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OKLAHOMA WATER RESOURCES BOARD

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

Water-Resources Investigations Report 99–4104

U.S. Department of the Interior
U.S. Geological Survey

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By Richard R. Luckey and Mark F. Becker

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Luckey, R.R., and Becker, M.F.—**Hydrogeology, water use, and simulation of flow in the High Plains aquifer in northwestern Oklahoma**—USGS/WRIR 99–4104

Printed on recycled paper

U.S. Department of the Interior
BRUCE BABBITT, Secretary

U.S. Geological Survey
CHARLES G. GROAT, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: OKLAHOMA CITY 1999

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Conversion Factors and Datum

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
acre-foot (acre-ft)	1,233	cubic meter (m^3)
Flow rate		
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
Hydraulic gradient		
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
Transmissivity		
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F - 32) / 1.8

Sea level: In this report “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly call Sea Level Datum of 1929.

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

By Richard R. Luckey and Mark F. Becker

Abstract

The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, began a three-year study of the High Plains aquifer in northwestern Oklahoma in 1996. The primary purpose of this study was to develop a ground-water flow model to provide the Water Board with the information it needs to manage the quantity of water withdrawn from the aquifer. The study area consists of about 7,100 square miles in Oklahoma and about 20,800 square miles in adjacent states to provide appropriate hydrologic boundaries for the flow model.

The High Plains aquifer includes all sediments from the base of the Ogallala Formation to the potentiometric surface. The saturated thickness in Oklahoma ranges from more than 400 feet to less than 50 feet. Natural recharge to the aquifer from precipitation occurs throughout the area but is extremely variable. Dryland agricultural practices appear to enhance recharge from precipitation, and part of the water pumped for irrigation also recharges the aquifer. Natural discharge occurs as discharge to streams, evapotranspiration where the depth to water is shallow, and diffuse ground-water flow across the eastern boundary. Artificial discharge occurs as discharge to wells.

Irrigation accounted for 96 percent of all use of water from the High Plains aquifer in the Oklahoma portion of the study area in 1992 and 93 percent in 1997. Total estimated water use in 1992 for the Oklahoma portion of the study area was 396,000 acre-feet and was about 3.2 million acre-feet for the entire study area.

Since development of the aquifer, water levels have declined more than 100 feet in small areas of Texas County, Oklahoma, and more than 50 feet in areas of Cimarron County. Only a small area of Beaver County had declines of more than 10 feet, and Ellis County had rises of more than 10 feet.

A flow model constructed using the MODFLOW computer code had 21,073 active cells in one layer and had a 6,000-foot grid in both the north-south and east-west directions. The model was used to simulate the period before major development of the aquifer and the period of development. The model was calibrated using observed conditions available as of 1998.

The predevelopment-period model integrated data or estimates on the base of aquifer, hydraulic conductivity, streambed and drain conductances, and recharge from precipitation to calculate the predevelopment altitude of the water table, discharge to the rivers and streams, and other discharges. Hydraulic conductivity, recharge, and streambed conductance were varied during calibration so that the model produced a reasonable representation of the observed water table altitude and the estimated discharge to streams. Hydraulic conductivity was reduced in the area of salt dissolution in underlying Permian-age rocks. Recharge from precipitation was estimated to be 4.0 percent of precipitation in greater recharge zones and 0.37 percent in lesser recharge zones. Within Oklahoma, the mean difference between water levels simulated by the model and measured water levels at 86 observation points is -2.8 feet, the mean absolute difference is 44.1 feet, and the root mean square difference is 52.0 feet. The simulated discharge is much larger than the estimated discharge for the Beaver River, is somewhat larger for Cimarron River and Wolf Creek, and is about the same for Crooked Creek.

The development-period model added specific yield, pumpage, and recharge due to irrigation and dryland cultivation to simulate the period 1946 through 1997. During calibration, estimated specific yield was reduced by 15 percent in Oklahoma east of the Cimarron-Texas County line. Simulated recharge due to irrigation ranges from 24 percent for the 1940s and 1950s to 2 percent for the 1990s. Estimated recharge due to dryland cultivation is about 3.9 percent of precipitation. The mean difference between the simulated and observed water-level changes from predevelopment to 1998 at 162 observation points in Oklahoma is less than 0.01 foot, the mean absolute difference is 13.1 feet, and the root mean square difference is 17.9 feet. The model simulates 7.8 cubic feet per second discharge to the Beaver River above Optima Reservoir at the end of 1997, whereas the river was actually dry to this point by this time. The model simulates a decrease in discharge to the Cimarron River and Wolf Creek that appears to be reasonable.

The sensitivity of the predevelopment-period model to changes in recharge and hydraulic conductivity was tested. Simulated water levels are sensitive to changes in both recharge

and hydraulic conductivity. Simulated discharge to streams is sensitive to recharge but is insensitive to hydraulic conductivity. Recharge and hydraulic conductivity are closely related with respect to water levels but are not related with respect to discharge to streams. The sensitivity of the development-period model to changes in specific yield and recharge due to dryland cultivation was tested. The model appears more sensitive to specific yield, but the two inputs were not varied over the same range in percent change.

The calibrated development-period model was used to simulate water-level changes from 1998 to 2020 using mean 1996-97 pumpage. The largest simulated water-level changes in Oklahoma occur in Texas County where water levels are simulated to decline 25 to 50 additional feet over a large area. Water levels also are simulated to decline 10 to 25 additional feet in two large areas of Cimarron County, two areas in Beaver County, and one area in Ellis County, all in Oklahoma. Water levels are simulated to decline more than 100 additional feet in several areas in Kansas and were simulated to decline 50 to 100 additional feet in several areas in Texas.

Introduction

The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board (referred to in this report as the Water Board), began a three-year study of the High Plains aquifer (fig. 1) in northwestern Oklahoma in 1996. The purpose of the study was to (1) provide the Water Board with the information needed to manage the quantity of water withdrawn from the High Plains aquifer, and (2) begin monitoring the water chemistry in the aquifer to determine if the quality of water is being degraded.

This study was conducted to develop a ground-water flow model of the High Plains aquifer in Oklahoma. This model was used to provide the Water Board with the information it needs to determine “maximum annual yield.” After the study, the model may be used by the Water Board for other purposes.

The Water Board is required by law to “make a determination of the maximum annual yield of fresh water to be produced from each ground water basin or subbasin” based on a minimum life of 20 years, based on the following information:

1. The total land area overlying the basin or subbasin;
2. The amount of water in storage in the basin or subbasin;
3. The rate of recharge to and discharge from the basin or subbasin;
4. Transmissivity of the basin or subbasin; and
5. The possibility of pollution of the basin or subbasin from natural sources.

This information is contained in the “Summary of Information Required by Oklahoma Ground Water Law” appendix of this report.

Purpose and Scope

This report describes the hydrology of the High Plains aquifer in Oklahoma and adjacent areas, estimates historical water use, and describes the construction, calibration, and use of a flow model of the aquifer. This report emphasizes the Oklahoma portion of the aquifer but includes parts of adjacent Colorado, Kansas, New Mexico, and Texas.

Description of Study Area

The High Plains is a major agricultural area, supported in large part by water from the High Plains aquifer (fig. 1). The aquifer underlies about 174,000 square miles in parts of eight states (Weeks and others, 1988) including about 7,100 square miles in northwestern Oklahoma. This aquifer is the shallowest and most abundant source of ground water in the region, and the irrigated agricultural economy of the region depends primarily on this aquifer.

The study area in Oklahoma consists of about 7,100 square miles and covers all or part of Beaver, Cimarron, Dewey, Ellis, Harper, Texas, and Woodward Counties (fig. 2). The High Plains aquifer extends into adjacent states; to provide appropriate hydrologic boundaries for the flow model in Oklahoma, the study area was expanded to include about 3,000 square miles in Colorado, 7,000 square miles in Kansas, 2,300 square miles in New Mexico, and 8,500 square miles in Texas. Less effort was expended to calibrate the model in those portions of the study area remote from Oklahoma than was for areas closer or within Oklahoma. The boundaries of the study area are the erosional extent of the aquifer on the west, the extent of the aquifer or the Canadian River on the south, the extent of the aquifer or an arbitrary line at about 99.7° longitude in Kansas on the east, and the extent of the aquifer or the Arkansas River on the north. The area of the High Plains aquifer extending eastward from about 99.7° longitude in Kansas was not included in the study area due to the distance from Oklahoma. Any stresses applied to the excluded portion of the aquifer would have no effect on the Oklahoma portion of the aquifer.

The Oklahoma High Plains, like most of the High Plains, has a middle-latitude, dry-continental climate with abundant sunshine, moderate precipitation, frequent winds, low humidity, and high evaporation (Weeks and others, 1988, p. 3). Normal precipitation (1961-90) in the Oklahoma portion of the study area ranges from less than 16 to more than 24 inches per year with most of the panhandle receiving less than 22 inches per year (Oregon Climate Service, 1999). The panhandle refers to that part of Oklahoma west of 100° longitude. Precipitation is even less in parts of the Colorado and New Mexico portions of the study area. Precipitation is highly variable from year to year and major droughts occurred in the 1930s and 1950s (fig. 3). The 1980s tended to be wetter than average and the 1990s had closer to average precipitation. Much of the precipitation occurs as a result of summer thunderstorms, resulting in highly variable rainfall amounts. About 75 percent of the annual pre-

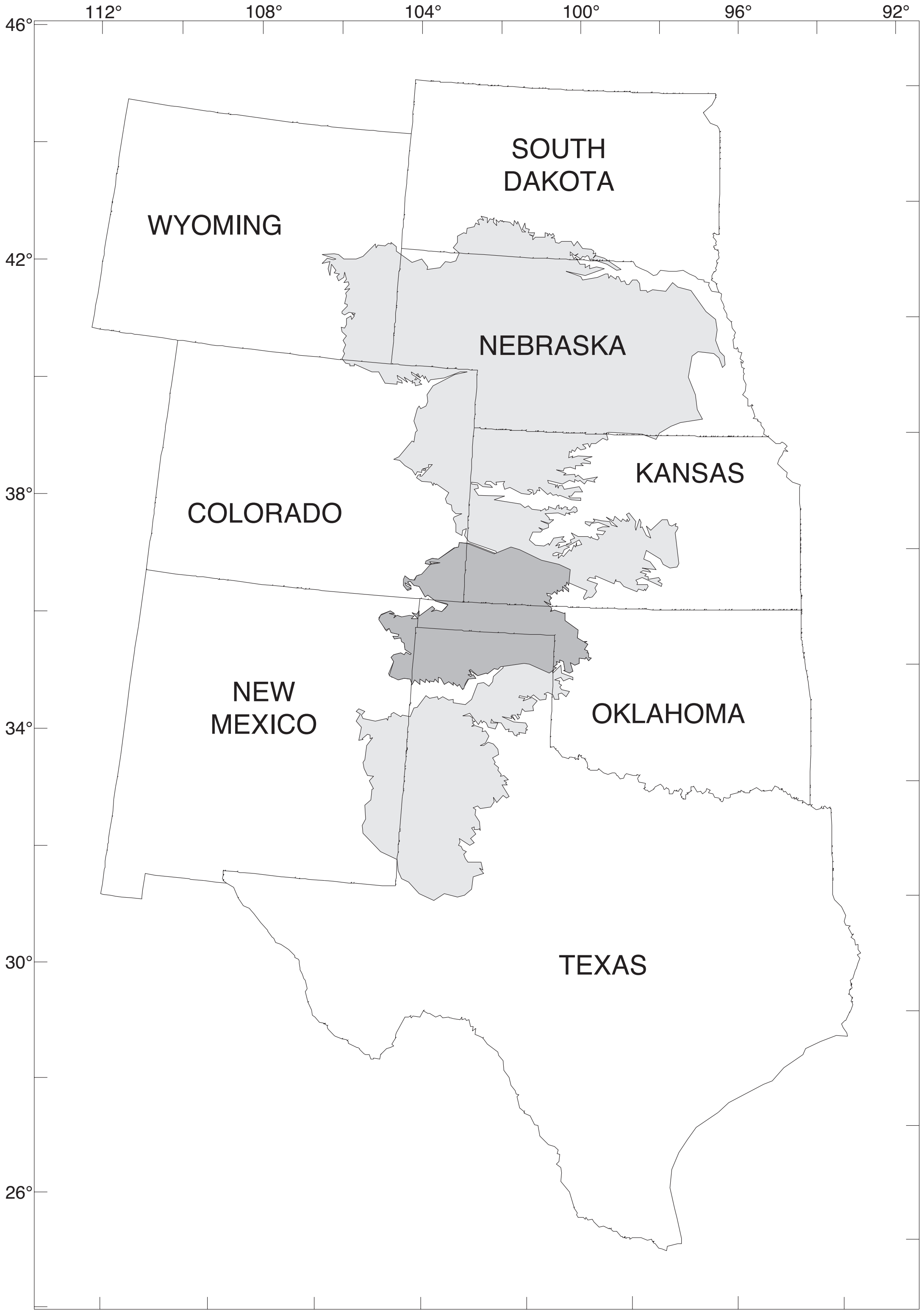


Figure 1. Location of study area (darker shade). Lighter shade is extent of High Plains aquifer outside the study area.

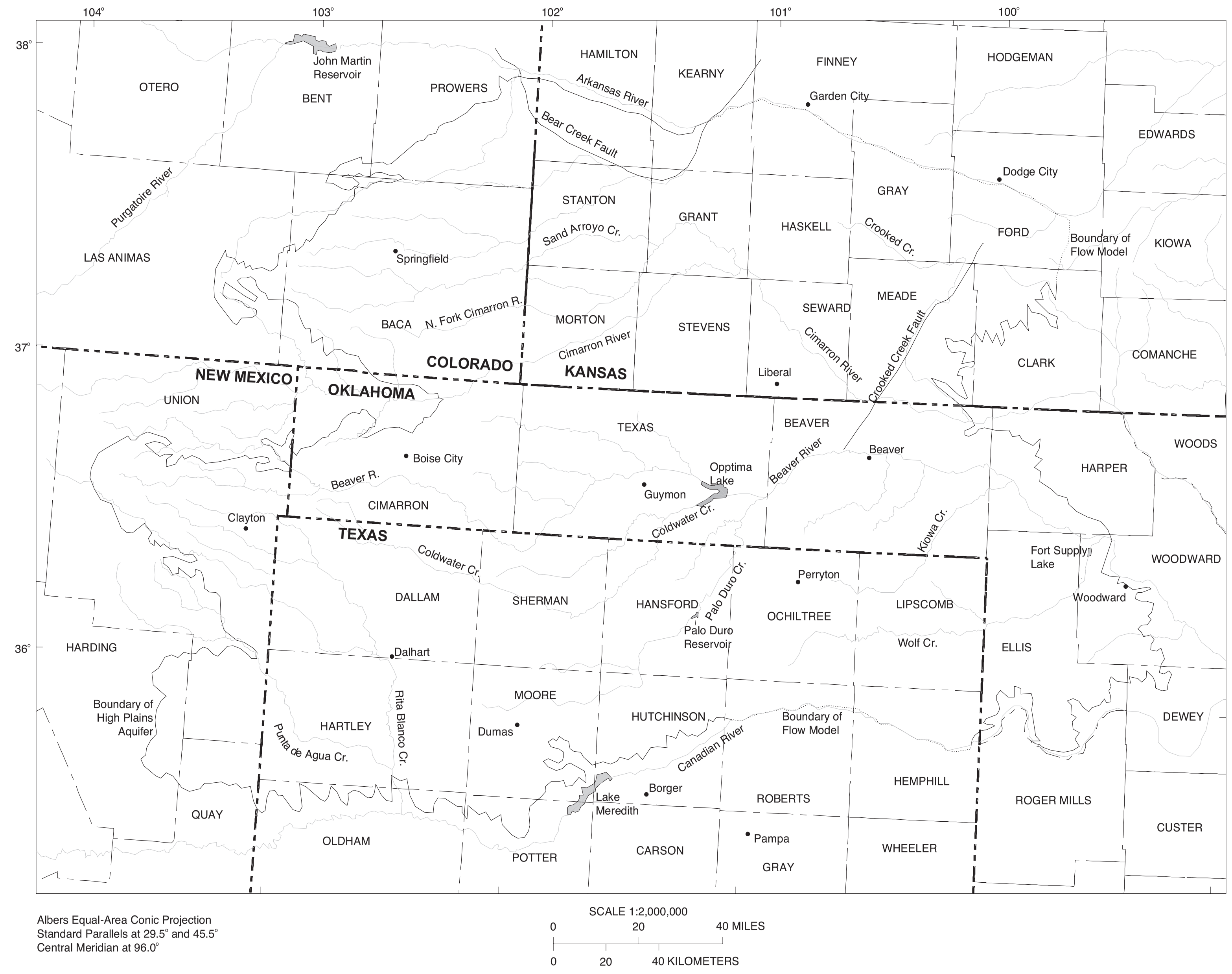


Figure 2. Geographic features within the study area.

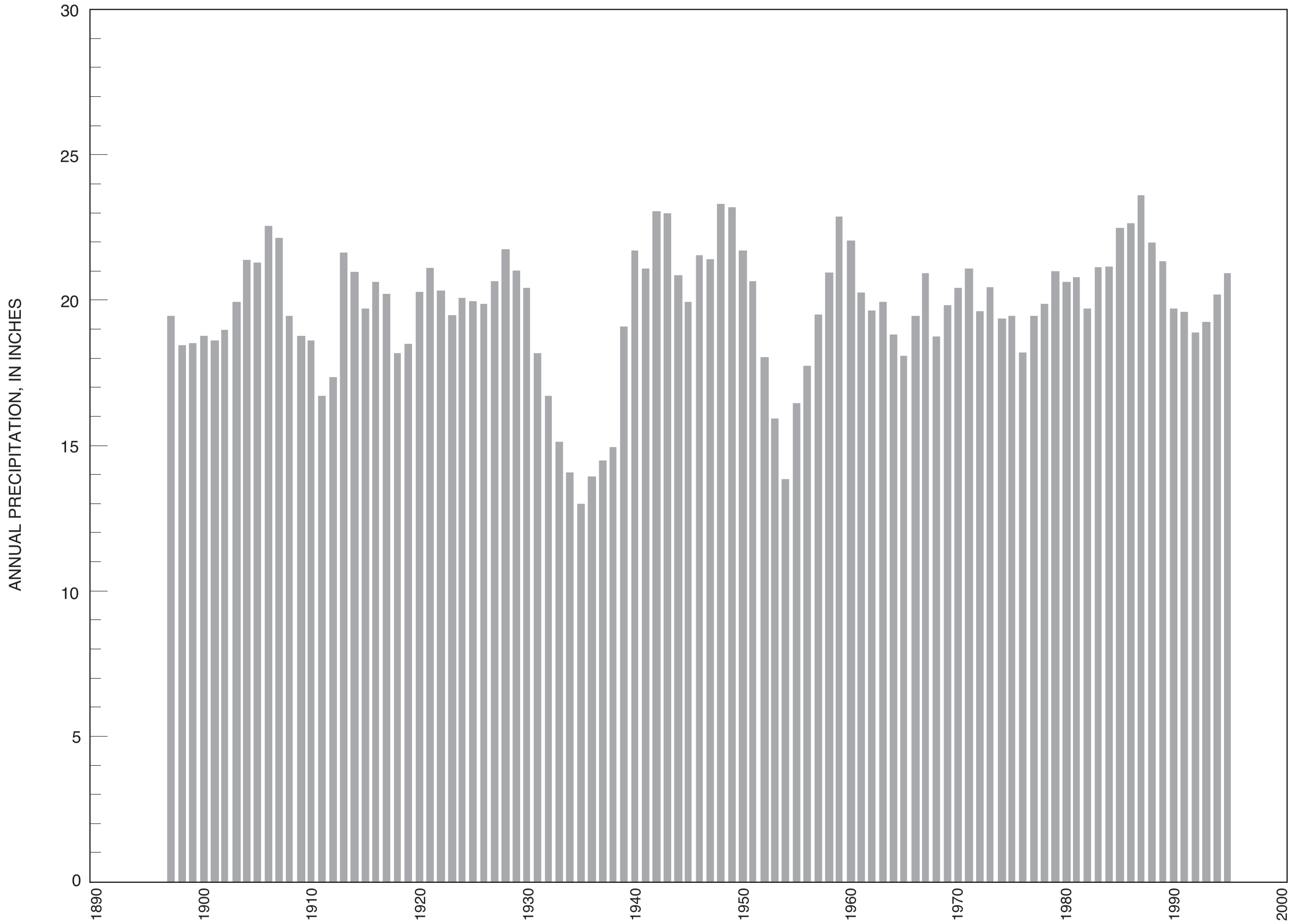


Figure 3. Five-year moving-average annual precipitation for the Panhandle Climatic Division of Oklahoma. Data from U.S. Department of Commerce, National Climatic Data Center.

cipitation falls in May through September. Winters are generally dry, although snow and blizzards are not uncommon in the northern and western parts of the study area. Less than 10 percent of the annual precipitation falls in November through February. References to precipitation and other climate variables in this report are based on data in the annual climate summaries of the various states (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1951-97) unless otherwise noted.

July is the hottest month with a mean 1961-90 temperature of about 80°F in the Oklahoma portion of the study area. Maximum temperatures exceed 100°F most years, and exceed 90°F about 75 days per year. January is the coldest month with a mean 1961-90 temperature of about 33°F. Minimum temperatures are less than 0°F in many years and are less than 32°F about 120 days a year.

Winds are common and they, combined with high summer temperatures and frequent low humidity, cause high evaporation and transpiration rates. The prevailing wind is from the south with a mean annual speed of about 14 miles per hour (U.S. Environmental Science Services Administration, 1968, p. 74). The mean annual humidity is about 55 percent (U.S. Environmental Science Services Administration, 1968, p. 63). Class A pan evaporation ranges from about 80 inches per year at the western edge to over 90 inches per year over much of the study area (Gutentag and others, 1984, fig. 2).

Most of the study area is in the Great Plains physiographic province (Fenneman, 1931); the extreme eastern part lies in the Osage Plains section of the Central Lowlands province. The topography is generally flat to gently rolling although it is broken along the drainages. Some areas of sand dunes exist and are primarily on the north side of the major drainages; most are stabilized by vegetation. The altitude of land surface ranges from over 5,800 feet above sea level in Union County, New Mexico, to about 2,000 feet in Woodward County, Oklahoma.

The major drainages within the study area are those of the Cimarron River, Beaver River, and Wolf Creek (fig. 2). The Arkansas River and Canadian River form part of the boundary of the study area. The headwaters of the Cimarron River are west of the High Plains. The Cimarron River has some perennial flow before it enters the High Plains, but that flow quickly disappears after the river enters the High Plains. The Cimarron River was once perennial just east of 101 longitude (Gutentag and others, 1981, p. 43-45), but the start of perennial flow had moved considerably downstream by 1997 (Luckey and Becker, 1998, p. 20). A tributary of the Cimarron River, Crooked Creek, drains the northeast part of the study area in Kansas. Most of the headwaters of the Beaver River are on the High Plains. The river was once perennial west of Guymon, Oklahoma, but by 1997, it seldom flowed upstream of Optima Lake (fig. 2). Its major tributaries, Coldwater Creek, Palo Duro Creek, and Kiowa Creek, drain much of the study area in Oklahoma and Texas. Wolf Creek originates on the High Plains and drains the southeast part of the study area in Oklahoma and Texas. It was once perennial over most of its reach, and in 1997, it still had flow as far west as 10038¢ longitude (Luckey and Becker, 1998, p. 25).

Large reservoirs that affect streamflow on the High Plains have been constructed within or near the study area. These reservoirs include Lake Meredith on the Canadian River in Texas, Fort Supply Lake on Wolf Creek in Oklahoma, Palo Duro Reservoir on Palo Duro Creek in Texas, Optima Lake on the Beaver River in Oklahoma, and John Martin Reservoir on the Arkansas River in Colorado (fig. 2).

The population of the study area, based on 1990 county census data, is about 150,000. The most populous towns in the Oklahoma portion of the study area and their 1990 population are Woodward (12,340), Guymon (7,803), Beaver (1,584), and Boise City (1,509). Springfield (1,475) is the most populous town in the Colorado portion of the study area; Liberal (16,573) is the most populous town in the

Kansas portion; Clayton (2,487) is the most populous town in the New Mexico portion; and Dumas (12,871) is the most populous town in the Texas portion.

The economy of the study area is based largely on agriculture, natural gas and petroleum production, and related service industries. Based on the Census of Agriculture (U.S. Department of Commerce, 1992), the estimated value of crops and livestock in the study area in 1992 was about $4.5 billion. For the Oklahoma portion of the study area, the estimated value of crops and livestock was about $880 million. Cattle account for much of the value of agricultural products; in 1992 there were about 2.7 million cattle in the study area; this number increased to 2.9 million in 1997. The estimated number of cattle in the Oklahoma portion of the study area was 620,000 in 1992 and 750,000 in 1997. Swine account for a smaller, but rapidly growing, segment of agriculture. The estimated number of swine in the Oklahoma portion of the study area was 20,000 in 1992 and increased to 1.4 million in 1997. A pork processing plant in Guymon, Oklahoma, processes about 16,000 head per day, six days a week (Seaboard Corp., written commun., 1997). This plant has created economic growth and increased population in the Oklahoma panhandle, particularly in Texas County.

Agricultural land use for the entire study area was mapped for 1978 and irrigated land was mapped for 1980 (Thelin and Heimes, 1987). However, the mapping for 1978 did not include irrigated wheat (Thelin and Heimes, 1987, p. 14), a major irrigated crop in the study area, and thus underestimated irrigated crop land and overestimated dry crop land. The Census of Agriculture (U.S. Department of Commerce, 1949-92) reported irrigated crop land and total crop land for 1978. Based on both land-use mapping (Thelin and Heimes, 1987) and the Census of Agriculture (U.S. Department of Commerce, 1949-92), the study area in 1978 was about 57 percent rangeland, 29 percent dry crop land, and 14 percent irrigated crop land. The Oklahoma portion of the study area in 1978 was about 56 percent rangeland, 36 percent dry crop land, and 8 percent irrigated crop land. Since 1978, the percentage of irrigated land may have decreased and the percentage of dry crop land may have increased. The Census of Agriculture (U.S. Department of Commerce, 1949-92) reported an 8 percent decrease in irrigated crop land between 1978 and 1992 for the study area and a 2 percent decrease for the Oklahoma portion of the study area. In the late 1800s, when the area was first homesteaded, most of the land was open range, but some dryland farming of small grains and row crops was attempted. Wheat has generally been the dominant crop in the study area, in terms of acreage harvested. Corn was the number two crop in 1992 but this has not always been so. The following table is based on the Census of Agriculture (U.S. Department of Commerce, 1949-92):

Crop	Harvested acres		
	1954	1974	1992
Wheat	2,300,000	3,100,000	2,600,000
Corn	8,000	700,000	800,000
Sorghum	2,400,000	1,200,000	700,000
Hay	100,000	200,000	300,000
Other small grains	52,000	8,000	11,000
Miscellaneous	54,000	12,000	54,000

Harvested acreage is much less than total crop land because not all crop land is harvested each year, particularly dry crop land. For example, wheat fields may be grazed rather than harvested if the crop is poor or crop prices are low.

Previous Studies

Several studies of the water resources of the Oklahoma High Plains have been conducted, starting with Texas County (Schoff, 1939) and Cimarron County (Schoff, 1943). Marine and Schoff (1962) reported on the ground-water resources of Beaver County, and Wood and Stacy (1965) reported on Woodward County. Wood and Hart (1967) reported on the ground-water resources of Texas County; Morton and Goemaat (1973) reported on Beaver County; Sapik and Goemaat (1973) reported on Cimarron County; Hart and others (1976) reported on the three panhandle counties; and Morton (1980b) reported on the area east of the panhandle. Other studies that considered the High Plains aquifer and underlying Permian-age rocks are described by Irwin and Morton (1969) and Morton (1973). A flow model of Texas County was constructed by Morton (1980a) for purposes similar to those of this report. Havens and Christenson (1984) constructed a model of the Oklahoma High Plains to project water-level changes and saturated-thickness changes to 1993 and 2020.

McLaughlin (1954) and Hershey and Hampton (1975) reported on the ground-water resources of the Colorado portion of the study area. McLaughlin (1946), Gutentag and others (1981), and Stullken and others (1985) reported on the ground-water resources of the Kansas portion of the study area. Cooper and Davis (1967) reported on the ground-water resources of the New Mexico portion of the study area. Seni (1980) and Knowles and others (1982a, 1982b) reported on the ground-water resources of the Texas portion of the study area.

A five-year study of the entire High Plains aquifer covering parts of eight states was initiated by the U.S. Geological Survey in 1978 (Weeks, 1978) as part of the Regional Aquifer-System Analysis. Major reports produced by that study include Gutentag and others (1984), Luckey and others (1986), Thelin and Heimes (1987), Luckey and others (1988), and Weeks and others (1988). Specific products for the Oklahoma portion of the aquifer included a base-of-aquifer map (Havens, 1982a), a 1980 water-table map (Havens, 1982b), a predevelopment water-table map (Havens, 1982c), a saturated-thickness map (Havens, 1982d), and a water-level change map (Havens, 1983). The maps and data sets (Ferrigno, 1986) developed by the eight-state High Plains study provided much of the basis for this study.

Geology

The geologic units of interest in this report range in age from Permian to Quaternary. Gutentag and others (1984) presented a comprehensive description of the geology of the High Plains region, and Hart and others (1976) and Irwin and Morton (1969) provided a more specific discussion of the geology of the Oklahoma portion of the study area. A summary of the geologic units within the study area is shown in table 1.

