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QUANTIFICATION OF SPATIALLY VARYING HYDROGEOLOGIC PROPERTIES FOR A PREDICTIVE MODEL OF GROUNDWATER FLOW IN THE OGALLALA AQUIFER, NORTHERN TEXAS PANHANDLE

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Abstract.—The Ogallala aquifer, an extensive unconfined aquifer, is the main source of agricultural and drinking water across the Texas Panhandle and the U.S. High Plains. After 50 yrs of water production at rates in excess of recharge, less than half of the original saturated thickness remains in parts of the aquifer in the northern Texas Panhandle. Numerical models of groundwater flow in the Ogallala are tools with which to manage the aquifer; at least 15 numerical groundwater-flow models have been developed for different parts of the Ogallala aquifer in Texas. Regional models of groundwater flow in the heterogeneous Ogallala aquifer should draw on as many spatially varying data as possible. Besides the basic geometry of the aquifer (top and bottom and lateral boundaries), model input for hydraulic conductivity and recharge can be delimited using spatial attributes. Contouring hydraulic conductivity on the basis of trends in depositional systems and percentage sand and gravel in the aquifer represents both geological heterogeneity and a degree of lateral continuity not captured in simple variogram geostatistics. Recharge rates can be predicted on the basis of long-term precipitation trends and locally adjusted where soils are more or less permeable than average. The combination of mapping hydraulic conductivity using depositional systems and recharge using precipitation and soil factors minimized model calibration error to less than 5 % of the hydraulic-head change across the study area. Reaching a low model calibration error with negligible parameter adjustment raises confidence in the applicability of a groundwater-flow model to aquifer management.

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 is an important part of managing the aquifer's resource and of developing regional plans to meet future water needs. Because of the complexity of the aquifer, due to heterogeneous geological materials as well as numerous points of groundwater withdrawal, it is necessary to use a numerical or computer model to make predictions accurate and detailed enough to be used in aquifer management.

Few regional aquifers have been as extensively studied as the Ogallala aquifer (for example, Gutentag and others, 1984; Knowles and others, 1984; Luckey and others, 1986; Nativ, 1988; Weeks and Gutentag, 1988; Dutton, 1995; Gustavson, 1996; Mullican and others, 1997; Scanlon and Goldsmith, 1997). Numerical models of groundwater flow have been important tools for managing the groundwater resource and evaluating future changes in water level and saturated thickness. At least 15 numerical groundwater-flow models have been developed for different parts of the Ogallala aquifer in Texas (Fig. 1). Numerical models integrate much of the known information on an aquifer, allow consideration of how the water-level response to pumping is influenced by aquifer properties, and help identify what information and conceptual understanding needs additional development. Each of the previous Ogallala models has had a specific purpose and carried associated strengths and weaknesses (Mace and Dutton, 1998).

This paper focuses on how spatially variable properties for hydraulic conductivity, storativity, and recharge were characterized for input to a predictive model of groundwater flow in the northern part of the Texas Panhandle (Fig. 1f). Previous studies have used fewer data on hydraulic conductivity. This study draws extensively on specific-capacity well-test data to estimate hydraulic conductivity and contours hydraulic conductivity guided by depositional facies and percentage sand-and-gravel maps. Previous studies have also used either constant recharge rates or varied recharge in order to improve model calibration. This study assigned recharge on the basis of precipitation and spatially varying soil properties. We found that these combined maps of hydraulic conductivity and recharge were important for minimizing model calibration error with negligible parameter adjustment.

MODEL INFORMATION

The study area lies north of the Prairie Dog Town Fork of the Red River and the Canadian River. The model area, however, extends westward and eastward to the limits of the Ogallala Formation, and northward to the Cimarron River, so that the model perimeter is defined by natural or hydrologic boundaries (Fig. 1f).

Hydrostratigraphy

Gutentag and others (1984) advocated referring to the groundwater system in the study area as the High Plains aquifer for two main reasons. First, groundwater can move between the Ogallala Formation and adjacent Permian, Mesozoic, and Quaternary formations, so the term Ogallala aquifer is inadequate to refer to the whole aquifer system. Second, not all of the Ogallala Formation is saturated. The term "High Plains aquifer" addresses these issues and avoids use of 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.

The Ogallala Formation in the study area consists of Tertiary-age alluvial-fan, fluvial, lacustrine, and eolian deposits derived

