Final Contract Report

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


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Prepared for

Panhandle Water Planning Group
Panhandle Regional Planning Commission
(contract number UTA01-462)

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December 2001

QAe8011

CONTENTS

Tables



Figures

ABSTRACT

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 ft, or about 4 ft/yr. 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 recalibrated to improve predictions of future water-level changes. Model development was part of a statewide process of developing regional water 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 spatially controlled geologic and hydrologic data as much as possible, and (3) placing the model edges so as to minimize their effects on the area of interest in Texas. The model was recalibrated during the present study to improve the match between simulated and observed water levels in Dallam, Roberts, and Donley Counties. 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 water needs.

The model was calibrated under two sets of conditions: "predevelopment" without withdrawal by pumping and "current" conditions, representing 1950 and 1998, respectively. The model (root mean square) error for the predevelopment calibration was about 36 ft and includes uncertainties due to the inherent model simplifications and approximations of recharge, transmissivity, base-flow discharge to rivers and springs, and model geometry. For the

predevelopment calibration, model calibration (root mean square) error is less than about 2 percent of the change in water level across the Texas part of the study area, and the residual difference in water level for most (58 percent) of the calibration data is less than ±25 ft. The model error for the 1998 calibration was about 58 ft. For the 1998 calibration, model calibration error is less than 4 percent of the change in water level, and the residual difference in water level for 57 percent of data is less than ±50 ft. The model error for 1998 includes uncertainties associated with the predevelopment calibration, as well as approximations of specific yield, historical pumping rates, and return flow.

Using groundwater demands projected by the Panhandle Water Planning Group (PWPG), the model predicts that by 2050 major areas of the aquifer will have less than 50 ft of remaining saturated thickness and that parts of the aquifer in Carson, Dallam, Hartley, Hutchinson, Moore, Potter, Randall, Roberts, and Sherman Counties could be dry. This finding was based on projections for both average precipitation and drought-of-record conditions. This prediction may not be realized because

- a goal of the PWPG and groundwater conservation districts 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 58 ft.

The model can be used, however, to identify areas where there may be surpluses or needs in groundwater resources, to evaluate water-management alternatives, and to estimate what rates of groundwater pumping would ensure that the water-management goal of the PWPG and 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

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) (fig. 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 water plan.

Preliminary estimates of water remaining in storage in the Ogallala aquifer in the PWPA from 2000 to 2050 were made using a water-budget method (table 1), in which original water in place was estimated using 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 ft by 2050. A numerical model of the occurrence and movement of groundwater in the Ogallala aquifer was developed (Dutton and others, 2000; Dutton and others, 2001). The model was used to predict with more accuracy and precision the remaining Ogallala groundwater within each county of the PWPA, given specific groundwater demands, and identify areas in the Ogallala aquifer that might have either surpluses or water needs relative to expected demands. During 2001, recalibration of the model focused on improving the match between simulated and observed water levels in Dallam, Hartley, Roberts, and Donley Counties. This report presents the results of the recalibration and builds on the previous studies.

During 2001 the TWDB began developing a model of the Ogallala aquifer in the Southern High Plains (fig. 1) as part of the Groundwater Availability Modeling (GAM) program. That Southern High Plains GAM model is designed to fit together with this model of the Ogallala aquifer in the PWPA.

## STUDY AREA

The focus of the study is the 18 counties in the PWPA in the northern part of the Texas Panhandle that are underlain by the Ogallala aquifer, but the study area extends to natural or hydrologic boundaries in Kansas, New Mexico, and Oklahoma (figs. 2, 3). The western and eastern boundaries of the study area lie at the limit of the Ogallala Formation (the High Plains Escarpment) in New Mexico, Oklahoma, and Texas. The boundary to the north was set at the Cimarron River in Oklahoma and Kansas. The boundary to the south is an artificial boundary that crosses the narrow width of the Ogallala aquifer between the Canadian River and the Prairie Dog Town Fork of the Red River in Randall County (figs. 1, 3). Only those parts of Oldham and Randall Counties that lie within this area were included in the model.

All of the study area lies within the Panhandle (Region A) Water Planning Area. The study area includes all or parts of six groundwater conservation districts: Dallam County Underground Water Conservation District, North Plains Groundwater Conservation District, Hemphill County Underground Water Conservation District, Panhandle Groundwater Conservation District, Collingsworth County Underground Water Conservation District, and the northernmost part of the High Plains Underground Water Conservation District No. 1 (fig. 4). The North Plains and Panhandle groundwater conservation districts are the largest districts in the study area. The study area overlies the Cimarron, Canadian, and Red River Basins (fig. 5). The Canadian River Municipal Water Authority was formed to supply municipal water supplies to Amarillo, Borger, Brownfield, Lamesa, Levelland, Lubbock, O'Donnell, Pampa, Plainview, Slaton, and Tahoka, using surface water from Lake Meredith (fig. 1). In 2001 it began also pumping water from the Ogallala aquifer in Roberts County to blend with its surface water for salinity control and to supplement the available supply from Lake Meredith.

## Physiography and Climate

The study area is located mainly in the northern part of the Texas Panhandle and includes the Texas portion of the Central High Plains and the northernmost part of the Southern High Plains (fig. 1). The area comprises part of what has been called the "Llano Estacado" or "Texas High Plains." The study area in Texas encompasses approximately 21,000 $mi^2$ (54,390 $km^2$). The terrain is essentially an isolated, grass-covered, flat, caliche-capped plateau. The western and eastern limits of the study area lie at the High Plains Caprock Escarpment. The study area is bounded on the north by the Cimarron River in Oklahoma, Kansas, and southeastern Colorado and on the south by the Canadian River and the Prairie Dog Town Fork of the Red River. East of the study area is the Rolling Plains physiographic province. West of the study area is the Pecos River valley.

Topography generally rises from east to northwest across the study area, from an elevation of about 3,300 ft (914 m) in Donley County to around 4,700 ft (1,433 m) in Dallam

County (fig. 5). The plateau is dotted by numerous shallow circular depressions, or playas, which collect runoff from precipitation and focus recharge to the aquifer units (Scanlon and others, 1994; Mullican and others, 1997). Topographic relief across playas ranges from a few feet to more than 50 ft (15.2 m); width ranges from a few hundred feet to more than 1 mi (1.5 km). Only a small portion of rainfall drains to streams that traverse the plateau (Knowles and others, 1984).

The study-area climate is semiarid to arid continental, with moderate precipitation, low humidity, and high evaporation. Precipitation decreases from east to west across the study area from more than 26 inches/yr in western Oklahoma to less than 16 inches/yr in northeastern New Mexico, whereas potential evapotranspiration increases (Larkin and Bomar, 1983) (figs. 6, 7). July typically has the greatest monthly rainfall (2 to 3 inches [5.1 to 7.6 cm]); January has the least precipitation (0.25 to 0.5 inches [0.64 to 1.3 cm]). Depending on the climatic event, atmospheric moisture is either from the Pacific Ocean or the Gulf of Mexico. Snow comprises a significant portion of precipitation in winter. Lowest average temperatures occur in January with the lowest temperatures (18$^{o}$F [-7.8$^{o}$C]) occurring in the northwesternmost part of the area (Dallam County). Highest average temperatures (96$^{o}$F [35.6$^{o}$C]) occur along the eastern margin of the plateau (Wheeler County) in July. Lake evaporation rates are high and average 73 to 75 inches/yr (185.4 to 190.5 cm/yr). Highest evaporation rates (10.5 inches [26.7 cm]) occur during July along the north-south-trending Texas-Oklahoma border (Larkin and Bomar, 1983). Prevailing winds in the area are from the south and southeast, but significant northerly winds occur during frontal passages in winter (Johnson, 1965). The drought of record was during the period from 1952 to 1956 (fig. 7).

## Geology

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 (fig. 8). At the northwestern limit of the study area in northeastern New Mexico, the Ogallala Formation is also interbedded and locally covered by Tertiary-age volcanic deposits.