The study area includes the Anadarko Basin, the Hugoton Embayment, and the Dalhart Basin (fig. 4). These sedimentary basins are bounded by the Amarillo Uplift to the south (south of the area shown in figure 4) and the Sierra Grande Uplift to the west. Local structural features are the Cimarron Arch, extending north-south across eastern Cimarron County, Oklahoma, into Texas, and an unnamed positive feature located in the southwest corner of Beaver County, Oklahoma, and adjacent areas where Permian-age sediments are exposed at land surface. Faults that have displaced Permian- through Tertiary-age sediments are the Bear Creek Fault in Kansas south of the Arkansas River and the Crooked Creek Fault in Kansas and Oklahoma in the eastern part of the study area. These faults offset the base-of-aquifer surface and cause abrupt changes in saturated thickness.

The topography of the pre-Tertiary surface and salt dissolution in underlying Permian-age rocks controlled the deposition of the Tertiary sediments and, consequently, their thickness. Where the pre-Tertiary surface was topographically high, the Tertiary sediments tend to be thinner and where the pre-Tertiary surface was topographically low, the overlying Tertiary sediments tend to be thicker (Hart and others, 1976, p. 13). Considerable salt dissolution in the underlying Permian-age rocks probably occurred during deposition of the Tertiary sediments (Gustavson and others, 1980, p. 32) and, where dissolution

Table 1. Generalized section of geologic units (modified from Morton and Goemaat, 1973; Hart and others, 1976; and Gutentag and others, 1984)

System	Series	Geologic unit		Approximate thickness (feet)	Physical character
Quaternary	Pleistocene and Holocene	Dune sand		0 to 50	Light-brown, rounded to subrounded, fine to medium sand with small amounts of clay, silt, and coarse sand. Formed into hills, ridges, and mounds.
		Valley-fill deposits		0 to 60	Light-brown to gray, clay, silt, sand, and gravel. Associated with present streams.
Tertiary	Miocene	Ogallala Formation		0 to 600	Brown to light tan, salmon, pink, and various pastel shades, clay, silt, sand, and gravel. Caliche common near surface; remainder mostly unconsolidated, but may contain caliche.
Cretaceous	Upper Cretaceous	Colorado Group	Greenhorn Limestone		Gray limestone and calcareous shale.
			Graneros Shale		Gray to black shale.
	Lower Cretaceous	Dakota Sandstone		0 to 200	Buff to light-brown, fine to medium grained sandstone with interbedded shale.
		Glencairn Formation (Kiowa Shale)		0 to 65	Gray to black shale with some fine-grained sandstone in upper part.
		Lytle Sandstone (Cheyenne Sandstone)		0 to 125	White to buff, fine to medium-grained sandstone with some interbedded shales. Unit contains some conglomerate in lower part.
Jurassic	Upper Jurassic	Morrison Formation		0 to 470	Varicolored shale, sandstone, limestone, dolostone, and conglomerate.
		Exeter Member of Entrada Sandstone		0 to 50	White to buff, fine to medium-grained sandstone.
Triassic	Upper Triassic	Dockum Group	Upper sandstone	0 to 450	Varicolored claystone, siltstone, sandstone, limestone, and conglomerate.
			Lower sandstone	0 to 200	Varicolored, fine to medium-grained sandstone with some clay and shale.
Permian		Undifferentiated red beds		>3,000	Predominately red or orange, shale, mudstone, siltstone, sandstone, dolostone, and anhydrite with some gypsum, limestone and halite.

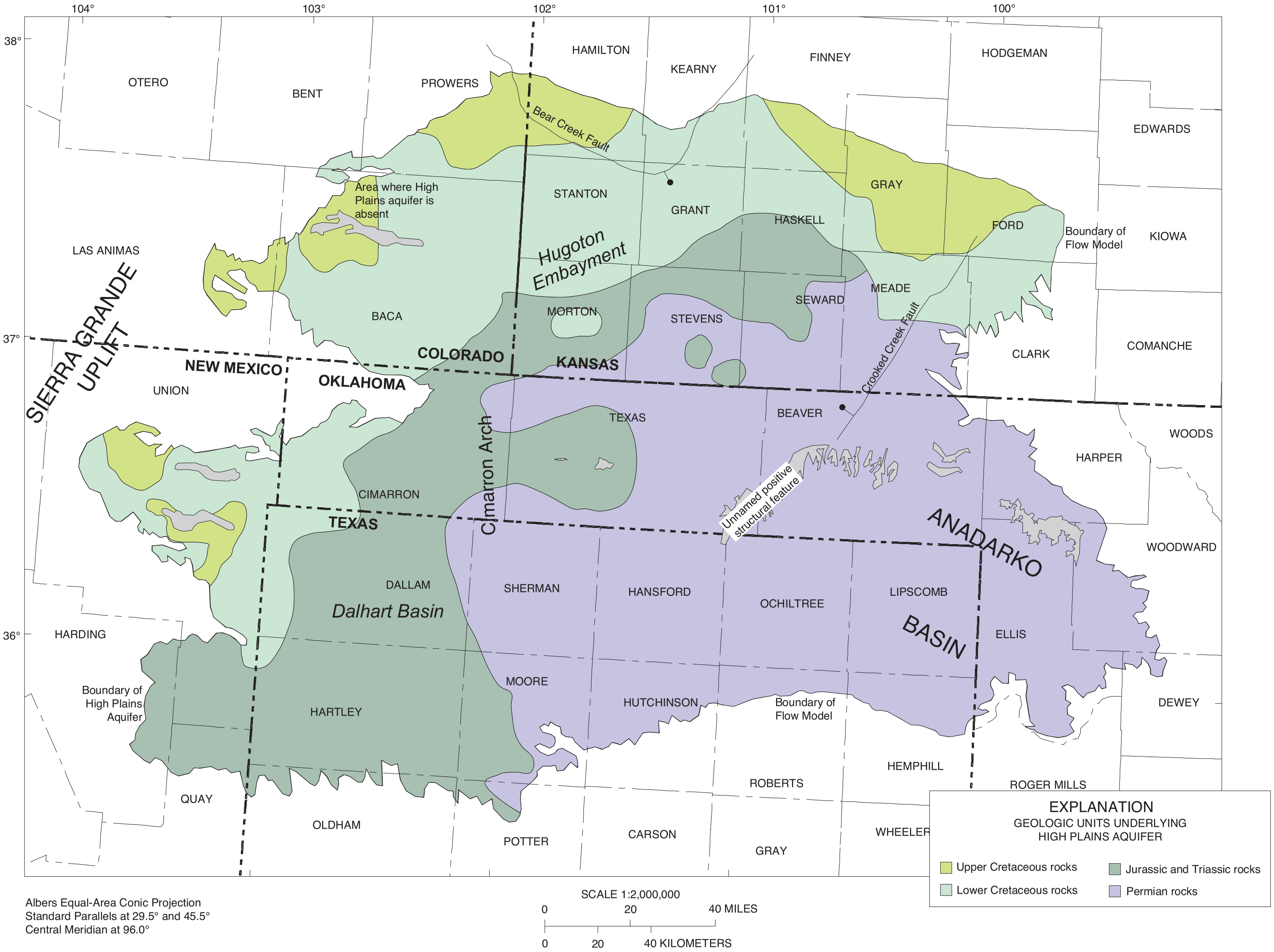


Figure 4. Major structural features and geologic units underlying the High Plains aquifer (modified from Hart and others, 1976, and Gutentag and others, 1984).

occurred, it created collapse features, which in turn caused the Tertiary sediments to be thicker.

Permian-age rocks directly underlie Tertiary-age sediments in much of the eastern half of the study area (fig. 4). Permian-age rocks consist of undifferentiated shales, mudstones, siltstones, and sandstones. Some thin beds of gypsum, anhydrite, limestone, and dolomite also are present. Permian-age rocks are readily identified by their orange to brick-red colors and can exceed several thousand feet in thickness within the study area. Permian-age rocks are at land surface in some areas in the eastern part of the study area.

Unconformably overlying the Permian-age rocks is the Dockum Group of Late Triassic age. The Dockum Group is composed of sandstone with interbedded shales grading upward to a shaly sandstone or siltstone. The Dockum Group is present in Cimarron and western Texas Counties in Oklahoma, most of the Kansas portion of the study area, the western portion in Texas, and all of the portions in Colorado and New Mexico.

Sediments of Late Jurassic age unconformably overlie the Dockum Group and consist of two geologic units, the Exeter Member of the Entrada Sandstone and the overlying Morrison Formation. The Exeter Member has a maximum thickness of about 50 feet in Oklahoma (Hart and others, 1976, table 1) and is a well sorted sandstone. The overlying Morrison Formation has a maximum thickness of 470 feet in Oklahoma. Most of the western and northern portions of the study area are underlain by sediments of Late Jurassic age.

Cretaceous-age sediments unconformably overlie the Jurassic-age sediments and include the Lytle Sandstone, Glencairn Formation, Dakota Sandstone, and the Colorado Group. The Lytle Sandstone (Kues and Lucas, 1987), previously called the Cheyenne Sandstone, is present in the western and northern one-third of the study area. The Lytle Sandstone, a thinly to massively bedded sandstone with some interbedded shales, has a maximum thickness in Oklahoma of about 125 feet (Hart and others, 1976, table 1). The Glencairn Formation (Kues and Lucas, 1987), previously called the Kiowa Shale, is a fossiliferous shale with interbedded sandstones and has a maximum thickness in Oklahoma of about 65 feet. The Dakota Sandstone lies unconformably upon the Glencairn Formation and has a maximum thickness in Oklahoma of 200 feet. Overlying the Dakota Sandstone is the Colorado Group composed of interbedded shales and limestones.

The Ogallala Formation of late Tertiary age is a remnant of a vast eastward-sloping alluvial plain that once reached as far west as the present Rocky Mountains. The Ogallala Formation is composed of sediments eroded from ancestral Rocky Mountains that were deposited eastward by aggrading streams filling valleys on the pre-Ogallala surface. The dominant mode of deposition of the Ogallala Formation likely was by braided streams that coalesced to form broad alluvial fans (Gutentag and others, 1984, p. 23). In a braided-stream environment, coarser sediments are deposited within the stream channel, whereas finer sediments are the result of over-bank deposits. As the streams meandered across the flood plains, the sediments were continuously reworked, resulting in extremely heterogeneous deposits. The Ogallala Formation has been compared to a widespread wet alluvial-fan system (Seni, 1980, p. 28). The depositional environment was further complicated because salt dissolution was actively occurring in underlying Permian-age rocks, resulting in collapse structures repeatedly forming within the Ogallala Formation. Sinkholes likely were filled with fine-grained lake deposits, but channels leading into sinkholes could contain coarse-grained sediments because of the high-energy depositional environment. Although the deposition environment of this unit was primarily fluvial, periods of eolian deposition occurred. The composition of the Ogallala Formation is a heterogeneous clastic material with some interbedded calcium carbonate layers, particularly in the upper part. Grain sizes range from clay to gravel with varying degrees of sorting. The maximum thickness of the Ogallala Formation in Oklahoma is 650 feet (Hart and others, 1976, table 1).

Quaternary-age deposits consist of alluvium and terrace deposits, collectively called valley-fill deposits, and dune deposits. The Quaternary-age deposits are generally associated with streams crossing the High Plains. The alluvium is limited to the current channel of the stream, and the terrace deposits are associated with previous levels of the stream. Dune deposits tend to be located on the northern sides of major streams and are formed by the prevailing southerly winds redistributing the valley-fill deposits. Sediments in the valley-fill deposits range in size from clay to gravel, whereas most of the dune deposits consist of fine to medium sand.

Hydrology

The High Plains aquifer in the study area consists of the saturated part of the Ogallala Formation and any saturated material of Quaternary age that is hydraulically connected with the Ogallala Formation. The High Plains aquifer was previously called the Ogallala aquifer over much of the High Plains, but the new name came into use because the High Plains aquifer consists of additional geologic units, particularly in Nebraska, South Dakota, and Wyoming. The High Plains aquifer can be conceptualized as a vast three-dimensional subsurface reservoir, much like a rigid sponge. The aquifer is composed of clay, silt, sand, and gravel with the sand and gravel sections contributing most of the water to wells, although considerable water is stored in the clay and silt sections. The High Plains aquifer is the shallowest, and generally the most abundant, source of fresh water in the study area.

Depth to water in the Oklahoma High Plains ranges from less than 10 feet in parts of Ellis, Harper, and Woodward Counties and along the lower reaches of the stream valleys to more than 300 feet in parts of Cimarron and Texas Counties. Depth to water can change dramatically over relatively short distances, primarily because of changes in land-surface altitude. Land surface has much more relief than does the underlying water table. The range in measured depths to water by county in Oklahoma for January 1998:

County	Depth to water (feet)	
	Minimum	Maximum
Beaver	9	240
Cimarron	29	332
Ellis	2	216
Harper	6	54
Texas	65	329
Woodward	2	157

Other freshwater aquifers exist below the High Plains aquifer, particularly in the western part of the study area. Permian beds also may yield some fresh water but are used only if there is no alternative. The Exeter Member of the Entrada Sandstone can provide sufficient water for stock and domestic use. The Dakota Sandstone, the Lytle Sandstone, and the Dockum Group all provide sufficient water for stock and domestic use and may provide sufficient water for irrigation, particularly when combined with the High Plains aquifer or with each other. The Dakota Sandstone yields as much as 150 gallons per minute; the Lytle Sandstone yields as much as 500 gallons per minute; the Exeter Member yields as much as 20 gallons per minute; and the Dockum Group yields as much as 500 gallons per minute (Hart and others, 1976, table 1 and p. 17). However, average yields are generally much less. In contrast, with proper test drilling and well completion, the High Plains aquifer can generally yield at least 500 gallons per minute, except where it is very thin, and can yield as much as 2,000 gallons per minute in some places.

Base of Aquifer

The base of the High Plains aquifer generally occurs at the base of the Ogallala Formation but in a few areas near the eastern edge, may occur at the base of Quaternary-age deposits. Permian-age rocks directly underlie the High Plains aquifer in the eastern half of the study area (fig 4). Permian-age rocks are very distinctive and easy to identify in borehole cuttings, so the base of the aquifer can be clearly defined. Rocks of Triassic, Jurassic, and Cretaceous age underlie the aquifer in the western half of the study area. These rocks usually are easy to identify in a borehole by color or texture, although in some places, the base of the aquifer may be somewhat more difficult to identify.

A new base-of-aquifer map was prepared for the Oklahoma portion of the study area (fig. 5); for the remainder of the study area, the existing base-of-aquifer map was used (Weeks and Gutentag, 1981; Cederstrand and Becker, 1998a). In preparing the new map, more effort was spent on the area east of Guymon, Oklahoma. The map prepared by Havens (1982a) was used with only minor modifications west of Guymon where the original map was deemed satisfactory for the model. The map was prepared using data from about 550 wells that penetrated Permian-age rocks, altitudes of land surface at about 500 points where Permian-age rocks outcropped, and the existing base-of-aquifer maps (Havens 1982a; Weeks and Gutentag, 1981; Cederstrand and Becker, 1998a). East of the Cimarron-Texas County line, the topography of the base of aquifer is quite chaotic with local relief sometimes quite large. There are prominent pre-Ogallala hills in northern Texas County and prominent sinkholes in Beaver and Ellis Counties. Weeks and Gutentag (1981) show similar sinkholes in the Kansas and Texas portions of the study area.

Potentiometric Surface

The January 1998 potentiometric surface of the High Plains aquifer in Oklahoma is shown in figure 6 and is based on a network of about 220 wells that are measured annually by the Water Board. The potentiometric surface is the surface to which water will rise in a tightly cased well and is generally synonymous with the term water table over much of the High Plains. The surface generally slopes to the east, although locally it slopes toward streams that drain the aquifer. The gradient is larger in the west, where it is 20 to 30 feet per mile, and is smaller in the east, where it is 5 to 20 feet per mile. In eastern Texas County, Oklahoma, the gradient is locally toward Coldwater Creek and the Beaver River. In Ellis and Woodward Counties, Oklahoma, the gradient is locally toward Wolf Creek.

The potentiometric surface of the High Plains aquifer in Oklahoma is more than 4,600 feet above sea level near the New Mexico-Oklahoma state line and is less than 2,000 feet above sea level near the boundary of the study area in Harper and Woodward Counties. On a regional scale, water moves from west to east perpendicular to the potentiometric-surface contours.

The potentiometric surface has been lowered by pumping, particularly in northern and south-central Texas County, Oklahoma. The obvious change in gradient shown in figure 6 north of Guymon, Oklahoma, is due to pumping. Prior to large-scale development of the High Plains aquifer for irrigation, the potentiometric surface was much more uniform in this area (Havens, 1982c).

Saturated Thickness

The January 1998 saturated thickness of the High Plains aquifer in Oklahoma is shown in figure 7. The saturated thickness map was constructed by subtracting the base-of-aquifer map from the 1998 potentiometric-surface map and manually correcting the map in some areas near the aquifer boundary or outcrops. The corrections were necessary because the 1998 potentiometric-surface map and the base-of-aquifer map may not exactly match in areas where the saturated thickness should

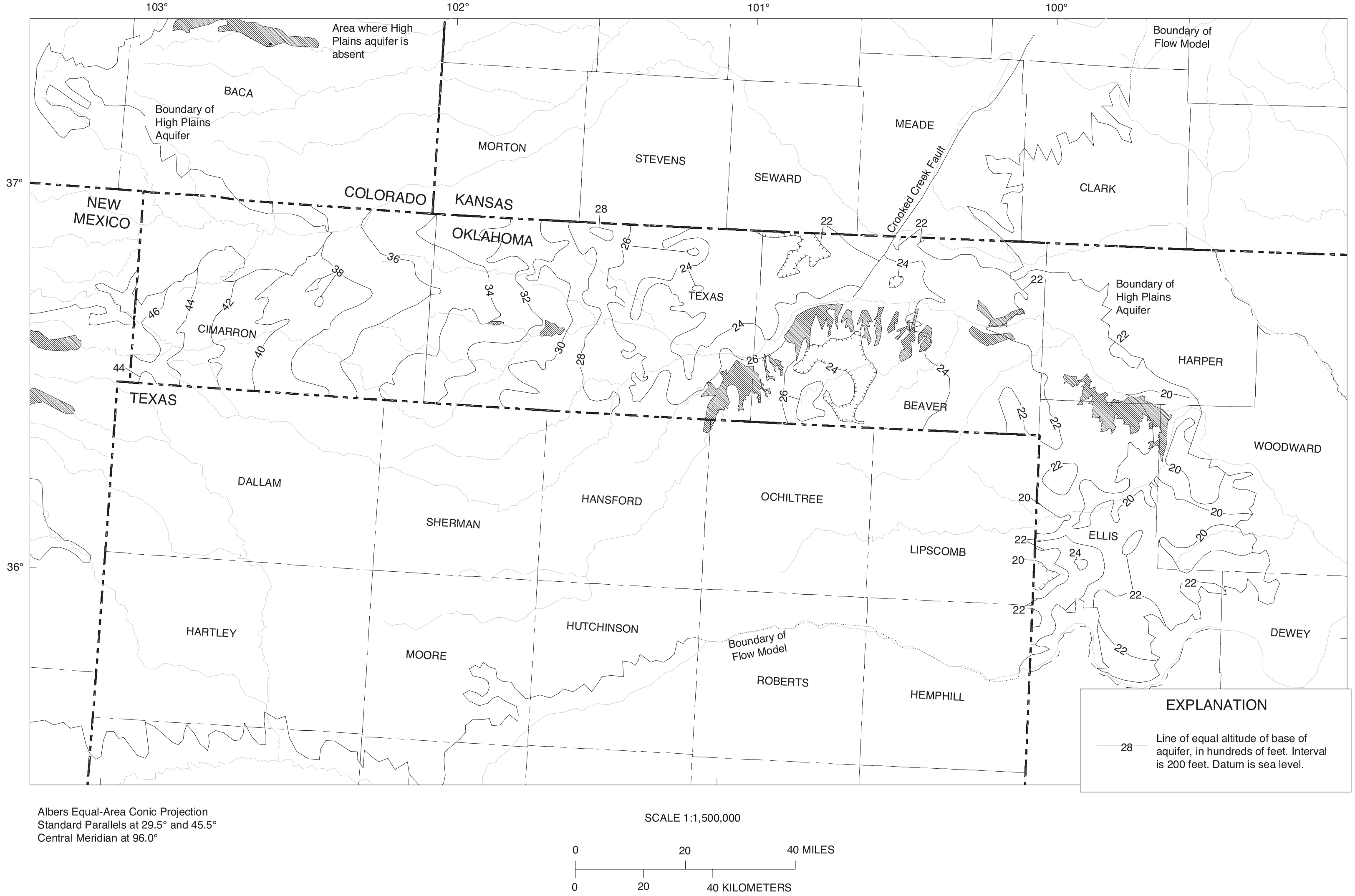


Figure 5. Altitude of the base of the High Plains aquifer in Oklahoma.

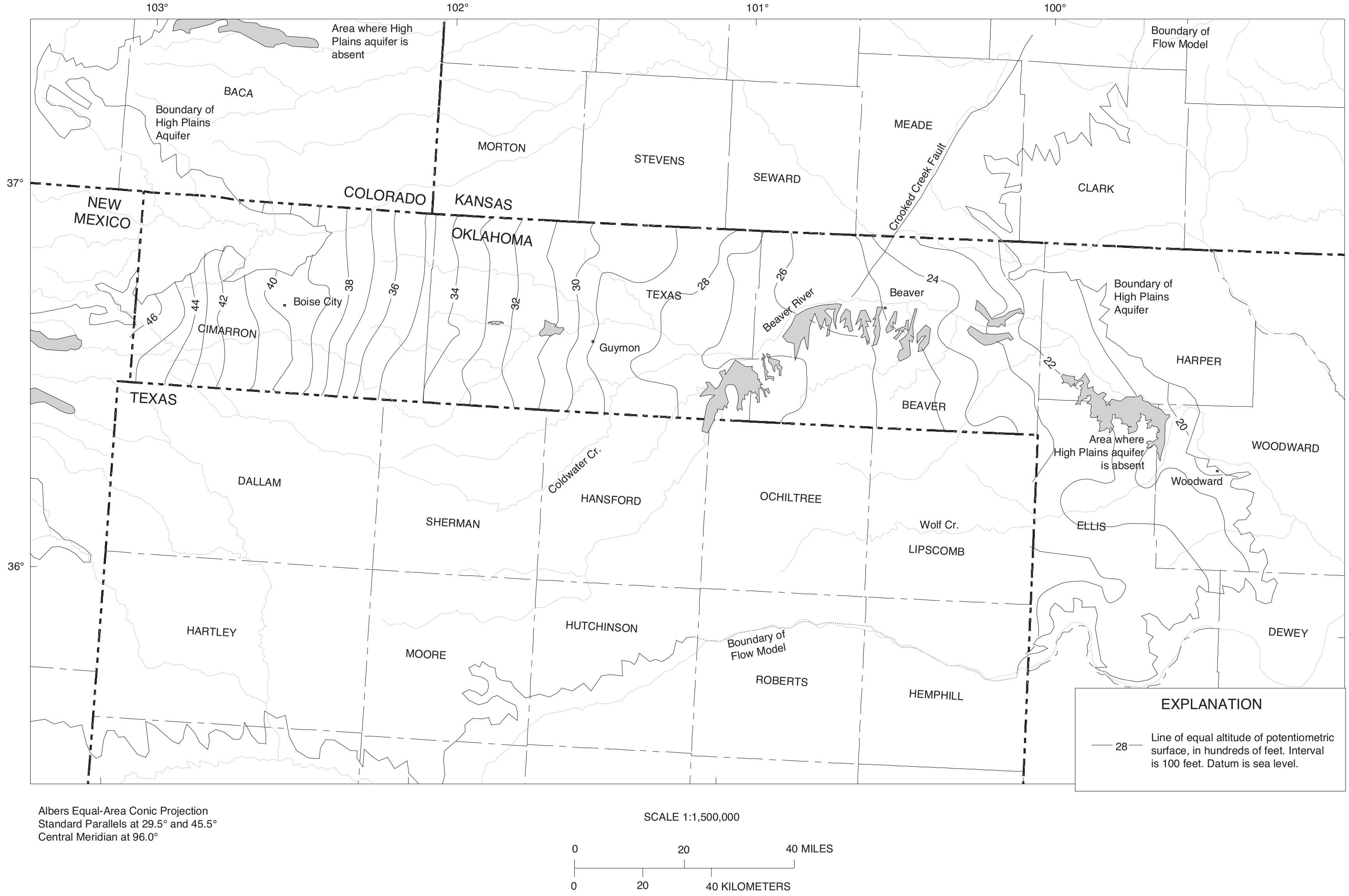
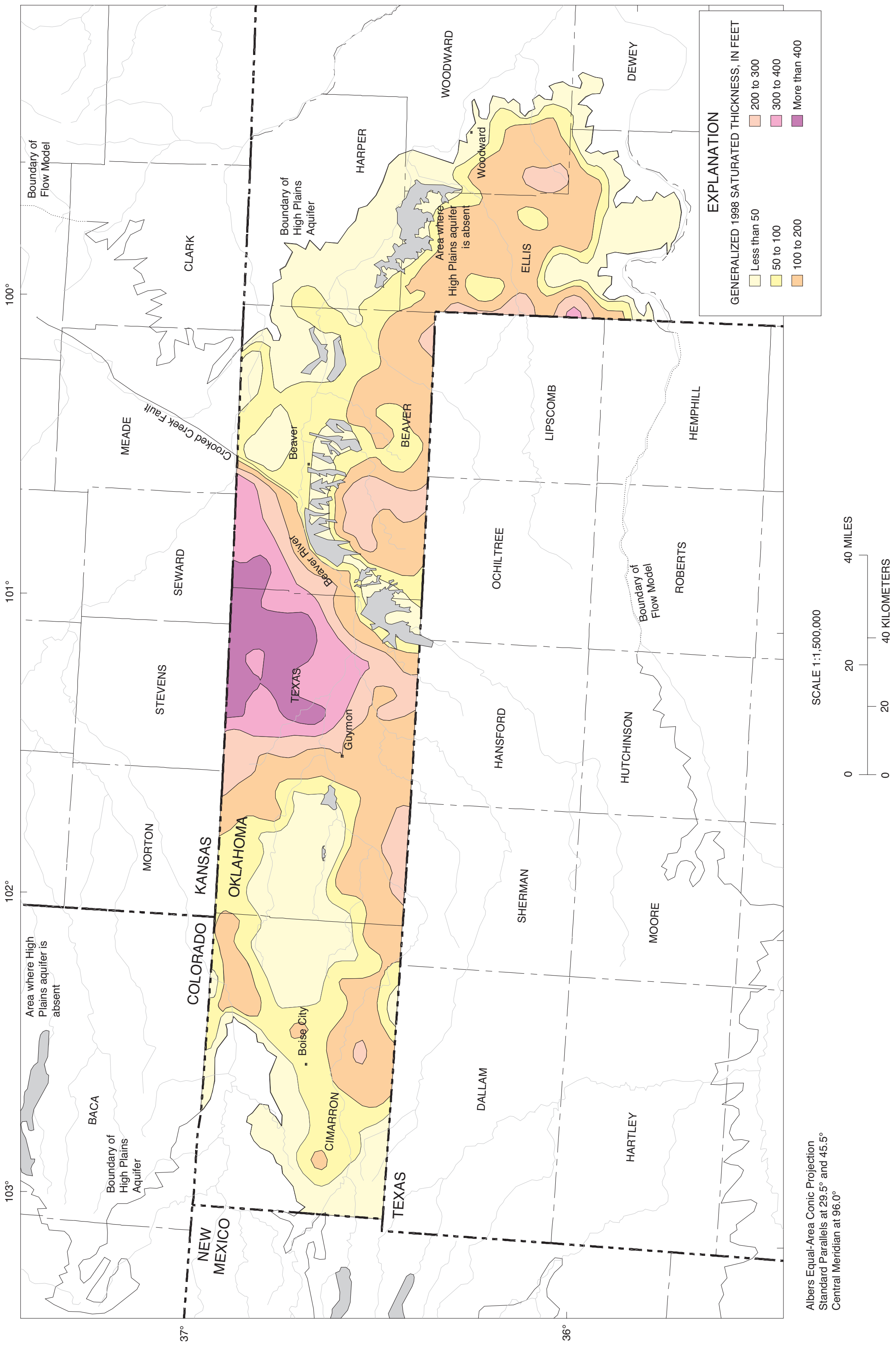


Figure 6. Altitude of January 1998 potentiometric surface of the High Plains aquifer in Oklahoma.



Albers Equal-Area Conic Projection
Standard Parallels at 29.5° and 45.5°
Central Meridian at 96.0°

Figure 7. Generalized January 1998 saturated thickness of the High Plains aquifer in Oklahoma.

approach zero. The 1998 saturated thickness was greatest in northern Texas County where it exceeded 400 feet over a substantial area. The 1998 saturated thickness was less than 50 feet and approached zero in a large area in eastern Cimarron County and western Texas County where there is a bedrock high. The 1998 saturated thickness was less than 50 feet in southeastern Texas County, central Beaver County, and parts of Ellis, Harper, and Woodward Counties where Permian-age rocks are near or at land surface. The 1998 saturated thickness also was less than 50 feet near both the western and eastern boundaries of the aquifer. Saturated thickness changed abruptly at the Crooked Creek fault in the eastern part of the study area. West of the fault, the 1998 saturated thickness was as much as 200 feet more than it was east of the fault.

The mean 1998 saturated thickness of the High Plains aquifer for the Oklahoma portion of the study area was 125 feet, and it ranged from essentially zero to almost 430 feet. The mean saturated thickness by county:

County	Mean saturated thickness (feet)
Beaver	134
Cimarron	67
Ellis	96
Harper	24
Texas	200
Woodward	94

Well yields from the High Plains aquifer are generally correlated with saturated thickness. Where saturated thickness is greater, well yields tend to be greater and where saturated thickness is less, well yields tend to be less.