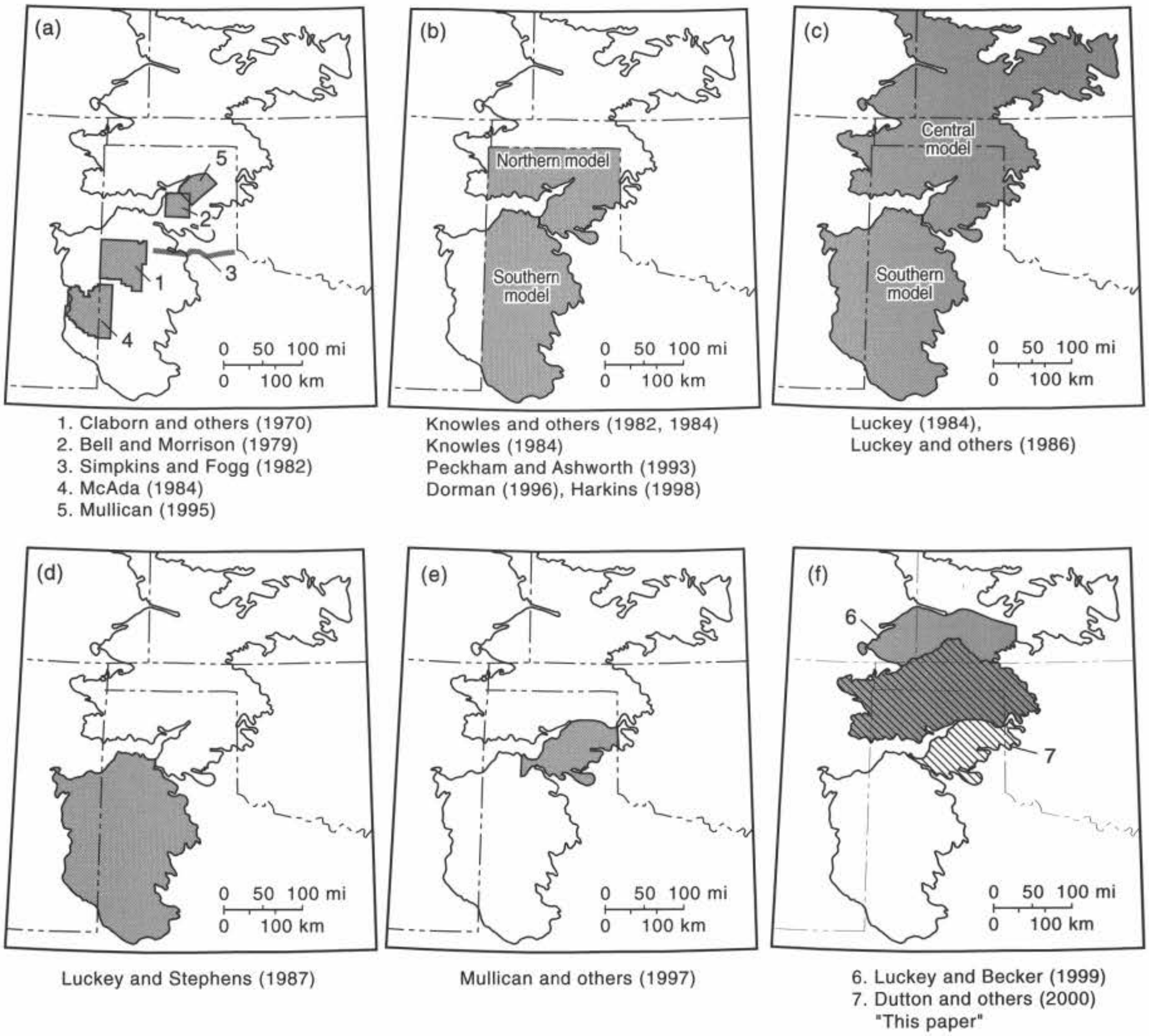

FIGURE 1. Location and area of coverage of models of the Ogallala aquifer in Texas.

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

Seni (1980) interpreted the Ogallala to have accumulated in alluvial-fan depositional environments with overlapping fan lobes (Fig. 3). According to Seni (1980), much of the study area includes distal-fan facies with narrow channel systems separated by broad, low net-sand areas. Seni (1980) did not everywhere break out the overlying Blackwater Draw Formation. Gustavson (1996) distinguished between alluvial deposits filling paleoval-

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

FIGURE 2. Stratigraphic nomenclature of Permian and younger strata, including the Ogallala Formation, in the study area.

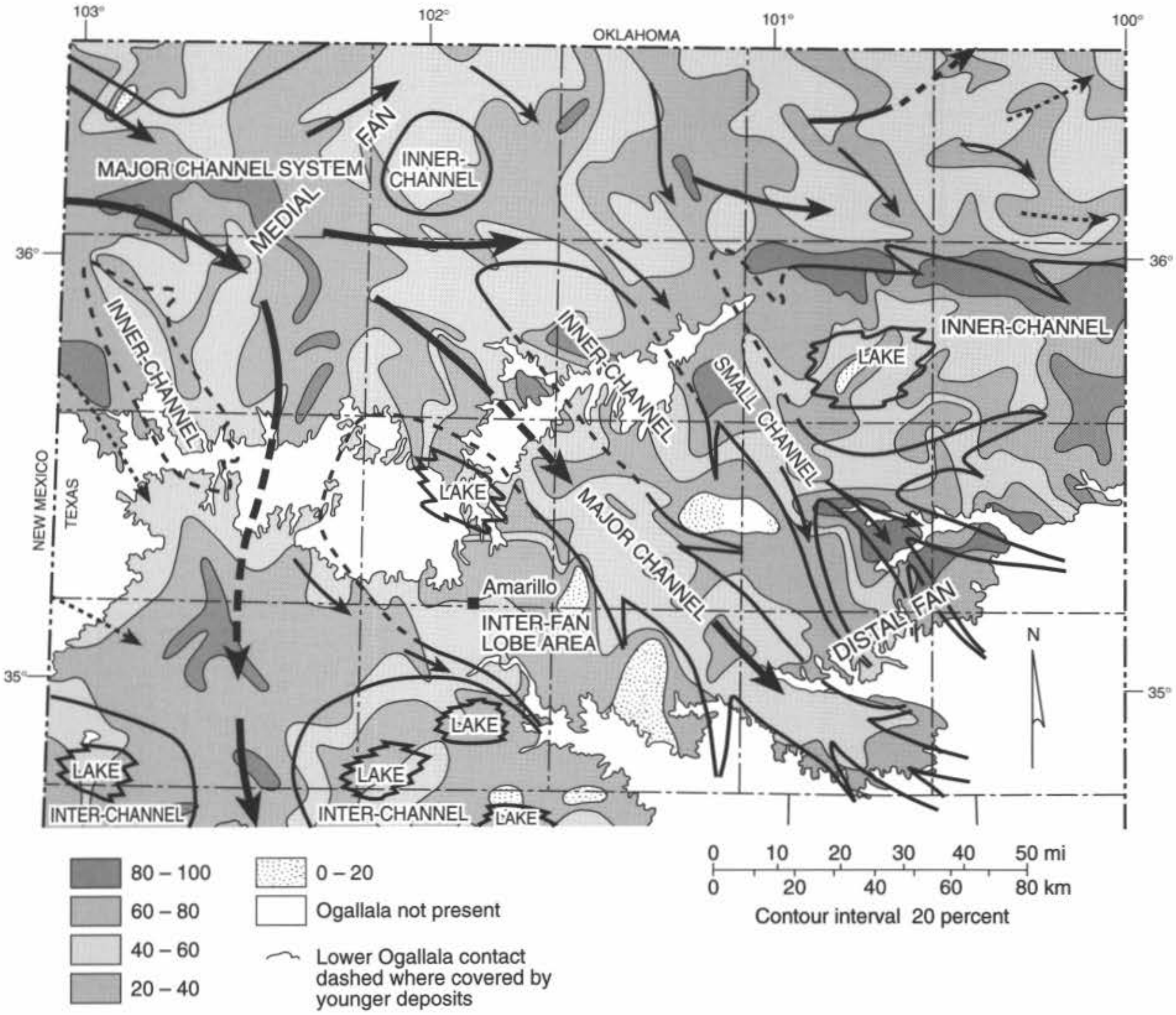

FIGURE 3. Percentage sand and gravel in the Ogallala Formation and inferred depositional facies (modified from Seni, 1980, figs. 10 and 11).

leys and widespread eolian sediments capping the fluvial sections and paleouplands and mapped the top of the Ogallala at an erosion-resistant caprock comprised of a calicified soil layer.

Both depositional models define an aquifer framework or architecture having appreciable lateral and vertical heterogeneity. Aquifer heterogeneity is the spatial variability in properties that control the occurrence and movement of groundwater, such as hydraulic conductivity and specific yield, and is largely related to geologic features. Areas of the aquifer with a greater amount of sand and gravel have greater hydraulic conductivity. The lower part of the formation in paleovalley-fill alluvium 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 Formation and overlying Quaternary Blackwater Draw Formation underlie the High Plains. Retreat of the edge of the High Plains surface has left a steep escarpment in most areas, which is held up in part by the caprock caliche (Gustavson and Simpkins, 1989; Gustavson, 1996). The other main physiographic feature in the study area is the Canadian River Breaks, consisting of dissected erosional drainage bordering the Canadian River.

