Water in Storage and Approaches to Ground-Water Management, High Plains Aquifer, 2000

By V.L. McGuire, M.R. Johnson, R.L. Schieffer, J.S. Stanton, S.K. Sebree, and I.M. Verstraeten

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FOREWORD

The High Plains aquifer is the principal source for irrigation and drinking water in one of the major agricultural areas in the Nation. For any natural resource (for example, water, minerals, or energy), decisions about future utilizations depend on having a clear understanding of the status of the resource, the amount that has already been extracted, the amount remaining, and the impact of further depletion. This Circular reports on the available water in the High Plains aquifer in 2000 and the changes that have taken place in recent decades. The Circular is intended to help those who are interested or involved in the protection, management, and sustainable use of the High Plains aquifer to understand it better and make the best possible decisions. The information is based on the cooperative efforts of local, State, and Federal agencies to monitor water levels throughout the aquifer on a regular basis.

Robert M. Hirsch
Associate Director for Water

CONTENTS

CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.509	square kilometer
acre	0.4047	hectare
acre foot	1,233	cubic meter
cubic foot	0.02832	cubic meter
gallon	3.785	liter
gallon per minute	0.06309	liter per second
gallon per day	0.003785	cubic meter per day
foot per day	0.3048	meters per day

Degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) by using the following equation:

$$°C = 5/9\ (°F - 32) \text{ or } °C = (°F - 32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). If the vertical datum was not available, the datum was assumed to be NGVD 29. Historical data collected and stored as North American Vertical Datum of 1988 (NAVD 88) were converted to NGVD 29 for this publication. In previous reports of the High Plains water-level monitoring program, the term “sea level” was used to describe the vertical datum.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). If the horizontal datum was not available, the datum was assumed to be NAD 83. Historical data collected and stored as North American Datum of 1927 (NAD 27) were converted to NAD 83 for this publication.

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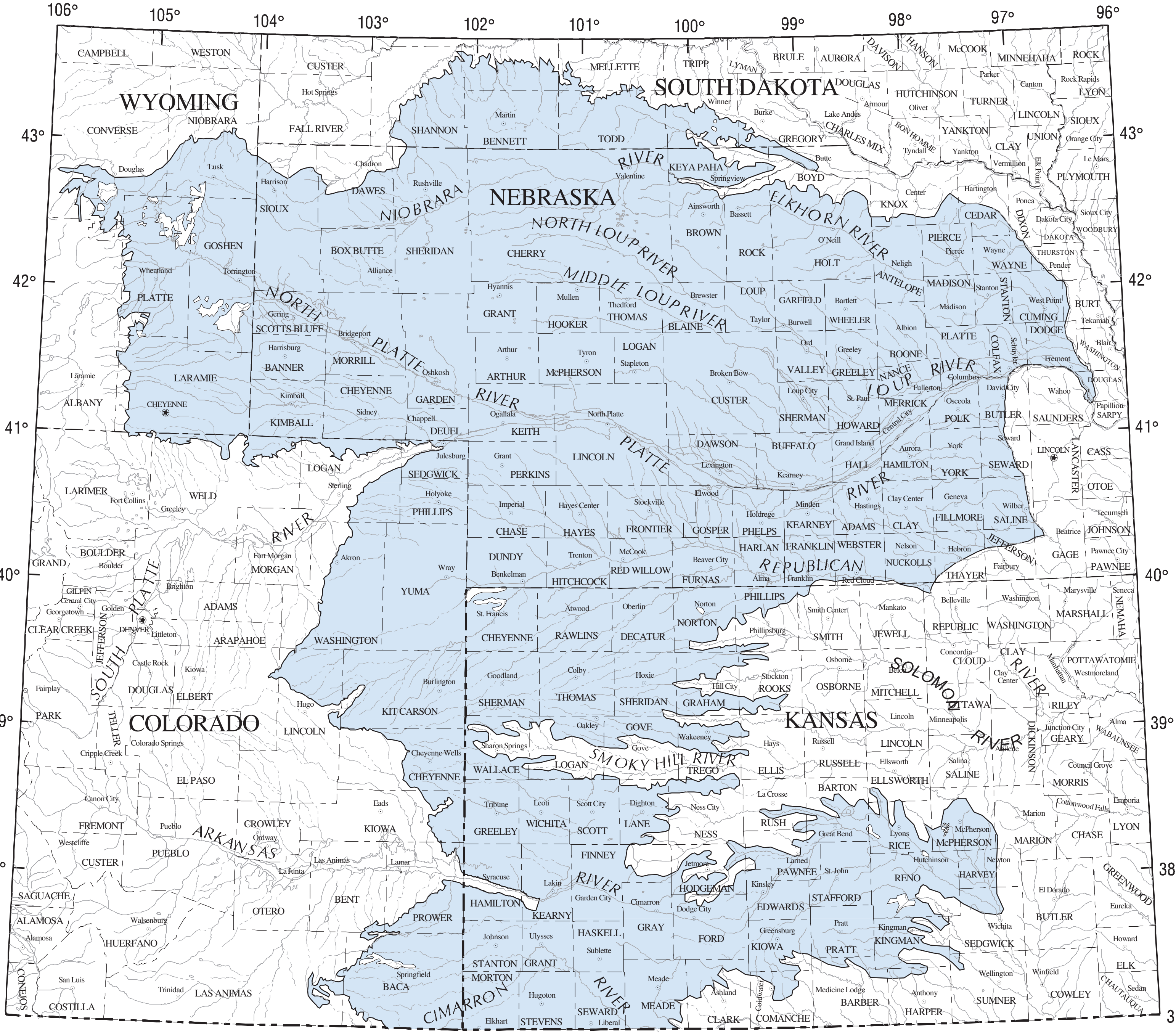
Outcrop of the Ogallala Formation, Keith County, Nebraska. (Photograph courtesy of R.R. Luckey, U.S. Geological Survey.)

Wheat field, Roger Mills County, Oklahoma. (Photograph courtesy of M.H. Belden, Oklahoma Water Resources Board.)

INTRODUCTION

The High Plains (or Ogallala) aquifer underlies a 111-million-acre area (173,000 square miles) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1). The area that overlies the aquifer is characterized as varying "between a semiarid to arid environment and a moist subhumid environment" (Lohman, 1953) with gently sloping plains, fertile soil, abundant sunshine, few streams, and frequent winds. Though the area can receive a moderate amount of precipitation, precipitation in most of the area generally is inadequate to provide economically sufficient yield of typical crops—alfalfa, corn, cotton, sorghum, soybeans, and wheat. The 30-year average annual precipitation ranges from about 14 inches in the western part of the area to about 32 inches in the eastern part (fig. 2). The High Plains aquifer is generally composed of unconsolidated alluvial deposits. About 94 percent of the water pumped from the aquifer in 1995 was used for irrigation. Through irrigation of crops with ground water from the High Plains aquifer, the area overlying the aquifer has become one of the major agricultural producing regions of the world.

> ***". . . The whole world depends on the Ogallala (High Plains aquifer). Its wheat goes, in large part, to Russia, China, and Africa's Sahel. Its pork ends up in Japanese and American supermarkets. Its beef goes everywhere . . . ."*** **(Opie, 2000)**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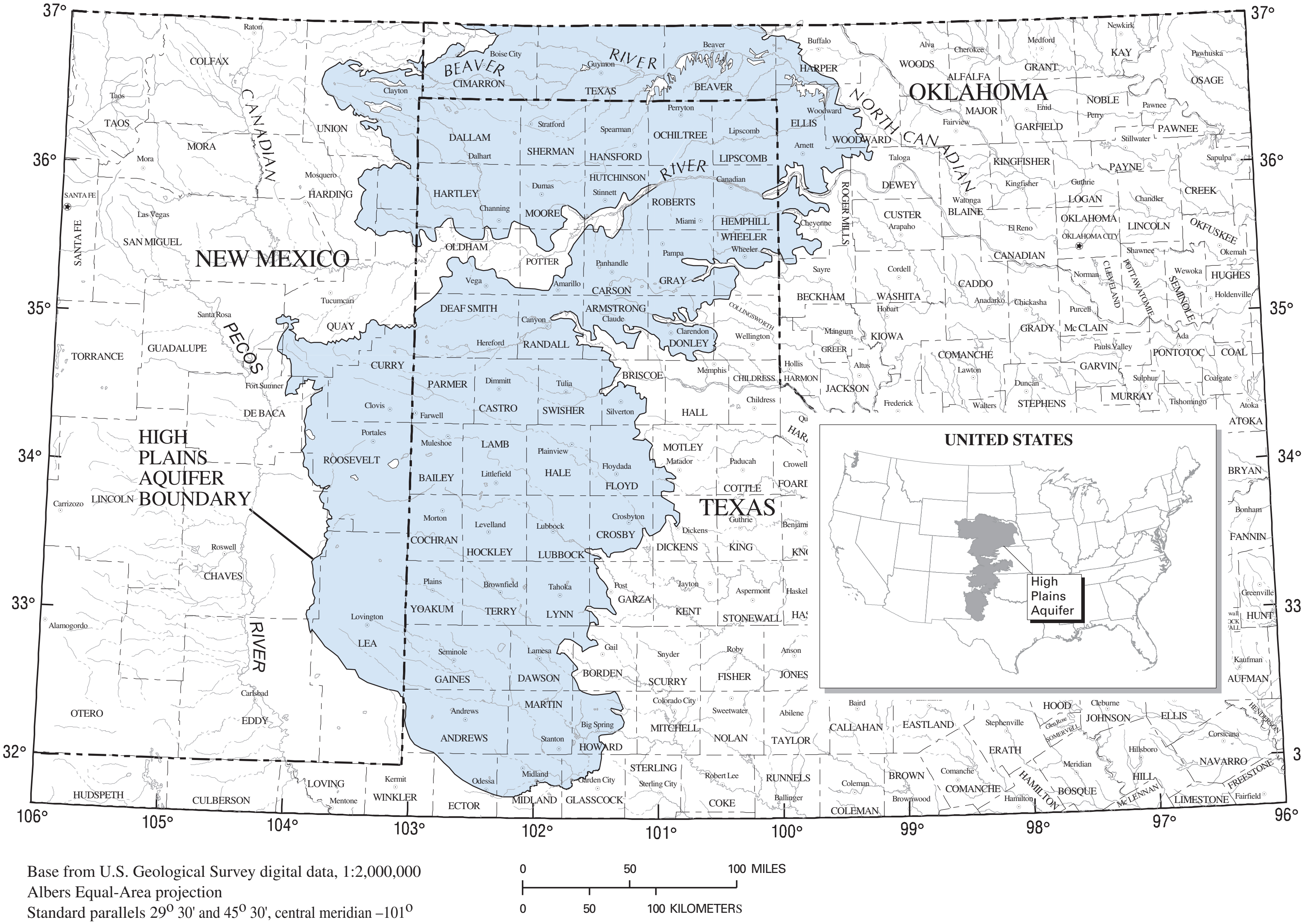

Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian –101°

Figure 1. *Location of the High Plains aquifer. The aquifer boundary used in this report is modified, primarily in northeastern Colorado, from the previously published boundary to better match geologic boundaries described in recent studies (Gutentag and others, 1984; Green, 1992; Green and Drouillard, 1994; Cederstrand and Becker, 1999a).*

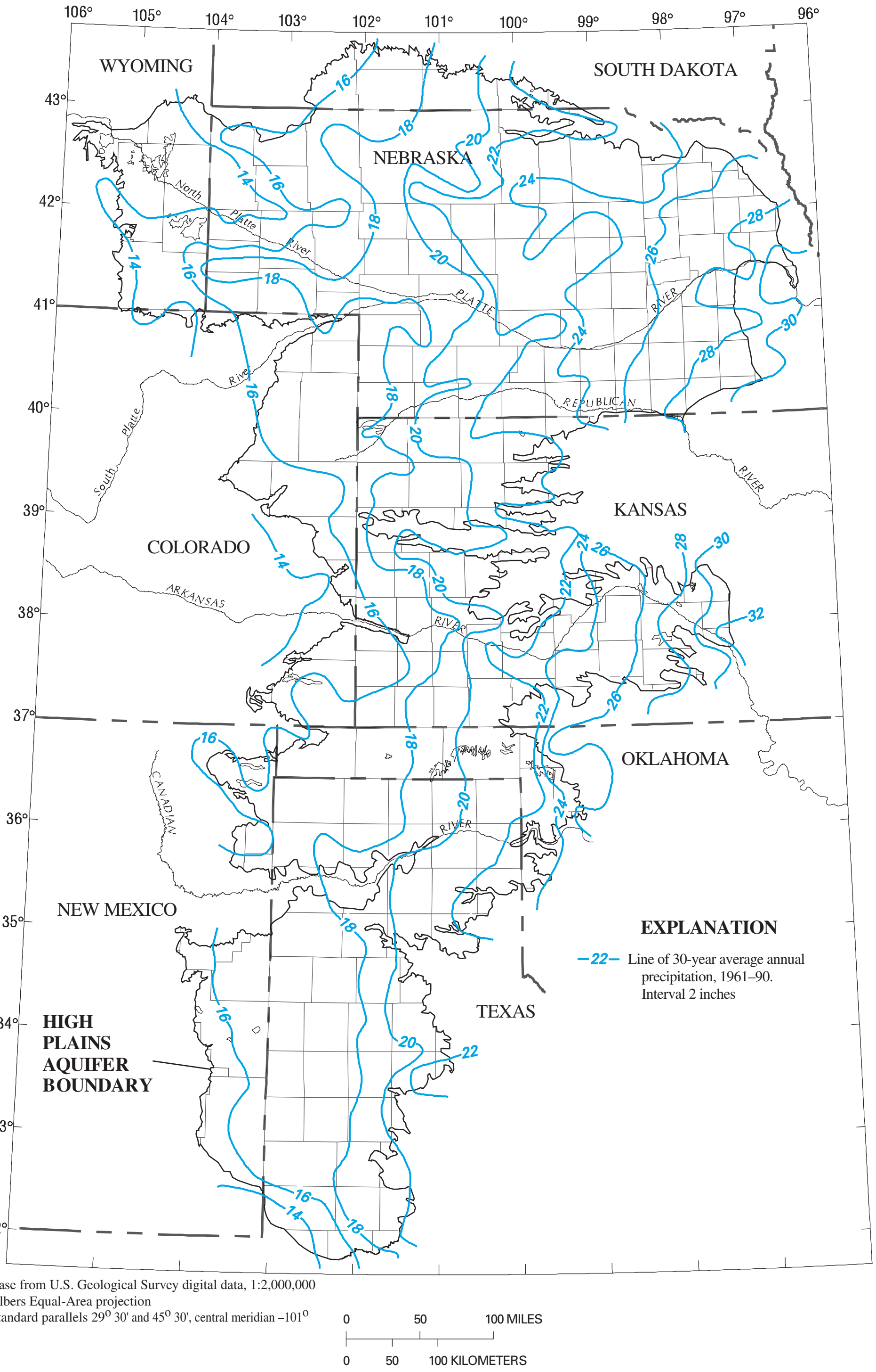

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Figure 2. *Average annual precipitation in the High Plains area. (Data from the National Oceanic and Atmospheric Administration, 1996.)*

In the area that overlies the High Plains aquifer, farmers began extensive use of ground water for irrigation in the 1940's. The estimated irrigated acreage increased rapidly from 1940 to 1980 and did not change greatly from 1980 to 1997: 1949—2.1 million acres, 1980—13.7 million acres, and 1997—13.9 million acres; irrigated acreage is estimated from farmer surveys or from satellite images (fig. 3; Heimes and Luckey, 1982; Thelin and Heimes, 1987; U.S. Department of Agriculture, 1999). Figure 4 shows the distribution of irrigated acres in the early 1990's. The location of irrigated acres was estimated by vegetative conditions derived from Landsat satellite imagery and is presented as a percentage of a map cell that is 1-minute latitude by 1-minute longitude (Qi and others, 2002). During the satellite survey, greater than normal precipitation occurred in some areas. The greater than normal precipitation resulted in flooding in parts of the area and more viable crops in other parts of the area. Therefore, the amount of irrigated acreage probably is underestimated in some areas and overestimated in others (Qi and others, 2002).

Annual pumpage from the High Plains aquifer for irrigation increased from 4 to 19 million acre-feet from 1949 to 1974; annual pumpage did not change greatly from 1974 to 1995 (fig. 5; Heimes and Luckey, 1982; USGS National Water-Data Storage and Retrieval System database). These pumpage totals were based on estimated and measured pumpage. Pumpage was estimated from crop consumptive irrigation requirements, which is the calculated minimum supplemental water required to maintain adequate soil water for optimal plant growth using factors such as crop type, soil, and weather patterns; from power usage; or from other data. Pumpage can be measured by flowmeters.

