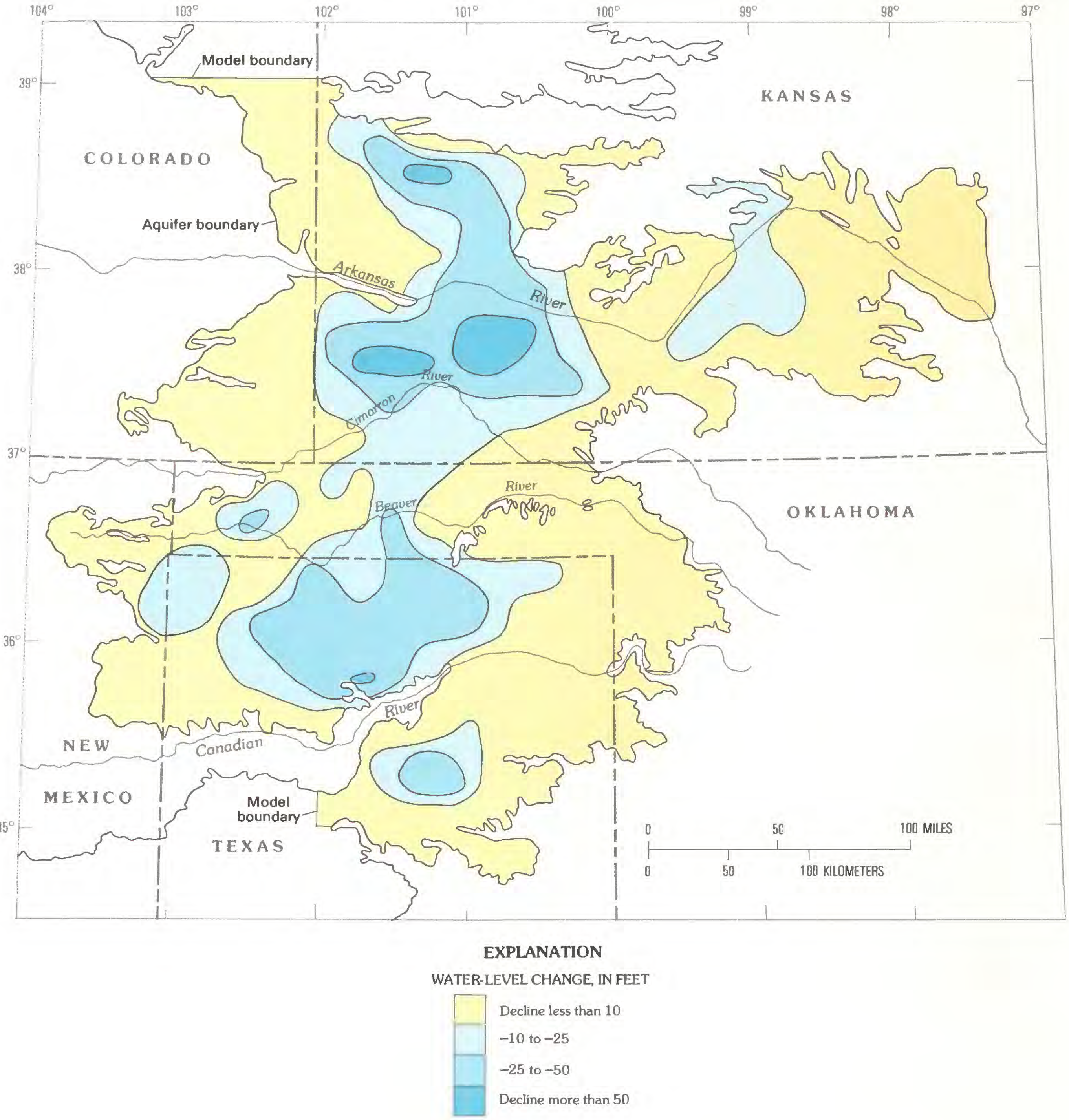


FIGURE 19.—Simulated predevelopment to 1980 water-level change with net withdrawal equal to 100 percent of irrigation requirement for the central High Plains.

The initial hydraulic-conductivity estimates were obtained from Gutentag and others (1984, figure 10). Average values were determined for each node; the values ranged from 15 to 300 ft/d with a mean of 43 ft/d.

Predevelopment discharge to major rivers was estimated from streamflow records. Discharge along the northern and eastern boundaries were estimated using Darcy's law. Estimating the long-term discharge in

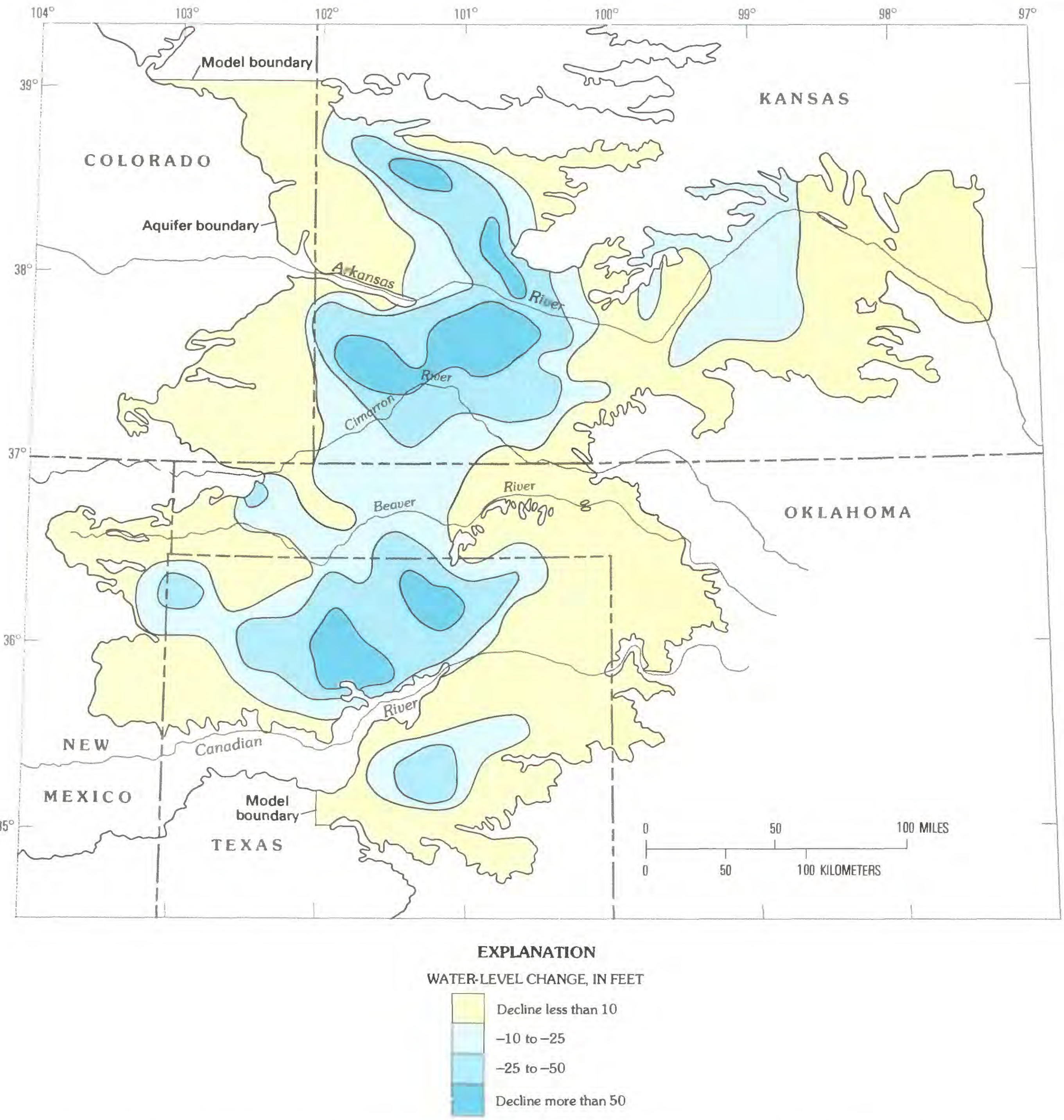


FIGURE 20.—Simulated predevelopment to 1980 water-level change with net withdrawal equal to 130 percent of irrigation requirement for the central High Plains.

areas where the water level is close to land surface is difficult; that is why only net recharge was modeled in these areas.

Results obtained during calibration of the central High Plains model indicated that recharge was related to soil type; the same correlation was assumed for the northern High Plains. Generalized soil types for the northern High Plains are shown in figure 22. The re-

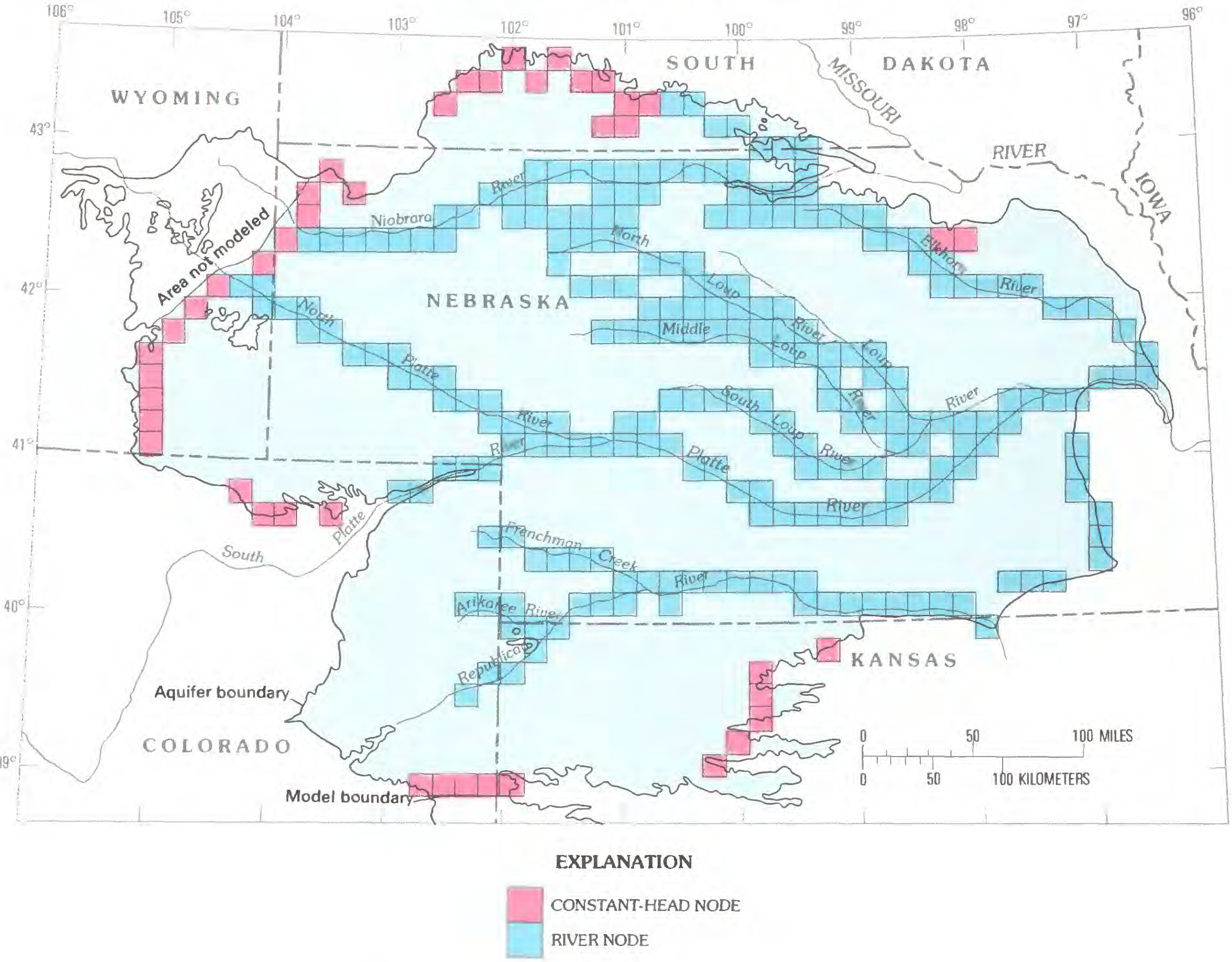


FIGURE 21.—Boundary conditions for the models of the northern High Plains.

charge distribution that resulted in a good correspondence between the observed and simulated predevelopment water levels is shown in figure 23. The net recharge ranged from 0.06 in./yr in the silt loam and clay loam soils to 1.20 in./yr in most of the sandy soils in central Nebraska. The sandy soils throughout most of the northern High Plains are in areas of sand dunes. The net recharge in the western part of the sandy soil of Nebraska is 0.30 in./yr. This area has numerous lakes and marshes in the interdune area and probably has a much larger ground-water discharge to evapotranspiration than the rest of the areas containing sandy soil. These estimates of recharge, particularly for the sandy soil, generally are less than those reported by other investigators (Gutentag and others, 1984, table 7). However, these estimates are for net recharge. The relationship between soil type and estimated net recharge for the northern High Plains is:

Soil types and location	Estimated net recharge, in inches per year
Clay loam and silt loam soils	0.06
Loam soils	.11
Sandy loam soils	.20
Sandy soils in west-central Nebraska	.30
Sandy soils in Colorado and southwestern Nebraska	.84
Sandy soils elsewhere	1.20

