WATER-LEVEL CHANGES IN THE HIGH PLAINS AQUIFER--PREDEVELOPMENT TO 1991

by Timothy McGrath and Jack T. Dugan

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Multiply	*By*	*To obtain*
acre	0.4047	hectare
acre-foot	1,233	cubic meter
foot	0.3048	meter
gallon per minute	0.06309	liter per second
inch	25.40	millimeter
mile	1.609	kilometer
million gallons per day	0.003785	million cubic meters per day
square mile	2.590	square kilometer

To convert degree Fahrenheit (°F) to degree Celsius (°C) use the following formula:

$$°C = 5/9\ (°F - 32).$$

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 called Sea Level Datum of 1929.

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ABSTRACT

Regional variability in water-level change in the High Plains aquifer underlying parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming results from large regional differences in climate, soils, land use, and ground-water withdrawals for irrigation. From the beginning of significant development of the High Plains aquifer for irrigation to 1980, substantial water-level declines have occurred in several areas. The estimated average area-weighted water-level decline from predevelopment to 1980 for the High Plains was 9.9 feet, an average annual decline of about 0.25 foot. These declines exceeded 100 feet in some parts of the Central and Southern High Plains. Declines were much smaller and less extensive in the Northern High Plains as a result of later irrigation development.

Since 1980, water levels in those areas of large declines in the Central and Southern High Plains have continued to decline, but at a much slower annual rate. The estimated average area-weighted water-level decline from 1980 to 1991 for the entire High Plains was 1.41 feet, an average annual decline of about 0.13 foot. The relatively small decline since 1980, in relation to the declines prior to 1980, is associated with a decrease in ground-water application for irrigated agriculture and greater than normal precipitation. Water-conserving practices and technology, in addition to reductions in irrigated acreages, contributed to the decrease in ground-water withdrawals for irrigation. Water-level declines exceeding 20 feet since 1980, however, are widespread in parts of southwestern Kansas, east-central New Mexico, and the Oklahoma and Texas Panhandles. Widespread declines of 10 to 20 feet and exceeding 20 feet in smaller areas occurred in northeastern Colorado, northwestern Kansas, southwestern Nebraska, and the Nebraska Panhandle from 1980 to 1991. Water-level rises exceeding 20 feet occurred in the extreme Southern High Plains in Texas where precipitation was much greater than normal from 1980 to 1991. Widespread water-level rises from 5 to 20 feet occurred in eastern Nebraska during the same period in association with greater than normal precipitation.

The estimated average area-weighted water-level decline from 1990 to 1991 was 0.42 foot, even though precipitation was slightly greater than normal in 1990 in the High Plains. Water-level declines of 3 to 5 feet were widespread in the intensively irrigated areas of southwestern Kansas and the northern part of the Southern High Plains in Texas. These declines appear to be related to 1990 precipitation patterns in the Southern High Plains in Texas, but not in southwestern Kansas. Declines of 1 to 3 feet were common throughout the intensively irrigated areas of the Northern High Plains and the less intensively irrigated areas of the Central and Southern High Plains. Water levels continued to rise, generally 1 to 3 feet, in the extreme Southern High Plains in Texas. Rises of 1 to 3 feet also occurred in parts of eastern Nebraska where precipitation was as much as 4 to 6 inches greater than normal in 1990.

INTRODUCTION

The Omnibus Water Resources Development Act of 1986 (Public Law 99-662) amended the Water Resources Research Act of 1984 (Public Law 98-242). The amendment added a Title III to the legislation, which states in Section 306 that the U.S. Geological Survey in cooperation ". . . with the States of the High Plains region is authorized and directed to monitor the levels of the Ogallala [High Plains] aquifer, and report annually to Congress." Congress recognized that accurate information on the conditions and changes in the High Plains aquifer is necessary to make sound management decisions concerning the use of water, to project future economic conditions, and to conduct hydrologic research pertaining to the High Plains.

The High Plains aquifer (formerly called the Ogallala aquifer) underlies one of the major agricultural areas in the United States (fig. 1). About 20 percent of the irrigated land in the United States is in the High Plains, and about 30 percent of the ground water used for irrigation in the United States is pumped from the High Plains aquifer (Weeks and others, 1988).

Many studies of parts of the aquifer have been completed by irrigation districts, local agencies, State agencies, the U.S. Geological Survey (USGS), and other Federal agencies. A major study that examined the physical features of the entire aquifer was completed by the U.S. Geological Survey. The High Plains Regional Aquifer-System Analysis (High Plains RASA) described the geology and hydrology of the aquifer in detail (Gutentag and others, 1984; Weeks and others, 1988). Computer models for each of three subdivisions of the High Plains (fig. 1) were developed during that study to simulate the effects of several proposed water-management practices on the aquifer. The analyses made as part of the High Plains RASA were based on data collected before 1981. Beginning in 1988, water-level data again were systematically collected and compiled in an aquifer-wide data base (Kastner and others, 1989). The USGS and State and local agencies have compiled water-level data collected since 1980 at more than 12,000 locations.

This report, the fourth in a series, was prepared to fulfill requirements of Section 306, Title III of Public Law 98-242 as amended. It describes the High Plains aquifer, the factors that affect water levels in the aquifer, the history of development of the aquifer, water-level changes from predevelopment through the nonirrigation season (generally October through March) of 1979-80 (herein referred to as predevelopment to 1980), water-level changes between the nonirrigation season of 1979-80 and the nonirrigation season of 1990-91 (herein referred to as 1980 to 1991), precipitation patterns from 1981 through 1990 (herein referred to as 1981-90), and water-level changes between the nonirrigation seasons of 1989-90 and 1990-91 (herein referred to as 1990 to 1991), and precipitation patterns for 1990. The changes are shown on maps and are supplemented by long-term hydrographs of water levels in selected wells.

This report differs in several respects from the previous report (Dugan and Schild, 1992). Sections and accompanying illustrations showing saturated thickness of the High Plains aquifer in 1980, estimated average potential recharge, consumptive irrigation requirements, and net consumptive water use under irrigated conditions have been added to the discussion of factors affecting water-level changes in the High Plains. The report has been streamlined from previous reports by combining water-level change sections (1980 to 1991 and 1990 to 1991) with respective precipitation sections (1981-90 and 1990). This presentation permits water-level changes to be more easily compared to precipitation patterns during the time period. Overall, the water-level data base has been expanded with an increase in observation wells in selected areas. This expanded data base will provide improved definition of patterns of water-level change.

This report is possible because of the efforts of the numerous individuals of local, State, and Federal agencies who have inventoried the well sites, measured the water levels, and processed the data for more than 12,000 locations on an ongoing basis. In addition, the ground-water-data personnel at each of the USGS offices located in the High Plains have collected and computerized these data from the numerous, diverse sources and analyzed the results for their states. The following USGS personnel have provided invaluable assistance in quality assurance, supplying local expertise, and report review: E.R. Banta, Colorado; B.J. Pabst and J.B. Gillispie, Kansas; G.V. Steele, Nebraska; R.R. Cruz, New Mexico; J.E. May, Oklahoma; K.M. Neitzert, South Dakota; F.C. Wells, Texas; and K.A. Miller, Wyoming. The following U.S. Geological Survey personnel supplied invaluable water-use data: R.G. Dash, Colorado; L.A. Garrabrandt, New Mexico; Z.D. Hill, Nebraska; and H.A. Perlman, Georgia.