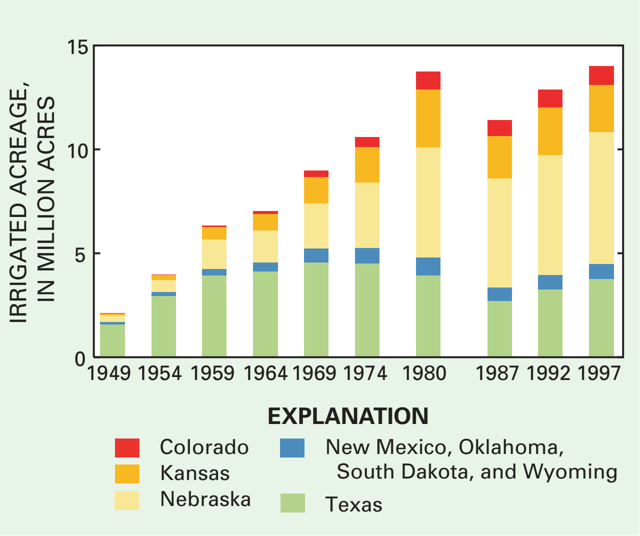
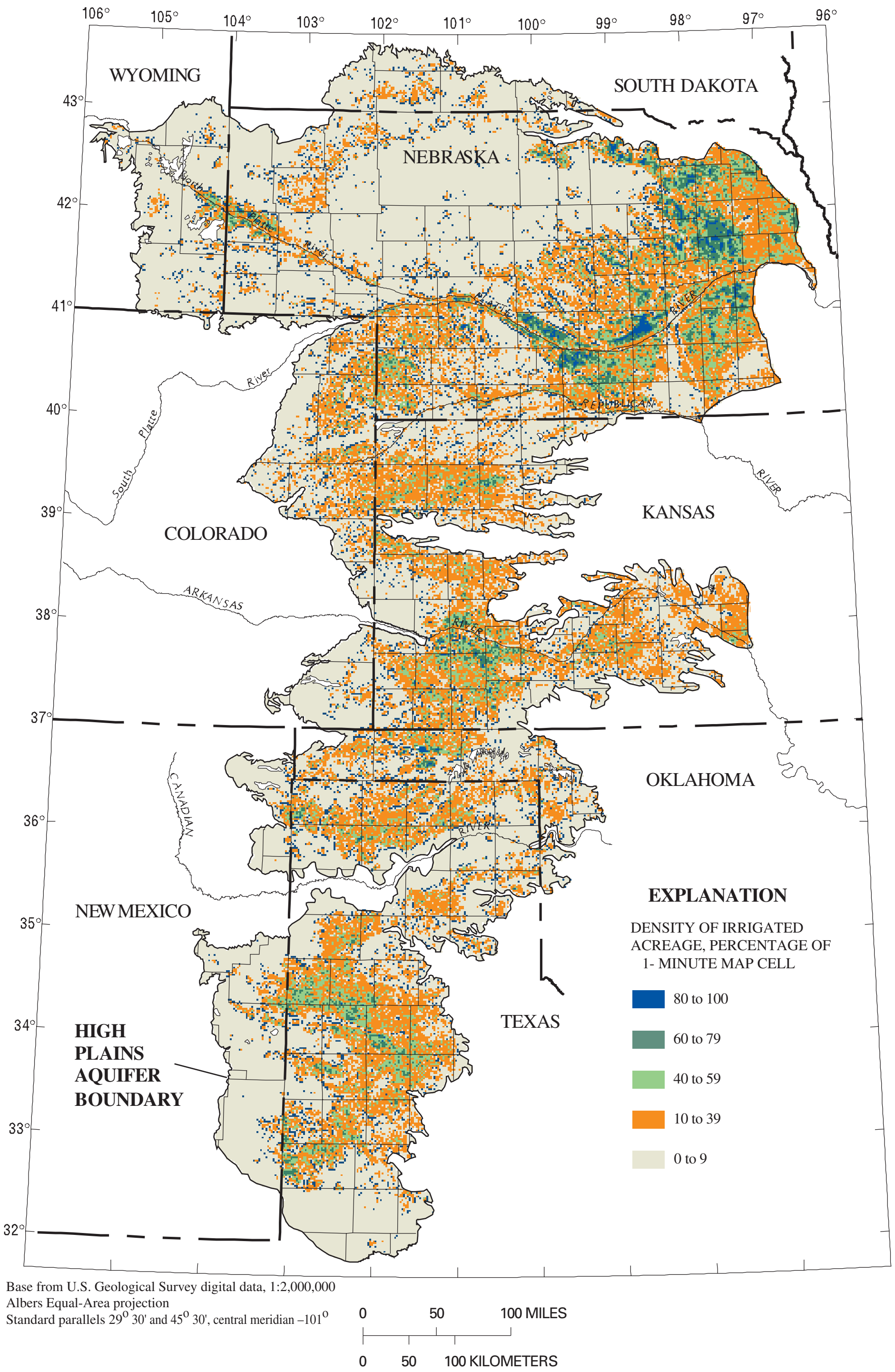


Figure 3. *Irrigated acreage in the High Plains area, by State, for selected years from 1949 to 1997 (Heimes and Luckey, 1982; Thelin and Heimes, 1987; U.S. Department of Agriculture, 1999).*



Base from U.S. Geological Survey digital data, 1:2,000,000
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Figure 4. *Irrigated acreage in the High Plains area estimated from Landsat imagery, nominal date 1992 (Qi and others, 2002).*

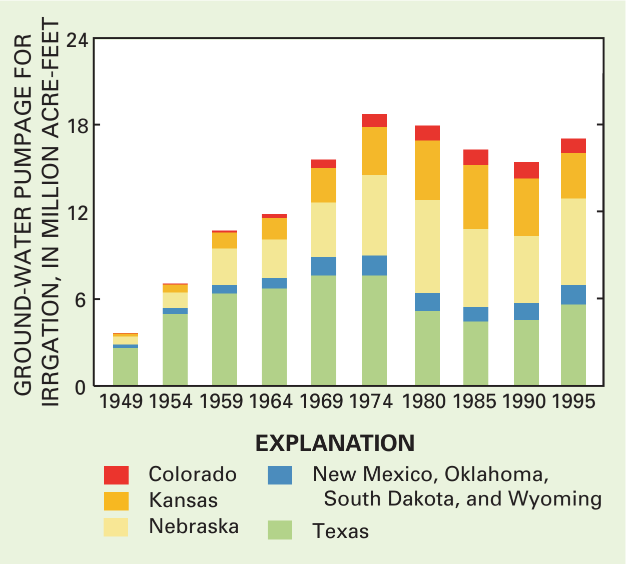


Figure 5. *Ground-water pumpage from the High Plains aquifer for irrigation by State for selected years, 1949 to 1995 (Heimes and Luckey, 1982; U.S. Geological Survey National Water-Data Storage and Retrieval System database).*

The use of ground water from the High Plains aquifer resulted in substantial water-level declines in the aquifer. By 1980, more than 100 feet of water-level declines occurred in some parts of the aquifer, and by 1999 withdrawals resulted in more than 40 feet of additional water-level decline in larger areas of the aquifer (Luckey and others, 1981; McGuire, 2001).

Studies that characterize the aquifer's available water and the water chemistry were conducted beginning in the early 1900's and are continuing to the present time. See "Selected Regional Studies of the High Plains Aquifer" for a brief description of some of these studies. Additional studies have been conducted in selected areas to estimate the effect of water-level declines and to evaluate methods to increase the usable water in the aquifer. See "Selected Local Studies of the High Plains Aquifer" for a brief description of some of these studies.

This report describes the amount of drainable water in storage in the High Plains aquifer in 2000 and the changes in the amount of drainable water in storage in the aquifer from the time prior to significant ground-water development for irrigation (termed predevelopment in this report) to 2000. Drainable water in storage is the fraction of water in the aquifer that drains by gravity and generally can be withdrawn by wells. Remaining water in the aquifer is held to the aquifer material by capillary forces and generally cannot be withdrawn by wells. Drainable water in storage is termed "water in storage" in this report and was estimated using data collected from 1920 to 2000 from more than 20,000 wells screened in the High Plains aquifer. This report also summarizes approaches to ground-water management implemented by the States that overlie the High Plains aquifer.

Estimates of water in storage depend on the accuracy and availability of the water-level altitude and base-of-aquifer data in all areas of the aquifer. In areas where few water-level data are currently available, such as southeastern Colorado, northwestern Nebraska, and parts of Wyoming, published maps supplemented available data. Map scale and density of water-level altitude and base-of-aquifer data preclude showing small areas where the saturated thickness or water-level change value might be more or less than indicated.

SELECTED REGIONAL STUDIES OF THE HIGH PLAINS AQUIFER

A number of regional studies of the High Plains aquifer were conducted to characterize aquifer conditions; quantify the current effect and projected future ramifications of large-capacity pumping on the aquifer; evaluate the impact of natural and anthropogenic (human-caused) processes, including pumping, on water quality in the aquifer; and consider the importance of irrigation to the economy. Regional studies by Johnson (1901, 1902), Lohman (1953), Weeks and others (1988), Kromm and White (1992), and Dennehy and others (2002) are described below:

- The U.S. Geological Survey (USGS) conducted a regional study of the High Plains aquifer in the early 1900's. The study by Johnson (1901, 1902) summarized the geographic, physiographic, and hydrologic features of the area—scant rainfall, high evaporation, few streams, and vast ground-water resources. Johnson determined that farmers would need to irrigate fields with ground water to cultivate crops. However, because the depth to ground water was generally too great for irrigation wells to be economically feasible with the available well drilling and pump technology and because the recharge rate was very slow, Johnson concluded that the High Plains only could be developed for raising livestock and not for cultivated agriculture.
- A second regional study of the High Plains aquifer by the USGS was conducted by Lohman (1953) in the mid-1900's, after parts of the High Plains aquifer were developed for irrigation. Development of the aquifer for irrigation became possible because of advances in irrigation drilling and pump technology and increased crop prices. Lohman recognized that ground water was almost the sole water supply for large parts of the High Plains. In the High Plains of New Mexico and Texas, south of the Canadian River, ground-water withdrawals greatly exceeded ground-water recharge; therefore, water levels had already declined and would continue to decline. To effectively develop the aquifer, Lohman recommended collection of additional data on factors such as the amount of ground-water discharge to streams, aquifer recharge rates, and the amount of water in storage.
- A third regional study of the High Plains aquifer was conducted by Weeks and others (1988) in the early 1980's as part of the USGS Regional Aquifer-System Analysis Program. During this study, extensive amounts of data were collected to define the aquifer's hydrogeologic framework, water-quality characteristics, and hydrologic budget and stresses. These data were used to project water levels for the year 2020 under proposed long-term management strategies for the aquifer using the first computer model of the entire aquifer (Luckey and others, 1986; Luckey and others, 1988).
- Kromm and White (1992) reviewed (1) the social and economic impact related to changes in water availability and water quality in the High Plains aquifer, and (2) the approaches to ground-water management used in the States that overlie the aquifer.
- Dennehy and others (2002) described a fourth regional study of the High Plains aquifer by the USGS that began in 1998. The objective of this study, part of the USGS National Water-Quality Assessment Program, is to evaluate water quality in the aquifer. Water-quality issues to be addressed by the study include nitrate and pesticide concentrations and elevated salinity from natural and anthropogenic processes.

SELECTED LOCAL STUDIES OF THE HIGH PLAINS AQUIFER

Water-resource issues include possible effects of water-level declines and decreased water quality in the High Plains aquifer on water availability, streamflow, and viability of riparian areas. Studies that address current and projected effects of water-level declines and methods to increase the usable water in the aquifer are described below:

- The usable life of the High Plains aquifer in Kansas was estimated by using average annual water-level change trends from 1978 to 1988 and from 1988 to 1998. The 1978 to 1988 and 1988 to 1998 periods represent different climatic conditions—1978 to 1988 was drier, and 1988 to 1998 was wetter. Starting with the average saturated thickness of the aquifer, 1997 to 1999, the water-level change trends were extrapolated to estimate the number of years until the end of the aquifer's usable life for large-volume pumping. For the purpose of their study, the end of the aquifer's usable life in an area was defined by Schloss and Buddemeier (2000) as a saturated thickness of 30 feet or less.

  The map of usable life of the aquifer using the more rapid 1978 to 1988 trend shows that about an additional 8 percent of the aquifer area in Kansas is or will be depleted in less than 25 years. The map of usable life using the slower 1988 to 1998 trend shows about an additional 4 percent of the aquifer area in Kansas is depleted or will be depleted in less than 25 years. These maps of aquifer usable life are not a prediction of aquifer depletion but represent "the range of probable results if past use and climate patterns are extended into the future" (Schloss and Buddemeier, 2000).
- A ground-water-flow model of the High Plains aquifer in parts of Oklahoma, Colorado, Kansas, New Mexico, and Texas was used to project 2020 water levels using the 1996 to 1997 pumping rates as the annual pumping rate. The simulated results indicate that water levels will decline an additional 25 to 50 feet in parts of Texas County and 10 to 25 feet in parts of Beaver, Ellis, and Cimarron Counties in Oklahoma. Ground-water storage is projected to decrease by about 50 million acre-feet in the study area by 2020 (Luckey and Becker, 1999).
- In northeastern Colorado, the High Plains aquifer currently is being depleted at about 1.5 times the rate of recharge to the aquifer. To balance recharge and discharge, annual pumping would need to be reduced from 1.0 million acre-feet to 0.4 million acre-feet. This decline in pumping will adversely affect crop yields and farm income. The adverse impact may be partially offset if improved irrigation and farm-management practices are implemented and if new Federal farm subsidies for water conservation are enacted (Van Slyke and Dass, 1999).
- Optima Dam and Reservoir, in the Panhandle of Oklahoma, originally was proposed and authorized by the U.S. Congress in 1936 primarily as a flood-control project on the Beaver River, west of Guymon, Oklahoma. The project was not planned and funded until the mid-1960's; construction began in March 1966, and the dam was finished and impoundment began in October 1978 (Oklahoma Water Resources Board, 1990). During the planning and construction phase, the number of large-capacity wells withdrawing ground water from the underlying High Plains aquifer for irrigation increased substantially. As ground-water withdrawals increased, the water table declined, and the number of no-flow days in the Beaver River increased (Wahl and Tortorelli, 1997). Currently, the river rarely flows, and the reservoir content has not exceeded 5 percent of capacity (Ken Wahl, U.S. Geological Survey, written commun., 2002).

Optima Dam and Reservoir on the Beaver River, Texas County, Oklahoma, on July 1, 2001. A view looking northwest and upstream at Optima Reservoir from the road on top of Optima Dam. The walkway to the top of the dam's outlet tower is in the left foreground. (Photograph courtesy of T.L. Wahl, U.S. Department of the Interior, Bureau of Reclamation.)

- The largest sand-dune area in the Western Hemisphere and one of the largest areas in the world with grass-stabilized dunes is located primarily in Nebraska and is called the "Sand Hills" (Bleed and Flowerday, 1990). The sand-dune area encompasses 12.4 million acres (19,300 square miles). Individual dunes are as much as 20 miles long, 400 feet high, and have as much as a 25-percent slope. The Sand Hills are used primarily for cattle ranching—grass or wild hay grows on 90 percent of the area. Crops are grown on about 5 percent of the area; about 80 percent of the cropland is irrigated. Because the soils in the Sand Hills are highly erodible and very permeable, cropland must be carefully managed to minimize erosion and contamination by agricultural chemicals (Bleed and Flowerday, 1990; Miller, 1990). In the Sand Hills, the depth to ground water ranges from 0 to 300 feet; seasonal fluctuations in the water table occur, but static water levels generally have not changed.

  Precipitation sustains the grasses that cover the dunes, recharges the High Plains aquifer, and, with ground-water discharge, maintains the numerous lakes, marshes, and subirrigated meadows between the dunes. Water evaporating from the interdunal wetlands may help to maintain grasses on the dunes by supplying additional water vapor to the atmosphere locally (Bleed and Flowerday, 1990; Loope and Swinehart, 2000). If ground-water levels decline significantly, ground-water discharge to lakes, marshes, and subirrigated meadows would decrease. If interdunal wetlands dry up or decrease in size, the plant and animal communities in the interdunal areas would be affected, and grasses on the dunes might be adversely impacted.

A lake in the Nebraska Sand Hills, Arthur County, Nebraska. (Photograph courtesy of R.R. Luckey, U.S. Geological Survey.)

- Salinity concentrations affect whether water can be used for irrigation, and the use of water for irrigation can increase the salinity of the underlying ground water. One measure of salinity is dissolved-solids concentration. The major chemical constituents that contribute to salinity are bicarbonate, calcium, chloride, magnesium, potassium, sodium, and sulfate; these constituents naturally occur in varying amounts in soils and rocks. Water can increase in dissolved solids as it moves through earth material by partially dissolving rocks and minerals. The sand, gravel, and clay that compose the High Plains aquifer generally contain low amounts of the saline constituents; therefore, the dissolved-solids concentration usually is small in ground water from the aquifer. However, some older bedrock units of Permian age that underlie the High Plains aquifer contain rocks and minerals with considerable amounts of saline constituents; ground water that flows through the Permian-age bedrock units can discharge into the High Plains aquifer and increase the dissolved-solids concentration in the aquifer (Litke, 2001). Ground-water pumping can further increase dissolved-solids concentration in the High Plains aquifer by inducing a flow gradient that increases discharge from the underlying bedrock units to the High Plains aquifer. In areas where water levels in the High Plains aquifer are declining, the volume of water with lower dissolved-solids concentration available to dilute discharge from the underlying bedrock unit is reduced.