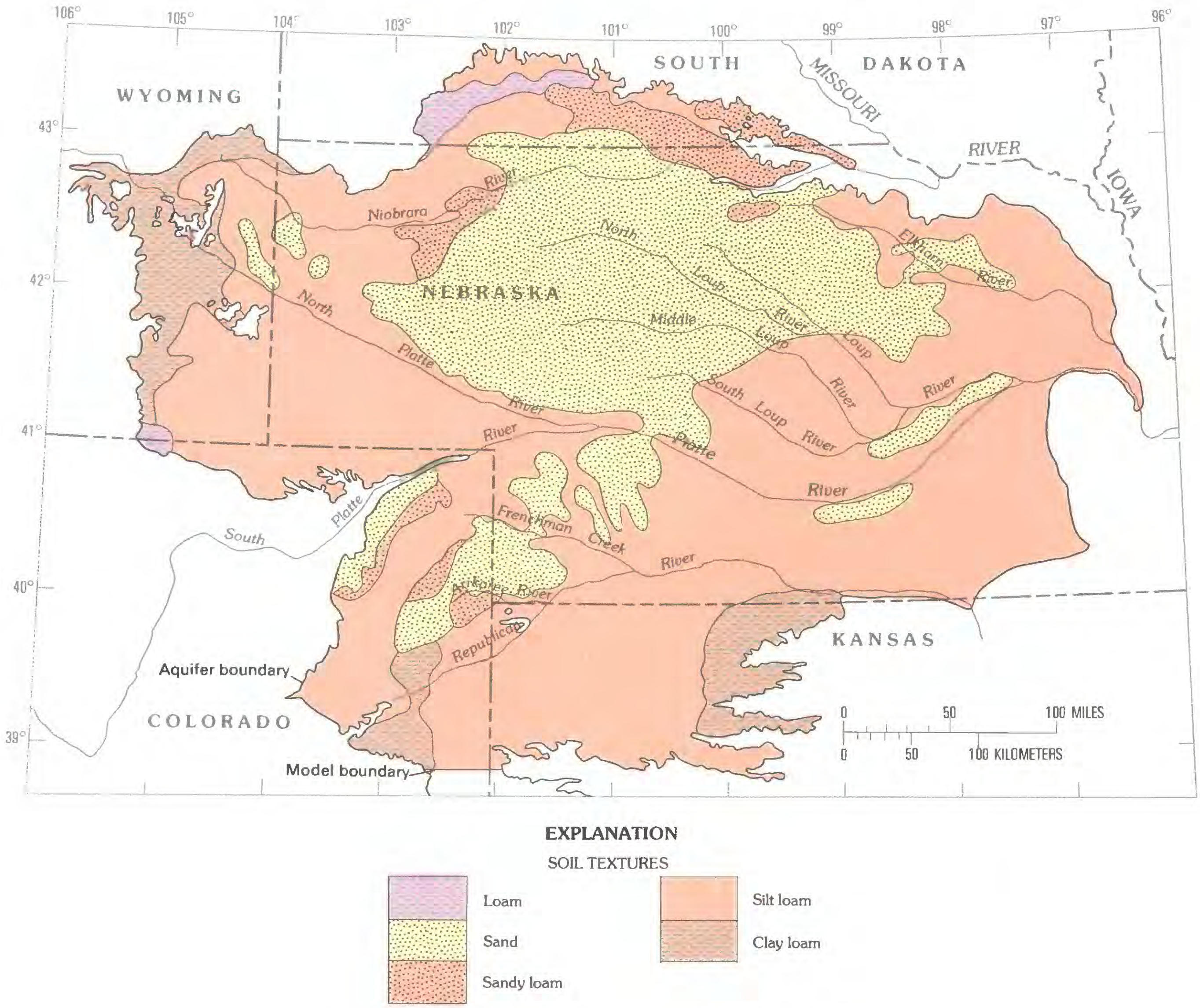


FIGURE 22.—Generalized soil types of the northern High Plains.

The observed and simulated predevelopment water levels are shown in figure 24. In general, they are closely correlated with the calculated water-level contours somewhat smoother. The biggest difference is near the 3,800-ft contour north of the North Platte River in the area of numerous sandhill lakes. The water level in this area is controlled by evapotranspiration from lakes and marshes. The model cannot adequately simulate the complex hydrology of this area because of the large node spacing. Smaller node spacing is needed to better simulate dunes, interdune areas, and the relationship between depth to water and evapotranspiration rate. Such a model is beyond the scope of the present study.

The mean difference between the observed and simulated predevelopment water level at 943 nodes was +0.94 ft with a standard deviation of 55 ft. At 93 percent of the nodes, the simulated water-level altitude is within 100 ft of the observed altitude.

Throughout much of the northern High Plains, the position of the water table largely is controlled by river systems, particularly in central Nebraska where sev-

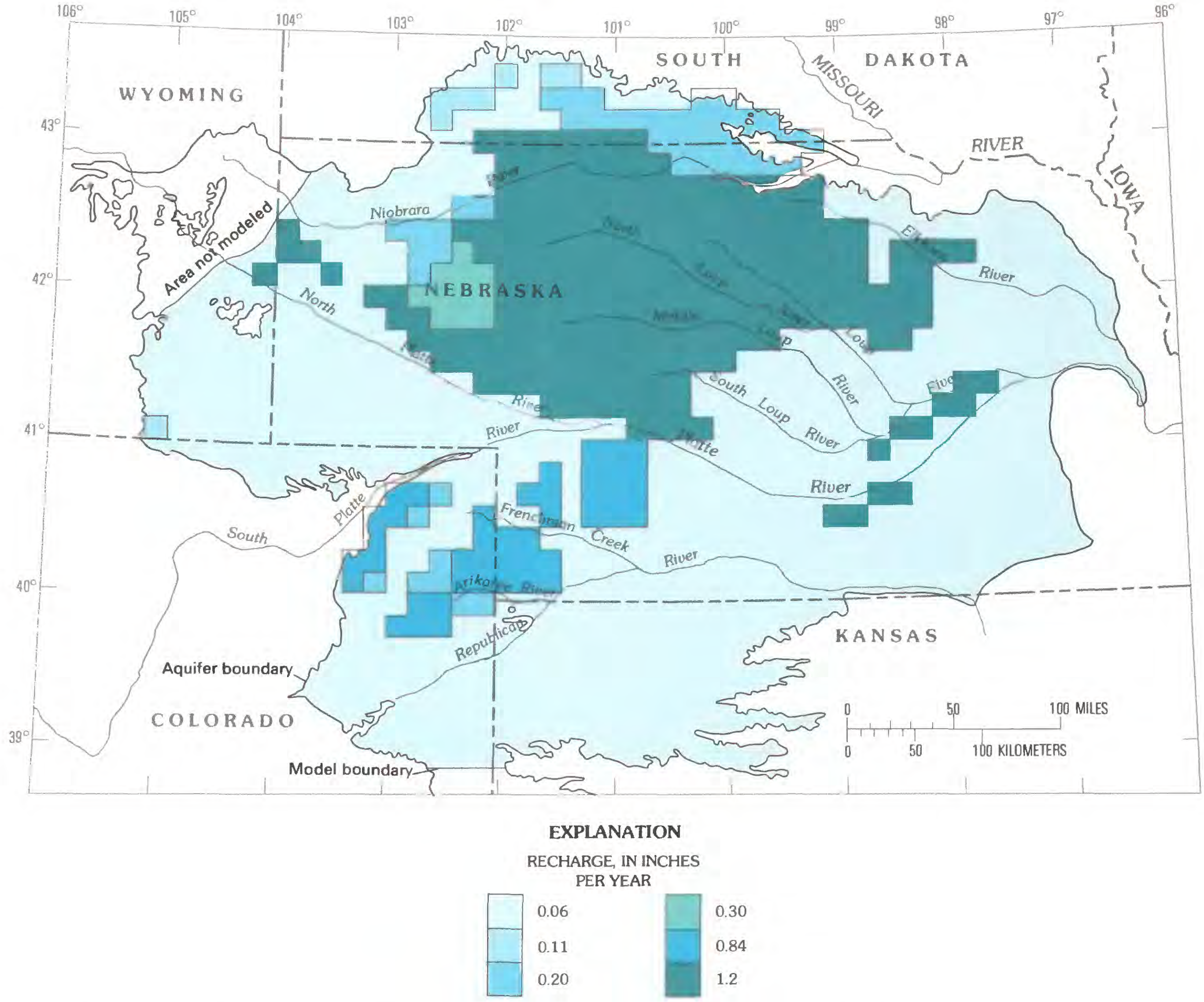
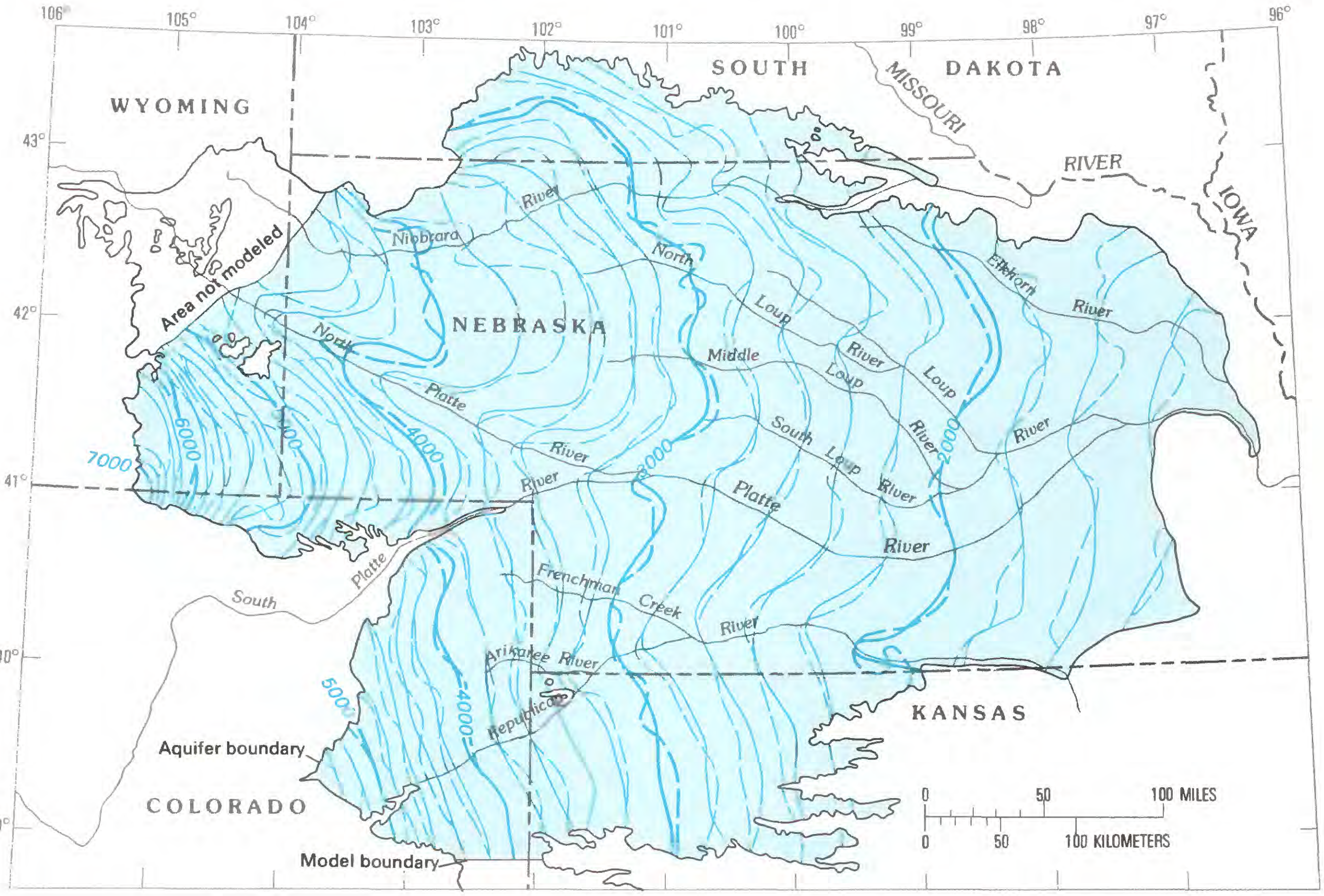


FIGURE 23.—Estimated predevelopment, long-term average recharge rates for the northern High Plains using the hydraulic-conductivity estimates adapted from Gutentag and others (1984).

eral major rivers drain the aquifer. In areas near major rivers, the model generally produces a water level configuration similar to that of observed predevelopment water levels because the river nodes control the model. The effect of the rivers on the water level in the aquifer far outweighs all other effects. Hence, to properly compare the observed and simulated water levels, more weight needs to be given to the areas away from the rivers.

Comparing the estimated and simulated base flow of the rivers is another way of measuring how well the model simulates the system. The base flow of a river represents the ground-water contribution to the river. Base flow is not a constant but varies from season to season and year to year. Base flow generally is highest during the winter months when evapotranspiration is minimal and lowest during the summer. Because evapotranspiration near rivers was not handled directly in the model, the winter period was used to compare base flows. The estimates of the base flow (table 6) are a combination of published estimates (Newport, 1959, p. 299; Sniegocki, 1959, p. 16–31,42; Bentall and Shaffer 1979, p. 98–121) and an examination of the November-February streamflow records. The estimated base flow includes only that part of the river within the northern High Plains. The estimates of the base flow are more accurate for the rivers that drain the sandhills because the flow of these rivers is much



EXPLANATION

WATER LEVEL CONTOUR — Contour interval 200 feet. National Geodetic Vertical Datum of 1929

--6000-- Observed

—6000— Simulated

FIGURE 24.—Observed and simulated predevelopment water level for the northern High Plains using the hydraulic-conductivity estimates adapted from Gutentag and others (1984).

more consistent. The estimate of the base flow of the Platte River system probably is the least accurate because this river is extensively regulated.