The Ogallala Formation ranges from 0 to over 800 ft (>243.8 m) in thickness, consisting of fluvial gravel, sand, and silt (fig. 6), and eolian sand and silt deposited on a regional post-Cretaceous unconformity. Although the Ogallala is subdivided into several members in areas north of Texas, the Texas section is formally undivided. The Ogallala has been interpreted as consisting of southeast-trending coalesced fans sourced from the Rocky Mountains during Miocene-Pliocene time (e.g., Seni, 1980). Ogallala sand and gravel deposits (fig. 9) are concentrated in paleovalleys developed on the Ogallala subcrop of Permian through Cretaceous rocks. Gustavson and Winkler (1988) identified a significant eolian component of the Ogallala Formation, whereby fluvial deposits dominate the paleovalleys while coeval eolian deposits dominate the drainage divides. Ogallala Formation eolian deposits subsequently blanketed the entire area. Seni’s (1980) mapping did not break out the lower and upper stratigraphy of the Ogallala. The sand and gravel deposits identified from drillers’ logs occur mainly in the lower part of the Ogallala Formation, which coincides with the saturated part of the formation. Most of the finer grained deposits in the upper Ogallala Formation lie above the water table.

The uppermost section of the Ogallala Formation is marked by several widespread calcretes and local silcretes. The top of the Ogallala section is marked by a regionally extensive, 6-ft-thick (2-m) bed of erosion-resistant $CaCO_3$-rich rock called the Caprock calcrete. The

Ogallala Formation is overlain by the mainly Pleistocene-aged Blackwater Draw Formation (fig. 8) eolian "cover sands," whose sources have been interpreted as the Pecos and Canadian River valleys (Gustavson, 1996).

Retreat of the edge of the High Plains surface has left a steep escarpment in most areas, which is held up in part by the erosion-resistant caprock, a calicified soil layer that separates the Ogallala from the Blackwater Draw Formations (Gustavson and Simpkins, 1989; Gustavson, 1996). Regional physiography has been strongly influenced by dissolution of buried Permian salt (fig. 8) that is largely responsible for development of the Pecos and Canadian River valleys, as well as for development of the eastern margin of the Caprock escarpment (Gustavson and Finley, 1985). 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). The other main physiographic feature in the study area is the Canadian River Breaks, consisting of the dissected erosional drainage bordering the Canadian River.

## PREVIOUS WORK

Few regional aquifers have been as extensively studied as the Ogallala aquifer (e.g., see regional hydrogeologic summaries by Gutentag and others, 1984; Knowles and others, 1984; Nativ and Smith, 1987). 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. More than a dozen numerical groundwater flow models have been developed for different parts of the Ogallala aquifer in Texas (fig. 10). Numerical models integrate much of the known information of an aquifer, allow consideration of how the water-level response to pumping is influenced by aquifer properties, and help identify what information and conceptualization need additional development. Each of the Ogallala models has had a specific purpose, and each has associated strengths and weaknesses (Mace and Dutton, 1998).

Each of the water-resource models has its particular strengths and weaknesses as well. Nine of the models are regional in extent (fig. 10b–f) and were developed by State and Federal agencies, including the Texas Water Development Board (TWDB), U.S. Geological Survey (USGS), and Bureau of Economic Geology (Mullican and others [1997]). Since its initial development (Knowles, 1981), the TWDB model has been updated and converted from PLASM (Prickett and Lonnquist, 1971) to MODFLOW (McDonald and Harbaugh, 1988). Several of the models are local or subregional in scope; three address water-resource issues for one or a few counties (fig. 10a). The Ogallala aquifer was included in another model (3 in fig. 10a) used in a study of a salt-dissolution zone.

Claborn and others (1970) at Texas Tech University, in cooperation with the High Plains Underground Water Conservation District No. 1, developed the first Ogallala aquifer model in Texas as a management tool (fig. 10a [1]). They used a polygonal finite-difference code developed by E. M. Weber of the California Department of Water Resources. They concluded that numerical models would be a valuable management tool for the aquifer but that high-quality data, especially accurate estimates of pumping, were lacking. Weaknesses of this model were its limited extent, limited calibration data, large block size, and artificial (nonhydrological) boundaries.

Knowles (1981, 1984) and Knowles and others (1982, 1984) developed northern and southern models of the Ogallala aquifer (fig. 10b) for the TWDB using a modified PLASM code (Prickett and Lonnquist, 1971). The division into two models minimized the number of blocks in each model to reduce computation time, reflecting the constraint of computing power, which was markedly less in 1984 than now. Model results showed that the groundwater supply would be inadequate by the year 2030, given projected demand. After about 10 years, Peckham and Ashworth (1993) audited the model results and adjusted the recharge rates and updated pumping rates. Dorman (1996) and Harkins (1998) converted the models to run using MODFLOW, a widely used code that has a number of user-friendly pre- and postprocessors. Additional changes were made to internally calculate pumping rate adjustments on the basis of transmissivity and saturated thickness. The revised models showed a slight increase in water availability, perhaps related to boundary conditions or to changes in projected demand, but they still predicted an overall decline in water levels from 1990 to 2040. Harkins (1998) noted that even reducing irrigation pumping by half, 10 counties in the southern model area were at risk to severely deplete the aquifer.

The strengths of the TWDB models include parameters based on hydrogeologic data and updated estimates of recharge and pumping rates. Weaknesses include continued limitations of input data, artificial western and northern boundaries, unrealistic relationships between surface and groundwater, and relatively coarse grids (block width of 4.66 km). Furthermore, the conversion between PLASM and MODFLOW versions of the models is questionable because of how the artificial boundary along the state lines is treated.

Luckey (1984) and Luckey and others (1986) developed models of the Ogallala aquifer as part of the USGS Regional Aquifer-System Analysis (RASA) program. The model for the southern and central parts of the U.S. High Plains includes the Ogallala aquifer in Texas (fig. 10c). The models use the code by Trescott and others (1976), modified by Larson (1978) and Luckey and others (1986), to improve control over iteration parameters and buffer change in transmissivity (i.e., saturated thickness) between iterations and to consider constant gradient boundary conditions for an unconfined aquifer. The models included estimated return flows from irrigation. Sensitivity analysis showed that estimates of recharge were highly dependent on assigned values of hydraulic conductivity. Drawdown of more than 100 ft (>30 m) between 1980 and 2020 was predicted. Luckey and Stephens (1987) revisited the southern model (fig. 10d) to determine the effect of reducing block width from 10 to 5 mi (~16 to ~8 km). The smaller block size resulted in small differences in predicted water levels but the same general conclusions. The USGS models include data based on hydrogeologic studies, consider return flow, and have natural boundaries. Weaknesses include how surface and groundwater are related and a very coarse grid. Luckey and Becker (1999) covered part of the area included in the central RASA model (compared fig. 10c and 10f). That model has 6,000-ft (~1.8-km) block widths and a single layer and was updated with hydrogeologic data collected during the 1980's.

Mullican and others (1997) investigated both the role of playas in recharging the Ogallala aquifer and advective movement of solutes. Their model was bounded to the north by a major river (fig. 10e). Block width was variable, ranging from 0.25 to 1 mi (~0.4 to ~1.6 km). The model was calibrated first for steady-state conditions and then for transient conditions through to 1990. Results showed that simulated water level was independent of spatial distribution of recharge in the model, whether focused at playas, distributed discretely through zones, or spread uniformly across the surface. The Mullican and others (1997) model includes a more realistic treatment of aquifer boundaries. Limitations of input data, especially transmissivity, are an inherent weakness of this model, as well as other models. Because the purpose of the model was to evaluate recharge scenarios and transport of contaminants, there are no predictions of water levels in response to future pumping. However, the Mullican and others (1997) model had to assign smaller pumping rates than those used by Knowles and others (1984), which caused excessive drawdown.

# HYDROLOGIC SETTING

The physical and hydrologic features that determine the occurrence and movement of groundwater in the aquifer are the subject of the hydrologic setting. The hydrologic setting presented here draws on previous studies on the depositional framework of the aquifer (Seni, 1980; Gustavson and Winkler, 1988), groundwater recharge (Nativ and Smith, 1987; Mullican and others, 1997 ), groundwater age (Dutton, 1995), and water levels and regional groundwater flow (Gutentag and others, 1984; Knowles and others, 1984; Luckey and Becker, 1999). We compiled and interpreted additional data in support of this model development. These additional studies included collating specific-capacity test data from water-well drillers' logs for calculation of transmissivity and hydraulic conductivity, mapping spatial patterns of hydraulic conductivity on the basis of depositional systems, assembling pumping information, and calculating possible ranges of return flow from irrigation.