Hydraulic conductivity also controls well yields but it generally has a smaller range than does saturated thickness.

Water-Level Changes

Water levels in the Oklahoma High Plains are measured annually by the Water Board, usually in January or February. The network consisted of about 220 wells in 1998. The network was started in 1966, primarily in Texas County, and was expanded into Beaver and Cimarron Counties in 1967. The network was expanded in the late 1970s to include all of the Oklahoma High Plains. By 1966, water levels already had started to decline in the most heavily pumped areas of Cimarron and Texas Counties but were probably relatively stable elsewhere.

A predevelopment to 1998 water-level change map was created by subtracting the 1998 water-level measurement from the earliest water-level measurement for 190 wells that were measured in 1998 and also were measured prior to 1980. In a few cases, the earliest water-level measurement was reported rather than measured and appeared to be anomalous, so the second earliest measurement was used. At two sites, the 1998 water-level measurement appeared anomalous, so the 1997 measurement was used. The 190 points were contoured using the 1980 irrigation density (Thelin and Heimes, 1987, plate 1) as a guide with the assumption that larger water-level declines would be limited to more densely irrigated areas. The contours also reflect the assumption that some water-level declines may have occurred prior to the first measurement.

The predevelopment to 1998 water-level change for the Oklahoma High Plains is shown in figure 8. Water levels have declined more than 100 feet in three small areas of Texas County and have declined more than 50 feet in a substantial part of the county. The larger declines generally correspond to areas of more dense irrigation development. Water levels have declined more than 50 feet in three areas of Cimarron County and have declined more than 25 feet in a substantial part of the county. Only a small part of Beaver County experienced declines of more than 25 feet and declines exceeded 10 feet only in two areas. Water levels rose by more than 10 feet in a substantial part of Ellis County.

The mean water-level change in the High Plains aquifer for the Oklahoma portion of the study area was 11.2 feet. Measured values ranged from a rise of almost 20 feet to a decline of almost 110 feet. If the first measurement had been made at an earlier date, the maximum observed rise due to induced recharge from dryland cultivation may have been larger and the maximum observed decline due to pumpage probably would have been larger. The mean water-level change by county:

County	Mean water-level change (feet)
Beaver	1.5
Cimarron	12.7
Ellis	-5.1
Harper	-3.9
Texas	31.5
Woodward	-3.0

Hydraulic Properties

Hydraulic conductivity and specific yield are the principal hydraulic properties that control flow in the High Plains aquifer. Hydraulic conductivity, the rate of flow through a unit cross-sectional area under a unit gradient at the prevailing viscosity, is expressed in feet per day in this report. Specific yield, the ratio of the volume of water that can be released by gravity drainage to the total volume of saturated rock, is expressed in percentage in this report. Streambed conductance and drain conductance are hydraulic parameters used in the model. A discussion of these parameters is in McDonald and Harbaugh (1988).

Hydraulic conductivity was mapped across the entire High Plains as part of the U.S. Geological Survey Regional Aquifer-System Analysis using the lithology described in drillers' logs. Hydraulic conductivity values were assigned to 24 lithologic descriptions commonly found in drillers' logs (Gutentag and others, 1984, table 5). Values were assigned to each lithologic unit described in several thousand drillers' logs and a thickness-weighted mean value for each well was computed. The wells were plotted and general trends were contoured. A more detailed version of the map presented by Gutentag and others (1984, fig. 10) is shown in figure 9 (Cederstrand and Becker, 1998c). Hydraulic conductivity ranges from less than 25 feet per day to more than 100 feet per day and, based on an area-weighted interpolation from the most detailed map (Cederstrand and Becker, 1998c), averages about 51 feet per day for the entire study area.

For the Oklahoma portion of the study area, hydraulic conductivity ranges from less than 25 feet per day to more than 100 feet per day and averages about 42 feet per day. The mean hydraulic conductivity by county in Oklahoma:

County	Mean hydraulic conductivity (feet per day)
Beaver	50
Cimarron	30
Ellis	39
Harper	50
Texas	43
Woodward	48

Hydraulic conductivity was one of the model inputs that was adjusted during calibration. As described in the “Predevelopment-Period Simulation” section of this report, simulated values of hydraulic conductivity were less than the mapped values over a substantial part of the study area.

Specific yield also was mapped across the entire High Plains as part of the U.S. Geological Survey Regional Aquifer-System Analysis. Specific-yield values were assigned to 24 lithologic descriptions commonly found in drillers' logs (Gutentag and others, 1984, table 5). Values were assigned to each lithologic unit described in several thousand drillers' logs and a thickness-weighted mean value for each well was computed. The wells were plotted and general trends were contoured. A detailed version of the map presented by Gutentag and others (1984, fig. 11) is shown in figure 10 (Cederstrand and Becker, 1998b). Specific yield ranges from less than 10 percent to more than 20 percent and, based on an area-weighted interpolation from the most detailed map (Cederstrand and Becker, 1998b), averages about 16 percent for the entire study area.

For the Oklahoma portion of the study area, specific yield ranges from less than 10 percent to more than 20 percent and averages about 18 percent. The mean specific yield by county in Oklahoma:

County	Mean specific yield (percent)
Beaver	19
Cimarron	17
Ellis	19
Harper	20
Texas	18
Woodward	19

Specific yield was adjusted during calibration. As described in the “Development-Period Simulation” section of this report, simulated values of specific yield were less than those mapped for part of the Oklahoma portion of the study area.

Recharge and Discharge

Natural recharge to the aquifer from precipitation probably occurs throughout the High Plains but is extremely variable in both time and space. In some areas, recharge events may be years or possibly decades apart, whereas in other areas, recharge may occur several times per year. More recharge probably occurs on sandy soils, which have large infiltration rates and small moisture capacity, than occurs on clayey soils, which have small infiltration rates and large moisture capacity. Distribution of recharge also may be affected by depth to water, playa lakes, and extensive caliche or clay layers, but these effects was not observed in this study.

Natural recharge also occurs in stream channels due to runoff, either from within the High Plains or external to it. Runoff that originates on the High Plains generally infiltrates very quickly. Only a small amount of runoff enters the High Plains in the study area; this occurs primarily on the Cimarron River and on the rivers that form the boundaries of the study area.

Hart and others (1976, p. 35) estimated natural recharge in the Oklahoma High Plains to be 0.25 to 0.50 inch per year. Havens and Christenson (1984, p. 18) estimated natural

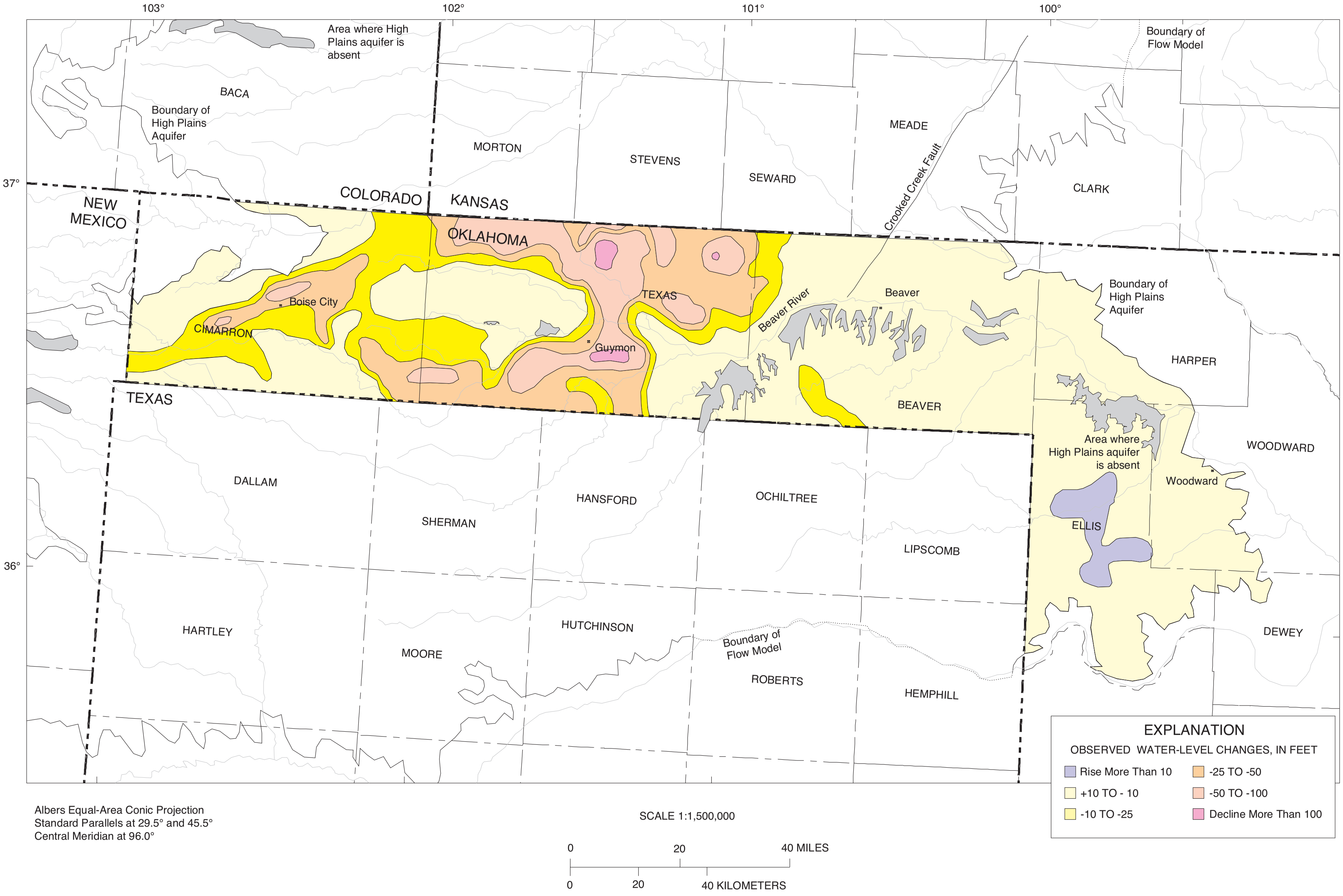


Figure 8. Predevelopment to January 1998 water-level change of the High Plains aquifer in Oklahoma.

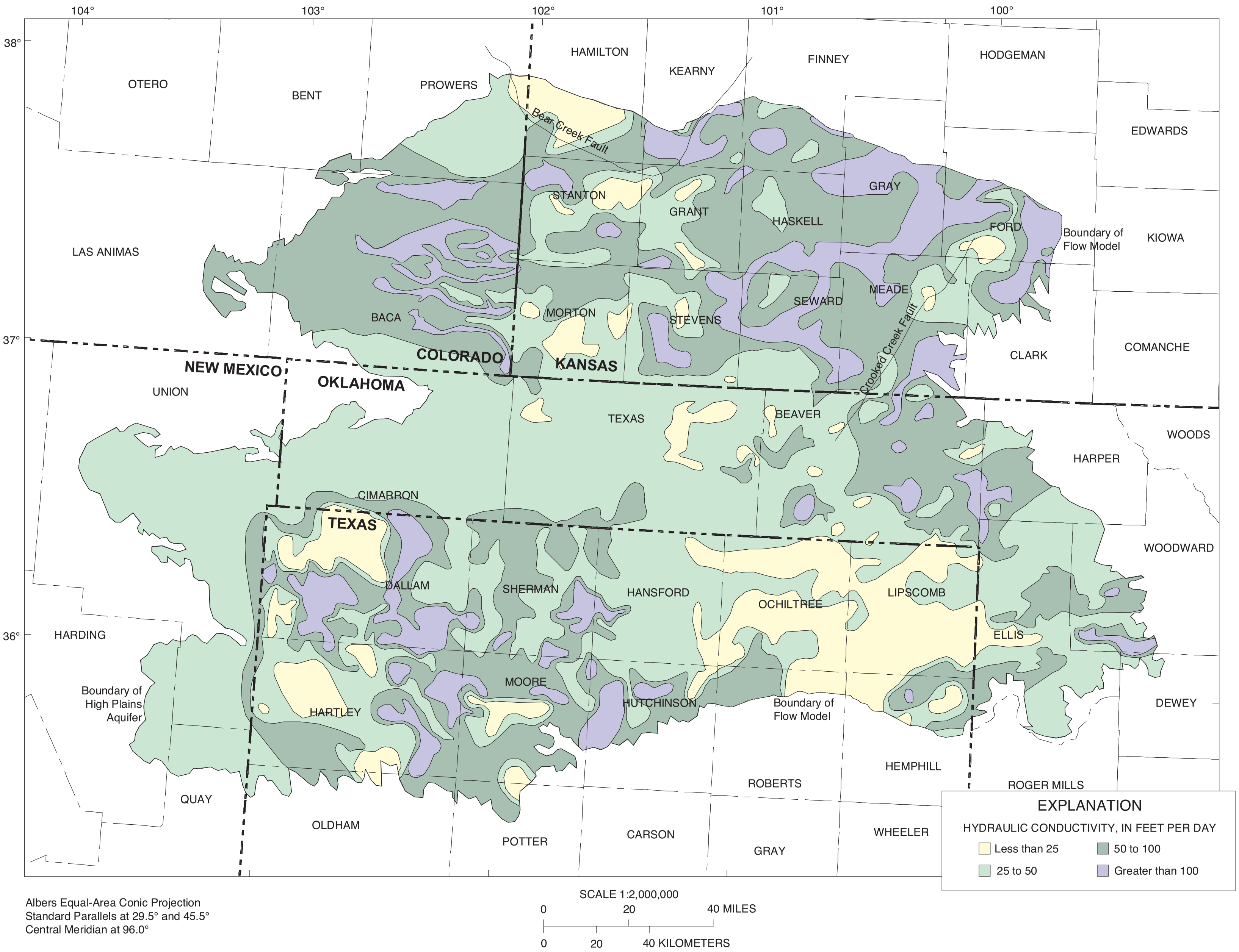


Figure 9. Hydraulic conductivity of the High Plains aquifer (Modified from Gutentag and others 1984, and Cederstrand and Becker, 1998c).

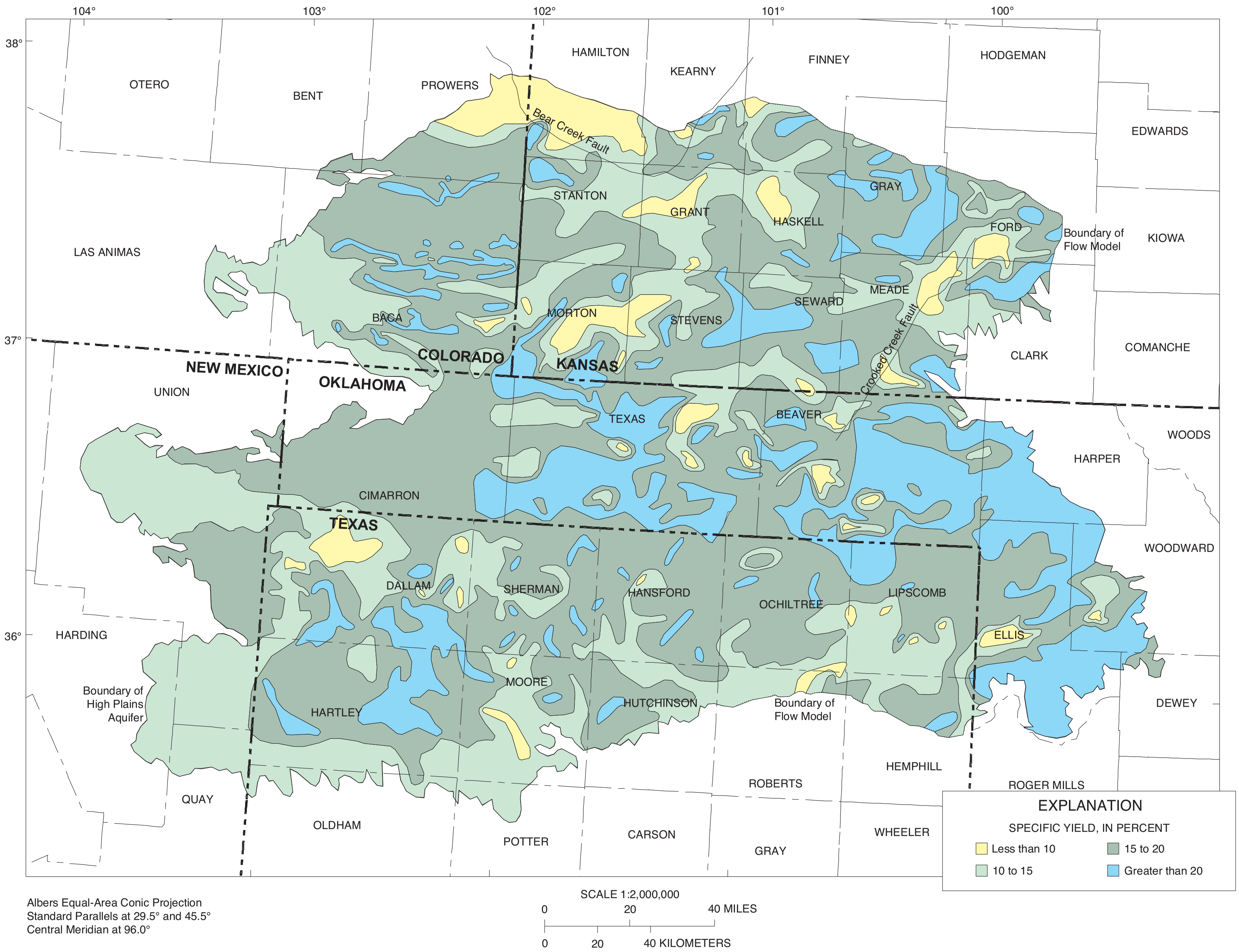


Figure 10. Specific yield of the High Plains aquifer (Modified from Gutentag and others, 1984, and Cederstrand and Becker, 1998b).

recharge for the same area to be 0.22 to 0.45 inch per year. Morton (1980, fig. 5) estimated natural recharge in Texas County, Oklahoma, to range from 0.2 to 2.2 inches per year. For this study, natural recharge was estimated for the entire study area as part of model calibration as described in the "Predevelopment-Period Calibration" section of this report.

Dryland agricultural practices appear to enhance recharge from precipitation, probably when the fields are fallow. During the fallow period, soil moisture is allowed to accumulate and most fields are cultivated after thunderstorms to create a capillary barrier to reduce bare-soil evaporation. If soil moisture reaches the moisture-holding capacity of the soil, additional precipitation may result in recharge. As part of model calibration, this effect was simulated and is described in the "Development-Period Calibration" section of this report.

Part of the water pumped for irrigation also recharges the aquifer. This recharge might occur not only from the irrigated field but also as water is being delivered to the field and after water has run off the field. Recharge is assumed to have been greater when flood irrigation from unlined ditches was the norm and now may be very small with well managed, precision application systems.

This High Plains aquifer may also receive recharge from underlying aquifers. Little is known about this distribution of this recharge, but the amount is thought to be small.

Natural discharge from the High Plains aquifer occurs as discharge to streams, evapotranspiration where the depth to water is shallow, discharge to underlying aquifers, and diffuse ground-water flow across the eastern boundary of the aquifer. Natural discharge to streams was estimated by Luckey and Becker (1998) to provide information by which the model described in this report could be calibrated. Most evapotranspiration occurs along stream channels during the summer. When evapotranspiration decreases during the winter, streamflow increases correspondingly. Small areas of evapotranspiration not along streams probably occur in the extreme eastern part of the study area; this discharge is small compared with discharge to streams. Discharge to underlying aquifers may occur in some areas. Little is known about the distribution of this discharge, but the amount is thought to be small. Diffuse ground-water flow occurs across the eastern boundary of the study area; this discharge is small compared with discharge to streams.

Artificial discharge from the High Plains aquifer occurs as discharge to wells. Prior to large-scale development of the aquifer for irrigation, this discharge was small and the aquifer was in a state of dynamic equilibrium with long-term recharge being equal to long-term discharge. Later, discharge to wells was very large and this large discharge upset the equilibrium in the aquifer.

Water Use

Water use from the High Plains aquifer was a major input required by the flow model. Water-use information was needed for the entire study area for the entire period over which substantial pumpage occurred. Water-use estimates for the High Plains of Oklahoma were available from various sources, including reported water use from the Water Board, Oklahoma Irrigation Surveys, and U.S. Geological Survey National Water Information System. Similar estimates were available for Colorado, Kansas, New Mexico, and Texas. However, these sources neither covered the entire period of substantial pumpage nor used a consistent estimation method over the entire study area. Therefore, water use was estimated in this study for the period 1946 through 1997, the development period of the model.

Irrigation was the largest use of water from the High Plains aquifer in Oklahoma, and it accounted for 96 percent of all use in 1992 and 93 percent of all use in 1997. Therefore, most of the effort was spent on estimating irrigation use. Water use by livestock was the second-largest use, and domestic use and public supply combined was somewhat less than stock use. Other uses, including commercial, industrial, and mining, were so small that they could be ignored when estimating water use.

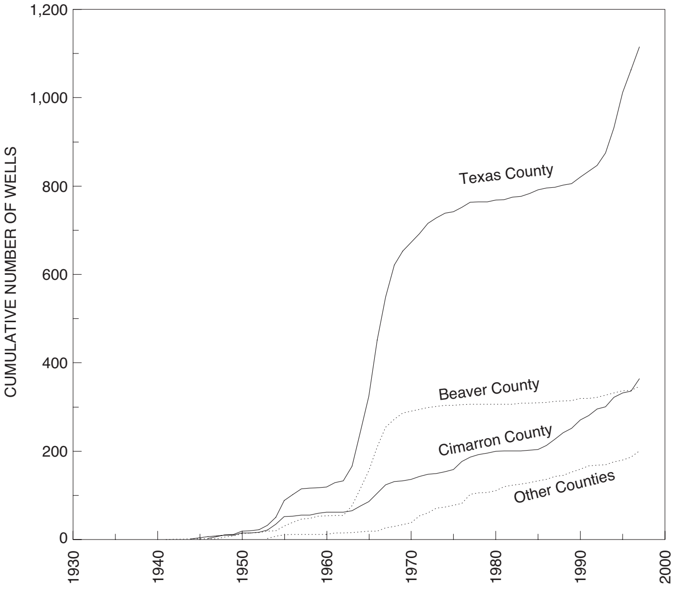


Figure 11. Number of large-capacity wells tapping the High Plains aquifer in Oklahoma.

The number of large-capacity wells (capacities of greater than 100 gallons per minute) in the Oklahoma High Plains is shown on figure 11. By 1950, there were less than 50 large-capacity wells in the Oklahoma High Plains and by 1960, there were less than 250 (Oklahoma Water Resources Board, written commun., 1999). However, in the 1960s, almost 900 large-capacity wells were drilled, with about 550 of them in Texas County. In the 1970s and 1980s, only about 430 large-capacity wells were drilled. From 1991 through 1997, about 450 large-capacity wells were drilled. Texas County has the greatest number of large-capacity wells with over 1,100, followed by Beaver and Cimarron Counties, with about 350 each. The remaining counties combined only have about 200 large-capacity wells.

Irrigation Use

Water use for irrigation was estimated based on Census of Agriculture data (U.S. Department of Commerce, 1949-92) for the period 1946-97 using the method outlined by Heimes and Luckey (1982). This method estimated irrigation water use as the product of calculated irrigation demand, reported irrigated acreage, and assumed irrigation efficiency.

Average monthly irrigation demand was calculated using the modified Blaney-Criddle method (U.S. Department of Agriculture, 1967), an empirical method that correlates water consumption by crops to mean monthly temperature and daylight hours. Growth-stage coefficient curves required by the method were available for the major crops grown in the study area. The calculations accounted for monthly effective precipitation, which was precipitation during the growing season that was available for use by the crop. The calculations also accounted for carry-over soil moisture, which was precipitation during the non-growing season that replenished soil moisture and later became available to the crop. The calculations used mean 1961-90 monthly precipitation and temperature. Using actual monthly values for the period 1946-97 would have greatly increased the effort required and was deemed unnecessary given that the development period that was simulated with the model covered a very long time period.

Water pumped for irrigation of corn, hay, sorghum, and wheat accounted for 94 percent of all irrigation water use in 1992, so monthly and annual irrigation demands were calculated for the study area for these four crops. The calculations were made on a grid of 15 minutes latitude by 15 minutes of longitude (about 17 by 14 miles), using mean 1961-90 monthly precipitation and temperature. Precipitation and temperature data were obtained from Christopher Daly (Oregon State University, written commun., November 1996) and the Oregon Climate Service (1999). Annual irrigation demands for the four crops, accounting for effective precipitation and carry-over soil moisture, were aggregated to the county level using the mean of all calculation points in or within 3 miles of the county.

Irrigation demand by crop and area for the Oklahoma portion of the study area, based on mean 1961-90 monthly precipitation and temperature with effective precipitation and carry-over soil moisture:

Crop	Irrigation demand (inches per year)			
	Cimarron County	Texas County	Beaver County	Eastern counties
Alfalfa	26.7	28.5	28.5	28.5
Corn for grain	16.4	17.3	17.2	17.3
Sorghum for grain	12.3	14.1	13.7	13.8
Wheat (winter)	9.6	9.2	8.0	7.2

Corn for silage accounted for less than 10 percent of all irrigated corn in 1992, so all corn was assigned the irrigation demand of corn for grain. Even though corn for silage had a smaller irrigation demand than corn for grain, that difference should not cause a major error in estimated water use. Similarly, only about 2 percent of all irrigated sorghum in 1992 was harvested for silage or forage, so all sorghum was assigned the irrigation demand of sorghum for grain. Alfalfa accounted for about 73 percent of all irrigated hay harvested in 1992, so all hay was assigned the irrigation demand for alfalfa, using the assumption that other types of hay had irrigation demands similar to alfalfa.

Water use for minor crops that were grown in the Oklahoma High Plains accounted for only about 6 percent of all irrigation water use in 1992, so irrigation demand for minor crops was estimated as described below. Small grains, such as barley, oats, and rye, were assumed to have the same irrigation demand as that for wheat based on data given by Houk (1951, table 10). Irrigation demands for sunflowers and soybeans were estimated using the calculated irrigation demand for sorghum and a multiplier. The multipliers were obtained from data presented by Hattendorf and others (1988, table 4) by taking the ratio of the seasonal water use by the crop to the seasonal water use by sorghum. The multiplier was 1.126 for sunflowers and 1.116 for soybeans. Irrigated pasture was assumed to have an irrigation demand of 20 inches per year (Natural Resources Conservation Service, 1998), and crops not reported individually in the Census of Agriculture (U.S. Department of Commerce, 1949-92) were assumed to have an irrigation demand of 16 inches per year.

Irrigated acreages were obtained for various years from the Census of Agriculture (U.S. Department of Commerce, 1949-92) for 12 counties in Kansas, eight counties in Texas, five counties in Oklahoma, and one each in Colorado and New Mexico. Irrigated acreages were compiled for all crops reported by the census. Different crops were reported for different years, but all years reported irrigated acreage for corn, hay, pasture, sorghum, and wheat. In addition, the census reported total irrigated acreage by county so acreage of crops not reported could be calculated. If acreage was not reported for a specific crop, as was the case when only a few farms grew a particular crop, the acreage was estimated using other information in the census or census data from other years. These estimates comprised only a small portion of estimated water use.

The 1978 census contained an apparent error in total irrigated acreage for Cimarron County, Oklahoma. The apparent error was corrected using the sum of irrigated acreages for the various crops and total irrigated acreage harvested. This correction reduced irrigated acreage by 30,000 acres and estimated water use by 57,000 acre-feet.

Irrigation efficiency (irrigation demand divided by application) had to be assumed to calculate irrigation water use because no estimates of efficiency were available for the area. Irrigation efficiency accounted for runoff from the field, deep percolation below the root zone, delivery system losses, and evaporation losses. Irrigation efficiency is assumed to have been less when fuel was cheap and flood irrigation from unlined ditches was the norm. Assumed irrigation efficiencies for 1949-78 are the same as those used by Luckey and others (1986, p. 9) for the central High Plains. Irrigation efficiency was assumed to increase after 1978 because of increasing fuel costs and because many irrigation systems were converted to center pivots, low pressure pivots, and more recently, LEPA (low energy, precision application) systems. The center pivots reduced both runoff and deep percolation, whereas low-pressure and LEPA systems also reduced evaporation losses. The following irrigation efficiencies were used to estimate water use by irrigation:

Census year(s)	Assumed irrigation efficiency
1949, 1954, 1959	45 percent
1964, 1969	60 percent
1974, 1978	70 percent
1982	80 percent
1987, 1992	85 percent

Other Use

Water use for stock, including confined animal feeding operations, was the second-largest use of water in the Oklahoma High Plains. It only accounted for about 2 percent of total water use in 1992 and 5 percent of total water use in 1997. Stock water use was estimated for each county in the study area by multiplying the number of cattle, swine, and sheep in a county by the estimated water use for each animal. The estimated water use per animal, based on information provided by various people in the area (Dr. Charles Strasia, Agricultural Specialist, OSU Extension Service; Dr. Robert Lake, Nutritionist, Hitch Enterprises; Jerome Frizzell, Director of Safety and Environmental Affairs, Seaboard Farms):

Stock type	Water use (gallons per day per animal)
cattle	11
swine	7
sheep	1.5

Table 2. Estimated water use by area from the High Plains aquifer in Oklahoma for Census of Agriculture years 1949 through 1992

[Columns may not add to total because of rounding]

Census year	Water use (acre-feet per year)				
	Cimarron County	Texas County	Beaver County	Eastern counties	Oklahoma total
1949	7,000	15,000	5,000	5,000	32,000
1954	11,000	29,000	10,000	12,000	63,000
1959	31,000	93,000	20,000	13,000	157,000
1964	58,000	111,000	15,000	13,000	197,000
1969	160,000	308,000	49,000	21,000	537,000
1974	107,000	291,000	39,000	33,000	469,000
1978	105,000	256,000	58,000	51,000	471,000
1982	64,000	207,000	36,000	40,000	347,000
1987	64,000	212,000	33,000	38,000	346,000
1992	70,000	217,000	41,000	68,000	396,000

The number of animals in each county for the various years was obtained from the Census of Agriculture (U.S. Department of Commerce, 1949-92). In addition, the number of animals in the Oklahoma portion of the study area in 1997 was estimated from information from the Oklahoma Agricultural Statistics Services (1997). Other animals, such as horses and poultry, are not numerous enough in the High Plains to be included in the estimates of stock water use.