A comparison of the estimated and simulated base flows show that the simulated base flow is less than the estimated base flow for all river systems except the Republican for this simulation (column 3 of table 6). The smaller simulated base flow probably is because some of the base flow is contributed from local and intermediate aquifer systems which are excluded in large-scale regional models such as the northern High Plains model.

The hydraulic conductivity, aquifer thickness, and hydraulic gradient control the rate of movement of water through the aquifer. For a given water-table configuration, greater hydraulic conductivity causes greater flow through the system and implies greater recharge and discharge rates. Gutentag and others (1984, fig. 10) indicate that the hydraulic conductivity of the northern High Plains is relatively small, particularly in the sandhills north of the Platte River. A major part of the recharge and the base flow to the rivers comes from the sandhills of Nebraska; therefore, the value assumed for the hydraulic conductivity in the sandhills is critical to the comparison of estimated and simulated base flows. The aquifer material in this region is principally fine sands and silts with little hydraulic conductivity. Determining an average hydraulic conductivity for these fine-grained sediments is subject to considerable interpretation. For example, Gutentag and others

TABLE 6.—*Comparison of estimated and simulated base flow of the major river systems in the northern High Plains*

River sytem	Base flow, in cubic feet per second			
	Estimated	Simulated by model		
		Initial hydraulic conductivity and recharge	Increased hydraulic conductivity and recharge[1]	Increased recharge in sandhills[2]
Niobrara	1,000	600	780	1,090
Elkhorn	600	250	320	460
Loup	1,850	740	930	1,570
Platte	1,250	560	670	920
Blue	260	60	80	80
Republican	300	340	430	410
Total	5,260	2,550	3,210	4,350

[1]Recharge was 27 percent more than that used during the initial simulation.
[2]Recharge in the sandhills was 2 in./yr; recharge outside of the sandhills was 20 percent more than in the initial simulation.

(1984, table 5) estimated the hydraulic conductivity of both silty sand and fine sand from drillers' logs to be 50 ft/d while Lappala (1978, table 6) estimated the hydraulic conductivity of the same sediments from geologist-interpreted logs as 13 and 40 ft/d, respectively. The hydraulic-conductivity map of the Nebraska part of the High Plains was adapted from the map presented by Gutentag and others (1984, fig. 10). They constructed their map on the basis of 2,685 geologist-interpreted logs and the table presented in Lappala (1978, table 6). The hydraulic-conductivity map outside of Nebraska was constructed during this study using mainly drillers' logs and the table presented by Gutentag and others (1984, table 5).

Records from 117 test holes in northwestern Nebraska were analyzed and a mean hydraulic conductivity at each site was computed using both of the tables referenced above. The mean hydraulic conductivity from the 117 test holes computed using Gutentag and others (1984) averaged 40 percent more than that using Lappala (1978). The hydraulic conductivity also was computed at 40 points in the Platte River basin from the saturated thickness and transmissivity maps in Lappala and others (1979). These values, which were distributed throughout much of Nebraska, averaged 30 percent more than the corresponding points on the hydraulic-conductivity map in Gutentag and others (1984, fig. 10). Although it was not possible to know which estimate for hydraulic conductivity is closest to the true value, the map used to obtain the hydraulic conductivities for the model consistently presents smaller estimates than other investigations using comparable geologist-interpreted logs. Larger hydraulic conductivities in the sandhills would result in larger computed base flow, but the estimates would have to be approximately doubled to make the simulated base flow correspond to the estimated base flow.

As a result of the above analysis, a simulation was made in which all of the hydraulic conductivities in Nebraska were increased by 33 percent. The pattern for recharge was the same as in the previous simulation but the individual values were increased because of the increased hydraulic conductivity throughout a large part of the model. The best correspondence between observed and simulated water levels occurred when all recharge values were increased 27 percent compared to the previously shown values (fig. 23). Recharge in this simulation ranged from 0.076 in./yr on the silt-loam and clay-loam soils to 1.52 in./yr in the sandhills in Nebraska as shown in figure 25.

The observed and simulated predevelopment water levels for this simulation are shown in figure 26. As in the previous simulation, the two correspond reasonably well. The mean difference between water levels at 943 nodes was +0.30 ft with a standard deviation of 55.2 ft. At 92 percent of the nodes, the simulated water level is within 100 ft of the observed water level. The difference between the water level in this simulation and the water level in the previous simulation is not large. The principal difference between the two simulations was in the base flow of the major river systems (column 4 of table 6). The simulated base flow was significantly larger than in the previous simulation for all river systems. For this simulation, the total simulated base flow was slightly more than 60 percent of the estimated base flow. The simulated base flow in the Loup and Elkhorn Rivers was still about one-half the estimated base flow even though it was significantly larger than in the previous simulation. The base flow in these rivers is well known and the model might be expected to simulate a higher base flow for these rivers.

Because the major river systems, particularly the Loup, Elkhorn, and Niobrara, are associated with the sandhills, a simulation with a larger recharge rate in the sandhills attempted to more accurately simulate the base flows. In this simulation, 2.0 in./yr recharge was assumed for the sandhills north of the Platte River and the rest of the recharge was 20 percent more than that shown in figure 23. The correspondence between the observed and simulated predevelopment water levels for this simulation is not nearly as good as the previous simulations. The mean difference between the observed and simulated water levels is +10.6 ft with a standard deviation of 56 ft. However, the simulated base flows (column 5 of table 6) were much closer to the estimated base flows. The total simulated base flow was about 86 percent of the total estimated base flow. The simulated base flows in the Elkhorn and Loup systems were somewhat less than the estimated flow, and the simulated base flow in the Niobrara system was somewhat more than the estimated base flow. Although this simulation was rejected because of the large differences between the observed and simulated water levels, it does indicate that the net recharge from precipitation that reaches the river systems from the sandhills probably exceeds 2.0 in./yr.

The last two simulations indicate that either: (1) The hydraulic-conductivity estimates for Nebraska need to be increased even more; or (2) the model does not adequately calculate the base flow to the rivers. The hydraulic conductivity, as altered, appears to represent the best currently available knowledge and needs to remain unchanged. In contrast, this model is a regional model that was not designed to calculate base flow to rivers and it does not accurately represent the flow system in the vicinity of rivers. The small calculated base flow probably is a result of the scale of the model.

Winter (1976) investigated the interaction of lakes and ground water. He divides the ground-water flow system into a local flow system, an intermediate flow system, and a regional flow system. In the local flow system, recharge travels through the aquifer to be discharged into the adjacent lake; in the intermediate flow system, recharge travels to a nearby lake. If these results are applicable to the northern High Plains, the base flow simulated in the model is only the regional component of the base flow. The estimated base flow contains the local and intermediate flow-system components as well as the regional component. The relative magnitudes of each of these components are unknown. Hence, drawing conclusions about the difference between the estimated base flow and the base flow simulated by the model is difficult, except that the simulated regional base flow should be less than the total estimated base flow. The degree of the difference between the simulated and estimated base flows is dependent on the scale of the model.

The simulation, in which (1) the hydraulic conductivity in Nebraska was increased by one-third compared to the previously estimated values, and (2) the recharge ranged from 0.076 to 1.52 in./yr, was selected as the simulation that best represents the regional aquifer system. This simulation was used as the basis for the development-period calibration.

TABLE 7.—*Pumpage in the northern High Plains, 1960 to 1980, by State*

State	Irrigation pumpage, in thousands of acre-feet per year			
	1960–64	1965–69	1970–74	1975–79
Colorado	195	409	637	905
Kansas	182	322	470	577
Nebraska	2,988	3,437	4,589	6,091
South Dakota	1	4	9	18
Wyoming	43	60	75	96
Total	3,409	4,232	5,780	7,687

DEVELOPMENT-PERIOD CALIBRATION

The northern High Plains has the shortest history of development of the three areas of the High Plains. Even by 1960, most of the northern High Plains had undergone little development for irrigation and the predevelopment water levels were virtually undisturbed. Hence, only one development period, 1960 to 1980, was simulated. Because of this relatively short period, the development-period calibration of the northern High Plains is less definitive than the development-period calibration of the other two areas.

Several additional stresses have been imposed on the aquifer in the northern High Plains since 1960. Pumpage for irrigation and return flow from irrigation were still the dominant new stresses on this part of the aquifer. However, additional recharge from various sources also was a very significant new stress on the aquifer in the northern High Plains.

In the northern High Plains, pumpage for irrigation was the only significant pumpage and pumpage for municipal, industrial, stock, and domestic use were ignored in the simulation. The pumpage estimates for 1960–80 for the northern High Plains are given in table 7. The data in the table indicate that approximately 105 million acre-ft of water were pumped from the aquifer in the northern High Plains between 1960 and 1980. This was somewhat more than that pumped in the central High Plains and about one-half that pumped in the southern High Plains.

A generalized water-level change map (fig. 27) was constructed from the map presented by Luckey and others (1981) by estimating the average water-level change for each node (100 mi^2) and contouring the changes. Water-level changes for each simulation were contoured and compared with the generalized observed water-level change map.

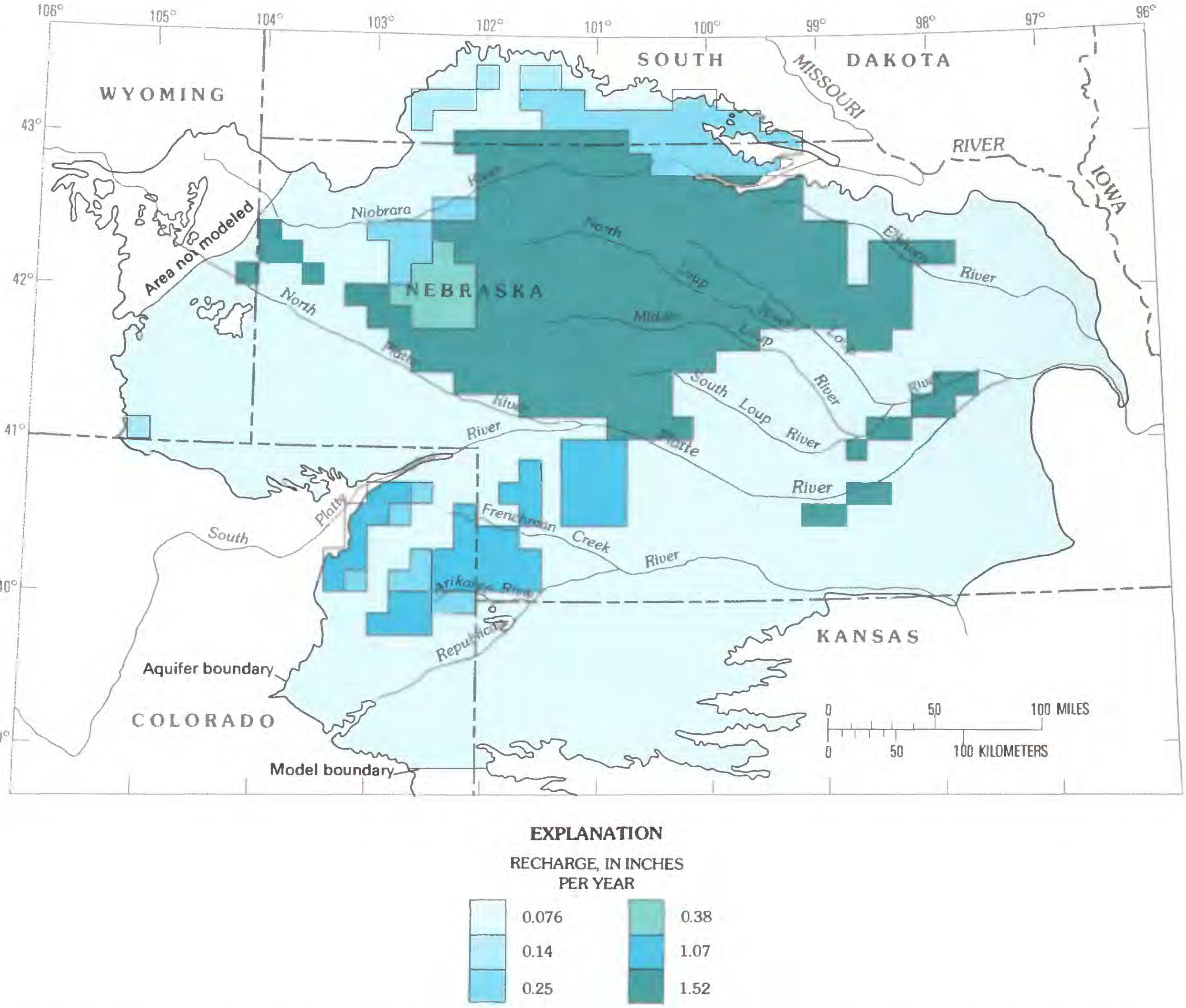
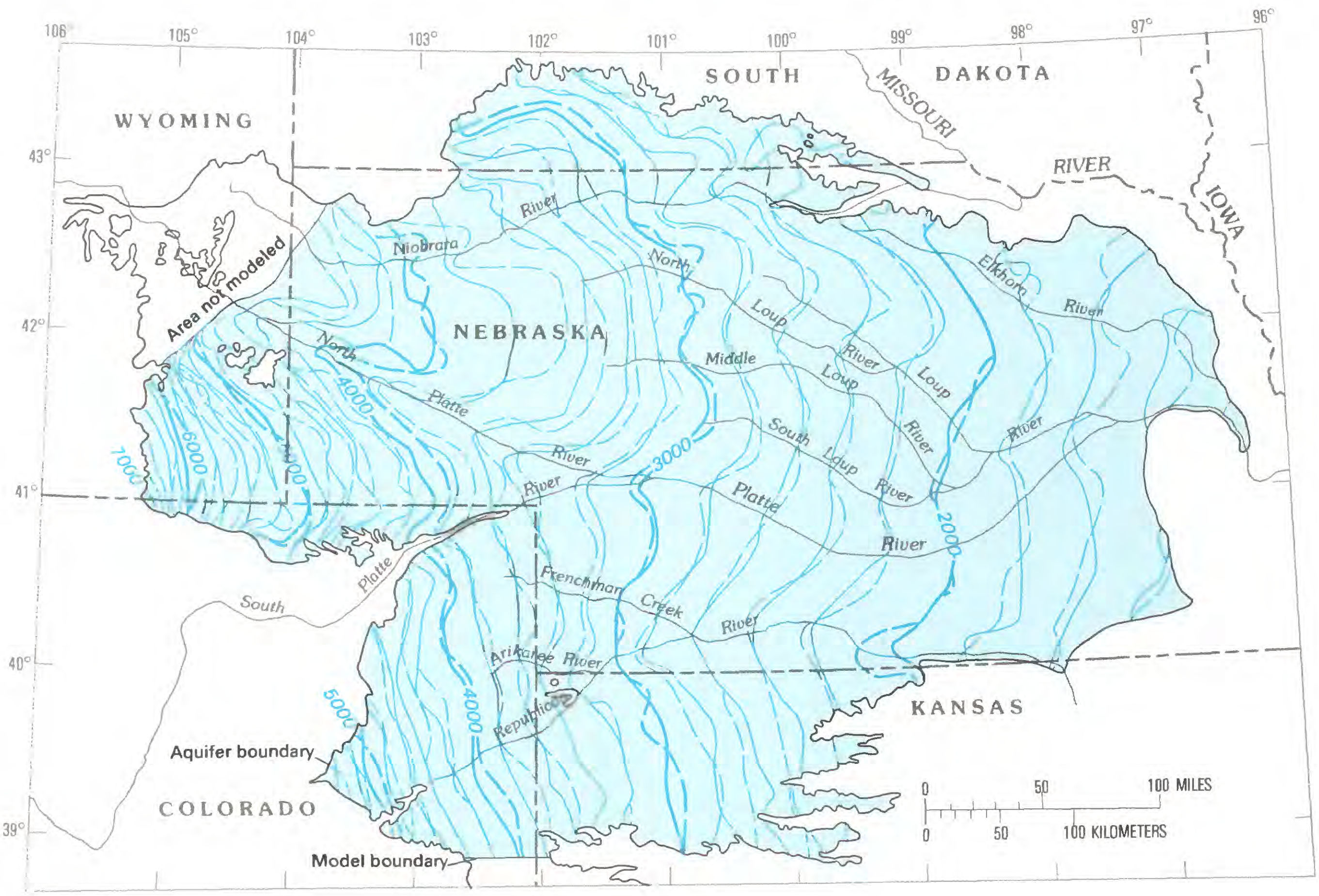