Gutentag and others (1984) referred to the groundwater system in the study area as the "High Plains aquifer" because 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. The term "High Plains aquifer" avoids a formational name that is also 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.

## Hydrostratigraphy

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 (fig. 9) 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.

The Ogallala aquifer is an unconfined aquifer; that is, the 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 (fig. 11a).

## Structure

The base of the Ogallala Formation is an erosional unconformity; the older Mesozoic-aged rocks were extensively eroded, leaving valleys and ridges. In places the Mesozoic section was completely eroded, and the Ogallala Formation lies on Permian-aged rocks, mainly on the eastern side of the study area (Gutentag and others, 1984). Additional influences on the structure of the base of the Ogallala Formation are the Basin and Range regional uplift of 15 to 30 million years ago and dissolution of Permian bedded salt.

The Basin and Range uplift and regional tilting of the Earth’s crust raised ground surface in eastern New Mexico and western Texas to thousands of feet above sea level (fig. 11a), thus setting the stage for the erosion and transport of the sediment that came to make up the Ogallala aquifer. While surface waters were transporting sediment to and across the study area, associated groundwaters were moving down to the top of the underlying Permian salt section, dissolving halite and anhydrite and discharging as salt springs farther east (Gustavson and Finley, 1985; Dutton, 1990; Gustavson and others, 1994). As the salt was dissolved, ground surface subsided and collapsed into the underground caverns left by salt dissolution. Ground subsidence occurred while the Ogallala sediments were being deposited, resulting in some places (such as western Carson County where the City of Amarillo has one of its well fields) having greater thickness of aquifer material.

Structure of the bottom of the aquifer in the Texas part of the study area is defined by numerous wells. The base of the Ogallala aquifer was contoured (fig. 12) using mapping tools in Arcview®, which 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 the Ogallala aquifer are sparse, for example, in Hartley and Dallam Counties. The base of the aquifer in Oklahoma, Kansas, and New Mexico was set on the basis of the model input data used by Luckey and Becker (1999).

Data control for the base of the Ogallala aquifer (fig. 12) was generally good except that 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, as part of the High Plains aquifer system, thus overestimating 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.

Locally the elevation of the base was lowered to ensure that model cells representing the "predevelopment" water level did not dewater. This adjustment was made mainly in eastern Union County, New Mexico, and westernmost Dallam County.

## Water Levels and Regional Groundwater Flow

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). 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. The hand-contoured map then was digitized and assigned to model cells as initial values for model input.

Dutton and others (2000) could not match reported water levels in eastern Dallam County; simulation results consistently overestimated reported water levels by more than 150 ft. Three data points in particular, measured in 1959 and 1967, were oversimulated. Dallam water levels measured after 1958 average much less than those of earlier measurements. The revised version of the model assumes that post-1958 water-level measurements in Dallam County are not representative of "predevelopment" water levels and are excluded from the calibration. Another datum excluded from the recalibrated model is the 1968 water-level measurement of 2,722 ft in well no. 05-09-202 in Roberts County, which the Dutton and others (2000) model consistently underestimated. This level is 46 ft higher than that of all subsequent readings in that well, which show little variation through time.

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).

Under historical conditions, the water table initially inclined generally eastward in directions parallel to the slope of ground surface (figs. 11a, 13) (Knowles and others, 1984). South of the Prairie Dog Town Fork of the Red River, the water table dipped to the southeast (Knowles and others, 1984). In the area between the Canadian River and Prairie Dog Town Fork, the dip generally was toward the northeast. Contours of water-level elevation become nearly parallel to those of the escarpment around the edge of the Ogallala aquifer. Because groundwater flow is largely perpendicular to the contours of water-level elevation, this fact indicates that groundwater generally flows eastward but follows an arcuate path curving toward discharge areas, for example, in springs and seeps of the Canadian River valley or at the toe of the escarpment. North of the Canadian River, the water table and apparent flow direction are generally directed to the east. Flow rates in the Ogallala aquifer between the Canadian River and Prairie Dog Town Fork are estimated to be roughly 80 to 100 ft/yr (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).

Water levels in the aquifer in the northern part of the Texas Panhandle declined an average of about 5.5 ft/yr from 1960 to 1980 (Knowles and others, 1984), although there also was comparable water-level recovery in parts of the aquifer south of the Canadian River. The drawdown of water levels in some well fields such as the Amarillo well field in Carson County locally changes the direction of regional flow paths. Figure 14 illustrates observed changes in water levels in selected wells with long monitoring records. Locations of the wells are shown in figure 15.

The water table for 1998 is based on abundant water-level measurements taken between December 1997 and April 1998 (fig. 16).

## Recharge and Return Flow

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/yr (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. Recharge to the unconfined aquifer beneath the southern High Plains is focused through playa basins (Nativ and Smith, 1987; Osterkamp and Wood, 1987; Nativ and Riggio, 1989; 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 1940’s and 1950’s to less than 4 percent by the 1980’s. 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

The top of the model was assigned a constant rate of recharge (a hydraulic boundary) for each stress period. Recharge rates (fig. 17) were set as a function of precipitation and soil types (table 2). 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/yr where precipitation ranged from 16.5 to 22.5 inches/yr, respectively. During calibration the straight-line relationship between recharge and precipitation was changed. The final version of the model has three line segments defining the relation between recharge and precipitation. Recharge is increased with precipitation more rapidly (steeper slope) at precipitation rates of more than 21 inches/yr than at precipitation rates between 17 and 21 inches/yr, and recharge is constant at precipitation rates of less than 17 inches/yr. This three-part relation between recharge and precipitation may approximate a more complex, nonlinear relation that also is affected by evapotranspiration. Further research on predicting recharge from precipitation and other variables is needed.

Recharge was also varied with soil type. GIS polygons of soil types were downloaded from the U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) STATSGO database (http://www.ftw.nrcs.usda.gov/stat_data:html). The numerous soil types were joined into eight groups (table 2). 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). In the previous model (Dutton and others, 2000), 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 2). The weighting factor of 0.67 previously used for soil groups 4 to 7 (table 2) is the ratio of recharge rates used by Mullican and others (1997) for Blackwater Draw (0.236 inches/yr) and Ogallala (0.354 inches/yr) soils. To improve the calibration of the revised model, additional recharge was prescribed for Ogallala soils and less for Blackwater Draw soils (table 2)

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 and 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 from irrigation loss probably was large during the 1940’s and 1950’s (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 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 (fig. 15). Loss rate was initially taken from Luckey and Becker (1999) and set equal to 24 percent for the 1950’s and decreased to 2 percent since the 1990’s. 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 2); 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 (fig. 15). Several simulations were made to evaluate the sensitivity of model results to assumed return-flow velocity and travel time, with velocity values between 5 and 40 ft/yr. It is possible that velocity averages less than 5 ft/yr.

## Rivers, Streams, Springs, and Lakes

River bottomlands can be groundwater-discharge areas. Groundwater discharge provides varying amounts of base flow to the Cimarron, Beaver (or North Canadian), and Canadian Rivers and to Wolf and Sweetwater Creeks (fig. 5). Luckey and Becker (1999) estimated average discharge across the study area to be 60 cubic feet per second (cfs) to the Cimarron, 30 cfs to the Beaver/North Canadian, 30 cfs to Wolf Creek, and 45 cfs to the Canadian. The Cimarron River does not have perennial flow across the western side of the High Plains (fig. 5; Luckey and Becker, 1999). Notable springs and seeps in river valleys and along the High Plains Escarpment discharged at rates of 1 to 2 cfs (Brune, 1975). Because water levels have fallen during the past several decades, the amount of spring flow has decreased; some historical springs have ceased to flow.

The largest lake in the area, Lake Meredith, is a reservoir constructed on the Canadian River and operated by the Canadian River Municipal Water Authority. Lake Meredith lies on Triassic and Permian bedrock and its surface water does not directly interact with groundwater in the Ogallala aquifer. The reservoir does not generally release water and contributes little water to downstream flow in the Canadian River. Other, smaller reservoirs in the study area are Palo Duro Reservoir in Hansford County and Greenbelt Reservoir in Donley County.

## Hydraulic Properties

This model 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 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.