Water use for domestic use and public supply is the third-largest use of water in the Oklahoma High Plains. It was only slightly less than stock use in 1992 and was less than one-half of stock use in 1997. Domestic and public supply water use was estimated for each year for each county for all years by multiplying the 1990 county population by 193 gallons per day, the mean per capita value for Oklahoma public supply for 1990 (Solley and others, 1993, table 10).

Water use for other purposes in the Oklahoma High Plains was too small to affect the input to the flow model and therefore was not estimated.

Total Use

Estimated water use for input to the flow model was the sum of irrigation use, stock use, and combined domestic and public-supply use. Water use was estimated by counties for most of the study area. Water use was not estimated for Woodward and Dewey Counties, Oklahoma. However, part of Harper County, Oklahoma, lies outside the High Plains and the irrigated area neglected in Woodward and Dewey Counties was assumed to be approximately offset by the extra irrigated area included in Harper County. Estimated total water use for the Oklahoma High Plains by area and Census of Agriculture year is shown in table 2.

Water use was estimated for each county in the study area outside of Oklahoma in the same manner that it was for Oklahoma. Estimated water use in Texas was the sum of estimated water uses for Dallam, Hansford, Hartley, Hutchinson, Lipscomb, Moore, Ochiltree, and Sherman Counties. The irrigated areas neglected in Hemphill, Oldham, Potter, and Roberts Counties were assumed to be offset by extra irrigated areas included in Hutchinson County that is outside the study area. Estimated water use in Kansas was the sum of the estimated water uses for Grant, Haskell, Meade, Morton, Seward, Stanton, and Stevens Counties plus part (fraction in parentheses) of the estimated water uses for Finney (0.6), Ford (0.4), Gray (0.7), Hamilton (0.5), and Kearney (0.6) Counties. The fractions are based on the approximate area of the county within the study area and the percentages of irrigated acreages within the county (Thelin and Heimes, 1987, plate 1). Estimated water use from the High Plains aquifer in Colorado was one-fourth of the total estimated water use in Baca County. The remainder of the water use was assumed to be from aquifers other than the High Plains aquifer. Prowers County, Colorado, which had a small amount of water use from the High Plains aquifer, was neglected. Estimated water use from the High Plains aquifer in New Mexico was one-half the total estimated water use in Union County. The remainder of the water use was assumed to be from aquifers other than the High Plains aquifer. Almost no water use from the High Plains aquifer occurred in Harding or Quay Counties, New Mexico, so these counties were neglected. Estimated total water use from the High Plains aquifer in the study area by state and census of agriculture year is shown in table 3.

Table 3. Estimated water use by state from the High Plains aquifer in the study area for Census of Agriculture years 1949 through 1992

[Columns may not add to total because of rounding]

Census year	Water use (acre-feet per year)					
	Colorado	Kansas	New Mexico	Oklahoma	Texas	Total
1949	1,000	196,000	5,000	32,000	44,000	278,000
1954	2,000	447,000	8,000	63,000	248,000	767,000
1959	11,000	829,000	4,000	157,000	572,000	1,574,000
1964	16,000	868,000	3,000	197,000	833,000	1,917,000
1969	9,000	1,369,000	12,000	537,000	1,577,000	3,504,000
1974	4,000	1,582,000	6,000	469,000	1,297,000	3,358,000
1978	3,000	2,002,000	15,000	471,000	1,651,000	4,141,000
1982	1,000	1,622,000	6,000	347,000	1,089,000	3,064,000
1987	1,000	1,414,000	7,000	346,000	876,000	2,646,000
1992	700	1,678,000	7,000	396,000	1,079,000	3,161,000

Water use for the simulation period (1946-97) was divided into six pumping periods. Five pumping periods were 10 years each with the first pumping period beginning with 1946 and the fifth pumping period ending with 1995.

Estimated water use by pumping period for the Oklahoma portion of the study area:

[Columns may not add to total because of rounding]

Pumping period	Water use (acre-feet per year)				
	Cimarron County	Texas County	Beaver County	Eastern counties	Oklahoma study area total
1946-55	9,000	20,000	6,000	8,000	43,000
1956-65	41,000	96,000	17,000	13,000	166,000
1966-75	127,000	278,000	41,000	25,000	472,000
1976-85	82,000	232,000	44,000	43,000	402,000
1985-95	68,000	216,000	38,000	56,000	378,000
1996-97	70,000	224,000	40,000	56,000	389,000

Estimated water use by pumping period for the entire study area:

[Columns may not add to total because of rounding]

Pumping period	Water use (acre-feet per year)					
	Colorado	Kansas	New Mexico	Oklahoma	Texas	Study area total
1946-55	1,000	285,000	6,000	43,000	126,000	460,000
1956-65	12,000	808,000	4,000	166,000	650,000	1,640,000
1966-75	8,000	1,408,000	9,000	472,000	1,390,000	3,287,000
1976-85	2,000	1,738,000	9,000	402,000	1,291,000	3,443,000
1986-95	1,000	1,575,000	7,000	378,000	1,001,000	2,961,000
1996-97	1,000	1,575,000	7,000	389,000	1,001,000	2,972,000

The sixth pumping period was two years long and included 1996 and 1997. Average annual water use for each pumping period was calculated as the mean of the estimated water use for each year of the period. Water use for non-census of agriculture years was estimated as the time-weighted average of the water use for the census years before and after the year for which the estimate was made. Water use in 1944 was assumed to be one-fourth of that estimated for 1949. Water use in 1997 was assumed to be the same as water use in 1992, except that 1997 water use was adjusted for the increase in the number of cattle and swine in Oklahoma. Cattle numbers were available by county for December 1, 1997, from the Oklahoma Agricultural Statistics Service (1997), and these numbers were used in lieu of data reported by the Census of Agriculture (U.S. Department of Commerce, 1949-92). Cattle numbers in the Oklahoma portion of the study area had increased from 623,000 in 1992 to 750,000 in 1997. Swine numbers were available only on a statewide basis. Statewide swine inventory had increased from 261,000 in December 1992 to 1,640,000 in December 1997. The difference of about 1.4 million was assumed to have occurred in the panhandle with 70 percent of the increase assumed to have occurred in Texas County and the remainder assumed to have occurred equally in Beaver and Cimarron Counties. Total stock water use in the Oklahoma High Plains was estimated to have increased from 8,000 acre-feet in 1992 to 20,000 acre-feet in 1997. This was 2 percent of total water use in 1992 and 5 percent of total water use in 1997. In 1997, 46 percent of stock water was used by cattle and 54 percent was used by swine. Total water use in the Oklahoma High Plains in 1996-97 was estimated to have been about 400,000 acre-feet, as indicated in the above tables.

Ground-Water Flow Model

A ground-water flow model is a simplified representation of flow in an aquifer that can be used to simulate and understand the real system and to calculate water levels and discharges to streams, both spatially and over time. A model can be used to predict the aquifer state under different sets of circumstances. The flow model used in this study is called a digital flow model because it is based on the equations describing ground-water flow and the equations are solved on a digital computer using numerical techniques. Computers allow the simultaneous solution of thousands of equations throughout the model domain over possibly hundreds of time steps.

The ground-water flow equation is based on Darcy's Law, which states that flow through porous media is directly proportional to water-level change over the flow path and is inversely proportional to the length of the path. The flow equation is developed from Darcy's Law by applying the principles of conversation of energy and mass and is generally expressed as a partial differential equation. In some circumstances, usually involving systems with very simple boundaries and parameters, the ground-water flow equation can be solved directly. More often, an approximate equation is substituted for the partial-differential equation. In this study, a finite-difference equation, which treats time and space as discrete, rather than continuums, is substituted. As long as the time and space discritizations are appropriate for the problem being solved, this substitution does not introduce serious errors into the solution.

Four general categories of information are needed for model input: (1) Aquifer geometry, which includes the vertical and areal limits of the system; (2) aquifer boundary conditions, which include specifying either the flow across the boundaries or water levels at the boundaries; (3) aquifer parameters, which include hydraulic conductivity, specific yield, streambed conductance, and drain conductance; and (4) aquifer stresses, which include any additions or withdrawals of water that are not accounted for by the boundary conditions.

The finite-difference technique subdivides the aquifer into a grid of blocks called cells. Aquifer parameters are assumed to be constant within a cell but may vary from cell to cell. The flow of water into or out of each cell from various sources must be calculated. The technique used in this study places a node at the centroid of a cell; water levels are calculated at the node. Figure 12 illustrates a typical cell, although all the phenomena shown in the figure are unlikely to occur at most cells.

A computer code called MODFLOW (McDonald and Harbaugh, 1988), which uses the finite-difference technique described above, was used to simulate ground-water flow in the High Plains aquifer in Oklahoma and adjacent areas. This code has been widely used in hydrologic investigations and is essentially a replacement for the computer code used by Morton (1980a) to model ground-water flow in Texas County, Oklahoma, and adjacent areas, and by Havens and Christenson (1984) to model ground-water flow in the Oklahoma High Plains and adjacent areas.

The first, and most important, step in model construction is to develop a conceptual model of the flow system. This step defines the important characteristics of the flow system, the nature of its boundaries, and its interactions with external systems. This step must be based on the purpose of the model and the scale over which the model will be used. The conceptual model may evolve somewhat as a result of calibration and use, but its basic framework must be established from the beginning.

The basic assumptions of the model and a discussion of these assumptions follows:

1. Flow in the aquifer obeys Darcy's Law. This approximation is valid for the High Plains aquifer at the scale over which this model is to be used and would not be valid only at very small scales.
2. The density of water is constant over time and space. This is approximately true for the High Plains aquifer, and any small variations in density would be masked by the uncertainty in model parameters, particularly hydraulic conductivity.
3. Flow is two dimensional. This assumption is a consequence of the grid construction and is not a necessary assumption. However, vertical-flow components appear to be much smaller than horizontal-flow components over most of the area. Given the scale and purpose of this model, the assumption appears appropriate.
4. Hydraulic conductivity is isotropic in the horizontal direction. This is not a necessary assumption when using MODFLOW, but this assumption was made for this study because there was no indication that hydraulic conductivity was anisotropic in the horizontal direction, which is unlikely over a large scale given the depositional environment of the aquifer.
5. Aquifer parameters are constant within a cell. This assumption is unlikely, but given the uncertainties in model parameters and the scale and use of this model, this assumption is appropriate.

After a model is constructed, it should be calibrated prior to use for analysis or prediction. Calibration is a process of systematically adjusting selected model inputs within reasonable limits while comparing simulated versus observed conditions. It is generally best to vary only one model input at a time so the effect of the variation is not masked by other variables. In calibrating this model, simulated water levels and discharges to streams were compared against observed levels and estimated discharges while hydraulic conductivity, streambed conductance, specific yield, recharge from precipitation, recharge due to irrigation, and recharge due to dryland cultivation were varied.

Ground-water flow models are numerical representations that simplify and aggregate natural systems. Models are not unique; different combinations of inputs may produce similar results. For example, hydraulic conductivity and recharge are closely interrelated with respect to water levels and, so long as the ratio between these inputs is correct, the actual values could be in considerable error and the modeled water levels would still match observed water levels. However, hydraulic conductivity and recharge are not interrelated with respect to discharge to streams, so incorrect values for recharge may be detected if simulated discharge to streams can be compared to observed values.

Ideally, models should only be used for purposes for which they are intended and at scales that are appropriate for the

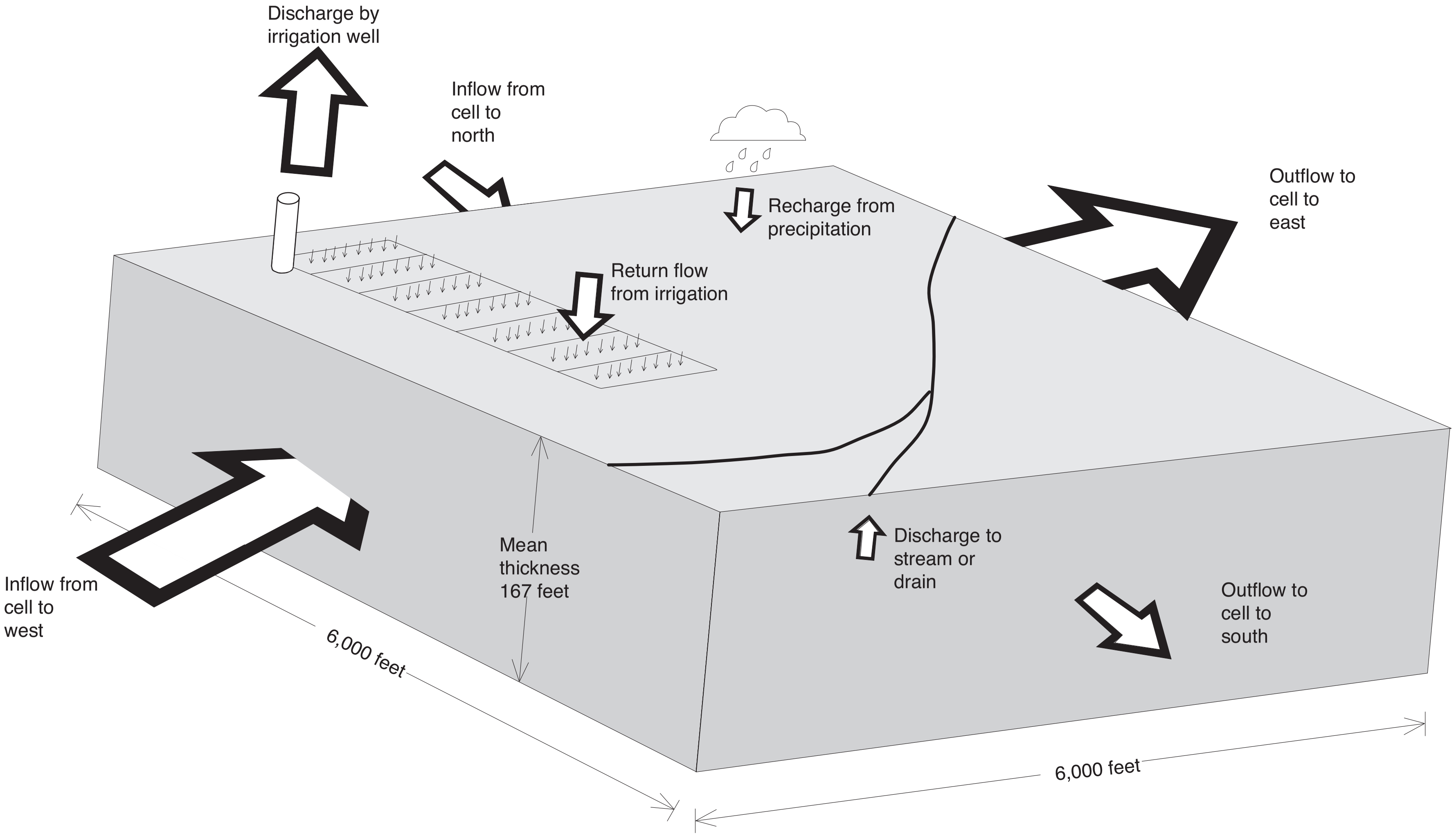


Figure 12. Model cell with typical inflows and outflows.

model. This model was constructed for simulating flow and understanding the effects of pumpage at the township scale. It would not be appropriate to use this model to track contaminant transport nor would it be appropriate to use it to calculate the water levels in a particular well. In addition, models ideally should not be used outside the range over which they were calibrated, but that is often a practical necessity. This model was calibrated using water-level changes that occurred from predevelopment to January 1998, although declines were simulated beyond that date. The further out in time the simulations are made, the less likely they are to be accurate.

Model Design

This model was constructed to simulate the flow system of the High Plains aquifer in Oklahoma, but its boundaries extended considerable distances into adjacent states (fig. 13). The lateral boundaries were chosen sufficiently far from Oklahoma so that errors in specifying conditions at the boundaries would have minimal affect on the Oklahoma portion of the model. Most of the lateral boundary consists of the erosional extent of the Ogallala Formation, and this part of the boundary was treated as a zero-flow boundary. The eastern zero-flow boundary occurs where the aquifer adjoins Permian-age rocks. The Permian-age rocks probably transmit very little water, so the zero-flow boundary condition is appropriate. About 15 miles of the northern end of the eastern boundary is treated differently; the aquifer continues east of this area and, in the real system, some water probably crosses this boundary. This cross-boundary flow is simulated in the model using drains to remove water that, in the real system, is crossing this boundary. Much of the western zero-flow boundary occurs where the aquifer adjoins Cretaceous-age rocks. In some parts of the boundary, the Lytle and Dakota Sandstones may contribute some water to the High Plains aquifer along parts of the western boundary, but the amount was assumed to be small. The remainder of the Cretaceous-age rocks probably transmit very little water. The southern boundary consists of the erosional limit of the Ogallala Formation and the Canadian River. This boundary is far from Oklahoma, except for extreme southeast Ellis County. The northern boundary consists largely of the Arkansas River. The areas south of the Canadian River and north of the Arkansas River are treated as zero-flow boundaries although some water surely moves through the aquifer beneath the rivers. In the model, the simulated flows to these rivers may be incorrect because of the water moving beneath the rivers. However, these boundaries are generally very far from Oklahoma and the simulated discharge to the Arkansas River and the Canadian River was not of concern in this study.

The lower boundary of the model is the base of the Ogallala Formation and is treated as a zero-flow boundary. This boundary condition probably is appropriate for the eastern two-thirds of the model. In the western part of the model area, the High Plains aquifer is underlain by rocks of Triassic, Jurassic, and Cretaceous age. In this area, exchange of water may take place between the High Plains aquifer and the Dockum Group, the Exeter Member of the Entrada Sandstone, the Lytle Sandstone, and the Dakota Sandstone (table 1). Little is known about the distribution, amounts, and direction of this exchange and determining this exchange of water was beyond the scope of this study. The model may be less accurate in western Texas County and in Cimarron County, Oklahoma, because this exchange of water is not accounted for, but model results do not indicate any major problems due to this assumption. Model results indicate that ignoring this exchange may have been more problematic south of Oklahoma near the New Mexico-Texas state line.

The upper boundary of the model is the water table. Recharge moves down across this boundary, and discharge to streams moves up across this boundary. Recharge was one of the model inputs that was varied during calibration and, as part of the calibration process, simulated discharge to streams was compared to estimated historical discharge (Luckey and Becker, 1998).

The model area was gridded using 154 rows, 226 columns, and one layer for a total of 34,804 cells (fig. 14). The rows are oriented in an east-west direction, and the columns are oriented in a north-south direction. Each cell is 6,000 feet wide in both the north-south and east-west directions and covers an area of approximately 1.3 square miles. A cell covers the full vertical extent from the base of the aquifer to the water table; the mean vertical thickness of all cells is 167 feet. A cell is termed active if a water level is calculated at its node; the model has 21,073 active cells. Aquifer stresses, such as recharge and pumpage, are only applied to active cells. Most inactive cells are outside of the boundary of the High Plains aquifer or where the aquifer is absent within the boundary, although a few cells near the edge of the aquifer, where saturated thickness likely is minimal, are designated as inactive. Most of these inactive cells are in areas of Colorado and New Mexico and are far from the Oklahoma portion of the model. For reference, the node of the cell designated row 82, column 115 is at latitude 36°40′35″N., longitude 101°29′29″W., which is about 0.7 mile west-southwest of the intersection of Main and N. Fourth Streets in Guymon, Oklahoma.

The model was constructed using a single layer because, on a regional scale, the sediments that comprise the High Plains aquifer are distributed randomly in the vertical section (Gutentag and others, 1984, p. 23). In addition, published maps or cross-sections showing the distribution of sediments within the Ogallala Formation were not available for Oklahoma and the generation of such maps or cross sections was beyond the scope of this study. Although a single layer might not be ideal in local areas, a single layer was deemed appropriate for the purpose and scale of this study.

The model was used to simulate two different historic periods. The predevelopment-period simulation represents the period prior to major development of the aquifer for irrigation. During the predevelopment period, the aquifer was in a state of dynamic equilibrium with long-term recharge being balanced by an equal amount of discharge. The development-period sim-

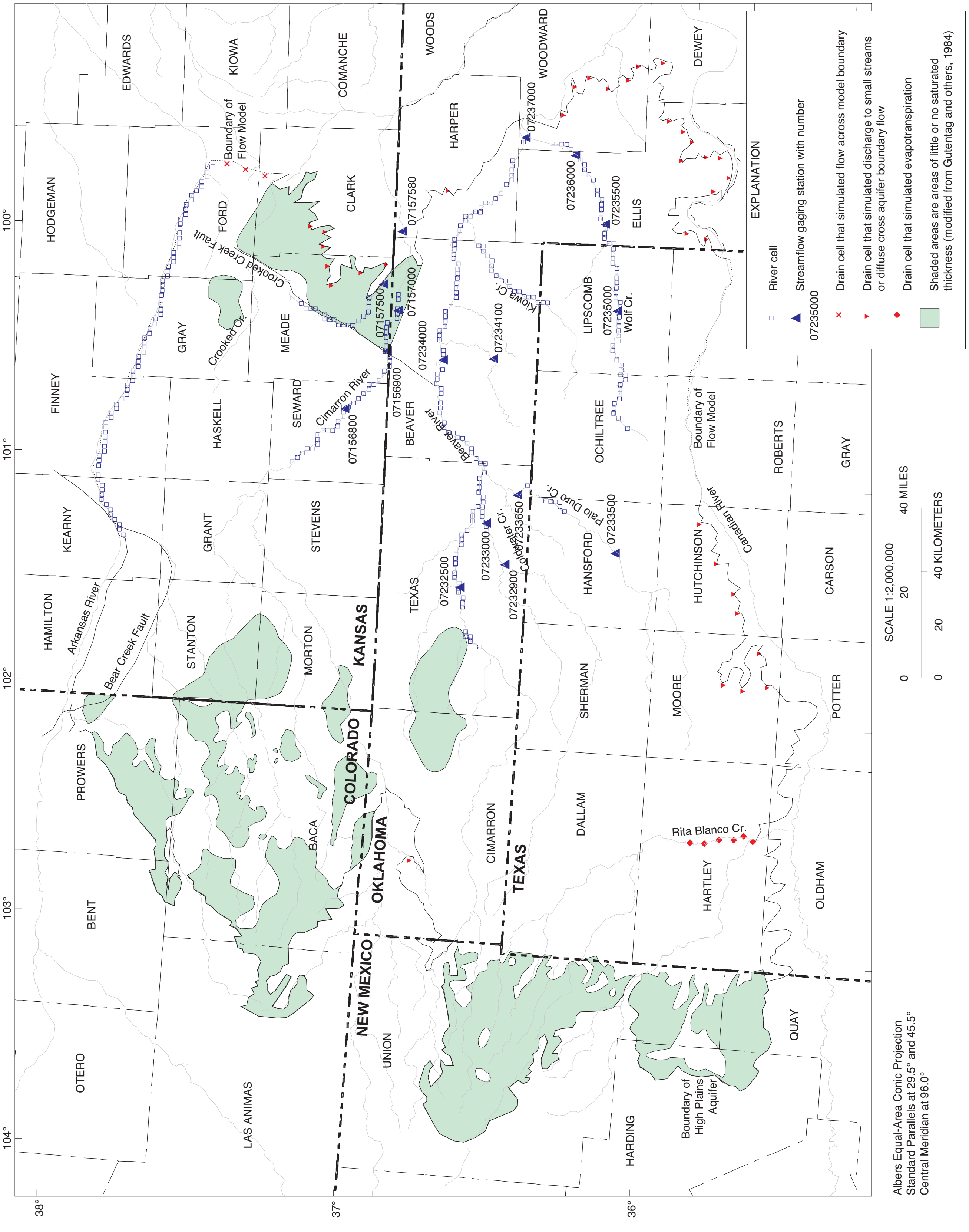


Figure 13. Boundary conditions for the model of the High Plains aquifer in Oklahoma.

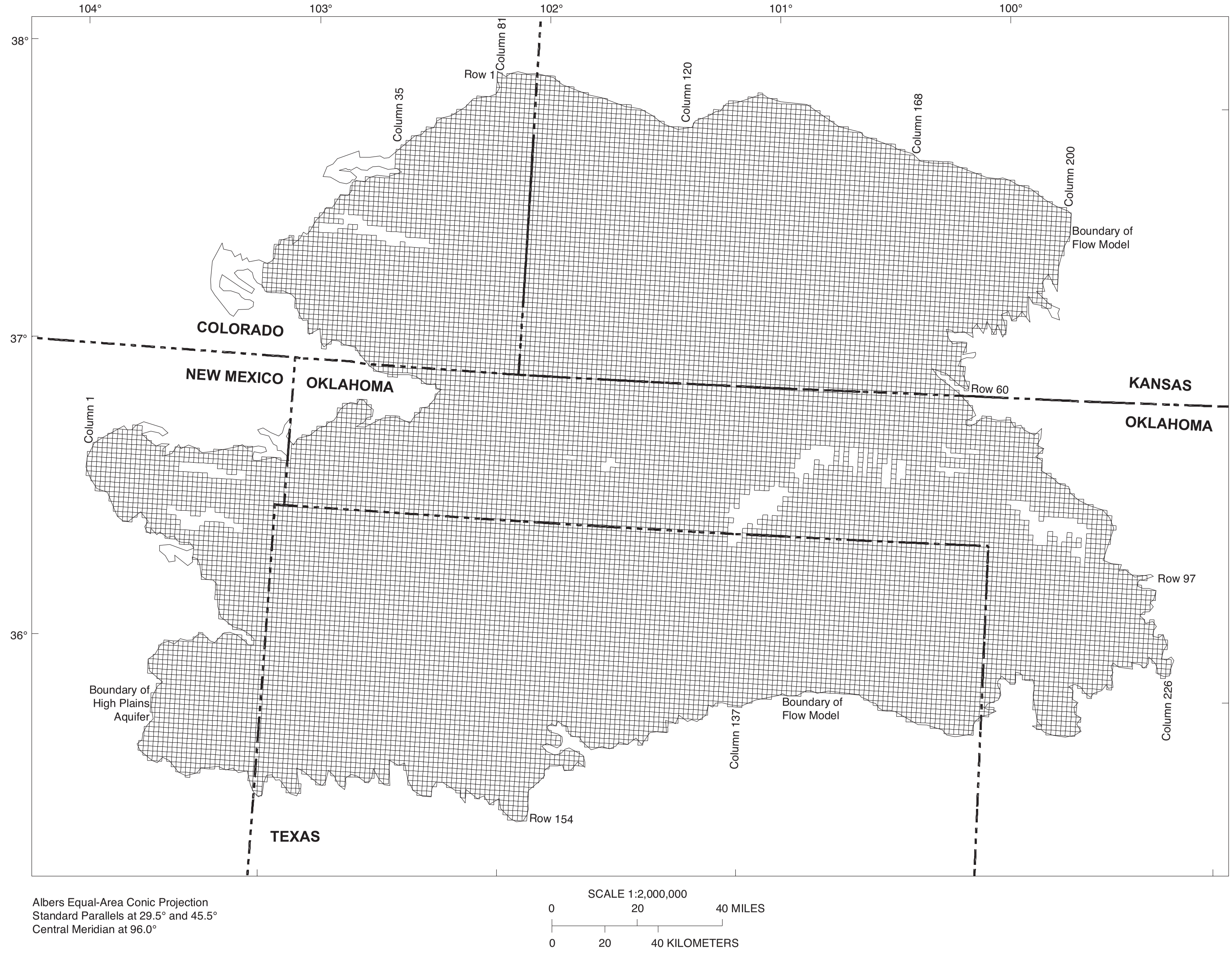


Figure 14. Grid for the model of the High Plains aquifer in Oklahoma (only active cells are shown).

ulation represents the period after the start of major development of the aquifer for irrigation. During the development period, discharge from the aquifer by irrigation wells greatly exceeded recharge, which caused long-term water-level declines in much of the aquifer. The model also was used to simulate a future period.

Rivers and streams were simulated in the model (fig. 13) using the river package of MODFLOW (McDonald and Harbaugh, 1988). This package simulates the interchange of water between the aquifer and a stream using a low-permeability streambed conductance, although generally no discrete low-permeability layer is present in real streams. Streambed conductances had to be estimated during model calibration and there was little to guide the process beyond stream width, stream discharge, and water levels near the stream. In this study, streambed conductances were estimated by stream, and in some cases, by reaches within a stream. During the development period, a few stream segments were no longer treated as river cells in the model as water-level declines caused the start of perennial flow to move downstream. However, these cells remained active in the model.