FIGURE 25.—Estimated predevelopment, long-term average recharge rates for the northern High Plains using the revised hydraulic-conductivity estimates.

The return flow to the aquifer from irrigation was one of the two components of the model that was adjusted during calibration. Because return flow was assumed to reach the aquifer within the 5-year pumping period, changing return flow was exactly equivalent to changing net withdrawal. The return flow was assumed to be a function of the difference between total pumpage and irrigation requirement. The simulated water-level changes most nearly matched the observed water-level changes when return flow was equal to 100 percent of the difference between total pumpage and irrigation requirement. In this simulation, the return flow ranged from 46 percent of total pumpage early in the period to 30 percent later in the period and averaged 36 percent.

Additional recharge from various sources was the other component of the model that was adjusted during calibration. The recharge from precipitation determined during the predevelopment-period calibration was assumed to have continued during the development period. For the 20 years simulated, recharge from precipitation was 46.9 million acre-ft for the northern High Plains.

Recharge to the aquifer in the northern High Plains has been significantly increased by human activities. The most dramatic effects of increased recharge occur in central Nebraska on the south side of the Platte River. Leakage from canals and reservoirs and return flow from surface-water irrigation have caused water levels to rise as much as 90 ft (Johnson and Pederson,



EXPLANATION

WATER LEVEL CONTOUR — Contour interval 200 feet. National Geodetic Vertical Datum of 1929

--4000-- Observed

—4000— Simulated

FIGURE 26.—Observed and simulated predevelopment water level for the northern High Plains using the revised hydraulic-conductivity estimates.

1982, p. 22). Canal and reservoir leakage for this area was estimated from canal diversion and delivery records to be 5.0 million acre-ft for 1960–80. Additional canal and reservoir leakage along the Loup River was estimated by the same procedure to be 1.2 million acre-ft for the same period. Return flow from surface-water irrigation, principally along the Platte River, was estimated to be 3 in./yr throughout the irrigated land for a total of 3.2 million acre-ft for the 20 years.

Cultivation practices associated with dryland farming can increase recharge from precipitation compared to the rate of recharge on rangeland (Ogilbee, 1962, p. 25). For the northern High Plains, additional recharge due to cultivation was estimated to be 0.5 in./yr throughout the dryland area. Water-level changes due to this additional recharge have been small, so this value cannot be accurately estimated. The total estimated increased recharge throughout the dryland area for 1960–80 was 9.7 million acre-ft.

Additional recharge was needed east of 100° longitude to successfully simulate the observed water-level changes. The additional recharge was added only on the irrigated land at a rate of 2.5 in./yr north of 41° latitude and 5.0 in./yr south of 41° latitude. The total for the 20 years was 28.0 million acre-ft. Several factors that could account for the recharge increase were investigated: (1) Decrease in runoff to streams due to cultivation; (2) decrease in base flow to streams due to ground-water withdrawal; (3) decrease in downward leakage to underlying aquifers; (4) reduction of evapotranspiration due to lower water levels; (5) increase in recharge from precipitation due to conversion of natural

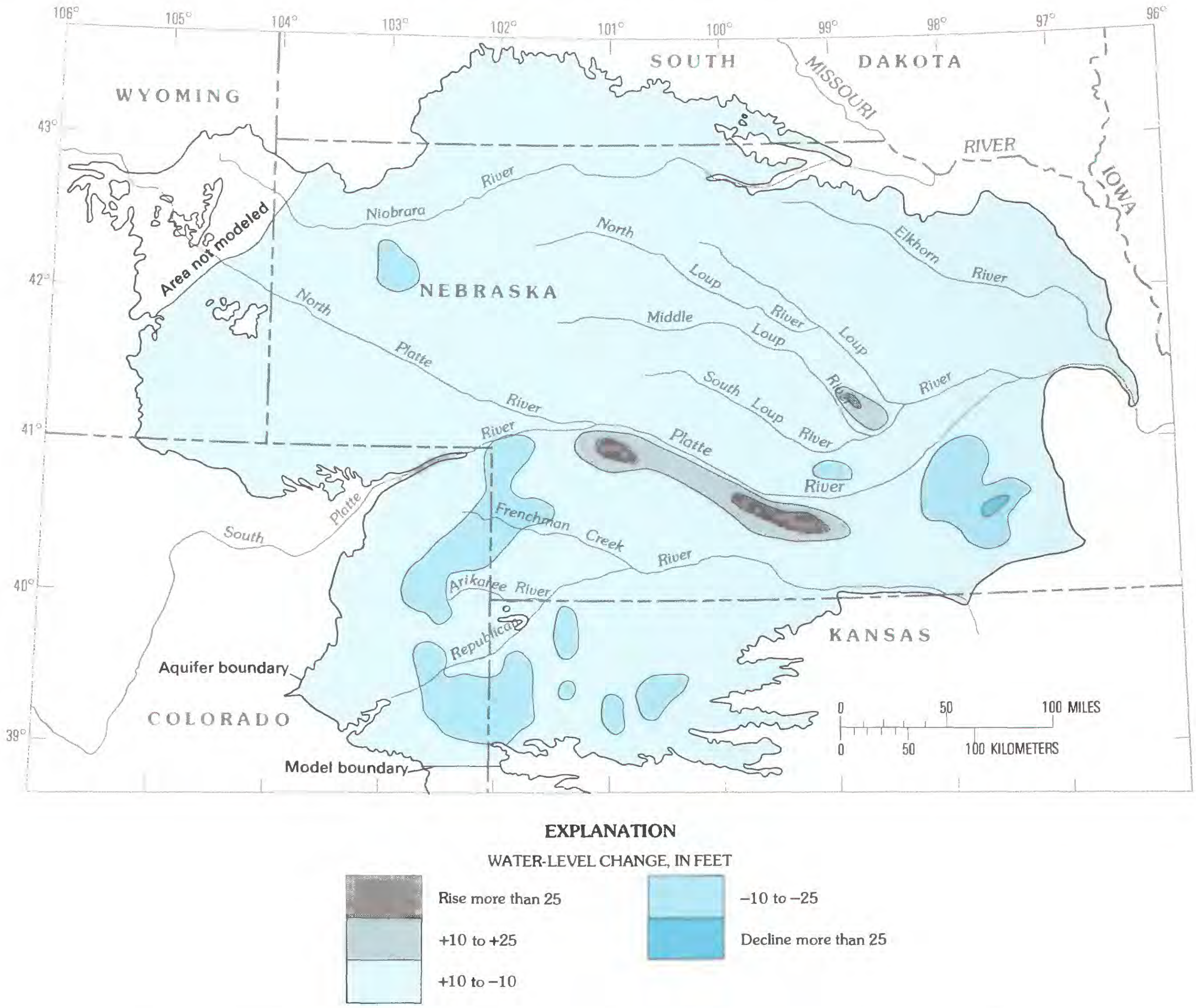


FIGURE 27.—Generalized, observed predevelopment to 1980 water-level change for the northern High Plains.

grasslands to croplands; (6) increase in downward leakage from a saturated zone above the water table; (7) greater specific yield of the aquifer than previously estimated; (8) smaller total pumpage than estimated; and (9) significantly more return flow from irrigation east of 100° longitude. These factors were studied in the Big Blue and Little Blue River basins in southeastern Nebraska.

Streamflow records were examined to evaluate the first two factors. A decrease in runoff should result in a decrease in the high flow of streams. A decrease in base flow should result in a decrease in the low flow of streams. The estimated combined decrease in the high and low streamflow for 1960–80 for the Big Blue and Little Blue River basins was 2.5–3.0 million acre-ft. This was equivalent to about 15 percent of the increase in recharge in these basins.

The third through sixth factors could contribute only minor quantities to the apparent increase in recharge. Estimates of the change in downward leakage to underlying aquifers were made using what few data were available. These estimates indicate that the change in downward leakage could at most be a small fraction of 1 percent of the apparent increase in recharge. Salvage of evapotranspiration in shallow-water table areas also could account for only an insignificant proportion of the water because of the very limited area with a shallow water table. Increased recharge from precipitation resulting from the conversion of grassland to cropland must have been small or water levels would have risen significantly during the period of dryland farming. If all of the increased recharge came from this source, water levels would have risen about 1 ft per year during the period of dryland farming. Water-level records do not show such rises; therefore, the increased recharge due to grassland conversion could only be a small proportion of the apparent increase in recharge. The sixth factor, increased downward leakage from a saturated zone above the water table, may occur in some areas but the extent of these areas is much too small to provide a significant proportion of the apparent increase in recharge.

The seventh factor, greater specific yield than previously estimated, was considered. The specific yield for the entire High Plains was estimated in the same manner, but possibly some of the estimates should have been made differently in the eastern part of the High Plains. The specific yield of the aquifer was estimated from lithologic logs (Gutentag and others, 1984, p. 23). A value for the specific yield was assigned to each lithologic unit and a mean value was computed for each site. Although the aquifer material in the eastern part of the northern High Plains is younger than the aquifer material in most of the High Plains, this procedure should work regardless of the age of the aquifer material. The specific yield would have to be approximately doubled to about 0.35 in the Big Blue and Little Blue River basins to make the model simulate accurately without increasing recharge, and such a specific yield appears unrealistically large.

The eighth factor depends on the method used to estimate total pumpage and irrigation requirement. Total pumpage was estimated from the data presented in Heimes and Luckey (1982). The estimates were dependent on the crop demands computed using the modified Blaney-Criddle formula (U.S. Department of Agriculture, 1967). The Blaney-Criddle formula was developed for semiarid areas, but the eastern part of the High Plains has a more humid climate. Data presented by Heimes and Luckey (1983, tables 2 and 4) indicate that the ratio between measured 1980 total pumpage and calculated irrigation requirement for corn is about 15 percent less for York County in eastern Nebraska than it is for Kit Carson County in eastern Colorado. Although no definitive conclusions can be drawn from such meager data, they indicate that the irrigation requirement may be somewhat overestimated in eastern Nebraska. This overestimate could account for part of the additional recharge needed to calibrate the model.

The last factor, greater return flow, also depends on calculated irrigation requirement. Huntoon (1974) was able to calibrate a model of the Big Blue River basin by assuming return flow was 60 percent of total pumpage, but he noted that this appeared highly suspect (Huntoon, 1974, p. 44). Return flow throughout the rest of the High Plains during 1960–80 was about 40 percent of total pumpage based on this study; no reason exists to believe that return flow in the Big Blue River basin should be significantly different from the rest of the High Plains. If return flow were increased to 60 percent of total pumpage for this area, irrigation requirement would be less than 70 percent of that estimated using the modified Blaney-Criddle formula. However, greater return flow east of 100° longitude could account for part of the apparent increase in recharge if the Blaney-Criddle formula significantly overestimated crop demand for this area.