Aquifer geometry

Aquifer geometry (ground surface, aquifer base, water table) is probably the best characterized of all the input data. Nonetheless, the water table and base of the aquifer are not perfectly known, and data input to the model still requires some simplification and approximation.

Structure of the bottom of the aquifer is defined by numerous wells. The base of the aquifer for the model was mapped locally at the base of "red beds," Permian and Mesozoic rocks bearing groundwater in continuity with Ogallala groundwater. Mapping the base of the aquifer using tools in ArcInfo/ArcView (triangulated irregular networks [TIN's], gridding the TIN surfaces, and assigning values to the model grid) resulted in a reasonable representation of regional trends (Fig. 4). The map might not accurately depict local features, however, especially where data are sparse.

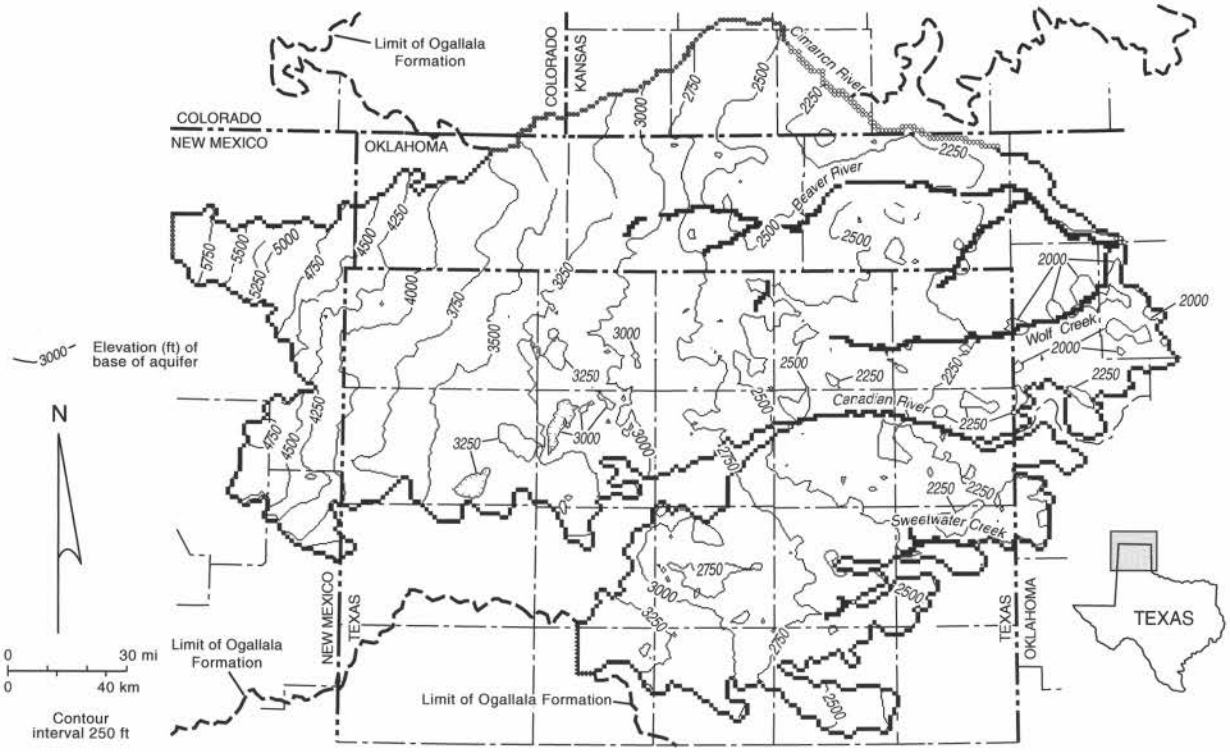

FIGURE 4. Structural elevation of the base of the Ogallala Formation as used in the numerical model. Elevation contours range from ~610 to ~1750 m (2000 to 5750 ft) above mean sea level.

Ground surface was input using digital elevation model data; it is most precisely known. The elevation of the "predevelopment" water-table surface (Fig. 5) was based on the earliest measured water levels. Hydraulic head is an expression of potential energy per unit weight of water; a map of hydraulic-head elevations represents the water table in an unconfined aquifer. This picture of the "predevelopment" water table (Fig. 5) is imperfect because (a) data were composited from a wide range of years to include the first recorded measurements in different areas of the model; (b) some amount of groundwater was already being withdrawn in each area of the model when the earliest water levels were being reported; and (c) early data are sparse, 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 predevelopment water table (Fig. 5) resemble those depicted by Knowles and others (1984) and Luckey and others (1986); each study used a common set of data.

Saturated thickness of groundwater in the Ogallala aquifer in the study area was more than 210 m (>690 ft) in southwestern Kansas and the Oklahoma Panhandle, but it was generally less than 90 m (<295 ft) in Texas under predevelopment conditions. 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. 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). The thinnest saturated sections of the Ogallala aquifer were in eastern New Mexico and around the perimeter or limit of the aquifer.

The elevation of the water table has changed more than 46 m (>150 ft) in the study area since the 1950's owing to withdrawal of groundwater at rates greatly exceeding the recharge rate. The drawdown of water levels in well fields such as the Amarillo well field in Carson County locally changes the direction of regional flow paths. Water levels in the aquifer in the northern part of the Texas Panhandle declined an average of about 2 m/yr (5.5 ft/yr) during 1960–80 (Knowles and others, 1984), although there also was comparable water-level recovery in parts of the aquifer beneath the southern High Plains south of the Canadian River.

Aquifer parameters

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. Hydraulic conductivity expresses the ease with which water moves through a unit cross section of the aquifer under a unit gradient in hydraulic head. A major improvement to hydraulic properties over previous studies is the inclusion of specific-capacity information, which significantly increases the number of measurement points for the aquifer.

We took information from Mullican and others (1997) and compiled test results from a groundwater database (Texas Water Development Board [TWDB], 1999). Mullican and others (1997) had information on 70 aquifer tests, which included high-quality