Lakes were not explicitly simulated in the model. The oldest large lake in the study area, Fort Supply Lake on Wolf Creek, was completed in 1942. It occupies about four models cells near the eastern edge of the aquifer between a bedrock outcrop and the aquifer boundary. Optima Lake on the Beaver River was completed in 1978 but, through 1998, contained very little water. It occupies about four model cells. Palo Duro Reservoir on Palo Duro Creek was completed in 1991 upstream from where the creek begins to receive discharge for the aquifer. It is smaller than either Fort Supply Lake or Optima Lake.

Drain cells were used in the model for various purposes (fig. 13). Drain cells are similar to stream cells except that the flow can only occur from the aquifer to the drains, whereas in stream cells, the flow can be in either direction. Drain cells were used to simulate a number of small streams that originate near the aquifer boundary and also to simulate diffuse cross-boundary flow. Several drain cells were used to simulate the lower reach of Rita Blanco Creek in western Texas. This stream occupies a deep canyon in its lower reaches and evapotranspiration probably occurs along this stretch of stream during much of the year. Three drain cells (fig. 13) were used to simulate flow across about a 15-mile section of the northern part of the eastern model boundary in Kansas where the High Plains aquifer extends east of the model area.

Stream cells were converted to drain cells for the simulation of the future period. This was done as a matter of convenience so that the upper perennial reaches of streams were not inappropriately supplying water to the aquifer. If the stream cells had not been converted to drain cells, upper stream segments would have had to be converted from river cells to normal cells in the model as water-level declines caused the start of perennial flow to move downstream.

Predevelopment-Period Simulation

The predevelopment-period model calculated the predevelopment altitude of the water table, discharge to the rivers and streams, diffuse cross-boundary discharge, discharge to small streams simulated with drains, and discharge across the northern part of the eastern model boundary in Kansas. The model integrated data or estimates on the altitude of the base of aquifer, hydraulic conductivity, streambed conductance, and recharge from precipitation. The altitude of the base of aquifer was altered during calibration at a few stream cells so that the stream remained above the base of aquifer. Hydraulic conductivity, recharge, and streambed conductance were varied within reasonable ranges during the calibration process so that the model produced a reasonable representation of measured predevelopment water levels in Oklahoma, the observed water table throughout the model area, and the estimated discharge to rivers and streams (Luckey and Becker, 1998).

Changes in model inputs as a result of the calibration process are reported here. Changes were made only where they could be clearly justified, were hydrologically sound, and were supported by some evidence. Changes were generally made over large areas but were not made over small areas simply to improve the fit of simulated values to observed values.

Differences between simulated and observed water levels or estimated discharges to streams remained after the calibration process. Where the differences were sufficiently far from Oklahoma that they would not affect the model in Oklahoma, little effort was spent on further calibration. However, this report examines potential causes for the differences for the benefit of future investigators. Where differences occurred in Oklahoma or nearby, considerable effort was spent on adjusting model inputs. If the differences could not be resolved, the model was not arbitrarily changed in individual areas simply to improve the fit of simulated values to observed values, and potential causes for the differences are discussed in this report. Areas where the differences are substantial may need additional investigation in the future.

The initial estimates of hydraulic conductivity (fig. 9) were obtained from a detailed version of the map presented by Gutentag and others (1984, fig. 10; Cederstrand and Becker, 1998c). The hydraulic conductivity, as averaged for model cells, ranged from 10 feet per day to over 200 feet per day, although the Cederstrand and Becker (1998c) map indicates a small area where it exceeded 300 feet per day. The arithmetic mean of the initial estimates of hydraulic conductivities for all active cells in the model was 50.7 feet per day. A number of simulations were made using the initial hydraulic-conductivity estimates and reasonable recharge rates, with the result that simulated predevelopment water levels were considerably below observed water levels, particularly in the central part of the model where the saturated thickness is greatest. The differences averaged about 27 feet over the entire model, exceeded 50 feet over large areas, and exceeded 200 feet in several areas. Simulations were made in which recharge was dramatically increased, but this change caused simulated water levels outside the central part of the model to be too high and simulated discharge to streams to be too large. The alternative solution was to reduce the initial estimated hydraulic conductivity.

Luckey and others (1986, p. 19) had the same problem with an earlier ground-water flow model that included the present model area. They reduced estimated hydraulic conductivity in areas where the base-of-aquifer surface had been altered due to salt dissolution in the underlying Permian-age rocks, arguing that “salt dissolution and sinkhole formation in the central High Plains cause extreme local variation in hydraulic conductivity because of disturbed and chaotic bedding combined with extreme changes in lateral lithologies” and, on a regional scale “the parameter value is a harmonic average of local extremes.”

The harmonic average is always less than the arithmetic average, and it is frequently much less because it is particularly sensitive to the smallest values. Thus, on a regional scale, zones of low hydraulic conductivity substantially impede ground-water flow, and these zones of low hydraulic conductivity dominate the flow system. This is analogous to segments of freeways being connected with narrow dirt roads; the effect of the dirt roads dominates the flow of traffic.

Gustavson and others (1980) studied active salt dissolution beneath and south of the Canadian River “breaks” and stated that more than 600 feet of salt could have been removed from Permian-age rocks in the area north of the Canadian River. They also pointed out how to tell where salt dissolution had taken place (Gustavson and others, 1980, p. 9):

> “The area north of the dissolution zone contains Permian through Cretaceous sediments beneath the Ogallala Formation. This area was exposed to erosion throughout the Late Cretaceous and early Tertiary, which was sufficient time to establish an integrated drainage system. It is evident that the erosion surface beneath the Ogallala Formation has been severely disturbed and no longer reflects any vestiges of a drainage pattern.”

With this information, the base-of-aquifer map was used to determine the area within the model area where salt dissolution had taken place (fig. 15). There were 10,742 active model cells in the area of salt dissolution, comprising about 51 percent of the model area. Simulated hydraulic conductivity was systematically reduced in the area of salt dissolution in Permian-age rocks and a reasonable fit between the simulated and observed water levels was obtained when hydraulic conductivity in this area was limited to 15 feet per day. With this limit, the mean simulated hydraulic conductivity for the entire model area was 32 feet per day, compared to the original estimated value of 51 feet per day.

For the Oklahoma portion of the study area, simulated hydraulic conductivity ranged from 10 to 122 feet per day and averaged 33 feet per day. The mean simulated hydraulic conductivity by county in Oklahoma:

County	Mean simulated hydraulic conductivity (feet per day)
Beaver	40
Cimarron	30
Ellis	29
Harper	50
Texas	31
Woodward	29

To estimate recharge from precipitation, the model area was divided into zones of greater and lesser recharge (fig. 16). The zones of greater recharge represented either sand dunes or areas of extremely sandy soils, whereas the zones of lesser recharge represented the remainder of the area. Recharge from precipitation was estimated as mean 1961-90 precipitation (fig. 16; Oregon Climate Service, 1999) times a zone factor, with a different zone factor for each to the two zones. The zone factors were determined during calibration. The best fit between simulated and observed water levels occurred when about 4.0 percent of precipitation was recharged in the greater recharge zones and about 0.37 percent of precipitation was recharged in the lesser recharge zones. Mean recharge for the greater recharge zones was 0.69 inch per year and mean recharge for the lesser recharge zones was 0.068 inch per year. Although the greater recharge zones included only 14 percent of the model area, they accounted for 62 percent of the total simulated recharge.

For the Oklahoma portion of the study area, simulated recharge from precipitation ranged from 0.06 inch per year to 0.90 inch per year and averaged 0.18 inch per year. The mean simulated recharge from precipitation by county in Oklahoma:

County	Mean simulated recharge from precipitation (inch per year)
Beaver	0.13
Cimarron	0.18
Ellis	0.27
Harper	0.49
Texas	0.09
Woodward	0.29

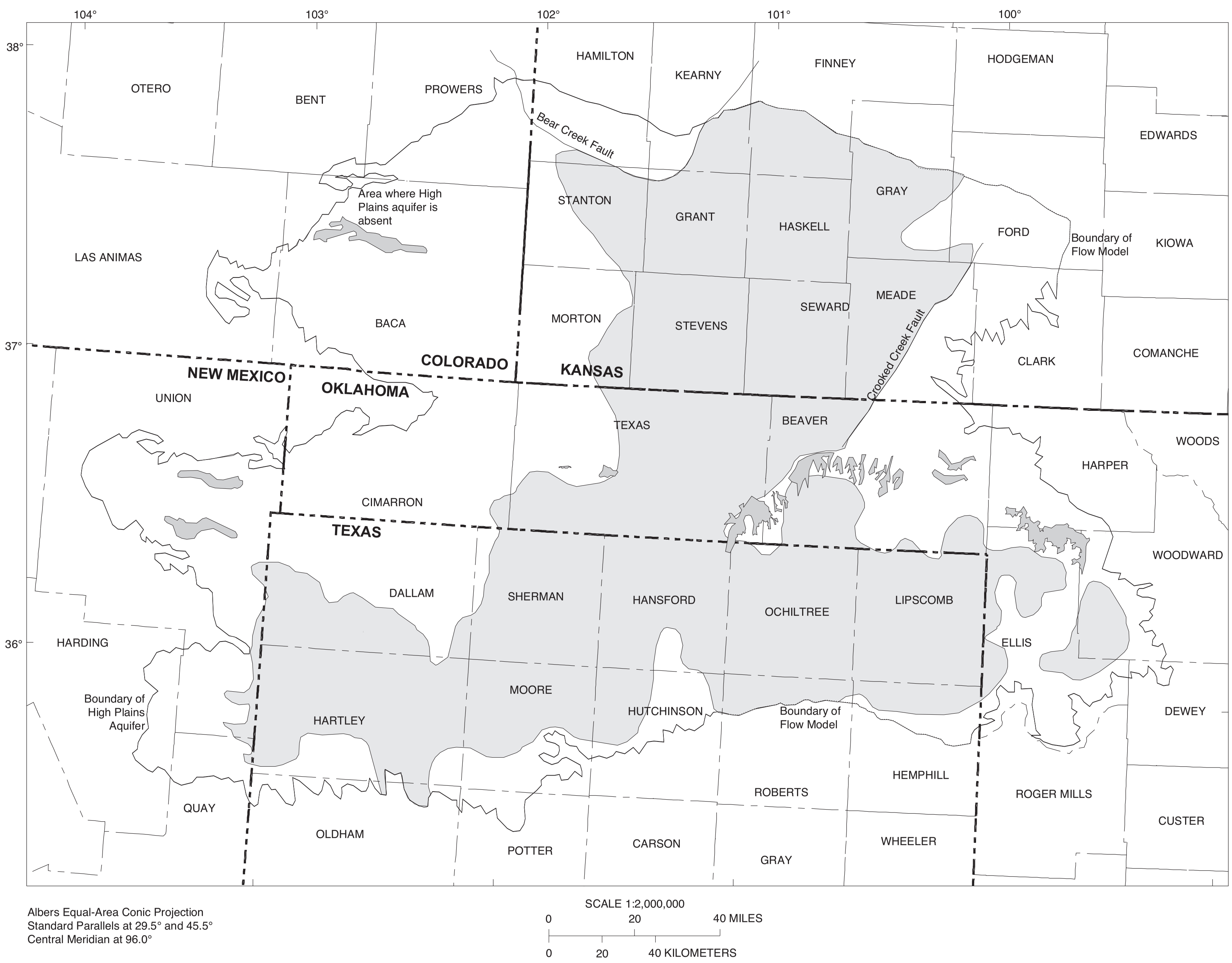


Figure 15. Areas where salt dissolution has occurred in Permian-age rocks underlying the High Plains aquifer (lightly shaded areas).

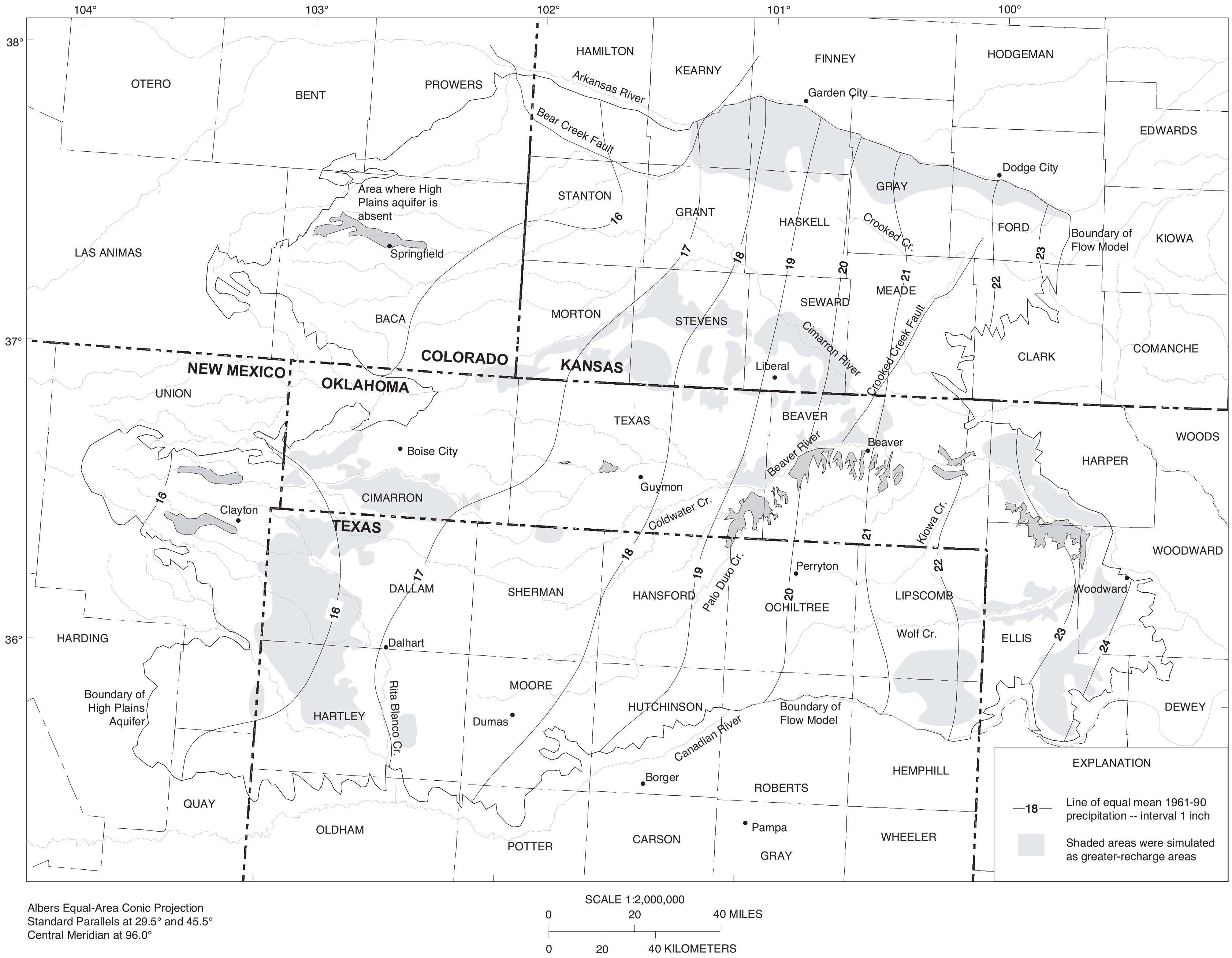


Figure 16. Mean 1961-90 precipitation and simulated greater-recharge areas.

Streambed conductances were altered during calibration and the following ranges of values were used in the calibrated model:

Stream	Streambed conductance (feet squared per day)	
	Minimum	Maximum
Arkansas River	5,000	5,000
Crooked Creek	6,000	6,000
Cimarron River	3,000	3,000
Beaver River	1,250	2,500
Coldwater Creek	1,000	1,000
Palo Duro Creek	1,000	1,000
Kiowa Creek	62	62
Wolf Creek	250	2,500
Canadian River	75	700

The streambed conductances of the Arkansas River, Crooked Creek, and Cimarron River were set to values at which the model started to become sensitive to them. The streambed conductances of the Beaver River and Kiowa Creek were decreased during calibration to achieve a reasonable fit between simulated and observed water levels. Even lesser values would have slightly improved the fit between observed and estimated discharge to the Beaver River, but would have badly degraded the water-level fit. The streambed conductance of Palo Duro Creek was increased during calibration to achieve a reasonable fit between simulated and observed water levels. This adjustment slightly degraded the discharge fit of the Beaver River. The streambed conductance of Wolf Creek was set to 250 feet squared per day in the upper section where the creek is very small and 2,500 feet squared per day in the lower section where the creek was larger. Streambed conductance was set to 750 feet squared per day in a short segment between these two extremes. The streambed conductance of the Canadian River was decreased during calibration to achieve a reasonable fit between simulated and observed water levels. The minimum value was in the central part of the simulated stream (columns 150 through 160) where topographic maps indicate an absence of springs on the north side of the river. West of this section, a value of 300 feet squared per day was used and east of this section, the maximum value was used.

Drain conductances were set to 10,000 feet squared per day for all drains except the three that were used to simulate flow across the model boundary to the eastern part of the aquifer in Kansas. This value was chosen to be large enough so that the model was not very sensitive to it. The conductances at the three drains in Kansas were set to 100,000 feet squared per day so flow would not be impeded. The altitudes of the drains were set to the altitude of the predevelopment water table unless there were springs or perennial streams that indicated that the altitude should be set to a lower value.

Simulated predevelopment water levels were compared to observed water levels at 86 points in Oklahoma. Observed water levels were selected from measurements made before 1950 in wells that were within 1,000 feet of model nodes. A graph of the relation between simulated and observed predevelopment water levels is shown in figure 17. Statistics for the differences:

Mean difference	-2.8 feet
Mean absolute difference	44.1 feet
Root mean square difference	52.0 feet
Calibration points within 10 feet	11.6 percent
Calibration points within 25 feet	26.7 percent
Calibration points within 50 feet	60.5 percent
Calibration points within 100 feet	95.3 percent

A map of the differences between the simulated and observed predevelopment water levels for the entire model area is shown on figure 18 and a histogram of the differences is shown on figure 19. Some statistics on the differences between simulated and observed water levels at model nodes:

Mean	-2.9 x 10-5 foot
Standard deviation	43.2 feet
Nodes within 25 feet	45.7 percent
Nodes within 50 feet	76.4 percent
Nodes within 75 feet	91.8 percent
Nodes within 100 feet	97.7 percent
Nodes within 150 feet	99.7 percent

The mean difference between simulated and observed predevelopment water levels for the 1,131 active nodes in Cimarron County, Oklahoma, is -11.4 feet and the standard deviation is 35 feet. The fifth and ninety-fifth percentiles are -63 and 65 feet, respectively. The simulated level is more than 75 feet below the observed level in the extreme south-central part of the county, and is between 25 and 75 feet below the observed level in three areas of the county (fig. 18). The area with the largest difference was simulated as a greater recharge area (fig. 16), but

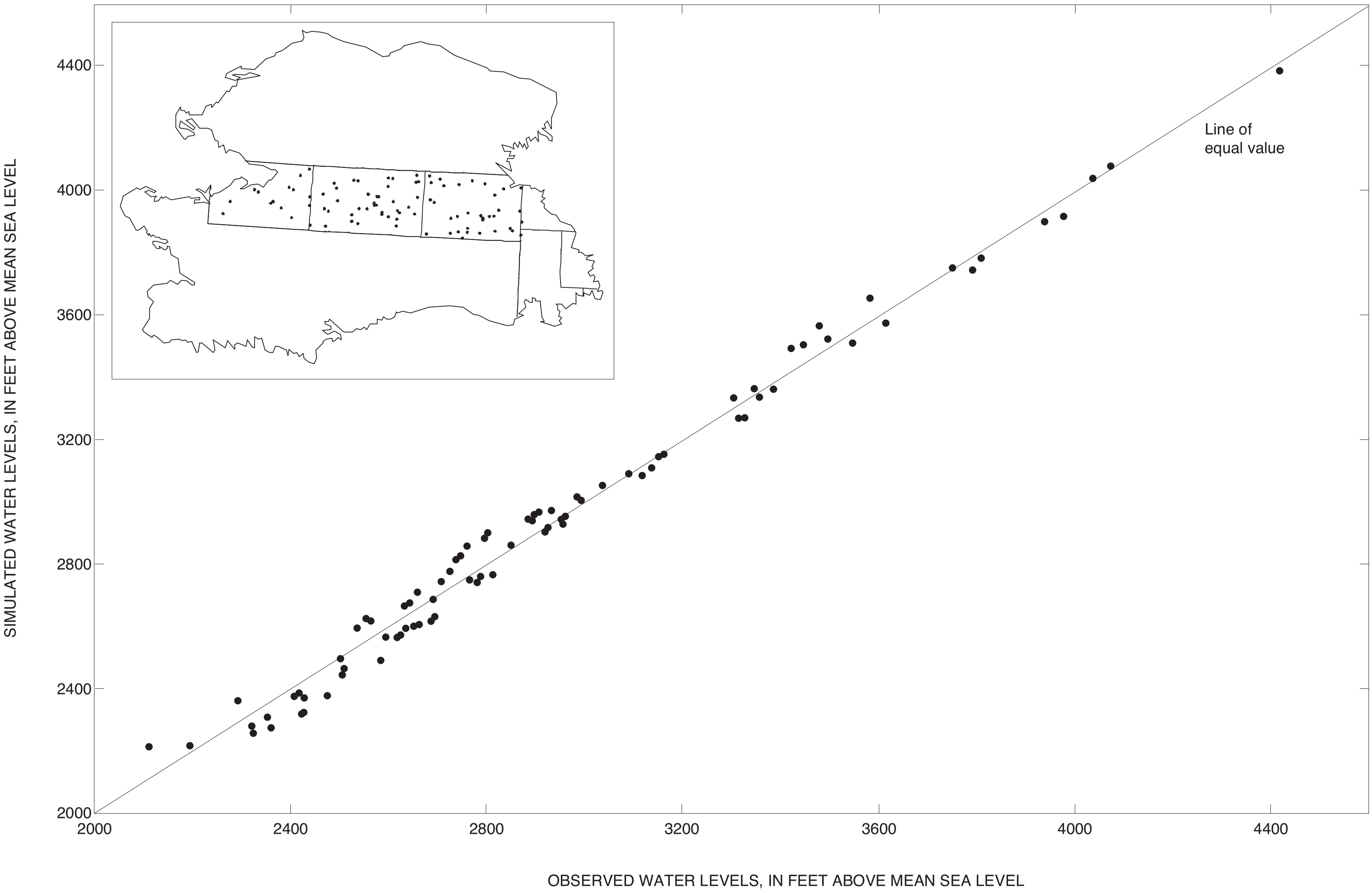


Figure 17. Relation between simulated and observed water levels at observation wells in Oklahoma for the predevelopment-period model. Insert in upper left corner of graph shows location of observation wells.

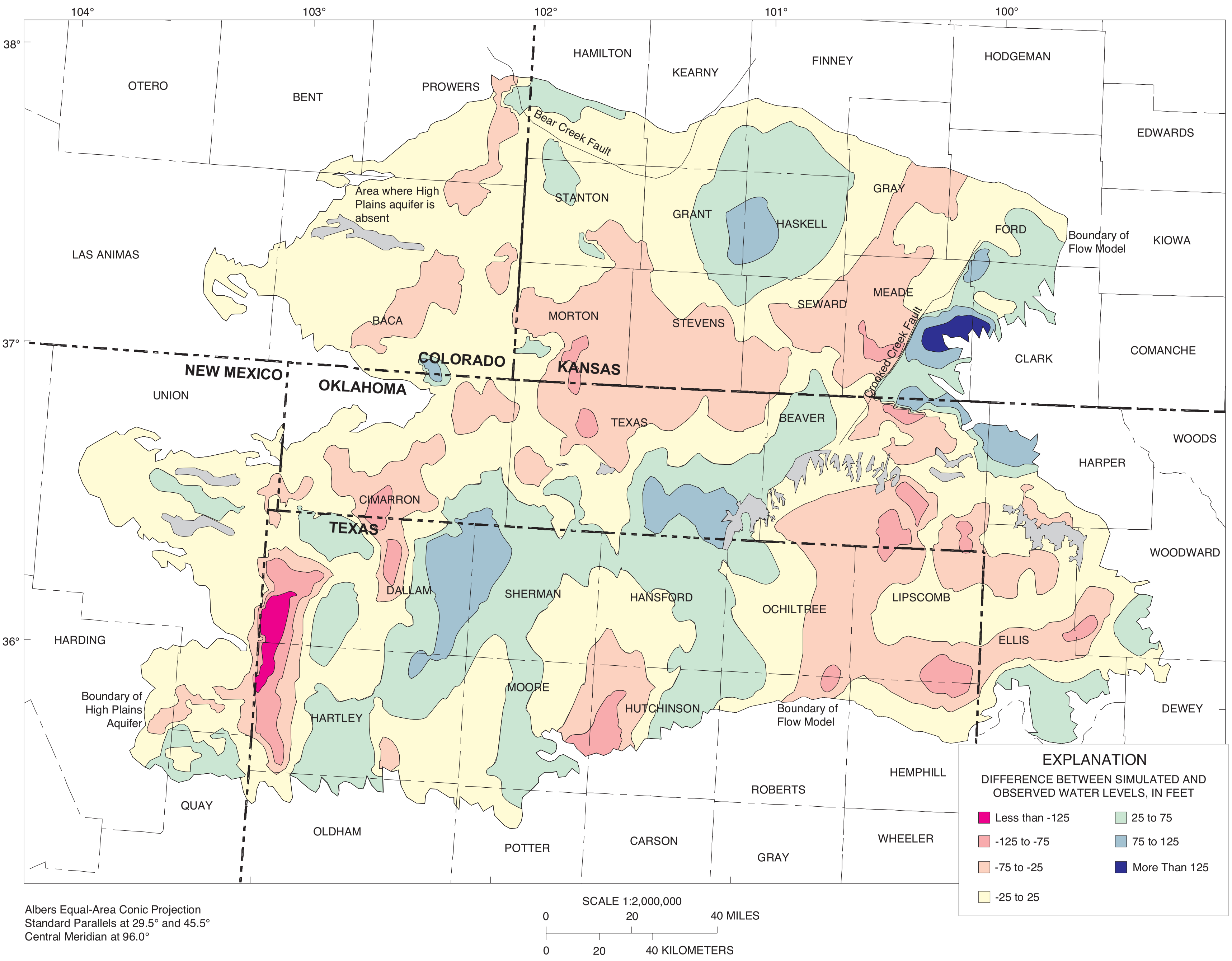


Figure 18. Difference between simulated and observed predevelopment water levels.

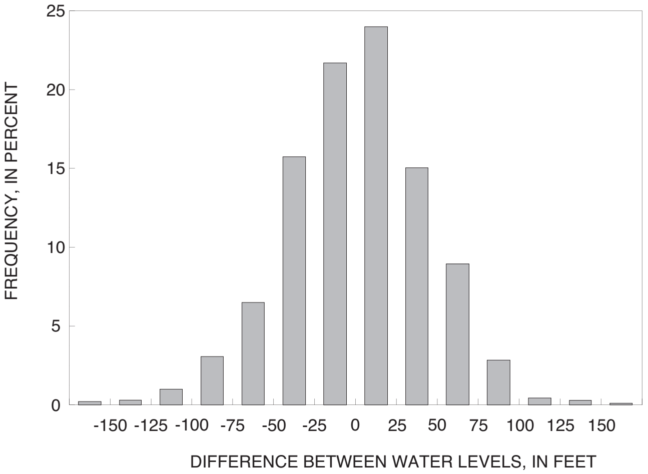


Figure 19. Difference between simulated and observed predevelopment water levels at model nodes.

perhaps actual recharge was still underestimated. There are some closed topographic depressions in this area that may facilitate recharge, but such closed depressions are not unusual in the High Plains and these particular depressions do not appear unique.

The mean difference between simulated and observed predevelopment water levels for the 1,548 active nodes in Texas County, Oklahoma, is 4.2 feet and the standard deviation is 48 feet. The fifth and ninety-fifth percentiles are -67 and 91 feet, respectively. Simulated water levels are below observed levels in the northern part of the county and into Kansas (fig. 18). Within the county, the differences are more than 75 feet in two areas and between 25 and 75 feet in one large area and two smaller areas. Small parts of this general area and the adjacent areas in Kansas were simulated as greater recharge zones and perhaps more of the area should have been so simulated. However, that change would have caused more discharge to streams, and simulated discharge to streams would have been much too large. Simulated water levels are above observed levels in the southeastern part of the county and into Texas. The difference was more than 75 feet west of where Permian-age rocks outcrop and between 25 and 75 feet in a substantial area west of the outcrops. The Permian-age rocks were treated as impermeable in the model, and water was simulated as accumulating up-gradient from them. In reality, the rocks may transmit some water. The area where simulated levels are more than 75 feet above observed levels includes the area where Coldwater Creek once began to flow. The creek was included in the model to this point in some preliminary simulations, and the simulated creek prevented water levels from rising so high in this area. However, the simulated creek carried little water and caused simulated water levels to be excessively depressed to the east, so it was removed from the predevelopment-period model.

The mean difference between simulated and observed predevelopment water levels for the 1,260 nodes in Beaver County, Oklahoma, is -17.5 feet and the standard deviation is 48 feet. The fifth and ninety-fifth percentiles are -86 and 60 feet, respectively. Simulated levels are more than 75 feet below observed levels in three different areas in the southern part of the county and are between 25 and 75 feet below observed levels in substantial areas of the county (fig. 18). Those differences may be partially due to treating Permian-age rocks to the west as impermeable, but more likely are due to recharge in the area being underestimated in the model. Simulated levels are both well above and well below observed water levels in the northeastern part of the county. Part of this area has little or no saturated thickness (fig. 13), whereas other parts have very large saturated thicknesses (fig. 7). Rapid changes in saturated thickness occur at a scale of less than a model cell, so the model was not spatially fine enough to simulate these rapid changes in saturated thickness.