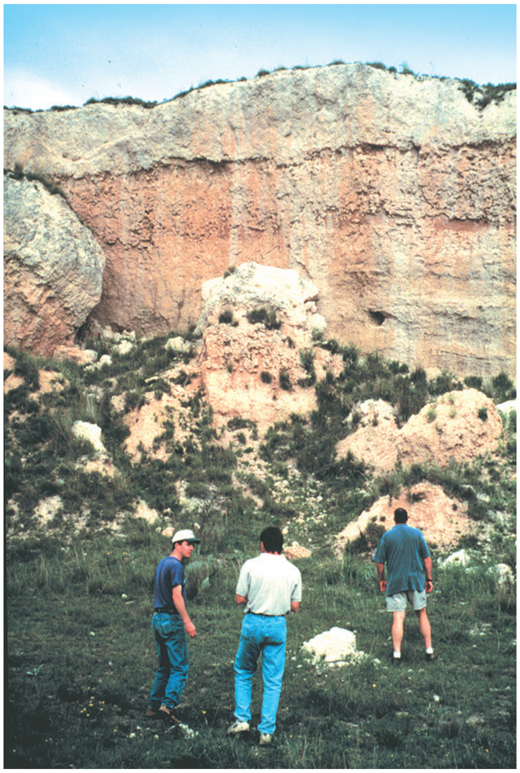
- In the early 1980's, the Texas Legislature funded investigations on the feasibility of "squeezing" water from the dewatered part of the Ogallala Formation in Texas. The water is "squeezed" out by injecting air under pressure from specially designed wells screened above the current water table. The air pressure forces water in the unsaturated zone, held by capillary forces, down to the water table where the water then can be recovered by conventional wells. In 1995, the volume of additional water that could be recovered from the aquifer by using this method was estimated to be 360 million acre-feet. The projected cost of recovery by this method is about $50 per acre-foot. At this cost, the method would likely be "economically feasible (only) for municipal and industrial water-supply purposes" (High Plains Underground Water Conservation District No. 1, 2000; Texas Department of Water Resources, 1982, 1985).
- The High Plains States Groundwater Demonstration Project was initiated in 1983 to study the potential for artificial recharge of aquifers in 17 Western States. Two artificial-recharge demonstration sites for the High Plains aquifer were located in southcentral Nebraska, near Wood River and York, and one site was located in southcentral Kansas, near Wichita. At the two Nebraska sites, ground water was used for irrigation, domestic supply, and livestock supply; at the Kansas site, ground water was used for public supply and industrial purposes. At each site, personnel evaluated one or more recharge techniques, including infiltration and spreading basins, reservoirs, and passive injection wells. The results of these studies, completed in 1999, indicate that the various techniques with some treatment of the source water recharged the aquifer 50 to 3,200 acre-feet per year at an estimated cost of $25 to $2,300 per acre-foot. Only the site near Wichita, Kansas, will be expanded to a full-scale ground-water recharge facility (Bureau of Reclamation, U.S. Department of the Interior, 2000).

CHARACTERISTICS OF THE HIGH PLAINS AQUIFER

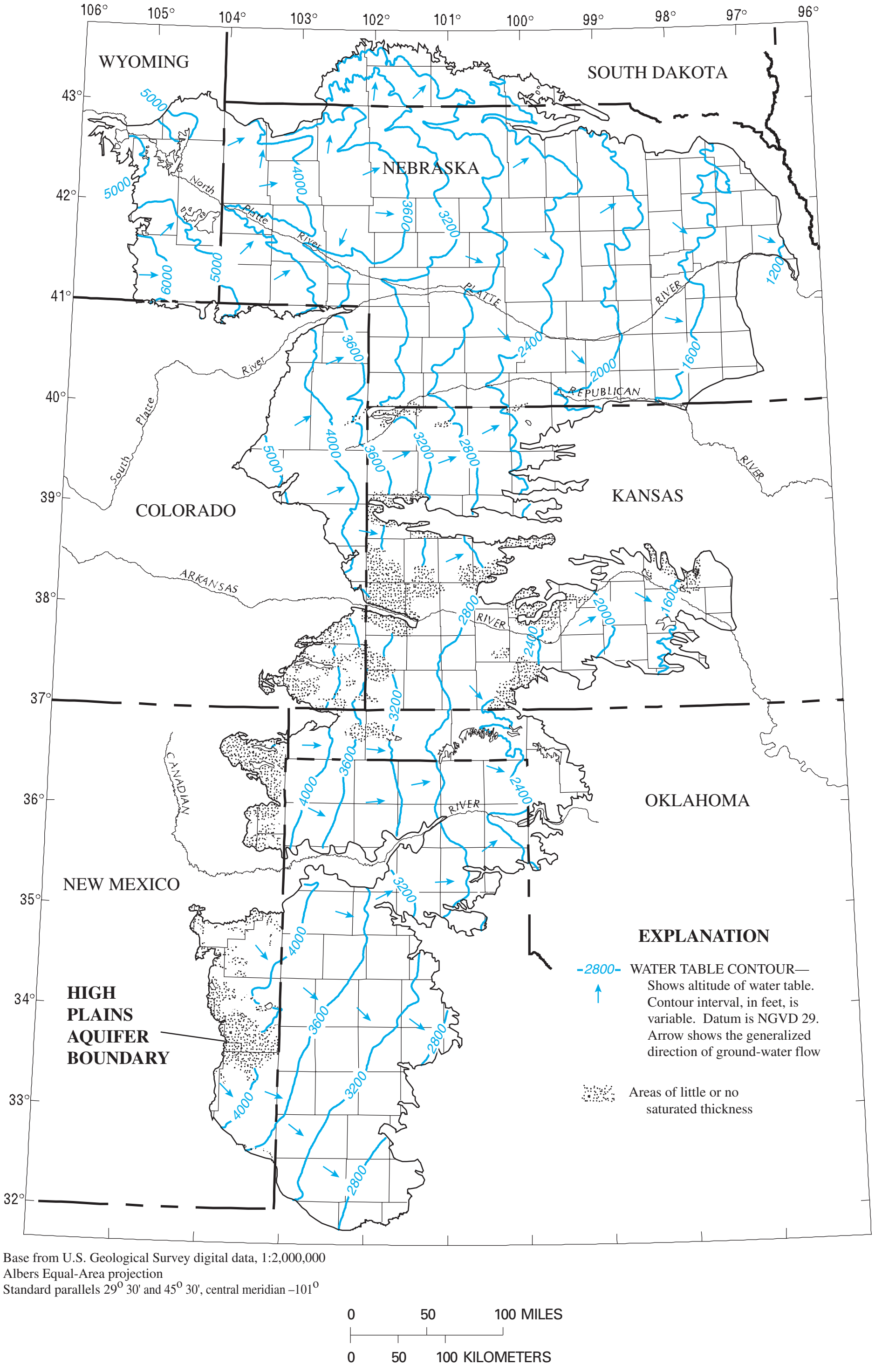
The water table, the upper boundary of the High Plains aquifer, ranges in altitude from about 6,000 to 1,200 feet above NGVD 29. Figure 6 is a map of the predevelopment water table. A map of the water table in the year 2000 would be similar to the predevelopment water table because water-level declines associated with large-scale pumping since predevelopment would not show at the 400- to 1,000-foot contour interval used in figure 6. In the High Plains aquifer, the ground-water flow direction is generally from west to east; arrows in figure 6 show the flow pattern. In the aquifer, the average ground-water flow velocity is about 1 foot per day (Gutentag and others, 1984).

The High Plains aquifer generally consists of one or more hydraulically connected geologic units of late Tertiary to Quaternary age. The extent of the geologic units in the aquifer is shown in figure 7 and described in figure 8. In figure 7, except for dune sand and some alluvial deposits associated with streams in the Republican River Basin, the Quaternary deposits are combined and are only shown where they do not overlie Tertiary-age aquifer units. In Texas, some collapse structures, filled with Triassic, Jurassic, and Lower Cretaceous rocks with secondary permeability, are considered part of the High Plains aquifer, but because they are a minor part of the aquifer, they are not shown in figure 7 (Gutentag and others, 1984). In Texas and New Mexico, there are additional small areas where the Ogallala Formation is not present, and the aquifer consists of rocks of Jurassic, Triassic, and Cretaceous age.

The geologic units that form the base of the High Plains aquifer are Permian to Tertiary age and are described in figure 8 and shown in figure 9. The altitude of the base of the aquifer ranges from about 6,000 to 1,200 feet above NGVD 29 (fig. 9). Three geohydrologic sections illustrate the thickness and slope of the aquifer and the contact with the underlying bedrock units (fig. 10). The locations of the geohydrologic sections are shown in figure 9.



Outcrop of the Ogallala Formation near the Canadian River in Hemphill County, Texas. (Photograph courtesy of K.F. Dennehy, U.S. Geological Survey.)



Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian –101°

Figure 6. *Predevelopment water table and direction of ground-water flow in the High Plains aquifer. (Modified from Gutentag and others, 1984; Cederstrand and Becker, 1999b.)*

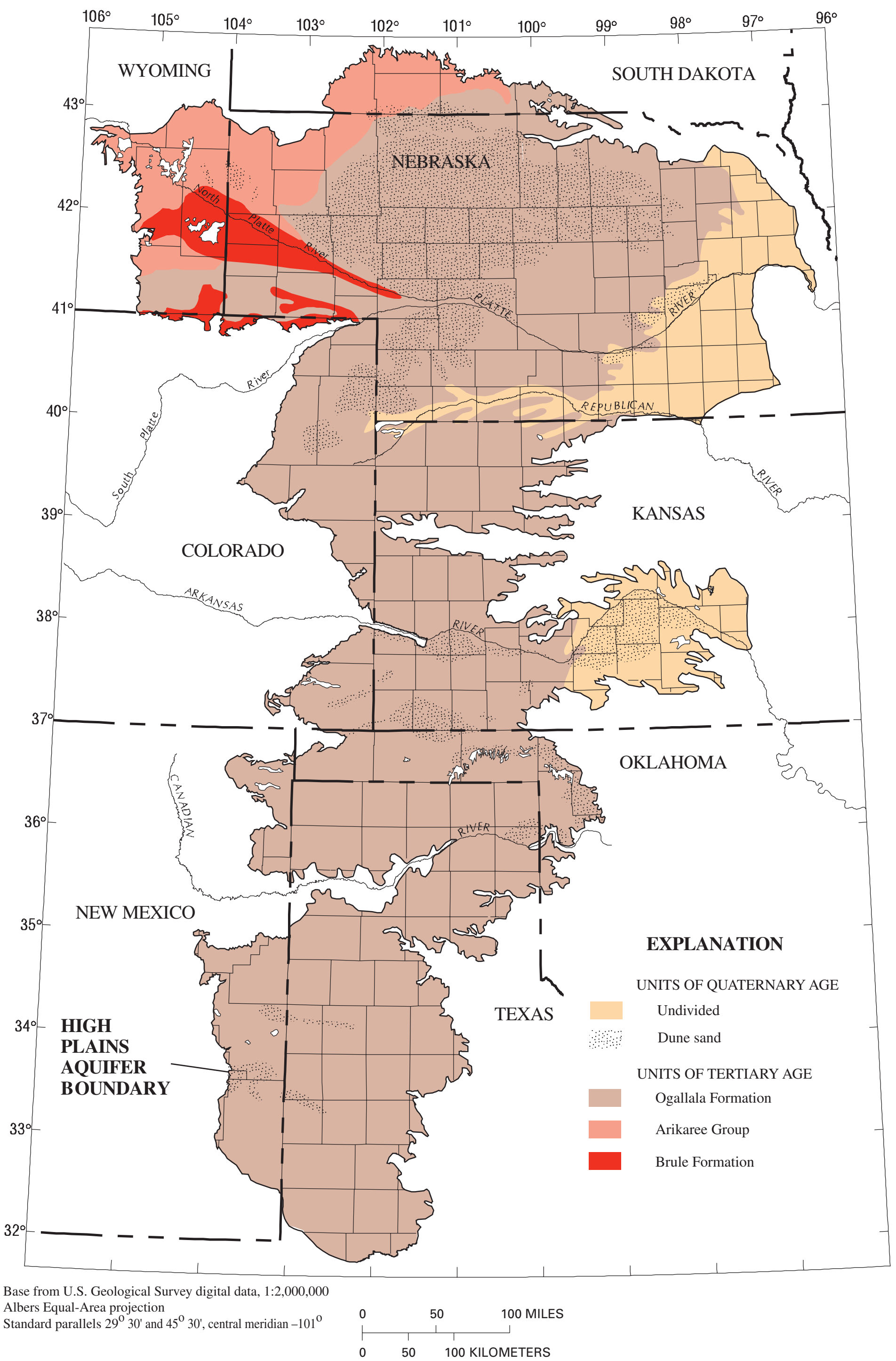


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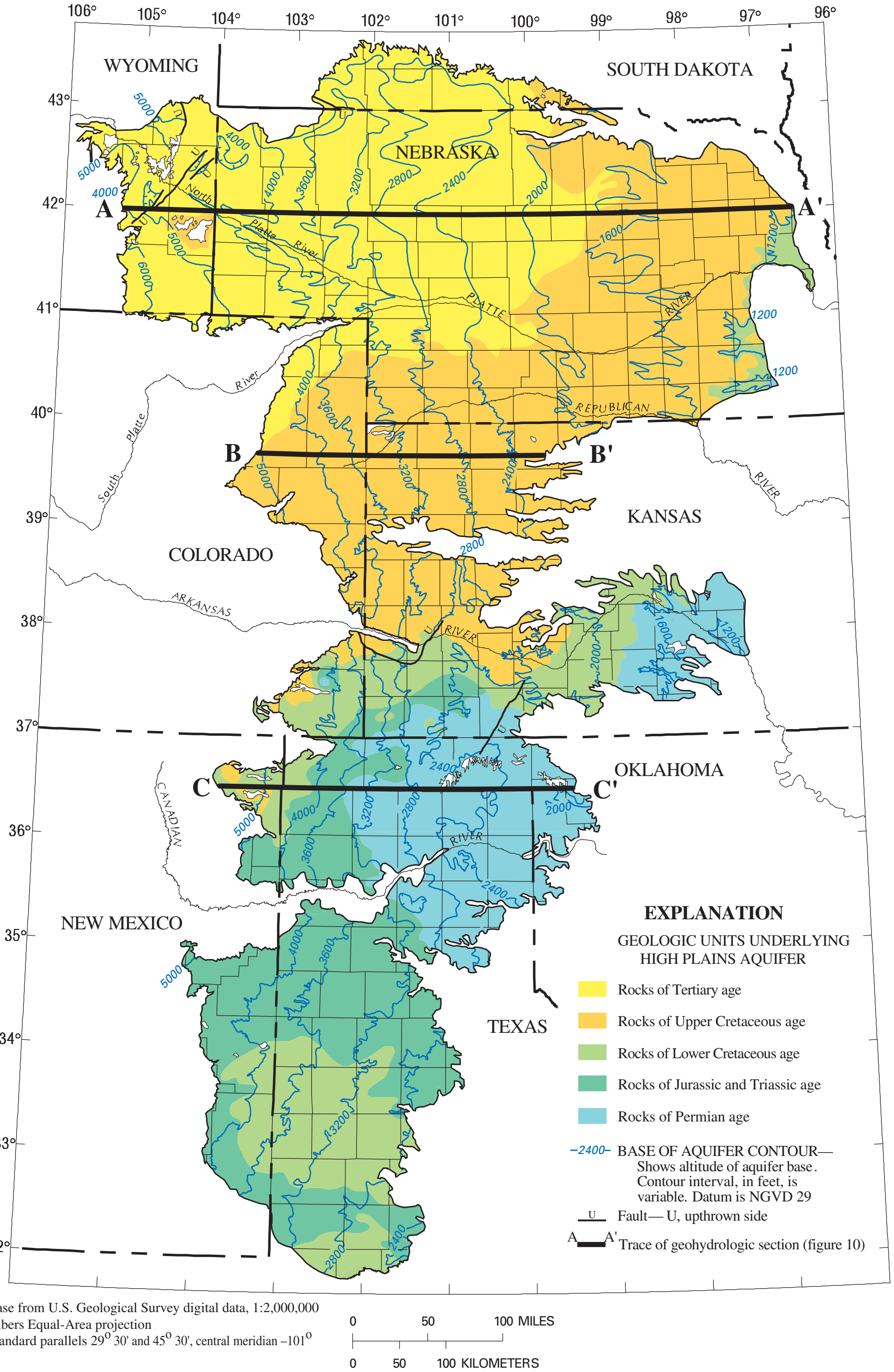
Figure 7. *Principal geologic units that constitute the High Plains aquifer. (Modified from Gutentag and others, 1984; Bleed and Flowerday, 1990; Dennehy and others, 2002.)*