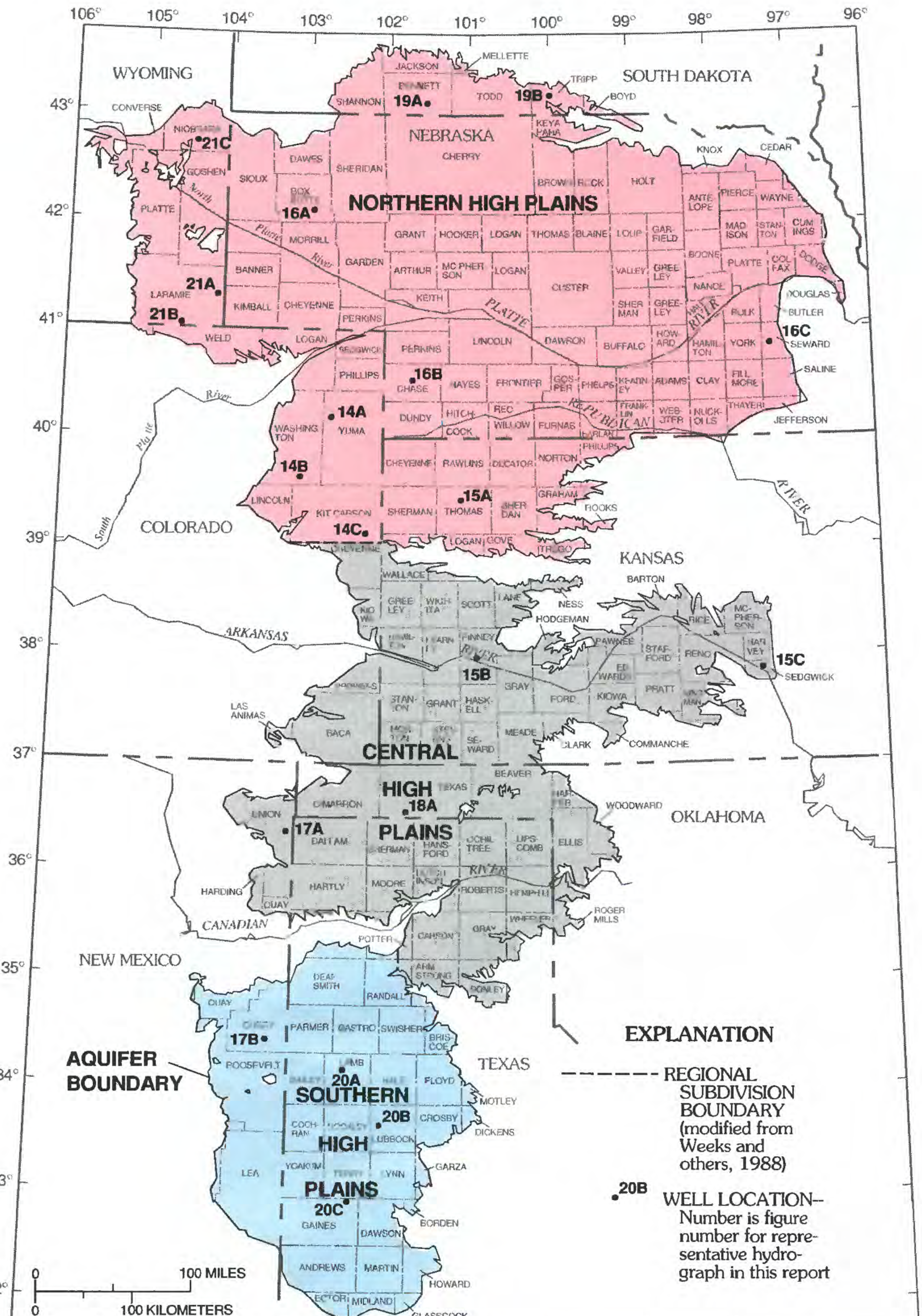

Figure 1. Subdivisions of the High Plains aquifer and location of selected observation wells (modified from Dugan and Schild, 1992).

EXTENT AND DESCRIPTION OF THE HIGH PLAINS AQUIFER

The High Plains aquifer is an extensive volume of saturated, generally unconsolidated deposits underlying the High Plains region. This aquifer formerly was known as the Ogallala aquifer, but the different geologic units and ages of the deposits constituting the aquifer necessitated a more inclusive designation. The High Plains aquifer consists mainly of one or more hydraulically connected geologic units of late Tertiary or Quaternary age; the Ogallala Formation is generally the principal unit (Gutentag and others, 1984, p. 8). The High Plains aquifer underlies about 174,050 square miles in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (table 1).

The High Plains is a remnant of an alluvial plain that once extended eastward from the ancestral Rocky Mountains. The formation of the plain was followed by periods of uplift when streams eroded the deposits near the mountain front. This erosion isolated the plain from the mountains in all areas except in the area known as the Gangplank in southeastern Wyoming (Thornbury, 1956, p. 288). In some places the original plain was dissected by eroding streams, but in other areas, Quaternary-age sediments were deposited on the plain. In much of the northern High Plains, Quaternary sediments consist of wind-deposited silts, known as loess, and dune sands.

The two oldest geologic units included in the High Plains aquifer are the Brule Formation and Arikaree Group (table 2). The Brule consists mainly of well-cemented siltstone. In most areas, the ability of the Brule to transmit water generally is not sufficient to provide an economic supply of water to wells. In some areas, however, principally in parts of Colorado, Wyoming, and western Nebraska, the rock is fractured, yields adequate quantities of water to wells, and is considered a part of the High Plains aquifer. The Arikaree Group was deposited after the Brule Formation and consists of massive fine-grained sandstone that generally does not yield large quantities of water. The Arikaree, however, is an important local source of water in parts of the northwestern High Plains in Nebraska, South Dakota, and Wyoming.

The Ogallala Formation was deposited after the Arikaree Group by streams flowing from the ancestral Rocky Mountains. The Ogallala is the principal water-yielding unit of the High Plains aquifer over most of the High Plains and is composed of a variety of materials, including clay, silt, sand, and gravel. The Ogallala generally yields large quantities of water to wells.

Sand dunes were formed on the older High Plains deposits in several areas. The most extensive of these areas is in the Sand Hills of north-central Nebraska, where the sand deposits can exceed 300 feet in thickness, and in

Table 1. *Characteristics of the High Plains aquifer*

[Modified from Gutentag and others, 1984]

Characteristic	Units of measure-ment	Total	State							
			Colorado	Kansas	Nebraska	New Mexico	Oklahoma	South Dakota	Texas	Wyoming
Area underlain by aquifer	Square miles	174,050	14,900	30,500	63,650	9,450	7,350	4,750	35,450	8,000
Percentage of total aquifer area	Percent	100	8.6	175	36.6	5.4	4.2	27	204	4.6
Percentage of each State underlain by aquifer	Percent	--	14	38	83	8	11	7	13	8
Volume drain-able water in storage in 1980	Million acre-feet	3,250	120	320	2,130	50	110	60	390	70

Table 2. *Geologic units comprising the High Plains aquifer*

[Sources: Emry and others, 1987; Tedford and others, 1987; Swinehart, 1989]

Geologic unit comprising the aquifer	System (series) and time of deposition, in millions of years before present	Composition	Location where geologic unit is a substantial part of the High Plains aquifer							
			Colorado	Kansas	Nebraska	New Mexico	Oklahoma	South Dakota	Texas	Wyoming
Valley-fill and alluvial deposits	Quaternary (Holocene and Pleistocene), 1.8 to present	Clay, silt, sand, and gravel, unconsolidated.		X	X	X				
Dune sand	Quaternary (Holocene), 0.008 to 0.0015	Sand, very fine- to medium-grained, windblown.		X	X					
Ogallala Formation	Tertiary (Miocene), 19 to 5	Clay, silt, sand, and gravel generally unconsolidated; where cemented by calcium carbonate, mortar beds formed.	X	X	X	X	X	X	X	X
Arikaree Group	Tertiary (Miocene and Oligocene), 29 to 19	Sandstone, very fine to fine-grained, with beds of volcanic ash, silty sand, and sandy clay.			X			X		X
Brule Formation	Tertiary (Oligocene), 31 to 29	Siltstone, massive, with beds of sandstone, volcanic ash, and clay.	X		X					X

Kansas south of the Arkansas River. The dunes subsequently were stabilized by vegetation, but major dune formation continued until about 1,500 years before the present (Swinehart, 1989). Where the dune sand is saturated and hydraulically connected to the other units of the High Plains aquifer, it is considered part of the aquifer and generally yields large quantities of water to wells.

During Quaternary time, streams eroded older formations and redeposited the resulting sediment as valley-fill and alluvial material. Present-day streams continue to erode and deposit sediment. Where the stream deposits are saturated and hydraulically connected to the other units of the High Plains aquifer, they are considered to be part of the High Plains aquifer.

The deposits of Quaternary age are widespread and are locally important sources of water. However, only in Kansas, Nebraska, and New Mexico are the Quaternary deposits an areally substantial part of the High Plains aquifer. The intensive irrigation in the Platte River Valley of Central Nebraska is based largely on ground water exclusively from Quaternary deposits (Peckenpaugh and Dugan, 1983; Peckenpaugh and others, 1987).

FACTORS AFFECTING WATER-LEVEL CHANGE

If the High Plains aquifer were unaffected by human activities, it would be in a state of equilibrium in which natural discharge from the aquifer would be approximately equal to natural recharge to the aquifer. Water levels would be relatively stable under these conditions. However, human activities such as pumpage from wells, surface-water diversions for irrigation and hydroelectric-power generation, and cultivation and grazing practices result in nonequilibrium in the aquifer; discharge does not equal recharge in many areas. This nonequilibrium results in substantial changes in ground-water levels.

Recharge

Precipitation is the only source of ground-water recharge available throughout the High Plains. In some areas, however, natural recharge can result from seepage losses from streams and lakes. This recharge is particularly important along parts of the Platte River system in Colorado, Nebraska, and Wyoming, where substantial seepage losses of streamflow originating outside the High Plains result in recharge to the High Plains aquifer. This recharge process has contributed to a degree of stability of water levels in parts of central Nebraska. Recharge from infiltration of water lost by seepage from surface-water diversions for irrigation and hydroelectric-power generation has caused water levels to rise in a few areas of the High Plains, particularly in south-central Nebraska.

Recharge from precipitation is quite variable in the High Plains, both in time and in space. Factors that affect this variability include the precipitation regime, evapotranspiration, soils, vegetation, land-use practices, and underlying geology. These factors determine how much of the precipitation reaches the aquifer. The relation among these factors also makes the process of recharge from precipitation complex and dynamic. This basic concept of ground-water recharge from precipitation is expressed in an equation (Dugan and Peckenpaugh, 1985) describing the soil-water balance:

$$R = P + S - O - E - C, \qquad (1)$$

where R = recharge, in inches;

P = precipitation, in inches;

S = antecedent soil water (stored), in inches;

O = surface runoff, in inches;

E = actual evapotranspiration, in inches; and

C = water storage capacity of the soil zone, in inches.