The mean difference between simulated and observed predevelopment water levels for the 1,366 active nodes in Harper, Woodward, Ellis, and Dewey Counties, Oklahoma, is 0.7 foot and the standard deviation is 44 feet. The fifth and ninety-fifth percentiles are -66 and 86 feet, respectively. Simulated water levels are more than 75 feet above observed levels in an area of northwestern Harper County (fig. 18), but this difference occurs in an area of sparse data. However, because of the lack of data, the model may not be very reliable in this area. Simulated water levels are 25 to 75 feet below observed levels in parts of Ellis County and adjacent Woodward County and are more than 75 feet below observed levels in a small area. Although part of this area was simulated as a greater recharge area (fig. 16), recharge still may have been underestimated in the model. Simulated water levels are 25 to 75 feet above observed levels in extreme southern Ellis County. This is an area of very sparse data; it is unknown whether the cause of the difference is the simulated levels or the observed levels.

In Texas, simulated water levels are more than 125 feet below observed levels in an area in the extreme western part and were 75 to 125 feet below in a much larger area (fig. 18). Much of this area was simulated as a greater recharge zone (fig. 16), but simulated levels were still too low. In the real system in this area, water may be moving into the High Plains aquifer from underlying aquifers. Regardless of why simulated levels were so low, this area is far enough away that it did not affect the model in Oklahoma. Simulated water levels are 75 to 125 feet above observed levels in northeast Dallam County and northwest Sherman County and are 25 to 75 feet above observed levels in a much larger area. This area is just down gradient from the area where simulated levels are too low. In the real system in this area, water may be moving from the High Plains aquifer into underlying aquifers.

In Kansas, simulated water levels are 75 to 125 feet above observed levels in an area that includes parts of Grant and Haskell Counties (fig. 18). To the southeast and downgradient, simulated water levels are 75 to 125 feet below observed levels in Meade County. If hydraulic conductivity were not limited to 15 feet per day in this area, both differences in levels may have disappeared. However, little effort was spent to calibrate the model in this area because it is far enough away that it does not affect the model in Oklahoma. Simulated water levels are well above observed water levels in eastern Meade and western Clark Counties, Kansas, and a small part of Beaver County, Oklahoma, all east of the Crooked Creek fault. This area has little or no saturated thickness (fig. 13), so observed levels are poorly known. However, simulated levels are certainly too high because the levels indicate substantial saturated thickness. If the areas of incorrect simulated water levels northwest of the Crooked Creek fault were corrected and the streambed conductance of Crooked Creek were increased, the incorrect simulated levels east of the fault might also be corrected.

Estimated and simulated predevelopment discharge to streams at streamflow stations is shown on table 4. The location of the stations is shown on figure 13. Discharge from the aquifer to streams cannot be directly observed but must be estimated from total streamflow, hence the term estimated discharge. Estimated discharge, as well as the reliability of the estimates, was reported by Luckey and Becker (1998, table 2). Discharge was not estimated for the Arkansas and Canadian Rivers because the aquifer extends past these rivers, and it would have been impossible to estimate the discharge that comes from only the model area.

Simulated predevelopment discharge to the Cimarron River is 5 to 10 cubic feet per second more than estimated discharge at the three upstream streamflow gaging stations and is more than 20 cubic feet per second more at the downstream station (table 4). However, the estimate of discharge at the downstream station is in error because the analysis (Luckey and Becker, 1998) failed to account for diversions by a canal above the station. Because of the diversions, predevelopment discharge at this station cannot be estimated. Simulated and estimated discharge to Crooked Creek are nearly the same. Simulated discharge to Wolf Creek is 2 to 4 cubic feet per second more than estimated discharge at three streamflow stations and one estimation point.

The simulated discharge to the Beaver River and its tributaries is much larger than estimated discharge, except for the most upstream station (table 4). The reliability of the estimated discharge is considered poor at some points, but the range in uncertainty could not include the simulated discharge at the town of Beaver or at Wolf Creek. A major effort was made during the calibration process to decrease simulated flow to the Beaver River by decreasing streambed conductance, but this change degraded the fit between simulated and observed water levels by an unacceptable amount. The reason that the model did not reasonably simulate flow to the Beaver River could not be ascertained.

The simulated discharge to drains (fig. 13) across the eastern boundary of the aquifer in Oklahoma in Harper, Woodward, and Dewey Counties is 7.3 cubic feet per second and the simulated discharge across the southern boundary in Ellis County is 6.8 cubic feet per second. The simulated discharge to the drain in Cimarron County, Oklahoma, is 0.2 cubic foot per second. There are no observed values to compare these against, but the simulated discharges seem reasonable.

The simulated discharge to drains across the eastern boundary of the aquifer in Kansas is 8.1 cubic feet per second. Two of the seven drains have discharges in excess of 2 cubic feet per second. There are no observed values to compare these against, but the simulated flows seem too large. If the simulated flows are too large, the causes may have been the same factors that caused simulated water levels to be too high east of the Crooked Creek fault.

The simulated discharge to drains across the southern boundary in Texas is 19.2 cubic feet per second. The discharge of one drain exceeds 6 cubic feet per second, and the discharge of two additional drains exceeds 2 cubic feet per second. Topographic maps show numerous springs in the area of these three drains, so the simulated flows may be reasonable.

The simulated discharge to drains that represented Rita Blanco Creek where it occupies a deep canyon is 24.7 cubic feet per second. Topographic maps show some ponds and areas of trees in the bottom of the canyon, so evapotranspiration must be occurring in this area throughout much of the year. The simulated flow seems very large, but may be realistic. On the other hand, the simulated flow may, in part, represent water that, in the real system, moves into deeper aquifers. Regardless of whether or not the simulated flow is reasonable, this area is far enough away that it does not affect the model in Oklahoma.

Simulated recharge from precipitation in the predevelopment-period model is 310 cubic feet per second. Because the ground-water flow system was simulated as being in a state of dynamic equilibrium, recharge is balanced by an equal amount of discharge. The simulated discharge to streams is 242 cubic feet per second, and the simulated discharge to drains is 68 cubic feet per second.

The predevelopment-period model generally simulated water levels similar to observed levels in much of the model area. Where differences were larger, the model is considered less reliable with respect to water levels than where the differences were small. The predevelopment-period model also simulated discharges to streams that were similar to estimated values, except for the Beaver River system. The model is therefore considered less reliable with respect to discharge to the Beaver River. This model is considered adequate for its intended purpose, that is, to simulate and understand flow and the effects of pumpage at the township level in the High Plains aquifer of Oklahoma.

Development-Period Simulation

The development-period model simulated the period from 1946 through 1997 and calculated the altitude of the water table, discharge to the rivers and streams, diffuse cross-boundary discharge, discharge to small streams simulated with drains, and discharge across the eastern flow boundary in Kansas. The ground-water system simulated in the development-period model was not in a state of dynamic equilibrium, and recharge and discharge were not in balance. The imbalance allowed water levels to change over time. Simulated water-level

Table 4. Estimated and simulated predevelopment discharge to streams from the High Plains aquifer

[Col., column; --, value not estimated or simulated; ~, approximately; estimated discharge and the remarks concerning its reliability are from Luckey and Becker (1998, table2)]

Station number	Station name	Model cell		Discharge (cubic feet per second)		Remarks
		Row	Col.	Esti-mated	Simu-lated	
07156800	Cimarron River near Liberal, Kansas	53	51	20	30.2	Estimated predevelopment discharge is based on low flows for the winters of 1938-39 through 1941-42.
07156900	Cimarron River near Forgan, Oklahoma	61	163	45	49.6	Estimated predevelopment discharge is based on the winters of 1965-66 through 1984-85 because winter low flow appears to have decreased substantially over time.
07157000	Cimarron River near Mocane, Oklahoma	63	172	48	57.4	Estimated predevelopment discharge is based on the winter low flow for the winters of 1942-43 through 1964-65.
07157500	Crooked Creek near Englewood, Kansas	57	174	10	9.0	Estimated predevelopment discharge is based on the winter low flow for the winters of 1942-43 through 1992-93; estimate may be low. Station is downstream from model area; model cell is most downstream cell.
07157580	Cimarron River near Englewood, Kansas	63	175	see remark	62.1	Estimated discharge (Luckey and Becker, 1998) is in error because analysis failed to account for canal diversions above the station. Because of the diversions, predevelopment discharge cannot be estimated. Station is downstream from model area; model cell is most downstream cell.
07232500	Beaver River near Guymon, Oklahoma	79	115	5	2.8	Estimated predevelopment discharge is based on the winter low flow for the winters of 1937-38 through 1974-75.
07232900	Coldwater Creek near Guymon, Oklahoma	--	--	~ 1	--	Estimated predevelopment discharge, based on downstream station, is approximate and considered to be poor. Station is upstream from part of stream simulated in the model.
07233000	Coldwater Creek near Hardesty, Oklahoma	84	129	2.5	4.3	Estimated predevelopment discharge is based on the winter low flow for the winters of 1939-40 through 1958-59 with adjustment because of the assumption that winter low flows have decreased over time.
07233500	Palo Duro Creek near Spearman, Texas	--	--	0.5	--	Estimated predevelopment discharge is based on the winter low flow for the early part of record and assumption that winter low flow has decreased over time. Station is upstream from part of stream simulated in the model.
07233650	Palo Duro Creek at Range, Oklahoma	92	137	~ 3	7.6	Estimated predevelopment discharge is approximate and considered to be poor.

Table 4. Estimated and simulated predevelopment discharge to streams from the High Plains aquifer

[Col., column; --, value not estimated or simulated; ~, approximately; estimated discharge and the remarks concerning its reliability are from Luckey and Becker (1998, table2)]

Station number	Station name	Model cell		Discharge (cubic feet per second)		Remarks
		Row	Col.	Esti-mated	Simu-lated	
07234000	Beaver River at Beaver, Oklahoma	73	162	12	47.9	Estimated predevelopment discharge is based on estimates at upstream and downstream stations and work of Wahl and Tortorelli (1997). Estimate of predevelopment discharge is considered to be poor. Simulated discharge includes Beaver River (36.0) plus upstream tributaries (11.9).
07234100	Clear Creek near Elmwood, Oklahoma	--	--	2.4	--	Estimated predevelopment discharge is based on the winter low flows for the winters of 1965-66 through 1992-93 with more weight given to the first decade of record because winter low flow appears to have decreased over time. Clear Creek not simulated in the model.
07235000	Wolf Creek at Lipscomb, Texas	109	174	3	4.9	Estimated predevelopment discharge is based on the winter low flow for the winters of 1961-62 through 1976-77 because winter low flows appear to have decreased over time.
07235500	Wolf Creek near Shattuck, Oklahoma	105	192	10	12.8	Estimate of predevelopment discharge, which is based on the winter low flow for the winters of 1937-38 through 1945-46, is considered to be poor.
07236000	Wolf Creek near Fargo, Oklahoma	98	206	28	30.6	Estimated predevelopment discharge is based on the winter low flow for the winters of 1942-43 through 1975-76.
07237000	Wolf Creek near Fort Supply, Oklahoma	93	208	--	34.4	Predevelopment discharge could not be estimated.
Estimation point only	Beaver River at confluence with Wolf Creek	87	209	10	69.4	Estimated predevelopment discharge is considered to be poor. Simulated discharge includes Beaver River (57.3) plus upstream tributaries (12.1).
Estimation point only	Wolf Creek at confluence with Beaver River	93	208	30	34.4	Estimated predevelopment discharge is based on estimate at upstream station and assumption that creek received some additional discharge in its lower reaches.

changes for January 1946 to January 1998 were calculated by subtracting the simulated ending water levels from the corresponding simulated beginning water levels; the simulated changes were compared to the observed changes in the calibration process.

The model used the altitude of the base of aquifer, hydraulic conductivity, streambed conductance, recharge from precipitation, and the calculated water-table altitude from the predevelopment-period simulation. These model inputs were not altered during the calibration process. One additional aquifer parameter, specific yield, and three additional aquifer stresses, pumpage, recharge due to irrigation, and recharge due to dryland cultivation, were required for the development-period model. Initial estimates of specific yield were obtained from a detailed version of the map presented by Gutentag and others (1984, fig. 11; Cederstrand and Becker, 1998b); these estimates were modified for Oklahoma, except Cimarron County, during the calibration process. Pumpage was estimated as described in the "Water Use" section of this report and was not changed during the calibration process. However, it was necessary to distribute the county-level pumpage to model cells and that process is described as follows. Recharge due to irrigation and recharge due to dryland cultivation were varied during the calibration process so that the model produced a reasonable representation of observed water-level changes from predevelopment to January 1998.

Changes in model inputs as a result of the calibration process are reported here. Changes were made only where they could be clearly justified, seemed to be reasonable, or were supported by some evidence. Changes were made over large areas but were not made over small areas simply to improve the fit of simulated values to observed values.

The model was calibrated by comparing simulated and observed predevelopment to 1998 water-level changes at observation wells. Because the range in water-level changes is much smaller than the range in water levels, a more accurate calibration could be achieved using water-level changes rather than 1998 water levels. Differences between simulated and observed water-level changes were compared only within Oklahoma although elsewhere the simulated water-level changes were checked to make sure they were reasonable. Observed predevelopment to 1998 water-level changes outside of Oklahoma were not available in time to be used in the calibration. The differences were compared quantitatively at observation points in Oklahoma and were compared qualitatively elsewhere in Oklahoma by comparing maps of simulated change with observed changes (fig. 8).

The period 1946 through 1997 was simulated using six stress periods, five periods of 10 years each and one period of 2 years. Pumpage was constant within a stress period and was the average of estimated pumpage for all years within the period. The estimated pumpage was based on mean 1961-90 monthly precipitation and temperature. Given the long period simulated, the use of mean pumpage, temperature, and precipitation was assumed to have introduced negligible error by the end of the 52-year simulation. The first five stress periods were subdivided into 100 time steps, and the last stress period was subdivided into 20 steps. Each time step was 36.525 days long. Pumpage was assumed to occur throughout the year, whereas most pumpage actually occurred during the summer. However, this assumption also should have introduced negligible error by the end of the 52-year simulation.

The most appropriate method of distributing county-level pumpage to model cells was determined during calibration by comparing areas of simulated water-level changes to areas of observed water-level changes in Oklahoma. Irrigation density in 1980 (Thelin and Heimes, 1987, plate 1) was the primary information that was used to distribute county-level pumpage to model cells; irrigation density was not available for other years except 1978 (Thelin and Heimes, 1987, fig. 11). Saturated thickness of the High Plains aquifer was used as secondary information to distribute county-level pumpage to model cells.

Irrigated acreage in 1980 (Thelin and Heimes, 1987, plate 1) was summed for each county and for each active cell in the model. Cells that had less than 10 irrigated acres were assigned zero pumpage using the assumption that the area mapped as irrigated probably was either small groves of trees or farmsteads. Outside of Oklahoma, cells with less than 15 feet of simulated predevelopment saturated thickness also were assigned zero pumpage using the assumption that these areas were irrigated from a source other than the High Plains aquifer. For the three panhandle counties of Oklahoma, cells with less than 30 feet of simulated predevelopment saturated thickness were assigned zero pumpage; there was no saturated-thickness requirement for the remainder of Oklahoma. Pumpage for those cells that met the minimum irrigated-acreage requirement and, if appropriate, the minimum saturated-thickness requirement, was estimated as cell irrigated acreage times county pumpage divided by county irrigated acreage. For Oklahoma counties, cell pumpage was adjusted so that total simulated pumpage for the county equaled total estimated pumpage. This adjustment accounted for irrigated acreage in cells that did not meet the minimum irrigated-acreage or saturated-thickness requirements. The adjustment ranged from 4 percent for Ellis County to 23 percent for Cimarron County. Adjustments were not made outside Oklahoma, and simulated pumpage outside Oklahoma was approximately 5 percent less than estimated pumpage.

Initial estimated specific yield (Gutentag and others, 1984, fig. 11; Cederstrand and Becker, 1998b) in Oklahoma appears to be greater than that in adjacent states (fig. 10). Mean estimated specific yield was calculated for county-sized areas in Oklahoma and for comparable sized areas in adjacent Kansas, New Mexico, and Texas (fig. 20). The mean specific yield for the areas in Oklahoma was greater than the areas to the north and south, and the relative difference ranged from 4 percent for Cimarron County to 16 percent for Beaver County. The area east of Beaver County could not be directly compared to anything in Kansas or Texas but also appeared to be greater. This apparent difference does not mean that the values in Oklahoma are in error, but it does provide a rationale for reducing the estimates. The best fit between simulated and observed water levels was achieved when the initial estimated specific yield was reduced by 15 percent in Oklahoma east of the Cimarron-Texas County line. Initial estimated specific yield was not altered in Cimarron County, Oklahoma, or outside Oklahoma.

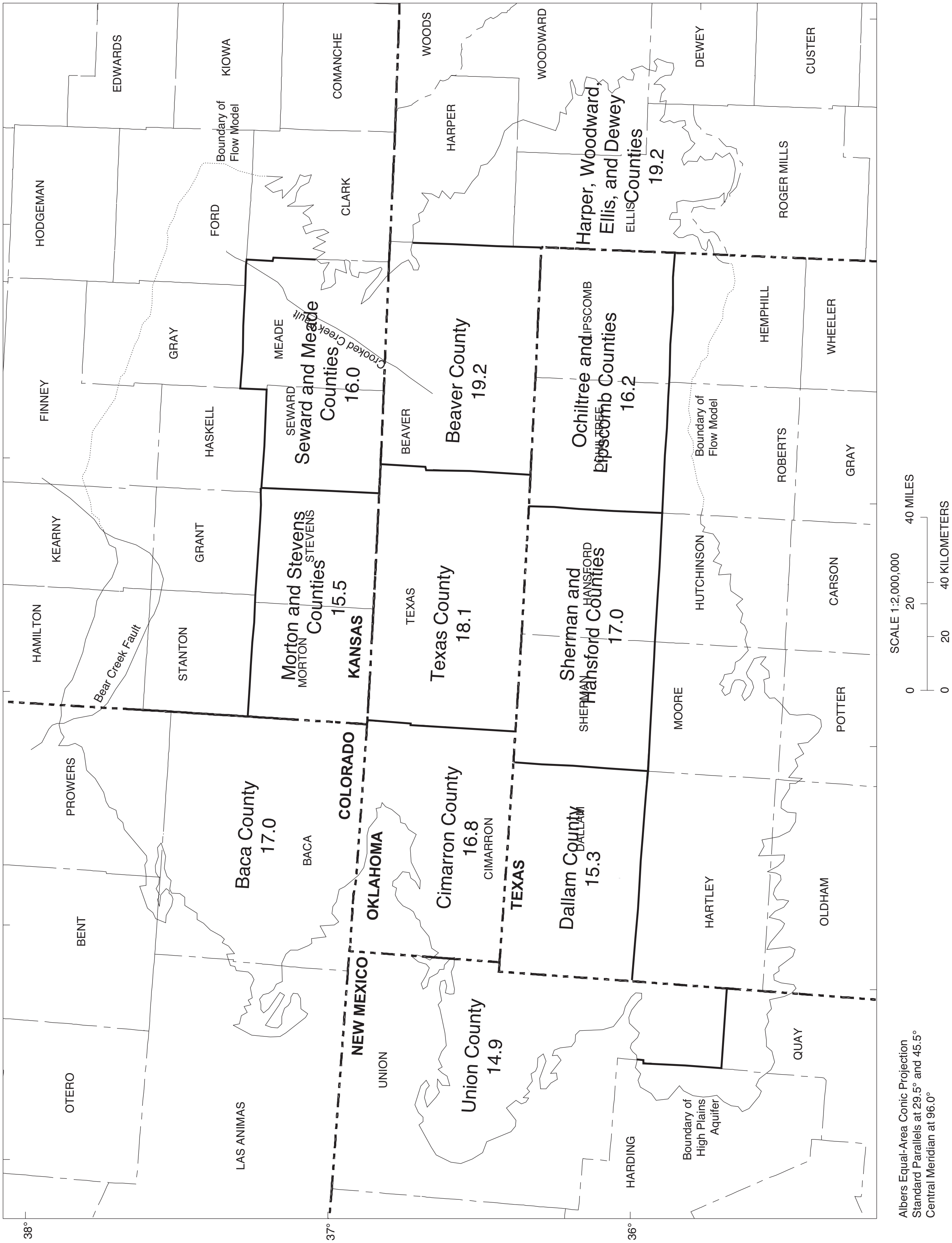


Figure 20. Mean estimated specific yield, in percent, by county-sized areas for Oklahoma and adjacent areas.

For the Oklahoma portion of the study area, simulated specific yield for individual model cells ranged from 4 percent to 27 percent and averaged 16 percent. The mean simulated specific yield by county in Oklahoma:

County	Mean simulated specific yield (percent)
Beaver	16.3
Cimarron	16.8
Ellis	16.3
Harper	17.0
Texas	15.4
Woodward	16.0

As discussed in the "Water Use" section, pumpage was computed as irrigation demand divided by efficiency. Inefficiency occurs because not all of the pumped water can be applied exactly where and when the crop needs it. Some pumpage infiltrates and recharges the aquifer, some runs off, and some evaporates. This can be expressed as

Pumpage = Irrigation Demand + Recharge due to irrigation + Runoff + Evaporation

For the development-period model, pumpage and irrigation demand were fixed as described in the "Water Use" section. The percent of pumpage that recharges the aquifer, the percent of pumpage that becomes runoff, and the percent of pumpage that becomes evaporation were varied until the best fit between simulated and observed water-level changes was achieved in irrigated areas. Runoff was assumed to leave the area as streamflow or be consumed by plants other than crops; it was assumed not to recharge the aquifer. Runoff probably was larger during early periods when flood irrigation was common. The best fit between simulated and observed water-level changes occurred when runoff was 30 percent through 1959 and then was steadily decreased and reached 1 percent in 1997. Evaporation was assumed to be a function of the delivery system and was assumed not to reduce irrigation demand. Evaporation probably was larger during later periods when sprinkler irrigation was common. The best fit between simulated and observed water-level changes occurred when evaporation was 1 percent through 1959 and then was steadily increased and reached 8 percent in 1997.

Simulated recharge due to irrigation averaged 24 percent of pumpage for the 1940s and 1950s, averaged 14 percent for the 1960s, averaged 7 percent for the 1970s, averaged 4 percent for the 1980s, and averaged 2 percent for the 1990s. Recharge due to irrigation was subtracted from total pumpage before the simulation was made, so only net pumpage was input into the model. Subtracting recharge due to irrigation from total pumpage external to the model means that recharge due to irrigation was assumed to occur within the same stress period as the pumpage. It is unknown if this is a valid assumption, but given the long period simulated and the low recharge near the end of the simulation, this assumption probably did not cause substantial error in the model.

Recharge due to dryland cultivation also was estimated as part of the calibration process and was varied until the best fit between simulated and observed water-level changes was achieved in dryland areas. The upper limit of this recharge was estimated from the hydrograph of well 03N-07E-09 BBB 1 (fig. 21). This well had the largest rise of approximately 25 observation wells with substantial rising water levels in the Oklahoma High Plains. The water level in the well rose about 20 feet in 50 years. The rate of water-level rise was relatively constant, although the effects of the drought of the 1950s (fig. 3) can be clearly seen in the hydrograph (fig. 21). The well is located in an area of sandy soils completely surrounded by dryland fields. The estimated mean 1961-90 precipitation in the area is 16.5 inches per year (fig. 16) and the estimated specific yield is 18 percent (Gutentag and others, 1984, fig. 11; Cederstrand and Becker, 1998b). If dryland cultivation caused an additional 5.2 percent of precipitation to be recharged, the observed water-level rise in well 03N-07E-09 BBB 1 could be accounted for. Recharge due to dryland cultivation was varied from 0.0 to 5.2 percent of mean 1961-90 precipitation over the dryland area as mapped by Thelin and Heimes (1987) for 1978, in various simulations. Irrigated wheat was included in the area in dryland cultivation by Thelin and Heimes (1987, p. 14); similar recharge could occur on irrigated wheat if cultivation practices were similar to those on dryland wheat. Recharge due to dryland cultivation was used to drive the mean error between simulated and observed water-level changes at observation wells close to zero. The estimated recharge due to dryland cultivation is about 3.9 percent of mean 1961-90 precipitation over the area in dryland cultivation. This recharge is about 476 cubic feet per second for the entire study area with about 143 cubic feet per second being in the Oklahoma portion of the area.

A graph comparing simulated and observed predevelopment to 1998 water-level changes at 162 observations wells in Oklahoma is shown in figure 22. Statistics for the differences:

Mean difference	-2.9 x 10-3 foot
Mean absolute difference	13.1 feet
Root mean square difference	17.9 feet
Maximum absolute difference	63.7 feet
Calibration points within 5 feet	30.9 percent
Calibration points within 10 feet	56.8 percent
Calibration points within 25 feet	81.5 percent
Calibration points within 50 feet	98.1 percent

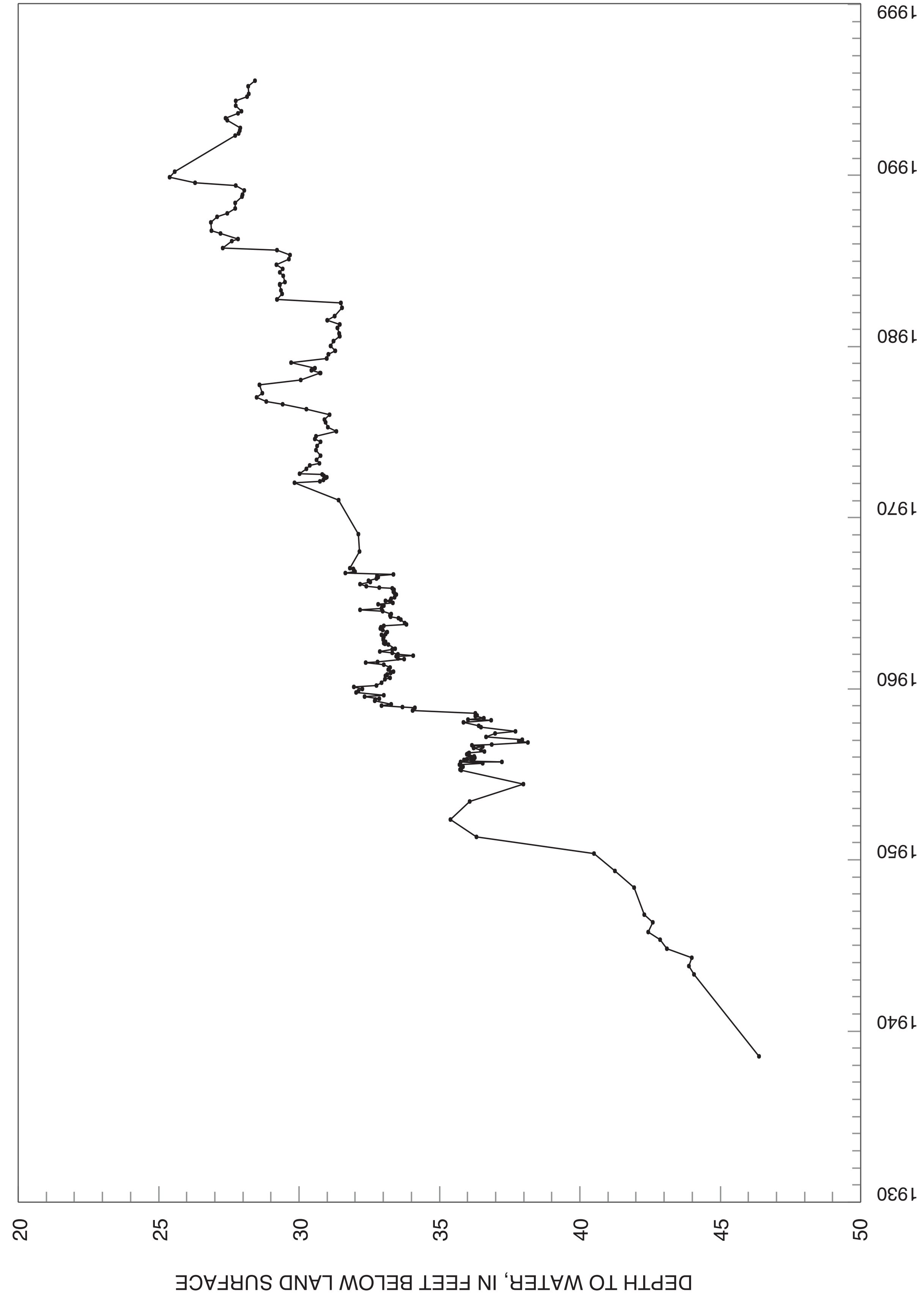


Figure 21. Hydrograph for well 03N-07E-09 BBB 1, east-central Cimarron County, Oklahoma.