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 that of previous studies is the inclusion of specific-capacity information, which can significantly increase the number of measurement points for an aquifer (Mace, 2001).

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 well bore (1,130 wells included information that allowed us to calculate saturated thickness).

On the basis of 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 log-normally distributed (fig. 19) with a geometric mean of about 14.8 ft/day and a standard deviation that spans from 5 to 44 ft/day. A log-normal 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. Using spatial correlation, we can infer that points that are closer together are more similar to each other than points that are farther 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 ft. The range suggests that hydraulic conductivity is spatially correlated within 140,000 ft (26 mi) 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. 20). Figure 19 compares the statistical distribution of the measured and final calibrated distribution of hydraulic conductivity for the Texas part of the model. Hydraulic-conductivity values were also assigned using kriging based on a semivariogram for the Texas data. During model calibration, hydraulic conductivity in parts of Dallam, Hartley, Moore, and Sherman Counties, Texas, was increased in order to lower simulated water levels and improve model calibration. Increases by factors of 2 to 5 were oriented along the major channel of sand and gravel in the area, whereas in a small area of northeastern Dallam County initial estimates of more than 5 ft/day were increased to between 50 and 60 ft/day. Additional data collection is needed in areas of sparse data where input parameters needed to be revised.

Specific yield (fig. 21) was derived 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®.

## Discharge

Since the 1950's, discharge from the Ogallala aquifer has been more by pumping from wells than at springs and seeps along river bottomlands and the toe of the High Plains Escarpment. Cross-formational flow is assumed to be less than discharge to springs and seeps. By far the greatest volume of discharge since the 1950's is pumping. More groundwater is pumped from the Ogallala aquifer than any other aquifer in Texas. The rate of groundwater withdrawal for irrigation markedly increased after 1950 (Texas Water Development Board, 1996; fig. 3). Historically, withdrawal for irrigation has composed from 57 to 96 percent of the total groundwater demand (Dutton and Reedy, 2000). Average total annual withdrawal was greatest during the 1980's. During the 1990's the total rate of withdrawal appears to have decreased to about 1.24 million acre-feet/yr. Future demand, on the basis of consensus-based projections and assuming water availability (Freese and Nichols, Inc., 2000), is expected to continue to increase, although after 2000 at lower rates than in the past (fig. 22). This projection assumes no future growth in demand for irrigation.

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, which 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 was simulated as being pumped from the Ogallala aquifer in the model area (table 3). 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 were made by the Texas Agricultural Experiment Station (TAES) on the basis of rainfall and irrigation efficiencies (Dutton and Reedy, 2000).

For 1999 to 2050, approximately 82 million acre-feet of groundwater was simulated as being pumped from the Ogallala aquifer (table 3). Projected groundwater withdrawal for 2000 to 2050 (table 3) 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 (e.g., 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). Because irrigation withdrawal is projected to make up approximately 85 percent of total withdrawal, these differences have the potential to impact model results.

Average annual withdrawal for irrigation was greatest during the 1980’s, at approximately 1.5 million acre-feet/yr (fig. 22). During the 1990’s the total rate of irrigation withdrawal appears to have decreased to about 1.2 million acre-feet/yr. 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/yr per acre during 1960 to 1998 and were about 0.44 acre-foot/yr 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/yr 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 that was related to power generation in Potter County was allocated to two cells representing wells used by the Southwestern 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 23 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. 22), was taken from digital files compiled 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.

The volume of cross-formational flow at the base of the aquifer flow is assumed to be small compared with the large volume of flow within the Ogallala aquifer (fig. 11). Downward discharge from the Ogallala aquifer, however, 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, 2000). 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.

## CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE AQUIFER

A conceptual model represents our best understanding of the occurrence and movement of water in an aquifer, including the processes for inflow and outflow of water. The salient points of the conceptual model are summarized as follows.

- The Ogallala aquifer can be modeled as a one-layer aquifer (fig. 11). In some areas, for example, Dallam County, groundwater moves between the Ogallala and adjacent Cretaceous formations (fig. 8). The hydrologic properties of the modeled layer in such an area must average the real hydrologic properties of the respective formations. We will assume that flow between the Ogallala aquifer and other underlying formations, such as the Triassic and Permian beds, is small compared with the flow within the Ogallala aquifer.
- Recharge is generally less than 2 percent of precipitation. It is greater toward the east than to the west, following the trend in precipitation. Recharge also is greater under sand and loam soils than under more clayey soils. Recharge to the Ogallala aquifer across most of the study area on the High Plains is focused through playas; there is little runoff through the poorly integrated surface-water drainage network. Focused recharge from playas, however, can be modeled on a regional scale using a distributed recharge rate (Mullican and others, 1997).

The recharge values applied in the model represent the net sum of precipitation less evapotranspiration and runoff.

- Under predevelopment conditions, for example, before 1940, there was about 307 million acre-feet of water stored in the aquifer in the study area. Over the previous hundreds of years, the annual recharge and discharge rates must have been approximately in balance. Discharge from the aquifer under predevelopment conditions was by seeps and springs along creeks and rivers and at the base of the High Plains Escarpment.
- Since the late 1940's, pumping of groundwater has accounted for most of the discharge of groundwater from the Ogallala aquifer. Pumping has been at rates of 20 to 30 times the recharge rate.
- Movement of groundwater within the Ogallala aquifer is generally from west to east, following the gradient of water-table elevation, which in turn reflects the dip of ground surface. Velocity of water in the aquifer is controlled in part by the distribution of hydraulic conductivity, which in turn is significantly correlated to the presence of sand and gravel deposited in river and fan environments.
- Drawdown in water levels and decrease in saturated thickness since the late 1940's has been caused by pumping. The location of the greatest drawdown reflects the distribution of pumping and also the hydrologic properties (hydraulic conductivity and specific yield). The distribution of specific yield is poorly known but might also be controlled by the arrangement of sand, gravel, and other materials in the aquifer.

MODEL DESIGN

The general equation for regional flow of groundwater derives from a water-balance equation (Domenico and Schwartz, 1990, p. 101–102):

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

where div q (units of 1/time) represents the net outflow rate per unit volume of aquifer, q is specific discharge or velocity of water moving into and out of a unit volume of an aquifer (length/time), $R^{*}$ represents various sources and sinks of water such as recharge (source) and extraction wells (sinks) as a volumetric rate per unit volume of an aquifer (1/time), $S_S$ is specific storage (1/length), and $\partial h/\partial t$ expresses the rate of change of hydraulic head (h) or water level. Hydraulic head is an expression of potential energy per unit weight of water. In this report the datum for water level is mean sea level. Any imbalance in the left-hand side of equation 1 results in a change of hydraulic head or water level. 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 water level. 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 water level. For an unconfined aquifer such as the Ogallala aquifer, storage changes mainly by the 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 a volume of water moves through a unit cross-sectional area of an aquifer under a unit gradient in hydraulic head or water level (grad h) in horizontal and vertical directions. The negative sign indicates that groundwater movement is in the direction of decreasing water level.

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 general flow equation in terms of transmissivity (T) and storativity (S):

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(T_z \frac{\partial h}{\partial z}\right) - R^{*} = S \frac{\partial h}{\partial t} \tag{4}$$

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:

$$T = K \times b \tag{5a}$$

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 water level, is equal to the saturated thickness of the aquifer times specific storage:

$$S = Ss \times b \tag{5b}$$

Solving equations 3b or 4 for the distribution of hydraulic head or water level 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.

The storativity of the Ogallala aquifer (which is unconfined) can be replaced in equation 4 by specific yield (Sy). Specific yield is the volume of water released from an unconfined aquifer per unit surface area of aquifer and per unit decline in water level. Specific yield is a function of effective or drainable porosity; a certain amount of water is retained by the aquifer material. Because transmissivity changes as water level moves up and down in an unconfined aquifer, hydraulic conductivity is input to the model and transmissivity is calculated by the computer code each time the simulated water level is calculated.

MODFLOW simulates some sources and sinks of water (R* in equations 1, 3, and 4) 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 water level and the water level 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, for example, “river” and “drain,” allow for prescribed changes in flux as water level changes. In the MODFLOW module “general head boundary (GHB),” flux is a linear function of the head difference.