The nonuniform distribution of precipitation probably causes most of the variability in recharge to the High Plains aquifer. Average annual precipitation ranges from about 14 inches in the extreme western High Plains to about 30 inches in parts of eastern Nebraska and central Kansas (fig. 2). About 75 percent of the annual precipitation normally occurs during the warm season, April through September. Much of the precipitation during this season comes from local thunderstorms, which can cause variable patterns of precipitation, irrigation requirements, and recharge in a small area during a given time period. Recharge, however, is dependent mostly on cool-season precipitation (October through March) when evapotranspiration is less. Although areal variability in precipitation generally is less localized in the cool season than in the warm season, cool-season precipitation amounts can vary substantially from year to year.

The amount of water in the soil that becomes available for recharge is largely dependent on evapotranspiration. Potential evapotranspiration (fig. 2) is the maximum water loss that would occur by evaporation and transpiration from an area with complete vegetative cover, provided that an adequate supply of soil water is available at all times to meet vegetation demands. Potential evapotranspiration is determined by the amount of atmospheric energy available for the removal of water from the soil either directly as evaporation or as transpiration from vegetation. Potential evapotranspiration is dependent on various climatic and atmospheric elements that include solar radiation, temperature, humidity, and wind velocity. The increase in potential evapotranspiration from northeast to southwest across the High Plains is a consequence of (1) an increase in solar radiation, (2) an increase in temperature, (3) a decrease in humidity, and (4) an increase in wind velocity. Actual evapotranspiration is further dependent on the type of vegetation, length of growing season, and the availability of soil water.

The seasonal relation of precipitation to evapotranspiration strongly affects the recharge process. In the High Plains, recharge occurs mostly during the nongrowing season when evapotranspiration is minimal and soil water can accumulate in the root zone and percolate downward. This accumulative process may extend over a period of time during the nongrowing season, when late-autumn precipitation remains in the soil column throughout the winter and percolates downward out of the root zone only after spring precipitation and winter snowmelt cause the soil's available water capacity to be exceeded. Thus, antecedent soil-water conditions, winter snow, early-spring precipitation prior to the onset of the growing season, and evapotranspiration are critical to recharge during the nongrowing season.

The hydrologic characteristics of the soils can have a significant effect on recharge and resultant water-level change. Sandy soils permit a greater recharge than finer textured soils. Under equivalent vegetative and climatic conditions, recharge rates can be several times faster for sandy soils than for silty clay-loam soils as a result of the sandy soil's smaller available water capacity and greater permeability. Slope also affects the rate at which precipitation infiltrates the soil and becomes soil water. Steeply sloping soils with silty-clay loam texture, common in parts of the High Plains, are characterized by large overland runoff and small infiltration during moderate- to high-intensity rainfall. A more complete discussion and generalized map of the hydrologic characteristics of soils and their relative effects on recharge in the High Plains are found in Dugan, Hobbs, and Ihm (1990).

Recharge also is affected by vegetation type. Each vegetation type has a unique consumptive water requirement (the amount of soil water that vegetation would use, if available), which ultimately affects the soil water available for recharge and irrigation needs. Therefore, variability of vegetation types across the High Plains affects patterns of water-level change.

Various government programs to remove cropland from production, including the U.S. Department of Agriculture's Conservation Reserve Program, which was implemented in 1986 as part of the Food Security Act, have resulted in changes in vegetation patterns in the High Plains. Under the Conservation Reserve Program, cropland is returned to grassland or forest land for a minimum of 10 years. Although the conversion of cropland to grassland in the High Plains could result in a decrease in recharge because of the larger water requirement for grasses than crops (Luckey and others, 1981), the resulting effects on water levels likely will be more than offset by the opposing effects of decreases in ground-water withdrawals for irrigation as a result of these conversions from irrigated agriculture to nonirrigated uses.

Certain cropping practices in the High Plains can have a substantial effect on recharge. The rotation of cropland between winter wheat and fallow in the western High Plains can result in more than 25 percent of the land being fallow in any given year in some areas. Fallow conditions can increase recharge by decreasing transpiration of soil water by crops.

In eastern and central Nebraska, southwestern Kansas, and much of the Texas Panhandle, most land is cultivated. The consumptive water requirement of most cultivated crops is less than native grasses, which causes a substantial increase in recharge.

Certain tillage practices, including minimum tillage, enhance recharge by limiting water losses to runoff and evaporation. Land leveling for flood irrigation and terracing also limit runoff and increase infiltration.

Estimated potential recharge to the High Plains aquifer during 1951-80 (fig. 3) was calculated with a computer program that calculates the surplus soil water available for recharge from the given climatic, soil, and vegetation factors discussed above. The program is based on the soil-water balance described by equation 1. The values for recharge shown in figure 3 represent only the amount of soil water available for recharge and not necessarily the amount reaching the aquifer. The time required for soil water to actually reach the aquifer and become recharge depends on depth to the water table and the characteristics of the geologic materials in the unsaturated zone between the soil zone and the water table. Thus, the soil water available for recharge at any given time can arrive at the water table in a few hours or only after many months.

The relation between precipitation (fig. 2) and estimated potential recharge (fig. 3) is apparent. Estimated average annual recharge amounts range from about 25 percent of the average annual precipitation in eastern Nebraska to less than 0.5 percent in the western parts of the High Plains. Generally, where average annual precipitation exceeds 24 inches in the High Plains, average annual recharge exceeds 4 inches. Potential recharge exceeds 6 inches in parts of eastern Nebraska and central Kansas, where the soils are sandy and precipitation exceeds 25 inches. In parts of the far western High Plains, however, where precipitation is less than 16 inches, evapotranspiration generally exceeds 60 inches, and soils are fine textured, estimated average annual recharge is less than 0.25 inch. Estimates of annual recharge of 6 inches and 0.25 inch in these areas, respectively, by Weeks and others (1988) compare well with those of J.T. Dugan and R.B. Zelt (U.S. Geological Survey, written commun., 1993).

Although the effect of precipitation on estimated potential recharge is evident, other factors also are important in defining local recharge patterns. Estimated recharge that is relatively large for the climatic conditions in parts of north-central and southwestern Nebraska, northeastern Colorado, south-central Kansas, and western Texas is largely attributable to sandy soils (Dugan, Hobbs, and Ihm, 1990; J.T. Dugan and R.B. Zelt, U.S. Geological Survey, written commun., 1993).

Effects of cropping practices also are evident in the patterns of estimated potential recharge in the High Plains. Rates of recharge are increased in the southern Nebraska Panhandle, most of the Kansas High Plains, northeastern Colorado, and parts of the Oklahoma and Texas Panhandles as a result of large areas of fallow land associated with winter wheat. Estimated recharge also is increased substantially in eastern and southern Nebraska, central and southwestern Kansas, and much of the Texas Panhandle where intensive cultivation has replaced native grasslands (J.T. Dugan and R.B. Zelt, U.S. Geological Survey, written commun., 1993).

Recharge throughout the High Plains may vary considerably from one year to the next, principally because of variations in precipitation. In many years recharge may not occur in areas where annual precipitation generally is small. Most of the long-term average recharge can result from a few short, wet periods. The recharge process commonly is cyclical in the High Plains--two or more consecutive years in which conditions are favorable for recharge, followed by several years when these conditions are not present and recharge is negligible.

Discharge

Ground water is discharged from the High Plains aquifer both naturally and artificially. Natural discharge from the aquifer occurs as evapotranspiration from plants and soil where the water table is near land surface and as seepage from the aquifer through springs and to streams where the water table intersects the land surface. Long-term natural discharge would tend to balance long-term natural recharge. Artificial discharge from the aquifer generally occurs as pumpage from wells. Artificial discharge can cause an imbalance in the recharge-discharge relation in the aquifer; when discharge exceeds recharge, some ground water is removed from storage. Part of the imbalance can be offset by a decrease in natural discharge or an increase in induced recharge from streams caused by the lowering of the water table.

Comprehensive data for ground-water withdrawals from the High Plains aquifer are collected and published at 5-year intervals by the U.S. Geological Survey in cooperation with State and local agencies. Some of these data are derived from records of metered wells; however, most water withdrawn from the High Plains aquifer is from wells that are not metered, particularly those used for withdrawal of water for irrigation, rural domestic consumption, and livestock. Estimated irrigation pumpage is extrapolated from (1) available metered pumpage, and (2) computations of pumpage based on consumptive irrigation requirements, acreages of irrigated crops, and irrigation efficiency data. Rural domestic water use and livestock consumption are extrapolated from average consumption per capita and per head of livestock for a known population and number of livestock, respectively.

Withdrawals from the High Plains aquifer declined between both 1980 and 1985 and 1985 and 1990. The estimated total volume of water withdrawn from the High Plains aquifer was 20,519,000 acre-feet in 1980 (Wayne Solley, U.S. Geological Survey, oral commun., 1988), 17,071,500 acre-feet in 1985, and 16,534,800 acre-feet in 1990 (table 3). Thus, withdrawals decreased about 17 percent between 1980 and 1985 and about 3 percent between 1985 and 1990. The 3-percent decrease in total withdrawals between 1985 and 1990 was largely due to a nearly 4-percent decrease in water withdrawals for irrigation and livestock use between 1985 and 1990. If livestock water use remained relatively constant between 1985 and 1990, the decrease in agricultural water use was almost entirely attributable to decreases in irrigation. Nonagricultural water uses increased about 15 percent between 1985 and 1990 (table 3). Further comparison of changes in nonagricultural water uses between 1985 and 1990 is not possible because of differences in water-use classification.

