Final Topical Report

Saturated Thickness in the Ogallala Aquifer in the Panhandle Water Planning Area—Simulation of 2000 through 2050 Withdrawal Projections

by

Alan R. Dutton

Robert C. Reedy

Robert E. Mace*

*Currently at Texas Water Development Board

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Bureau of Economic Geology

Scott W. Tinker, Director

The University of Texas at Austin

University Station, Box X

Austin, Texas 78713-8924

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EXECUTIVE SUMMARY

The Ogallala aquifer is one of Texas' major aquifer systems. This study focused on the part of the Ogallala aquifer that underlies 18 of the 21 counties of the Panhandle Water Planning Area (PWPA). In the past 50 years, water-level drawdown in parts of the unconfined aquifer has been as much as 190 feet, or about 4 feet per year. Pumping rates for the next 50 years to 2050 have been projected to be greater than previous rates, and additional drawdown is possible.

A numerical, or computer, model of the occurrence and movement of groundwater in the Ogallala aquifer was developed to predict future water-level changes. Model development was part of a state-wide process of developing water-resource management plans under Senate Bill 1, 75th Texas Legislative Session. This model improved on previous models by (1) covering the Ogallala aquifer within most of each county in the PWPA with detailed resolution, (2) using as much as possible spatially controlled geologic and hydrologic data, and (3) placing of the model edges to minimize their effects on the area of interest in Texas. The model is intended to be used as a tool to assess surpluses and deficits in aquifer resources and to evaluate water management strategies that might address resource deficits.

The model was calibrated under two sets of conditions: "predevelopment" without appreciable rates of pumping, and "current" conditions, representing 1950 and 1998, respectively. The model (root mean square) error for the predevelopment calibration was about 64 feet and includes uncertainties due to the inherent model simplifications and approximations of recharge, transmissivity, base-flow discharge to rivers and springs, and model geometry. The model error for the 1998 calibration was about 74 feet. The somewhat larger model error for 1998 includes uncertainties associated with the predevelopment calibration and approximation of specific yield, historical pumping rates, and return flow. These model errors represent less than 2 percent of the change in hydraulic head across the Texas part of the model. In much of the Texas part of the model, the residual difference in hydraulic head is less than ±50 feet.

Using groundwater demands projected by the Panhandle Water Planning Group (PWPG) and the Texas Water Development Board (TWDB), the model predicts that by 2050 major areas of the aquifer will have less than 50 feet of remaining saturated thickness and that parts of the aquifer in Dallam, Sherman, Hartley, Moore, Potter, and Carson Counties may be dry. Details of this prediction may not be realized because of the following:

- a goal of the PWPG in the area is that at least half the 1998 saturated thickness of the aquifer will remain by 2050;
- pumping rates were not decreased as water levels fell in this version of the model;
- the model is not well calibrated for the extreme event of aquifer dewatering, so predicting saturated thickness where the water table is near the base of the aquifer may have an error greater than 74 feet.

The model can be used, however, to identify areas where there may be surpluses and deficits in groundwater resources, to evaluate water-management alternatives, and to estimate what rates of groundwater pumping in various parts of the PWPA would ensure the goal of groundwater conservation districts is met. The model also may be used as an aquifer management tool to evaluate or compare proposed scenarios of groundwater development.

INTRODUCTION

Purpose and Objectives

The Ogallala aquifer, which makes up the main part of the High Plains aquifer along with adjacent and hydraulically interconnected older and younger formations, is the main source of agricultural and public-water supply in much of the Texas Panhandle (fig. 1). Prediction of the amount of remaining groundwater in the Ogallala aquifer over the course of the next 50 years is an important part of managing the aquifer's resource and of developing regional plans to meet future water needs. This report focuses on groundwater in the Ogallala aquifer in the Panhandle Water Planning Area (PWPA) (figs. 1, 2). Under Senate Bill 1, 75th Texas Legislative Session, the Panhandle Water Planning Group (PWPG) is charged with developing a regional water plan for the PWPA. The regional plan will be used by the Texas Water Development Board (TWDB) in developing a state-wide water-resource management plan.

Preliminary estimates of water remaining in storage in the Ogallala aquifer in the PWPA during 2000 to 2050 were made using a water-budget method, in which original water in place was estimated using data in a geographic information system (GIS) and water inflow and outflow were added and subtracted in a spreadsheet (Dutton and Reedy, 2000). That preliminary analysis predicted that saturated thickness in the Ogallala aquifer in Dallam, Moore, Oldham, Potter, and Randall Counties will decline to less than 50 feet by 2050. A numerical model of the occurrence and movement of groundwater in the Ogallala aquifer was developed to

- predict with more accuracy and precision the remaining Ogallala groundwater within each county of the PWPA, given specific groundwater demands, and
- assess surpluses and deficits in Ogallala aquifer resources to meet demands.

Goals for developing this model were to provide a water-management tool that would cover the PWPA area, set model boundaries having minimal impact on results in the area of interest, and use measured hydrologic properties and other data to constrain model parameters and ensure results are representative of aquifer conditions.

A preliminary version of the numerical model was reported in August 2000 (Dutton and others, 2000). That version of the model assumed a constant transmissivity, recharge that varied with soil type, and no return flow. The model predicted that by 2050, appreciable parts of Dallam, Sherman, Hartley, Moore, Potter, and Carson Counties would have run out of groundwater in the Ogallala aquifer or have less than 50 feet of saturated section. Dutton and others (2000) stated that the accuracy of this prediction was limited because pumping rates were not decreased as water level fell and the model was not well calibrated for dewatering conditions since transmissivity was held constant. It was also pointed out that groundwater conservation districts in the area have the goal of limiting drawdown so that at least half the 1998 column of water in the aquifer will remain by 2050.

Between May and October 2000 additional work focused on revising the model to improve accuracy of the prediction of 2050 water levels. The changes included (a) specifying hydraulic conductivity and varying transmissivity with water level, (b) varying recharge with precipitation rate as well as soil type, and (c) including estimates of return flow. This report documents the final revised model. This report documents model construction and calibration and use of the model to predict saturated thickness from 2000 to 2050, given consensus-based estimates of future demand for groundwater.

CONCEPTUAL HYDROGEOLOGIC MODEL

Few regional aquifers have been as extensively studied as the Ogallala aquifer. Computer, or numerical, models of groundwater flow have been important tools for managing the groundwater resource and evaluating future changes in water level and saturated thickness. At least 15 numerical groundwater flow models have been developed for different parts of the Ogallala aquifer in Texas (Mace and Dutton, 1998). Numerical models integrate much of the known information on an aquifer, allow consideration of how the water-level response to pumping is influenced by aquifer properties, and help identify what information and conceptual understanding needs additional development. Each of the previous Ogallala models has had a specific purpose and carried associated strengths and weaknesses.

On the basis of this previous work, a conceptual model was developed for the occurrence and movement of water in the Ogallala aquifer in the study area. This conceptual model was used as a starting point for constructing the numerical model.

Water Resources and Water Demand

More water is pumped from the Ogallala aquifer than any other aquifer in Texas. The volume of water in the aquifer in the PWPA as of 1950 was estimated by the water-budget method as approximately 307 million acre-feet of water (table 1). Estimates of average saturated thickness of groundwater originally in place in the Ogallala aquifer range from 20 feet in Oldham County to 282 feet in Hansford County. Saturated thickness is less than 50 feet in parts of several counties, for example, in much of Oldham County and in southwestern Randall County (Knowles and others, 1984, v. 3, p. 433).

The rate of groundwater withdrawal for irrigation markedly increased after 1950 (Texas Water Development Board, 1996; fig. 3). Historically, withdrawal for irrigation has made up from 57 to 96 percent of the total groundwater demand (Dutton and Reedy, 2000). Average total annual withdrawal was greatest during the 1980s. During the 1990s the total rate of withdrawal appears to have decreased to about 1.24 million acre-feet per year. Future demand, on the basis of consensus-based projections and assuming water availability (Freese and Nichols, Inc., 2000), is expected to continue to increase but after 2000 at lower rates than in the past (fig. 3). This assumes no future growth in demand for irrigation.

Hydrostratigraphy

The Ogallala Formation in the study area consists of Tertiary-age alluvial fan, fluvial, lacustrine, and eolian deposits derived from erosion of the Rocky Mountains (Seni, 1980; Gustavson and Winkler, 1988). The Ogallala Formation in the study area unconformably overlies Permian, Triassic, and other Mesozoic formations (Gutentag and others, 1984) and in turn may be covered by Quaternary fluvial, lacustrine, and eolian deposits (table 2). Ogallala sediments filled paleovalleys eroded into the pre-Ogallala surface (Seni, 1980; Gustavson and Winkler, 1988). Deposition of the Ogallala Formation in some areas was contemporaneous with dissolution of underlying Permian salt beds, resulting in additional ground-surface subsidence and increased accumulation of Ogallala sediment (Gustavson and Finley, 1985). At the northwestern limit of the study area in northeastern New Mexico, the Ogallala Formation is also interbedded and locally covered with Tertiary-age volcanic deposits (fig. 1).

This depositional framework of the Ogallala aquifer has resulted in lateral and vertical heterogeneity. Aquifer heterogeneity is the spatial variability in properties that control the occurrence and movement of groundwater, such as hydraulic conductivity and specific yield, and is largely related to geologic features. Areas of the aquifer with a greater amount of sand and gravel have greater hydraulic conductivity. The lower part of the formation tends to have more coarse-grained sediment and greater hydraulic conductivity than the upper part. Within any section, sediment bedding may slightly impede the vertical circulation of groundwater.

Gutentag and others (1984) advocated referring to the groundwater system in the study area as the High Plains aquifer, for two main reasons. First, groundwater can move between the Ogallala Formation and adjacent Permian, Mesozoic, and Quaternary formations, so the term Ogallala aquifer is inadequate to refer to the whole aquifer system. Second, it also may be noted that not all of the Ogallala Formation is saturated. The term "High Plains aquifer" addresses these issues and avoids using a formational name also as an aquifer name. Because the focus of this study is on groundwater in the Ogallala Formation, however, the term "Ogallala aquifer" is used in this report, following local usage.

The Ogallala aquifer is an unconfined aquifer; that is, volume of water in storage changes by the filling and draining of pore or void space in the material that makes up the aquifer. The regional water table marks the top of the saturated zone within the Ogallala aquifer.

The Ogallala Formation and overlying Blackwater Draw Formation underlie the High Plains. Retreat of the edge of the High Plains surface has left a steep escarpment in most areas, which is held up in part by an erosion-resistant caprock, a calicified soil layer that separates the Ogallala from the Blackwater Draw Formations (Gustavson and Simpkins, 1989; Gustavson, 1996). The other main physiographic feature in the study area is the Canadian River Breaks, consisting of the dissected erosional drainage bordering the Canadian River.

Flow Paths

The conceptual model of flow paths in the Ogallala aquifer includes the following understandings, hypotheses, and assumptions:

- Under historical conditions, groundwater moved generally eastward in directions parallel to the slope of ground surface. South of the Prairie Dog Town Fork of the Red River (figs. 1, 2), flow is generally directed to the southeast (Knowles and others, 1984). In the area between the Canadian River and Prairie Dog Town Fork, flow is generally toward the northeast but follows an arcuate path curving toward either river valley. North of the Canadian River, flow is generally to the east.
- The drawdown of water levels in well fields such as the Amarillo well field in Carson County locally changes the direction of regional flow paths.
- The volume of flow within the Ogallala aquifer is large relative to the volume of cross-formational flow at the base of the aquifer. The Ogallala aquifer is thought to be the source of groundwater in the Triassic-age Dockum Group (Santa Rosa) that underlies the Ogallala Formation beneath much of the High Plains (Dutton, 1995). Over geologic time, downward movement of water out of the Ogallala around the perimeter of the High Plains drives dissolution of Permian salt beds (Simpkins and Fogg, 1982; Dutton, 1990); however, the rate of downward flow is low (Simpkins and Fogg, 1982; Senger and Fogg, 1987; Dutton and Simpkins, 1989; Dutton, 1995). There is evidence of upward movement of water from underlying formations where chlorinity of groundwater is more than 50 milligrams per liter in northern Carson and Gray Counties (Mehta and others, in press).
- Water levels in the aquifer in the northern part of the Texas Panhandle declined an average of about 5.5 feet per year during 1960–80 (Knowles and others, 1984), although there also was comparable water-level recovery in parts of the aquifer south of the Canadian River.

- Flow rates in the Ogallala aquifer between the Canadian River and Prairie Dog Town Fork are estimated to be roughly 80 to 100 feet per year (Mullican and others, 1997). Carbon-14 activity of six Ogallala groundwater samples in Texas ranges from 20.8 to 61 percent of Modern carbon, suggesting an average age of less than several thousand years (Dutton, 1995). Local presence of naturally occurring tritium indicates that in places some Ogallala groundwater is less than 50 years old (Nativ, 1988; Dutton, 1995).

Recharge and Discharge

The conceptual model of recharge and discharge is based on the following information and assumptions:

- The study-area climate is dry continental with moderate precipitation, low humidity, and high evaporation. Precipitation decreases from east to west across the Texas Panhandle from more than 22 inches per year to less than 16 inches per year, whereas potential evapotranspiration increases (Larkin and Bomar, 1983).
- Groundwater in the Ogallala aquifer is recharged from downward percolation of water from the surface of the High Plains.
- The distribution of recharge is poorly known; estimates range from 0.01 to 6 inches per year (Mullican and others, 1997).
- In much of the study area, runoff of surface water is not well integrated in streams, and much of the runoff collects in playa basins. Playas can focus recharge to the aquifer (Mullican and others, 1997).
- Estimates of regional recharge rates are averages of the higher rates beneath playas and lower rates beneath interplaya settings (Mullican and others, 1997).
- Regional and local recharge rates may vary with the characteristics of the soils that underlie playa and interplaya areas.

- Return flow is the recharge to the aquifer owing to deep percolation of excess irrigation water. An unknown proportion of irrigation water passes below root depth and out of the reach of evapotranspiration. Luckey and Becker (1999) assumed that return flow decreased from 24 percent during the 1940s and 1950s to less than 4 percent by the 1980s. Efficiency of irrigation application has continued to increase during the past decades.
- The time of travel between ground surface and the water table is unknown
- River bottomlands can be groundwater-discharge areas. Notable springs and seeps in river valleys and along the High Plains Escarpment discharged at rates of 1 to 2 cubic feet per second (cfs) (Brune, 1975).
- Since water levels have fallen during the past several decades, the amount of spring flow has decreased; some historical springs have ceased to flow.
- Groundwater discharge continues to provide varying amounts of base flow to the Cimarron, Beaver, and Canadian Rivers and to Wolf and Sweetwater Creeks (fig. 1). The Cimarron River does not have perennial flow across the western side of the High Plains (fig. 1; Luckey and Becker, 1999).

MODEL DESIGN AND APPROACH

Models are simplifications of groundwater flow and give only an approximate representation of actual aquifer conditions. The accuracy and applicability of model results depend on the selection of data and the assumptions made in building the model. A given model result may be obtained from various nonunique combinations of input data. Model design and calibration, therefore, attempt to constrain possible results.

Five general categories of information and decision making are involved in model construction: (1) model architecture, (2) aquifer geometry, (3) boundary conditions, (4) aquifer parameters, and (5) aquifer stresses such as pumping. ArcInfo/ArcView, a geographic information system (GIS), was used to collect, organize, and map model data and assign values to the model grid.

Model Architecture

Model architecture refers to the code, size of blocks, and the number of layers used in the model. The choice of code is important to ensure that important processes in the aquifer are represented accurately.

The governing equation for regional flow of groundwater derives from a water-balance equation:

$$\text{inflow} - \text{outflow} = -\text{div } q - R^{*} = S_s \, \partial h/\partial t, \quad (1)$$

where div q represents any difference between the rates of specific discharge of water (q, volumetric flow of fluid per unit time per unit volume) flowing into and out of a unit volume of an aquifer, R^{*} represents the volumetric flux of various sources and sinks of water such as recharge (source) and extraction wells (sinks) per unit volume of an aquifer, S_s is specific storage, and $\partial h/\partial t$ expresses the rate of change of hydraulic head (h). Hydraulic head is an expression of potential energy per unit weight of water. In this report the datum for hydraulic head is mean sea level. Any imbalance in the left-hand side of equation 1 results in a change of hydraulic head (h). The sources and sink of water as summed up in the R^{*}-term are expressed in the model as boundary conditions and aquifer stresses, as described in following sections.

Specific storage is a proportionality factor between the divergence or difference of water inflow and outflow rates and the rate of change of hydraulic head. It measures the volume of water released as a result of expansion of water and compression of the porous media per unit volume and unit decline in hydraulic head. For an unconfined aquifer such as the Ogallala aquifer, storage changes mainly by filling or draining of pore space.

Flow rates (q) are generally not directly measured in aquifers. Equation 1 is typically solved by factoring in the expression of Darcy's law describing the flow of groundwater:

$$q = -K \text{ grad } h, \tag{2}$$

where K is hydraulic conductivity, which expresses the ease with which water moves through a unit volume of the aquifer, and grad h is the gradient of hydraulic head in horizontal and vertical directions. The negative sign indicates that groundwater movement is in the direction of decreasing hydraulic head.

Combining equations 1 and 2 yields the general form of the governing equation for groundwater flow:

$$-\text{div}(-K \text{ grad } h) - R^* = S_s \, \partial h/\partial t \tag{3a}$$

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - R^* = S_s \frac{\partial h}{\partial t} \tag{3b}$$

where x, y, and z are Cartesian coordinates of the system and K_x, K_y, and K_z are the directional components of hydraulic conductivity. This model of the Ogallala aquifer assumes only horizontal flow and ignores the third term on the left-hand side of equation 3b. Multiplying both sides of equation (3b) by saturated thickness (b) expresses the governing equation in terms of transmissivity (T) and storativity (S). Transmissivity, which is the ease with which water moves through a unit width of a column of an aquifer, is equal to the saturated thickness times hydraulic conductivity:

$$K \times b = T \tag{4a}$$

Similarly, storativity, which is equal to the volume of water released from a vertical column of the aquifer per unit surface area of the aquifer and unit decline in hydraulic head, is equal to the saturated thickness of the aquifer times specific storage:

$$S_s \times b = S \tag{4b}$$

Solving equation 3b for the distribution of hydraulic head in time and space also requires specified values of initial and lateral boundary conditions. A numerical model represents an approximate solution to the flow equation, given a particular set of boundary conditions. Constructing a numerical model involves specifying all of the parameters in equations 1 to 4 and in the initial and boundary conditions. This study used MODFLOW (Harbaugh and McDonald, 1996) to solve the flow equation according to the finite-difference method (Anderson and Woessner, 1992). MODFLOW is a tested and widely used groundwater modeling program. Processing MODFLOW (version 4.00.5000; Chiang and others, 1998) was used as the modeling interface to help load and package data into the formats needed for running simulations in MODFLOW and for looking at simulation results.

MODFLOW simulates some sources and sinks of water using variations on a head-dependent flux equation (Harbaugh and McDonald, 1996). Movement into and out of the aquifer at model cells, for example, those representing rivers and springs, depends on (a) the relative difference in elevation between simulated hydraulic head and the hydraulic head prescribed for the boundary condition, and (b) a conductance term that is a combination of hydraulic conductivity at the boundary and the dimensions of the boundary feature (Harbaugh and McDonald, 1996). MODFLOW modules such as "river" and "drain" allow for prescribed changes in flux as water level changes. A MODFLOW module known as a "general head boundary (GHB)," in which flux is always a linear function of the head difference, also was used.

The model grid for the finite-difference model was defined by 256 columns and 188 rows. Rows were aligned west-to-east, and columns were aligned north-to-south. Cells or blocks of the model were square and 1 mile long on each side (1-square-mile area). The model grid was projected in ArcView using the Albers equal-area projection. The Ogallala aquifer was simulated as one layer; no vertical heterogeneity within the Ogallala aquifer was modeled. There were 24,207 active cells representing the aquifer in the model.

Aquifer Geometry

Geometry of the model consists of the physical dimensions of the aquifer: the perimeter of the modeled part of the aquifer and the topography of the top and bottom (figs. 4, 5) of the modeled layer. To move lateral boundary conditions away from the area of interest in Texas, lateral boundaries to the west and east were set at the limit of the Ogallala Formation in New Mexico and Oklahoma. The boundary to the north was set at the Cimarron River in Oklahoma and Kansas. The boundary to the south crosses between the Canadian River and the Prairie Dog Town Fork of the Red River (figs. 1, 2). Only those parts of Oldham and Randall Counties that lie within this area were included in the model.