System	Series	Geologic unit	Thickness, in feet	Physical characteristics
QUATERNARY	Pleistocene and Holocene	Valley-fill deposits	0 to 60	Stream-laid deposits of gravel, sand, silt, and clay associated with the most recent cycle of erosion and deposition along present streams. Forms part of the High Plains aquifer where saturated and hydraulically connected to underlying Quaternary and Tertiary deposits.
		Dune sand	0 to 300	Fine to medium sand with small amounts of clay, silt, and coarse sand formed into hills and ridges by the wind. Forms part of the High Plains aquifer where saturated.
		Loess	0 to 250	Silt with lesser amounts of very fine sand and clay deposited as windblown dust.
	Pleistocene	Unconsolidated alluvial deposits	0 to 550	Stream-laid deposits of gravel, sand, silt, and clay locally cemented by calcium carbonate into caliche or mortar beds. Forms part of High Plains aquifer where hydraulically connected laterally or vertically to deposits of Tertiary age.
TERTIARY	Miocene	Ogallala Formation	0 to 700	Poorly sorted clay, silt, sand, and gravel generally unconsolidated; forms caliche layers or mortar beds where cemented by calcium carbonate. The Ogallala where saturated composes a large part of the High Plains aquifer.
		Arikaree Group	0 to 1,000	Predominantly massive very fine to fine-grained sandstone with localized beds of volcanic ash, silty sand, siltstone, claystone, sandy clay, limestone, marl, and mortar beds. Considered part of the High Plains aquifer.
	Oligocene	White River Group Brule Formation Chadron Formation	0 to 700	Upper unit, Brule Formation, predominantly massive siltstone containing sandstone beds and channel deposits of sandstone with localized lenticular beds of volcanic ash, claystone, and fine sand. The Brule Formation is considered part of the High Plains aquifer only where it contains saturated sandstones or interconnected fractures. Lower unit, Chadron Formation, mainly consists of varicolored, bentonitic, loosely to moderately cemented clay and silt that contains channel deposits of sandstone and conglomerate.
CRETACEOUS	Upper Cretaceous	Undifferentiated rocks	0 to 8,000	Shales, chalks, limestone, and sandstones. Upper part may contain lignite and coal beds.
	Lower Cretaceous	Undifferentiated rocks	0 to 700	Fine- to medium-grained, thin-bedded to massive, cliff-forming sandstone interbedded with shale. Black and varicolored shale to thin- to thick-bedded limestone.
JURASSIC	Middle and Upper Jurassic	Undifferentiated rocks	0 to 600	Varicolored shale, fine- to very coarse-grained sandstone, limestone, dolomite, and conglomerate.
TRIASSIC	Upper Triassic	Dockum Group	0 to 2,000	Upper unit, varicolored siltstone, claystone, conglomerate, fine-grained sandstone, limestone. Lower unit, varicolored fine- to medium-grained sandstone with some claystone and interbedded shale.
PERMIAN	Lower and Upper Permian	Undifferentiated rocks	300 to 3,000	Interbedded predominantly red-shale, siltstone, sandstone, gypsum, anhydrite, dolomite, bedded salt, and local limestone beds.

Figure 8. *Generalized description of geologic units that compose (blue shading) and underlie (gray shading) the High Plains aquifer. (Modified from Weeks and Gutentag, 1981.)*



Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian –101°

Figure 9. *Geologic units underlying the High Plains aquifer, altitude of the base of High Plains aquifer, and location of geohydrologic sections in figure 10. (Modified from Weeks and Gutentag, 1981; Cederstrand and Becker, 1998; Torres and others, 1999.)*

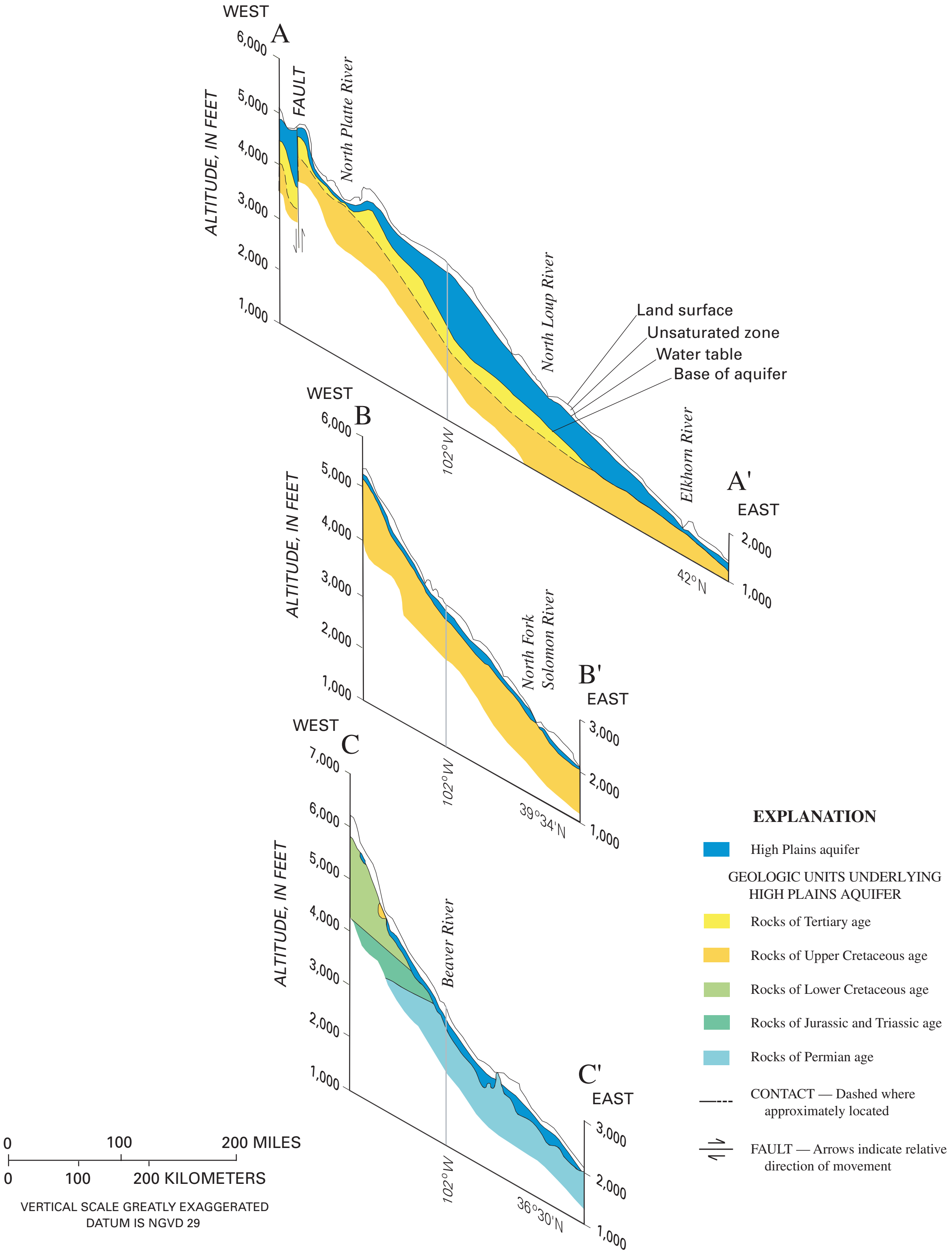


***Figure 10.** Geohydrologic sections through the High Plains aquifer. See figure 9 for section locations. (Modified from Weeks and Gutentag, 1981.)*

WATER-LEVEL MONITORING

A network of 8,641 wells was used to monitor water levels in the High Plains aquifer in 2000 (table 1; fig. 11). This network consists of many smaller networks of wells measured by numerous agencies (table 2). State and local agencies are responsible for the majority of the water-level measurements. Most of the wells in the network are measured one or two times each year—in winter, or early spring and fall. Winter or early spring measurements generally represent nonpumping conditions, when the water level should show maximum recovery from pumping in the previous growing season. Fall measurements made after the end of pumping season represent the maximum effect from pumping. In 2000, 127 of the wells were equipped with instruments that continually measure and record water levels; the locations of these recorder wells are shown in figure 11.

In this report, the "predevelopment water level" in the aquifer is defined as the water level in the aquifer before extensive ground-water pumping. The predevelopment water level was generally estimated by using the earliest water-level measurement available in more than 20,000 wells. The median measurement year in the predevelopment period was 1957; depths to water in the predevelopment period ranged from ground surface to more than 300 feet below ground surface (table 1; fig. 12). About 4,300 of the wells measured in the predevelopment period also were measured in 2000 or in 1996 through 2000; the wells measured from 1996 to 1999 were included only for New Mexico, where wells are measured on a rotating 5-year schedule (table 1; fig. 13).

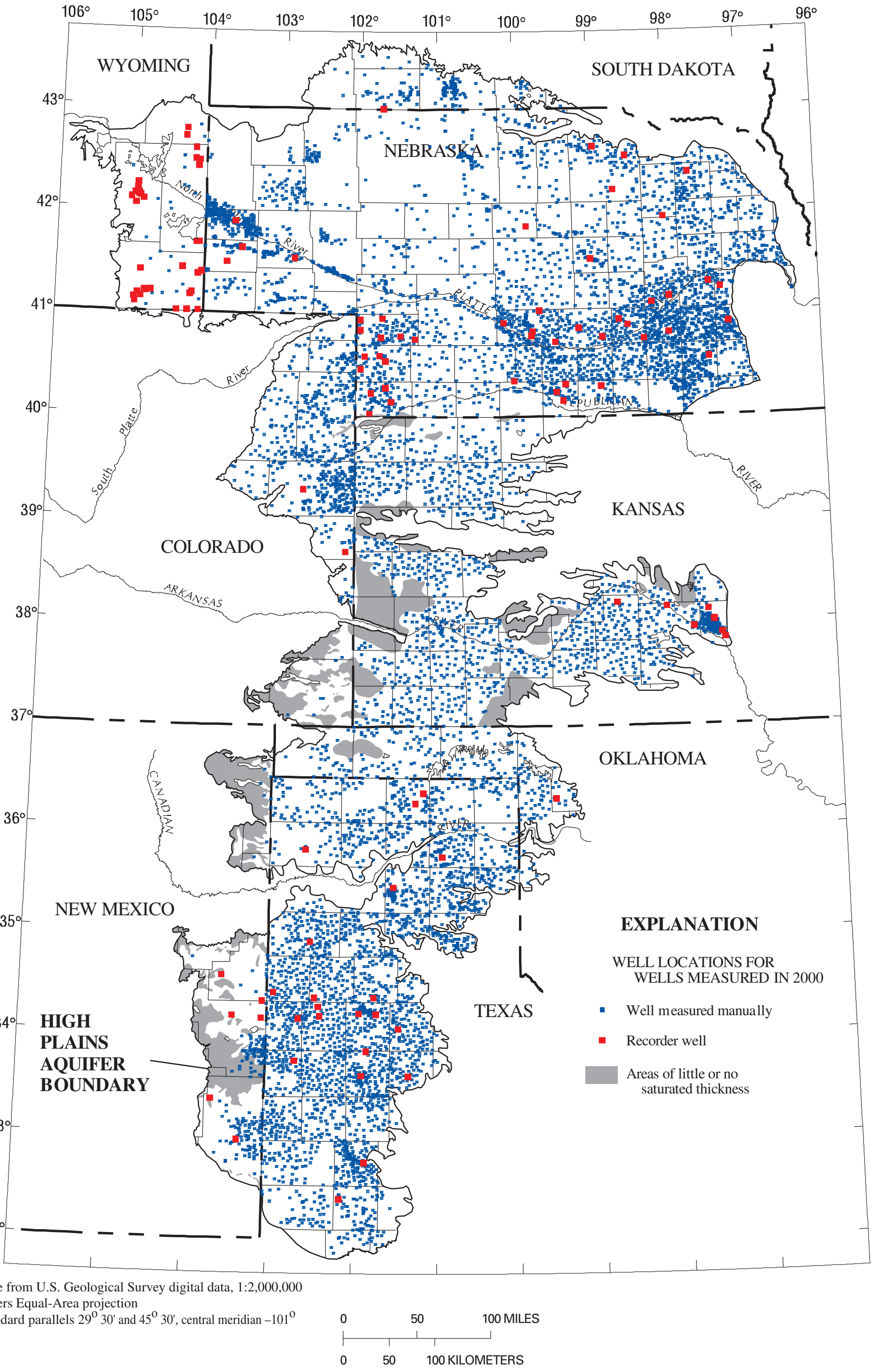
Table 1. *Number of wells measured in the High Plains ground-water monitoring program in the predevelopment period and in 2000*

State	Number of wells measured in the predevelopment period	Median measurement year in the predevelopment period	Number of wells measured in 2000		Number of wells measured in the predevelopment period and in 2000
			Wells measured manually	Recorder wells	
Colorado	614	1969	547	2	404
Kansas	4,169	1964	1,211	14	574
Nebraska	6,681	1952	3,654	49	1,714
New Mexico	3,197	1961	162	6	488*
Oklahoma	1,269	1938	215	1	178
South Dakota	72	1978	159	1	71
Texas	4,816	1957	2,538	21	857
Wyoming	26	1977	28	33	20
Eight States	**20,844**	**1957**	**8,514**	**127**	**4,306**

*Also includes wells measured in 1996 to 1999.

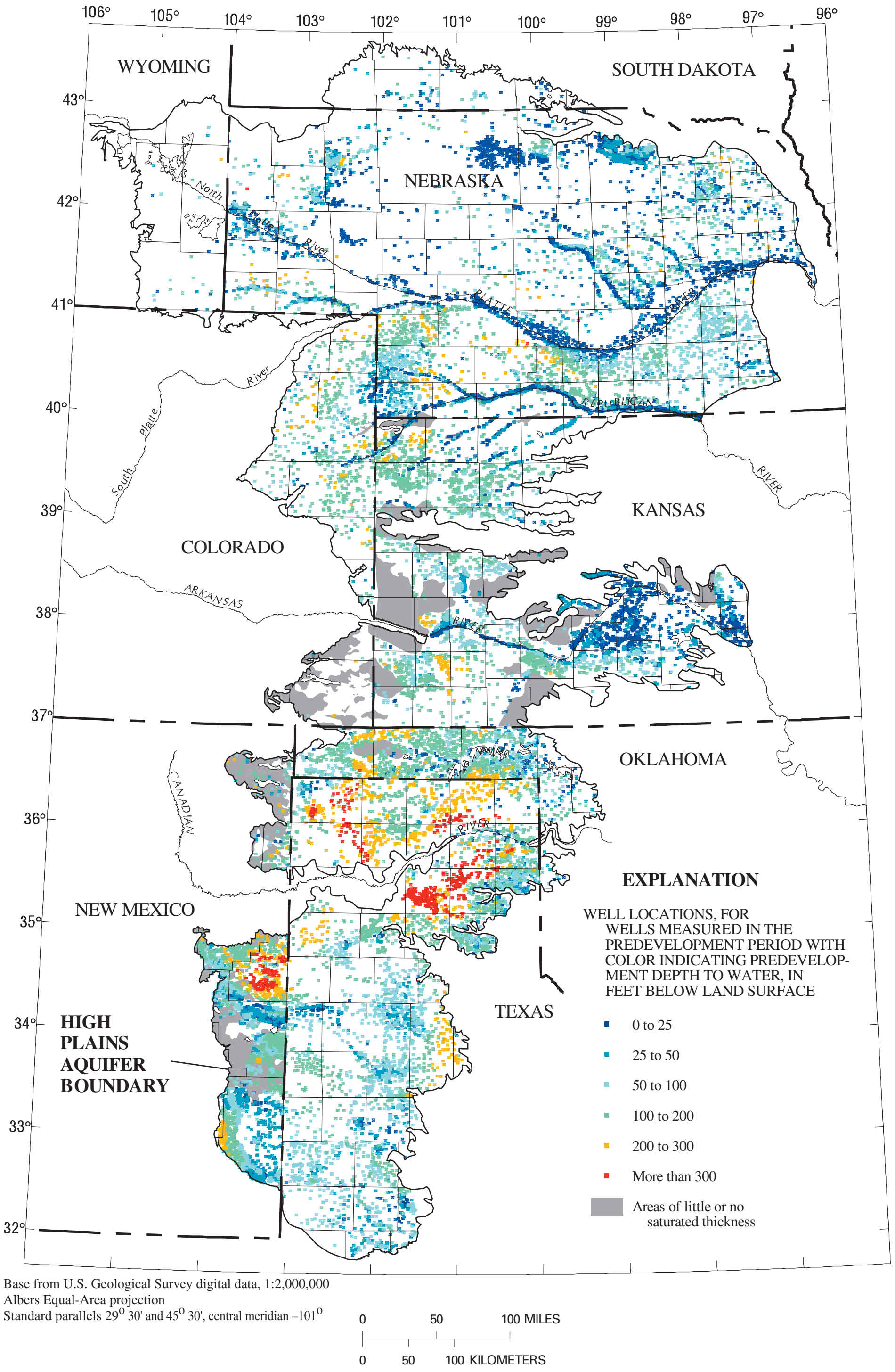
Table 2. *State, local, and Federal agencies that participated in the High Plains ground-water monitoring program in 2000*