None of these factors individually could account for the 28 million acre-ft of apparent increase in recharge, but collectively they might account for this quantity of water. Undoubtedly, all nine factors could contribute some to the apparent increase in recharge needed to calibrate the model. However, additional research on total pumpage, crop demand, specific yield, and related factors is needed before this apparent increase in recharge can be fully understood.

The development-period composite recharge is shown in figure 28. This recharge is assumed to be the sum of five separate components: (1) Predevelopment-period calibration recharge; (2) canal and reservoir leakage; (3) return flow from surface-water irrigation; (4) increased recharge due to dryland cultivation; and (5) additional recharge east of 100° longitude.

The additional development-period recharge due to human activities (47.0 million acre-ft) and the return flow from ground-water irrigation (37.5 million acre-ft) balance most of the 105.0 million acre-ft that were pumped in the northern High Plains between 1960 and 1980. Hence, the overall change in storage has been small, even though large water-level declines and rises have occurred in various areas.

The simulated water-level changes for the northern High Plains are shown in figure 29. Generally, a good correlation exists between the simulated water-level changes and observed water-level changes shown in figure 27. In the western part of the area, the observed and simulated declines match very closely. In the eastern part of the area between the Platte and Republican Rivers, the simulated declines are greater than the observed declines. Along the downstream reach of the Elkhorn River, the model simulated an area of water-level rise that does not exist on the observed water-level change map. These discrepancies in the eastern part of the High Plains indicate that, even with the

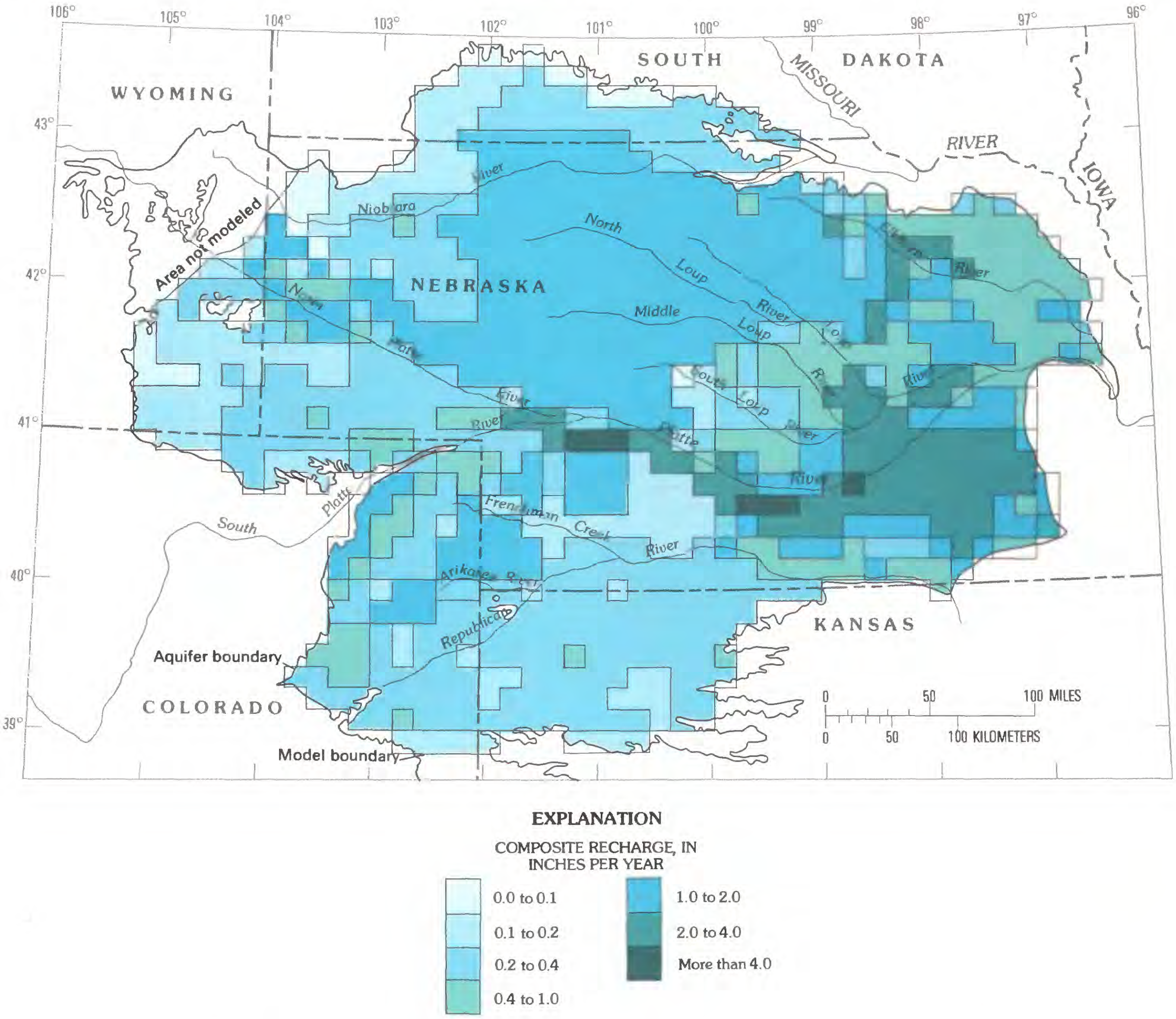


FIGURE 28.—Composite 1960-80 recharge for the development-period model of the northern High Plains.

recharge that was added east of 100° longitude, the model does not adequately simulate the hydrologic system in this area.

The simulated water-level rises in south-central Nebraska are of about the same order of magnitude as the observed water-level rises but are less extensive. This may be due to the coarseness of the grid of the model. The model failed to simulate water-level rises between the Middle Loup and North Loup Rivers. This probably is due to the scale of the model. The model in this area is completely controlled by river nodes so that simulated water-level rises do not occur. The model simulated a net decrease in storage in the aquifer of about 15 million acre-ft of water. The observed change in storage outside of the +10 to −10 ft change area was 6 million acre-ft. The other 9 million acre-ft of change probably occurred in the +10 to −10 ft change area.

This simulation was accepted as a reasonable representation of the development-period operation of the aquifer in the northern High Plains. Despite the shortcomings discussed above, it is adequate for calculating the future state of the system.

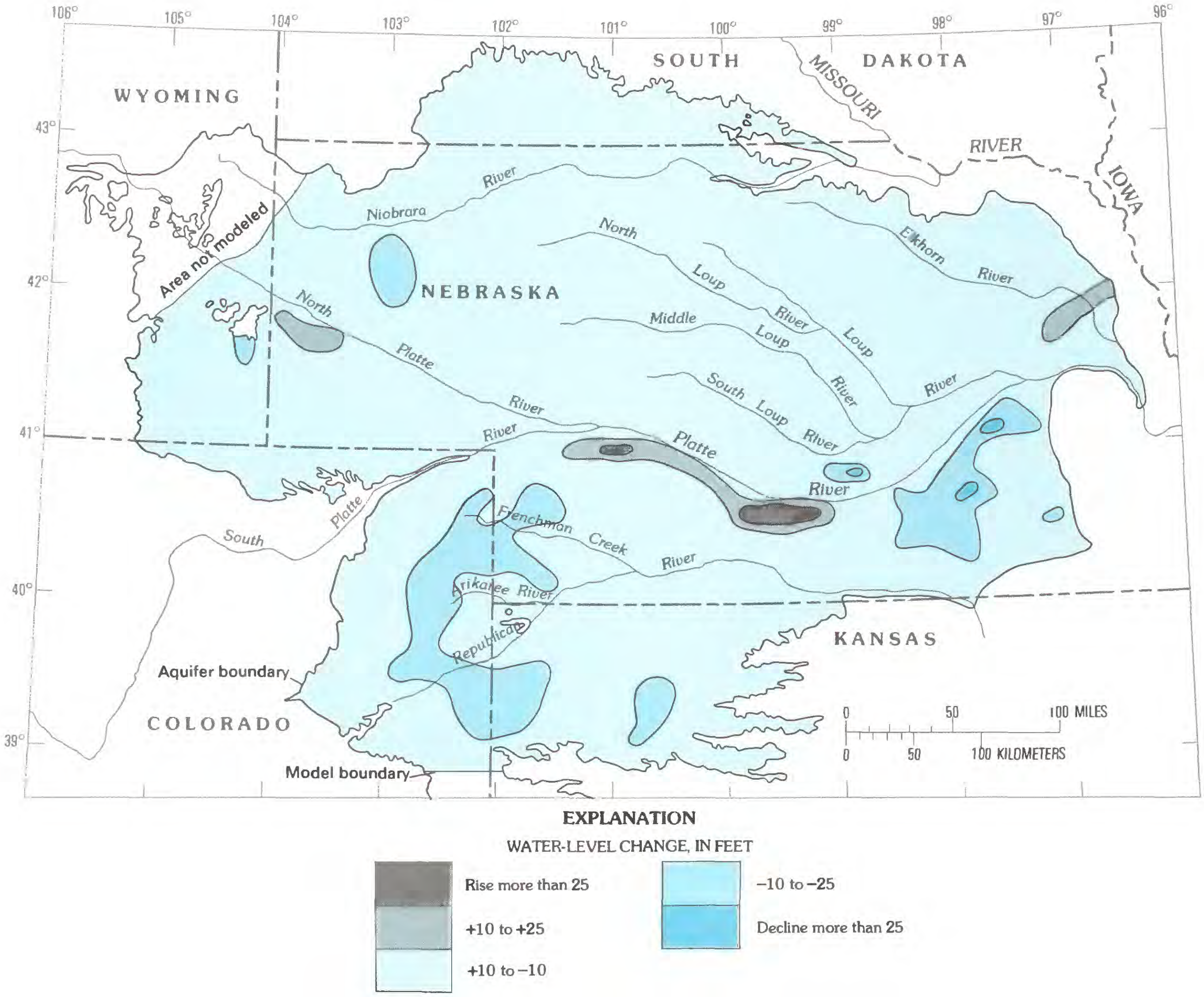


FIGURE 29.—Simulated predevelopment to 1980 water-level change for the northern High Plains.

SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the High Plains models to determine the response of the models to changes in model inputs. The response of the simulated water levels and base flows to changes in the model inputs was determined. The sensitivity analysis can be used to guide future data collection.

A separate sensitivity analysis was made for the predevelopment- and the development-period models for each of the three areas of the High Plains. The sensitivity analysis consisted of uniformly increasing or decreasing the model inputs and noting the change in water levels and base flow to rivers. The simulation results were recorded either as a change in the absolute value of the mean residual between the observed and the simulated water levels or as a change in the total base flow to rivers. For the predevelopment-period models, the effects of change in recharge and hydraulic conductivity were investigated. For the development-period models, the effects of the change in hydraulic conductivity, specific yield, and net withdrawal were investigated. Each of these items was increased or decreased uniformly; the effect of a change in distribution of the parameters was not investigated. In general, the distribution of a particular model input for the High Plains aquifer is well defined; so, it is not appropriate to check the effect of a change in distribution.

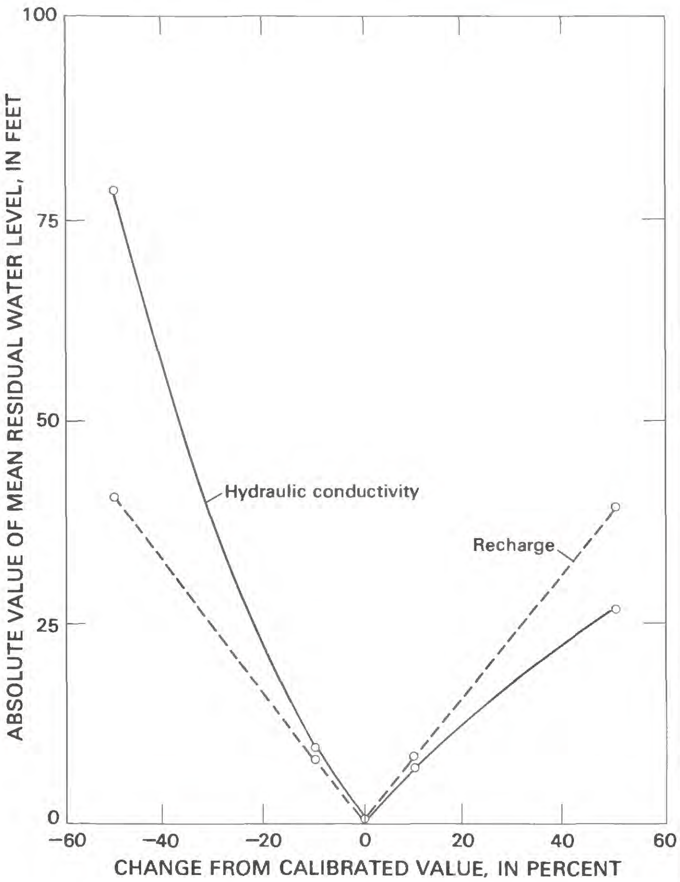


FIGURE 30.—Predevelopment-period-model sensitivity analysis for the southern High Plains.

Likewise, the boundary conditions on the High Plains models are well defined and a sensitivity analysis on the effect of changing boundary conditions has not been made.