Aquifer geometry is probably the best characterized of all the input data. Ground-surface topography (fig. 4) was defined by a 1:250,000-scale digital elevation model (DEM) downloaded from a U.S. Geological Survey Internet site (ftp://edcftp.cr.usgs.gov/pub/data/DEM). Structure of the bottom of the aquifer is defined by numerous wells. The elevation of the water-table surface was based on measured water levels. Nonetheless, the water table and base of the aquifer are not perfectly known, and data input to the model still required some simplification and approximation.

The base of the Ogallala aquifer was contoured using mapping tools in ArcView. This involved creating triangulated irregular networks (TINs), gridding the TIN surfaces, and assigning values to the model grid. The resulting contoured map is a reasonable representation of regional trends but might not accurately depict local features, especially where data are sparse. Where well data on the base of the aquifer in Texas were sparse, contoured maps presented in Knowles and others (1984, v. 2 and 3) for each county were digitized and used as breaklines in the GIS triangulation process. Possible error is greatest where data on the base of Ogallala aquifer are sparse, for example, in Hartley and Dallam Counties. Locally the elevation of the base was lowered to ensure model cells representing the predevelopment water level did not dewater. This adjustment was mainly in eastern Union County, New Mexico, and western Dallam County.

Reported measurements of depth to water in wells in Texas were downloaded from the TWDB Internet site (http://www.twdb.state.tx.us/Newwell/well_info.html). Information on water levels and hydrogeologic properties of the Ogallala aquifer outside of Texas included digital data used in a numerical model by Luckey and Becker (1999) and hydrogeologic data for Quay and Union Counties, New Mexico (Berkstresser and Mourant, 1966; Cooper and Davis, 1967). The map of the "predevelopment" water table is based on the earliest reported measurements within all areas. For example, in one area the first reported water-level data may be for 1940, in another for 1960, and in another for 1970. This composite surface was assumed to represent the "predevelopment" water table as of 1950. The map of the "predevelopment" water table was contoured by hand; earliest data were given precedence and the initial water level was assumed to be higher than later measurements. Uncertainty in depicting the 1950 "predevelopment" surface is assumed to be at least commensurate with other simplifications in the model. The water table for 1998 is based on water-level measurements taken in 1997 and 1998.

Data control for both the water-table elevation and base of the Ogallala aquifer (fig. 5) were generally good except as follows:

- Water-level data were sparse in parts of several counties (including but not limited to Lipscomb, Ochiltree, Oldham, Potter, and Randall Counties). Control points and break lines were added in GIS to adjust the mapped water-table surface and calculated saturated thicknesses to resemble those shown in Knowles and others (1984).
- The base of the aquifer in the Ogallala Formation is not consistently mapped throughout Dallam, Moore, and Randall Counties (Knowles and others, 1984, v. 2 and 3). For part of these counties the mapped base includes formations underlying the Ogallala aquifer. This overestimates the volume of water in storage in the Ogallala in these counties. In areas

where well control was sparse, maps of the base of the Ogallala presented in Knowles and others (1984) were used to constrain the structure drawn in GIS.

Boundary Conditions

Numerical models solve the general equation of groundwater flow (equation 3b) with spatial boundary conditions and initial conditions (a boundary condition in time). Initial conditions used in the model assumed that recharge and discharge for the Ogallala aquifer were near equilibrium (pseudo-steady state) prior to 1950, after which rates of pumping increased throughout the region.

Spatial boundary conditions involve specifying inflow and outflow fluxes (R*, equations 1 and 3) across the top, bottom, and perimeter of the modeled aquifer. Boundaries may be approximations of (1) physical conditions, such as the limit or pinch-out of the Ogallala aquifer, or (2) hydraulic conditions, such as groundwater divides and streamlines. Boundaries may also be set at artificial positions, determined by neither physical nor hydrological features. Of the three types, physical and hydraulic boundaries are preferable because they more accurately represent actual boundaries in the natural system. Artificial boundaries are generally used to limit the upstream or downstream extent of a model to the area of interest and are most appropriate for steady-state models. They are appropriate in transient models if the variation of water levels at the boundary is minimal over time and the area of interest is a sufficient distance away from the boundary. Several previous models of the Ogallala aquifer included significant artificial boundaries (Mace and Dutton, 1998).

This model of the Ogallala aquifer uses a combination of physical, hydrological, and artificial boundaries, minimizing the extent of the last:

- The limited amount of water that flows across the base of the Ogallala aquifer (a physical boundary) was assumed to be negligible in comparison with the overall water budget. The lower boundary of the aquifer, therefore, was defined as a no-flow boundary.

- The top of the model was assigned a constant rate of recharge (a hydraulic boundary) for each stress period.
- Recharge rates (fig. 6) were set as a function of precipitation and soil types (table 3). Data on long-term average (1950 to 1990) precipitation were compiled from the National Weather Service Internet site. These data were contoured and interpolated for the cells in the model area. Initially recharge was assumed to vary linearly from 0.1 to 0.5 inches per year where precipitation ranged from 16.5 to 22.5 inches per year, respectively. During calibration the straight-line relationship between recharge and precipitation was changed. The final version of the model has (1) a greater percentage of precipitation becoming recharge on the wetter, eastern side of the study area than to the west, and (2) minimum recharge set at 19 inches per year of precipitation. Further research on the relation of recharge to precipitation is needed.
- Recharge was also varied with soil type. GIS polygons of soil types were downloaded from http://www.ftw.nrcs.usda.gov/stat_data:html, the U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) Internet database. The numerous soil types were joined into eight groups (table 3). Groups 1 to 3 mainly have loamy surface and subsurface soils, whereas Groups 4 to 7 have loamy surface but clayey subsurface soils (Gustavson, 1996). Groups 1 and 2 roughly correspond to the extent of the Ogallala Formation outcrop, especially south of the Canadian River. Group 8 is made up of windblown sands (Eifler and Barnes, 1969) that are younger deposits than the Blackwater Draw Formation (table 2). Recharge estimated from precipitation was not changed (weighting factor of 1.0) for "Ogallala" soils. Recharge was decreased for "Blackwater Draw" soils and increased for sandy Group 8 soils (table 3).
- Groundwater recharge as calibrated in the revised model was less than 1 percent of precipitation across about 72 percent of the model area. The other 99 percent is assumed to have returned to the atmosphere by evapotranspiration or run off as surface water. Groundwater recharge was set at less than 2 percent of precipitation across 92 percent of

the model area but was between 5 to 6 percent of precipitation in 3 percent of the area. The higher recharge rates were on sandy soils on the eastern, wetter side of the High Plains.

- Return flow was not included in the earlier version of the model (Dutton and others, 2000) since pumpage, return flow, and specific-yield calibration are interrelated and the latter two are poorly known. Irrigation loss probably was large during the 1940s and 1950s (Luckey and Becker, 1999) but may have gone to increasing moisture content of the unsaturated zone. During the past few decades irrigation losses have decreased. Luckey and Becker (1999) assumed return flow is most likely to be less than 5 percent of irrigation in the future.
- Return flow was assigned in the revised model and varied with irrigation rate, loss rate or inefficiency, soil type, depth to water, and velocity or rate of downward movement of water from the root zone to the water table. Loss rate was initially taken from Luckey and Becker (1999) and set equal to 24 percent for the 1950s and decreased to 2 percent since the 1990s. To evaluate the sensitivity of model results to return flow, simulations also were made with twice these loss rates. The same soil-weighting factors were applied to return flow as to recharge from precipitation (table 3); less return flow was predicted from irrigation on Blackwater Draw soils than on Ogallala soils. Depth to water was approximated using preliminary model results without return flow. Depth to water increases through time at most model cells, increasing the travel time for water to move from the root zone to the water table. Accordingly, return flow may recharge the water table later than the year in which irrigation was applied, and the delay or lag may increase through time as depth to water increases. Finally, velocity of water through the unsaturated zone was assumed to lie between 5 and 40 feet per year. Several simulations were made to evaluate the sensitivity of model results to assumed velocities.
- The perimeter was defined by physical and hydraulic boundaries. Most of the perimeter of the Ogallala aquifer coincides with the limit of the Ogallala Formation where

groundwater is discharged in small springs and seeps, or as evapotranspiration where the water table is close to ground surface. This part of the boundary was simulated using the "drain" package of MODFLOW (fig. 2). Luckey and Becker (1999) used 10,000 square feet per day for drain conductance for grid-cell areas of 36×10^6 square feet. This model proportionally decreased drain conductance to 7,744 square feet per day for its 27.8×10^6 square foot (1-square-mile) grid-cell area. Drain elevation was set to 75 percent of saturated thickness, about 35 to 40 feet above the base of the aquifer.

- Part of the northern boundary of the model follows the Cimarron River and included a no-flow boundary and a river boundary (fig. 2). Along about the half of its course across the study area, the Cimarron River has little or no perennial flow and is assumed to coincide with a groundwater flow line (Luckey and Becker, 1999). This reach, therefore, was treated as a no-flow boundary for all stress periods (fig. 2). On the northeast side of the model, the Cimarron River in Kansas and Oklahoma was treated as a river boundary.
- MODFLOW's "river" module was also used to represent the interaction of surface and groundwater along segments of the Cimarron, Beaver, and Canadian Rivers and Wolf and Sweetwater Creeks (fig. 2). The "river" module includes three parameters: river stage, river-bottom elevation, and riverbed hydraulic conductance (table 4). Initial values of river stage were set to 20 feet beneath the "predevelopment" water table to ensure river segments were simulated as gaining streams for the predevelopment model. This adjustment was needed because ground-surface elevation in each 1-square-mile cell is averaged and does not represent surface elevation at the river. River-bottom elevation was set 20 feet beneath the river stage. Riverbed conductance was initially set as a function of how much the river channel meanders in the model cell, then adjusted as part of model calibration to match reported regional rates of groundwater contribution to base flow (table 4).
- MODFLOW's "general-head boundary" module was used to close the southwest side of the model between the Canadian River and Prairie Dog Town Fork of the Red River (fig.

2). Boundary head was set to the predevelopment surface, and conductance was set equal to the average hydraulic conductivity times cell width and divided by saturated thickness.

Aquifer Parameters

This model of the unconfined aquifer used a combination of measured and interpolated values for aquifer parameters. Data for transmissivity, hydraulic conductivity, and specific yield are typically sparse for model calibration. Parameter values for large areas of the models are estimated or extrapolated. Hydraulic conductivity was assumed to be locally isotropic, that is, the same in x and y directions within each cell. It was also assumed that the Ogallala aquifer is made up of consolidated materials and that no compaction occurs with change in volume of water in storage.

An earlier version of the model (Dutton and others, 2000) was calibrated with a specified transmissivity; that is, transmissivity did not vary with water level. That model predicted parts of the aquifer could dewater, an extreme condition outside of the model calibration. Additional effort, therefore, focused on revising and recalibrating the model with specified hydraulic conductivity. In the revised model, transmissivity varies with water level and decreases as saturated thickness decreases.

To estimate hydraulic properties for the study area in Texas and expand upon previous studies, we (1) compiled available information on aquifer properties or tests from published reports and well records, (2) used specific-capacity information to estimate transmissivity and hydraulic conductivity, (3) used statistics to summarize results, and (4) used geological maps to "condition," or map, values of hydraulic conductivity. A major improvement to hydraulic properties over previous studies is the inclusion of specific-capacity information, which can significantly increase the number of measurement points for an aquifer.

We compiled tests from Mullican and others (1997) and from the groundwater database at the Texas Water Development Board (Texas Water Development Board, 1999). Mullican and others (1997) had information on 70 aquifer tests, which included high-quality specific-capacity tests. We were able to cull data from an additional 1,271 specific-capacity tests in the TWDB groundwater database. To estimate transmissivity and hydraulic conductivity from specific capacity, we used an analytical technique developed by Theis (1963). Hydraulic conductivity was determined by dividing transmissivity by the saturated thickness exposed to the wellbore (1,130 wells included information that allowed us to calculate saturated thickness).

Based on results from the data compilation and specific-capacity analysis, we found that hydraulic conductivity for all the tests in the Ogallala aquifer appears to be lognormally distributed (fig. 7) with a geometric mean of about 14.8 feet per day and a standard deviation that spans from 5 to 44 feet per day. A lognormal distribution means that the logarithms of the values are normally distributed, and a geometric mean is the antilogarithm of the mean of the logarithms of the values.

Semivariograms (see Clark, 1979; McCuen and Snyder, 1986) show that hydraulic conductivity in the Ogallala aquifer is spatially correlated. Spatial correlation infers that points that are closer together are more similar to each other than points that are further apart. Fitting a spherical theoretical semivariogram to the experimental semivariogram resulted in a nugget of 0.12 $[\log(\text{ft/day})]^2$, a sill of 0.22 $[\log(\text{ft/day})]^2$, and a range of 140,000 feet. The range suggests that hydraulic conductivity is spatially correlated within 140,000 feet (26 miles) in the Ogallala aquifer.

Hydraulic conductivity was assigned to the Texas part of the model on the basis of depositional systems of the Ogallala Formation (Seni, 1980). Measured values of hydraulic conductivity were posted and overlain on the depositional-systems maps. Contours and trend lines from the depositional-systems maps were then used as a guide to contour the hydraulic-conductivity data (fig. 8). Figure 7 compares the statistical distribution of the measured and final calibrated distribution of hydraulic conductivity for the Texas part of the model. Hydraulic-conductivity values for Texas and adjacent parts of the model were pooled using kriging. The kriging parameters were based on a semivariogram for the Texas data and the 1-square-mile cell size. Only minor changes to hydraulic conductivity were made during model calibration. Changes were made in southern Hartley and northern Oldham Counties, Texas, and in eastern Union County, New Mexico, where there were no available hydraulic-conductivity data.

Maps of specific yield were taken from Knowles and others (1984) and merged with cell values used by Luckey and Becker (1999) for the non-Texas part of the model. Grid center values of specific yield were interpolated using ArcView. Only minor adjustments were made, for example, in eastern Union County, New Mexico, since calibration results could not be appreciably improved by adjusting specific yield within reasonable limits.

Pumping

Accurate estimates of water withdrawal by pumping can be crucial to highly accurate modeling of water-level drawdown (Konikow, 1986). Pumping rates affect the calibration of the model and prediction of future water levels. Because there are few direct measures of historical pumping rates, pumping is generally estimated indirectly and may be a major source of calibration error in this and other numerical models. Errors in reconstructing pumping can be attributed to both uncertainty in total amount of pumping in a county and the allocation to specific cells in a county (Mullican and others, 1997).

For 1950 to 1998, approximately 54 million acre-feet of groundwater were simulated as being pumped from the Ogallala aquifer (table 5). This historical withdrawal was reconstructed from several sources. Pumping for municipal, industrial, irrigation, livestock, mining, and power uses during 1958, 1964, 1969, and 1974 was taken from worksheets compiled for the Knowles and others (1984) study. Pumping for 1980 to 1996 was tallied from a groundwater-summary database compiled by the TWDB (Dutton and Reedy, 2000). Decadal estimates of irrigation withdrawal for 1950 to 1997 also were made by the Texas Agricultural Experiment Station (TAES) on the basis of rainfall and irrigation efficiencies (Dutton and Reedy, 2000). Both

TWDB and TAES irrigation estimates were run. The TWDB estimates serve as a "worst-case" estimate giving more predicted drawdown.

For 1999 to 2050, approximately 82 million acre-feet of groundwater was simulated as being pumped from the Ogallala aquifer (table 5). Projected groundwater withdrawal for 2000 to 2050 (table 5) was derived from the consensus-based estimates of water demand compiled by Freese and Nichols, Inc. (2000). That projection of total water use by county is irrespective of source of water (for example, surface water or groundwater, and Ogallala aquifer versus other groundwater-bearing formations). Revisions to derive a table of projected withdrawals from the Ogallala aquifer included subtracting out surface-water sources and groundwater supplied from sources other than the Ogallala aquifer, and water produced in one county but supplied to meet demand in another (Dutton and Reedy, 2000).

Projections of irrigation withdrawal from the Ogallala aquifer have been developed by TAES for this project (Freese and Nichols, Inc., 2000) and by the TWDB as part of its statewide planning. The TAES estimates are about 15 percent less than the TWDB values in 2000 but only 2 percent different by 2050 (Freese and Nichols, Inc., 2000). As irrigation withdrawal is projected to make up approximately 85 percent of total withdrawal, these differences have the potential to impact model results, as stated in the opening paragraph in this section. Both sets of numbers were run to compare the resulting predictions of saturated thicknesses and volumes of groundwater remaining in the aquifer in 2050. The TWDB irrigation projections may be considered more conservative in that their higher withdrawal rates may overestimate water-level decline through 2050.

Average annual withdrawal for irrigation was greatest during the 1980s at approximately 1.5 million acre-feet per year (fig. 3). During the 1990s the total rate of irrigation withdrawal appears to have decreased to about 1.2 million acre-feet per year. Irrigation water in 1997 made up on average 86 percent of groundwater production from the Ogallala aquifer but ranged from 59 percent for Randall County to 98 percent in Dallam, Hartley, and Sherman Counties. Irrigation withdrawal is projected to average about 84 to 92 percent of total water production from the Ogallala aquifer over the next 50 years. Irrigation rates for Texas as applied in the model ranged about 0.17 to 0.52 acre-foot per year per acre during 1960 to 1998 and were about 0.44 acre-foot per year per acre for 2000 to 2050. For 1998 to 2050, about 99.5 percent of simulated irrigation rates were less than 1.5 acre-feet per year per acre.

Irrigation withdrawal in the Texas part of the study area was distributed using ArcView on the basis of results of a 1994 survey obtained in GIS format from the Texas Natural Resources Information System (TNRIS). That database identified polygons with irrigated acreage and specified the percentage of the polygon area under irrigation in 1994. We assumed that the same pattern of irrigated acreage applied for the entire modeling period (1950 to 2050). Total county withdrawal of groundwater for irrigation for a given year was proportionately distributed across the model grid to those cells with irrigated acreage.

Withdrawal of groundwater for municipal use was distributed to model cells using a database from the Texas Natural Resource Conservation Commission (TNRCC) Water Utilities Division, which identified the number, location, and drilling date of public water-supply wells in each county. Total municipal water pumping for each county was allocated equally among these public water-supply wells. Groundwater pumping for industrial and stock uses was distributed using data from the TWDB on locations of industrial and stock wells and their drilling date. Groundwater use related to power generation in Potter County was allocated to two cells representing wells used by the Southwest Public Service Company (Gale Henslee, 2000, personal communication).

Total withdrawal assigned to each model cell for each stress period was summed from a database using a Visual Basic program and loaded into the Processing MODFLOW utility. Figure 9 shows the distribution of simulated pumping for 1998. The same footprint of pumping cells was used to simulate pumping for 1998 to 2050; the proportion of withdrawal rates between cells was maintained. Historical and future water use in the study area outside of Texas, undifferentiated by water-use category (fig. 3), was taken from digital files by Luckey and Becker (1999).

Some model cells are predicted to go dry between 2000 and 2050, given these pumping rates, as will be discussed. As the cells go dry, the model cells are made inactive and pumping from those cells stops. The pumping allocated to those cells was not reallocated to remaining active cells. Thus the final amount of pumping in the predictive model runs was less than the consensus-based demand used as model input.

Model Calibration Approach

Once the model was constructed, the model was calibrated in two stages: steady state and transient. Model calibration was evaluated by

- comparing contours of the simulated and "observed" water tables for "predevelopment" and 1998 periods,
- mapping the residual of differences between simulated and "observed" water levels for individual well locations, and
- calculating the root mean square error of simulated versus observed hydraulic head (Anderson and Woessner, 1992).

First, the calibration of the predevelopment model was based on reproducing the estimated "predevelopment," or 1950, distribution of water levels as follows:

- During this first calibration stage, hydraulic conductivity, recharge rate, and parameter values for drains and rivers were inspected to see whether any changes were needed to improve the goodness-of-fit, or reduce model calibration error, calculated between simulated and observed values of hydraulic head. Only slight changes were made to hydraulic conductivity and recharge as previously discussed. The relation between recharge and precipitation rates was changed from one to three straight-line segments; the three segments may approximate a more complex relation between these two rates. Additional recharge was added to Donley County.

- Drain parameters were adjusted so that simulated discharge around the perimeter of the model would be consistent with historical observations of spring discharge (Brune, 1975).
- River conductances were iteratively adjusted so simulated groundwater discharge would match reported values of base flow (Luckey and others, 1986; Luckey and Becker, 1999).
- The predevelopment model was run as a transient model over a 6,000-year simulation time. Head changes after 6,000 years were found to be less than 0.01 foot. The 6,000-year time was broken up into 60 stress periods with 400 to 600 equal time steps for model convergence.