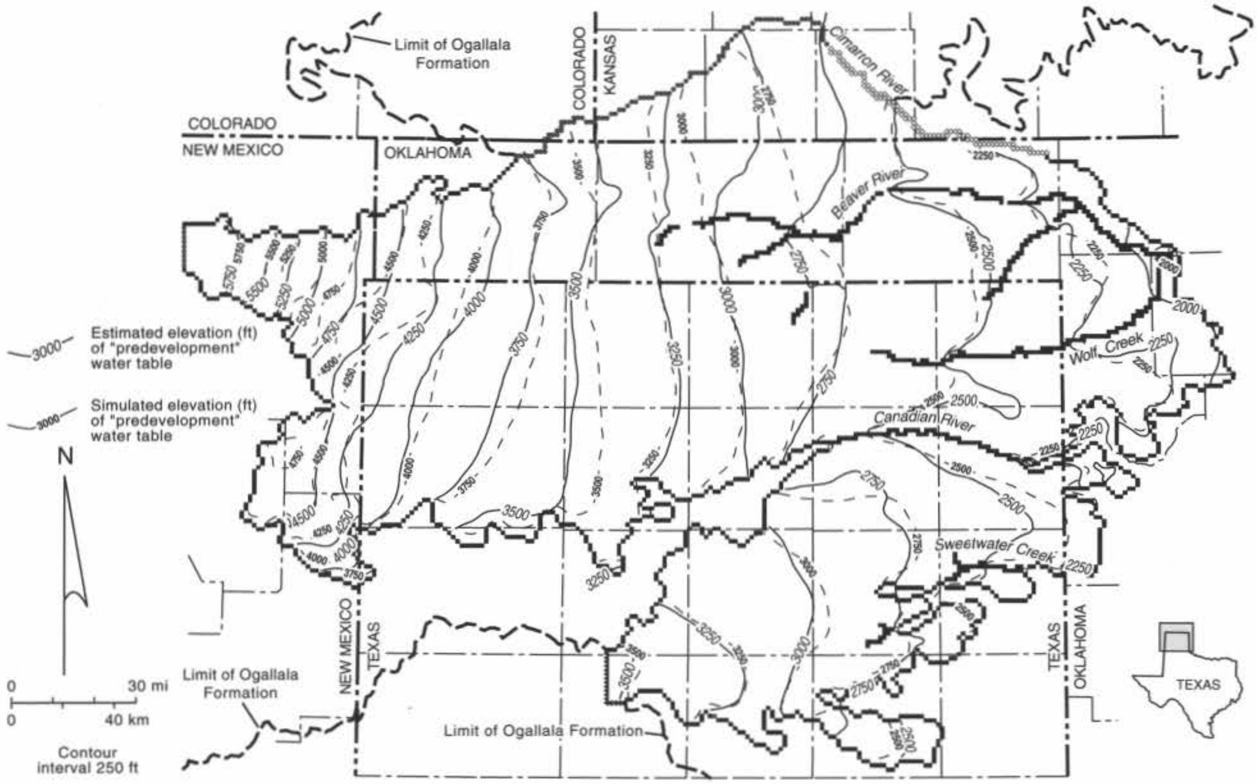

FIGURE 5. Comparison of estimated and simulated elevations of "predevelopment" water table. Contours of water-table elevation range from ~610 to ~1750 m (2000 to 5750 ft) above mean sea level.

specific-capacity tests. We were able to cull data from an additional 1270 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) and described in Mace (in press). Hydraulic conductivity was determined by dividing transmissivity by the saturated thickness exposed to the well bore. Locations of tested wells are recorded with an accuracy generally less than ±1 km (<±3200 ft). Few records include quality-measured spatial coordinates.

Based on results from the data compilation and specific-capacity analysis, we found that hydraulic conductivity for all the tests in the Ogallala aquifer appears to be lognormally distributed (Fig. 6) with a geometric mean of about 4.5 m/d (14.8 ft/d) and a standard deviation that spans from 1.5 to 13.4 m/d (5 to 44 ft/d). A lognormal distribution means that the logarithms of the values are normally distributed, and a geometric mean is the antilogarithm of the mean of the logarithms of the values.

Semivariograms (see Clark, 1979; McCuen and Snyder, 1986) show that hydraulic conductivity in the Ogallala aquifer is spatially correlated. Spatial correlation implies 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 $[\log(m/day)]^2$, a sill of 0.22 $[\log(m/day)]^2$, and a range of ~44 km (~26 mi). The range suggests that hydraulic conductivity is spatially correlated within that distance in the Ogallala aquifer.

Hydraulic conductivity in the Ogallala aquifer was contoured on the basis of posted data and the Seni (1980) maps of inter-

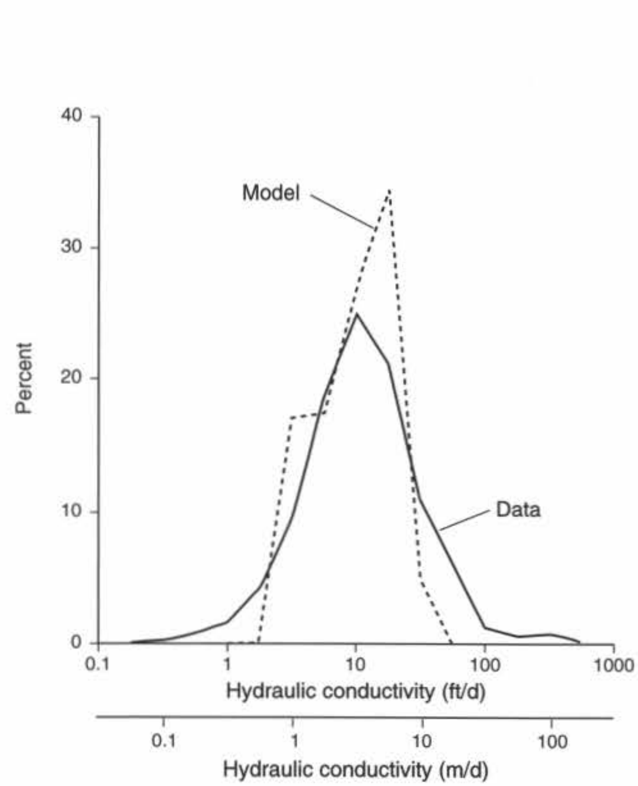

FIGURE 6. Comparison of measured and calibrated values of hydraulic conductivity used in the Texas part of the model.