These ground-water withdrawal statistics apply only to individual years, which may not necessarily be representative of long-term water use. Withdrawals, particularly for irrigation, are affected by climatic conditions, particularly precipitation, which can cause large variations in water requirements. None of the years--1980, 1985, and 1990--appear to represent unusual precipitation conditions in the High Plains. Some of the decreases in withdrawals between 1980 and 1985, however, are attributable to precipitation increases and, consequently, relatively smaller irrigation requirements in parts of the High Plains in 1985, particularly in Nebraska (Steele, 1988). The apparent 10-year decline in total ground-water withdrawals from the High Plains aquifer largely is a result of reduction in withdrawals for irrigation. This reduction is a result of several factors, including:

(1) Climatic conditions since 1980 have been conducive to decreased water demands. Prolonged drought conditions generally were absent from 1980 to 1990 in most of the major irrigated areas of the High Plains. Precipitation was above normal in nearly all parts of the High Plains in 1981-90, averaging nearly 2 inches above normal for the area.

(2) There has been a long-term decrease in the amount of irrigated cropland in parts of the High Plains. In Texas, the irrigated land in the High Plains decreased by 1.39 million acres between 1979 and 1991 (Dugan and Schild, 1992, p. 44). Throughout the remainder of the High Plains States, irrigated acres either have

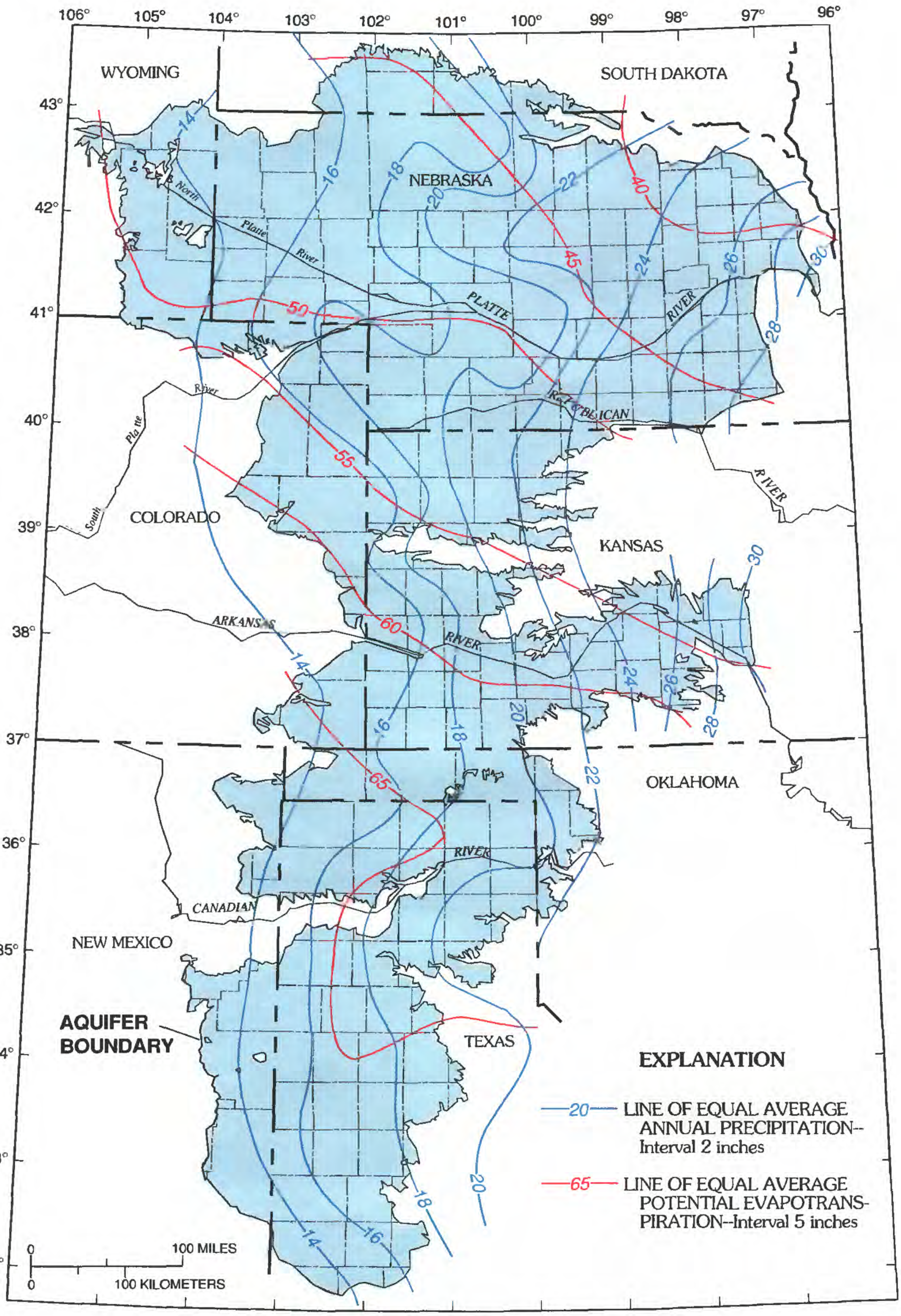

Figure 2. Average annual precipitation and potential evapotranspiration, 1951-80 (J.T. Dugan and R.B. Zelt, U.S. Geological Survey, written commun., 1993).

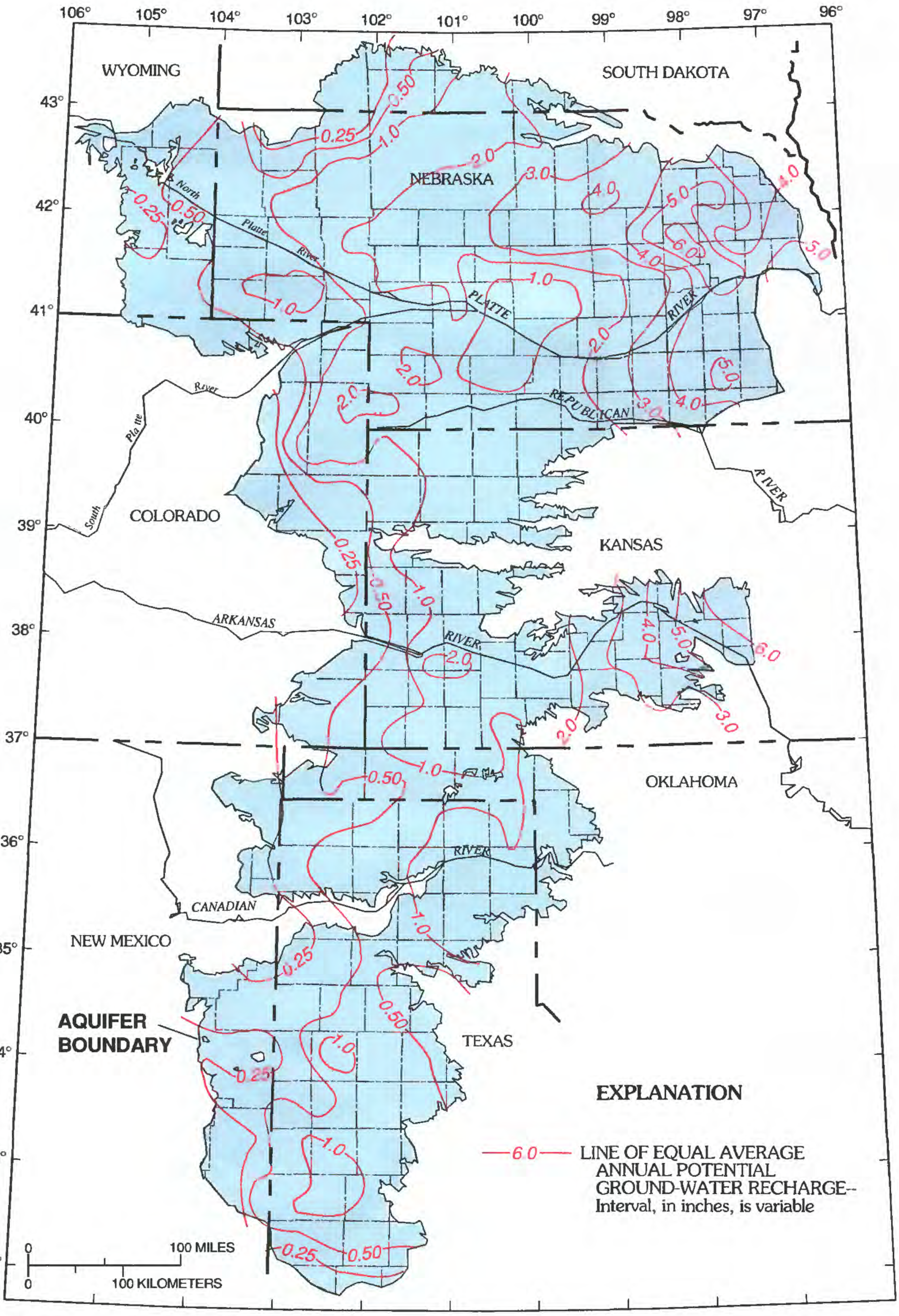

Figure 3. Estimated average annual potential ground-water recharge, 1951-80 (modified from J.T. Dugan and R.B. Zelt, U.S. Geological Survey, written commun., 1993).