Second, the model was calibrated against water-level changes between 1950 and 1998. Model input at this stage included (1) simulated steady-state hydraulic-head values, (2) parameter values from the steady-state calibration (hydraulic conductivity, and drain and river packages), (3) estimated pumping rates, and (4) recharge rate modified to include return flow. This period is referred to as a "transient" period in that hydraulic head is changing in response to pumping rates that also are changing: As pumping rates were interpolated to a yearly basis, each stress period was 1 year. A stress period is a time interval in a model when all inflow and outflow are constant. Transient calibration included the following steps:

- After checking model calibration for 1998, model parameters for the predevelopment simulation were readjusted as needed, for example, aquifer-base elevation along the Texas–New Mexico border.
- No changes to storage were made during model calibration. Coefficient of storage in an unconfined aquifer, or specific yield, typically ranges between 0.05 and 0.3, which leaves little room for parameter adjustment to improve model calibration. Uncertainty in prescribing the distribution of pumping rates probably has a much bigger effect on model calibration than error in specific yield, and it would be inappropriate to try to correct for the pumping-rate error by pushing specific yield to unreasonable values.

CALIBRATION

Steady-State Calibration

Steady-state calibration involved adjusting hydraulic properties, recharge rate, and parameter values for drains and rivers to reduce model calibration error. It is considered steady state because pumping was left out of this version of the model to represent "predevelopment" conditions. It was assumed that before pumping came to make up a significant amount of aquifer discharge, recharge was balanced over the long term (tens to hundreds of years) by discharge to springs and seeps in river valleys and along the escarpment.

There is a direct relation between recharge rate and hydraulic conductivity for the model. If recharge rate were set higher in all or part of the model, hydraulic conductivity would have to be increased to compensate and keep calibration error unchanged. It would take a higher hydraulic conductivity to move the greater volume of water recharging the aquifer and keep simulated water level the same. This pattern was documented in sensitivity analyses by Luckey and Becker (1999, p. 52).

Figure 10 compares the estimated and simulated elevations of the "predevelopment" water table. The picture of the "predevelopment" water table is imperfect because

- data were composited from a wide range of years to include the first recorded measurements in different areas of the model;
- some amount of groundwater was already being withdrawn in each area of the model when the earliest water levels were being reported; and
- some areas have sparse data on water levels, and elevation of the water table is extrapolated partly on the basis of the shape of ground-surface topography.

The major features of the estimated and simulated water table (fig. 10) reproduce those depicted by Knowles and others (1984) and Luckey and others (1986) for the water-table surfaces of the area; each study used a common pool of data. The major features are

- water-level contours generally strike north in the area north of the Canadian River, and northwest in the area between the Canadian River and Prairie Dog Town Fork of the Red River (fig. 10);
- contours bend upstream across the broad valleys of the Canadian and Beaver Rivers, indicating the tendency of groundwater to discharge to springs and seeps along the river bottomlands;
- contours bend upstream along the part of the Cimarron River simulated as a river segment at the northeastern side of the model and are perpendicular to the model boundary along the part farther upstream that was modeled as a no-flow boundary (fig. 2);
- simulated groundwater discharge contributes about 66 cubic feet per second of base flow to the Canadian River (table 6), consistent with historical trends (John Williams, personal communication, 2000) and previous model results (Luckey and Becker, 1999);
- contours bend slightly to the west in the vicinity of the model perimeter, reflecting the influence of the "drain" package used to simulate discharge to springs and seeps.
- groundwater discharge at springs and seeps around the model perimeter amounts to an average of 0.06 cubic foot per second per cell, with 98 percent of "drain" cells having discharge of less than 1 cubic foot per second and maximum simulated discharge of 2.1 cubic feet per second. As previously mentioned, notable springs discharge at rates of 1 to 2 cubic feet per second (Brune, 1975).

Contours of the simulated water table reasonably match the estimated, or "observed," predevelopment water table (fig. 10) across most of the study area. Areas of poor fit include the Canadian River and Beaver River valleys, where uncertainty in the boundary values assigned to riverbed conductance and stage height affect model results, and in New Mexico and along the Texas–New Mexico border data are sparse for mapping the aquifer base and water table in New Mexico, so it is possible that the estimated water table in that area includes appreciable error itself.

Figure 11a compares water levels measured for specific wells to the simulated water levels calculated for corresponding cells. The root mean square error of simulated versus observed hydraulic head (Anderson and Woessner, 1992) is about 64 feet, and there is no evident bias. This error is less than 4 percent of the head drop across the Texas part of the model (1,750 to 2,525 feet), whereas a typical calibration goal is 10 percent for a numerical model.

Figure 12 maps the calculated residual, or difference, between the reported and simulated water levels shown in figure 11a. Considerable effort was made to reduce the residual in northern Union County, New Mexico, and to reduce its effect on results in western Dallam and Hartley Counties. Additional geologic research on the hydrogeology of the Ogallala aquifer in Union County, New Mexico, and along the Texas–New Mexico border would help improve model results in the northwestern Texas Panhandle.

Saturated thickness of groundwater in the Ogallala aquifer in the study area was as much as 700 feet in southwestern Kansas and the Oklahoma Panhandle, but it was generally less than 300 feet in Texas under predevelopment conditions (table 7, fig. 13). Given that the top of the saturated section is fairly smooth, much of the variation in saturated thickness is due to relief on the base of the Ogallala (fig. 5). In Carson County, the thick accumulation of Ogallala sediments reflects continued Tertiary-age deposition contemporaneous with ground-surface subsidence above salt-dissolution zones (Gustavson and Finley, 1985). A zone of low saturated thickness striking northwest across north-central Carson County reflects the "ridge" on the base of the Ogallala described by Mullican and others (1997). The thinnest saturated sections of the Ogallala were in eastern New Mexico and around the perimeter or limit of the aquifer.

Transient Calibration

Many of the regional features of the predevelopment water table remain for the 1998 water table (fig. 14), including the following:

- Contours on the 1998 water table strike north in the area north of the Canadian River and arc from northwest to south-southeast in the area between the Canadian River and Prairie Dog Town Fork.
- Contours still bend upstream across the broad valleys of the Canadian and Beaver Rivers, as seen in the "predevelopment" water-table surface.
- Contours bend upgradient in the vicinity of the model perimeter, reflecting continued influence of the "drain" package used to simulate discharge to springs and seeps, although about 7 percent of the springs have ceased to flow in the simulation.

There is generally good correspondence between estimated and simulated contours of water level for 1998 (fig. 14). It is hard to discern an overall change in calibration by comparing water-level contours (figs. 10 versus 14) or even calculated residuals (figs. 12 versus 15), perhaps partly because calibrations for both 1950 and 1998 are fairly good. Figure 11b shows that the mean square error of calibration for 1998 is 74 feet. This is larger than the calibration error for the "predevelopment" water table because of additional uncertainties associated with return flow, pumping rates, and specific yield. The mean square errors of calibration of the earlier model (Dutton and others, 2000) were 37 and 54 feet for predevelopment and transient models, respectively. The earlier model's calibration was somewhat forced in that transmissivity had been adjusted to improve model fit. This revised model includes little parameter adjustment and is a more "natural" model. Model error remains less than 5 percent of the head change across the Texas part of the model.

Groundwater discharge to base flow is simulated as decreasing by 15 to 52 percent to the Cimarron and Beaver Rivers and Wolf Creek but not by much to the Canadian River (table 6). Model results suggest simulated base flow to the Canadian River was largely unchanged between 1950 and 1998.

Saturated thickness decreased in the simulation from 1950 to 1998 (table 7; figs. 13, 16) because withdrawal was much greater than recharge rate. The greatest decrease in saturated thickness and greatest simulated drawdown of water levels between 1950 and 1998 in the model area in Texas were in Moore and Sherman Counties (table 7, fig. 17). The model also simulated a more than 100-foot decrease in water level in Amarillo's Carson County well field (fig. 17).

Volume of water in storage was determined for model cells by multiplying saturated thickness times cell area (1 square mile) and specific yield, and summed for all cells in a county. Averaged across all counties, the difference is 3 to 5 percent, but for individual counties the calibration residual translates into a difference in volume of 0 to 24 percent (table 8). The accuracy of the volume estimate for 1950 and 1998 depends on the same factors as did the accuracy of the water-table elevation (composite and sparse data, drawdown effects), plus accuracy of estimated and model-calibrated values of specific yield.

The magnitude and effect of return flow remain poorly known. The difference between maximum rate of return flow and no return flow accounts for less than 20 feet of drawdown between 1950 and 1998, and not much more than 20 feet by 2050. Other model uncertainties associated with hydraulic properties and pumping rate account for at least this much error. Comparison of observed and simulated hydrographs, therefore, does not suffice to back out the most likely rate of return flow. Return flow may be important to future water budgets in areas that had high irrigation rates and low irrigation efficiency.

MODEL PREDICTIONS

A main purpose of model calibration was to qualify a model for use in predicting the remaining groundwater within each county of the PWPA from 2000 to 2050, given specific groundwater demands. As previously stated, however, uncertainty in projected pumping rates may be the most important factor in determining the accuracy of water-level forecasts (Konikow, 1986). Calibration error related to allocating pumping to too many or too few cells of a model is compounded if the projection of total future pumping does not prove accurate. It is important, therefore, to plan for future audits to see how well model results predicted water levels, and to revise predictions on the basis of revised estimates of future pumping rates.

Average saturated thickness in 2050 is predicted to be more than 100 feet in 10 counties in the model area and more than 200 feet in Hemphill and Roberts Counties (table 7). Given the prescribed rate of pumping for the period from 2000 to 2050 and the other assumptions of the calibrated model, however, water levels are expected to decline during 2000 to 2050 in all counties (figs. 18, 19). Major changes predicted by the model include the following:

- Although average saturated thickness in most counties in the PWPA is simulated to be above 50 feet (table 7), there are areas within each county in which saturated thickness falls to less than 50 feet (table 9, figs. 20 to 25).
- Drawdown from 1998 to 2050 is predicted to be more than 150 feet in some areas (fig. 19), given the forecast amount of pumping.
- By 2020, parts of the model area in Oklahoma and Dallam and Potter Counties, Texas, are predicted to begin to go dry (fig. 22). This finding is consistent with similar model results obtained by Luckey and Becker (1999, p. 53–55).
- By 2050, parts of Dallam, Sherman, Hartley, Moore, Potter, Carson, and Donley Counties are simulated as being dry or having less than 50 feet of saturated section (fig. 25). The results for Donley County may be inaccurate since the predevelopment model underestimated water in storage in the Ogallala aquifer in that county (fig. 13, table 8). Parts of Oldham and Randall Counties, of course, have long had saturated thickness of less than 50 feet. Table 10 tallies the percentage of counties in which saturated thickness is less than half of the 1998 saturated thickness. More than 60 percent of Oldham County had less than 50 feet of saturated thickness in 1998 (table 9). Even so, simulated drawdown will leave at least half of that water through 2050 (zero values in table 10), given forecast pumping rates.

The dewatered areas were determined by MODFLOW where simulated water level reached the aquifer base. Model prediction of dewatered areas might not be accurate for several reasons. Pumping rates were prescribed by consensus of what future demand will be (fig. 3), rather than what the aquifer might sustain, and pumping rates were not decreased as water levels fell in this version of the model. As saturated thickness decreases, it may not be cost effective for irrigators to operate large-capacity wells or multiple small-capacity wells. Also, groundwater conservation districts in the area have the goal of limiting drawdown so that at least half the 1998 column of water in the aquifer will remain by 2050.

The model is better calibrated for simulating dewatering conditions than the earlier model (Dutton and others, 2000). Transmissivity decreases as saturated thickness decreases. On the other hand, the hydraulic conductivity tends to be greater in the basal section of the Ogallala than in the upper section, so the effect of decreasing saturated thickness on transmissivity might be partly compensated for by an increase in average hydraulic conductivity.

The withdrawal of groundwater predicted for 2000 to 2050, which is much greater than the recharge rate, results in a further decrease in volume of water in storage in the Ogallala aquifer (table 11). Volume in storage was calculated from simulated saturated thickness, model-cell area, and calibrated specific yield. Volume of water in the aquifer is projected to decrease from approximately 250 to 277 million acre feet in 1998 (table 8) to about 199 million acre feet by 2050 (table 11). Dallam and Moore Counties are forecast to have on average less than half their 1998 volume of water by 2050, given the TAES irrigation projections and the other consensus-based demands. Sherman County is projected to have on average 52 percent of its 1998 water volume. Total volume of water, however, does not by itself completely describe the availability of groundwater in 2050. Some areas within each county are predicted to have less than half the 1998 saturated thickness (table 10), and there may be a marked deficit in groundwater resources in parts of several counties (for example, Dallam and Moore) by 2050 (fig. 25), given the forecast pumping rates and other model assumptions. Also, as only parts of Oldham and Randall Counties were included in the model, table 11 does not fully characterize whether there is a county-wide surplus or deficit in water availability.

As previously stated, irrigation projections by TWDB are somewhat higher than those of the TAES used in this study. Using the TWDB irrigation projections may give a so-called "worst-case" scenario in which less groundwater would remain by 2050, owing to the greater withdrawal rates. In addition, the earlier model (Dutton and others, 2000) may overestimate future drawdown relative to the results of the revised model. According to the earlier model (Dutton and others, 2000), volume of remaining groundwater is projected to decrease to less than 180 million acre feet by 2050 using the TWDB irrigation values (table 12). In addition to Dallam, Moore, and Sherman Counties, Carson County is forecast to have less than half of its 1998 groundwater volume remaining by 2050. The results of the earlier model may be taken as a "worst-case" projection with higher pumping rates and greater simulated drawdown.

DISCUSSION

The most appropriate use of these model predictions is to

- identify areas where apparent supply of groundwater is adequate to meet forecast demand through 2050,
- identify areas in each county where supply of groundwater might not meet projected demand, and
- point out areas where saturated thickness is predicted to be less than 50 feet (the model calibration error), where there may be a need for water-supply alternatives, drought contingency plans, and water-management strategies that might address resource deficits.

The predicted drawdown and decrease in saturated thickness shown in figures 18 to 24 assume no decrease in pumping rate as water levels fall, contrary to regulations of the groundwater conservation districts, except where model cells are simulated to go dry. A water-management goal of the groundwater conservation districts is to limit future drawdown so that at least half of the 1998 saturated section will remain in 2050. The regional model of the Ogallala remains not well calibrated for the extreme event of aquifer dewatering. The model was calibrated for average hydrologic properties, which may differ from properties at the base of the aquifer.

There are various uncertainties associated with predicting exactly where the aquifer might go dry if projected pumping rates are sustained. Accordingly, model predictions can be used to identify areas where there may be surpluses and deficits in water resources, but they should not be used to predict to the nearest square mile where the Ogallala aquifer might go dry.

A variety of water-management plans might be evaluated by using the groundwater flow model. Additional research is needed to reevaluate projected demand for groundwater, assess surpluses and deficits in groundwater resources, and identify water-management alternatives, including various spatial reallocations of water withdrawal. The model also can be used to further research recharge rates and to identify areas where additional data collection would help improve model accuracy.

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Table 1. Tally of water in storage in the Ogallala aquifer in the PWPA estimated using the water-budget method. Numbers determined from calculations in geographic information system (GIS). From Dutton and Reedy (2000).

		Average specific	Volume in storage[3] (million acre-feet)			Average saturated thickness[4] (feet)		
County	Area[1] (1,000 acres)	yield[2] (%)	Predevelopment	1998	Depletion (%)	Predevelopment	1998	Decline (feet)
Armstrong	369	14.1	4.48	3.95	11.2	78	72	6
Carson	605	17	19.17	14.85	22.6	184	146	38
Dallam	951	17.1	26.15	20.26	22.5	158	126	32
Donley	360	16.2	7.21	7.25	-0.6	99	94	5
Gray	570	18	14.85	14.12	4.9	141	133	8
Hansford	576	17.4	28.42	21.17	25.5	282	209	73
Hartley	910	17.9	35.19	28.10	20.1	211	169	42
Hemphill	584	17.2	16.99	16.60	2.3	171	169	2
Hutchinson	456	16.8	15.41	12.09	21.5	197	156	41
Lipscomb	576	14.9	20.02	16.94	15.4	228	195	33
Moore	534	14.7	18.87	13.36	29.2	232	169	63
Ochiltree	580	15.5	22.61	17.60	22.2	247	195	52
Oldham	383	13.7	3.26	2.84	12.9	20	21	-1
Potter	251	14.9	3.11	2.75	11.6	76	75	1
Randall	543	15	6.39	4.88	23.6	86	64	22
Roberts	573	17.7	27.97	26.92	3.8	278	267	11
Sherman	597	17.5	28.73	19.17	33.3	276	186	90
Wheeler	363	17.2	8.28	7.09	14.4	130	106	24
Total*/Average	9,781*	16.3	307.11*	249.94*	16.4	172	142	30

Footnotes:
[1]Aquifer area was determined in GIS from assigning model grid cells within counties.
[2]Specific yield is an average of all cells in a county; the average cannot be used to consistently convert between volume and saturated thickness.
[3]Volume is weighted value determined in GIS by multiplying saturated thickness by specific yield for each cell, multiplying by the 1-square-mile area of each cell, and summing for all cells in each county. Different numbers will be obtained by multiplying average saturated thickness by average specific yield for each county.
[4]Saturated thickness was determined directly in GIS as the difference in elevations of the water table and the base of aquifer.

Table 2. Stratigraphic nomenclature of Permian and younger strata, including the Ogallala Formation, in the study area. Modified from Gustavson and Simpkins (1989).

AGE	GEOLOGIC UNIT	
Quaternary	Blackwater Draw Formation	Tahoka Formation Double Lakes Formation Tule Formation
Tertiary	Blanco Formation	Cita Canyon lake beds
	Ogallala Formation	
Cretaceous	Edwards Group	
Triassic	Dockum Group	
Permian	Ochoan Series Guadalupian Series Leonardian Series	

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Table 3. Weighting factors for recharge rates. Recharge rates were assigned in the model on the basis of long-term average precipitation and locally adjusted on the basis of weighting factors derived from soil textures. Soil data compiled from USDA-NRCS.

Soil group	Soil textures	Area in model (square miles)	Soil permeability (inches per hour)	Weighting factor
1	Loam–Silt loam	6,933	1.0	1.0
2	Loamy sand–Sandy loam	8,280	14.6	1.0
3	Sandy loam–Clayey loam–Silty clay loam	2,255	4.4	1.0
4	Silty clay loam–Silty clay	5,311	0.1	0.67
5	Silt loam–Clayey loam	517	0.5	0.67
6	Clay loam–Clay	341	0.3	0.67
7	Sandy loam–Loam–Clay loam	124	4.4	0.67
8	Sand	957	29.7	2.77

Table 4. River conductance values assigned in the "River" module of MODFLOW. Conductance varies with the tortuosity and length of the river segment in each cell of the model.

	River conductance (square feet per day)		
River	Maximum	Minimum	Average
Cimarron River	8,057	258	5,446
Beaver River	5,351	7	604
Wolf Creek	5,351	33	3,176
Canadian River	3,726	43	2,665
Sweetwater Creek	1,121	41	551

Table 5. Rates of groundwater withdrawal (thousand acre-feet) applied in the model. Note negative signs for well discharge removed for convenience of presentation.