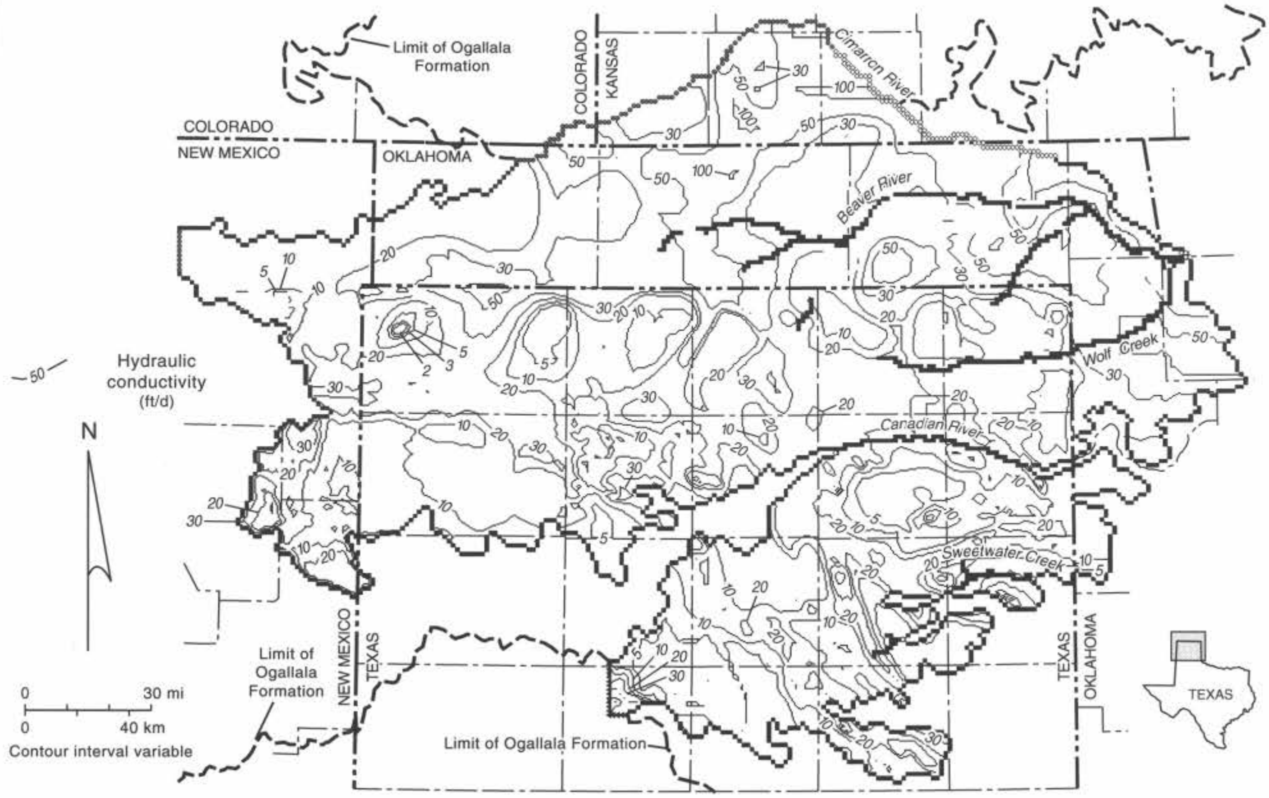

FIGURE 7. Hydraulic conductivity of the Ogallala aquifer used for historical and predictive simulations. Contours of hydraulic conductivity range from ~0.6 to ~30 m/d (2 to 100 ft/d).

preted depositional facies and percent of sand and gravel (Fig. 3). Contours and trend lines from the geologic maps were then used as a guide to contour the hydraulic-conductivity data (Fig. 7). We assumed that the elongate trends at the base of the aquifer interpreted by Seni (1980) as channel systems reasonably approximate laterally continuous flow units in the aquifer. Sand-percent maps were used because the Ogallala Formation is eroded in the Canadian River Valley. Hydraulic-conductivity data are consistent with Seni's (1980) channel axes and bifurcating lobes. Details of depositional channels of high hydraulic conductivity can be resolved in data-rich areas corresponding to channels within various fan lobes. For other depositional axes, data are too sparse to constrain the precise location of narrow channels of high hydraulic conductivity. Depositional channels of high hydraulic conductivity probably follow narrow and meandering bifurcating paths within those broadly defined trends. Statistical distributions of measured and final calibrated hydraulic conductivity are similar for the Texas part of the model (Fig. 6), with only minor changes to hydraulic conductivity made during model calibration.

Hydraulic conductivity of the Ogallala was previously mapped by Knowles and others (1984; see also Nativ, 1988). Without geologic conditioning, the Knowles and others (1984) map suggests no regional continuity in hydraulic conductivity. For comparison, we also mapped the hydraulic conductivity of the Ogallala aquifer by kriging, using geostatistical parameters from the semivariogram analysis. Because the kriged and geologically conditioned maps share the same hydrologic data, they have some resemblance, with northwest-southeast trends of high hydraulic conductivity corresponding to the depositional axes. The kriged map, however, is more like the Knowles and others (1984) map in suggesting a much lower degree of regional continuity in "high-permeability" channels. This study's map of hydraulic conductivity (Fig. 7) assumes a greater degree of lateral continuity because it is drawn on the basis of the interpreted map of depositional systems (Fig. 3).

Contemporaneous and postdepositional salt dissolution and subsidence (Gustavson and Finley, 1985; Gustavson and Winkler, 1988; Gustavson, 1996) may have affected hydraulic conductivity of the Ogallala. Additional analysis is needed to determine which, if either, process might have contributed to several apparent disruptions in continuity of the permeability channels.

Maps of specific yield were taken from Knowles and others (1984) and merged with cell values used by Luckey and Becker (1999) for the non-Texas part of the model. Storativity is a bulk or composite hydrologic property that expresses the volume of water released from a vertical column of an aquifer per unit surface area and unit decline in hydraulic head. It is a function of porosity, compressibility of water, and elasticity of the aquifer matrix. For an unconfined aquifer, storativity is represented by specific yield. Specific yield is generally less than porosity because some water held in the matrix cannot be removed by gravity drainage. Additional work is needed to determine whether the depositional systems maps of aquifer fabric can be used to map or predict specific yield in the Ogallala aquifer.

Recharge

The study area has a dry continental climate with moderate precipitation, low humidity, and high evaporation. Precipitation decreases from east to west across the Texas Panhandle from more than 56 cm/yr (>22 in/yr) to less than 40 cm/yr (<16 in/yr), whereas potential evapotranspiration increases (Larkin and Bomar, 1983).

The Ogallala aquifer is recharged by downward percolation of water from the surface of the High Plains. The distribution of recharge is poorly known; estimates of recharge rates range from 0.25 to 15 cm/yr (0.01 to 6 in/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. Playas can focus recharge to the aquifer (Wood and Petraitis, 1984; Mullican and others, 1997). Estimates of regional recharge rates are weighted 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.

Recharge rates (Fig. 8) were set as a function of precipitation and soil types (Table 1). Data on long-term average (1950 to 1990) precipitation were compiled from U.S. National Oceanic and Atmospheric Administration (2000). These data were contoured and interpolated for the cells in the model area. Recharge was assumed initially to vary linearly from 0.25 to 1.27 cm/yr (0.1 to 0.5 in/yr) where precipitation ranged from 42 to 57 cm/yr (16.5 to 22.5 in/yr), respectively. During calibration the straight-line relationship between recharge and precipitation was changed so that (1) recharge is a greater percentage of precipitation on the wetter, eastern side of the study area than to the west and (2) recharge is at a minimum wherever precipitation is less than 48 cm/yr (<19 in/yr) in the central to western part of the study area. Further research on the relation of recharge to precipitation is needed.

TABLE 1. Soil-based weighting factors for recharge rates. Recharge rates were assigned in the model on the basis of long-term average precipitation and locally adjusted on the basis of weighting factors derived from soil textures. Soil data compiled from U.S. Department of Agriculture (2000).