Table 3. *Ground-water withdrawals from the High Plains aquifer in 1990 and 1985 by use*

[Compiled from U.S. Geological Survey National Water-Data Storage and Retrieval System. Withdrawals in thousands of acre-feet]

State	Year	Nonagricultural use: Domestic (public and private water supplies)	Nonagricultural use: Mining, industrial, commercial, and thermo-electric-power generation	Agricultural use: Livestock	Agricultural use: Irrigation	Total
Colorado	1990	11.6	5.5	8.6	989.5	1,015.2
	1985	------------6.2-----------		---------877.1---------		883.3
Kansas	1990	54.4	19.4	51.6	3,936.6	4,062.0
	1985	-----------92.7-----------		---------4,324.0---------		4,416.7
Nebraska	1990	167.7	19.7	101.4	4,736.4	5,025.2
	1985	----------197.1-----------		---------5,598.5---------		5,795.6
New Mexico	1990	29.0	22.5	4.2	738.4	794.1
	1985	-----------50.0-----------		---------603.0---------		653.0
Oklahoma	1990	17.3	0.9	13.0	375.3	406.5
	1985	------------8.0-----------		---------270.0---------		278.0
South Dakota	1990	2.9	0	1.2	18.3	22.4
	1985	-------------------3.0----------------		---------21.7---------		24.7
Texas	1990	106.5	194.0	47.9	4,702.4	5,050.8
	1985	-----------188.8---------		---------4,531.7---------		4,720.5
Wyoming	1990	11.8	0.5	1.3	145.0	158.6
	1985	-----------33.0---------		---------266.7---------		299.7
Total	1990	401.2	262.5	229.2	15,641.9	16,534.8
	1985	------------578.8----------		---------16,492.7--------		17,071.5

stabilized or have decreased since the late 1970's or early 1980's (Kastner and others, 1989; Dugan and Schild, 1992). Stable or declining agricultural commodity prices and increased irrigation and other production costs since the late 1970's have made irrigation of crops only marginally profitable. Increased lift costs in areas of declining water tables and increased energy prices have reduced the profit margin on irrigated land. In some areas, the number of irrigated acres has declined because reduced saturated thickness of the aquifer has reduced well yields.

(3) Improved agricultural management practices have reduced the volume of water needed to fulfill irrigation requirements. These practices include widespread use of minimum-tillage methods, more precise irrigation scheduling and application rates through monitoring of soil-water conditions, technological and operational improvements in irrigation delivery systems, and improved plant varieties that utilize available soil water more efficiently.

Kansas, Nebraska, and Texas, which have nearly 75 percent of the land area of the High Plains aquifer (table 1), accounted for about 85 percent of both the total withdrawals and withdrawals for irrigation from the High Plains aquifer in 1990 (table 3). Three large areas of large withdrawal rates occur in the High Plains: (1) eastern and south-central Nebraska; (2) southwestern and south-central Kansas; and (3) the northern part of the Southern High Plains in Texas and New Mexico (fig. 4). Areas with slightly smaller withdrawal rates include an area encompassing northeastern Colorado, southwestern Nebraska, and northwestern Kansas, and the northwestern Panhandle of Texas. In all of these areas, the saturated thickness of the aquifer, well yields, soils, and topography are conducive for irrigated agriculture.

The rates of withdrawals shown in figure 4 indicate the intensity of irrigation development in a county and withdrawal rates per irrigated acre. The withdrawal rates per irrigated acre in southwestern Kansas and parts of the Texas Panhandle tend to be larger than in eastern and south-central Nebraska where the percentage of irrigated land in the county is as large. Ground-water withdrawals from the High Plains aquifer in 1990 ranged from less than 0.02 acre-foot per acre (0.25 inch) to more than 1 acre-foot per acre (12 inches) in Haskell County in southwestern Kansas (figs. 1 and 4).

Ground-water withdrawals for irrigated crops do not represent the actual consumption or water permanently removed from the aquifer. Only that water consumed by evapotranspiration or that which runs off into drainage ways is actually lost. Because runoff generally is minimal for most irrigation systems currently in use and because the volume of water applied to crops often exceeds evapotranspiration, a substantial volume of the applied water may infiltrate through the soil and unsaturated zones and return to the aquifer as recharge. Thus, ground-water withdrawals alone do not fully explain water-level changes.

Consumptive Irrigation Requirements in the High Plains

The consumptive irrigation requirement provides an estimate of the volume of water consumed by irrigated crops through evapotranspiration and therefore actually lost from the aquifer. It is an estimate of the minimum irrigation required to maintain adequate soil water for optimal plant growth. This requirement, which is unique for each crop, is largely dependent on: (1) potential evapotranspiration, (2) the growth characteristics of the crop, (3) soil water available at the beginning of the irrigation season, and (4) irrigation-season precipitation. The hydrologic characteristics of the soil have only a limited effect on the consumptive water requirement of a specific crop (J.T. Dugan and R.B. Zelt, U.S. Geological Survey, written commun., 1993).

The consumptive irrigation requirement does not represent a minimum pumpage requirement, which assumes some inefficiencies in irrigation-distribution systems. The consumptive irrigation requirement as an estimate of water lost from the aquifer is based on the assumption that irrigation efficiency is 100 percent and that any excess water applied either infiltrates back to the aquifer or becomes runoff (usually negligible).

Average annual consumptive water requirements during 1951-80 for the principal irrigated crop in the High Plains, corn, ranged

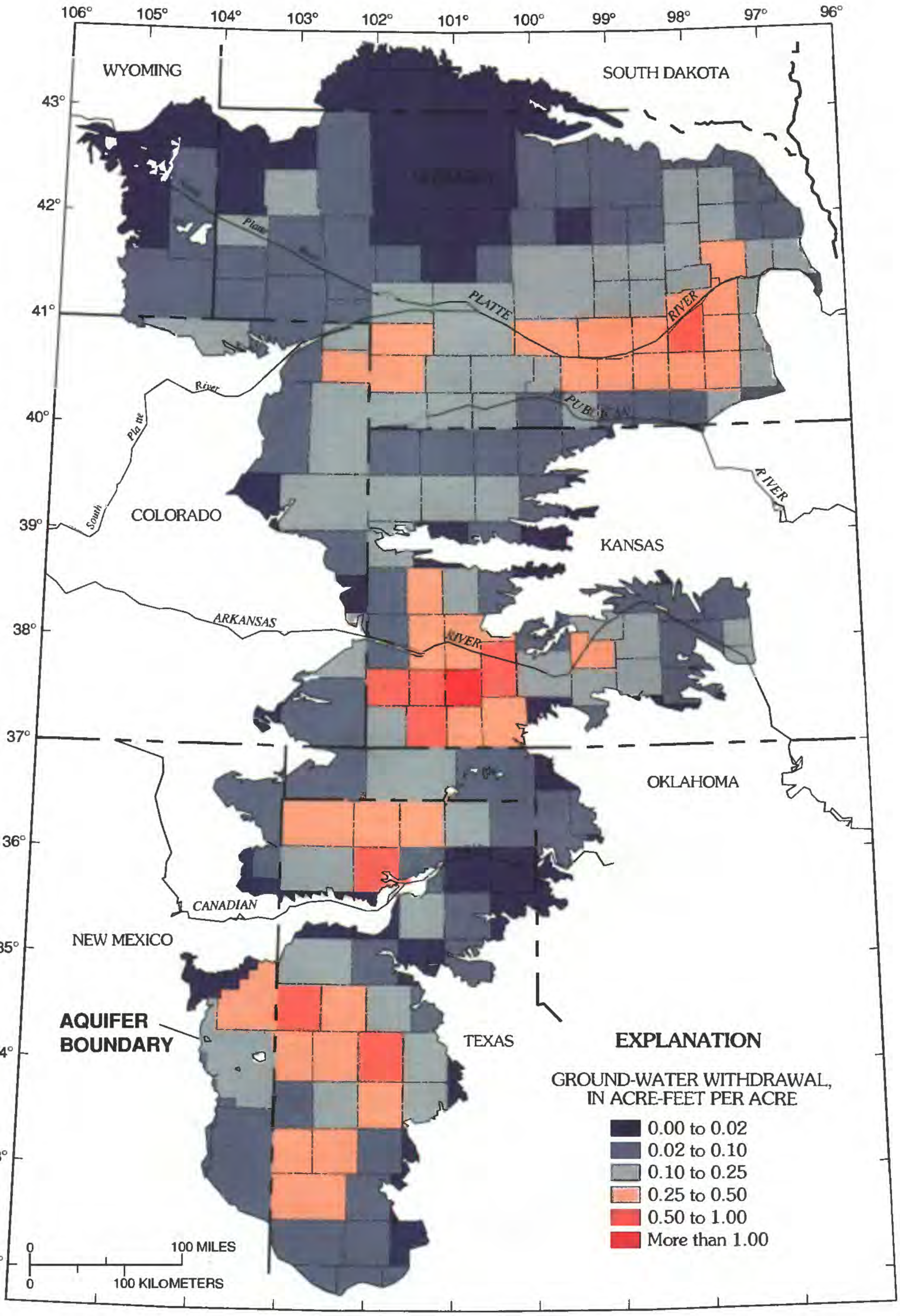

Figure 4. Ground-water withdrawal rates by county during 1990 (data from U.S. Geological Survey National Water-Data Storage and Retrieval System).

from about 8 inches in northeastern Nebraska to about 22 inches in northeastern New Mexico (fig. 5). The combination of large potential evapotranspiration and less precipitation caused the largest consumptive water requirements to occur in the western parts of the Central High Plains. Average annual consumptive irrigation requirements in areas of substantial irrigation ranged from 9 to 15 inches in Nebraska, 16 to 20 inches in southwestern Kansas, and 14 to 19 inches in the Texas Panhandle.