The results of the sensitivity analysis for recharge and hydraulic conductivity for the southern High Plains predevelopment-period model are shown in figure 30. Both recharge and hydraulic conductivity were changed by as much as 50 percent of the calibrated value. The effect of the change in the parameter or stress was measured through the change in the absolute value of the mean residual between observed and simulated water levels. The simulated water levels were about equally sensitive to a change in recharge or to a change in hydraulic conductivity. The largest absolute value of the mean residual in the sensitivity analysis was 78 ft when hydraulic conductivity was decreased 50 percent. This compares to the mean residual of +0.22 ft at calibration.

The sensitivity analysis for the central High Plains predevelopment-period model for the same two variables is shown in figure 31. Again, the simulated water levels were equally sensitive to changes in recharge and hydraulic conductivity. However, for this model, the largest absolute value of the mean residual was only about 27 ft when hydraulic conductivity was decreased 50 percent. The central High Plains predevelopment-period model was less sensitive to a change in either recharge or hydraulic conductivity compared to the southern High Plains model because water levels in this model were partly controlled by rivers.

The sensitivity of the simulated base flow to rivers as related to changes in recharge and hydraulic conductivity also is shown in figure 31. The figure indicates that the model is more sensitive to changes in recharge than to changes in hydraulic conductivity. When the estimated hydraulic conductivity increased 50 percent, the simulated base flow to rivers decreased 11 percent; but when recharge increased 50 percent, the simulated base flow to rivers increased 60 percent. Increased recharge added more water to the model whereas increased hydraulic conductivity simply let some water that had previously been leaving the model through the rivers leave the model through boundary outflow.

A sensitivity analysis was done for the northern High Plains predevelopment-period model for changes in both recharge and hydraulic conductivity. The effects of change in recharge and change in hydraulic conductivity on both the absolute value of the mean residual and the base flow to rivers were very similar to the results for the central High Plains predevelopment-period model and, thus, are not presented.

Minimizing the absolute value of the mean water-level residual is only one possible calibration criterion. This criterion tends to balance the errors in the model but allows the possibility of compensating errors. A very small mean water-level residual does not necessarily imply a properly calibrated model unless the distribution of the residuals also are investigated. Two other calibration criteria were evaluated for the predevelopment-period model of the southern High Plains aquifer. Minimizing the standard deviation of the residuals between observed and simulated water levels does not allow for compensating errors and emphasizes the larger residuals. Minimizing the mean of the absolute values of the residuals also does not allow for compensating errors and does not emphasize the larger residuals.

The results of differing calibration criteria for the predevelopment period of the southern High Plains model are shown in figure 32. The slope of the absolute value of the mean residual calibration criterion is the steepest of the three criteria and, hence, is the best criterion in the sense that it is easiest to find the mini-

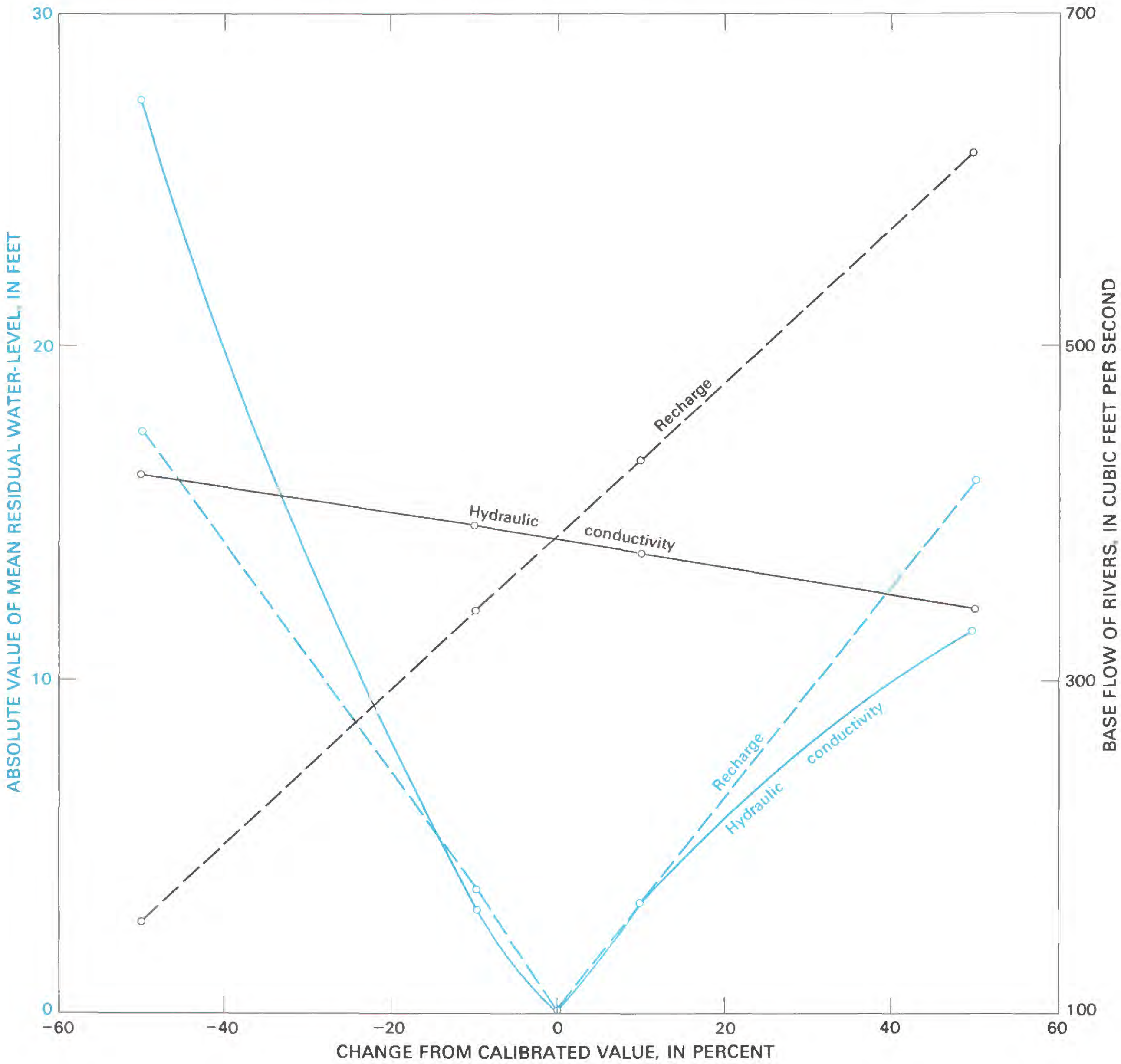


FIGURE 31.—Predevelopment-period-model sensitivity analysis for the central High Plains.

mum value of this criterion. The calibration criterion of minimizing the standard deviation of the residuals has the least slope. Interestingly, the minimum of each of the calibration criteria occurs at different places. If the criterion of standard deviation of the residuals were chosen, the average estimated recharge at calibration would have been about 20 percent less than it was using the criterion of absolute value of the mean residual.

The usual procedure in a sensitivity analysis is to vary one parameter at a time and evaluate the response of the model to the change in that parameter. However, the model parameters are not all independent of each other and changing one parameter during calibration might necessitate changing another parameter.

The effects of simultaneously varying recharge and hydraulic conductivity in the southern High Plains predevelopment-period model are shown in figure 33. In this figure, the vertical axis shows the change in hydraulic conductivity and the horizontal axis shows the change in recharge. The lines in the figure are lines of equal mean residuals. Near the lower right corner

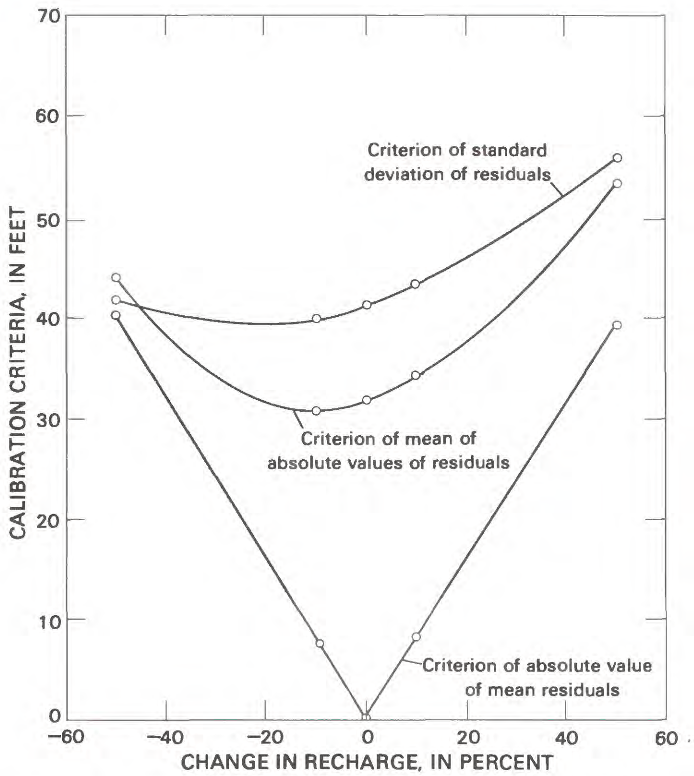


FIGURE 32.—Results of changing the calibration criteria for the predevelopment-period model of the southern High Plains.

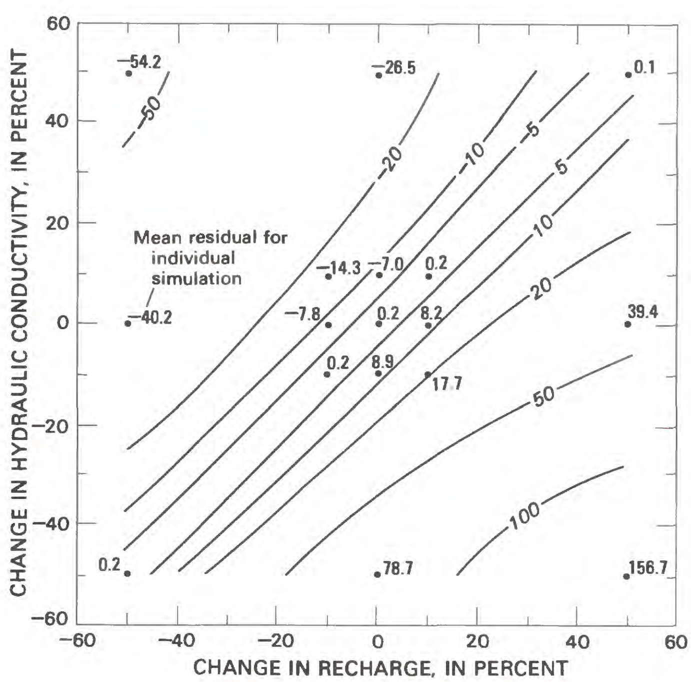


FIGURE 33.—Results of simultaneously changing recharge and hydraulic conductivity in the predevelopment-period model of the southern High Plains. Lines represent equal mean residuals.

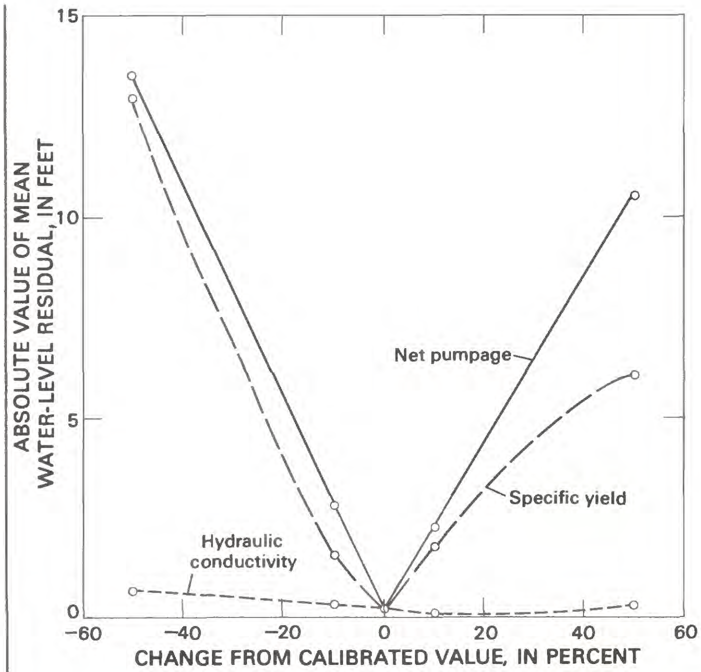


FIGURE 34.—Development-period-model sensitivity analysis for southern High Plains.

of the figure where recharge was increased 30 percent and hydraulic conductivity was decreased 38 percent, the mean residual was 100 ft. In the upper left corner of the figure where hydraulic conductivity was increased 45 percent and recharge was decreased 45 percent, the mean residual was −50 ft. From the lower left corner to the upper right corner of the figure is a trough in which the mean residual is near zero. The existence of this trough indicates that the hydraulic conductivity and recharge are very interrelated, and, as long as these two model inputs are in balance, the model has a small mean residual. When these model inputs are out of balance with each other, the residual becomes large. Therefore, if the hydraulic conductivity is accurately known, the model can be used to accurately determine the recharge. Likewise, if the hydraulic conductivity is poorly known, then the recharge will be poorly determined.

The early discussions in this section could give the impression that these two model inputs are known within narrow limits, but this is based on the assumption that all of the other inputs are accurately known. The data in figure 33 indicate that, in the calibrated model, recharge and hydraulic conductivity are in balance with each other, but they are not necessarily accurately known.