## Code and Processor

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 5.1; Chiang and Kinzelbach, 2001) 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. Other pre- and postsimulation software should be able to read the input files for MODFLOW. We developed and ran the model on a Dell Latitude laptop computer with a 256-MHz Pentium II Processor and 256-MB RAM running Windows NT.

## Grid of Model Layer

The model grid for the finite-difference model was defined by 256 columns and 188 rows (fig. 24). Rows were aligned west-to-east, and columns were aligned north-to-south. Cells or blocks of the model were square and 1 mi long on each side (1-$mi^2$ 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.

## Model Parameters

We distributed model parameters, as previously described, using both Surfer® and Arcview®.

- The top of the model layer was set equal to ground-surface topography (fig. 5), as defined by a 1:250,000-scale digital elevation model (DEM) downloaded from a USGS Internet site (ftp://edcftp.cr.usgs.gov/pub/data/DEM). Values were assigned to the model grid using Arcview®.
- Aquifer base was assigned to the model grid using Arcview®.
- Hydraulic conductivity was assigned using Surfer® with input data consisting of the raw data (as log-transformed values), as well as digitized traces of the hand-contoured map of hydraulic conductivity. This forced the digitized version to match the geological interpretation of the hydraulic-conductivity distribution. Another version of the input data was generated without the digitized contour traces and included in a model calibration run for comparison. That version was determined using kriging, with the kriging parameters assigned from the variogram analysis.
- Hydraulic conductivity was adjusted during predevelopment-model calibration in parts of Dallam, Hartley, Moore, and Sherman Counties, Texas. To lower simulated water levels, hydraulic conductivity along the trend of a major channel of sand and gravel was increased by factors of 2 to 5, and in a small area of northeastern Dallam County initial estimates of less than 5 ft/day were increased to between 50 and 60 ft/day.
- Specific yield for the Texas part of the model was digitized from maps in Knowles and others (1984). For Oklahoma and Kansas we redistributed grid data from the Luckey and Becker (1999) model. Luckey and Becker (1999) assigned a uniform value of 0.15 to the New Mexico part of their model. We smoothed the Texas part of

the map into eastern New Mexico to avoid a state-line artifact in the model. Model input was generated using Arcview®.

- The aquifer was defined as unconfined in all locations.

## Model Boundaries

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, although it minimized the extent of the last:

- The perimeter was defined mainly 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 is evapotranspired where the water table is close to ground surface. We used the perimeter of the Ogallala aquifer as defined by the TWDB.

- 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. 24). 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. What resulted represents an "artificial" boundary in the model, that is, approximating neither a physical nor hydrological boundary.
- Part of the perimeter was simulated using the "drain" package of MODFLOW (fig. 24) to represent seeps along the High Plains Escarpment. Luckey and Becker (1999) used 10,000 $ft^2$/day for drain conductance for grid-cell areas of $36 \times 10^6$ $ft^2$. This model proportionally decreased drain conductance to 7,744 $ft^2$/day for its $27.8 \times 10^6$ $ft^2$ (1 $mi^2$) grid-cell area. Drain elevation was set to 75 percent of saturated thickness, about 35 to 40 ft 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. 24). Along about the halfway mark 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. 24). On the northeast side of the model, the Cimarron River in Kansas and Oklahoma was treated as a river boundary.
- The northwesternmost boundary of the model area in Union County, New Mexico, was treated as a no-flow boundary (fig. 24). At this highest upgradient side of the aquifer we assumed there was neither discharge by springs and seeps nor inflow to the aquifer from adjacent formations.
- MODFLOW's "river" module was also used to represent the interaction of surface and groundwater along segments of the Cimarron, Beaver/North Canadian, and Canadian

Rivers and Wolf and Sweetwater Creeks (fig. 24). 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 ft beneath the “predevelopment” water table to ensure that river segments were simulated as gaining streams for the “predevelopment model”. This adjustment was needed because ground-surface elevation in each 1-$mi^2$ cell is averaged and does not represent surface elevation at the river. River-bottom elevation was set 20 ft beneath the river stage. Initial input values for riverbed conductance were set as a function of how much the river channel meanders in the model cell. We also assumed for initial input a value of 10 for the ratio of channel width to riverbed thickness and a unit hydraulic conductivity for riverbed sediments. We adjusted riverbed conductance as part of model calibration to match reported regional rates of groundwater contribution to base flow (table 4).

- Recharge was defined as a function of precipitation rate and soil properties, as previously discussed. The relation between recharge and precipitation was prescribed using three line segments, with slope increasing with precipitation and constant recharge at precipitation of less than 17 inches/yr. Recharge was greater where surficial soils are underlain by the Ogallala Formation than where they are underlain by the Blackwater Draw Formation (table 2) and greatest where surficial soils are very sandy at the eastern edge of the model area.
- The base of the aquifer was assumed to be a no-flow boundary, that is, allowing no exchange of groundwater between the Ogallala aquifer and underlying formations.

## MODELING APPROACH

Once the model was constructed, it was calibrated in two stages: steady state and transient. Work during 2001 targeted reducing the root-mean-square model error for both steady-state (64 ft) and transient (74 ft) model calibration; the 74-ft calibration error for 1998 water-level measurements was about 4 percent of the 1,750-ft drop in water level across the Texas part of the model (Dutton and others, 2000). The calibrated model then was used to make predictions of possible water-level changes through 2050, given various assumptions about pumping rate.

First, the calibration of a "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 water level. Hydraulic conductivity was increased in parts of Dallam, Hartley, Moore, and Sherman Counties, Texas, following geological features. 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. Less recharge was used in parts of Dallam County to help decrease simulated water level, and more recharge was applied in Union County, New Mexico, as ground-surface elevation rose higher to the west, to help bring simulated water levels up along the Texas and New Mexico border.
- 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. The 6,000-year time was broken up into 60 stress periods with 400 to 600 equal time steps for model convergence. We found it easier to obtain a converged solution to the general flow equation (equation 4) running the model as a long-term transient simulation than as a steady-state simulation—probably because the initial input values of hydraulic head (fig. 13) are not perfectly balanced with all other input parameters. The long simulation period and small time steps allow the model to converge to a stable solution with small interative changes in saturated thickness and transmissivity and without cells incorrectly going dry. It turns out that the model converges on a “steady-state” solution after less than a 4,000-year simulation period with further head changes of less than 0.01 ft for the 4,000- to 6,000-year period.

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 water level is changing in response to pumping rates that also are changing. Because 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.

No changes in aquifer properties were made following the “predevelopment” calibration in the revised model. No changes to storage were made during transient 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 assigning unreasonable specific yield.

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 water level (Anderson and Woessner, 1992).

## STEADY-STATE MODEL

### 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 13 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 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. 13) 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. We found that

- 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. 13);
- contours bend upstream across the broad valleys of the Canadian and Beaver/North Canadian 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. 24);

- simulated groundwater discharge contributes about 66 cfs of base flow to the Canadian River (table 5), consistent with historical trends (John Williams, personal communication, 2000), although higher than the 45 cfs estimated by 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 cfs per cell, with 98 percent of "drain" cells having discharge of less than 1 cfs and maximum simulated discharge of 2.1 cfs. As previously mentioned, notable springs discharge at rates of 1 to 2 cfs (Brune, 1975).

Contours of the simulated water table reasonably match the estimated, or "observed," "predevelopment" water table (fig. 13) across most of the study area. Areas of poor fit include the Canadian River and Beaver/North Canadian 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. It is therefore possible that the estimated water table in that area includes appreciable error itself.

Figure 25a compares water levels measured for specific wells with the simulated water levels calculated for corresponding cells. The root mean square error of simulated versus observed water level (Anderson and Woessner, 1992) is about 36 ft, and there is no evident bias. The error includes uncertainties due to the inherent model simplifications and approximations of recharge, transmissivity, base-flow discharge to rivers and springs, and model geometry. Model calibration (root mean square) error is less than about 2 percent of the change in water level across the Texas part of the study area (1,750 to 2,525 ft).