Net Water Withdrawals from the High Plains Aquifer

Water-level declines in areas of the High Plains irrigated with ground water should reflect the net withdrawals of water from the aquifer. Actual net ground-water withdrawals, however, cannot be readily estimated because of insufficient data for irrigation pumpage, seepage of excess irrigation water back to the aquifer, and natural recharge. An estimate of net withdrawal rates (fig. 6) was derived by subtracting estimated recharge (fig. 3) from the consumptive irrigation requirements (fig. 5). Figure 6, therefore, does not actually represent net regional ground-water withdrawal rates, but the estimated net withdrawal rates for irrigated corn. It provides a uniform method for comparing regional differences in net demand on available ground-water resources.

Estimated average annual net withdrawal rates during 1951-80 ranged from about 2 inches (acre inches per acre) in parts of northeastern Nebraska to 20 inches in an area that includes parts of the Oklahoma and Texas Panhandles. In the areas of substantial ground-water withdrawals (fig. 4), net withdrawals for corn ranged from 6 to 12 inches in central Nebraska, 16 to 18 inches in southwestern Kansas, and from 14 to 20 inches in the extensively irrigated parts of the Texas Panhandle.

GROUND-WATER DEVELOPMENT AND WATER-LEVEL CHANGES, PREDEVELOPMENT TO 1980

The availability and development of water resources has had a major role in the development of the High Plains as an agricultural region. The perceived limitations of the natural environment of the High Plains, particularly the climate, made the availability of water even more important. Water, however, was not the only limiting factor in the development of the High Plains.

Permanent settlement of the High Plains did not begin until late in the 19th century. Most early assessments considered the region unsuited for permanent agriculture and only marginally suited for a grazing economy. Journals from a U.S. Army expedition led by Major Stephen Long that crossed the High Plains in 1819-20 described the region as an "...extensive section of the country...almost wholly unfit for cultivation, and of course uninhabitable by a people depending upon agriculture for their subsistence..." (Dick, 1975, p. 2). These and other negative perceptions of the plains lingered until after the Civil War and inhibited widespread interest in settling the region.

Many of the long-standing perceptions of the High Plains were based on substantiated observations. Frequent drought, insect infestations, prairie fires, sparsity of surface water, and scarcity of wood for building and fuel certainly were apparent in the High Plains. In addition, the large farming operations required for the given climatic limitations of the region had to await certain technological innovations in the middle of the 19th century, which included the steel plow to break the tough grassland sod and the mechanical reaper to harvest large acreages. Perhaps even more significant for commercial agriculture to succeed in the High Plains was a transportation system permitting access to markets, which had to await the coming of the railroad following the Civil War.

The settlement process in the High Plains proceeded rapidly as the various obstacles to development were overcome. Settlement was encouraged through such incentives as the various government land programs, including the Homestead Act of 1862 and the Railroad Land Grants following the Civil War. Also, the railroads used extensive advertising that extolled the virtues and attempted to dispel the negative perceptions of the High Plains to recruit a large number of immigrants from

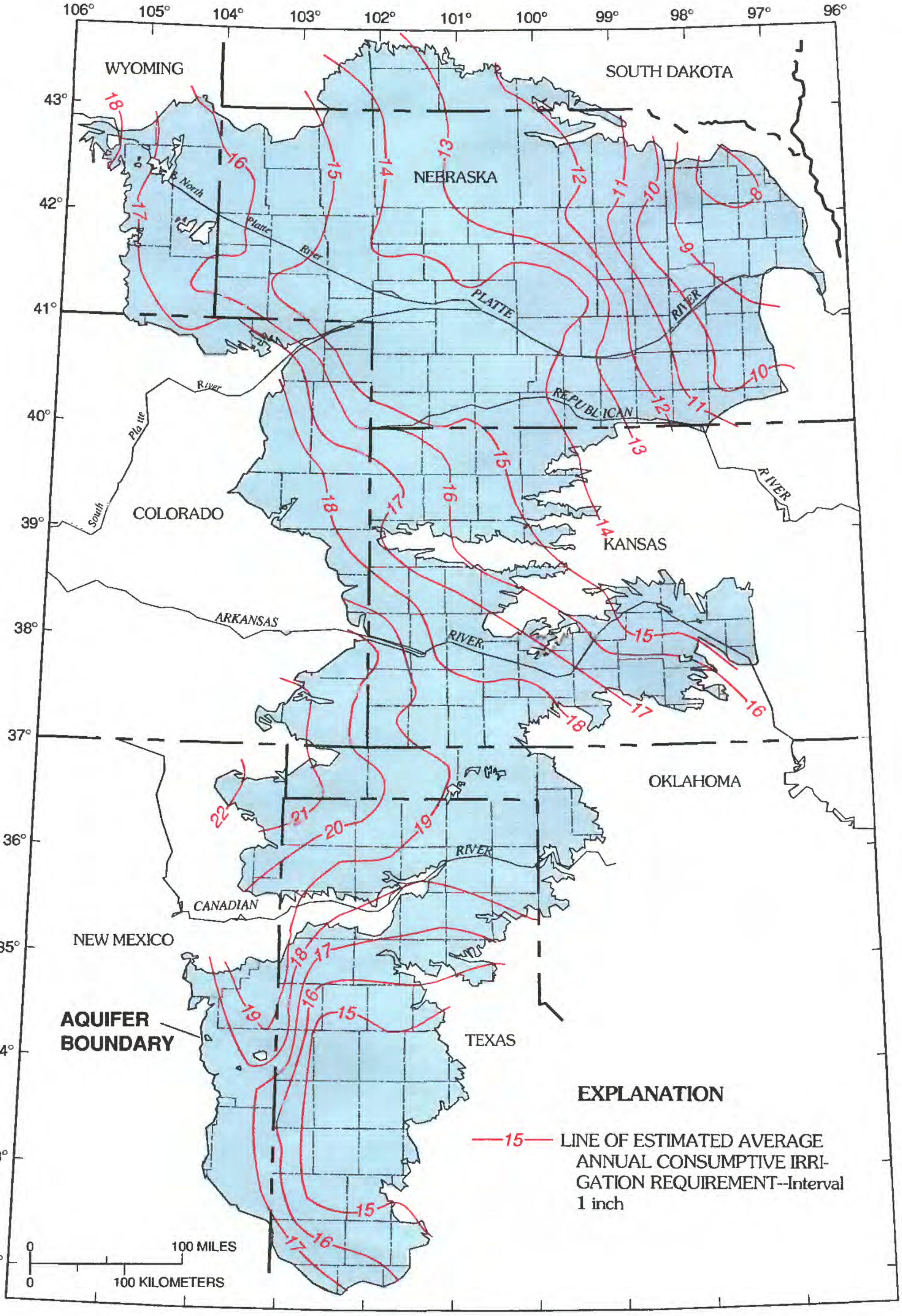

Figure 5. Estimated average annual consumptive irrigation requirement for corn, 1951-80 (modified from J.T. Dugan and R.B. Zelt, U.S. Geological Survey, written commun., 1993).