The sensitivity of the development-period models to changes in hydraulic conductivity, specific yield, and net withdrawal also was evaluated. The effect of net

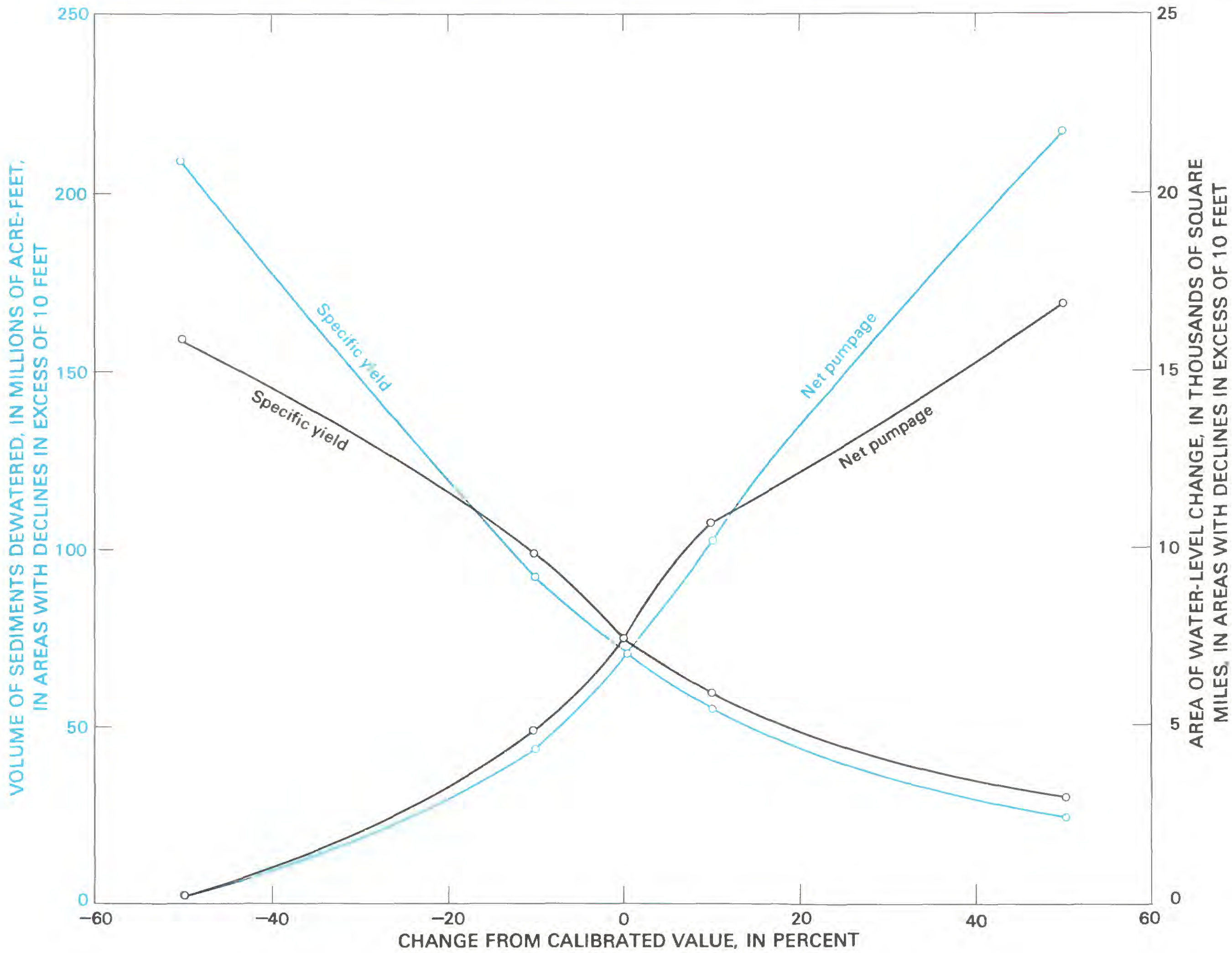


FIGURE 35.—Development-period-model sensitivity analysis for the northern High Plains.

withdrawal rather than total pumpage and return flow was studied because a change in total pumpage would necessitate a change in return flow because of the way in which return flow was simulated. The results of the sensitivity analysis for the southern High Plains development-period model are shown in figure 34. This model was extremely insensitive to changes in hydraulic conductivity; large changes in hydraulic conductivity caused only very small changes in the absolute value of the mean water-level residual. This is not surprising because hydraulic conductivity controls the rate of flow through the aquifer and the dominant factor during the development period is the withdrawal of water from the aquifer and not flow through the aquifer. The development-period model was sensitive to changes in both net withdrawal and specific yield. Hence, an accurate model for simulating the development history of the High Plains aquifer requires more accurate information for net withdrawal and specific yield than for hydraulic conductivity.

For reasons explained previously, the central and northern High Plains development-period models used the simulated area and volume of water-level changes for calibration. The effect of changing net withdrawal and specific yield in the the northern High Plains development-period model is shown in figure 35. In this figure, the effect of the change in these variables on the volume of the aquifer dewatered and the area of the water-level change is shown because both were used during the calibration process. The volume of aquifer dewatered is used rather than the volume of water removed from storage because the measurement of the latter depends on the assumed specific yield which is one of the parameters that was varied. Under both criteria (volume dewatered and area of water-level change), the development-period model was sensitive to changes in both net withdrawal and specific yield but was slightly more sensitive to changes in net withdrawal. Near the calibration point (zero change in calibrated value), the relationship between the model variables and the calibration criteria is approximately 1:1. As the estimated specific yield increased significantly, the model became less sensitive to changes in specific yield. Likewise, as net withdrawal decreased significantly, the model became less sensitive to net withdrawal.

A sensitivity analysis was made for the central High Plains development-period model. This analysis produced results nearly identical to the results for the northern High Plains development-period model. In the analysis of the central High Plains model, the only difference was that the sensitivity to net withdrawal remained relatively constant throughout the entire range of change. This is because in the northern High Plains model, as net withdrawal decreased significantly, the additional recharge due to human activities began to dominate the model and this additional recharge was not present in the central High Plains model.

Although net withdrawal and specific yield were not varied simultaneously in the development-period model sensitivity analysis, indications existed during the calibration that these two model inputs are interrelated in the same manner that recharge and hydraulic conductivity are interrelated in the predevelopment-period models. Hence, if net withdrawal is accurately known, then the model can be used to accurately determine the specific yield. However, if neither is accurately known, then the best that the model can do is to ensure that net withdrawal and specific yield are in balance with each other.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey began a study of the 174,000-mi^2 High Plains regional aquifer in 1978. The High Plains is one of the major irrigated areas of the United States and in 1980 accounted for more than 20 percent of the irrigated land and about 30 percent of the ground water pumped for irrigation in the United States. However, throughout much of the aquifer, the rate of withdrawal exceeds the rate of replenishment and large water-level declines have occurred in parts of the High Plains. One of the primary objectives of the study was to develop digital models of the aquifer system that could be used to simulate the aquifer system and evaluate future development of the water resources. This report describes the calibration of the digital models of the High Plains aquifer that were developed during the study and could be used to evaluate future water levels due to potential development.

The flow system in the High Plains aquifer was simulated using a digital, finite-difference technique to solve the ground-water flow equation. For simulation, the High Plains aquifer system was divided into three parts. The southern High Plains consists of about 29,000 mi^2 in Texas and New Mexico; the central High Plains consists of about 48,500 mi^2 in Texas, New Mexico, Oklahoma, Colorado, and Kansas; and the northern High Plains consists of about 96,500 mi^2 in Colorado, Kansas, Nebraska, Wyoming, and South Dakota. Each of the three parts of the High Plains aquifer system was simulated using a regular network of nodes spaced 10 mi apart in both the north-south and east-west directions. The southern High Plains models have 303 active nodes, the central High Plains models have 513 active nodes, and the northern High Plains models have 943 active nodes. One node is common between the southern and central High Plains models and five nodes are common between the central and northern High Plains models.

The history of the High Plains aquifer was divided into two periods: (1) The predevelopment period prior to large-scale development for irrigation and (2) the development period after the beginning of large-scale development for irrigation. Separate models were constructed and calibrated for the predevelopment and development periods with the results of the predevelopment-period calibration used as the initial conditions for the development-period calibration.

The objective of the predevelopment-period calibration was to simulate the system prior to human activities. The data requirements for the predevelopment-period models are simpler than the data requirements for the development-period models. Calibration of the predevelopment-period models increased the understanding of the hydrologic system and refined the estimates of hydraulic conductivity and recharge rates. In the predevelopment-period calibration, one aquifer parameter (the hydraulic conductivity) and one stress (recharge from precipitation) were varied to obtain the best correlation between the observed and simulated predevelopment water levels.

In the predevelopment-period model of the southern High Plains, the initial estimates of hydraulic conductivity were decreased in areas with large values of hydraulic conductivity. The estimated predevelopment recharge rate ranged from 0.086 to 1.03 in./yr. The

TABLE 8.—*Summary of calibration of High Plains models*

Area	Predevelopment-period models			Development-period models (all units in millions of acre-feet)		
	Water-level residuals				Change in storage	
	Standard Mean residual (feet)	Nodes with deviation of residuals (feet)	residuals less than 100 feet (percent)	Pumpage	Observed	Simulated
Southern High Plains....	+0.22	41.6	99	210	97	90
Central High Plains......	–0.28	38.5	98	94	50	55
Northern High Plains....	+0.30	55.2	92	107	6	15

largest recharge rates were assigned to the area near the Running Water Draw-White River lineaments. At calibration, the mean difference between the simulated and observed water levels was +0.22 ft (table 8). The extreme differences were −113 ft and +99 ft for 303 nodes in the model.

In the predevelopment-period model of the central High Plains, the initial estimates of hydraulic conductivity were decreased in areas with thick saturated material. This decrease is postulated to be caused by disturbed and chaotic bedding in the aquifer in areas where the underlying bedrock has collapsed due to salt dissolution in Permian rocks. The overall decrease in the hydraulic-conductivity estimates averaged about 20 percent. The estimated predevelopment recharge rate ranged from 0.056 to 0.84 in./yr. The estimates were distributed on the basis of soil types. Recharge rates were smallest for the clay-loam and silt-loam soils and were largest for sandy soils in the sand dunes. At calibration, the mean difference between the observed and simulated water levels was −0.28 ft (table 8).

The predevelopment water level in much of the northern High Plains was controlled by the rivers draining the area. Hence, the simulated water levels in the northern High Plains were less sensitive to the estimates of hydraulic conductivity and recharge from precipitation. Two separate simulations—one using the initial hydraulic-conductivity estimates and one with the hydraulic-conductivity estimates in Nebraska increased by 33 percent of the initial values—produced nearly identical simulated water levels. Recharge rates were changed during the two simulations to produce the best correlation between observed and simulated water levels. However, the latter simulation produced a more reasonable base flow to streams, and this simulation was selected as the best representation of the aquifer because it was more consistent with work previously done in Nebraska.

In the northern High Plains model, the estimated predevelopment recharge rate ranged from 0.076 to 1.52 in./yr and was distributed according to soil type. The recharge rate was smallest for the clay-loam and silt-loam soils and was largest for sandy soils in part of the sand dunes in central Nebraska. At calibration, the mean difference between the observed and simulated water levels was +0.30 ft and, at 92 percent of 943 nodes in the model, the simulated water level was within 100 ft of the observed water level (table 8). Most of the errors in excess of 100 ft occurred in areas where data were sparse. At calibration, the simulated base flow averaged 61 percent of the estimated base flow, probably because the model can only simulate the regional component of the base flow.

The objective of the development-period calibration was to simulate the change in the system due to human activities. Calibration of the development-period models began with the results of the predevelopment-period calibration. In the development-period calibration, two stresses—return flow from irrigation and increased recharge rates due to human activities during the development period—were varied to obtain the best correlation between observed and simulated water levels or water-level changes.

The southern High Plains aquifer has had a long history of irrigation development dating from the 1930's. Because of this long history, the development-period calibration was divided into two periods: 1940–60 and 1960–80. Return flow from irrigation was varied to achieve the best correlation between the observed and simulated historic water levels. In the first period (1940–60), the return flow was adjusted such that net withdrawal (total pumpage minus return flow) was equal to 90 percent of the estimated irrigation requirement. In the second simulation period (1960–80), the best correlation between observed and simulated water levels again occurred when net withdrawal was 90 percent of the estimated irrigation requirement.

In the 1960–80 simulation, 2 in./yr of additional recharge were added to all irrigated land. The additional recharge represents about 1.0 million acre-ft of water per year. The additional recharge from 1960 to 1980 could be attributed to a broad area of the southern High Plains where the playas were full of water and water was standing in fields in 1970. The additional recharge could have been added at twice the rate during only the last one-half of the second simulation period, and such a simulation would produce nearly identical results. The mean difference between the observed and simulated water levels during the first simulation period was −0.22 ft and the simulated change in storage was 19 percent less than the observed change in storage. The difference between the observed and simulated water levels for the second period was +0.28 ft and the simulated change in storage was 2 percent more than the observed change in storage. The combined simulated change in storage for the two periods (1940 to 1980) was 7 percent less than the observed change in storage (table 8).

The central High Plains was developed for irrigation more recently than the southern High Plains. By the 1950's, only relatively small areas had been significantly disturbed from the predevelopment condition. Only one development-calibration period, 1950–80, was used for the central High Plains model. Return flow from irrigation was varied to achieve the best correlation between observed and simulated water-level changes and calibration was obtained when return flow was adjusted such that net withdrawal equaled 100 percent of the irrigation requirement. On a volumetric basis, the simulated water-level changes were 9 percent less than the observed changes. On an areal basis, the simulated water-level changes were 6 percent more than the observed changes. The simulated change in storage was 9 percent more than the observed change in storage.