State and local agencies	
Colorado	Colorado State Engineer's Office
Kansas	Kansas Department of Agriculture, Division of Water Resources Kansas Geological Survey
Nebraska	Central Nebraska Public Power and Irrigation District Harlan County Extension Office Nebraska Natural Resource Districts University of Nebraska–Lincoln, Conservation and Survey Division
New Mexico	New Mexico Office of the State Engineer
Oklahoma	Oklahoma Water Resources Board
South Dakota	South Dakota Department of Environment and Natural Resources
Texas	Texas Water Development Board participating with the Underground Conservation Districts and other agencies
Wyoming	Wyoming State Engineer's Office
Federal agencies	
U.S. Department of the Interior	Bureau of Reclamation U.S. Fish and Wildlife Service U.S. Geological Survey



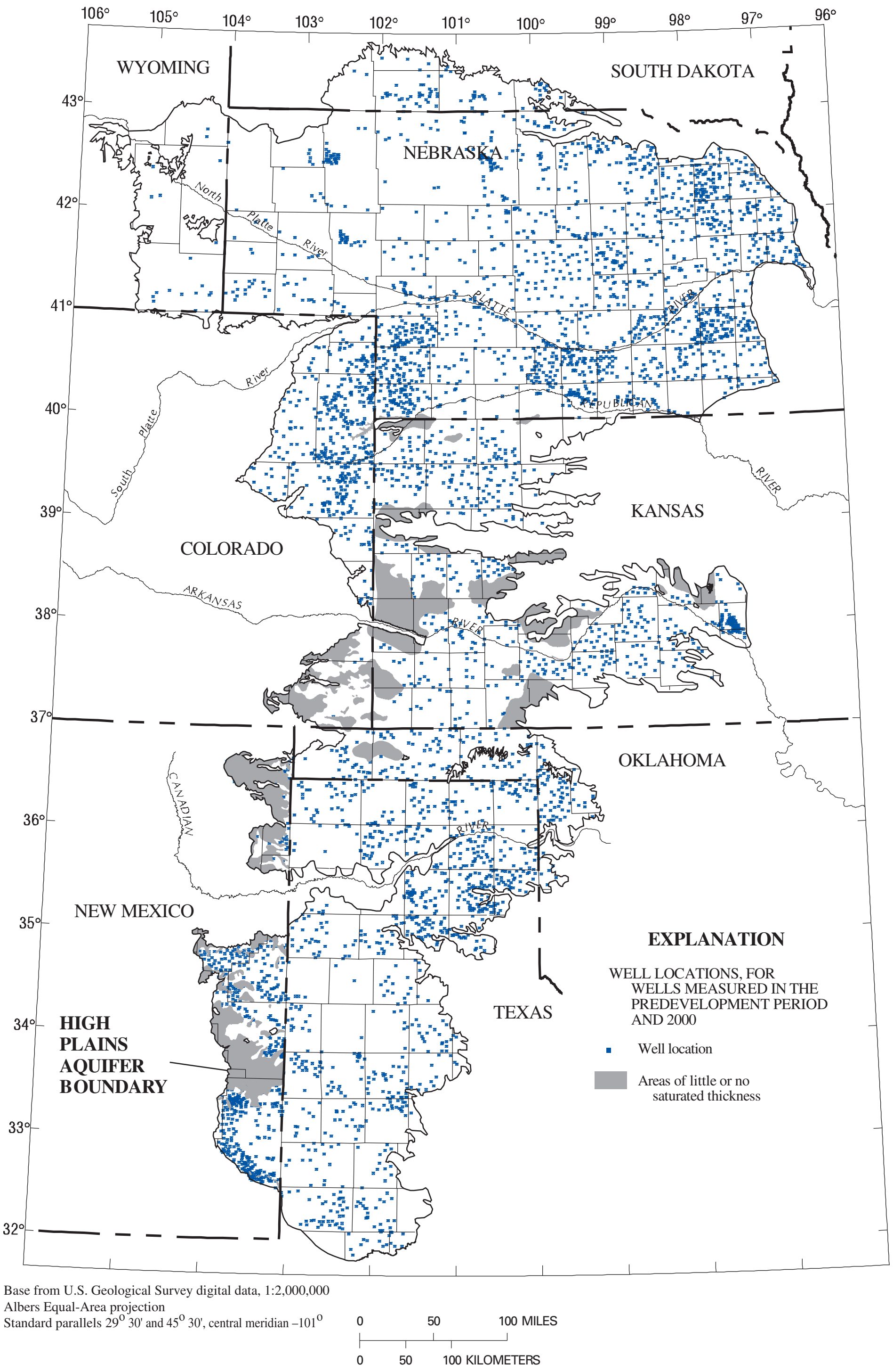
Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian –101°

Figure 11. *Well locations for wells screened in the High Plains aquifer and measured in the year 2000.*



Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian –101°

Figure 12. *Well locations and depth to water for wells screened in the High Plains aquifer and measured in the predevelopment period.*



Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian –101°

Figure 13. *Well locations for wells screened in the High Plains aquifer and measured in the predevelopment period and 2000, except in New Mexico. In New Mexico, well locations indicate wells measured in the predevelopment period and 1996 through 2000.*

WATER IN STORAGE, 2000

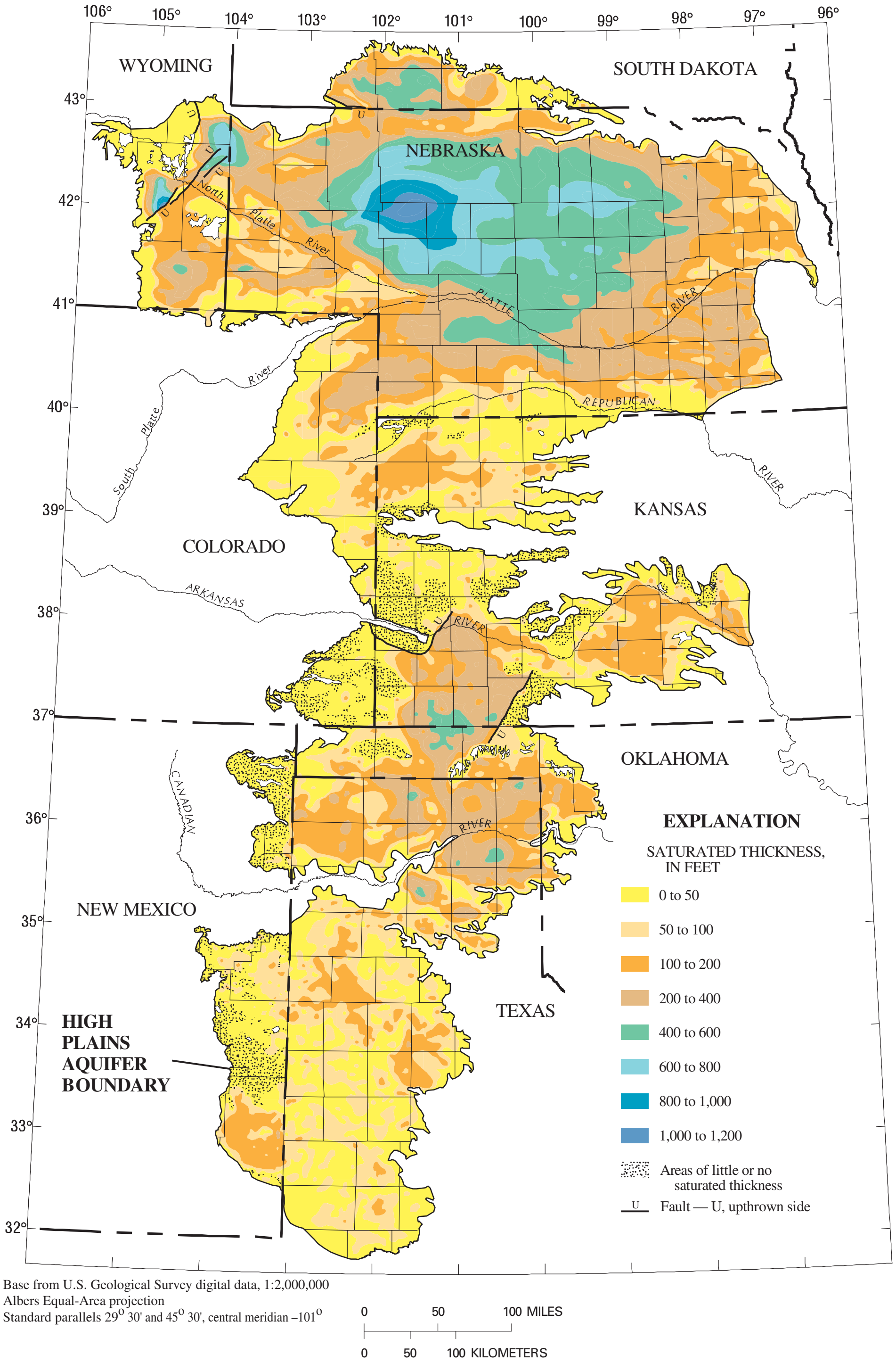
Water in storage in the High Plains aquifer for each State in 2000 was calculated by multiplying the average specific yield of the aquifer in the State by the volume of aquifer-saturated material underlying the State. The State totals were accumulated to calculate the aquifer total (see Box A for a brief description of the basic concepts of water in storage).

The specific yield of the High Plains aquifer was estimated using a description of the rocks that compose the aquifer (Gutentag and others, 1984). The average specific yield by State ranges from 7.6 percent in Wyoming to 18.5 percent in Oklahoma; the average specific yield for the aquifer in all eight States is 15.1 percent (table 3).

The volume of saturated material in the aquifer in each State is estimated from a saturated thickness map of the aquifer for 2000. The saturated thickness of the aquifer is the vertical distance between the water table and the base of the aquifer. A saturated thickness map of the High Plains aquifer in 2000 was created by superimposing contours of a water table for 2000 over contours of the base of the aquifer (modified from Weeks and Gutentag, 1981) and then connecting points of equal saturated thickness (fig. 14).

Table 3. *Average specific yield in the High Plains aquifer (Gutentag and others, 1984)*

State	Average specific yield, in percent
Colorado	15.4
Kansas	16.1
Nebraska	15.2
New Mexico	14.8
Oklahoma	18.5
South Dakota	9.2
Texas	15.6
Wyoming	7.6
Eight States	**15.1**



Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian –101°

Figure 14. *Saturated thickness of the High Plains aquifer, 2000. (Modified from Weeks and Gutentag, 1981.)*

The volume of water in storage in the High Plains aquifer in 2000 is about 2,980 million acre-feet. The volume of water in storage by State ranges from about 40 million acre-feet in New Mexico to about 2,000 million acre-feet in Nebraska (fig. 15). The total volume of water in storage in 2000 in the aquifer is approximately equal to the volume of Lake Huron, the third largest of the Great Lakes; if this volume of water were poured into a flat-bottomed container that had a bottom area equal to the area of the State of Colorado, the water would be about 45 feet deep.

Not all water in storage is economically available to large-capacity wells such as most irrigation and municipal wells; estimates of the volume of water in storage available to large-capacity wells ranges from 60 to 80 percent (Hansen, 1991). A minimum saturated thickness is required to operate a large-capacity well; the actual amount of saturated thickness required depends on well and pump design and aquifer characteristics. For planning purposes, the Kansas Geological Survey estimates that more than 30 feet of saturated thickness is required to operate a large-capacity well in the High Plains aquifer in Kansas (Schloss and Buddemeier, 2000).

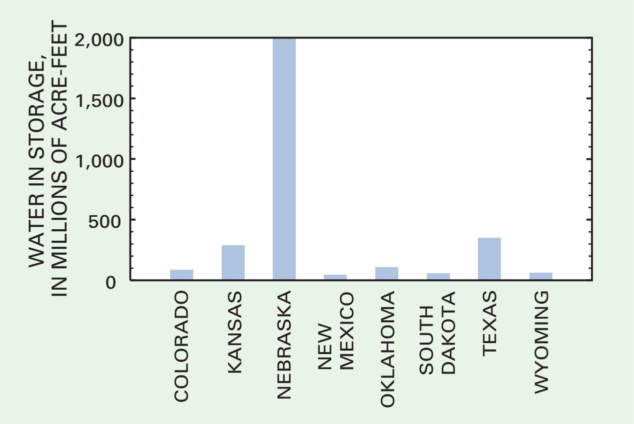


Figure 15. *Water in storage in the High Plains aquifer, 2000, by State.*

Basic Concepts of Water in Storage in the Aquifer

The upper boundary of the High Plains aquifer, which is an unconfined aquifer, is the water table. The lower boundary of the aquifer is generally impermeable bedrock. The distance between the water table and the base of the aquifer is the saturated thickness of the aquifer, and the water in storage is the volume of water that will drain by gravity from the aquifer (figs. 16 and 17).

Water beneath the land surface occurs in the unsaturated and saturated zones. Within the unsaturated zone, spaces between grains are filled with air and water. The water within the unsaturated zone is held by capillary forces around the grains and can evaporate or be absorbed by plant roots. If the volume of water in the unsaturated zone exceeds the volume that can be held by capillary forces, the water moves down toward the saturated zone, and if it reaches the saturated zone, the amount of water in the saturated zone increases. In the saturated zone, the spaces between the grains are completely filled with water.

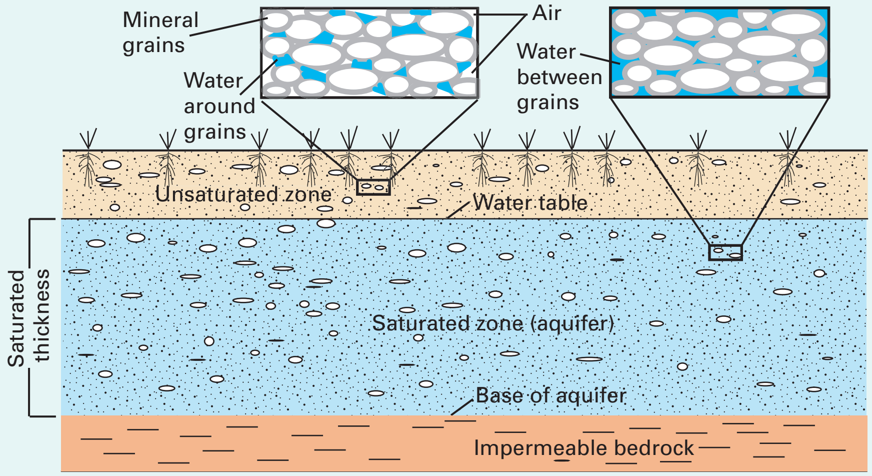


Figure 16*.* *Schematic of an unconfined aquifer showing unsaturated zone, water table, saturated zone (aquifer), base of aquifer, and underlying impermeable bedrock.*

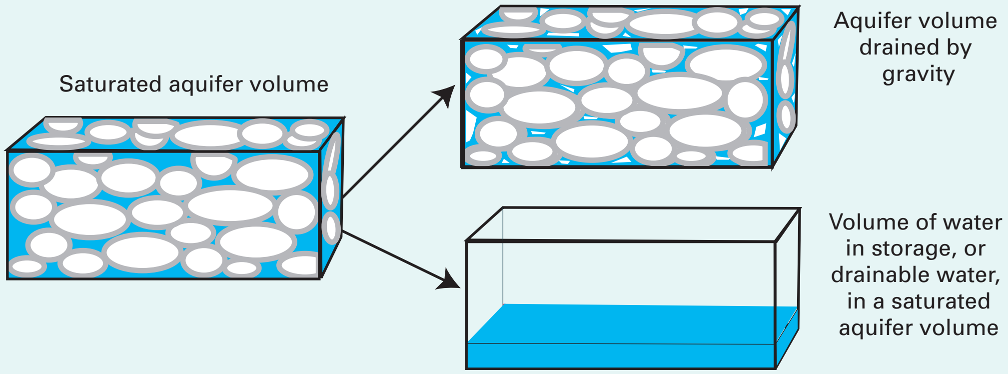


***Figure 17**. Schematic showing the amount of water in storage in a representative volume of the High Plains aquifer.*

Water in storage in the aquifer fluctuates in response to a change in the amount of water recharged to or discharged from the aquifer. Prior to development, recharge to the High Plains aquifer was primarily from precipitation and discharge from the aquifer was primarily to streams, springs, and seeps. After development, recharge to the aquifer is from precipitation, irrigation return flow, and seepage from structures such as irrigation canals. After development, discharge from the aquifer is to wells, streams, springs, and seeps. During predevelopment, the water budget, which includes components of recharge and discharge, generally was balanced. After development, the water budget is in a deficit condition in parts of the aquifer; that is, discharge is greater than recharge, and water in storage in the aquifer has decreased (Luckey and others, 1986).