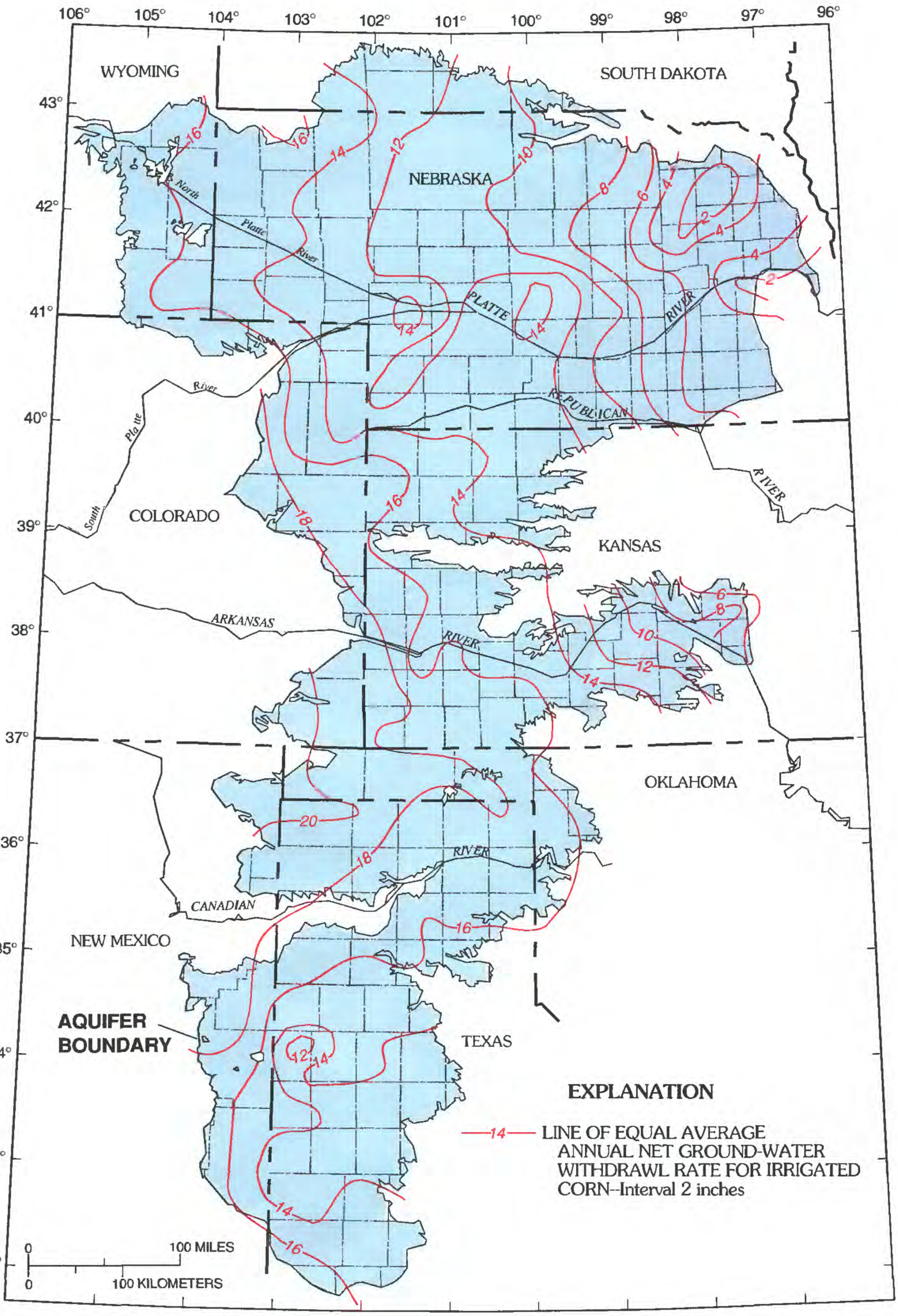

Figure 6. Estimated average annual net ground-water withdrawal rate for irrigated corn, 1951-80 (modified from J.T. Dugan and R.B. Zelt, U.S. Geological Survey, written commun., 1993).

Europe in order to dispose of the railroads' vast land holdings and create a market for their rail services.

Inadequate precipitation for many crops and frequent droughts soon made it apparent that nonirrigated agriculture would be difficult in the High Plains. Soon after the initial settlement phase, irrigation development began along some streams, such as the Platte and Arkansas Rivers, which permitted more intensive forms of agriculture and reliable crop production. However, surface-water irrigation was limited largely to major stream valleys. Widespread irrigation of the High Plains awaited the development of ground water.

Dryland farming techniques and crop experimentation met with only limited success in the late 19th and early 20th centuries; however, there was a spirit of optimism that a permanent improvement in climate would occur. The persistent drought of the 1930's brought true arid conditions, permanently altered perceptions about the plains, and provided the first major impetus for widespread irrigation development. The series of near-total crop failures coupled with the low commodity prices during the Great Depression indicated a need to minimize the agricultural risk factors in the High Plains. Irrigation was perceived as the solution to the large fluctuations in agricultural production and frequent catastrophic crop failures. Thus, the agricultural economy of the High Plains could be stabilized through irrigation.

After World War II, various factors served as further stimulants to irrigation development throughout the High Plains. High commodity prices and decreasing costs for irrigation associated with technological advances made irrigation economically feasible. Prolonged widespread drought and resultant crop failures during the 1950's reinforced the concept that irrigation was needed to minimize agricultural risk.

Significant development of ground water for irrigation in the High Plains depended upon such technological developments as the gasoline engine early in the 20th century. Early irrigation wells were shallow, commonly hand dug, and confined to shallow water-table areas in large stream valleys. Irrigation in the uplands, where the water table generally was at considerable depth depended on later development of efficient, low-cost drilling and pumping techniques, such as rotary drills and turbine pumps. Cost-efficient pumping from depths greater than 100 feet was not available until the early 1960's with the advent of more efficient powerplants to run turbine pumps (Weeks and others, 1988, p. A10).

An even more significant technological advancement introduced in the 1960's was the center-pivot irrigation system, a self-propelled sprinkler irrigation system that made it possible to irrigate areas where topography or soils were unsuited for gravity or flood irrigation methods. Millions of acres of sandy soils and rolling topography formerly unsuitable for irrigation became potentially irrigable.

Energy resources were perhaps as important as technology for the development of ground-water irrigation in the High Plains. The long period of ground-water irrigation expansion from World War II into the 1970's was attributable in large part to inexpensive energy. Rural electrification and development of natural gas fields and pipelines in the High Plains during the 1940's and 1950's provided low-cost energy for pumping. Where these energy sources were not available, low-cost diesel fuel was the principal alternative energy source. However, since the increase in petroleum costs starting in the 1970's, increasing energy prices have been a deterrent to additional expansion.

The process of irrigation development and associated water-level changes in the uplands of the High Plains generally proceeded from south-to-north. Numerous factors, including ease of developing water resources, availability of readily irrigable land, pre-existing cropping systems, and perceived economic benefits affected the patterns of irrigation development.

Documented water-level changes generally began to occur soon after irrigation began in the various parts of the High Plains. Water-level declines were apparent in the Southern High Plains by 1940, the Central High Plains by 1950, and the Northern High Plains by 1960. There were notable exceptions to this pattern of development, such as in Box Butte County, Nebraska, where ground-water development followed by water-level declines began in the early 1950's. Also, water-level rises began in the uplands of south-central and southwestern Nebraska in the early 1940's as a result of seepage from surface-water diversions from the Platte River system for irrigation and power generation. Some areas of the High Plains, including north-central Nebraska, South Dakota, and parts of Colorado and Wyoming are not suitable for extensive irrigation development principally because of soil, topographic, or hydrologic limitations; therefore, water levels have remained relatively stable in these areas.

The water-level changes from initial development or predevelopment to 1980 are shown in figure 7. Predevelopment water levels, as used here, are the estimated water levels that existed prior to any effects imposed by human activity. A predevelopment water level generally represents seasonally high water-table conditions, usually occurring in early spring.

By 1980, the largest decline in water levels had occurred in the Southern High Plains of Texas and New Mexico (fig. 7). Water levels declined more than 50 feet in a large part of this area with a maximum decline of nearly 200 feet occurring in Texas. Declines exceeding 50 feet occurred in several smaller areas of the Central High Plains of southwestern Kansas, the north-central Panhandle of Texas, and the central Panhandle of Oklahoma. Maximum declines in the Central High Plains exceeded 100 feet in two small areas of southwestern Kansas. Only small areas of 10- to 50-foot declines occurred in the Northern High Plains by 1980. In addition to the area of water-level rise associated with surface-water diversions in south-central and southwestern Nebraska, smaller areas of rise occurred in central Nebraska, along the Kansas-Oklahoma border, and the extreme Southern High Plains of Texas. The rise in central Nebraska also is associated with surface-water diversions (Luckey and others, 1981).

The regional differences in magnitude and areal extent of water-level declines from predevelopment to 1980 (fig. 7) are partly time dependent. The absence of areas of decline exceeding 50 feet in the Northern High Plains is partially attributable to the later development of irrigation in that area.

The 1980 saturated thickness of the High Plains aquifer ranged from less than 100 feet in much of the High Plains to more than 1,000 feet in parts of north-central Nebraska and Wyoming (fig. 8). The saturated thickness averaged about 340 feet in Nebraska, but the saturated thickness of the aquifer averaged only about 110 feet in the remainder of the study area. The saturated thickness was less than 100 feet in 46 percent of the High Plains area and exceeded 600 feet in only 5 percent of the area (Gutentag and others, 1984, p. 23-24). Saturated thickness in the major irrigated areas of Kansas, Nebraska, and the Northern Panhandle of Texas generally was 200 to 400 feet and was from 100 to 200 feet in the Southern High Plains of Texas. By 1980 saturated thickness had decreased substantially in parts of Kansas and Texas since predevelopment as a result of declining water levels prior to 1980 (fig. 8).

Large but discontinuous parts of the High Plains aquifer in the Central High Plains had little or no saturated thickness in 1980 (fig. 8). The largest of these areas was in west-central Kansas, but substantial areas of little or no saturated thickness also were in southeastern Colorado and northeastern New Mexico. In the Southern High Plains, a large part of the aquifer in east-central New Mexico had little or no saturated thickness. In the Northern High Plains only a small area in northwest Kansas had little or no saturated thickness.