Figure 26 maps the calculated residual, or difference, between the reported and simulated water levels shown in figure 25a. The residual difference in water level for most (58 percent) of this area is less than ±25 ft; the residual difference is ±50 for 84 percent of the measurements. A negative residual shows where simulated is less than observed (underestimate) and a positive residual reflects an overestimate. Most parameter adjustment was needed to reduce the residual in northern Union County, New Mexico, and western Dallam and Hartley Counties. Additional geologic research on the hydrogeology and hydraulic properties of the Ogallala aquifer in these areas 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 ft in southwestern Kansas and the Oklahoma Panhandle, but it was generally less than 300 ft in Texas under “predevelopment conditions” (fig. 27). 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. 12). 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.

The calculated water budget of the aquifer before pumping began (“predevelopment”) is shown in table 6. The volumetric balance of the model has an error of less than 1 percent, generally considered acceptable. The head-dependent cells assigned to the model boundary in Potter and Randall Counties (fig. 24) add less than 3 percent of the inflow of water to the model; the rest of water inflow is from recharge. For the “predevelopment period, there is no return flow from irrigation.

Comparing the amount of inflow (table 5) to the amount of water in storage (table 1) gives an estimate of the average length of time water remains in the aquifer, or how long it takes on average to pass through the aquifer. Dividing 307 million acre-feet in storage (table 1) by 389,737 acre-feet/year, the sum of water inflow (table 6) gives an average residence time of about 790 yr. The age of Ogallala groundwater varies with position along flow paths down gradient from points of recharge. An average age of ~790 yr is consistent with age dating of groundwater in the aquifer (Dutton, 1995).

### Sensitivity Analysis

A sensitivity analysis helps reveal the relative effect of various model properties on simulated results. A typical approach is to systematically vary one parameter by ±10 and ±20 percent from calibrated values and determine the change in simulated water level. This model of the Ogallala aquifer is more sensitive to change in hydraulic conductivity than recharge rate (fig. 28). The model appears more sensitive to the lower than upper boundary of recharge rate. River conductance is the least sensitive parameter because its radius of influence is less than 20 mi.

## TRANSIENT MODEL

### Calibration

Many of the regional features of the “predevelopment” water table remain for the 1998 water table (fig. 17):

- 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/North Canadian 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. 17). It is hard to discern an overall change in calibration by comparing water-level contours (figs. 13 versus 16) or even calculated residuals (figs. 26 versus 29), perhaps partly because calibrations for both 1950 and 1998 are fairly good. Figure 25b shows that the mean square error of calibration for 1998 is 58 ft. This error is larger than the calibration error for the “predevelopment” water table because of additional uncertainties associated with return flow, pumping rates, and specific yield. For the revised calibration, model-calibration error (58 ft) is 3.5 percent of the change in water level across the model area. The residual difference in water level is less than ±50 ft for 57 percent of calibration data and less than ±25 ft for 27 percent of the data. The mean square error of calibration of the earlier model (Dutton and others, 2000) was 74 ft for the transient model, about 4.2 percent of the water-level change across the model-calibration area.

Groundwater discharge to base flow is simulated as decreasing by 15 to 52 percent to the Cimarron and Beaver/North Canadian Rivers and Wolf Creek but not by much to the Canadian River (table 5). Model results suggest that simulated base flow to the Canadian River was largely unchanged between 1950 and 1998 and all rivers remained gaining, that is, receiving groundwater discharge.

Saturated thickness decreased in the simulation from 1950 to 1998 (figs. 27, 30) 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 (fig. 31). The model also simulated a more than 50-ft decrease in water level in Amarillo's Carson County well field and more than 100 ft in the irrigation area in central Carson County (fig. 31).

Volume of water in storage was determined for model cells by multiplying saturated thickness times cell area (1 $mi^2$) 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 7). The accuracy of the volume estimate for 1950 and 1998 depends on the same factors as did 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 ft of drawdown between 1950 and 1998 and not much more than 20 ft 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.

The calculated water budget of the aquifer in 1998 is shown in table 6. In 1998, there was a simulated decrease of 1.47 million acre-feet of water stored in the aquifer. This was approximately 0.6 percent of the water stored in the aquifer. As water levels decline, the amount of discharge to springs and seeps (model drains) and rivers is simulated also to decrease (table 6). Also, as model cells with assigned pumping begin to go dry, for example, in modeled parts of Oklahoma and Kansas (figs. 30, 31), those cells are made inactive in the model and pumping and recharge assigned to those model cells is stopped. The actual amount of well pumping in the model becomes less than assigned (table 6). An increase in return flow from irrigation masks the decrease in recharge owing to cells becoming inactive.

## 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 that is 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.

### Predicted Pumping Rates

Simulation of future groundwater demand included two scenarios: (1) average precipitation conditions and (2) average precipitation conditions ending during a decade with a recurrence of a drought of record. The projected irrigation withdrawal developed for the PWPG and used by Dutton and others (2000) reflects long-term average precipitation. These projected pumping rates were rerun with the recalibrated model. The 5 years of 1952 to 1956 include 5 of the 15 driest years recorded since 1940 (table 8). Average precipitation in the study area in 1956 was only 12.2 inches. We assumed that more irrigation would be used during a drought of record than during an average precipitation year so that agriculture would continue to have the same level of output. Increased irrigation-water demand by county was calculated by TAES using the same methodology used in calculating average-precipitation demand. Because recharge is small relative to pumping rate and travel time to the water table is long, we did not change recharge rate for the intervals with the recurring drought of record. We assumed that the drought of record would be repeated as a 5-year drought, with the same history of annual precipitation as that recorded for 1952 to 1956.

We made six predictive runs with the calibrated model:

- baseline run: groundwater demand, given average precipitation conditions through 2050.
- 2010 run: groundwater demand, given average precipitation conditions through 2005 followed by a 5-year drought of record during 2006 to 2010.
- 2020 run: groundwater demand, given average precipitation conditions through 2015 followed by a 5-year drought of record during 2016 to 2020.
- 2030 run: groundwater demand, given average precipitation conditions through 2025 followed by a 5-year drought of record during 2026 to 2030.
- 2040 run: groundwater demand, given average precipitation conditions through 2035 followed by a 5-year drought of record during 2036 to 2040.
- 2050 run: groundwater demand, given average precipitation conditions through 2045 followed by a 5-year drought of record during 2046 to 2050.

We determined the water level at the end of each simulated decade (2010, 2020, 2030, 2040, and 2050). Saturated thickness was determined for those 5 years by subtracting the elevation of the base of aquifer from the water-table elevation. Future drawdown was determined by subtracting the water level for those years from the 1998 water level, so drawdown has a positive numeric value.

## Results

Average saturated thickness in 2050 is predicted to be more than 100 feet in 14 counties in the model area and more than 200 feet in Lipscomb, Ochiltree, and Roberts Counties (table 8). 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. 16, 36, 41). Major changes predicted by the model include the following:

- Although average saturated thickness in all counties in the PWPA is simulated to be above 50 feet (table 8), there are areas within each county in which saturated thickness falls to less than 50 feet (table 9). More than half of Dallam and Moore Counties is predicted to have less than 50 ft of saturated thickness (table 9) and large areas where the aquifer might be dewatered (fig. 46).
- Drawdown from 1998 to 2050 is predicted to be more than 150 feet in some areas (fig. 41), given the forecast amount of pumping.
- By 2010, parts of the aquifer in Oklahoma and Kansas are simulated as going dry. A similar result for the period from 1998 to 2020 was reported by Luckey and Becker (1999, p. 55). This study used the water-demand numbers and hydrologic properties of Luckey and Becker (1999) for Oklahoma and Kansas, so the two models should give similar results. The areas simulated as going dry have high pumping rates, assigned by

Luckey and Becker (1999), although the dewatered area in Kansas may also be influenced by the no-flow boundary condition assigned to part of the Cimarron River (fig. 24).

- By 2020, parts of the model area in Dallam, Hartley, Moore, and Potter Counties, Texas, are predicted to begin to go dry (figs. 33, 43).
- By 2050, parts of Carson, Dallam, Hartley, Hutchinson, Moore, Potter, Randall, Roberts, and Sherman Counties are simulated as dewatered (figs. 36, 46) and . Parts of Oldham and Randall Counties, of course, have long had saturated thickness of less than 50 feet.
- By 2050, Carson, Dallam, Hartley, Hutchinson, Moore, and Sherman Counties are predicted to have less than half of their 1998 saturated thickness remaining (table 10).