The northern High Plains has the shortest history of development of the three areas of the High Plains. Even by 1960, most of the northern High Plains had undergone little development for irrigation and by 1980 major parts of the area still were undeveloped. Only one development-calibration period, 1960–80, was simulated for the northern High Plains aquifer. Return flow from irrigation was varied during the calibration process and the best correlation between observed and simulated water-level changes was achieved when return flow was adjusted so that net withdrawal equaled 100 percent of the irrigation requirement. Unlike the other two areas of the High Plains, other stresses besides pumpage and return flow were significant in the development-period model of the northern High Plains aquifer. These stresses include: (1) Canal and reservoir leakage; (2) increased recharge due to dryland cultivation; (3) return flow from surface-water irrigation; and (4) additional recharge east of 100° longitude. These additional stresses due to human activities (47.0 million acre-ft) and the return flow from ground-water irrigation (37.5 million acre-ft) in large part balanced the 105.0 million acre-ft of water pumped between 1960 and 1980. Hence, although large stresses have occurred, the net overall change in storage was small. The simulated net decrease in storage was 15 million acre-ft and the observed decrease in storage was 6 million acre-ft.

A sensitivity analysis was performed on the High Plains models to determine how errors in model parameters affect the simulation results. The sensitivity analysis for the predevelopment-period models indicated that the models were about equally sensitive to changes in recharge or changes in hydraulic conductivity. The analysis further indicated that these two model inputs are highly interrelated and as long as the two were in balance, the models will have a small mean water-level residual. Hence, the models could be used to accurately determine the recharge rate if the hydraulic conductivity is accurately known. The development-period models were sensitive to changes in net withrawal and specific yield and insensitive to changes in hydraulic conductivity. Specific yield and net withdrawal also are highly interrelated and, one cannot be determined with acceptable certainty through model analyses unless the other is accurately known.

Although the calibrations for each of the areas of the High Plains were done separately, the increased understanding of the system in one area contributes to the understanding of the other areas. Certain similarities between the models of the three areas were noted. In the predevelopment-period calibrations, the estimated predevelopment recharge rate, although somewhat variable within and among areas, was uniformly small outside of the sandy soils in the sand-dune areas. In the development-period calibrations, the difference between total pumpage and return flow for all areas was close to the estimated irrigation requirement. Other similarities between the models exist but were not as apparent as those already mentioned. Two such possible similarities are worth noting, although sufficient data were not available to pursue them further.

In the central High Plains model, the estimated hydraulic conductivity was decreased in the area where the bedrock was disturbed by dissolution of salts in the Permian age rocks. The simulated predevelopment water levels in the southern High Plains model were in error in a similar environment. If the estimated hydraulic conductivity in the extreme northern part of the southern High Plains had been decreased in a manner similar to that in the central High Plains model, the simulated water levels would better correlate with the observed water levels. The same phenomenon also might have occurred in the southwestern part of the southern High Plains.

There is a similarity between the additional recharge that was added to the development-period models of both the southern High Plains and the northern High Plains during 1960–80. In the southern High Plains model, the additional recharge was 2 in./yr throughout the irrigated area. In the northern High Plains model, the additional recharge was 5 in./yr east of 100° longitude and south of 41° latitude, and 2.5 in./yr east of 100° longitude and north of 41° latitude. The increase in recharge in the southern High Plains is thought to be due to playas full of water and water standing in fields in 1970 but the source of the increase in recharge in the northern High Plains remains unknown. Whether the additional recharge required in the southern High Plains model was related in any way to the additional recharge required in the northern High Plains model is not known.

The results of the predevelopment-period calibrations for each of the three areas of the High Plains were used as the initial conditions for the development-period calibration. Likewise, the calibrated development-period models for the southern, central, and northern High Plains described in this report can be used as the initial conditions for evaluating future water levels in the High Plains.

REFERENCES CITED

Bennett, G. D., 1979, The U.S. Geological Survey Regional Aquifer-System Analysis Program in relation to the drought of the 1970's [abs.]: American Geophysical Union Transactions, v. 60, no. 18, p. 250.

Bentall Ray, and Shaffer, F. B., 1979, Availability and use of water in Nebraska, 1975: Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, Nebraska Water Survey Paper 48, 121 p.

Cady, R. E., and Ginsberg, M. H., 1979, Interpretive study and numerical model of the hydrogeology, Upper Big Blue Natural Resources District: Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 185 p.

Cobb, P. M., Colarullo, S. J., and Heidari, Manoutchehr, 1983, A ground water flow model for the Great Bend aquifer, south-central Kansas: Kansas Geological Survey Open-File Report 83–20, 220 p.

Crist, M. A., 1975, Hydrologic analysis of the valley-fill aquifer, North Platte River valley, Goshen County, Wyoming: U.S. Geological Survey Water-Resources Investigations 3–75, 60 p.

———1977, Hydrologic evaluation of the Arkaree Formation near Lusk, Niobrara and Goshen Counties, Wyoming: U.S. Geological Survey Water-Resources Investigations 77–111, 23 p.

———1980, Effect of pumpage on ground-water levels as modeled in Laramie County, Wyoming: U.S. Geological Survey Water-Resources Investigations 80–1104, 26 p.

Dunlap, L. E., Kume, Jack, and Thomas, J. G., 1980, Geohydrology and model analysis for water-supply management in a small area of west-central Kansas: U.S. Geological Survey Water-Resources Investigations 80–91, 59 p.

Dunlap, L. E., Lindgren, R. J., and Sauer, C. G., 1984, Geohydrology and model analysis of stream-aquifer system along the Arkansas River in Kearney and Finney Counties, southwestern Kansas: U.S. Geological Survey Water-Supply Paper 2253, (52 p.).

Emery, P. A., 1966, Use of analog model to predict streamflow depletion, Big and Little Blue River basin, Nebraska: Ground Water, v. 4, no. 4, p. 13–19.

Emmett, L. F., Skelton, John, Luckey, R. R., Miller, D. E., Thompson, T. L., and Whitfield, J. W., 1978, Water resources and geology of the Springfield area, Missouri: Missouri Division of Geology and Land Survey Water Resources Report 34, 150 p.

Fader, S. W., and Stullken, L. E., 1978, Geohydrology of the Great Bend Prairie, south-central Kansas: Kansas Geological Survey Irrigation Series 4, 19 p.

Finch, W. I., and Wright, J. C., 1970, Linear features and ground-water distribution in the Ogallala Formation of the southern High Plains, *in* Mattox, R. B., and Miller, W. D., eds., Ogallala Aquifer Symposium: Texas Tech University, Lubbock, 1970, International Center for Arid and Semi-arid Land Studies Special Report 39, p. 49–57.

Gutentag, E. D., Heimes, F. J., Krothe, N. C., Luckey, R. R., and Weeks, J. B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–B, 63 p.

Gutentag, E. D., Lobmeyer, D. E., and Slagle, S. E., 1981, Geohydrology of southwestern Kansas: Kansas Geological Survey Irrigation Series 7, 73 p.

Gutentag, E. D., and Weeks, J. B., 1981, Evaluating vertical variability of transmissivity and specific yield for the High Plains regional aquifer system [abs.]: Geological Society of America Abstracts with Programs, Rocky Mountain Section, v. 13, no. 4, p. 199.

Havens, J. S., and Christensen, S. C., 1983, Numerical simulation of the High Plains regional aquifer, northwestern Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 83–4269, 27 p.

Heimes, F. J., and Luckey, R. R., 1982, Method for estimating historical irrigation requirements from ground water in the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations 82–40, 64 p.

———1983, Estimating 1980 ground-water pumpage for irrigation on the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations 83–4123, 36 p.

Hoxie, D. T., 1977, Digital model of the Arikaree aquifer near Wheatland, southeastern Wyoming: U.S. Geological Survey Open-File Report 77–676, 54 p.

———1979, Results of transient simulations of a digital model of the Arikaree aquifer near Wheatland, southeastern Wyoming: U.S. Geological Survey Open-File Report 79–1280, 17 p.

Huntoon, P. W., 1974, Predicted water-level declines for alternative ground-water developments in the upper Big Blue River basin, Nebraska: Conservation and Survey Division, Institute of Agricultural and Natural Resources, University of Nebraska–Lincoln, Resource Report 6, 106 p.

Johnson, M. S., and Pederson, D. T., 1982, Ground-water levels in Nebraska 1981: Conservation and Survey Division, Institute of Agriculture and Natural Resource, University of Nebraska–Lincoln, Nebraska Water Survey Paper 52, 65 p.

Kapple, G. W., Luckey, R. R., and Hofstra, W. E., 1976, Digital ground-water model of the Ogallala aquifer in parts of Washington and Yuma Counties, northern High Plains of Colorado: Colorado Water Conservation Board Water-Resources Circular 34, 25 p.

———1977, Digital ground-water model of the Ogallala aquifer in parts of Cheyenne and Kiowa Counties, northern High Plains of Colorado: Colorado Water Conservation Board Water-Resources Circular 35, 20 p.

Knowles, Tommy, Nordstrom, Phillip, and Klemt, W. B., 1982, Evaluating the ground-water resources of the High Plains of Texas: Texas Department of Water Resources Final Report LP–173, v. 1, 174 p.

Kolm, K. E., and Case, H. L., III, 1983, A two-dimensional, finite-difference model of the High Plains aquifer in southern South Dakota: U.S. Geological Survey Water-Resources Investigations Report 83–4175, 34 p.

Krothe, N. C., Oliver, J. W., and Weeks, J. B., 1982, Dissolved solids and sodium in water from the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–658.

Lappala, E. G., 1978, Quantitative hydrogeology of the Upper Republican Natural Resources District, southwest Nebraska: U.S. Geological Survey Water-Resources Investigations 78–38, 200 p.

Lappala, E. G., Emery, P. A., and Otradovsky, F. J., 1979, Simulated changes in ground-water levels and streamflow resulting from future development (1970–2020) in the Platte River basin, Nebraska: U.S. Geological Survey Water-Resources Investigations 79–26, 82 p.

Larson, S. P., 1978, Direct solution algorithm for the two-dimensional ground-water flow model: U.S. Geological Survey Open-File Report 79–202, 25 p.

Lindner–Lunsford, J. B., and Borman, R. G., 1984, Potential well yields from the Ogallala aquifer in the northern High Plains of Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA–685.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Luckey, R. R., Gutentag, E. D., and Weeks, J. B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–652.

Luckey, R. R., and Hofstra, W. E., 1973a, Digital model of the hydrologic system, northern High Plains of Colorado—A preliminary report: Colorado Water Conservation Board Water-Resources Circular 19, 40 p.

———1973b, Digital model of the hydrologic system of the northern part of the northern High Plains of Colorado: Colorado Water Conservation Board Water-Resources Circular 24, 22 p.

McAda, D. P., 1984, Mathematical model of the Ogallala aquifer in Lea County, New Mexico: U.S. Geological Survey Water-Resources Investigations 84–4062, 84 p.

Morton, R. B., 1980, Digital-model projection of saturated thickness and recoverable water in the Ogallala aquifer, Texas County, Oklahoma: U.S. Geological Survey Open-File Report 79–565, 34 p.

Newport, T. G., 1959, Ground-water resources of the lower Niobrara River and Ponca Creek basins, Nebraska and South Dakota, *with a section on* Chemical quality of the water by R. A. Krieger: U.S. Geological Survey Water-Supply Paper 1460–G, p. 273–323.

Ogilbee, W., 1962, Ground-water resources of Haskell and Knox Counties, Texas: Texas Water Commission Bulletin 6209, 174 p.

Pettijohn, R. A., and Chen, H. H., 1984, Hydrologic analysis of the High Plains aquifer system in Box Butte County, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 84–4046, 54 p.

Reddell, D. L., 1967, Distribution of ground-water recharge: Colorado State University, Agricultural Engineering Department Technical Report, 132 p.

Sniegocki, R. T., 1959, Geologic and ground-water reconnaissance of the Loup River drainage basin, Nebraska, *with a section on* Chemical quality of the water, by R. H. Langford: U.S. Geological Survey Water-Supply Paper 1493, 106 p.

Texas Department of Water Resources, 1981, Inventories of irrigation in Texas 1958, 1964, 1969, 1974, and 1979: Texas Department of Water Resources Report 263, 295 p.

Trescott, P. C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75–438, 108 p.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water Resources Investigations, Book 7, Chapter C1, 115 p.

U.S. Department of Agriculture, 1967, Irrigation water requirements: Soil Conservation Service, Engineering Division, Technical Release 21, 88 p.

U.S. Enviromental Protection Agency, 1976, National interim primary drinking water regulations: Office of Water Supply, EPA–570/9–76–003, 159 p.

———1977, National secondary drinking water regulations: Federal Register, v. 42, no. 62, Thursday, March 31, 1977, Part I, p. 17143–17147.

Weeks, J. B., 1978, Plan of study for the High Plains regional aquifer-system analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations 78–70, 28 p.

Weeks, J. B., and Gutentag, E. D., 1981, Bedrock geology, altitude of base, and 1980 saturated thickness of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–648.

Wendorf, Fred, 1970, The Lubbock subpluvial, *in* Dort, Wakefield, Jr., and Jones, J. K., Jr., eds., Pliestocene and recent environments of the central Great Plains: University of Kansas, Department of Geology Special Publication 3, p. 23–35.

White, W. M., Broadhurst, W. L., and Lang, J. W., 1940, Ground water in the High Plains in Texas: Texas State Board of Water Engineers, 56 p.

Winter, T. C., 1976, Numerical simulation analysis of the interaction of lakes and ground water: U.S. Geological Survey Professional Paper 1001, 45 p.

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