A water budget for the south-central High Plains aquifer during predevelopment and in 1997 shows an 18-percent decline in water in storage. Withdrawals by wells were the primary cause of the decline in water in storage. A decrease in natural discharge and an increase in recharge from irrigation return flow partially offset the withdrawals by wells (fig. 18).

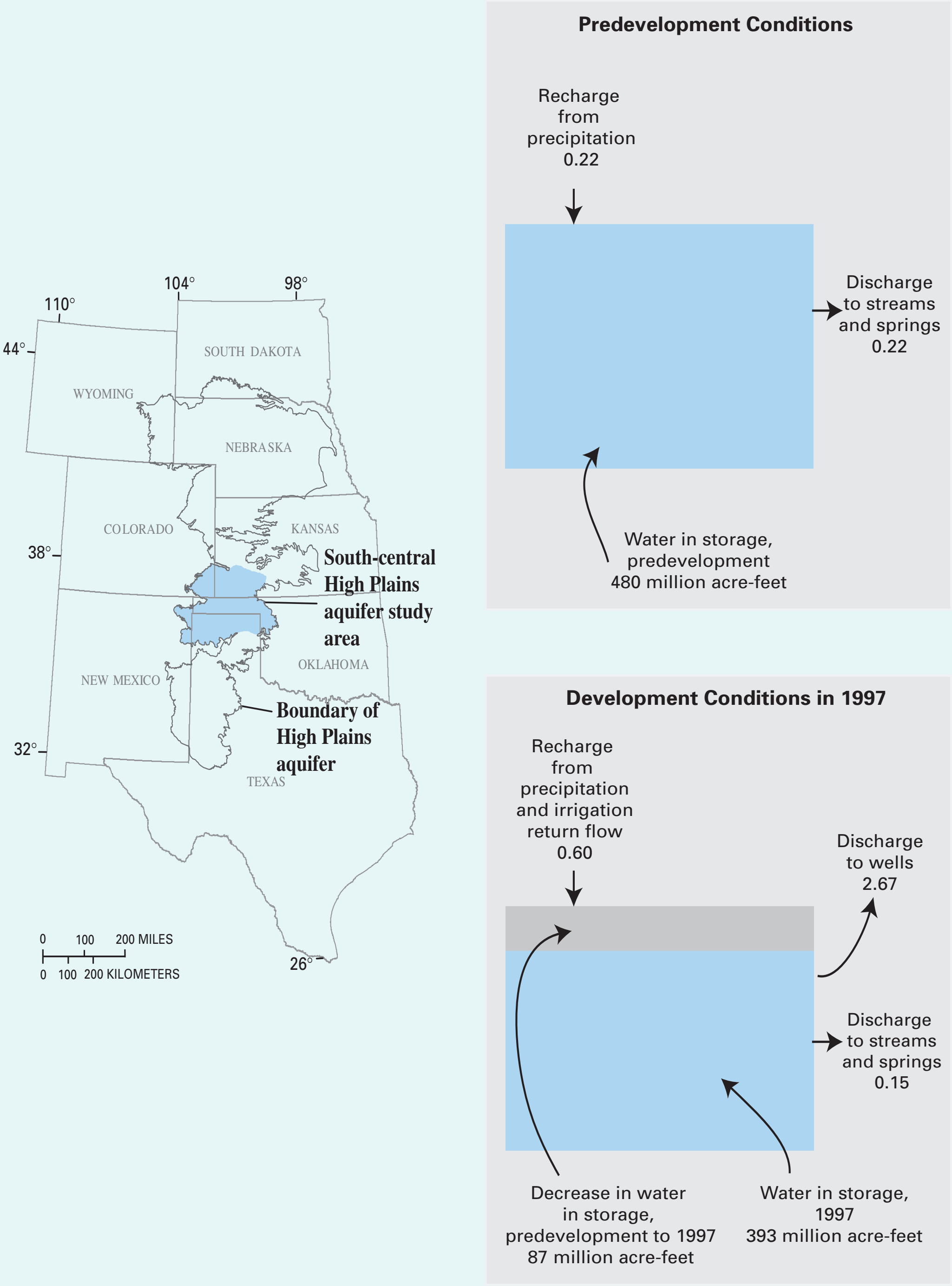


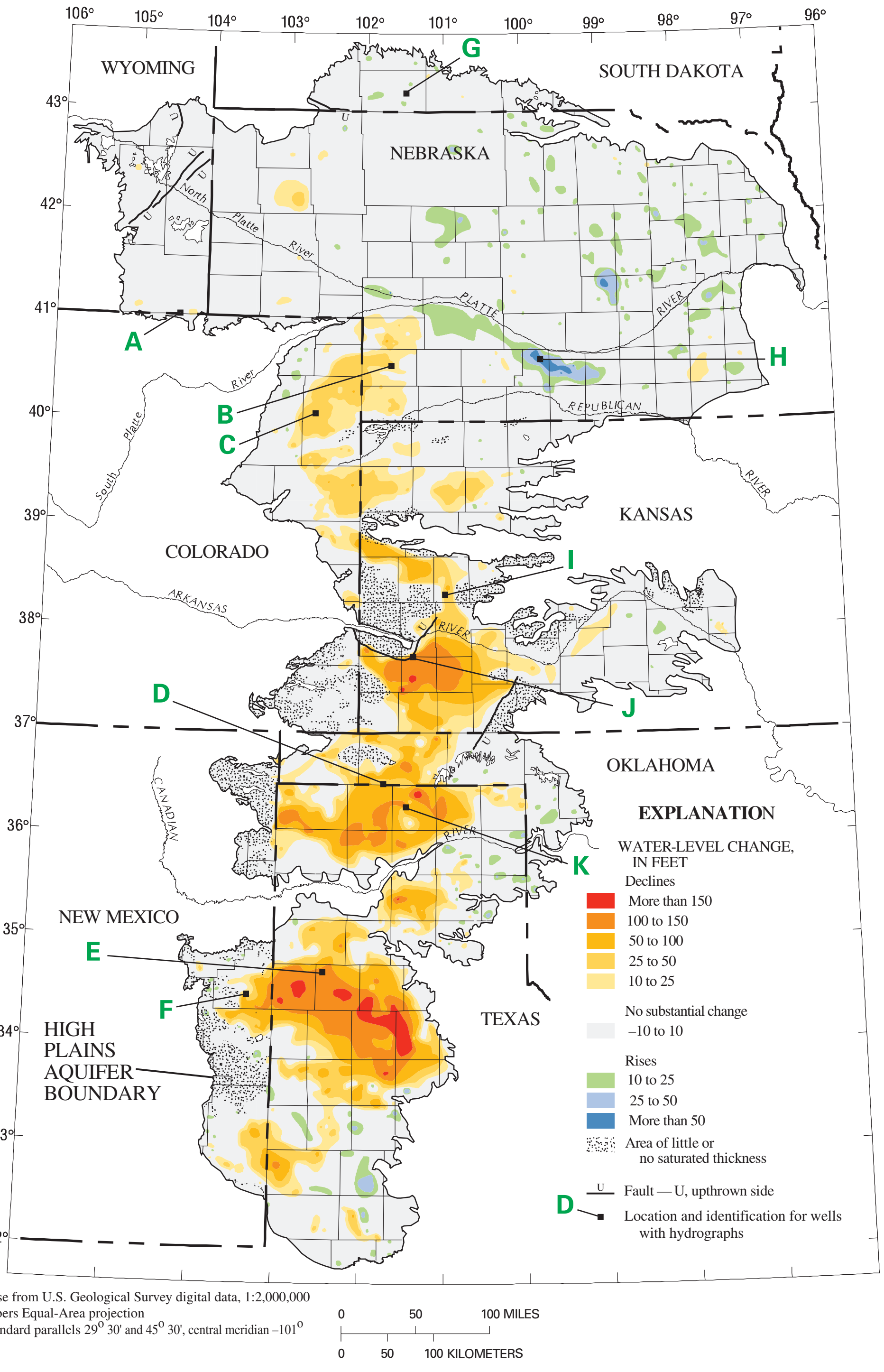
Figure 18. *Ground-water budget in the south-central High Plains aquifer study area during predevelopment and in 1997. Values without units are in million acre-feet per year (Luckey and Becker, 1999).*

CHANGES IN WATER IN STORAGE, PREDEVELOPMENT TO 2000

The changes in water in storage in the High Plains aquifer from predevelopment to 2000 can be derived by using the volume of aquifer material that has been dewatered and the average specific yield of the aquifer in each State (table 3). The volume of aquifer material that has been dewatered can be derived by using a map of water-level changes, predevelopment to 2000 (fig. 19). The map (fig. 19) was constructed by superimposing maps of the water table in predevelopment (fig. 6) and the water table in 2000 and connecting points of equal water-level change (modified from Luckey and others, 1981).

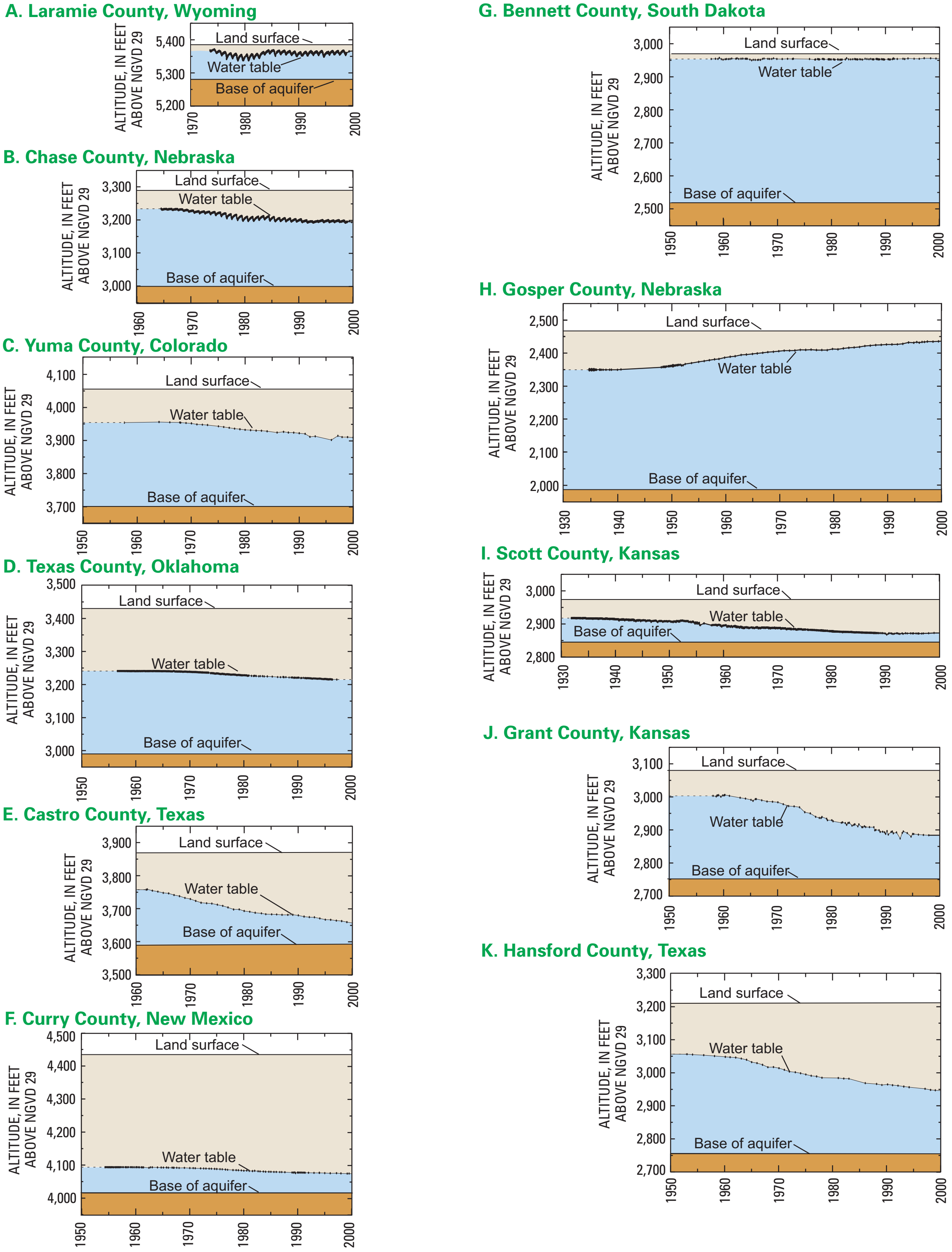
Change in water level at specific locations in the High Plains aquifer also can be illustrated using hydrographs for selected wells (fig. 20). A hydrograph shows the available history of water-level measurements in the well and the estimated saturated thickness of the aquifer at that location.

The average area-weighted water-level change in the High Plains aquifer from predevelopment to 2000 was a decline of 11.9 feet. The average area-weighted water-level change by State ranged from almost no change in Nebraska, South Dakota, and Wyoming to a decline of about 35 feet in Texas. The area within each State with 25 or more feet of water-level decline ranges from small areas in South Dakota and Wyoming to about 9 million acres in Texas (table 4).



Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian –101°

Figure 19. *Water-level changes in the High Plains aquifer, predevelopment to 2000, and location of selected wells with hydrographs. See hydrographs in figure 20.*



A. Laramie County, Wyoming

B. Chase County, Nebraska

C. Yuma County, Colorado

D. Texas County, Oklahoma

E. Castro County, Texas

F. Curry County, New Mexico

G. Bennett County, South Dakota

H. Gosper County, Nebraska

I. Scott County, Kansas

J. Grant County, Kansas

K. Hansford County, Texas

Figure 20. *Hydrographs for selected wells. See figure 19 for well location.*

Table 4. *Average area-weighted water-level change and area with 25 or more feet of water-level decline in the High Plains aquifer, predevelopment to 2000*

State	Average area-weighted water-level change, in feet	Area with 25 or more feet of water-level decline, in million acres
Colorado	–9.0	1.3
Kansas	–18.2	3.8
Nebraska	0.7	0.3
New Mexico	–14.5	0.8
Oklahoma	–13.3	0.9
South Dakota	0.3	0.0
Texas	–34.5	9.4
Wyoming	–0.1	0.0
Eight States	**–11.9**	**16.5**

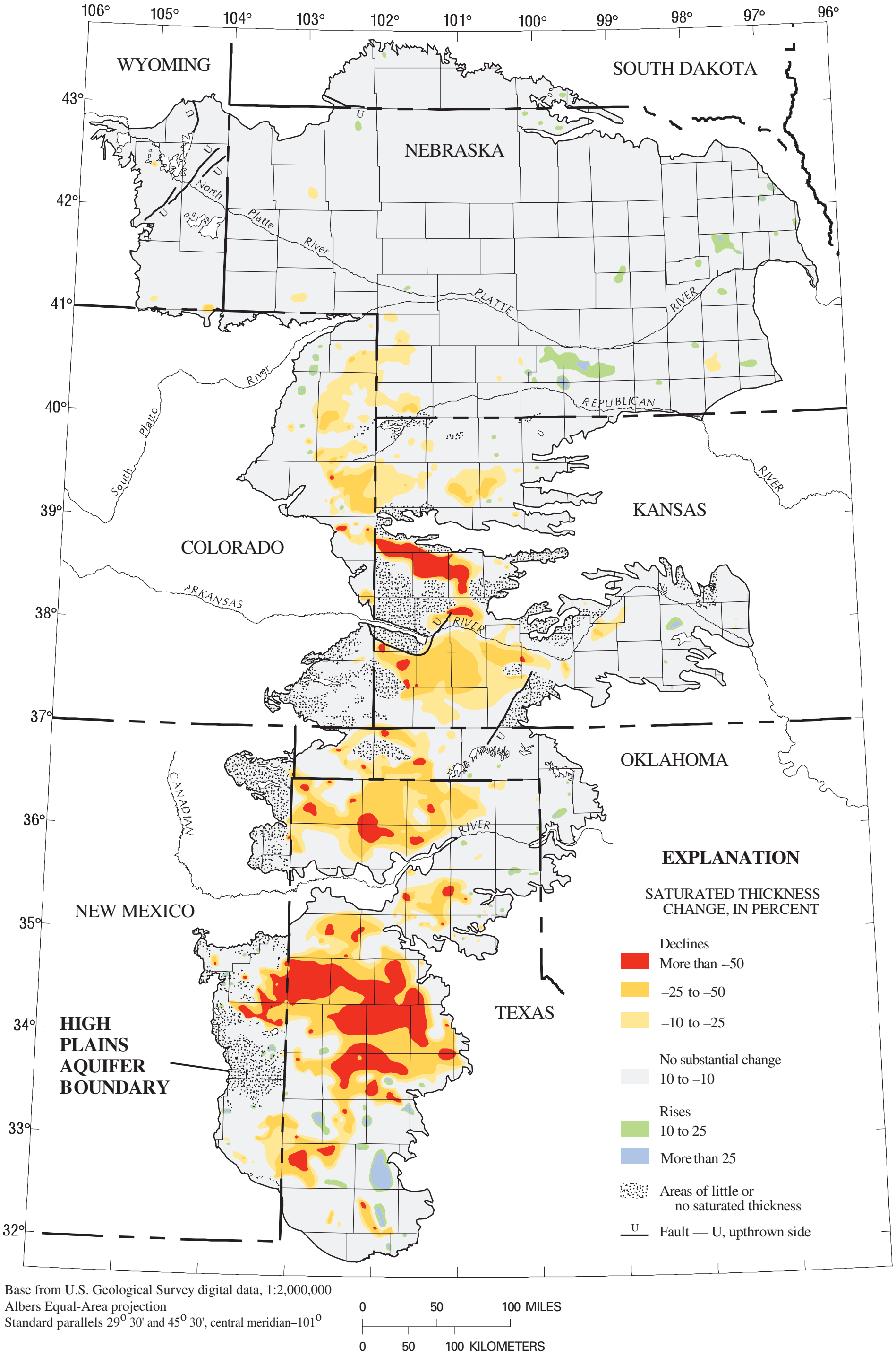
The volume of aquifer material dewatered from predevelopment to 2000 was calculated by multiplying the midpoint of each water-level change interval by the area of the water-level change interval (fig. 19) and summing the result. This method assumes the area of the High Plains aquifer within the interval "–10 to 10 feet" of water-level change (fig. 19) averages 0 feet of water-level change. If the average water-level change in the "+10 to –10 feet" interval areas is, for example, a decline of 4 feet, then this method underestimates the average area-weighted water-level change.