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. 23, table 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 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 255 million acre feet in 2000 (table 11) to about 191 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. Sherman County is projected to have on average 56 percent of its

1998 water volume. Total volume of water, however, does not by itself completely describe the availability of groundwater in 2050. As previously stated, 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 by 2050, 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.

Simulation results show that water levels decline over the 5 decades, with groundwater withdrawal being much greater than recharge rate for both average precipitation and drought of record years. Given that withdrawal rate is projected to continue to be more than 15 times recharge rate, the difference in demand between average precipitation and drought-of-record conditions does not make a significant difference in the findings of which counties can expect the most shortfall in groundwater resources.

## LIMITATIONS OF THE MODEL

Appropriate use of these model predictions is to identify areas

- where apparent supply of groundwater is adequate to meet forecast demand through 2050,
- where supply of groundwater might not meet projected demand, and
- where saturated thickness is predicted to be less than 50 ft (the model calibration error) and 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 37 to 46 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.

## CONCLUSIONS

The recalibrated numerical groundwater flow model of the Ogallala aquifer can be used to predict water-level changes in response to pumping and future droughts. The one-layer model implemented with MODFLOW has 24,242 active cells. Hydrologic processes represented in the model include recharge, discharge by seepage to springs and rivers, irrigation return flow, and well pumping. Hydraulic conductivity is assigned on the basis of a geological model of depositional systems for the sand and gravel that make up the aquifer.

Our modeling approach involved (1) calibrating a “predevelopment” model representing approximate, 1950 water-level conditions when the aquifer still was near steady state; (2) checking the calibration for winter 1998; and (3) using the model to predict water levels, water-level decline, and saturated thickness through 2050 under average precipitation and drought-of-record conditions.

The calibrated model provides a very good regional match to water levels for both “predevelopment” and 1998. The model calibration errors of 36 and 58 ft, respectively, are less than 5 percent of the water-level drop across the Texas part of the study area. Calibrated recharge rates are less than 2 percent of precipitation over most of the study area. Simulated water-level changes are most sensitive to changes in hydraulic conductivity and specific yield.

Water level and saturated thickness in most areas of the Ogallala aquifer in the study area will continue to decline, with pumping rates being much greater than recharge rate. The greatest declines are expected in Dallam, Sherman, Hartley, Moore, Potter, and Carson Counties. Groundwater discharge to the Canadian River is projected to continue little changed, with the CRMWA well field coming online in 2001.

The main limitation in applying this numerical model to simulating the Ogallala aquifer for the next 50 years is in mapping actual dewatering areas. First, it is likely that pumping will decrease or shift to other locations as water levels fall. In this model, pumping remains constant until a cell goes dry; then pumping becomes zero. Second, as the saturated thickness decreases, hydrologic properties of the remaining aquifer section might differ from the average properties represented in the model. Third, and not least, future projected pumping rates for irrigation are based on certain assumptions about continued level of economic activity and agricultural production; water demand is calculated to meet those levels.

Even with these limitations, we think that the major findings showing areas where expected groundwater demand in Dallam, Sherman, Hartley, Moore, Potter, and Carson Counties cannot be met are reasonable. This is, however, the first model projected to 2050. Knowles and others (1984) ran model projections to 2030. Luckey and Becker (1999) simulated changes for part of the model area through 2020; they predicted some dewatering areas in Kansas and Oklahoma. The model predictions are also matched by water-budget spreadsheet calculations on a countywide basis.

## ACKNOWLEDGMENTS

This study was sponsored by the Panhandle Water Planning Group (PWPG) of the Panhandle Regional Planning Commission under interagency contract numbers UTA99-0230 and UTA-462. A Modeling Committee of the PWPG provided helpful discussion, data for use in the model, and helpful reviews of the draft report. Members of the Modeling Committee included Jarrett Atkinson (Project Manager) for PWPG; Richard Bowers of North Plains Underground Water Conservation District No. 2; Ray Brady of Panhandle Groundwater Conservation District 3; Dan Coffey, Director of City of Amarillo Utilities; Charles Cooke of TCW Supply; Rusty Gilmore of Rita Blanca Well Service; Dale Hallmark of North Plains Underground Water Conservation District No. 2; Gale Henslee of Southwestern Public Service; Mike Page of Phillips Petroleum Company; Grady Skaggs for Oldham County; Frank Simms of Carson County Feeders; Ben Weinheimer of Texas Cattle Feeders Association; C. E. Williams of Panhandle Groundwater Conservation District No. 3 (PWPG Cochairman); and John Williams (Modeling

Committee Chairman) of the Canadian River Municipal Water Authority. Stefan Schuster was PWPA Project Manager for the Texas Water Development Board.

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Panhandle Water Planning Group, Panhandle Regional Planning Commission, or Texas Water Development Board.

## REFERENCES

Anderson, M. P., and Woessner, W. W., 1992, Applied groundwater modeling, simulation of flow and advective transport: New York, Academic Press, 381 p.

Bell, A. E., and S. Morrison, 1979, Analytical study of the Ogallala aquifer in Carson County, Texas, projections of saturated thickness, volume of water in storage, pumpage rates, pumping lifts, and well yields: Texas Department of Water Resources Report 242, 64 p.

Berkstresser, C. F., Jr., and Mourant, W. A., 1966, Groundwater resources and geology of Quay County, New Mexico: Socorro, New Mexico Institute of Mining and Technology, Bureau of Mines and Mineral Resources, Groundwater Report No. 9, 115 p.

Brune, G., 1975, Major and historical springs of Texas: Austin, Texas Water Development Board, Report 189, 95 p.

Chiang, W.-H., Kinzelbach, Wolfgamg, 2001, 3D-Groundwater modeling with PMWIN: Berlin, Springer-Verlag, 346 p.

Claborn, B. J., Austin, T. A., and Wells, D. M., 1970, Numerical model of the Ogallala as a management tool, *in* Mattox, R. B., and W. D. Miller, eds., Ogallala Aquifer Symposium:

Texas Tech University, International Center for Arid and Semi-Arid Land Studies, Special Report Number 39, p. 89–110.

Clark, Isobel, 1979, Practical geostatistics: London, Applied Science Publishers, Limited, 129 p.

Cooper, J. B., and Davis, L. V., 1967, General occurrence and quality of groundwater in Union County, New Mexico: Socorro, New Mexico Institute of Mining and Technology, Bureau of Mines and Mineral Resources, Groundwater Report No. 8, 168 p.

Domenico, P. A. and Schwartz, F. W., 1990, Physical and chemical hydrogeology: New York, John Wiley, 824 p.

Dorman, T. M., 1996, The Texas High Plains Aquifer System—modeling and projections for the southern region: Master’s Thesis, Civil Engineering Department, Texas Tech University, Lubbock, Texas.

Dutton, A. R., 1990, Hydrochemical processes involved in salt-dissolution zones, Texas Panhandle, U.S.A.: Hydrological Processes, v. 3, p. 75–89.

Dutton, A. R., 1995, Groundwater isotopic evidence for paleorecharge in U.S. High Plains aquifers: Quaternary Research v. 43, p. 221–231.

Dutton, A. R., Mace, R. E., and Reedy, R. C., 2001, Quantification of spatially varying hydrogeologic properties for a predictive model of groundwater flow in the Ogallala aquifer, northern Texas Panhandle, *in* Lucas, S. G., and Ulmer-Scholle, D. S., Geology of the Llano Estacado: New Mexico Geological Society Guidebook, 52nd Field Conference, p. 297–307.

Dutton, A. R., and Reedy, R. C., 2000, Comparison of water in storage in the Ogallala aquifer versus projected amounts of withdrawal from 1998 to 2050 in Planning Region A, Letter Report (rev. 1): The University of Texas at Austin, Bureau of Economic Geology, prepared for Panhandle Water Planning Group (PWPG) under contract number UTA99-0230, 15 p.

Dutton, A. R., Reedy, R. C., and Mace, R. E., 2000, Saturated thickness in the Ogallala aquifer in the Panhandle Water Planning Area—Simulation of 2000 through 2050 withdrawal projections: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Region A Panhandle Water Planning Group, Panhandle Regional Planning Commission under Contract number UTA99-0230, 75 p.

Dutton, A. R., and Simpkins, W. W., 1989, Isotopic evidence for paleohydrologic evolution of groundwater flow paths: Geology, v. 17, p. 653–656.