	1950–1959	1950–1969	1970–1979	1980–1989	1990–1999	2000	2001–2010	2011–2021	2021–2030	2031–2040	2041–2050
Irrigation											
Armstrong	79	152	117	81	43	5	46	46	46	46	46
Carson	295	803	1,043	979	744	93	927	927	927	927	927
Dallam	449	1,114	1,860	2,910	3,095	369	3,692	3,692	3,692	3,692	3,692
Donley	23	77	116	158	154	17	170	170	170	170	170
Gray	35	125	151	101	123	22	222	222	222	222	222
Hansford	231	1,202	1,924	1,423	1,217	121	1,215	1,215	1,215	1,215	1,215
Hartley	152	873	1,977	2,278	1,703	186	1,862	1,862	1,862	1,862	1,862
Hemphill	1	5	6	2	18	4	44	44	44	44	44
Hutchinson	174	490	707	622	324	42	417	417	417	417	417
Lipscomb	14	42	124	170	222	35	351	351	351	351	351
Moore	402	1,447	2,237	2,140	1,665	183	1,831	1,831	1,831	1,831	1,831
Ochiltree	91	524	993	843	440	47	473	473	473	473	473
Oldham	0	0	0	0	0	0	0	0	0	0	0
Potter	31	60	62	37	60	15	149	149	149	149	149
Randall	110	184	142	97	76	12	116	116	116	116	116
Roberts	17	57	73	50	46	6	58	58	58	58	58
Sherman	395	2,095	3,419	2,829	1,881	195	1,952	1,952	1,952	1,952	1,952
Wheeler	9	22	35	24	22	3	34	34	34	34	34
Municipal and Public Water Supply											
Armstrong	0	1	1	2	2	0	2	2	2	2	2
Carson	6	10	17	22	84	23	233	246	261	279	300
Dallam	23	7	9	10	9	1	11	11	11	10	10
Donley	4	4	4	4	2	0	0	0	0	0	0
Gray	31	39	19	24	34	3	29	29	26	24	23
Hansford	6	12	13	14	12	1	14	14	14	13	13
Hartley	1	1	2	3	4	1	12	13	12	12	12
Hemphill	2	3	10	12	7	1	8	8	8	8	7
Hutchinson	23	29	28	33	30	3	25	24	23	22	21
Lipscomb	3	4	6	8	8	1	8	8	8	8	7
Moore	15	21	34	54	58	4	44	47	50	53	57
Ochiltree	10	13	13	20	21	3	27	27	27	26	25
Oldham	0	0	0	0	0	0	0	0	0	0	0
Potter	0	0	1	4	6	1	10	10	10	11	11
Randall	55	81	43	75	76	3	28	31	33	37	41
Roberts	1	1	2	2	2	0	467	657	757	802	802
Sherman	3	3	6	7	7	1	7	7	7	6	6
Wheeler	12	11	11	11	8	1	8	8	8	7	7
Industrial and Manufacturing											
Armstrong	0	0	0	0	0	0	0	0	0	0	0
Carson	68	103	88	63	26	6	65	71	76	83	92
Dallam	0	0	2	0	0	0	2	2	2	2	2
Donley	18	50	52	32	37	4	40	42	43	45	48
Gray	3	7	11	0	0	0	0	1	1	1	1
Hansford	0	0	0	0	0	0	0	0	0	0	0
Hartley	0	0	5	0	0	0	0	0	0	0	0
Hemphill	0	0	0	1	0	0	0	0	0	0	0
Hutchinson	113	199	144	160	149	15	155	167	177	190	207
Lipscomb	0	0	0	0	0	0	2	2	2	2	2
Moore	65	147	126	57	43	7	75	79	82	86	92
Ochiltree	0	0	0	0	0	0	0	0	0	0	0
Oldham	0	0	0	0	0	0	0	0	0	0	0
Potter	8	16	18	5	0	0	0	0	0	0	0
Randall	0	0	0	0	0	0	1	1	1	1	1
Roberts	0	0	0	0	0	0	0	0	0	0	0
Sherman	0	0	0	0	0	0	0	0	0	0	0
Wheeler	1	2	2	0	0	0	0	0	0	0	0
Power Generation											
Potter	0	1	2	14	12	1	11	11	11	11	11

Table 5 (cont.)

	1950–1959	1950–1969	1970–1979	1980–1989	1990–1999	2000	2001–2010	2011–2021	2021–2030	2031–2040	2041–2050
Domestic and Stock											
Armstrong	1	1	2	4	5	0	5	5	6	6	7
Carson	2	2	2	9	13	1	11	12	13	13	14
Dallam	2	3	4	16	31	7	89	114	129	146	165
Donley	1	2	1	0	1	1	6	7	7	7	8
Gray	2	3	4	4	5	2	22	26	29	32	35
Hansford	1	4	6	26	26	5	73	96	108	120	134
Hartley	1	1	4	17	20	3	30	33	36	38	41
Hemphill	1	2	3	3	9	1	15	16	18	19	21
Hutchinson	1	2	2	1	1	0	5	5	6	6	7
Lipscomb	0	0	1	1	3	1	18	25	28	32	37
Moore	2	3	6	26	38	4	55	77	86	97	108
Ochiltree	2	3	4	10	12	7	70	78	88	100	113
Oldham	0	0	0	0	0	0	1	1	1	1	1
Potter	2	3	3	1	1	0	3	3	3	3	4
Randall	0	1	1	4	6	1	6	6	7	8	8
Roberts	0	1	1	1	1	1	6	6	6	7	8
Sherman	1	2	4	22	29	4	48	60	66	74	82
Wheeler	1	2	1	2	3	1	10	11	12	12	13

Table 6. Summary of groundwater discharge (cubic feet per second) to major rivers included in the model. Note that discharge from the aquifer to rivers is represented here as a positive value.

	Steady state	1960	1970	1980	1990	2000	2010	2020	2030	2040	2050
Cimarron River	52	50	45	38	31	25	19	13	8	5	1
Beaver River	94	93	91	87	83	78	73	68	63	59	54
Wolf Creek	59	58	56	52	47	40	33	27	22	18	14
Canadian River	66	66	65	65	64	63	62	61	59	57	55
Sweetwater Creek	13	13	13	13	13	13	13	13	13	13	12

Table 7. Average simulated saturated thickness (feet) in the modeled part of the Ogallala aquifer.

County	1950	1998	2000	2010	2020	2030	2040	2050
Armstrong	93	86	85	84	83	82	80	79
Carson	217	176	174	159	145	130	116	102
Dallam	215	163	158	137	118	104	92	81
Donley	76	69	69	67	65	63	62	61
Gray	155	146	145	141	136	131	127	122
Hansford	279	222	219	206	192	178	164	150
Hartley	275	234	232	220	209	198	186	176
Hemphill	208	207	207	206	205	204	203	202
Hutchinson	146	108	106	97	87	79	71	65
Lipscomb	199	193	193	189	186	183	180	177
Moore	249	157	153	130	107	84	65	49
Ochiltree	238	210	209	203	197	190	184	177
Oldham*	80	80	80	80	79	79	79	78
Potter	93	82	80	76	73	71	69	67
Randall*	121	94	94	90	88	86	84	81
Roberts	258	254	254	246	235	227	222	218
Sherman	303	208	204	186	167	147	128	109
Wheeler	177	175	175	174	173	172	171	170

*Includes only that part of county in model area (fig. 2).

Table 8. Comparison of estimated and simulated volumes of water in storage for 1950 and 1998.

				1950			1998		
County	County Area (mi^2)	County area in model (mi^2)	Aquifer area in model (mi^2)	Estimated volume (maf)	Simulated volume (maf)	Difference (%)	Estimated volume (maf)	Simulated volume (maf)	Difference (%)
Armstrong	915	927	513	4.48	4.60	-0.4	3.95	4.20	-2.0
Carson	922	930	915	19.17	21.70	5.0	14.85	17.66	4.8
Dallam	1,505	1,509	1,494	26.15	36.28	-5.0	20.26	27.04	10.4
Donley	936	930	539	7.21	4.42	3.9	7.25	4.01	11.4
Gray	929	939	893	14.85	28.06	-5.4	14.12	22.29	-3.9
Hansford	921	900	897	28.42	28.82	-5.8	21.17	24.41	-13.2
Hartley	1,463	1,470	1,411	35.19	45.33	10.3	28.10	38.39	13.3
Hemphill	912	923	910	16.99	20.47	-10.4	16.60	20.40	-12.6
Hutchinson	895	900	665	15.41	11.02	-14.1	12.09	8.04	-20.5
Lipscomb	933	927	927	20.02	17.80	-3.9	16.94	17.33	-19.8
Moore	909	930	852	18.87	20.84	-8.4	13.36	13.01	4.7
Ochiltree	919	900	897	22.61	21.47	-8.5	17.60	18.85	-24.4
Oldham	1,508	1,486	80	3.26	0.44	na	2.84	0.44	na
Potter	922	954	374	3.11	3.33	-19.0	2.75	2.92	-17.1
Randall	922	907	195	6.39	2.37	na	4.88	1.82	na
Roberts	924	904	899	27.97	25.62	-9.9	26.92	25.21	-12.5
Sherman	923	913	913	28.73	30.88	0.2	19.17	21.18	3.2
Wheeler	916	900	520	8.28	9.92	7.6	7.09	9.81	-5.9
Total	18,274	18,249	13,894	307.11	333.37	-4.0	249.94	277.00	-5.3**

maf Million acre feet
na Not applicable calculation
* Includes only that part of county in model area (fig. 2)
** Average of differences

Table 9. Percentage of county having saturated thickness of 50 feet or less in the modeled part of the Ogallala aquifer.

County	1950	1998	2000	2010	2020	2030	2040	2050
Armstrong	19.1	21.2	21.2	21.4	22.0	22.4	23.4	23.8
Carson	2.3	3.0	3.0	3.5	4.3	6.3	9.8	14.6
Dallam	4.3	9.8	10.8	20.7	32.4	37.3	42.6	49.2
Donley	53.8	63.6	63.8	65.1	66.8	66.6	67.2	67.2
Gray	10.8	11.9	11.9	12.2	12.8	13.7	14.2	15.3
Hansford	0.1	0.6	0.7	1.1	1.8	2.8	5.1	7.1
Hartley	4.3	4.6	4.6	4.8	5.7	6.4	6.7	9.4
Hemphill	3.0	3.0	3.0	3.0	3.2	3.2	3.2	3.5
Hutchinson	15.3	23.9	24.1	29.3	33.5	38.0	43.9	47.4
Lipscomb	0.3	0.3	0.3	0.3	0.3	0.4	0.5	0.6
Moore	11.4	13.6	14.2	16.8	24.1	36.9	50.8	60.8
Ochiltree	1.3	1.9	1.9	2.3	2.9	3.2	4.0	5.0
Oldham*	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5
Potter	35.0	39.8	41.2	44.4	45.7	46.8	47.9	48.4
Randall*	7.7	12.8	13.8	17.9	19.5	19.5	23.1	24.6
Roberts	0.3	0.3	0.3	0.3	0.7	1.4	1.8	1.8
Sherman	0.0	0.0	0.0	0.0	0.5	1.3	5.4	12.4
Wheeler	21.0	21.2	21.2	21.3	21.5	21.9	22.5	22.7

*Includes only that part of county in model area (fig. 2).

Table 10. Percentage of aquifer in modeled part of county having less than 50 percent of 1998 saturated thickness.

County	2000	2010	2020	2030	2040	2050
Armstrong	0.0	0.0	0.0	0.2	0.2	0.8
Carson	0.0	0.0	1.2	6.7	15.8	31.7
Dallam	0.2	10.2	24.2	33.5	44.4	51.7
Donley	0.0	0.6	3.2	4.8	5.9	7.1
Gray	0.0	0.1	0.4	0.8	1.9	2.8
Hansford	0.0	0.0	0.4	2.1	6.7	15.6
Hartley	0.0	0.0	1.4	3.4	11.3	19.7
Hemphill	0.0	0.0	0.0	0.0	0.0	0.0
Hutchinson	0.2	3.3	9.5	17.1	23.2	30.7
Lipscomb	0.0	0.0	0.0	0.0	0.0	0.0
Moore	0.0	1.4	13.7	37.6	55.3	68.3
Ochiltree	0.0	0.1	0.2	0.3	0.3	0.7
Oldham*	0.0	0.0	0.0	0.0	0.0	0.0
Potter	0.8	4.3	5.6	6.4	6.4	7.2
Randall*	0.0	1.5	2.6	3.1	4.6	5.6
Roberts	0.0	0.0	1.4	2.2	2.8	3.2
Sherman	0.0	0.0	0.5	4.9	20.6	43.4
Wheeler	0.0	0.2	0.2	0.2	0.2	0.2

*Includes only that part of county in model area (fig. 2).

Table 11. Volume of water in storage (million acre feet) projected for 2000 to 2050 in the Ogallala aquifer using TAES irrigation estimates. Projections should not be relied upon for anything other than their intended use in identifying areas with surpluses and deficits between supply and demand for groundwater in the PWPA, as discussed in the text.

County	2000	2010	2020	2030	2040	2050	1998 volume remaining in 2050 (%)
Armstrong	4.19	4.13	4.07	4.01	3.95	3.89	93
Carson	17.40	15.99	14.56	13.12	11.71	10.31	58
Dallam	26.33	22.65	19.25	16.76	14.69	12.81	47
Donley	3.98	3.87	3.76	3.68	3.60	3.55	89
Gray	22.03	20.70	19.31	17.91	16.51	15.11	68
Hansford	24.17	22.93	21.71	20.49	19.29	18.13	74
Hartley	38.02	36.08	34.15	32.23	30.35	28.52	74
Hemphill	20.38	20.29	20.18	20.07	19.96	19.85	97
Hutchinson	7.90	7.19	6.50	5.86	5.30	4.80	60
Lipscomb	17.27	16.96	16.66	16.37	16.09	15.83	91
Moore	12.65	10.73	8.79	6.90	5.23	3.94	30
Ochiltree	18.74	18.18	17.61	17.02	16.42	15.80	84
Oldham*	0.44	0.44	0.43	0.43	0.43	0.43	98
Potter	2.86	2.71	2.61	2.53	2.46	2.39	82
Randall*	1.80	1.74	1.69	1.65	1.61	1.56	86
Roberts	25.18	24.43	23.39	22.62	22.14	21.70	86
Sherman	20.83	18.94	16.96	14.97	13.00	11.06	52
Wheeler	9.80	9.75	9.70	9.65	9.60	9.55	97
Total	273.99	257.70	241.33	226.27	212.32	199.21	72

*Includes only that part of county in model area (fig. 2)

Table 12. Volume of water in storage (million acre feet) projected for 2000 to 2050 in the Ogallala aquifer using TWDB irrigation estimates and the specified-transmissivity model (Dutton and others, 2000). Projections should not be relied upon for anything other than their intended use in identifying areas with surpluses and deficits between supply and demand for groundwater in the PWPA, as discussed in the text. Volume projections on the basis of TWDB irrigation estimates may provide a "worst-case" scenario as TWDB rates generally are greater than TAES rates (see table 11) and the specified-transmissivity model predicts greater drawdown than the calculated-transmissivity model.

County	2000	2010	2020	2030	2040	2050	2000 volume remaining in 2050
Armstrong	4.01	3.92	3.82	3.72	3.60	3.47	86.5
Carson	13.87	12.42	10.95	9.49	8.08	6.71	48.4
Dallam	17.44	13.72	10.41	7.90	6.01	4.57	26.2
Donley	6.39	6.23	6.06	5.90	5.75	5.60	87.6
Gray	14.59	14.13	13.61	13.04	12.44	11.81	80.9
Hansford	23.71	22.32	20.90	19.48	18.03	16.58	69.9
Hartley	23.97	21.89	19.89	18.22	16.72	15.38	64.2
Hemphill	18.67	18.58	18.48	18.36	18.23	18.09	96.9
Hutchinson	14.43	13.65	12.84	12.01	11.14	10.23	70.9
Lipscomb	20.23	19.88	19.54	19.20	18.87	18.53	91.6
Moore	12.37	10.53	8.71	7.05	5.50	4.10	33.2
Ochiltree	21.78	21.21	20.64	20.05	19.46	18.85	86.5
Oldham*	0.73	0.71	0.69	0.67	0.64	0.62	84.6
Potter	3.15	2.82	2.58	2.35	2.15	1.96	62.1
Randall*	1.84	1.78	1.72	1.66	1.60	1.53	83.1
Roberts	30.24	29.47	28.41	27.27	26.11	25.03	82.7
Sherman	18.17	16.17	14.14	12.14	10.20	8.32	45.8
Wheeler	7.50	7.44	7.38	7.32	7.27	7.21	96.2
Total	253.10	236.86	220.78	205.83	191.79	178.59	70.6

*Includes only that part of county in model area (fig. 2)

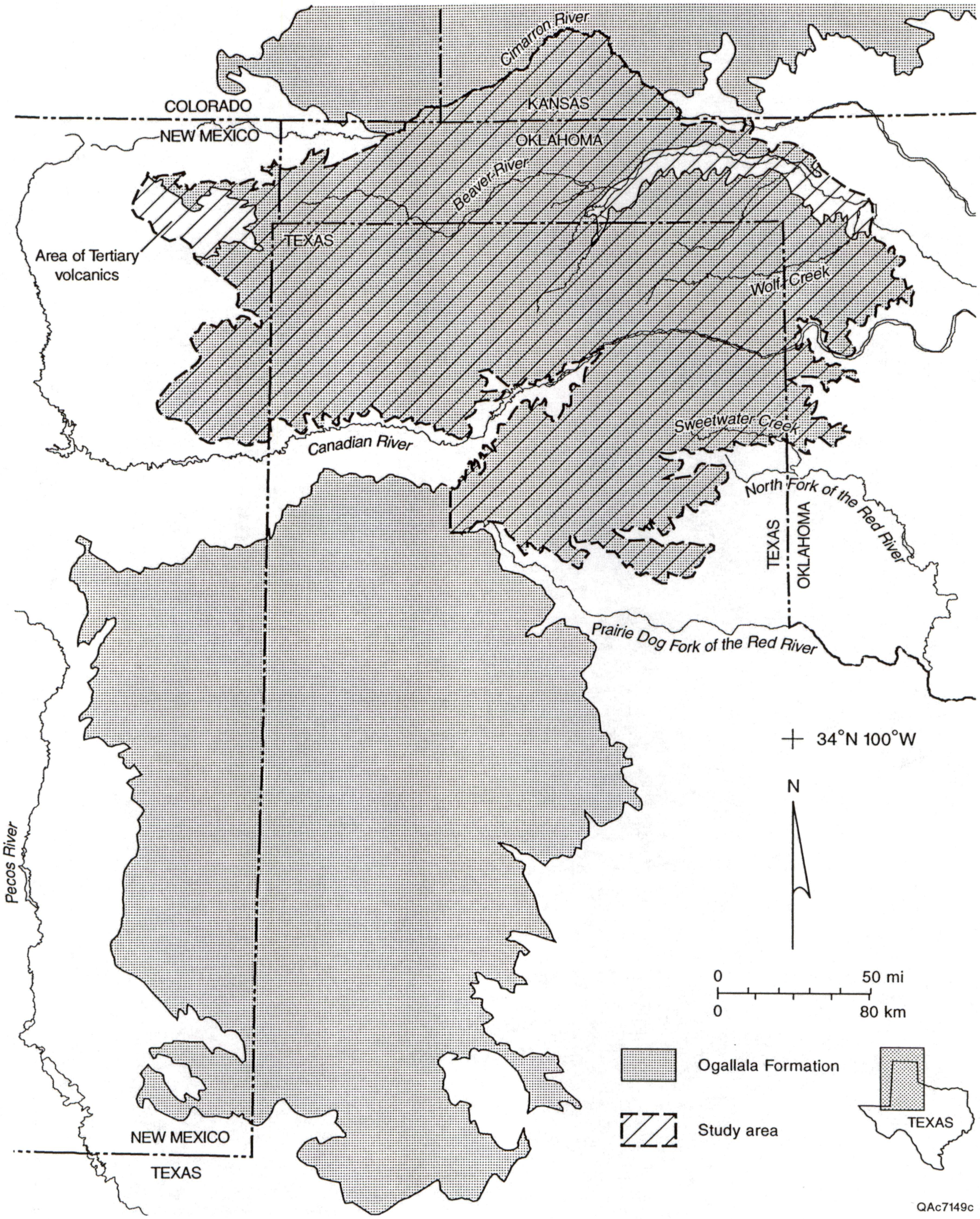

Figure 1. Location of the study area in the northern Texas Panhandle and parts of northwestern New Mexico, western Oklahoma, and southwestern Kansas. The study area was extended beyond Texas to provide natural hydrologic boundaries for a numerical model away from the area of interest. Modified from U.S. Geological Survey (1998).