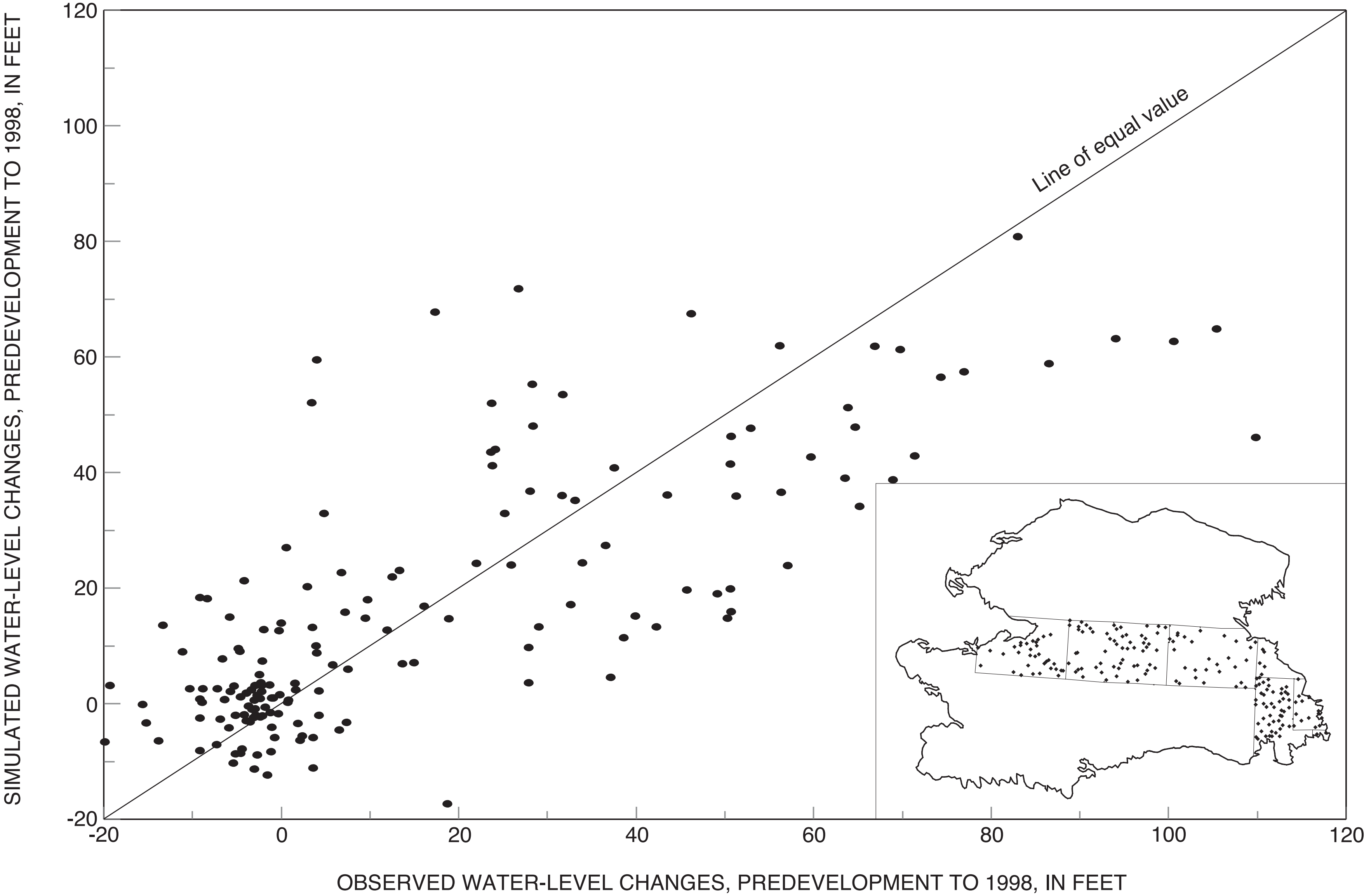


Figure 22. Relation between simulated and observed water-level changes in Oklahoma for the development-period model. Insert in lower right corner of graph shows location of observation wells.

A map of the simulated water-level changes is shown in figure 23. For Oklahoma, this map can be compared to figure 8. No map of observed predevelopment to 1998 water-level changes was available for the entire model area; however, maps for predevelopment to 1980 (Luckey and others, 1981) and 1980 to 1995 (McGuire and Sharpe, 1997) are available, and a map for predevelopment to 1997 is under construction (V.L. McGuire, U.S. Geological Survey, written commun., 1999).

The areal extent of simulated and observed water-level changes in Oklahoma is similar, although the model does not simulate changes as large as the largest observed changes (fig. 8). The areal extent of simulated and observed water-level changes in Kansas is similar (fig. 23; V.L. McGuire, U.S. Geological Survey, written commun., 1999) although the largest simulated changes are larger than the largest observed changes. The areal extent and magnitudes of simulated and observed water-level changes in Texas are generally similar (fig. 23; V.L. McGuire, U.S. Geological Survey, written commun., 1999).

A number of model cells were simulated as dry by the end of 1997. A dry cell means that the calculated water level was below the base of aquifer at some time during the simulation. Dry cells became inactive in the model; to calculate the simulated water-level change, the simulated water level was assumed to be equal to the base of aquifer. Once a cell became dry, aquifer stresses, such as recharge and pumpage, were no longer applied to the cell. In reality, an area the size of a model cell is unlikely to ever become completely dry because irrigation would become impractical before that could happen. However, the saturated thickness in smaller areas could be reduced so that well yields might be only a few gallons per minute. Most of the dry cells were near areas of little or no saturated thickness (fig. 13). These cells were assigned some pumpage during the simulation because they were partially irrigated in 1980, but may not have been irrigated by 1997 because of minimal saturated thickness.

About 200 model cells in the Oklahoma portion of the study area were simulated as dry by the end of 1997; this was about 4 percent of the active cells in Oklahoma. Most of these dry cells were in northeastern Cimarron County and northwestern Texas County near the area of little or no saturated thickness (fig. 13).

About 180 model cells in the Kansas portion of the study area were simulated as dry by the end of 1997. These cells were near areas of little or no saturated thickness (fig. 13) and were generally remote from Oklahoma. About 140 model cells near the New Mexico-Texas state line also were simulated as dry by the end of 1997. These cells were in the area where the difference between simulated and observed predevelopment water levels exceeded -75 feet (fig. 18). This area is remote from Oklahoma.

The simulated discharge to the Beaver River above Optima Lake at the end of 1997 is 7.8 cubic feet per second, a decrease of 11.6 cubic feet per second from the simulated predevelopment discharge. The river was actually dry most of the time in this area by 1997, so the model over estimates discharge to the river. The predevelopment-period model also over estimates the discharge to the Beaver River. The simulated discharge to Coldwater Creek at the end of 1997 is 3.6 cubic feet per second, and the simulated discharge to Palo Duro Creek is 6.0 cubic feet per second. Both seem to be too large as both streams were actually dry most of the time by 1997.

The simulated discharge to Crooked Creek at the end of 1997 is 9.1 cubic feet per second, a increase of 0.1 from simulated predevelopment discharge even though the upper part of the creek is simulated as going dry. The loss of flow to the upper part is consistent with observations and the increase in flow is too small to be compared with observations.

The simulated discharge to the Cimarron River at the end of 1997 is 51.2 cubic feet per second, a decrease of 10.9 cubic feet per second from simulated predevelopment discharge. Both the discharge and simulated change in discharge appear reasonable.

The simulated discharge to Wolf Creek at the confluence with the Beaver River at the end of 1997 is 30.8 cubic feet per second, a decrease of 3.6 cubic feet per second from simulated predevelopment discharge. Most of the decrease took place in the upper reaches of the stream. Both the discharge and simulated change in discharge appear reasonable.

During 1997, simulated recharge in the development-period model from all sources is 823 cubic feet per second, consisting of 476 cubic feet per second recharge due to dryland cultivation, 303 cubic feet per second background recharge from precipitation, and 44 cubic feet per second recharge due to irrigation. Simulated discharge from all sources is 3,897 cubic feet per second, consisting of 3,688 cubic feet per second to wells, 145 cubic feet per second to streams, and 64 cubic feet per second to drains. Because discharge exceeded recharge in the development-period model, ground-water storage is simulated to have decreased 87 million acre-feet from 1946 through 1997.

The development-period model generally simulates water-level changes similar to observed changes, especially in Oklahoma and in nearby areas. Where differences were larger, the model is considered less reliable with respect to water-level changes than where the differences were small. The development-period model also simulates discharges to streams that seemed reasonable, except for the Beaver River and its upstream tributaries. The model is therefore considered less reliable with respect to discharge to the Beaver River and its upstream tributaries. This model is considered adequate to simulate broad-scale future water-level changes in the High Plains aquifer of Oklahoma.

Model Sensitivity

A sensitivity analysis was performed on both the predevelopment-period model and the development-period model to determine their responses to changes in model inputs. The sensitivity analysis consisted of uniformly increasing or decreasing one or two model inputs and noting the change in simulated water levels or water-level changes and discharge to streams.

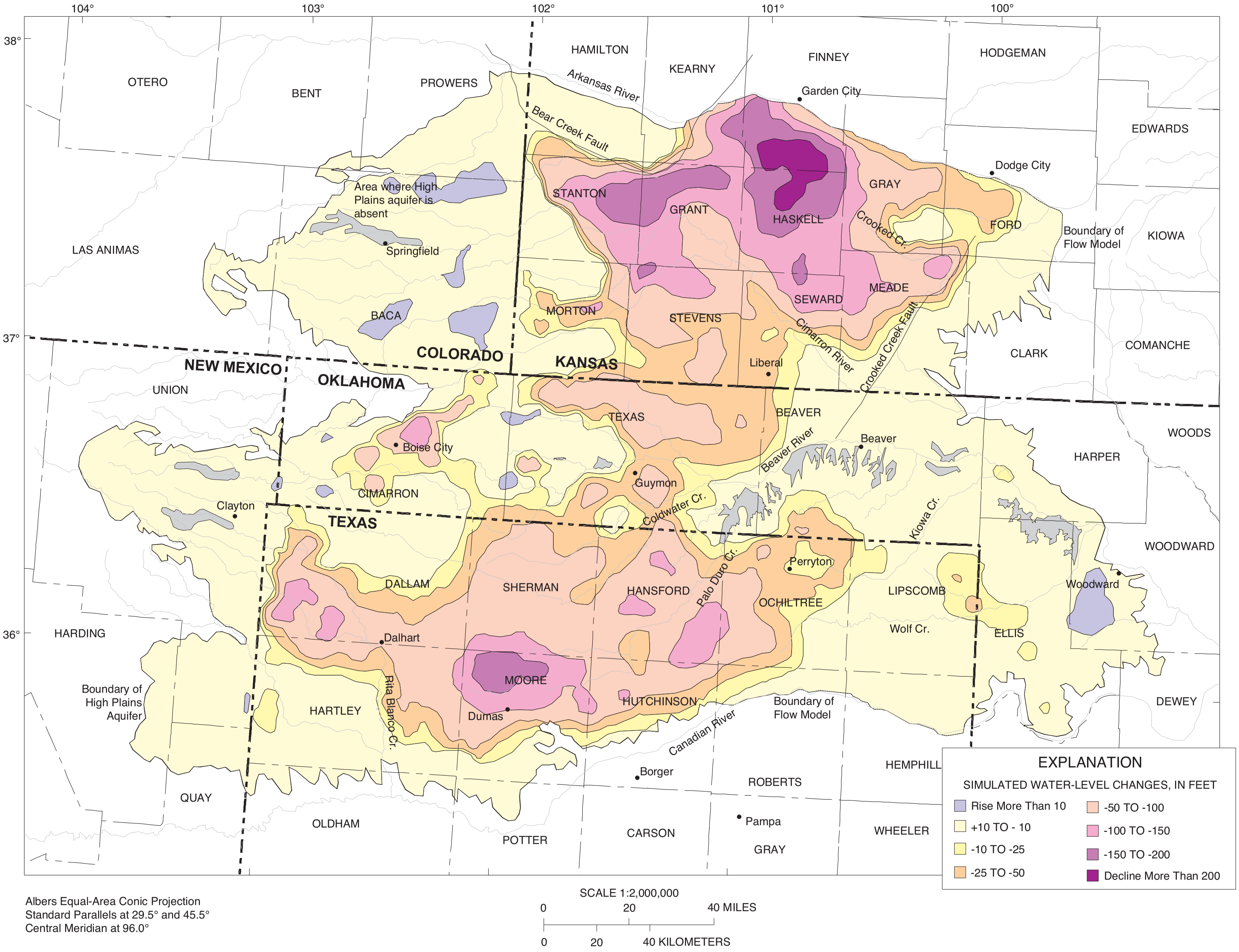


Figure 23. Simulated water-level changes for the development-period model.

For the predevelopment-period model, changes in recharge and hydraulic conductivity were investigated, and the effect of these changes on simulated water levels and discharge to streams was noted. For the development-period model, changes in specific yield and recharge due to dryland cultivation were investigated, and the effect of these changes on simulated water-level changes and discharge to streams was noted. Changes in the areal distribution of model inputs were not investigated because the distributions were based on physical conditions that seemed to be well defined.

For the predevelopment-period model, the effect of uniformly varying recharge while keeping all other model inputs fixed is shown on figure 24. Recharge was changed over a range of ±50 percent of the calibrated value. Changing recharge causes a nearly linear change in simulated discharge to streams.

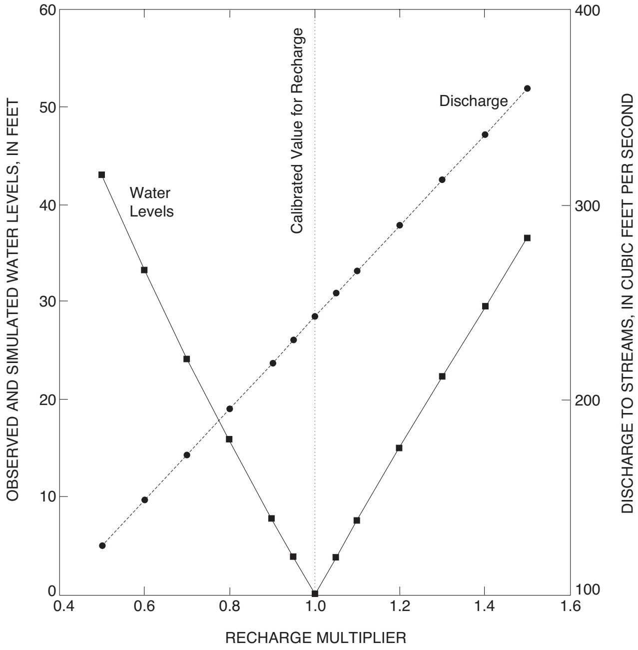


Figure 24. Effects of varying recharge on water levels and discharge to streams in the predevelopment-period model.

Increasing recharge by 50 percent causes a 48 percent increase in discharge to streams, with the remaining 2 percent going to drains. Decreasing recharge by 50 percent causes a 48 percent decrease in discharge to streams. Changing recharge also causes a generally linear change in simulated water levels. Increasing recharge by 50 percent causes mean simulated water levels to be about 37 feet above mean observed levels, whereas decreasing recharge by 50 percent causes mean simulated water levels to be about 43 feet below mean observed levels. Stream cells, and to a lesser degree drain cells, moderate the effect of changes in recharge on simulated water levels.

The effect of uniformly varying hydraulic conductivity in the predevelopment-period model while keeping all other model inputs fixed is shown on figure 25. Hydraulic conductivity was changed over a range of ±50 percent of the calibrated value. Changing hydraulic conductivity has almost no effect on simulated discharge to streams. Simulated discharge to streams is 239 cubic feet per second when hydraulic conductivity is decreased by 50 percent and is 244 cubic feet per second when hydraulic conductivity is increased by 50 percent. The small difference in simulated discharge to streams is caused by a redistribution of discharge to drains. Changing hydraulic conductivity causes a substantial change in simulated water levels. Decreasing hydraulic conductivity by 50 percent causes mean simulated water levels to be 54 feet above mean observed water levels; the rate of change in the difference between water levels increases the more hydraulic conductivity is decreased. Increasing hydraulic conductivity by 50 percent causes mean simulated water levels to be 22 feet below mean observed water levels. Stream cells, and to a lesser degree drain cells, moderate the effect of changes in hydraulic conductivity on simulated water levels.

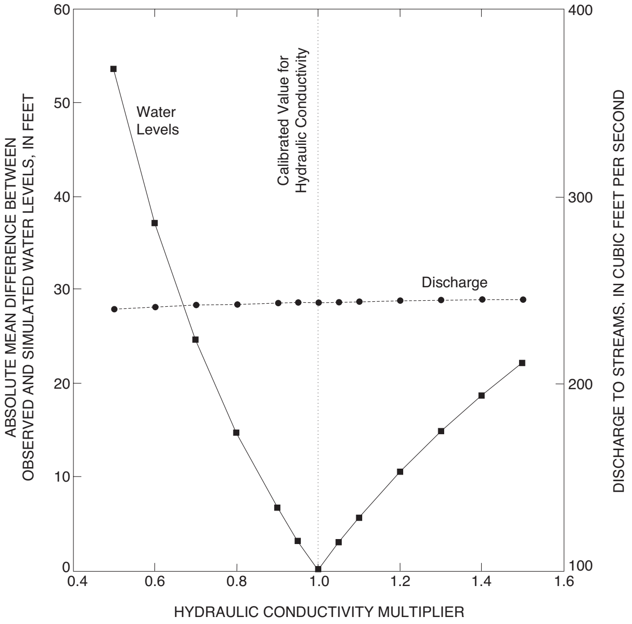


Figure 25. Effects of varying hydraulic conductivity on water levels and discharge to streams in the predevelopment-period model.

During calibration of the predevelopment-period model, it was apparent that simulated water levels could be made to match observed water levels by either changing recharge or hydraulic conductivity. If simulated water levels were below observed water levels, either recharge could be increased or hydraulic conductivity could be decreased. If simulated water levels were above observed water levels, either recharge could be decreased or hydraulic conductivity could be increased. The effect of simultaneously varying recharge and hydraulic conductivity is shown on figure 26. At the center of the figure, where both recharge and hydraulic conductivity were at cali-

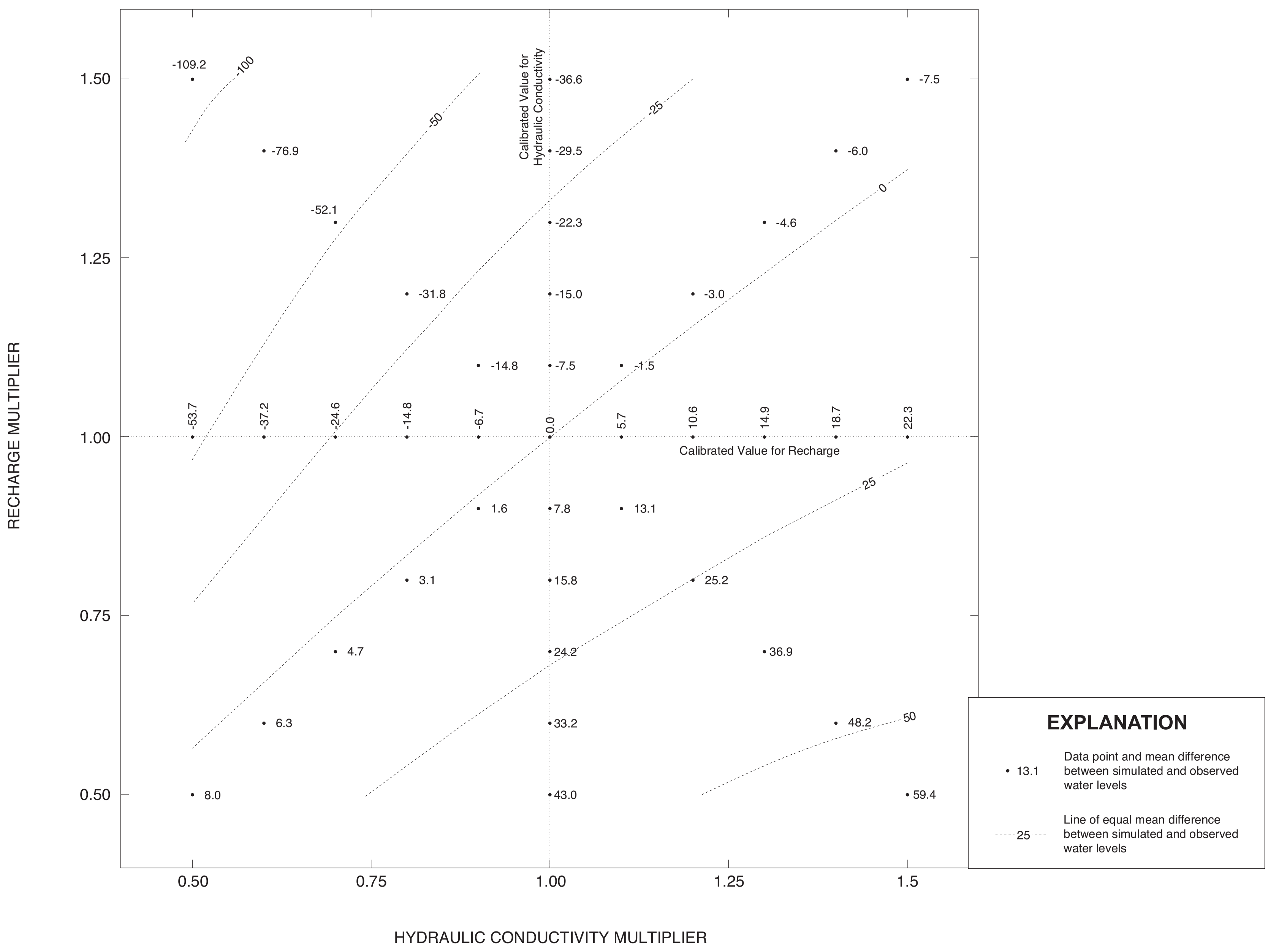


Figure 26. Effects of varying recharge and hydraulic conductivity on water levels in the predevelopment-period model.

brated values, the mean difference between simulated and observed water levels is essentially zero. As both recharge and hydraulic conductivity are decreased (going toward the lower left corner of the figure), the simulated water levels slowly rise above observed water levels, but even when both inputs are decreased by 50 percent, the mean difference is only 8 feet. Likewise, as both recharge and hydraulic conductivity are increased (going toward the upper right corner of the figure), the simulated water levels slowly drop below observed water levels, but when both inputs are increased by 50 percent, the mean difference is less than 8 feet. However, if either recharge or hydraulic conductivity is increased while the other is decreased, the mean difference between simulated and observed water levels changes rapidly. If recharge is increased by 10 percent while hydraulic conductivity is decreased by 10 percent, mean simulated and observed water levels differ by nearly 15 feet. If recharge is decreased by 10 percent while hydraulic conductivity is increased by 10 percent, mean simulated and observed water levels differ by more than 13 feet. If recharge is increased by 50 percent while hydraulic conductivity is decreased by 50 percent, mean simulated and observed water levels differ by more than 100 feet.

Although recharge and hydraulic conductivity are closely related with respect to simulated water levels, they are not closely related with respect to simulated discharge to streams. For a fixed hydraulic conductivity, changing simulated recharge causes a nearly equal change in simulated discharge to streams (fig. 24). For a fixed recharge, however, changing simulated hydraulic conductivity causes almost no change in simulated discharge to streams (fig. 25). Mean simulated water levels are only about 8 feet above observed water levels when both recharge and hydraulic conductivity are reduced 50 percent (fig. 26), but simulated discharge to streams decreases about 120 cubic feet per second. Likewise, mean simulated water levels are less than 8 feet below mean observed water levels when recharge and hydraulic conductivity are both increased 50 percent (fig. 26), but simulated discharge to streams increases almost 120 cubic feet per second. Only the ratio between simulated recharge and hydraulic conductivity could be determined with the predevelopment-period model by using observed water levels. Recharge could be determined using estimated discharge to streams. Thus, both recharge and hydraulic conductivity could be determined by the model.

For the development-period model, the effect of uniformly varying specific yield while keeping all other model inputs fixed is shown on figure 27. Specific yield was changed over a range of ±50 percent of the calibrated value. Increasing specific yield by 50 percent causes a 9 percent increase in simulated discharge to streams at the end of 1997, and decreasing specific yield 50 percent causes a 21 percent decrease in simulated discharge to streams. As simulated specific yield is increased, more of the water pumped comes from storage and less comes from decreased streamflow. Increasing simulated specific yield by 50 percent causes the mean simulated water-level change at observation points to be 5 feet less than the mean observed change. Decreasing simulated specific yield 50 percent causes the mean simulated water-level change at observation points to be 14 feet more than the mean observed change.

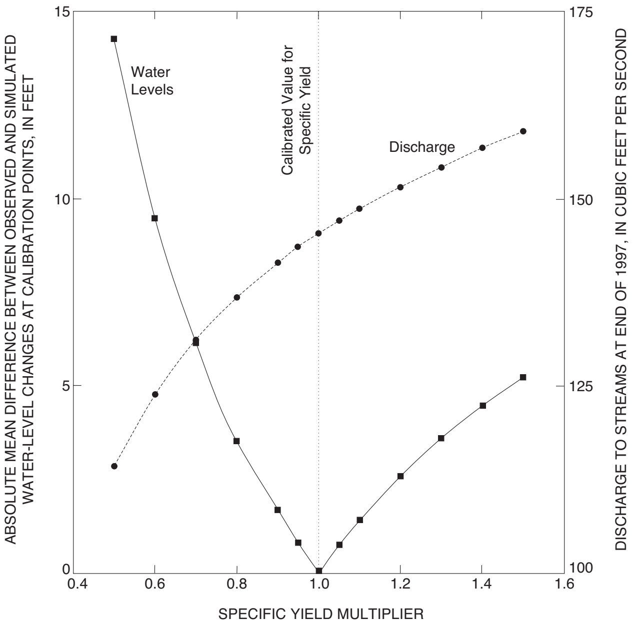


Figure 27. Effects of varying specific yield on water-level changes and discharge to streams in the development-period model.

For the development-period model, the effect of uniformly varying recharge due to dryland cultivation while keeping all other model inputs fixed is shown on figure 28. Recharge due to dryland cultivation was varied from 0.0 to 5.2 percent of precipitation, the upper limit postulated in the “Development-Period Simulation” section. At calibration, this recharge is about 3.9 percent of precipitation. When this recharge is 5.2 percent of precipitation, simulated discharge to streams at the end of 1997 increases by 8 cubic feet per second and the mean simulated water-level change at observation points decreases 2.5 feet. When this recharge is zero, simulated discharge to streams at the end of 1997 decreases by 26 cubic feet per second and the mean simulated water-level change at observation points increases 8 feet.

Simulated Response to Future Withdrawals

The calibrated development-period model was used to simulate water-level changes from 1998 to the beginning of 2020 using mean 1996-97 pumpage. Other model inputs, except stream cells, were the same as in the development-period model. Stream cells were converted to drain cells so that water could flow from the aquifer to the stream when the simulated water level was above the level of the stream, but water could not flow in the other direction if the water level fell below the level of the steam. This conversion was simply a labor-saving

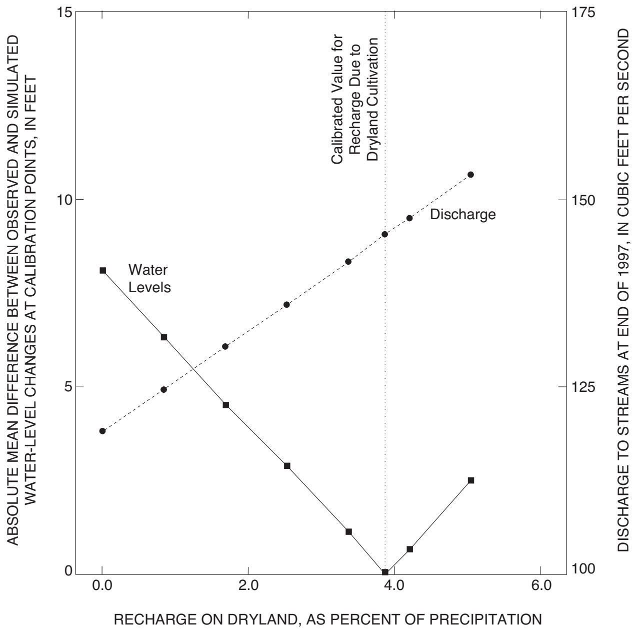


Figure 28. Effects of varying recharge due to dryland cultivation on water-level changes and discharge to streams in the development-period model.

device. The same thing could have been accomplished by removing stream cells as the simulation indicated segments of streams were no longer receiving discharge from the aquifer.

The simulated water-level change from the beginning of 1998 to 2020 assuming mean 1996-97 pumpage is shown in figure 29. This water-level change is in addition to the change that took place from predevelopment to the beginning of 1998. The largest simulated water-level changes in Oklahoma occur in Texas County where water levels are simulated to decline 25 to 50 additional feet over a large area of the north-central part of the county. Water levels also are simulated to decline 25 to 50 additional feet in two small areas in the south-central part of the county. Water levels are simulated to decline 10 to 25 additional feet over a substantial part of the county. Simulated water-level declines were limited by the small saturated thickness in the northwest and west-central part of the county.

Water levels are simulated to decline 10 to 25 additional feet in two large areas of Cimarron County, Oklahoma (fig. 29). Simulated water-level declines were limited by the small saturated thickness northeast of Boise City. Water levels are simulated to decline 10 to 25 additional feet in northwestern and southwestern Beaver County. Water levels are simulated to decline 10 to 25 additional feet between 1998 and 2020 in one area of Ellis County.

The largest simulated water-level declines, more than 100 additional feet, occur in several areas in Kansas (fig. 29). In Kansas, an area of simulated decline of 50 to 100 additional feet covers most of Grant and Haskell Counties and substantial parts of the adjacent counties. Very little additional decline is simulated to occur in southeastern Gray County, Kansas, but this is an area of little saturated thickness (fig. 13). Water levels are simulated to decline 50 to 100 additional feet in three areas in Texas and are simulated to decline 25 to 50 additional feet in other Texas counties in the study area except Hemphill and Lipscomb Counties. Water levels are simulated to rise more than 10 feet between 1998 and 2020 in three areas of Colorado and an adjacent area in Kansas.