Eifler, G. K., Jr., and Barnes, V. E., 1969, Amarillo sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, Scale 1:250,000.

Freese and Nichols, Inc., 2000, Current and projected population and water demand for the region: topical report prepared by Freese and Nichols, Inc., Texas Agricultural Experiment Station, and Texas Agricultural Extension Service for Panhandle Regional Planning Group, Amarillo, Texas, 20 p.

Gustavson, T. C., 1996, Fluvial and eolian depositional systems, paleosols, and paleoclimate of the upper Cenozoic Ogallala and Blackwater Draw Formations, Southern High Plains, Texas and New Mexico: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 239, 62 p.

Gustavson, T. C., and Finley, R. J., 1985, Late Cenozoic geomorphologic evolution of the Texas Panhandle and northeastern New Mexico—case studies of structural controls on regional drainage development: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 148, 42 p.

Gustavson, T. C., and Simpkins, W. W., 1989, Geomorphic processes and rates of retreat affecting the Caprock Escarpment: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 180, 49 p.

Gustavson, T. C., Hovorka, S. D., and Dutton, A. R., 1994, Origin of satin spar veins in evaporite basins: Journal of Sedimentary Research, v. A64, no. 1, p. 88–94.

Gustavson, T. C., and Winkler, D. A., 1988, Depositional facies of the Miocene-Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico: Geology, v. 16, p. 203–206.

Gutentag, E. D., Heimes, F. J., Krothe, N. C., Luckey, R. R., and Weeks, J. B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B, 57 p.

Harbaugh, A. W., and McDonald, M. G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference groundwater flow model: U.S. Geological Survey Open-File Report 96-485.

Harkins, D., 1998, The future of the Texas High Plains aquifer system—modeling and projections: Texas Tech University, Ph.D. dissertation, 278 p.

Johnson, W. C., 1965, Wind in the Southwestern Great Plains: U.S. Department of Agriculture, Agricultural Research Service Conservation Research Report No. 6, v. 65, p. 5.

Knowles, T. R.; 1981. Evaluating the ground-water resources of the High Plains of Texas, ground-water simulation program GWSIM-III: Texas Department of Water Resources, UM-36, 84 p.

Knowles, T. R., 1984, Assessment of the ground-water resources of the Texas High Plains, *in* Whetstone, G. A., ed. Proceedings, Ogallala Aquifer Symposium II: Texas Tech University Water Resources Center, p. 217–237

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

Knowles, Tommy, Nordstrom, Phillip, and Klemt, W. B., 1984, Evaluating the groundwater resources of the High Plains of Texas: Austin, Texas, Department of Water Resources Report 288, volumes 1 to 3.

Konikow, L. F., 1986, Predictive accuracy of a groundwater model—lessons from a postaudit: Groundwater, v. 24, no. 2, p. 173–184.

Larkin, T. J., and Bomar, G. W., 1983, Climatic atlas of Texas: Austin, Texas, Department of Water Resources, Report LP-192, 151 p.

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

Luckey, R. R., 1984, The High Plains regional aquifer-flow system simulation of the Central and Northern High Plains, *in* Whetstone, G. A., ed. Proceedings, Ogallala Aquifer Symposium II: Texas Tech University Water Resources Center, p. 48–66.

Luckey, R. L., and Becker, M. F., 1999, Hydrogeology, water use, and simulation of flow in the High Plains aquifer in northwestern Oklahoma, southeastern Colorado, southwestern Kansas, northeastern New Mexico, and northwestern Texas: U.S. Geological Survey Water-Resources Investigations Report 99-4104, 68 p.

Luckey, R. L., Gutentag, E. D., Heimes, F. J., and Weeks, J. B., 1986, Digital simulation of groundwater flow in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-D, 57 p.

Luckey, R. R., and Stephens, D. M., 1987, Effect of grid size on digital simulation of ground-water flow in the southern High Plains of Texas and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 87-4085, 32 p.

Mace, R. E., 2001, Estimating transmissivity using specific-capacity data: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 01-2, 44 p.

Mace, R. E., and Dutton, A. R., 1998, Numerical modeling of groundwater flow in the Ogallala aquifer in Texas, *in* Castellanos, J. Z., Carrillo, J. J., and Yanez, C. H., eds., Memoria del Simposio Internacional de Aguas Subterraneas: Sociedad Mexicana de la Ciencia del Suelo, p. 98–109.

McAda, D. P., 1984, Projected water-level declines in the Ogallala aquifer in Lea County, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 84-4062, 84 p.

McCuen, R. H., and Snyder, W. M., 1986, Hydrologic modeling: statistical methods and applications: Englewood Cliffs, New Jersey, Prentice Hall, 568 p.

McDonald, M. G.; and A. W. Harbaugh; 1988. A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, variously paginated.

Mehta, S., Fryar, A. F., Brady, R. M., and Morin, R. H., 2000, Modeling regional salinization of the Ogallala aquifer, southern High Plains, Texas, U.S.A.: Journal of Hydrology v. 238, p. 44–64.

Mullican, W. F., III, 1995, A technical review of the Canadian River Municipal Water Authority application for permit to transport water from Roberts and Hutchinson Counties: Panhandle Ground Water Conservation District, variously paginated.

Mullican, W. F., III, Johns, N. D., and Fryar, A. E., 1997, Playas and recharge of the Ogallala aquifer on the southern High Plains of Texas—an examination using numerical techniques: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 242, 72 p.

Nativ, Ronit, 1988, Hydrogeology and hydrochemistry of the Ogallala aquifer, Southern High Plains, Texas Panhandle and eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 177, 64 p.

Nativ, Ronit, and Riggio, Robert, 1989, Meteorologic and isotopic characteristics of precipitation events with implications for ground-water recharge, southern High Plains: Atmospheric Research v. 23, p. 51-82.

Nativ, Ronit, and Smith, D. A., 1987, Hydrogeology and geochemistry of the Ogallala aquifer, southern High Plains. Journal of Hydrology v. 91,217-253.

Osterkamp, W. R., and Wood, W. W., 1987, Playa-lake basins on the southern High Plains of Texas and New Mexico: part I. hydrologic, geomorphic, and geologic evidence for their development. Geological Society of America Bulletin v. 99, 215-223.

Peckham, D. S., and J. B. Ashworth, 1993, The High Plains aquifer system of Texas; 1980 to 1990 overview and projections: Texas Water Development Board 341, p. 1–13.

Prickett, T. A.; and C. G. Lonnquist; 1971. Selected digital computer techniques for groundwater resource evaluation: Illinois State Water Survey, Urbana, Illinois, Bulletin 55.

Senger, R. K., and Fogg, G. E., 1987, Regional underpressuring in deep brine aquifers, Palo Duro Basin, Texas. 1. Effects of hydrostratigraphy and topography: Water Resources Research, v. 23, p. 1481–1493.

Scanlon, B. R., Goldsmith, R. S., Hovorka, S. D., Mullican, W. F., III, and Xiang, Jiannan, 1994, Evidence for focused recharge beneath playas in the Southern High Plains, Texas, *in* Urban, L. V., and Wyatt, A. W., eds., Proceedings, playa basin symposium: Texas Tech University, Water Resources Center, p. 87–96.

Seni, S. J., 1980, Sand-body geometry and depositional systems, Ogallala Formation, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 105, 36 p.

Simpkins, W. W., and Fogg, G. E., 1982, Preliminary modeling of groundwater flow near salt-dissolution zones, Texas Panhandle, *in* Gustavson, T. C., and others, Geology and geohydrology of the Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 82-7, p. 130–137.

Texas Water Development Board, 1996, Surveys of irrigation in Texas 1958, 1964, 1969, 1974, 1979, 1984, 1989, and 1994: Austin, Texas, Report 347, 59 p.

Texas Water Development Board, 1999, Ground water database: Texas Water Development Board, located online at www.twdb.state.tx.us.

Theis, C. V., 1963, Estimating the transmissivity of a water-table aquifer from the specific capacity of a well: U.S. Geological Survey Water-Supply Paper 1536-I, p. 332–336.

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

U.S. Geological Survey, 1998, Geologic map of North America: http://ncgmp.cr.usgs.gov/ncgmp/gmna/gmna.htm.