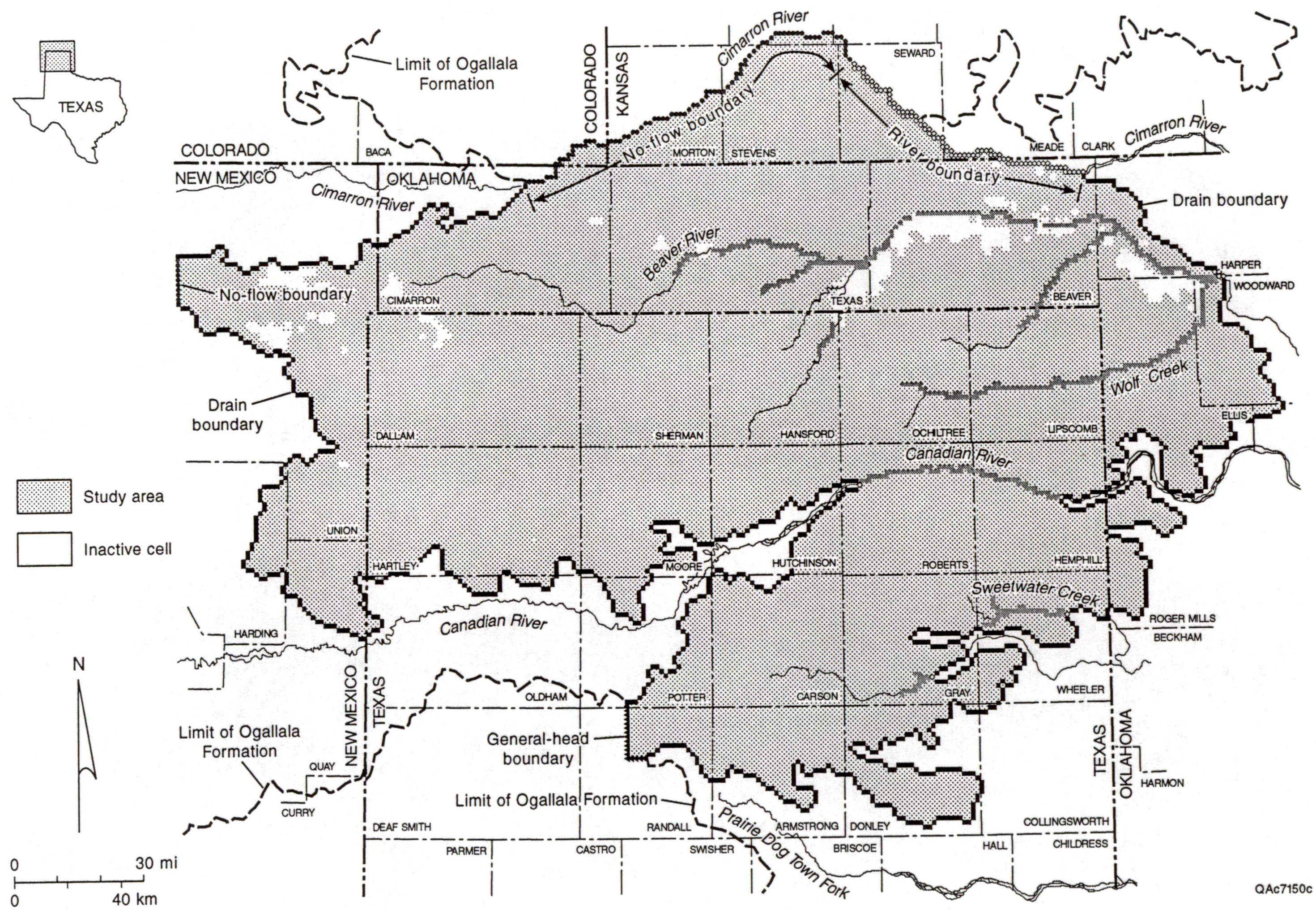

Figure 2. Map of modeled area and selection of boundary conditions.

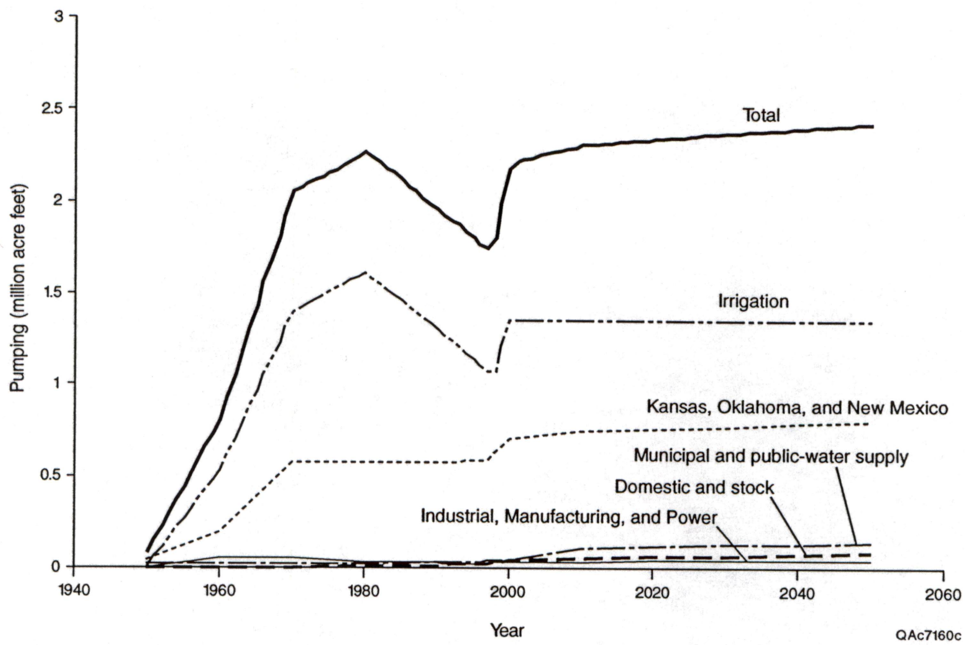

Figure 3. Change in total annual rate of groundwater withdrawal for irrigation, municipal, and other uses in Texas. Withdrawal rates for other states from Luckey and Becker (1999) as described in the text.

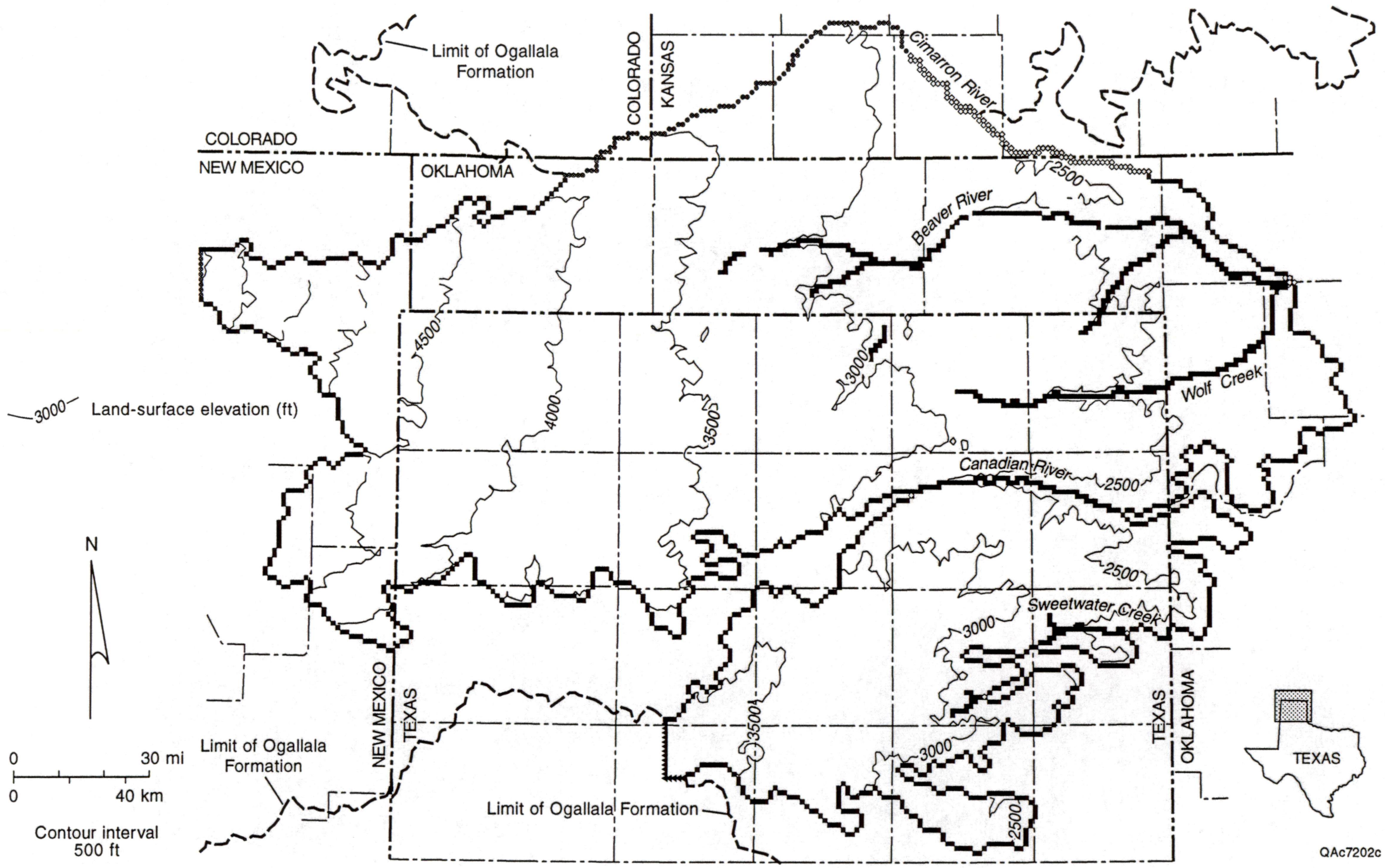

Figure 4. Ground-surface elevation across the study area.

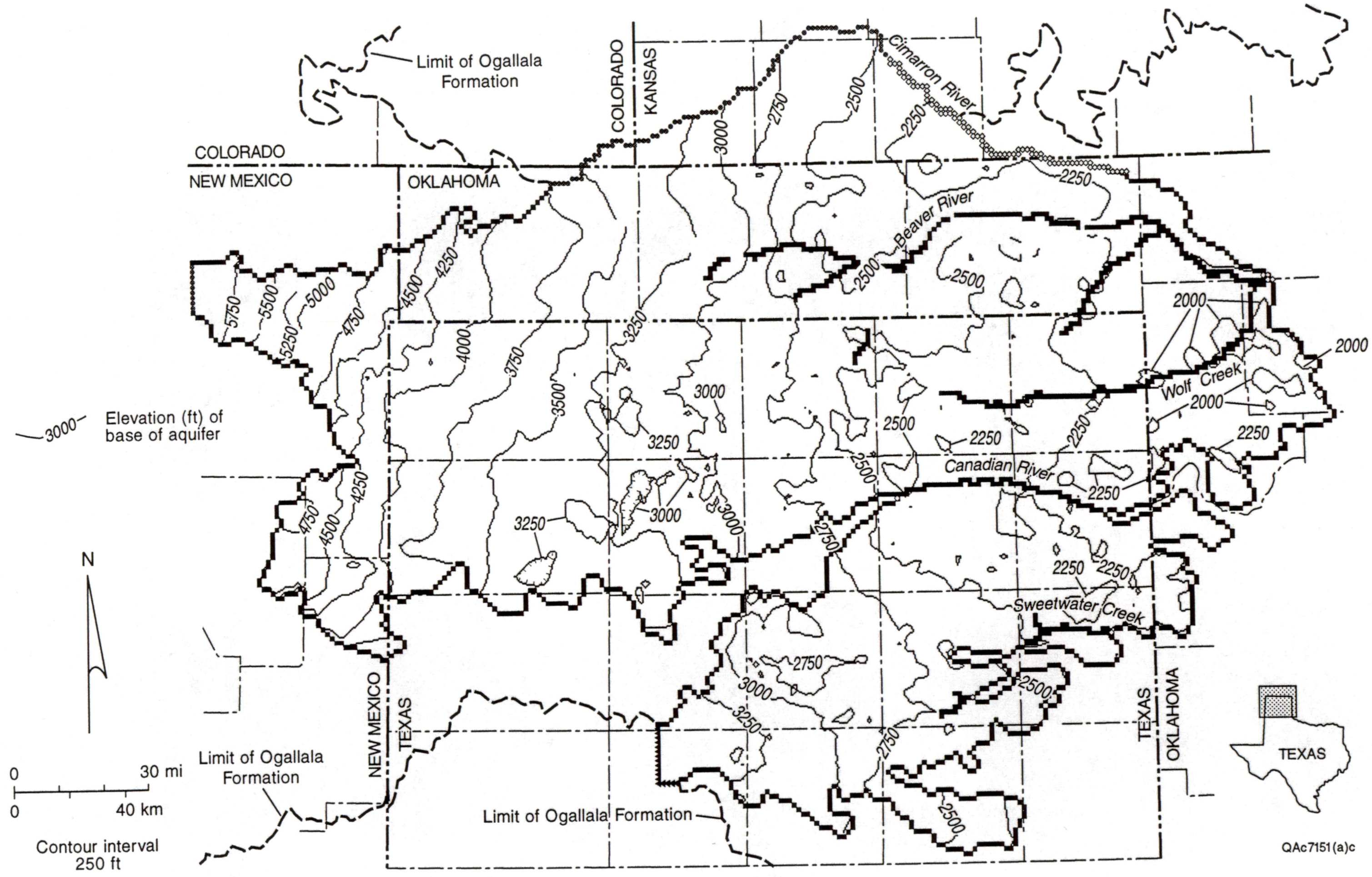

Figure 5. Structural elevation of the base of the Ogallala Formation as used in the numerical model. Sources of data and contouring method described in text.

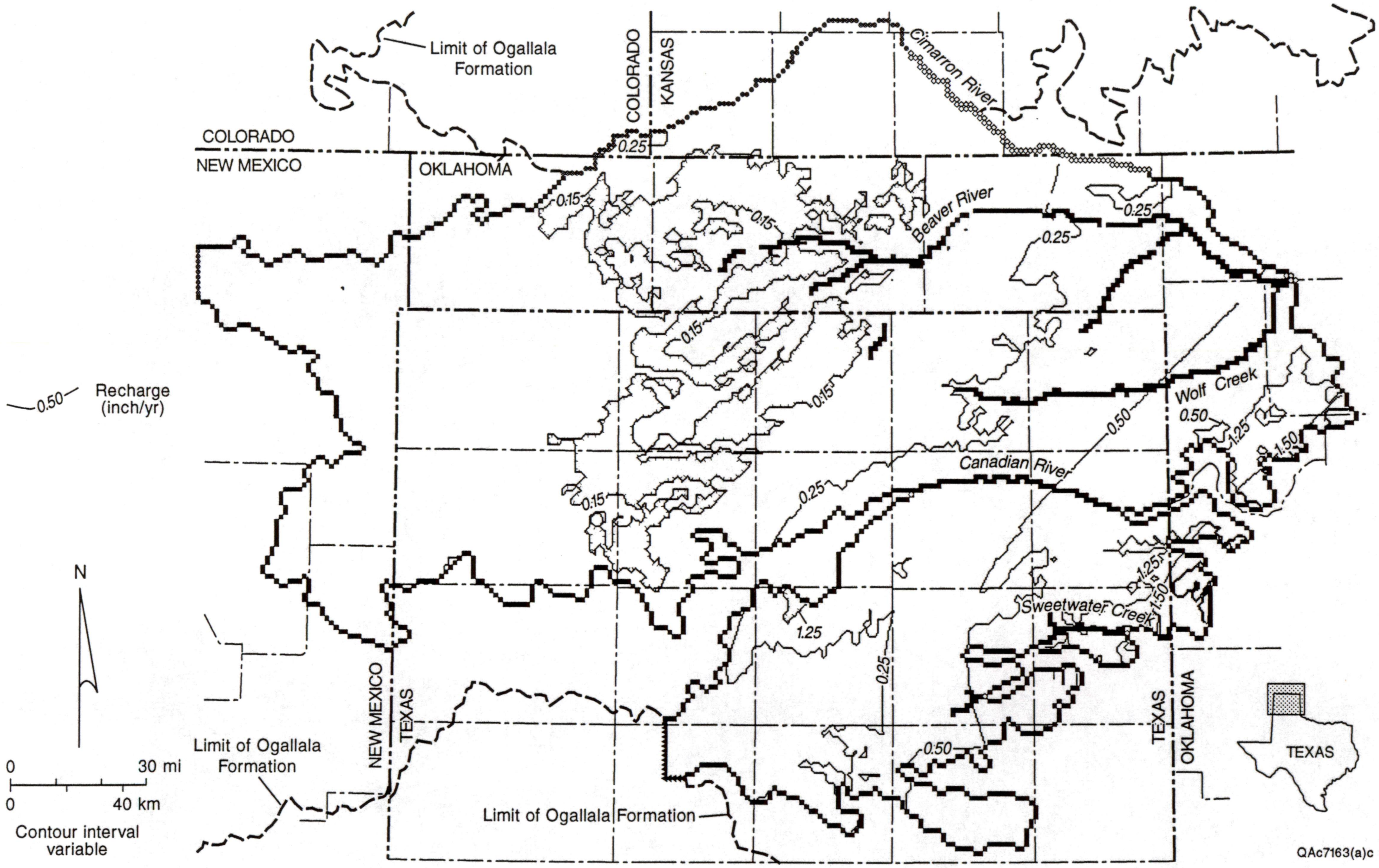

Figure 6. Recharge used in the numerical model assigned on the basis of precipitation and soil texture. See table 3 for description of soil groups.

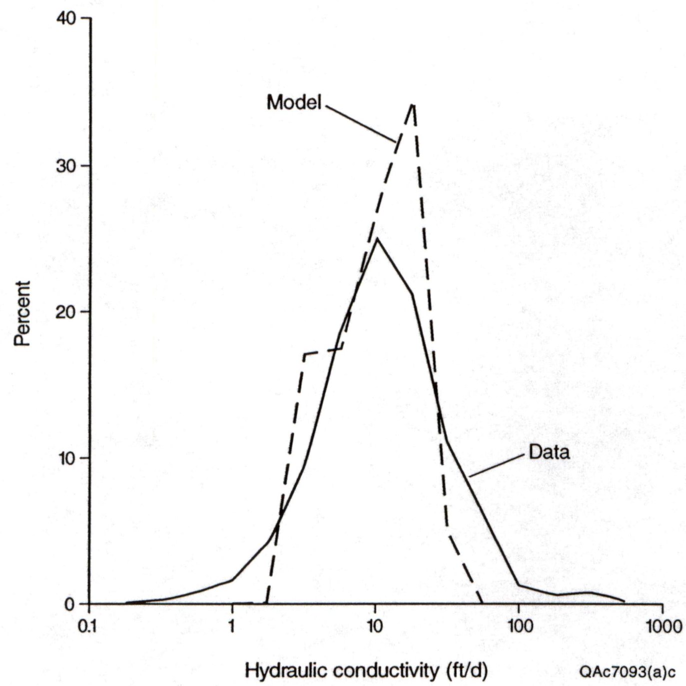

Figure 7. Comparison of measured and calibrated values of hydraulic conductivity used in the Texas part of the model.

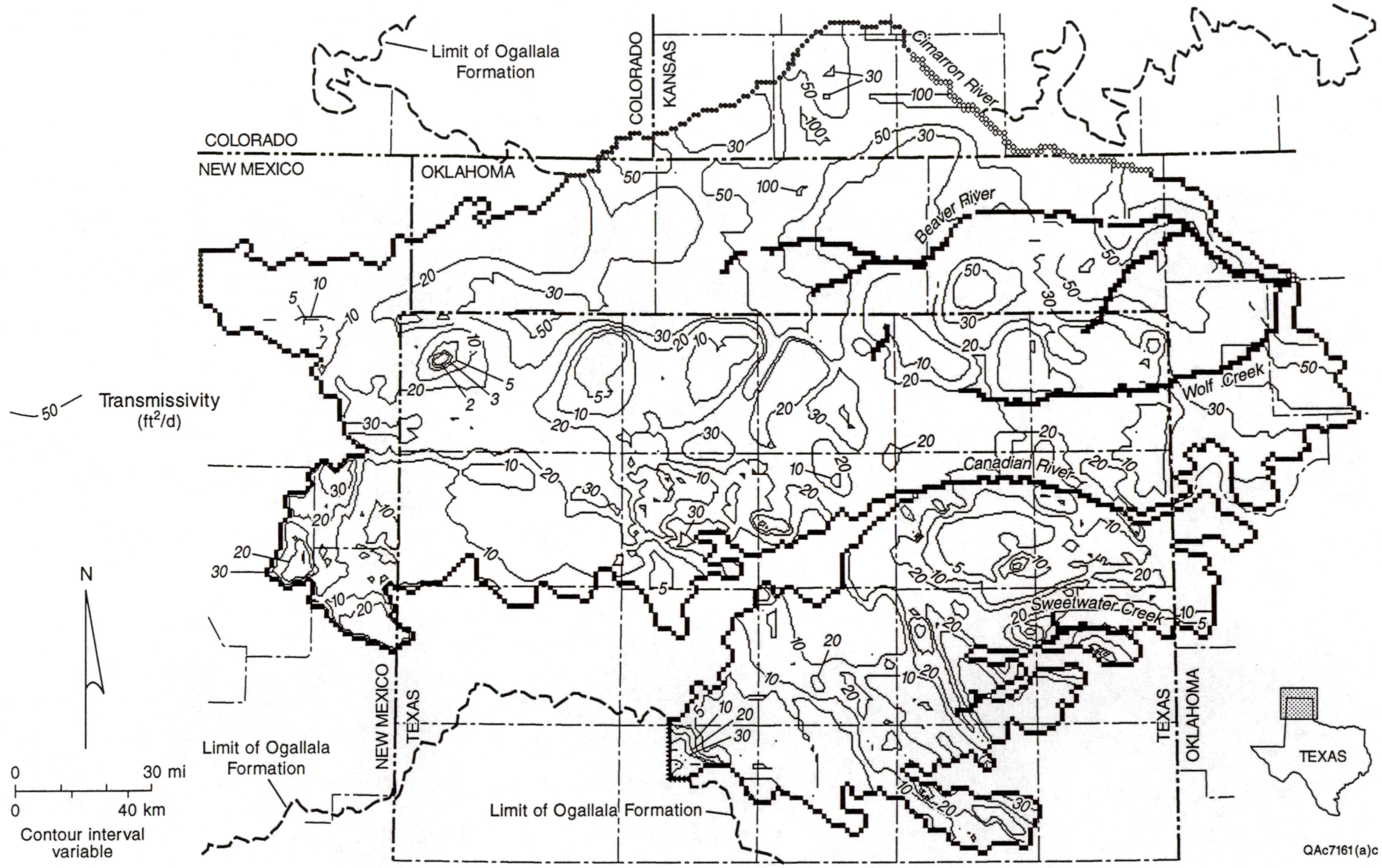

Figure 8. Hydraulic conductivity of the Ogallala aquifer used for historical and predictive simulations. Data, mapping, and calibration procedure described in text.