The change in the volume of water in storage in the High Plains aquifer from predevelopment to 2000 is a decrease of about 200 million acre-feet, which represents 6 percent of the volume of water in storage in the aquifer during predevelopment. The change by State ranges from an increase of 4 million acre-feet in Nebraska to a decrease of 124 million acre-feet in Texas (table 5). Most of the decline in storage occurred in the 17-million-acre area with 25 or more feet of water-level declines (fig. 19). In this part of the aquifer, the water in storage in the aquifer decreased about 190 million acre-feet from predevelopment to 2000, which is about 34 percent of the water in storage in this part of the aquifer during predevelopment.

The effect of a given change in the volume of water in storage in an area depends partly on the original saturated thickness of the aquifer. The map showing percent change in saturated thickness (fig. 21) represents the water-level change, predevelopment to 2000, as a percentage of predevelopment saturated thickness. The map is constructed by superimposing the map of water-level change, predevelopment to 2000 (fig. 19), on the map of saturated thickness, 2000 (fig. 14), calculating the predevelopment saturated thickness and percentage of change in predevelopment saturated thickness, and then connecting points of equal percent change in predevelopment saturated thickness.

Table 5. *Change in water in storage in the High Plains aquifer, predevelopment to 2000*

State	Change in water in storage, in million acre-feet
Colorado	–11
Kansas	–47
Nebraska	4
New Mexico	–8
Oklahoma	–11
South Dakota	0
Texas	–124
Wyoming	0
Eight States	**–197**



Base from U.S. Geological Survey digital data, 1:2,000,000
Albers Equal-Area projection
Standard parallels 29° 30' and 45° 30', central meridian–101°

Figure 21. *Percent change in saturated thickness of the High Plains aquifer, predevelopment to 2000.*

Figure 21 represents change in available water supply caused by declines in water levels. The map is similar in some areas to the water-level-change map (fig. 19). However, an area of large water-level change is not shown on this map if predevelopment saturated thickness was large and the change did not substantially alter the saturated thickness. Conversely, areas with small water-level change may result in a large percentage of change in saturated thickness because of a small predevelopment saturated thickness. For example, a water-level decline of 10 feet in an area where predevelopment saturated thickness was 300 feet represents a 3-percent change in predevelopment saturated thickness, whereas a decline of 10 feet in an area where original saturated thickness was less than 50 feet represents a change in saturated thickness of more than 20 percent. Decreases in saturated thickness can result in a reduction in well yield and an increase in the cost of pumping (see Box B).

In 2000, about 11 percent of the High Plains aquifer area had more than a 25-percent decrease in predevelopment saturated thickness, and 4 percent of the aquifer area had more than a 50-percent decrease. Kansas and Texas had the largest areas with more than a 25-percent decrease in predevelopment saturated thickness.

B

Increased Energy Costs Caused by Declining Water Levels

The energy cost to operate an irrigation well depends on a number of factors, including aquifer characteristics such as saturated thickness and permeability, well and pump characteristics, the distance the pump must lift the water, pump efficiency, and, for electrical pumps, electric motor efficiency. When water levels decline in an area, such as the declines that have occurred in parts of the High Plains aquifer from predevelopment to 2000 (fig. 22), energy costs can increase because the energy required to operate the pump is proportional to pump lift: doubling lift doubles the energy required. The energy costs also can increase because well yield is proportional to saturated thickness—as saturated thickness declines, well yields decline, and pump operation time increases.

For example, the cost for electricity to pump the water required to apply 24 inches on 126 acres of cropland at a pumping rate of 850 gallons per minute, assuming 65 percent pump efficiency and $0.07 per kilowatt hour, is about $5,900 for 200 feet of lift and $8,900 for 300 feet of lift (Broner, 2002). As a second example, the yield in a fully screened well decreases from 850 to 801 gallons per minute if the saturated thickness changes from 200 to 190 feet, assuming that aquifer permeability is constant and the radius of the cone of depression does not change. If a farmer needs to apply 24 inches of water on 126 acres of cropland, it would take 67 days at 850 gallons per minute and 71 days at 801 gallons per minute (Sloggert and Mapp, 1984).

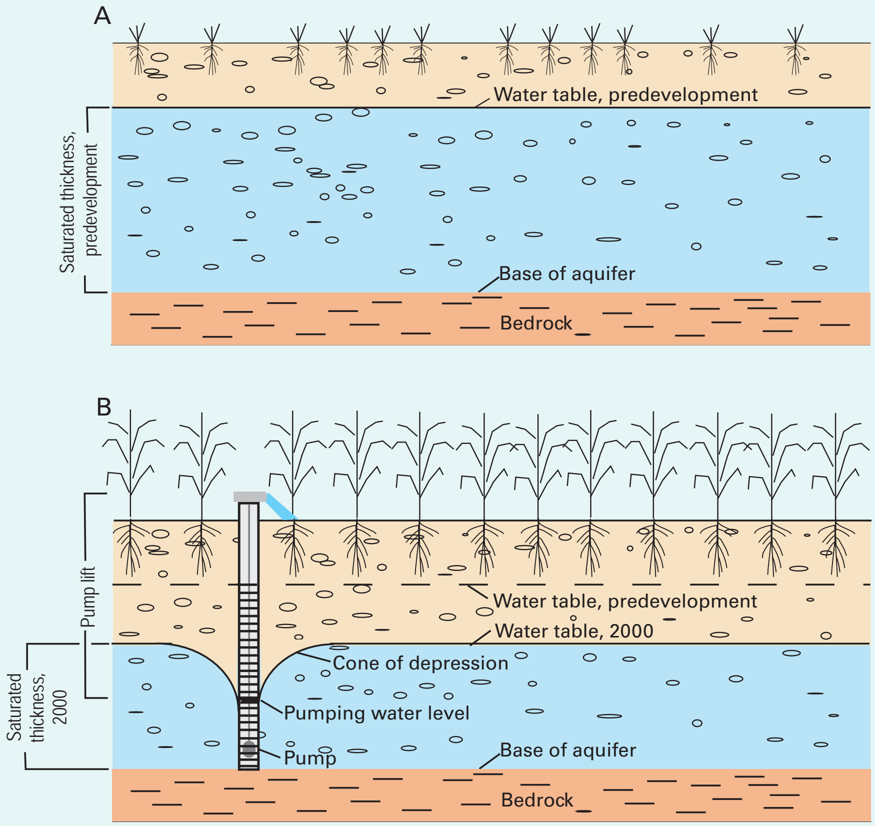


***Figure 22**. Schematic showing the water table and saturated thickness (A) during predevelopment and (B) after development in an area where regional water-level declines have occurred.*

APPROACHES TO GROUND-WATER MANAGEMENT

This section describes the approaches to ground-water management in each State that overlies the High Plains aquifer. The description of the ground-water-management approaches in each State includes discussions of ground-water ownership, controls, if any, on well installation and use, and regulations on water use. A similarity in the approaches to ground-water management in all of the States is that the water must be used for beneficial purposes, which generally implies that the water is used for a reasonable purpose and that the water is not wasted. The differences among these approaches to ground-water management include the legal doctrines, which form the basis for ground-water allocations.

On Federal and Indian lands, water rights are based on the reserved-rights doctrine. Under the reserved-rights doctrine, the Federal agencies and Indian Tribes are entitled to sufficient water to fulfill the purpose for which the lands were set aside. There are about 1.9 million acres of Indian land, mainly in South Dakota, and 2.5 million acres of Federal land that overlie the High Plains aquifer (Getches, 1997; U.S. Geological Survey, 2000). This report does not include a description of approaches to ground-water management on Federal and Indian lands.

The U.S. Supreme Court has held that ground water is an article of interstate commerce and, therefore, is subject to constitutional restrictions on State regulation of such commerce (U.S. Supreme Court, 1982). These constitutional restrictions allow States to limit interstate transfers of ground water if the limitations are based on legitimate needs of the State's citizens and not on arbitrary criteria.

Four legal doctrines form the basis for States' rules on allocations of ground water in the High Plains aquifer. These legal doctrines are rule of capture, reasonable use, correlative rights, and prior appropriation (Ashley and Smith, 1999; Getches, 1997).

- According to the **rule of capture or absolute ownership doctrine**, landowners can withdraw ground water for use without regard to the effect of the withdrawals on wells owned by adjacent landowners.
- According to the **reasonable use doctrine**, landowners are entitled to withdraw a reasonable amount of the ground water that underlies their land, as long as the landowners use the water for beneficial purposes.
- Under the **correlative rights doctrine**, landowners are entitled to withdraw a reasonable amount of the ground water that underlies their land, as long as the landowners use the water for beneficial purposes. The amount of water that can be withdrawn by a landowner is limited by the needs of others whose land overlies the aquifer and who have an equal right to a reasonable amount of the water.
- According to the **prior appropriation doctrine**, a landowner must apply for a permit from the State to use ground water. If the State approves the permit application, the State grants the landowner a right to a specified amount of water. Landowners whose water right predates the State's permit system can receive a grandfathered right. If there is not sufficient water to meet the needs of all appropriators, water rights are enforced by seniority. A simplified way to explain this system is "first in time, first in right."

Colorado

In Colorado, ground water is a public resource, and individuals or entities can obtain rights to use the ground water. Ground water in Colorado is classified as tributary, nontributary, or designated. The water in the High Plains aquifer in Colorado is considered designated ground water. Designated ground water is defined by the Colorado Legislature as "... ground water which in its natural course would not be available to and required for the fulfillment of decreed surface rights, or ground water in areas not adjacent to a continually flowing stream wherein ground water withdrawals have constituted the principal water usage for at least fifteen years ...." (State of Colorado, 2002). The Colorado Ground Water Commission (Commission) administers designated ground water in accordance with legislative intent. Designated ground water is administered within areas called designated basins, under a system based on a modified prior appropriation doctrine, to fully develop the resource while at the same time protect vested water rights. In designated basins, controls are implemented on well installation and water use to prolong the life of the aquifer and promote full economic development (State of Colorado, 2002).

The Commission has the authority to delineate designated basins, to enact rules and regulations for the administration of ground water, and to create ground-water-management districts to assist in administering the designated basins. The Commission formed two designated basins that overlie most of the High Plains aquifer in Colorado and established Ground-Water Management Districts to administer them. The two designated basins are the Northern High Plains Designated Basin in northeastern Colorado and the Southern High Plains Designated Basin in southeastern Colorado. The Ground-Water Management Districts have the authority to enact additional rules and regulations for the administration of ground water in their District (State of Colorado, 2002). However, only the Commission or the State Engineer has the authority to issue, deny, or change water rights within the Northern and Southern High Plains Designated Basins (State of Colorado, 2002; Colorado Supreme Court, 2000). The Commission issued policies, which, in 1992, became rules to regulate new well permits, changes in water rights, replacement well distances, maximum irrigation appropriations, metering requirements for wells, and requirements for replacement wells.

The Commission requires permits to use designated ground water. The State Engineer has the authority to grant permits for small-capacity wells. Since 1965, the Commission has had the authority to grant permits for large-capacity wells. Large-capacity wells in use before 1965 had to be recorded with the State Engineer before December 31, 1968, to remain in use (State of Colorado, 2002). Starting in 1967, the Commission limited the issuance of new, large-capacity well permits in all designated basins so no new large-capacity well permits generally would be issued closer than 0.5 mile from an existing well screened in the same aquifer (Colorado Division of Water Resources, 2001).

Rangeland in Kit Carson County, Colorado. (Photograph courtesy of R.R. Luckey, U.S. Geological Survey.)

In 1967, the Commission established depletion criteria for the Northern High Plains Designated Basin so that no new large-capacity well permits would be issued if the proposed withdrawal, after 25 years, was projected to deplete the aquifer by more than 40 percent within a 3-mile radius of the well. In 1990, the Commission issued a policy amending the Northern High Plains Designated Basin depletion criteria to 40 percent in 100 years.

The Commission did not establish depletion criteria for the Southern High Plains Designated Basin because of the complex geology of the area. Five aquifers exist in the Southern High Plains Designated Basin: the Alluvium, Cheyenne, Dakota, Dockum, and High Plains. Within the Southern High Plains, these aquifers are still open for appropriation, provided the new appropriator meets statutory and regulatory requirements (Colorado Division of Water Resources, 2001). Even though the Commission considers that ground water is still available for beneficial use in the Southern High Plains Designated Basin, water levels have been declining in the Southern High Plains Designated Basin since it originated. As a result, the Southern High Plains Ground-Water Management District and the Commission have undertaken a research project designed to better quantify the total withdrawal from each aquifer and the total amount of ground water in storage within each aquifer in the basin (Chuck Roberts, Colorado State Engineer's Office, oral commun., 2001).

The vast majority of the water extracted from the Northern and Southern High Plains Designated Basins is used for irrigation. When other needs for water arise within the Northern High Plains Designated Basin, such as for commercial use or public supply, these new uses may be fulfilled through the acquisition of existing water rights and subsequent changes to intended use. Changing water rights requires that the well be limited to the average annual historical consumptive use and proof that no material injury will occur to other vested water rights. New appropriations within the Northern High Plains Designated Basin are difficult to acquire because new withdrawals from the majority of the basin fail the depletion criteria. When other needs arise within the Southern High Plains Designated Basin, water users may apply for a new water right. Before granting a permit for the new water right within the Southern High Plains Designated Basin, the Commission verifies that the proposed new appropriation will not cause unreasonable impairment to other vested water rights (State of Colorado, 2002; Colorado Division of Water Resources, 2001).

Well permits are considered individual property rights that have considerable value and are of substantial importance to the individual owners. Well permits can be bought and sold independent of the property on which the well is located.

Kansas

In Kansas, ground water is a public resource. Since 1978, it has been unlawful in Kansas to use water for nondomestic purposes without either holding a vested right or receiving a permit to appropriate water. Water used for domestic purposes is defined as water used to satisfy the needs of a household, of livestock on pasture, and for as much as 2 acres of lawn and garden. A vested right is the right to continue the beneficial use of water that began before June 28, 1945 (Kansas Department of Agriculture, Division of Water Resources, 2001).

Water rights are property rights connected to the land where the water is used. The landowner must use the water for beneficial purposes, and all uses except domestic are regulated by a permit system. The permit system is generally based on the doctrine of prior appropriation. The State's Chief Engineer, who heads the Division of Water Resources in the Kansas Department of Agriculture, administers the permit system. Eligible voters and the State Engineer created five Groundwater-Management Districts in Kansas, which overlie most of the High Plains aquifer in Kansas. These Districts play a significant role in managing ground-water resources in their local area.

The Chief Engineer is responsible for administration of laws related to water rights and conservation and for the management of water resources in the State. Groundwater-Management District boards can propose regulations, which must not conflict with State law, and develop plans for the management of local ground-water supplies for nondomestic use within the District. These regulations and plans, which must be reviewed and adopted by the Chief Engineer, then become the regulations for that local area (Sophocleous, 1998; Huntzinger, 2001).

The Chief Engineer and Groundwater-Management District boards manage water resources by using either the concept of "safe yield" or "allowable depletion," depending on conditions in the area. The "safe yield" concept considers existing appropriations within a specified radius of the proposed well and limits total appropriations to a percentage of the estimated recharge to the aquifer in that radius. The "allowable depletion" concept considers existing appropriations within a specified radius of the proposed well and limits total appropriation to a level that will deplete the aquifer by a specified amount in a specified timeframe in that radius. The two Groundwater Management Districts in southwest Kansas and west-central Kansas use an "allowable depletion" approach; for example, in southwest Kansas, the District allows a 40-percent decrease in saturated thickness over a period of 25 years in that part of the aquifer. Many townships in southwest Kansas are now closed to additional appropriations because the township exceeds the allowable limits. The other Groundwater Management District in northwest Kansas that overlies the aquifer in that area of the State uses a safe yield approach. Other areas of the State limit new permits to "safe yield" or are closed and do not allow any new permits (Sophocleous, 1998; Kansas Department of Agriculture, Division of Water Resources, 2002).