Soil group	Soil textures	Area in model (km^2)	Soil permeability (cm/hr)	Weighting factor
1	Loam-Silt loam	17,956	2.5	1.0
2	Loamy sand-Sandy loam	21,445	37.1	1.0
3	Sandy loam-Clayey loam-Silty clay loam	5,840	11.2	1.0
4	Silty clay loam-Silty clay	13,755	0.3	0.67
5	Silt loam-Clayey loam	1,339	1.3	0.67
6	Clay loam-Clay	883	0.8	0.67
7	Sandy loam-Loam-Clay loam	321	11.2	0.67
8	Sand	2,479	75.4	2.77

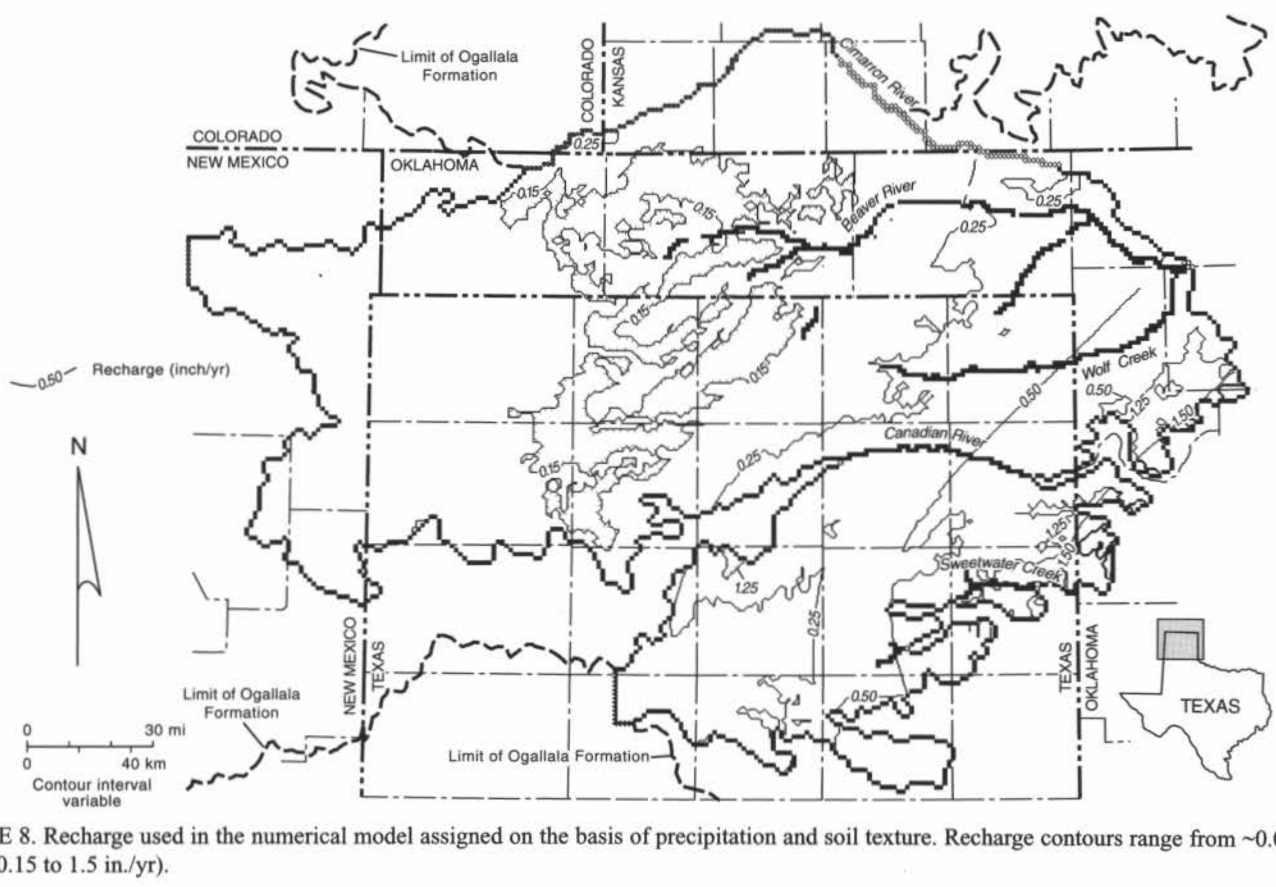

FIGURE 8. Recharge used in the numerical model assigned on the basis of precipitation and soil texture. Recharge contours range from ~0.06 to 0.6 cm/yr (0.15 to 1.5 in./yr).

Recharge estimates were furthered adjusted by soil type. GIS polygons of soil types were downloaded from U.S. Department of Agriculture (2000) and classified into eight groups (Table 1). Groups 1 to 3 have mainly loamy surface and subsurface soils, whereas Groups 4 to 7 have loamy surface but clayey subsurface soils. Groups 1 and 2 roughly correspond to the extent of the Ogallala Formation outcrop, especially south of the Canadian River. Group 4 south of the Canadian River corresponds to soils developed on the Blackwater Draw Formation (Table 1). Group 8 is made up of windblown sands that are younger deposits than the Blackwater Draw Formation. 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 1).

Groundwater recharge determined through model calibration was less than 1% of annual precipitation across about 72% of the model area. The other 99% of precipitation is assumed to have returned to the atmosphere by evapotranspiration or run off as surface water. Groundwater recharge was set at less than 2% of precipitation across 92% of the model area but was between 5 and 6% of precipitation in 3% of the area. The higher recharge rates were on sandy soils on the eastern, wetter side of the study area.

Return flow

Between 1950 and 1998, approximately 68 km^3 (55 million acre-feet) of groundwater was pumped from the Ogallala aquifer for irrigation in Texas. Average annual withdrawal for irrigation was greatest during the 1980's at approximately 1.9 km^3/yr (1.5 million acre-feet per year) (Fig. 9a). During the 1990's the total rate of irrigation withdrawal decreased to about 1.5 km^3/yr (1.2 million acre-feet per year). Irrigation water in 1998 made up, on average, 86% of total groundwater production from the Ogallala aquifer but ranged from 59 to 98%. Irrigation application rates ranged from about 5 to 16 cm/yr (0.17 to 0.52 acre-foot per acre per year) during 1960 to 1998.

Irrigation withdrawal in the Texas part of the model was distributed 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 to the entire modeling period. This assumption is reasonable because irrigation rate changed but location of irrigated fields did not change. Total county withdrawal of groundwater for irrigation for a given year was proportionately distributed across the model grid to those cells with irrigated acreage. Decadal estimates of irrigation withdrawal by county were made on the basis of rainfall and irrigation efficiencies (S. Amosson, personal communication, 2000).