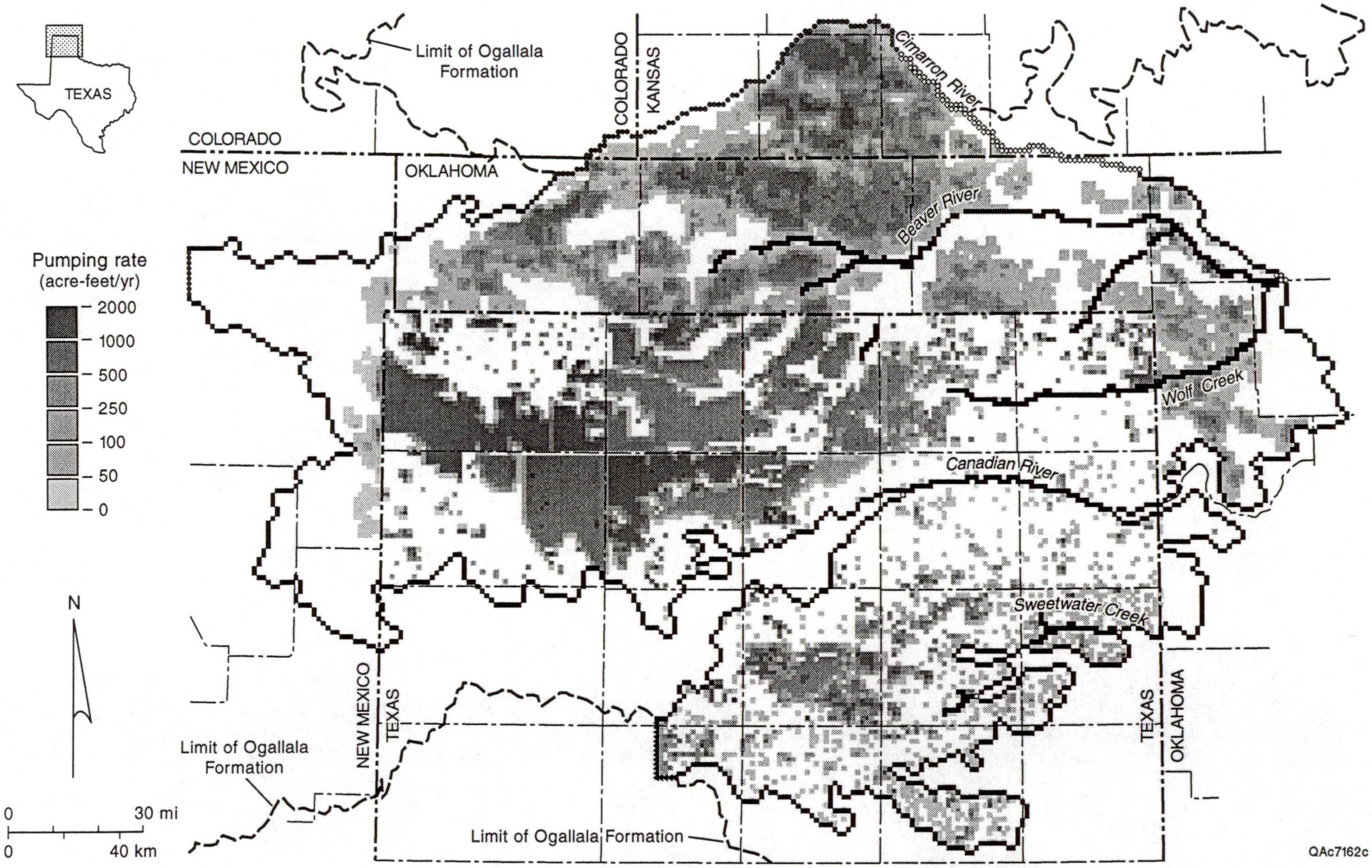

Figure 9. Pumping rates assigned to cells in the model. During 1950 to 1998, irrigation made up 57 to 96 percent of the total ground-water demand in various counties. Irrigation distribution was based on digital (GIS) results of a 1994 survey provided by TNRIS.

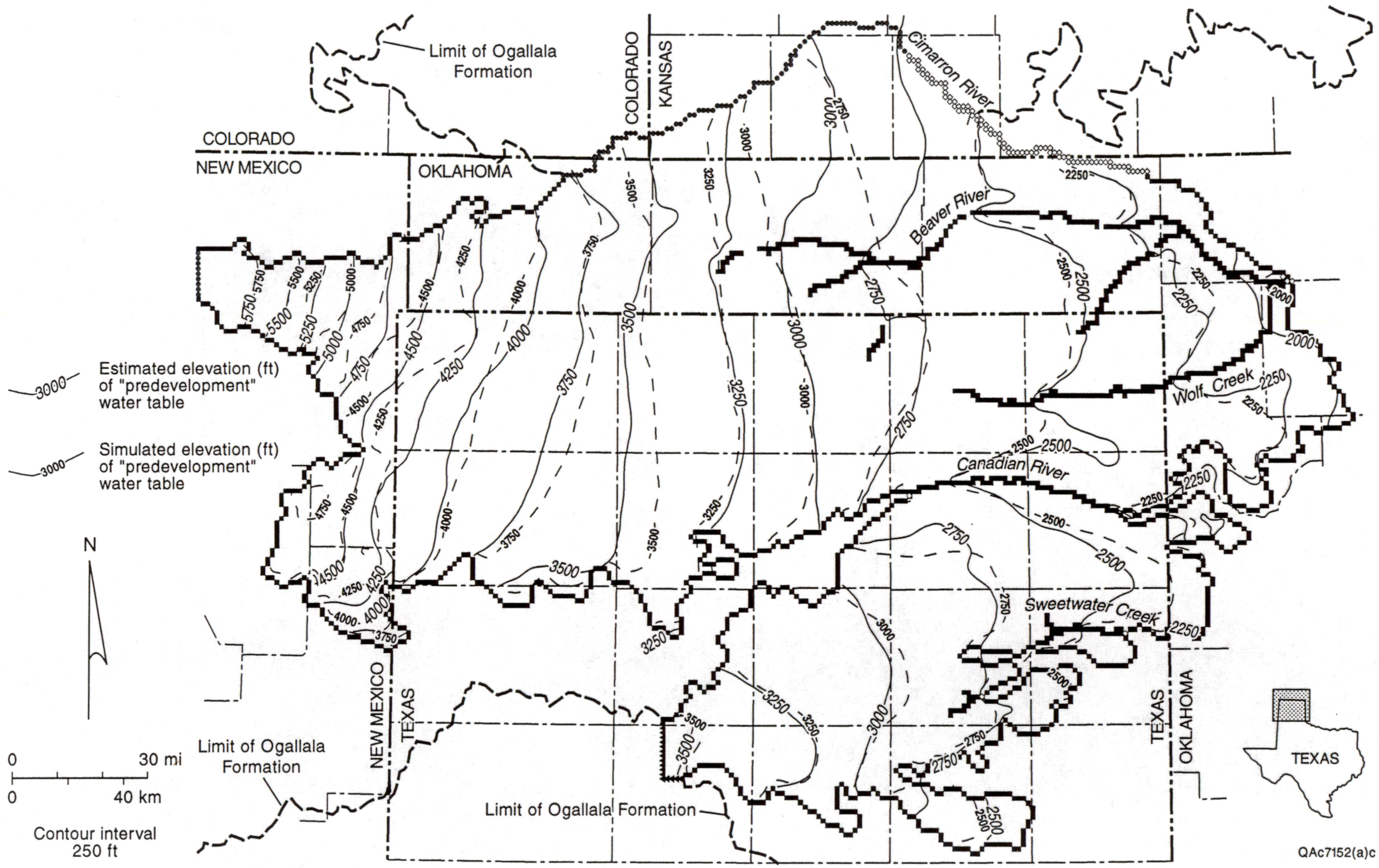

Figure 10. Comparison of estimated and simulated elevations of “predevelopment” water table.

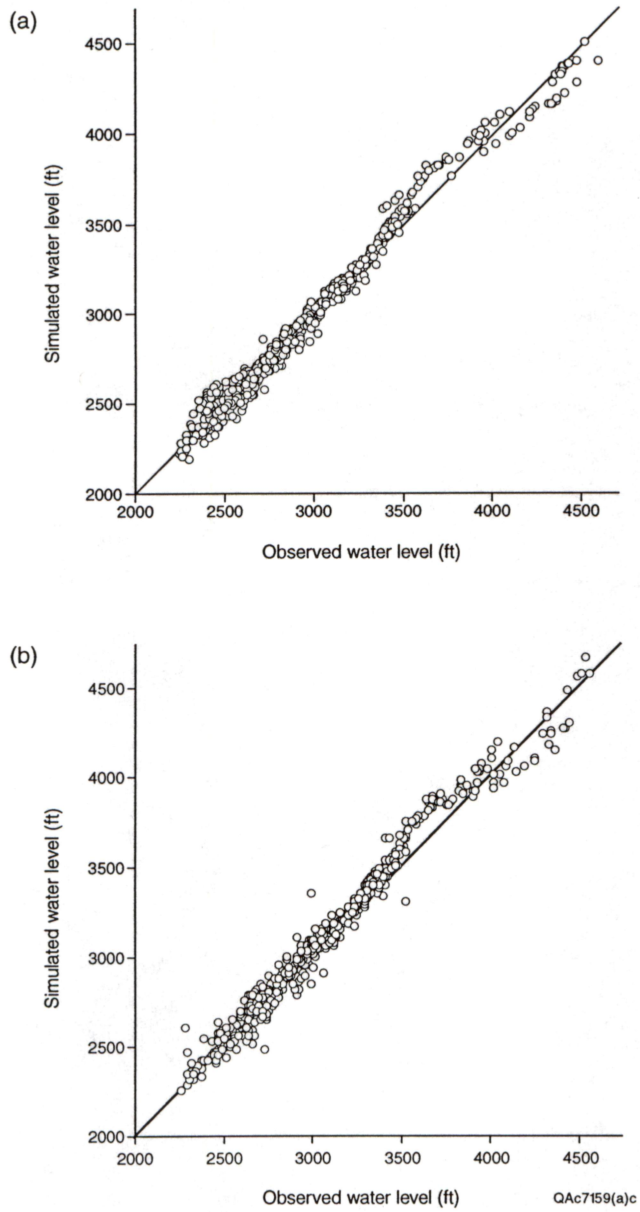

Figure 11. Calibration results for (a) "predevelopment," or 1950, water table and (b) 1998 water table. The calibration (mean-square) error for the "predevelopment" water table was 64 feet and for the 1998 water table was 74 feet.

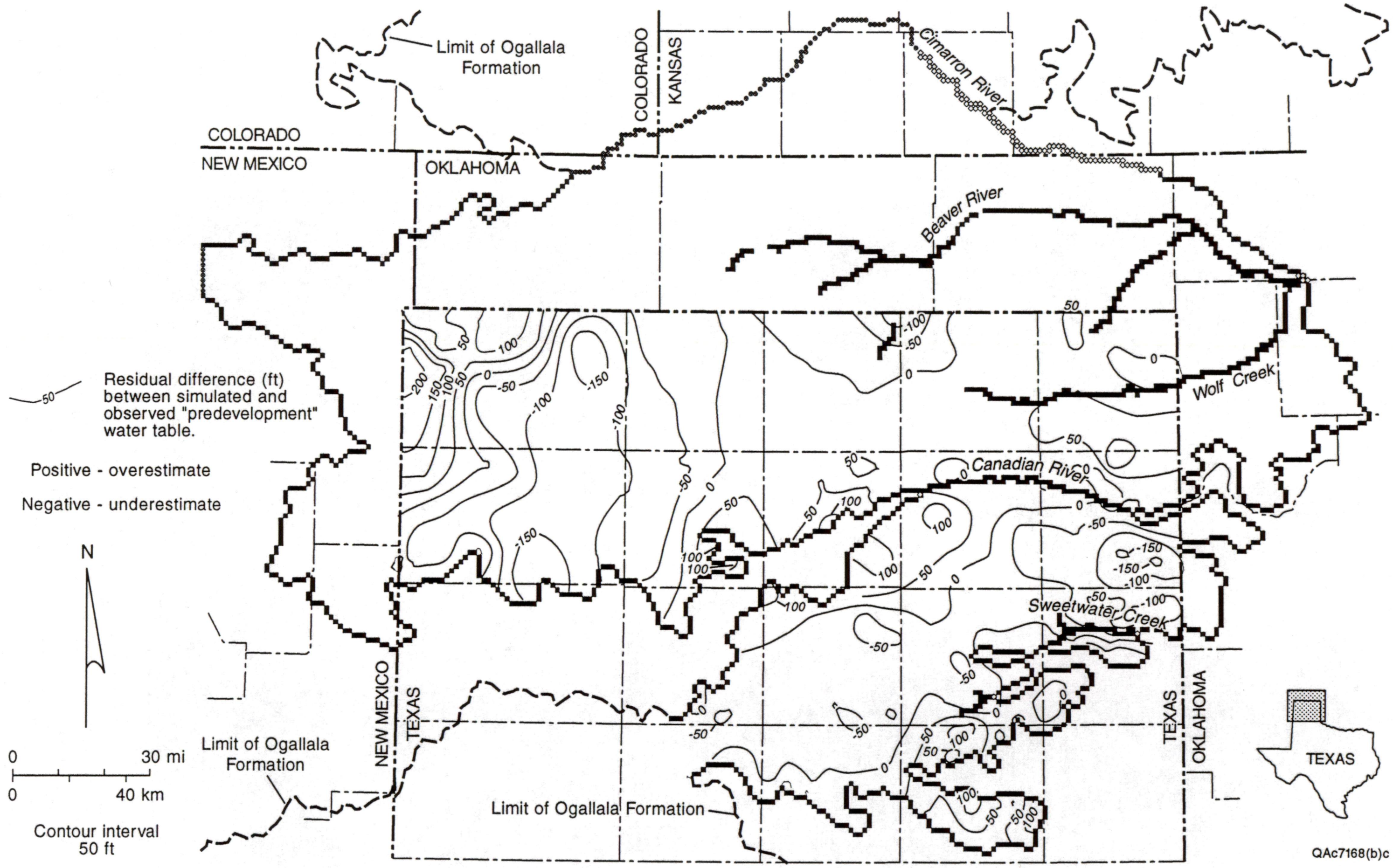

Figure 12. Residual between estimated and simulated elevations of "predevelopment" water table.

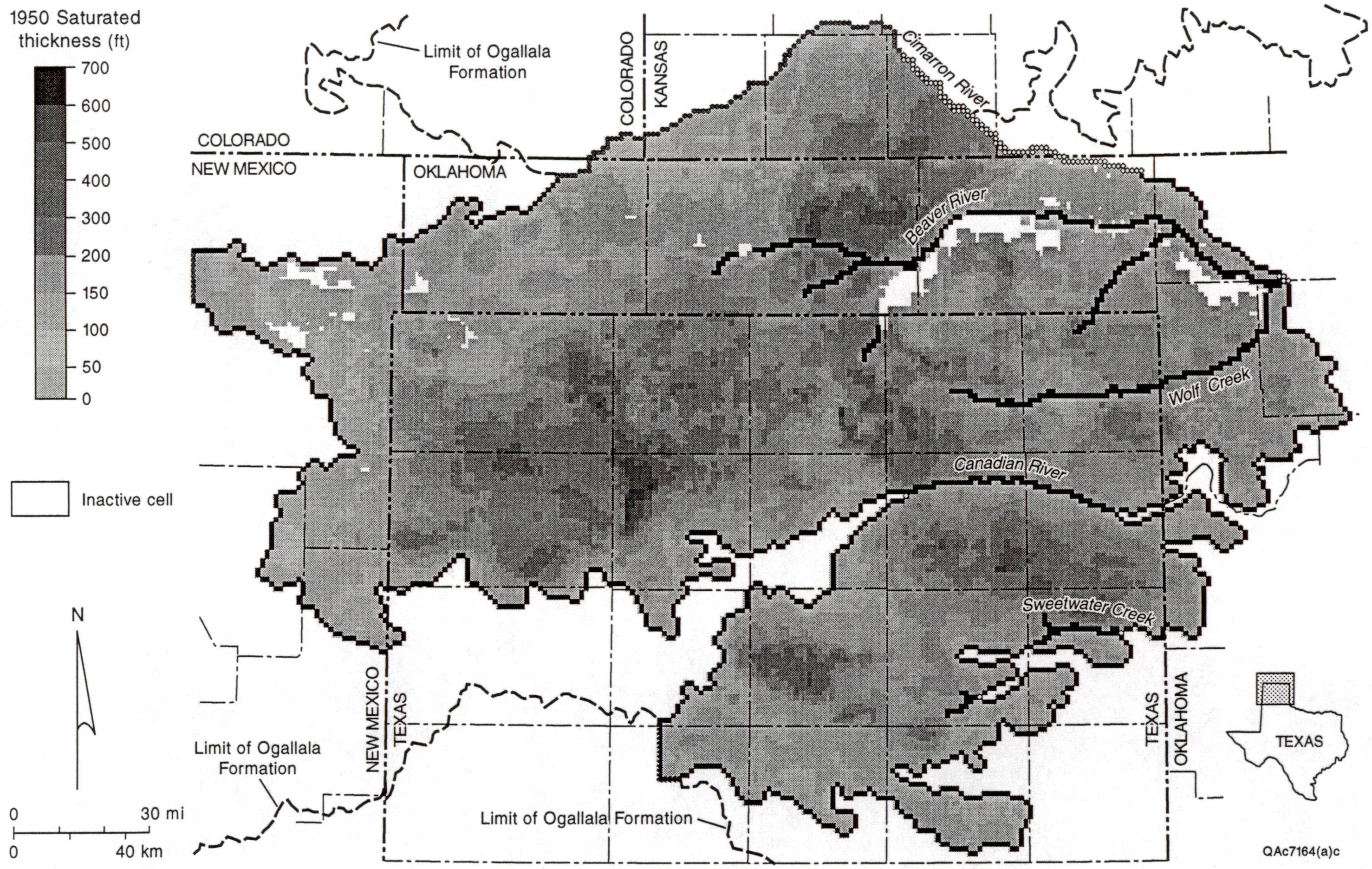

Figure 13. Simulated saturated thickness of the Ogallala aquifer under "predevelopment," or 1950, water-table conditions.