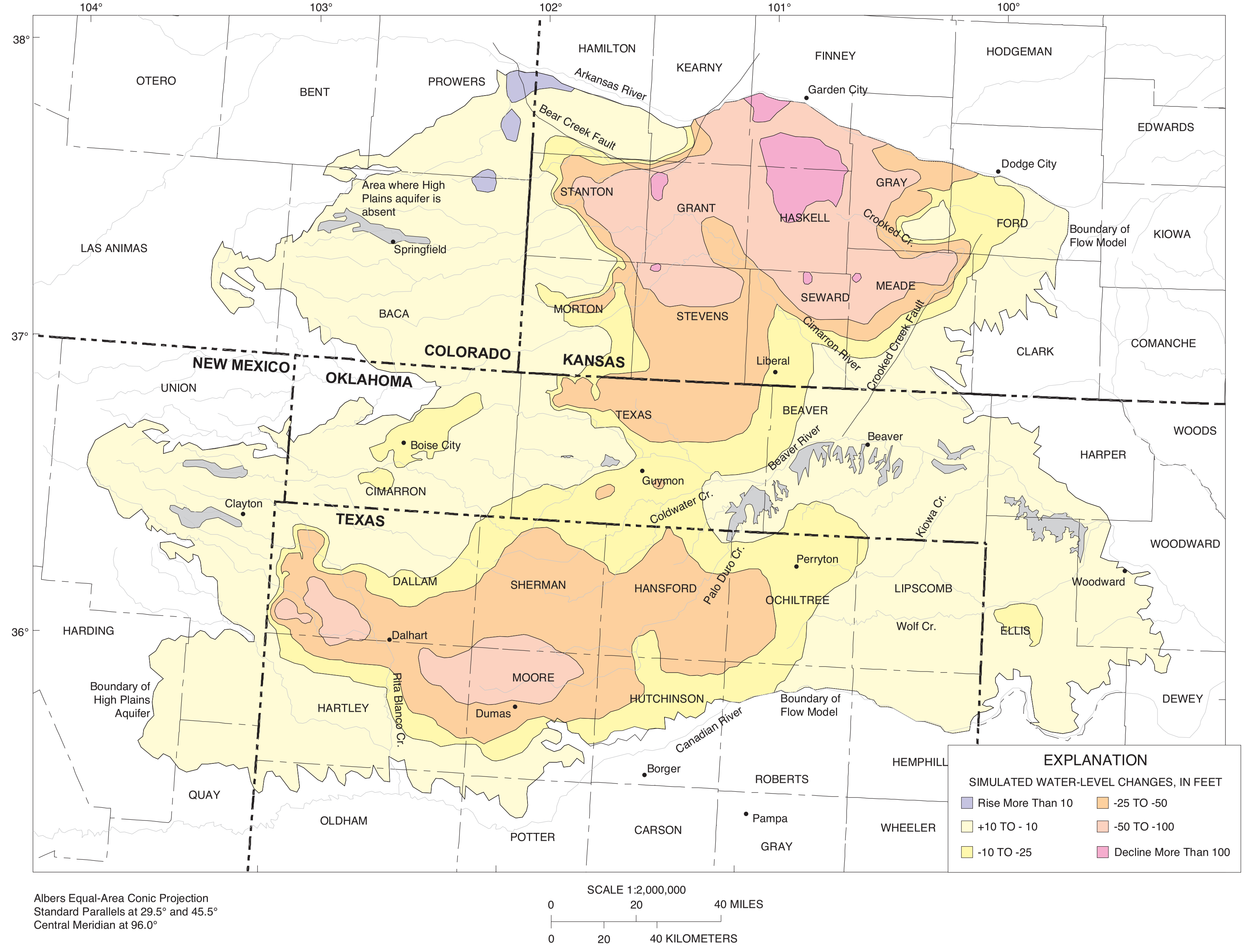
A number of model cells were simulated as becoming dry between the beginning of 1998 and 2020. A dry cell means that the calculated water level was below the base of aquifer at some time during the simulation. To calculate the simulated water-level change, the simulated water level was assumed to be equal to the base of aquifer. Once a cell became dry, aquifer stresses, such as recharge and pumpage, were no longer applied to the cell. Most of the dry cells were near areas of little or no saturated thickness (fig. 13) or near cells that had gone dry during the development-period simulation.

About 80 model cells in the Oklahoma portion of the study area were simulated as becoming dry between the beginning of 1998 and 2020; this is less than 1 percent of the active cells in Oklahoma. Most of these dry cells are in northeastern Cimarron County and northwestern Texas County near the area of little or no saturated thickness (fig. 13) or near cells that had gone dry during the development-period simulation.

About 150 model cells in the Kansas portion of the study were simulated as becoming dry between the beginning of 1998 and 2020. These cells are near areas of little or no saturated thickness (fig. 13) or near cells that had gone dry during the development-period simulation and are generally remote from Oklahoma. About 50 model cells near the New Mexico-Texas state line also were simulated as becoming dry by the beginning of 2020.

The simulated discharge to the Beaver River above Optima Lake at the beginning of 2020 is 4.9 cubic feet per second, a decrease of 2.9 cubic feet per second from the end of 1997, but still an unrealistic amount. Both the predevelopment-period model and the development-period model also over estimate discharge to the Beaver River above Optima Lake. The simulated discharge to Coldwater Creek, 3.1 cubic feet per second, and Palo Duro Creek, 5.2 cubic feet per second, also seem unrealistic. During the 22-year period, the simulated discharge to Coldwater Creek declined 0.5 cubic foot per second and 0.8 cubic foot per second to Palo Duro Creek. The simulated change in discharge to the three streams seems realistic even though the absolute values of the discharges seem unrealistic.

The simulated discharge to the Cimarron River at the beginning of 2020 is 40.9 cubic feet per second, a decrease of 10.3 cubic feet per second at the end of 1997. The simulated discharge to Crooked Creek is 10.2 cubic feet per second, an increase of 1.1 cubic feet per second from the end of 1997. This increase probably is due to the large simulated recharge due to dryland cultivation in the area. The simulated discharge to Wolf Creek is 27.3 cubic feet per second, a decrease of 3.5 cubic feet per second from the end of 1997.



Albers Equal-Area Conic Projection
Standard Parallels at 29.5° and 45.5°
Central Meridian at 96.0°

Figure 29. Simulated water-level changes for 1998-2020 using mean 1996-97 pumpage.

At the end of 2019, simulated recharge from all sources is 810 cubic feet per second, consisting of 470 cubic feet per second from recharge due to dryland cultivation, 297 cubic feet per second background recharge from precipitation, and 43 cubic feet per second recharge due to irrigation. Simulated discharge from all sources is 3,777 cubic feet per second, consisting of 3,563 cubic feet per second to wells, 159 cubic feet per second to streams, and 55 cubic feet per second to drains. Because discharge exceeded recharge, ground-water storage is simulated as decreasing by 49 million acre-feet from the beginning of 1998 to 2020.

This simulation does not take into account the possibility that pumpage may actually decline from 1996-97 levels because of increasing depth to water and the associated increase in cost of pumping. Actual pumpage from the beginning of 1998 to 2020 will be a complex function of pumping costs, crop prices, and many other variables. The simulation made here is only to illustrate what would happen if mean 1996-97 pumpage continued until 2020 and is not meant to be a prediction of actual declines between 1998 and 2020.

Summary

The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, began a three-year study of the High Plains aquifer in northwestern Oklahoma in 1996. The primary purpose of the study was to develop a ground-water flow model to provide the Water Board with the information it needed to manage the quantity of water withdrawn from the aquifer. To provide appropriate hydrologic boundaries for the flow model, the study area was extended in adjacent states. The study area consists of about 7,100 square miles in Oklahoma and about 20,800 square miles in adjacent states.

Major drainages within the study area are those of the Cimarron River, Beaver River, and Wolf Creek; the Arkansas and Canadian Rivers form part of the boundary of the study area. The study area has abundant sunshine, moderate precipitation, frequent winds, low humidity, and high evaporation. The economy of the area is based largely on agriculture, natural gas and petroleum production, and related service industries. In 1978, the study area was about 57 percent range land, 29 percent dry crop land, and 14 percent irrigated crop land. Wheat is the dominant crop in the area, followed by corn, sorghum, and hay. Cattle, and more recently swine, are major components of the agricultural economy. The estimated value of crops and livestock of the study area was about $4.5 billion in 1992.

Geologic units of interest in this report range in age from Permian to Quaternary. Permian-age rocks contain poor quality water, and where they are at land surface, the High Plains aquifer is absent. The Dockum Group of Triassic age provides water to wells in some areas. The Exeter Member of the Entrada Sandstone, one of two Jurassic-age units in the area, provides water to wells in some areas. Two of five Cretaceous units, the Lytle Sandstone and the Dakota Sandstone, also provide water to wells in some parts of the study area. The Ogallala Formation of Tertiary age makes up a major part of the High Plains aquifer, the shallowest and most abundant source of water in the area. Quaternary-age valley-fill deposits are associated with streams; dunes are formed from redistributed valley-fill deposits. Where saturated, the Quaternary-age deposits also are part of the High Plains aquifer.

The High Plains aquifer consists of the saturated part of the Ogallala Formation and any saturated material of Quaternary age that is hydraulically connected to the Ogallala Formation. The topography of the base of aquifer is quite variable with prominent hills and sinkholes. The potentiometric surface is much smoother and generally slopes to the east at about 5 to 30 feet per mile. The difference between the two surfaces, the saturated thickness of the aquifer, ranges from more than 400 feet in northern Texas County, Oklahoma, to less than 50 feet in numerous areas; the mean saturated thickness in the Oklahoma portion of the study area is 125 feet.

The Water Board maintains a network of observation wells to monitor water-level changes. Water levels have declined more than 100 feet in three small areas of Texas County, Oklahoma, since development of the High Plains aquifer. Declines have exceeded more than 50 feet in a substantial part of the county. Water levels have declined more than 50 feet in three areas of Cimarron County and have declined more than 25 feet in a substantial part of the county. Only a small part of Beaver County had declines of more than 10 feet. Water level rises of more than 10 feet have occurred in Ellis County.

Natural recharge to the aquifer from precipitation occurs throughout the area but is extremely variable in both time and space. Lesser amounts of recharge occur from streams that enter the High Plains. Dryland agricultural practices appear to enhance recharge from precipitation, and part of the water pumped for irrigation returns to the aquifer as recharge. Natural discharge occurs as discharge to streams, evapotranspiration where the depth to water is shallow, and diffuse ground-water flow across the eastern boundary of the aquifer. Artificial discharge occurs as discharge to wells.

Irrigation was the largest use of water from the High Plains aquifer in Oklahoma and accounted for 96 percent of all use in 1992 and 93 percent in 1997. Use by livestock comprised about 2 percent of total water use in 1992 and 5 percent in 1997. Domestic and public supply comprised slightly less than 2 percent of total water use. Total estimated water use in 1992 for the Oklahoma portion of the study area was 396,000 acre-feet, with Texas County accounting for 217,000 acre-feet, Cimarron County accounting for 70,000 acre-feet, Beaver County accounting for 41,000 acre-feet, and the area east of the panhandle accounting for 68,000 acre-feet. Total estimated water use in 1992 for the study area was about 3.2 million acre-feet with the Kansas portion accounting for about 1.7 million acre-feet and the Texas portion accounting for about 1.1 million acre-feet.

A ground-water flow model of the study area was constructed using a finite-difference technique. The study area was subdivided into a 6,000-foot grid in both the north-south and east-west directions and the model had a total of 21,073 active cells in one layer. The ground-water flow equation for every active cell was solved with the widely-used MODFLOW computer code. The western boundary and most of the eastern boundary of the model was defined by the extent of the High Plains aquifer and was treated as a zero-flow boundary. A small part of the eastern boundary in Kansas, far from Oklahoma, was treated as a drain. The northern and southern boundaries of the model were chosen far from Oklahoma and consisted of the Arkansas and Canadian Rivers or the extent of the aquifer. The lower boundary of the model, which was treated as zero flow, was the base of aquifer; the upper boundary was the water table. The model was used to simulate two different time periods, the period before major development of the aquifer and the period after development started. The model was calibrated for each period using observed conditions.

The predevelopment-period model calculated the predevelopment altitude of the water table, discharge to the rivers and streams, diffuse cross-boundary discharge, discharge to small streams simulated with drains, and discharge across the drain boundary in Kansas. The model integrated data or estimates on the altitude of the base of aquifer, hydraulic conductivity, streambed conductance, and recharge from precipitation.

Hydraulic conductivity, recharge, and streambed conductance were varied during calibration to produce a reasonable representation of the observed water table and the estimated discharge to rivers and streams. Hydraulic conductivity was reduced from initial estimates in the areas of salt dissolution in underlying Permian-age rocks. The mean simulated hydraulic conductivity of the entire model area was reduced from 51 feet per day to 32 feet per day. The mean simulated hydraulic conductivity for the Oklahoma portion of the study area is 33 feet per day. To estimate recharge from precipitation, the model was divided into zones of greater and lesser recharge. The zones of greater recharge represented either sand dunes or areas of extremely sandy soils, whereas zones of lesser recharge included the remainder of the area. Recharge from precipitation was estimated as mean 1961-90 precipitation times a zone factor. At calibration, recharge is 4.0 percent of precipitation in the greater recharge zones and 0.37 percent in the lesser recharge zones. The mean simulated recharge for the Oklahoma portion of the study area is 0.18 inch per year. Streambed conductance ranges from less than 100 feet squared per day for Kiowa Creek and part of the Canadian River to over 2,000 feet squared per day for Crooked Creek and the major rivers excluding the Canadian River.

Within Oklahoma, the mean difference between water levels simulated by the model and measured water levels at 86 observation points is -2.8 feet, the mean absolute difference is 44.1 feet, and the root mean square difference is 52.0 feet. Over the entire model area, the mean difference between the simulated and observed predevelopment water levels is essentially zero, the standard deviation is 43.2 feet, 76 percent of the nodes are within 50 feet, and 98 percent are within 100 feet. The simulated discharge to the Beaver River and its tributaries is much larger than the estimated discharge. The simulated discharges to the Cimarron River and Wolf Creek are somewhat larger than the estimated discharges, and the simulated and estimated discharges to Crooked Creek are nearly the same.

Simulated recharge from precipitation in the predevelopment-period model is 310 cubic feet per second (fig. 30). This recharge is balanced by an equal amount of discharge, with 242 cubic feet per second going to streams and 68 cubic feet per second going to drains.

The development-period model used the predevelopment-period model and added specific yield, pumpage, recharge due to irrigation, and recharge due to dryland cultivation. The period 1946 through 1997 was simulated. Simulated water-level changes from predevelopment to January 1998 were compared to observed water-level changes only within the Oklahoma portion of the study area and elsewhere the simulated changes were checked only to make sure they were reasonable.

County-level pumpage was not altered during calibration of the development-period model, but pumpage was distributed to model cells, primarily using irrigation density in 1980. Initial estimated specific yield was reduced by 15 percent in the Oklahoma portion of the model east of the Cimarron-Texas County line. The mean simulated specific yield for the Oklahoma portion of the study area is 16 percent. Recharge due to irrigation and recharge due to dryland cultivation were estimated during calibration. Simulated recharge due to irrigation ranges from 24 percent for the 1940s and 1950s to 2 percent for the 1990s. The estimated recharge due to dryland cultivation is about 3.9 percent of mean 1961-90 precipitation over the area in dryland cultivation.

Within the Oklahoma portion of the study area, the areal extent of simulated and observed predevelopment to 1998 water-level changes is similar, although the model does not simulate any changes as large as the largest observed changes. Mean difference between the simulated and observed water-level changes from predevelopment to 1998 at 162 observation points is less than 0.01 foot, the mean absolute difference is 13.1 feet, and the root mean square difference is 17.9 feet. The simulated change is within 10 feet at about 57 percent of the points and is within 25 feet at about 82 percent of the points. The model simulates 7.8 cubic feet per second discharge to the Beaver River above Optima Lake at the end of 1997, whereas the river was actually dry to this point by this time. The model simulates a decrease in discharge to the Cimarron River and Wolf Creek that appears to be reasonable.

During 1997, simulated recharge in the development-period model is 823 cubic feet per second and the simulated discharge is 3,897 cubic feet per second (fig. 30). About 95 percent of the discharge is to wells. Ground-water storage is simulated to have decreased by 87 million acre-feet from 1946 through 1997.

The sensitivity of the predevelopment-period model to recharge and hydraulic conductivity was tested. Simulated water levels are sensitive to both recharge and hydraulic conductivity. These two model inputs are closely related with respect to water levels, but are not related with respect to discharge to streams. Simulated discharge to streams is sensitive to

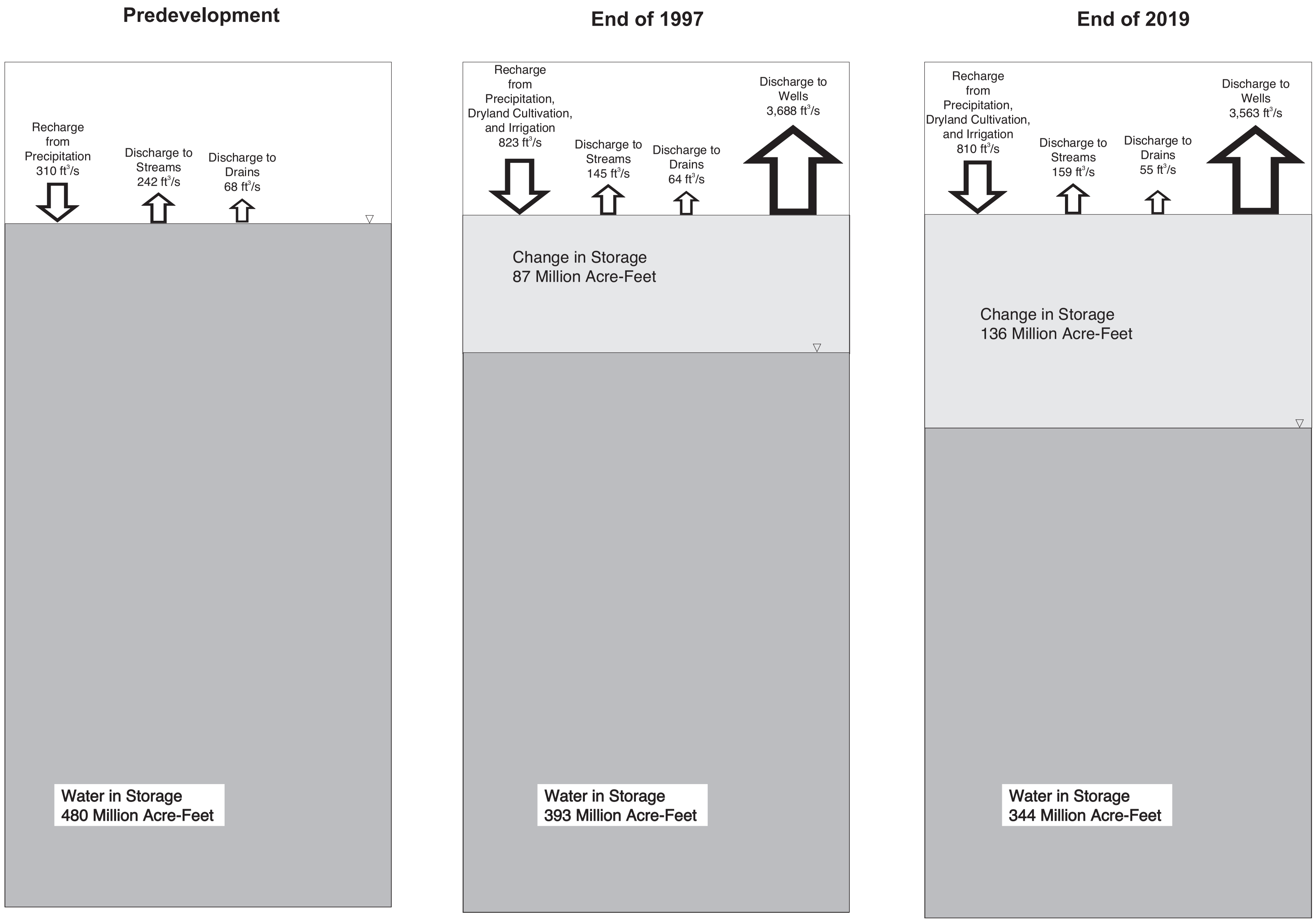


Figure 30. Summary of simulated water budgets. Inflows and outflows in cubic feet per second (ft^3/s).

recharge but is insensitive to hydraulic conductivity. By using both observed water levels and estimated discharge to streams, both recharge and hydraulic conductivity could be determined by the model.

The sensitivity of the development-period model to specific yield and recharge due to dryland cultivation was tested. The model appears more sensitive to specific yield, but the two inputs were not varied over the same range in percent change.

The calibrated development-period model was used to simulate water-level changes from the beginning of 1998 to 2020 using mean 1996-97 pumpage. The largest simulated water-level changes in Oklahoma occur in Texas County where water levels are simulated to decline 25 to 50 additional feet over a large area. Water levels also are simulated to decline 10 to 25 additional feet in two large areas in Cimarron County, two areas in Beaver County, and one area in Ellis County, all in Oklahoma. Water levels are simulated to decline more than 100 additional feet in several areas in Kansas and 50 to 100 additional feet in several areas in Texas. Water levels are simulated to rise more than 10 feet in three areas in Colorado and in an adjacent area in Kansas. Ground-water storage is simulated to decrease by 49 million acre-feet by the end of 1997 to the beginning of 2020 (fig. 30).

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Appendix

Appendix: Summary of Information Required by Oklahoma Water Law

The Oklahoma Water Resources Board is required by law to "make a determination of the maximum annual yield of fresh water to be produced from each ground water basin or subbasin" based on a minimum life of 20 years, based on the following information:

1. The total land area overlying the basin or subbasin;
2. The amount of water in storage in the basin or subbasin;
3. The rate of recharge to and discharge from the basin or subbasin;
4. Transmissivity of the basin or subbasin; and
5. The possibility of pollution of the basin or subbasin from natural sources.

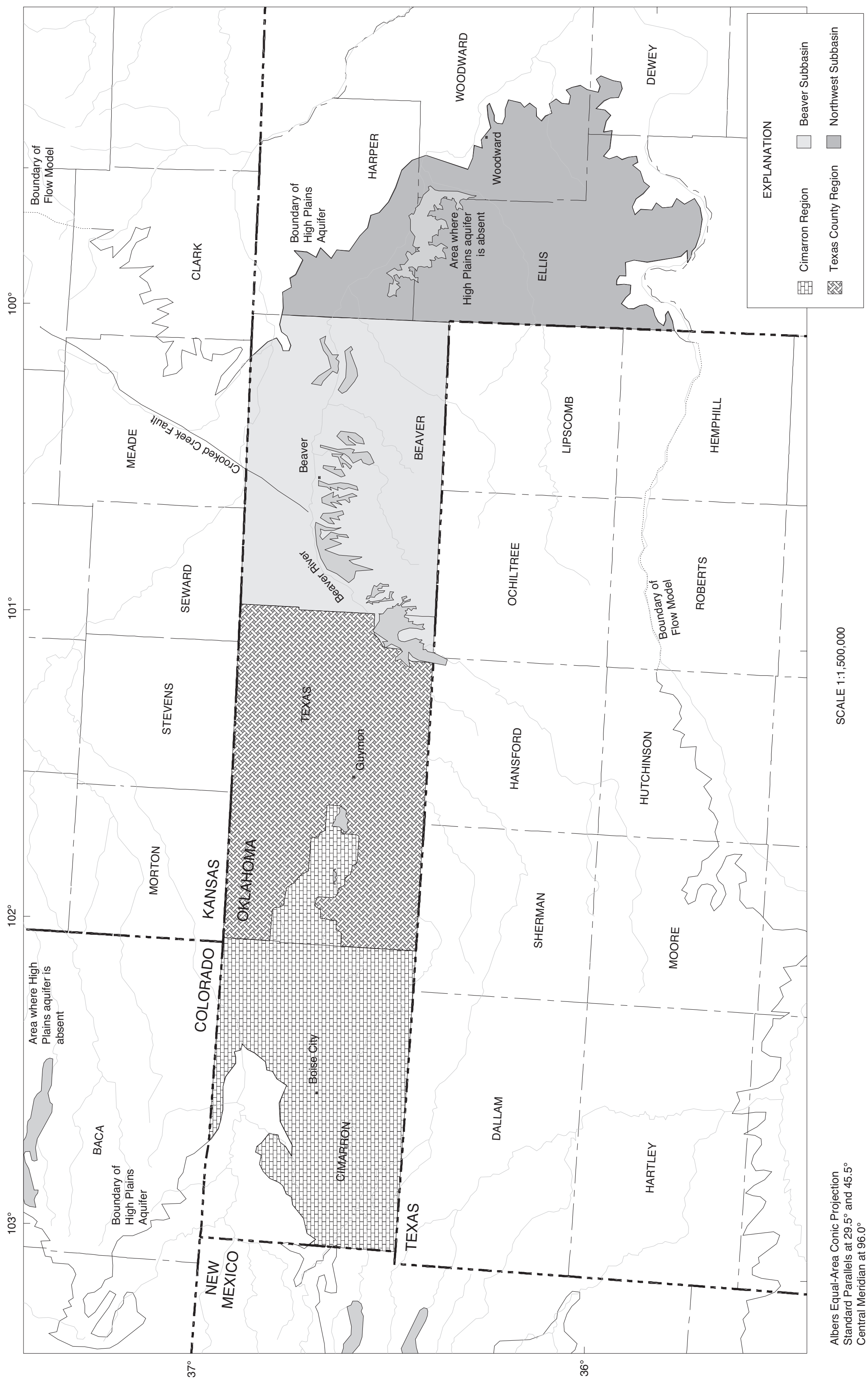
The High Plains aquifer in Oklahoma has been subdivided into four administrative areas by the Water Board. These areas are shown in figure 31 and are called "Cimarron Region, Texas County Region, Beaver Subbasin, and Northwest Subbasin" by the Water Board. Based on this study, the first four informational items are provided in table 5 to assist the Water Board in meeting its requirements under Oklahoma water law. The "Texas County Region" had previously been simulated by Morton (1980a), and the Water Board has already made a determination of maximum annual yield; it is included in table 5 for information only. The fifth informational item, assessing the possibility of pollution from natural sources, was not one of the purposes of this study, but in gathering information for this study, one possible source was obvious. Permian-age rocks directly underlie the High Plains aquifer in about two-thirds of the Oklahoma High Plains (fig. 4). These rocks generally do not transmit large quantities of water but are known to contain poor quality water. Excessive pumpage from the High Plains aquifer could induce upward migration of poor quality water from Permian-age rocks into the High Plains aquifer. Because of the limited water-transmitting capability of the Permian-age rocks, such migration probably would be of limited extent.

The model was used to determine the maximum amount of water that could be produced from each administrative area under the following conditions:

1. The calibrated development-period model was used in the simulation. Model stresses, except pumpage, were maintained during the simulations. Boundary conditions, except for streams, were maintained during the simulations. Stream cells were converted to drain cells so that water could flow from the aquifer to the stream when the simulated water level was above the level of the stream, but water could not flow in the other direction if the simulated water level fell below the level of the stream. Cells that had gone dry during the development-period simulation were assigned a small saturated thickness so the cells could be active in the simulation.
2. The administrative areas were analyzed one at a time. No pumpage was simulated to occur, except within the administrative area being analyzed. "Texas County Region" was analyzed for information only.
3. The simulations covered a 20-year period beginning on January 1, 1998.
4. A well was placed in every active model cell in the administrative area that had a simulated saturated thickness of 15 feet or greater on January 1, 1998. Wells were not placed in inactive cells within the administrative area where the High Plains aquifer was absent.
5. All wells were initially pumped at the same fixed rate. The initial rate did not change during the simulation except as noted in the next item.
6. If the simulated saturated thickness reached less than 15 feet at any time during the 20-year period, the well was shut down. If simulated saturated thickness recovered above 15 feet, the well was restarted. Pumpage was adjusted on an annual basis.

Various initial pumping rates were tested to find a rate that would cause the active model cells that were pumped to have an average simulated saturated thickness of 15 feet at the end of the 20-year period. This pumping rate was used to determine the maximum amount of water that could be produced from each administrative area as follows:

Administrative area	Pumping rate (acre-feet per acre)
Cimarron Region	1.6
Texas County Region	>2.0
Beaver Subbasin	>2.0
Northwest Subbasin	1.7



Albers Equal-Area Conic Projection
Standard Parallels at 29.5° and 45.5°
Central Meridian at 96.0°

Figure 31. Administrative areas of the High Plains aquifer in Oklahoma as defined by the Oklahoma Water Resources Board.

Table 5. Summary of information items one through four required by Oklahoma water law. This table is based on information that was available as of January 1, 1999. Total land area may include areas where the High Plains aquifer is absent. Water in storage, recharge, and transmissivity values are for the High Plains aquifer only. “Total recharge” is the sum of “Recharge prior to development of the aquifer;” “Recharge due to dryland cultivation,” and “Recharge due to irrigation in 1996 and 1997”

Administrative area	Total land area overlying basin (square miles)	Amount of water in storage on January 1, 1998 (Millions of acre-feet)	Natural recharge prior to development of the aquifer (Thousands of acre-feet per year)	Natural recharge due to dryland cultivation (Thousands of acre-feet per year)	Natural recharge due to irrigation in 1996 and 1997 (Thousands of acre-feet per year)	Total natural recharge (Thousands of acre-feet per year)	Transmissivity (feet squared per day)	
							Mean	Range
Cimarron Region	1,631	8.2	14.2	24.2	1.0	39.4	1,600	0 - 11,000
Texas County Region	1,785	37.1	9.1	29.2	2.5	40.8	5,200	0 - 15,000
Beaver Subbasin	1,857	18.1	11.4	26.8	0.5	38.7	2,900	0 - 17,000
Northwest Subbasin	1,855	19.4	29.4	26.2	0.7	56.3	3,100	0 - 15,000