The permit application date establishes the priority to continue the use of water during periods of shortage. A permit to appropriate water may be approved if the proposed annual rate of use and quantity are reasonable for the intended purpose and if the use of water will not impair existing water rights or unreasonably affect the public interest. The holder of a water right may change conditions of the permit, such as the proposed use, with approval from the Chief Engineer (Sophocleous, 1998).

Irrigated cropland, Morton County, Kansas. (Photograph courtesy of K.F. Dennehy, U.S. Geological Survey.)

Nebraska

In Nebraska, ground water is a public resource, and the use of ground water is governed by a modified correlative rights doctrine and by numerous legislative enactments. Except as provided by the legislature, landowners are entitled to withdraw a reasonable amount of the ground water under their land for beneficial use on that land. In those areas where no local or State regulations supersede, the Nebraska correlative rights doctrine provides for proportionate sharing whenever the natural supply of ground water becomes insufficient for all overlying landowners' needs (Mossman, 1996).

The Nebraska Legislature has substantially supplemented and modified many aspects of the judicially adopted correlative rights doctrine, including the "overlying land" limitation on use of ground water. Authority to transfer water off the overlying land has been granted for the following water uses, the first three of which require a permit from the Nebraska Department of Natural Resources (NDNR): public water supply, interstate use, industrial use, agricultural use, and domestic use of less than 50 gallons per minute. In addition, there are statutory preferences for the use of ground water, which courts can apply to resolve conflicts between well users. Domestic use, which includes normal livestock operations, has preference over all other uses. Agricultural use has preference over manufacturing and industrial uses (State of Nebraska, 2002).

Twenty-three Natural Resource Districts (NRDs) were created by the legislature in the early 1970's and were assigned multiple responsibilities relative to the management of Nebraska's soil and water resources. With limited State oversight, NRDs are given authority to manage and control ground-water use. Each NRD prepared a ground-water-management plan that was approved by the NDNR. The ground-water-management plan identifies ground-water depletion and water-quality issues in the district and specifies the regulatory or other procedures that the NRD will enact to address these issues. The High Plains aquifer underlies all or part of 21 NRDs.

An NRD may establish a ground-water-management area to mitigate issues with ground-water supply, ground-water quality, or issues between ground- and surface-water users. With a few exceptions, a new well may not be constructed in a ground-water-management area without an NRD well-construction permit (State of Nebraska, 2002). As of April 2003, ground-water-management areas are located in 18 of the 21 NRDs that overlie the High Plains aquifer in Nebraska; a goal of eight of these ground-water-management areas is to address ground-water supply problems (Tina Kurtz, Nebraska Department of Natural Resources, oral commun., 2003). Approaches to ground-water-supply issues include moratoriums on installation of new wells and restrictions on the amount of ground water that can be withdrawn.

Except for water wells constructed before September 1993 and used exclusively for domestic purposes, and for test holes and dewatering wells used for less than 90 days, all wells in the State must be registered with the NDNR. In most situations, the date a well is drilled generally does not give it a priority date or other basis for preferential treatment over other wells. However, spacing rules are imposed to prevent interference between a new well and existing wells (State of Nebraska, 2002).

A center-pivot irrigation system with drop tubes in Dundy County, Nebraska. (Photograph courtesy of M.K. Landon, U.S. Geological Survey.)

New Mexico

In New Mexico, ground water is a public resource, and the right to use ground water is governed by the prior appropriation doctrine. However, a process to regulate ground-water rights exists only in areas termed designated ground-water basins. The State Engineer can declare a ground-water basin by assuming jurisdiction over the appropriation of ground water in an area. There are six designated ground-water basins that encompass most of the High Plains aquifer in New Mexico (New Mexico Office of the State Engineer, 2001).

Within a designated ground-water basin, a water user must obtain an approved permit for a new water right or for changes to an existing water right from the State Engineer. The State Engineer generally approves permits for livestock, lawn and garden irrigation, and other domestic purposes. For other types of water uses, the State Engineer approves permits for the new or revised water rights if (1) no objections are filed, (2) unappropriated water exists in the basin, (3) no infringement on the water rights of prior appropriators occurs, and (4) it is not detrimental to the public welfare or the water conservation goals of the State. The State Engineer determines whether unappropriated water exists in the basins by monitoring water-level declines within a 9- to 25-square-mile area, depending on aquifer properties, around the site of a proposed new appropriation. If the annual water-table decline exceeds 2.5 feet, the State Engineer will not approve the permit because the rate of decline is excessive. Appropriators may appeal all decisions of the State Engineer to District Court. Outside designated ground-water basins, permits are not required, and individuals claiming that new appropriations will impair their senior water right can pursue legal action (Ashley and Smith, 1999; Templer, 1992).

In New Mexico, water rights can be bought and sold separately from the property on which the well is located. Water rights can be acquired for out-of-State use if approved by the State Engineer.

Irrigated and nonirrigated cropland, Lea County, New Mexico, and Gaines County, Texas. (Photograph courtesy of Phillip Ross, Ross Group, Hobbs, New Mexico.)

Oklahoma

In Oklahoma, ground water is owned by the landowners whose property overlies the aquifer. Use of ground water is governed by the reasonable-use doctrine and is subject to regulation by the Oklahoma Water Resources Board (OWRB). In 1949, the Oklahoma Legislature required that landowners or their lessees must obtain a license from the OWRB before using water from an aquifer, but that the OWRB could not issue a license if the annual amount of water used would exceed annual recharge to the aquifer. In 1972, the legislature repealed the 1949 law and replaced it with a new law; however, those landowners with previously established ground-water rights could continue to use their authorized amount. The 1972 law provided that landowners or their lessees must obtain a permit from the OWRB before using ground water for use other than domestic. The permit authorizes annual withdrawal of an amount based on acres to be irrigated and “maximum annual yield” for the aquifer in the area. “Maximum annual yield” is the amount of water that can be withdrawn annually from the aquifer in the area while ensuring the aquifer will yield water for at least 20 years. The OWRB evaluates the hydrogeologic characteristics of each aquifer to determine maximum annual yield in an area. Before approving a permit, the OWRB verifies that the proposed use is beneficial and will not cause pollution of water in the aquifer and that well-spacing requirements are met. Although State law does not prioritize beneficial use, water used for drinking, domestic use, and vital economic activity could receive precedence during drought or other local water emergencies (Ashley and Smith, 1999; Oklahoma Water Resources Board, 2001a; 2001b).

The High Plains aquifer in Oklahoma was subdivided into two administrative areas by the OWRB. The maximum annual yield in the Panhandle Region, which includes most of Beaver, Cimarron, and Texas Counties, is 2.0 acre-feet per acre. The maximum annual yield in the Northwest Region, which includes parts of Ellis, Harper, Dewey, and Woodward Counties, has been recently reduced from 2.0 acre-feet per acre to 1.4 acre-feet per acre for new permits; however, existing permit holders are allowed to continue to withdraw 2.0 acre-feet per acre (Oklahoma Water Resources Board, 2002).

Each year, all permit holders must report the amount of water used to the OWRB. A permit holder must receive approval from the OWRB to change the terms of their permit—for example, to change the annual amount of water used. A permit holder may transfer all or part of the ground-water right to another entity (Oklahoma Water Resources Board, 2001a; 2001b).

Cattle grazing on corn stubble, Cimarron County, Oklahoma. (Photograph courtesy of R.R. Luckey, U.S. Geological Survey.)

South Dakota

South Dakota Codified Law declares that all water within the State is a public resource, and the right to water use may be acquired by appropriation. Management of water quantity in South Dakota is accomplished through the water-rights permit program, established in 1955, and State Water Plan, established in 1972, and is administered by the South Dakota Department of Environment and Natural Resources (SDDENR). The Water Management Board (WMB) is a citizen board who work in conjunction with the SDDENR to regulate water use, approve and deny permits, validate vested rights, and cancel water-right permits or vested rights. However, most of the land overlying the High Plains aquifer in South Dakota lies within the boundary of either the Pine Ridge or Rosebud Indian Reservations, and the Tribes assert the right to control the development and use of ground-water resources within reservation boundaries (State of South Dakota, 2002; Syed Y. Huq, Rosebud Sioux Tribe, written commun., 2002).

The State requires a water-right permit for all uses except small domestic uses. The WMB generally does not issue a permit if the water to be withdrawn annually from a ground-water source will exceed the estimated annual recharge of water to that source; however, the WMB can make exceptions for public-supply wells. The spacing of large-capacity wells can be specified to prevent interference with other wells (State of South Dakota, 2002; State of South Dakota, Water Management Board, 2002).

An individual can obtain a water right for use at another location, including out-of-State. However, in the case of irrigation, the water right is linked to the irrigated land and is subject to transfer to the new owner upon property sale. Irrigation water rights can be transferred to a municipality or other water distribution system, such as a rural water system, and the use can be changed from irrigation to municipal or domestic (State of South Dakota, 2002).

A well house for a municipal well, Tripp County, South Dakota. (Photograph courtesy of K.M. Neitzert, U.S. Geological Survey.)

Texas

In Texas, no one has title to ground water until the water is withdrawn from the aquifer. The landowners whose land overlies the aquifer own the right to withdraw available water from the aquifer, subject to limitations. In addition, landowners can sell the withdrawn water for use at other locations. In 1998, the Texas Supreme Court upheld this method of allocating ground-water rights, which was established in Texas in 1904 and called the rule of capture (Texas Supreme Court, 1999). Limitations to the rule of capture in the High Plains aquifer in Texas are that (1) the person withdrawing the water cannot dewater a neighbor's well for malicious reasons or willfully waste the water, and (2) in areas with Ground-Water Conservation Districts, the district can enact some limitations on the ground-water withdrawal rate, the total amount withdrawn, and the well spacing (State of Texas, 2002).

In 1949, the Texas Legislature created a petition process for designating ground-water-management areas and established the structure for Ground-Water Conservation Districts. The legislature or the Texas Commission on Environmental Quality can create Ground-Water Conservation Districts either in response to a petition by landowners in the area or in response to critical water-quality or water-quantity issues identified in the area by hydrologic studies conducted by the Texas Water Development Board. If the district is to be funded by property taxes, local voters must approve the property tax assessment (State of Texas, 2002).

In the High Plains area of Texas, 14 Ground-Water Conservation Districts (May 2002) exist. The Ground-Water Conservation Districts regulate to a varying extent more than 81 percent of the area that overlies the High Plains aquifer in Texas (Texas Water Development Board, 2001). Where ground-water-management areas exist within a Ground-Water Conservation District, the district can regulate specific types of ground-water withdrawal by requiring ground-water-withdrawal permits and by controlling approval for permits to install new wells. However, the Ground-Water Conservation Districts cannot require permits for domestic or livestock wells, for wells that are designed to produce less than 25,000 gallons per day, or for wells to supply water for certain hydrocarbon or mineral production activities permitted through the Railroad Commission of Texas (State of Texas, 2002).

In Texas, water is an asset that can be sold and transferred to other locations, including out-of-State locations, with some exceptions. The possible exceptions occur in ground-water-management areas in which local Ground-Water Conservation Districts require a permit for water transfers and limit the transferred amount, depending on the proposed use of the water and the District's needs. The Ground-Water Conservation District cannot limit water-transfer agreements in effect before June 1997 (State of Texas, 2002).

Irrigated peanut field, Terry County, Texas. (Photograph courtesy of K.F. Dennehy, U.S. Geological Survey.)

Wyoming

In Wyoming, all natural waters are the property of the State. Individuals and entities, including municipalities and corporations, can acquire the right to use the water by appropriation. Wyoming water law, with some exceptions, is based on the doctrine of prior appropriation. The exceptions are that (1) municipalities can acquire water rights through the power of eminent domain if proper procedures are followed and the water-right holder is compensated, and (2) domestic and livestock use customarily have precedence over other water users (Richard Stockdale, Wyoming Deputy Engineer, written commun., 2001).

The State Engineer administers State laws and regulations related to water-right permits. The State Engineer generally issues water rights to anyone who plans to make beneficial use of the water. Recognized beneficial uses include, but are not limited to, irrigation, municipal, industrial, power generation, recreational, stock, domestic, pollution control, and instream flows. Water-rights holders for ground water are not limited to a specified amount of water (Wyoming State Engineer's Office, 2001).

The term "instream flow" refers to the flow in a stream that is adequate to meet specific needs, such as fish and wildlife habitat, or management objectives, such as interstate streamflow. Such flows, once set by the courts or the Wyoming Legislature, are a water right under the law and have priority over later water rights. The State Engineer issues instream-flow permits for ground-water withdrawals only to the Wyoming Water Development Commission (WWDC). The WWDC uses ground water withdrawn under instream-flow permits to increase streamflows to comply with mandated flow requirements (Richard Stockdale, Wyoming Deputy Engineer, oral commun., 2001).

Windmill-powered well and livestock-watering tank in Platte County, Wyoming. (Photograph courtesy of J.P. Mason, U.S. Geological Survey.)

The State Engineer has been registering ground-water rights for all uses except stock and domestic since 1947. Since 1957, permits from the State Engineer have been required before drilling all wells except stock and domestic; since 1969, a permit has been required before the drilling of all water wells with no exceptions. The State Engineer also issues permits for ground-water diversion and may recommend designation of an area as a ground-water-control area. In a ground-water-control area, the voters elect an Advisory Board to make recommendations for water administration to the State Engineer. Some of the recommendations may be ground-water-control measures such as limits on permits for new wells or on ground-water withdrawals. There are three ground-water-control areas in the High Plains of Wyoming—in northern Goshen, Laramie, and Platte Counties. In the Goshen and Platte County ground-water-control areas, no ground-water-control measures have been enacted. In Laramie County, permit applications for new wells are reviewed by the Advisory Board and the State Engineer with the result that few new permits have been granted since the ground-water-control area was established (Richard Stockdale, Wyoming Deputy Engineer, written commun., 2001; Ashley and Smith, 1999; Wyoming State Engineer's Office, 2001).

The Wyoming Board of Control (WBOC) is responsible for the adjudication of water rights and for assuring that the water is not wasted. The WBOC also must approve any changes to the terms of a permit, such as a change from one type of use to another or a change in the point or area of use, including use out of State. If a water-right holder wants to transfer more than 1,000 acre-feet per year for use out of State, authorization from the Wyoming Legislature must be obtained (Richard Stockdale, Wyoming Deputy Engineer, written commun., 2001; Wyoming State Engineer's Office, 2001).

SUMMARY AND CONCLUDING REMARKS

The High Plains aquifer underlies parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. By irrigating crops with ground water from the High Plains aquifer, the area that overlies the High Plains aquifer has become one of the major agricultural regions in the world. However, the use of ground water has resulted in substantial water-level declines in parts of the aquifer.

In 2000, the High Plains aquifer contained about 2,980 million acre-feet of water in storage. The volume of water in storage by State ranged from about 40 million acre-feet in New Mexico to 2,000 million acre-feet in Nebraska. The volume of water in storage in the High Plains aquifer in 2000 was about 197 million acre-feet, or 6 percent, less than the total water in storage prior to development of the aquifer for irrigation. About 95 percent of the loss of water in storage in the aquifer from predevelopment to 2000 is from an approximately 17-million-acre area with greater than 25 feet of water-level declines. In this 17-million-acre area, the decline in water in storage is about 34 percent of the water in storage in that part of the aquifer during predevelopment. The change in water in storage in the aquifer by State ranges from an overall rise in storage of 4 million acre-feet in Nebraska to an overall decline in storage of 124 million acre-feet in Texas.

All States that overlie the High Plains aquifer require that ground water withdrawn must be used for beneficial or reasonable purposes. Some of the States—Colorado, parts of Kansas, New Mexico, Oklahoma, and Texas—formally recognize that, in some areas of the State, water is being withdrawn from the aquifer at rates greater than the aquifer is being recharged. The ground-water-management approach in a State's area of jurisdiction can include restrictions on installation of new wells, on the amount of water that can be withdrawn from new and existing wells, and on the well owner's ability to change the use of water withdrawn from a well. The States designed these ground-water-management approaches to prevent aquifer depletion, to manage aquifer development, and to ensure the availability of aquifer resources for at least a specified number of years. In some States—Kansas, Nebraska, and Wyoming—some of the ground-water-management approaches in the High Plains aquifer area also are designed to limit water-level declines to try to maintain an acceptable amount of ground-water discharge to surface water.

State and local agencies compute available ground-water resources based on estimates of recharge and discharge from the ground-water system, aquifer characteristics, and other information about the hydrologic system. States monitor the effects of ground-water discharge by measuring water levels and, where ground water is connected to surface water, streamflow. Improved methods to calculate ground-water recharge would help the States to better determine available withdrawals. More accurate information on pumpage and acres irrigated could aid decision makers in resolving resource-allocation issues.

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