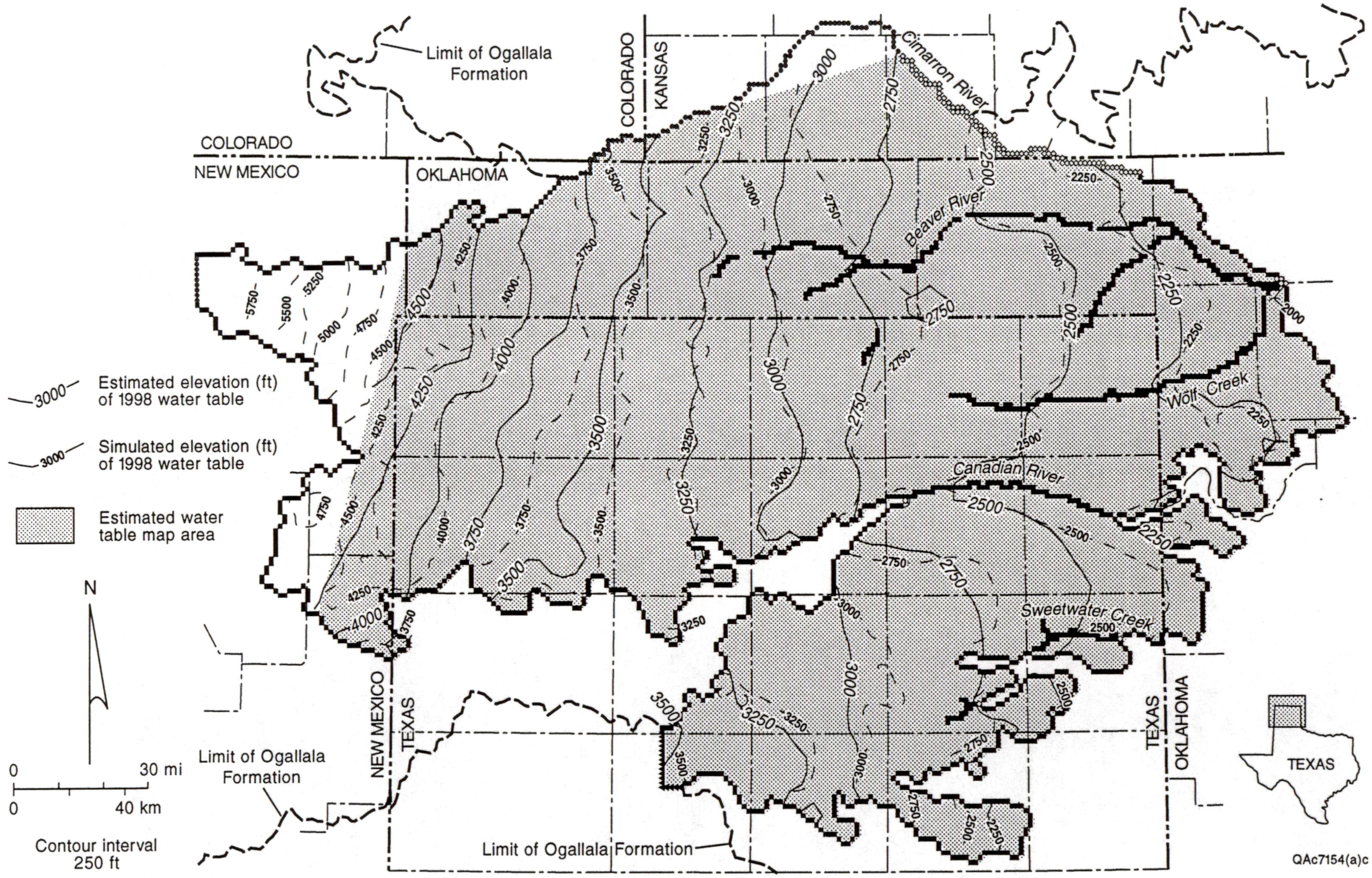

Figure 14. Comparison of estimated and simulated elevations of 1998 water table.

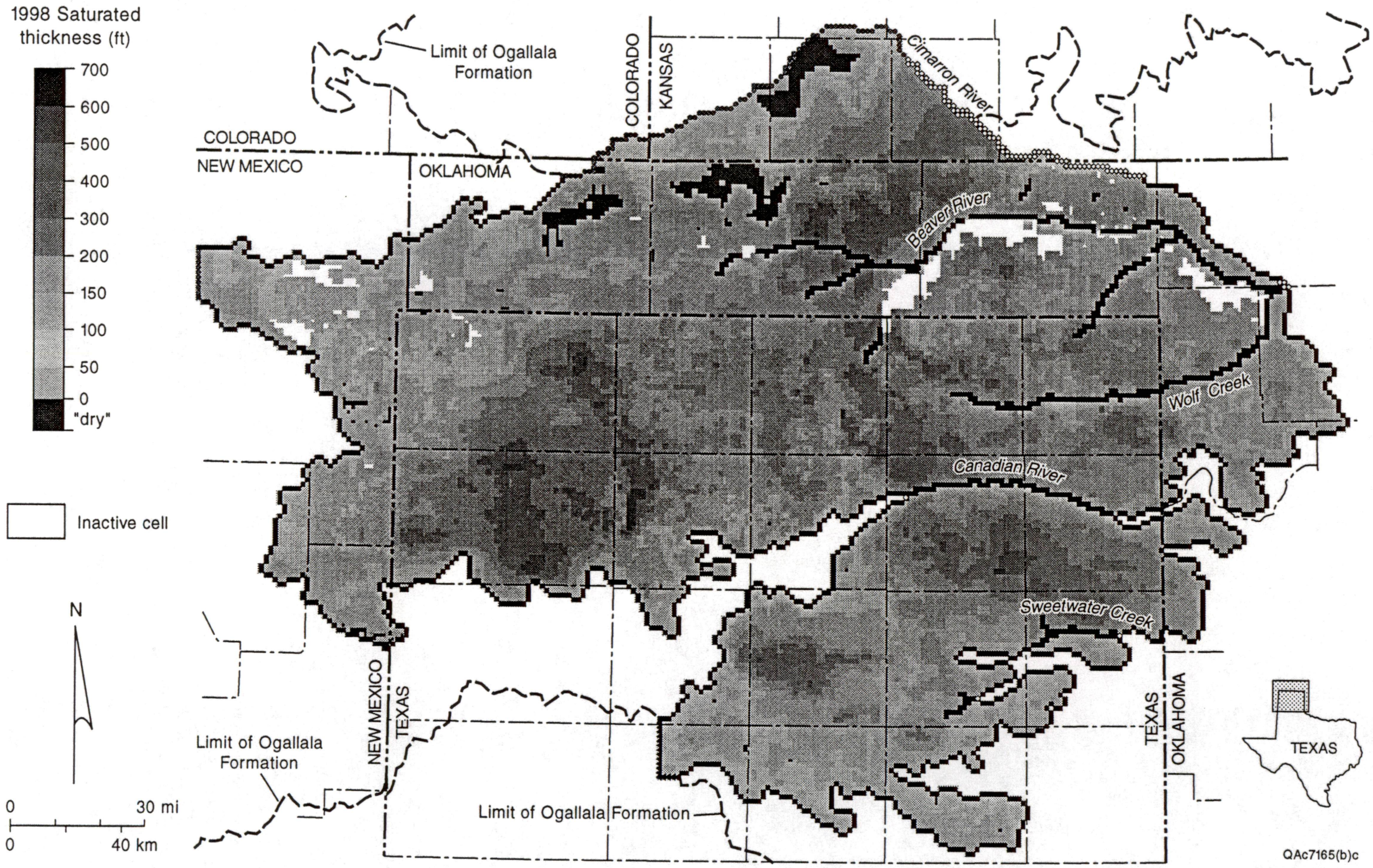

Figure 16. Simulated saturated thickness of the Ogallala aquifer under 1998 water-table conditions.

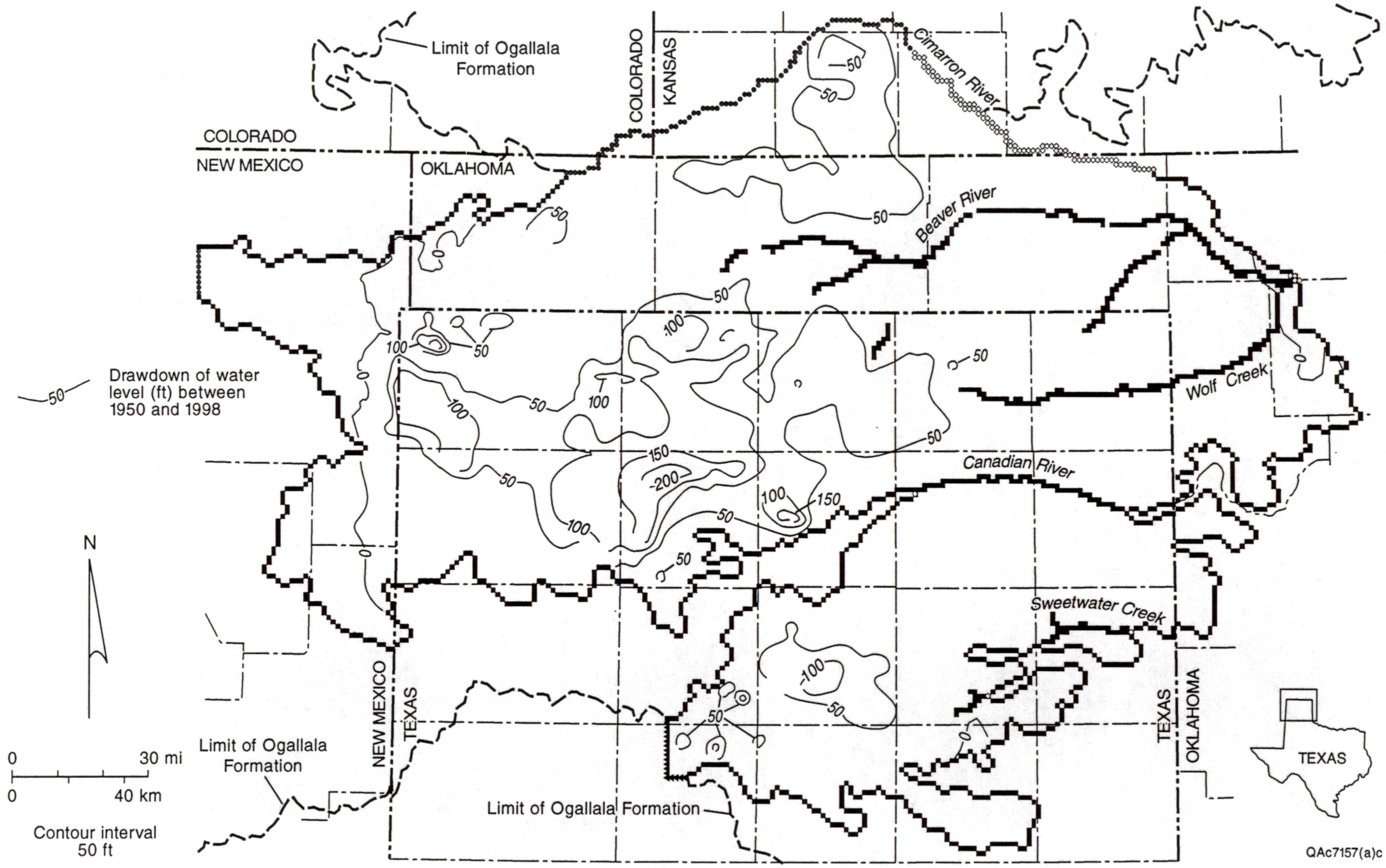

Figure 17. Drawdown in water levels in the Ogallala aquifer simulated for the period from 1950 to 1998.

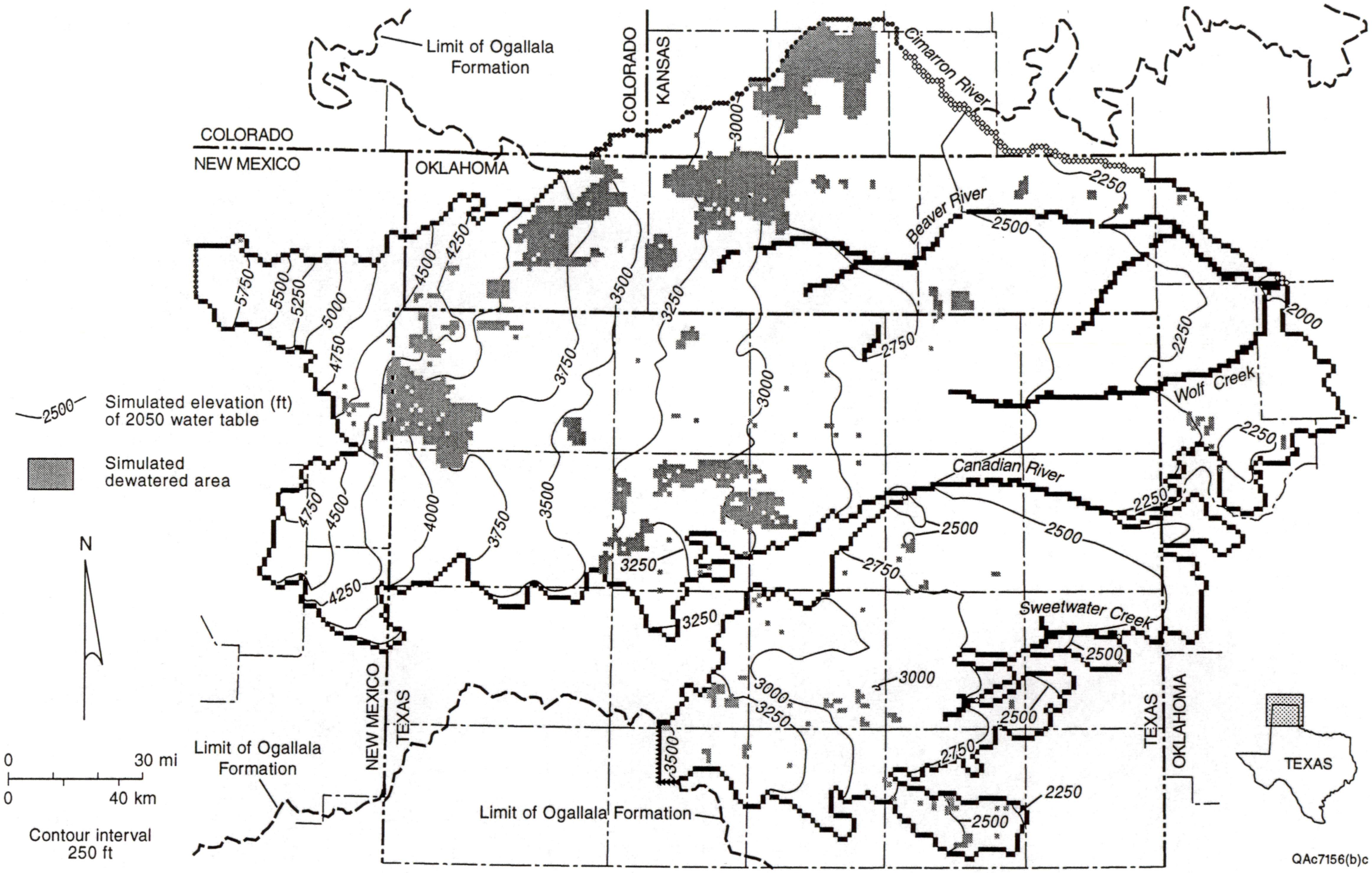

Figure 18. Water-table elevation predicted for the Ogallala aquifer in 2050, given the groundwater withdrawal rates and other assumptions used in the model.

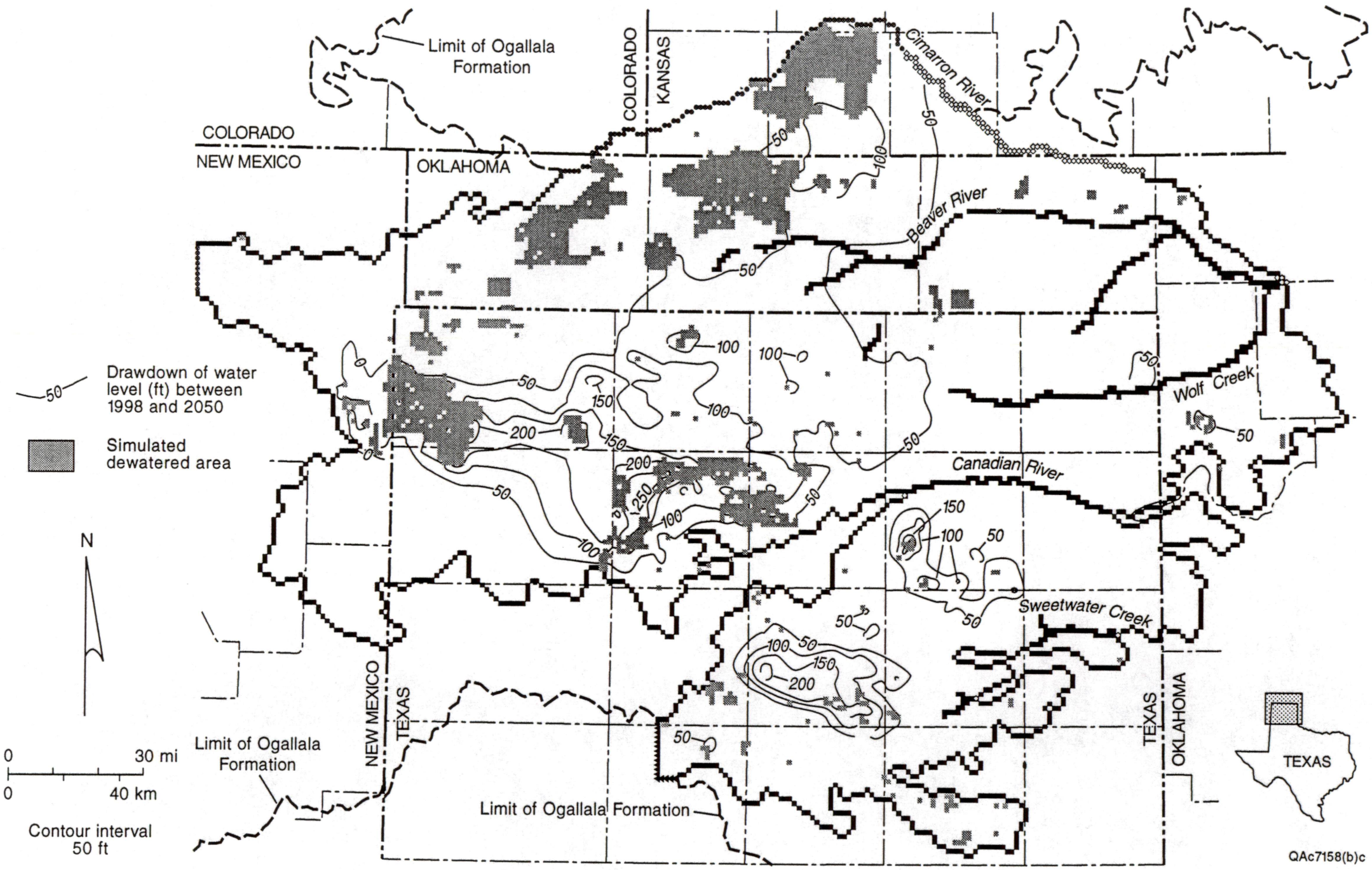

Figure 19. Drawdown in water levels in the Ogallala aquifer simulated for the period from 1998 to 2050.

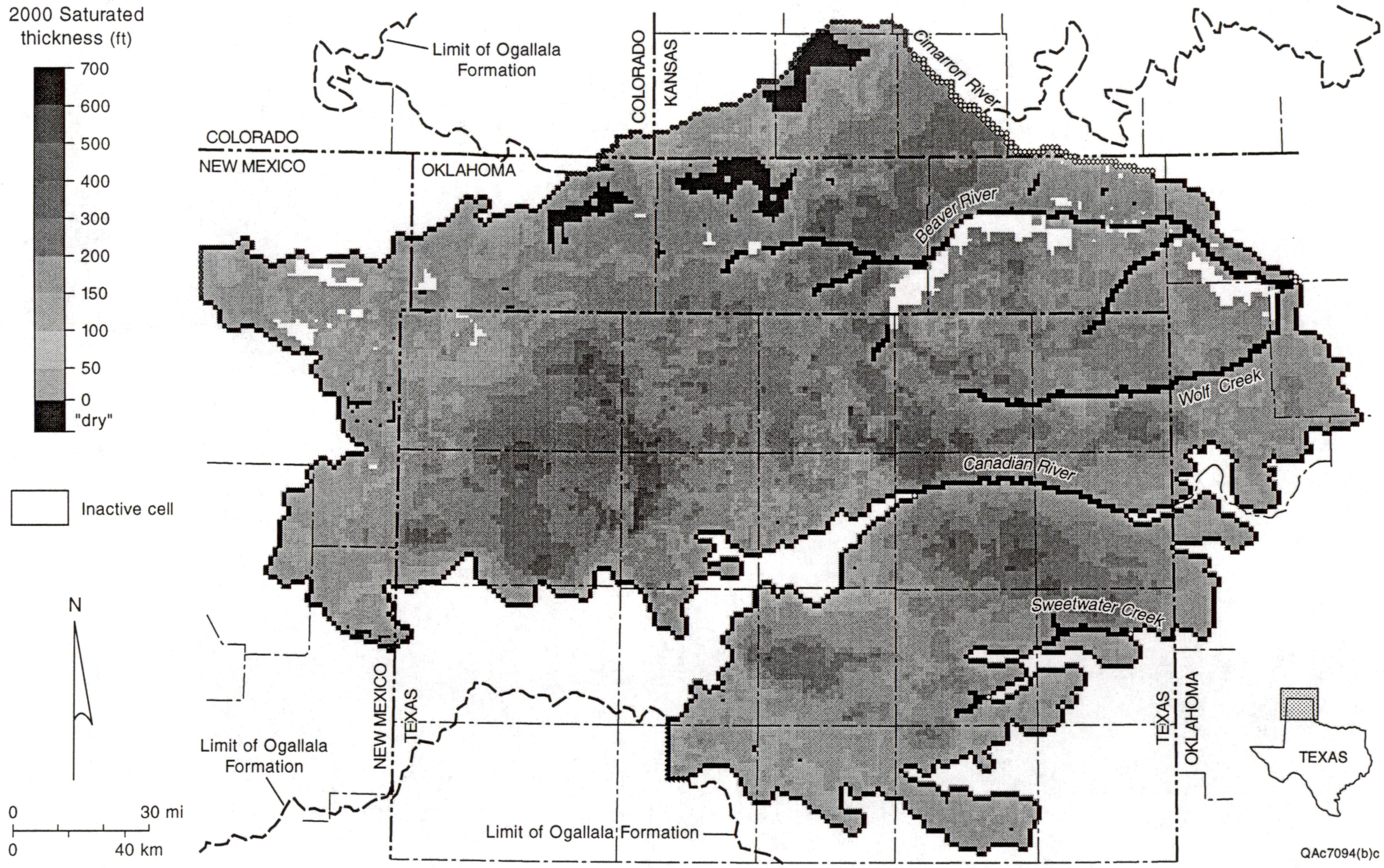

Figure 20. Saturated thickness of the Ogallala aquifer predicted for 2000.