An irrigation efficiency (e_i) of 100% indicates all applied irrigation is used by plants or is evapotranspired. Irrigation inefficiency ($1 - e_i$) expresses the generally unknown proportion of irrigation water that passes below the root depth and out of the reach of evapotranspiration. Return flow is the amount of irrigation water that ends up recharging the water table. Some water originally may

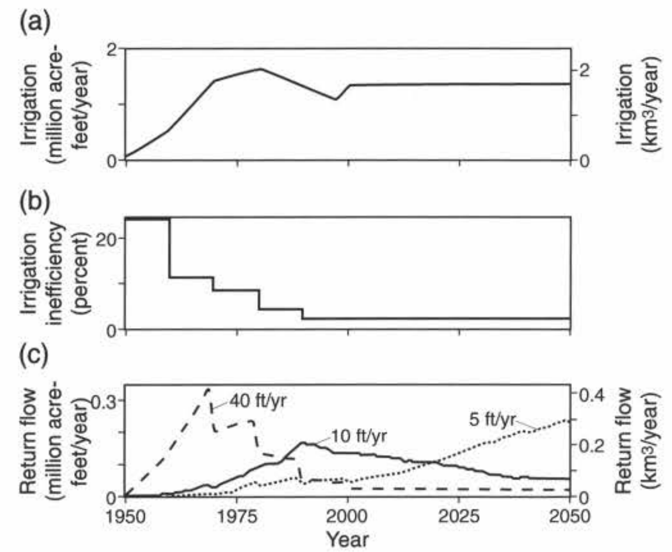

FIGURE 9. Estimation of return flow (c) from irrigation rates (a), inefficiency (b), and velocity at which water moves through the unsaturated zone. Changing depth to water and soil types were also taken into account. Irrigation inefficiency is 1.0 – irrigation efficiency. There is no lag in return flow (c) at high velocity (e.g., ~12 m/d [40 ft/d]). At lower velocity (e.g., 1.5 and 3 m/d [5 and 10 ft/d]), return flow is increasingly delayed from catching the falling water table.

have gone to increasing moisture content of the unsaturated zone and may not have reached the water table. Irrigation inefficiency probably was high during the 1940's and 1950's but decreased during the past few decades. Luckey and Becker (1999) assumed that irrigation inefficiency decreased from 24% during the 1940's and 1950's to less than 4% by the 1980's (Fig. 9b).

Return flow to the water table was estimated for the groundwater flow model on the basis of irrigation rate, inefficiency, soil type, depth to water, and velocity or rate of downward movement of water from the root zone to the water table. Irrigation inefficiency was initially set equal to 24% for the 1950's and decreased to 2% since the 1990's (Fig. 9b); simulations were also made with other loss rates. The same soil-weighting factors were applied to return flow as to recharge from precipitation (Table 1). Less return flow was predicted from irrigation on Blackwater Draw soils than on Ogallala-derived soils as if the former intrinsically have higher irrigation efficiency. Depth to water was approximated using preliminary model results without return flow. Depth to water increased through time at most model cells, as water levels were drawn down by pumping, increasing the travel time for water to move from the root zone to the water table. Accordingly, return flow may recharge the water table later than the year in which irrigation was applied, and the delay or lag may increase through time as depth to water increases. Finally, velocity of water through the unsaturated zone was assumed to lie between 1.5 and 12.2 m/yr (5 and 40 ft/yr).

Velocity of water moving downward through the unsaturated zone is an important but poorly constrained variable. Velocity through the unsaturated zone was varied to see the impact of transit time on simulated water levels. If that velocity is much greater than the rate of water-level decline (~2 m/yr [~5.5 ft/yr]), return flow quickly reaches the water table (Fig. 9c). If that downward velocity is similar to the rate of water-level decline, much of the return flow may be significantly delayed in reaching the water table, leaving more water in storage in the unsaturated zone. Figure 9c shows that at a low velocity, return flow may catch up to the water table in the future as rate of water-level decline slows down.

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 6 m (~20 ft) of drawdown between 1950 and 1998, and not much more than 6 m (~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 very well constrain the return-flow rate. Return flow may be important to future water budgets in areas that had high irrigation rates and low irrigation efficiency.

DISCUSSION

Contours of the simulated water table reasonably match the estimated 1950 water table at the start of the calibration period (Fig. 5). The estimated water table includes appreciable extrapolation error itself. Comparison of measured and simulated water levels for specific wells for 1998 at the end of the calibration period yields a model calibration error (root mean square error) of about 22.5 m (74 ft) (Fig. 10). This error has no evident bias and is less than 4% of the head drop across the Texas part of the model, whereas a typical calibration goal is 10 % for a numerical model. The calibration error includes uncertainties owing to all model parameters and inputs in the "predevelopment" calibration, including hydraulic conductivity, specific yield, pumping rates, recharge rates, return flow, and boundary conditions. This very good model calibration was obtained with negligible adjustment of parameters after data input. Ease of calibration partly reflects the use of a well-posed conceptual model and a geologically reasonable distribution of parameter values.

Early attempts at model calibration with recharge assigned uniformly across the study area and hydraulic conductivity mapped using kriging solely on the basis of variogram parameters yielded poorer calibration with root mean square error of more than 36.6 m (>120 ft). Considerable and somewhat arbitrary parameter adjustment was needed to decrease the numerical value of the calibration error. Although the calculated calibration errors of the preliminary model and the final model reported here were similar, the real calibration of the final model is better because it more closely honors original data and was obtained with negligible parameter adjustment.

Calculating model calibration error on the basis of measured and simulated water levels does not fully characterize a model. The root mean square error (RMSE) is slightly sensitive to whether hydraulic conductivity is assigned on the basis of depositional systems (RMSE = 22.5 m [74 ft]), kriged geostatistics (RMSE = 24.4 m [80 ft]), or average hydraulic conductivity (RMSE = 26.8 m [88 ft]). Depending on the purpose and scope of a model, ignoring heterogeneity may give satisfactory results. For example, a model predicting the drawdown of water levels in a well field in a small geographic area may be fairly insensitive to locally small variations in hydraulic conductivity. On the other hand, prediction of particle paths for contaminant transport calculations or groundwater-age modeling may be more sensitive at any scale to heterogeneities. Estimates of regional, long-term drawdown of water levels in extensive aquifers may also be sensitive enough to justify accounting for heterogeneity.

There is a direct relation between hydraulic conductivity and recharge rate in model calibration, everything else being held constant. If recharge rate were set higher in all or part of the model, hydraulic conductivity would have to be increased to compensate and keep model-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). The combination of mapping hydraulic conductivity using depositional systems and recharge using precipitation and soil factors was important to minimizing model error without arbitrary parameter adjustment.