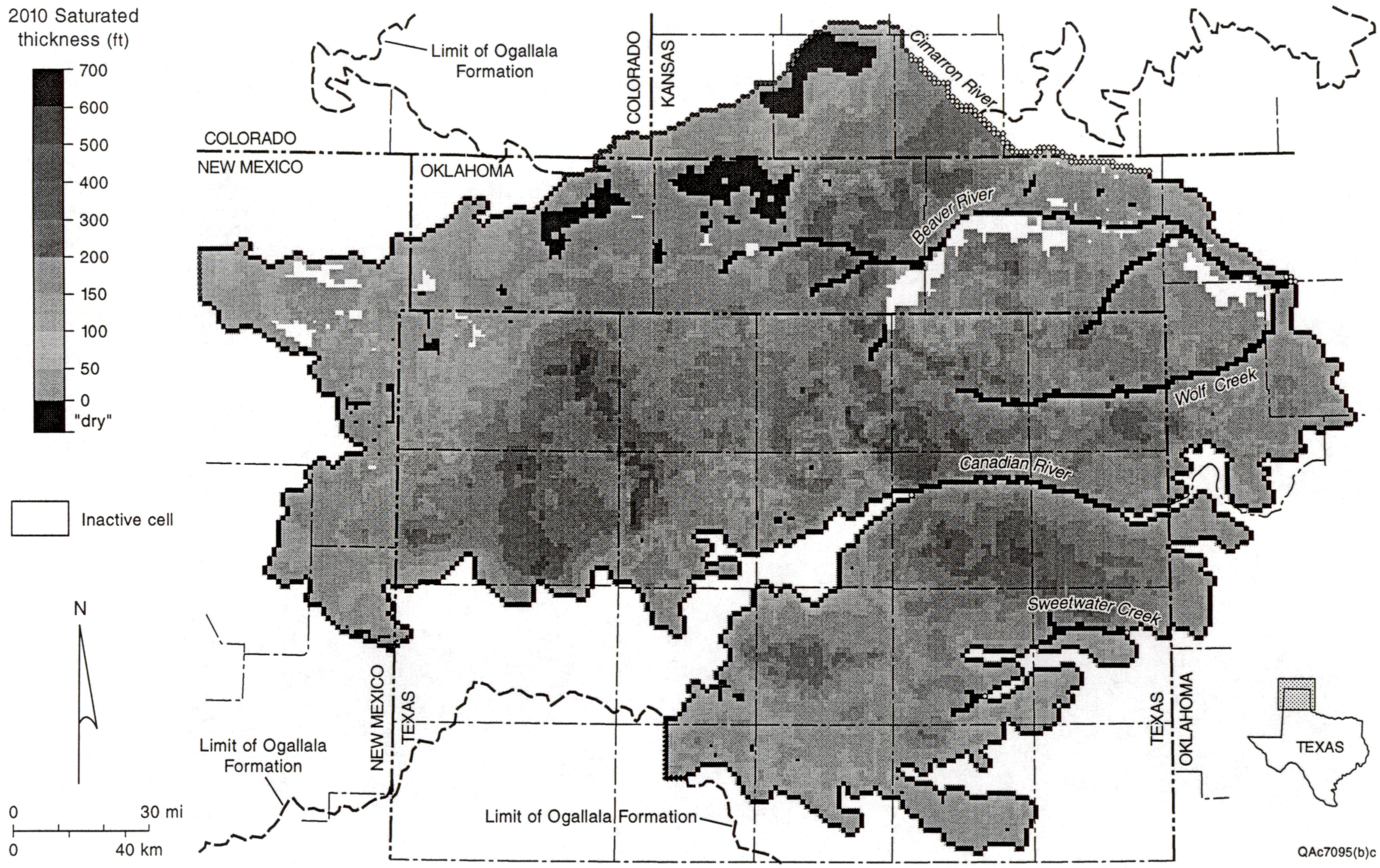

Figure 21. Saturated thickness of the Ogallala aquifer predicted for 2010.

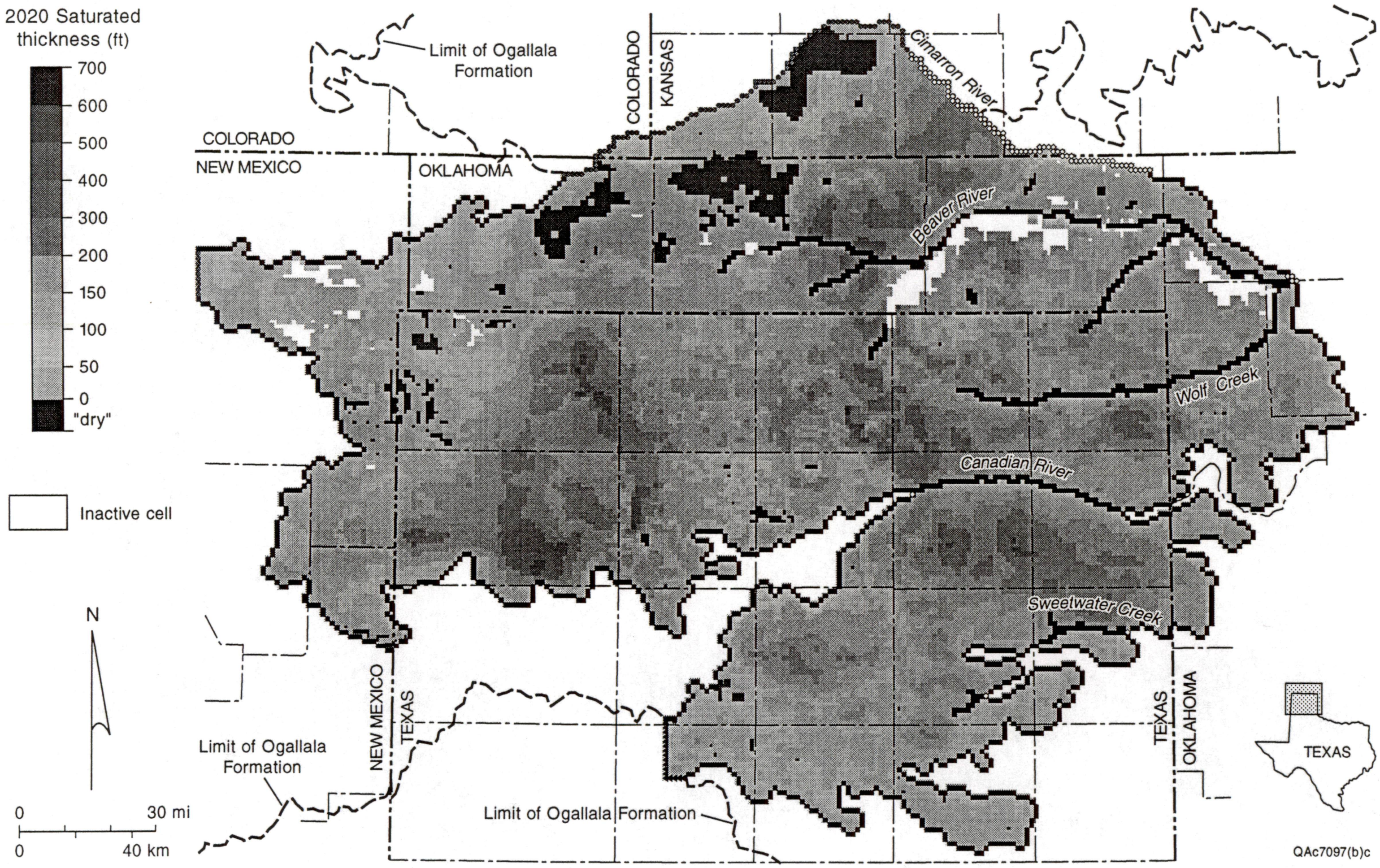

Figure 22. Saturated thickness of the Ogallala aquifer predicted for 2020.

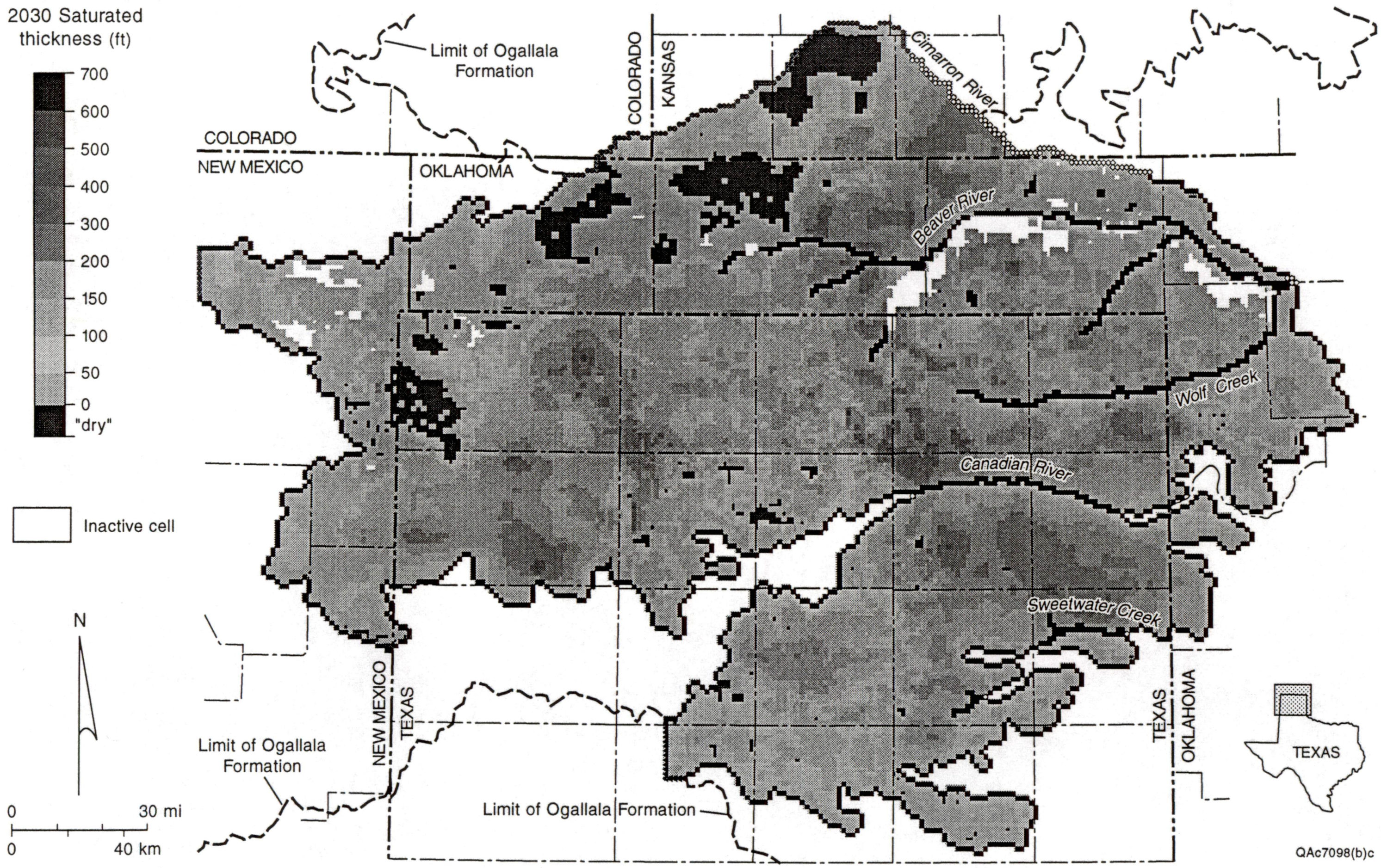

Figure 23. Saturated thickness of the Ogallala aquifer predicted for 2030.

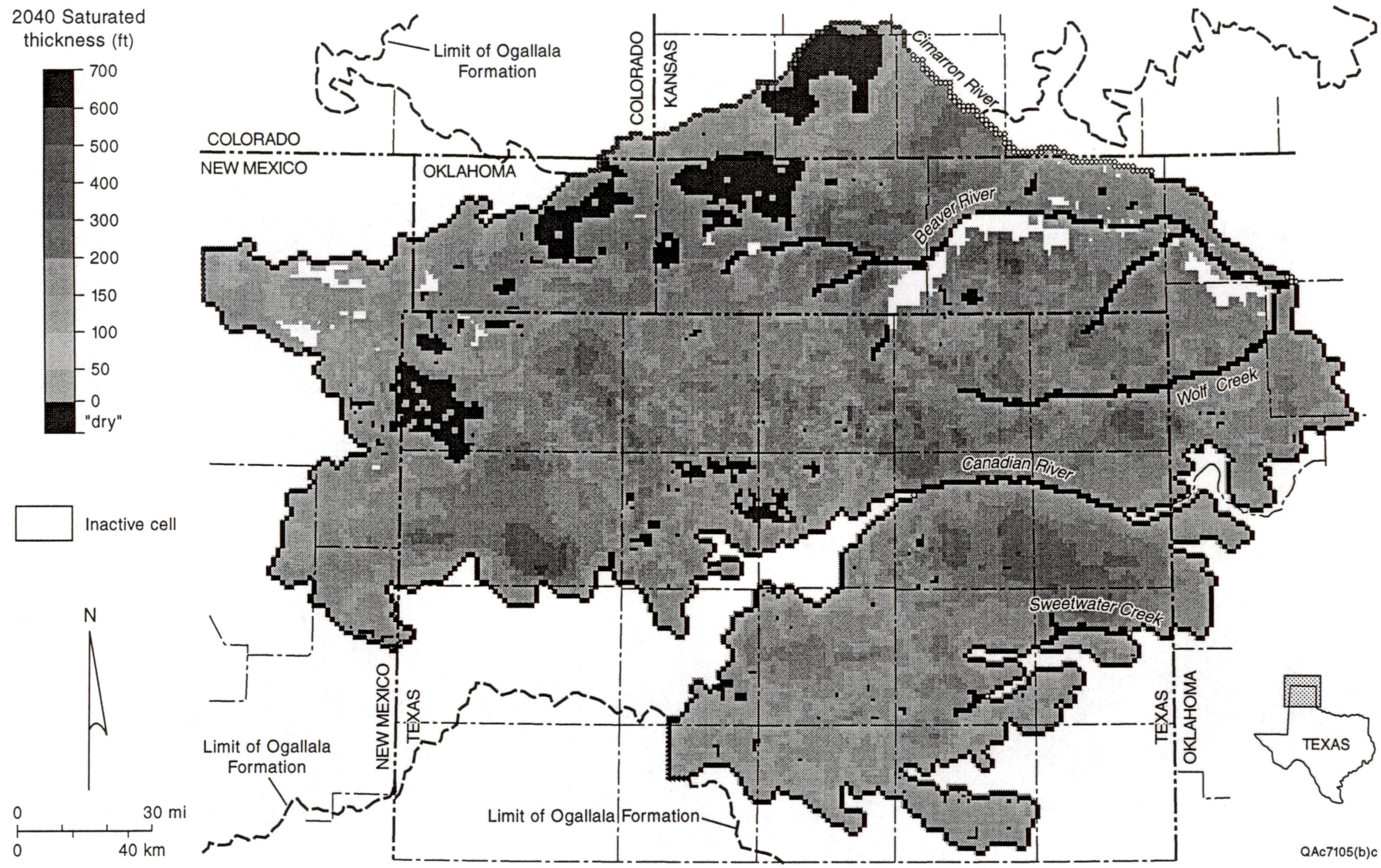

Figure 24. Saturated thickness of the Ogallala aquifer predicted for 2040.

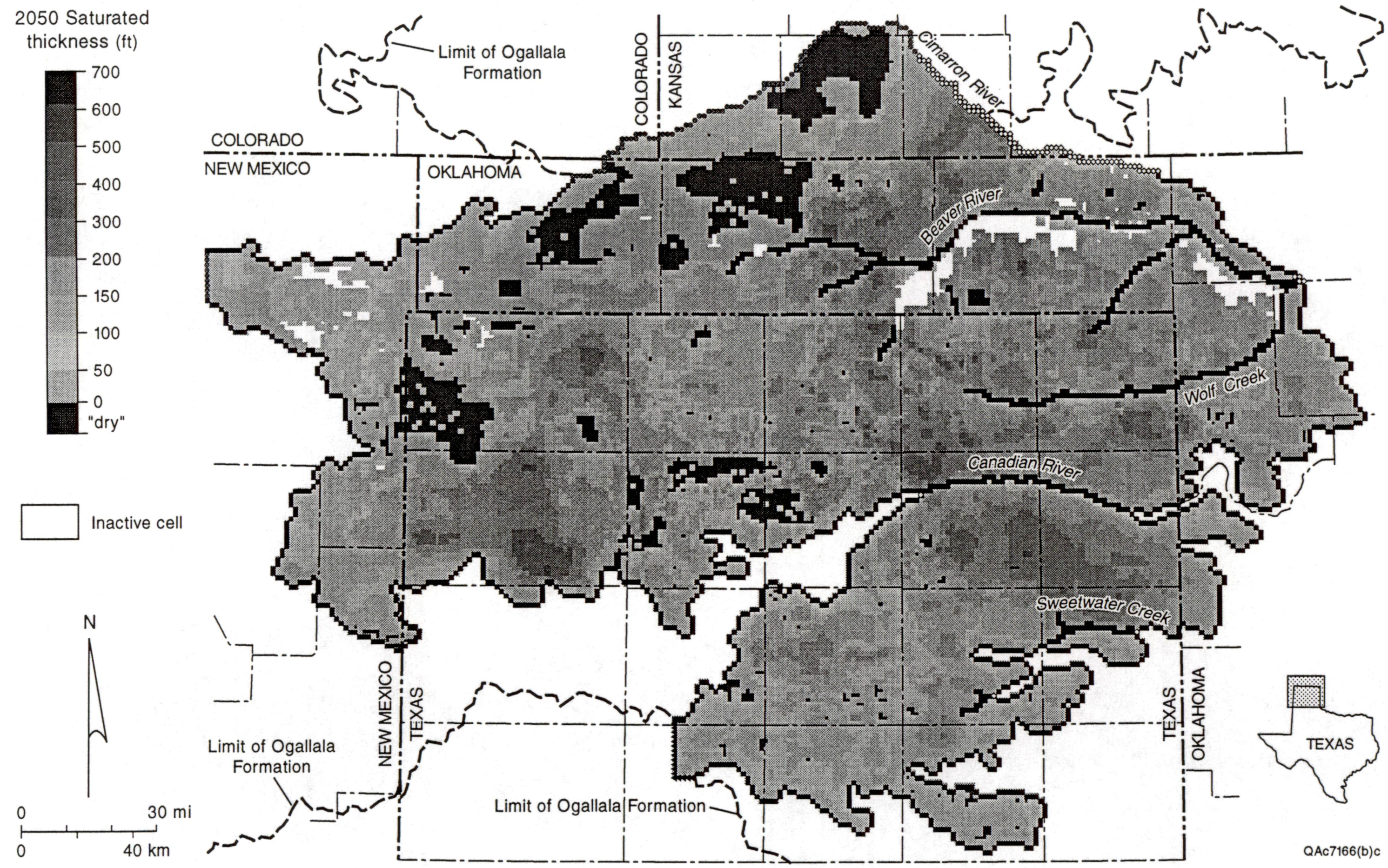

Figure 25. Saturated thickness of the Ogallala aquifer predicted for 2050.