Geological conditioning of maps of hydrologic properties has advantages and limitations. Chief among the advantages is that the depositional fabric or architecture of the aquifer that controls hydrologic properties is taken into account and not ignored (Koltermann and Gorelick, 1996; Fogg and others, 1998) This should result in a more realistic numerical model of groundwater flow. A key difference between geologically and nongeologically contoured maps of hydrologic properties, however, is the apparent extent of regional continuity. Examples in this paper show extensive lateral continuity of permeability channels enveloped in volumes of lower permeability areas because the depositional model implied a high degree of lateral continuity. Depositional systems

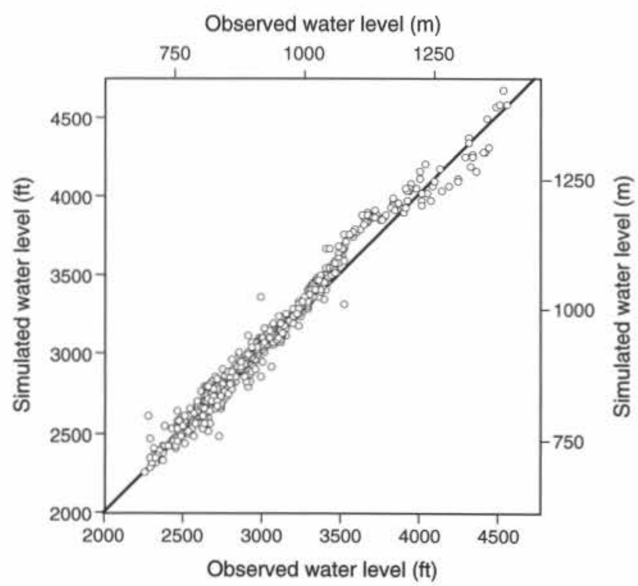

FIGURE 10. Calibration results for 1998 water-level measurements. The mean square error between observed and simulated water levels is 22.5 m (74 ft).

maps help constrain the architecture of the aquifer and distribution of hydraulic conductivity. We are also looking at whether the depositional systems maps of aquifer fabric can be used to map or predict specific yield.

Having sufficient data density to resolve fine-scale permeability features may limit the application of this geological conditioning approach. Key to our approach was using specific-capacity data to accumulate enough measurements of hydraulic conductivity to allow this detail of mapping. As previously stated, it is likely that the fine-scale details such as high-permeability channels revealed in data-rich areas probably occur also in data-poor areas. Discernment and judgment in drawing meandering trends of high hydraulic conductivity within channel lobes defined by net-sand or sand-percent maps is balanced against the uncertainty of where the "channel" axis is located. Another limitation may be the level of discernment or artistic license in a geological map. There may be multiple ways to contour and honor the hydrologic data while still reflecting the underlying geological fabric. In addition, the degree of lateral continuity implied by various depositional-systems interpretations may vary.

CONCLUSIONS

Use of appropriate data sets of spatially varying hydrogeologic parameters can facilitate obtaining well-calibrated groundwater-flow models. In this example, hydraulic conductivity was mapped consistently with trends in depositional facies and recharge was assigned on the basis of precipitation and soil type. Other parameters such as base of aquifer and predevelopment water table were mapped using extensive data. Reaching a low model-calibration error with negligible parameter adjustment raises confidence in applicability of a groundwater-flow model to aquifer management. Other factors besides calculated values of root mean square error of hydraulic head can determine how well a model may perform.

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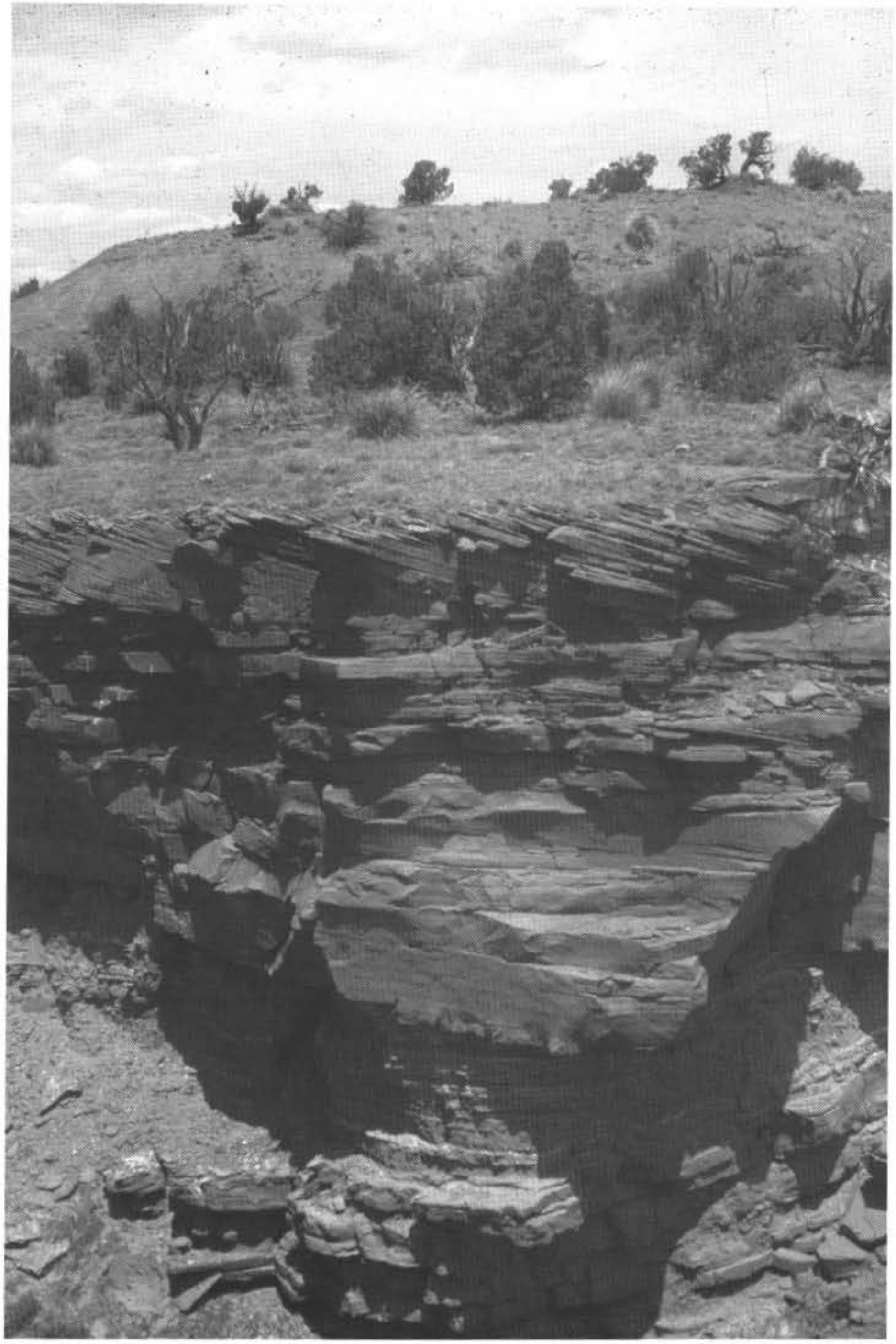

This fluvial sandstone is in the Upper Triassic Bull Canyon Formation at Bull Canyon in eastern Guadalupe County. Sandstone bodies like this are common in the Bull Canyon Formation, and make it difficult to accept the interpretation that the unit is primarily of lacustrine origin. Instead, it represents a vast riverine floodplain deposit.