Areas that had little or no saturated thickness in 1980 generally are along the boundaries of the High Plains or where deposits of late Tertiary and Quaternary age have been largely removed by erosion. The extent of the areas of little or no saturated thickness in 1980 probably is comparable to predevelopment conditions since these areas could not have sustained any substantial ground-water development. Adequate supplies of ground water even for livestock and rural domestic purposes generally are not available in these areas. Observation wells, if present in these areas, probably do not represent water-level conditions in the High Plains aquifer. Subsequent discussions of water-level changes

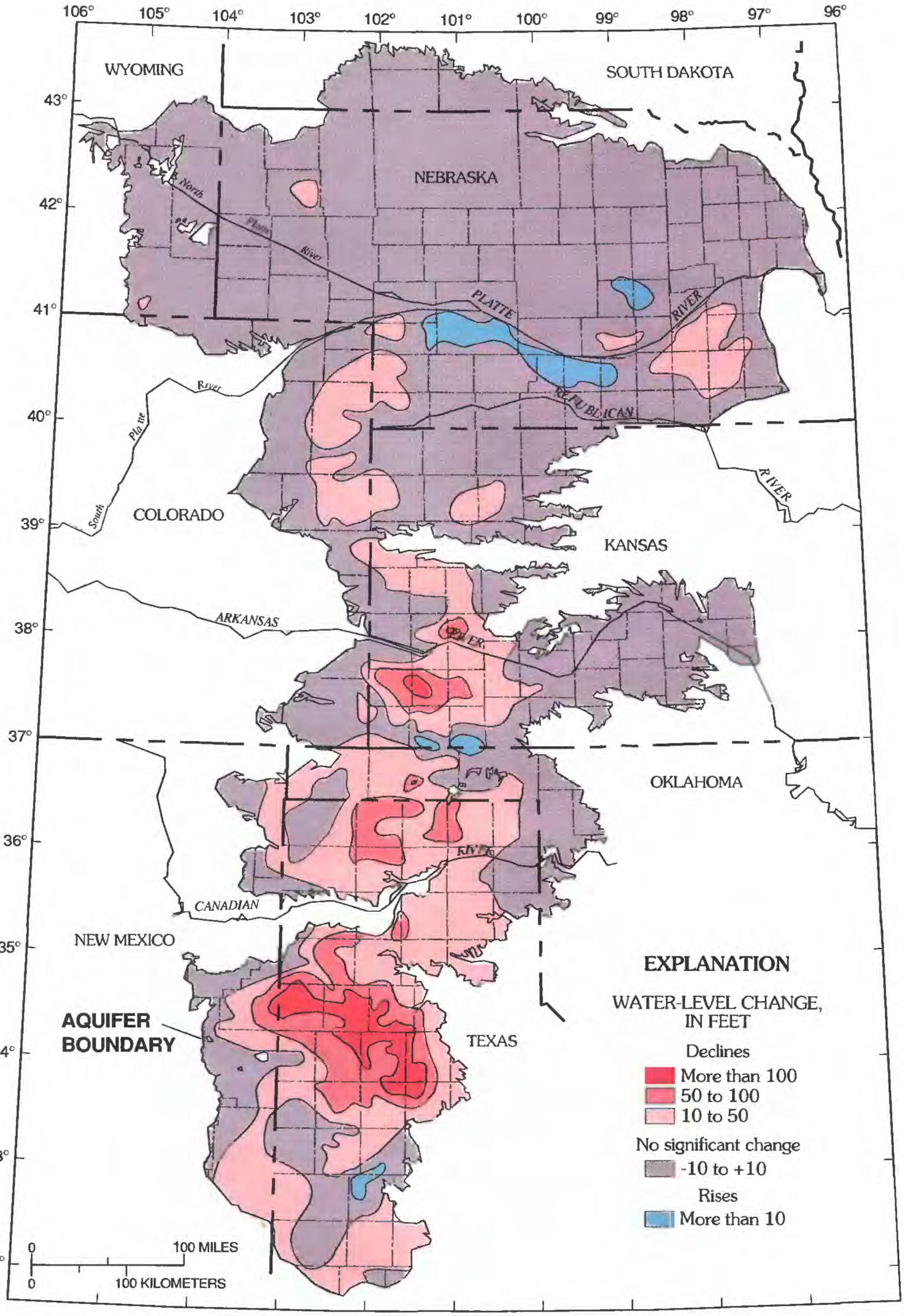

Figure 7. Water-level change in the High Plains aquifer, predevelopment to 1980 (modified from Luckey and others, 1981).

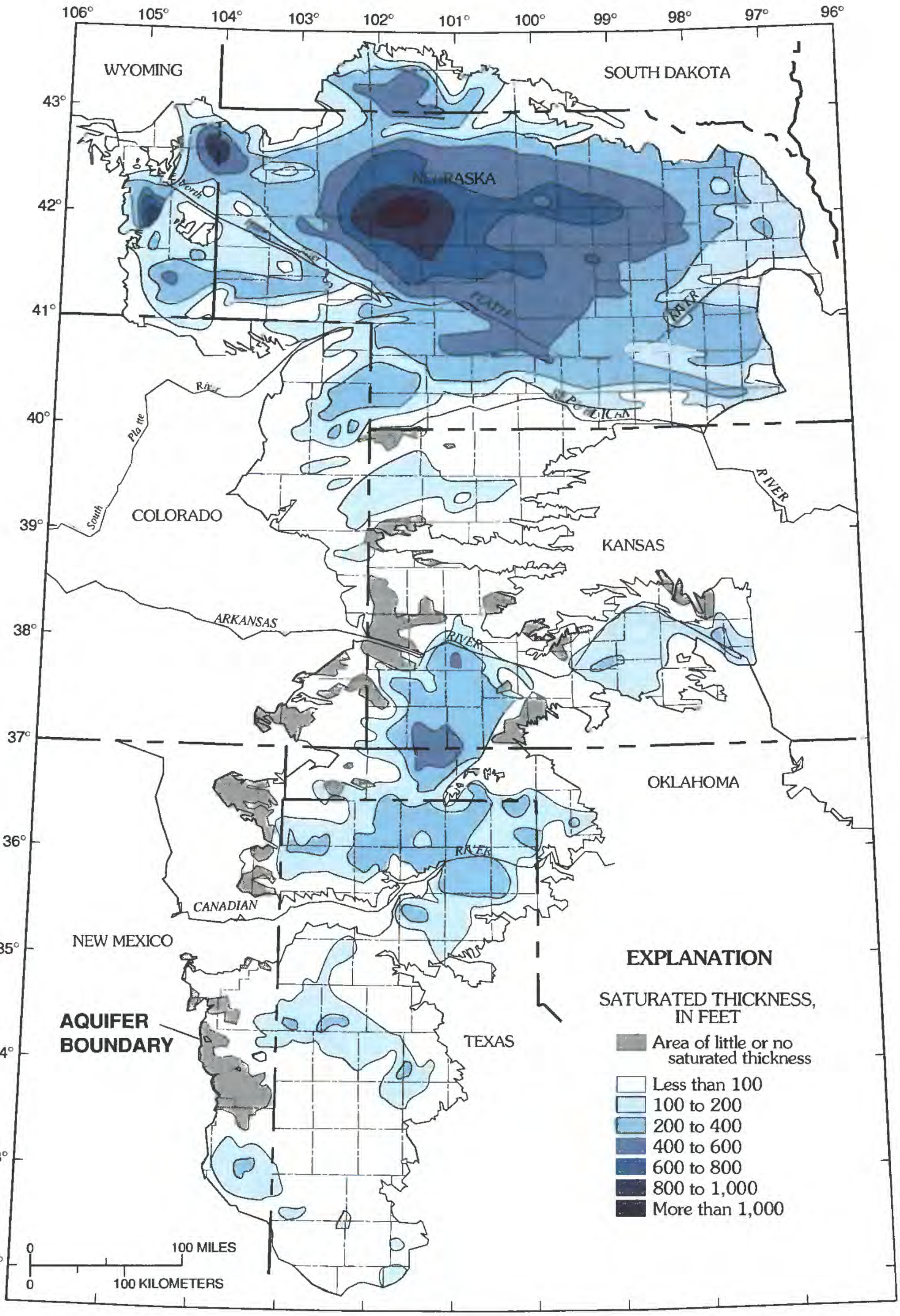

Figure 8. Saturated thickness of the High Plains aquifer, 1980 (modified from Weeks and Gutentag, 1981, and Gutentag and others, 1984).

in the High Plains aquifer do not consider these areas that had little or no saturated thickness in 1980.

An approximate estimate of the volume of ground water in storage in the High Plains aquifer can be calculated from average saturated thickness and aquifer specific yield. The area-weighted average saturated thickness of the High Plains aquifer was about 200 feet in 1980 (Gutentag and others, 1984). The specific yield (the volume of water that will drain by gravity from aquifer pore spaces) averages about 15 percent (0.15) of the total volume of saturated material (Gutentag and others, 1984). Therefore, the estimated total volume of water that could drain from the aquifer in 1980 was about 3,250 million acre-feet (table 1) (Gutentag and others, 1984). Pumping costs in relation to well yields, however, would limit the availability of much of this water.

GROUND-WATER-LEVEL OBSERVATION-WELL NETWORK

Monitoring of water-level changes in the High Plains aquifer is accomplished using an extensive observation-well network. Water-level changes between 1980 and 1991 were based on measurement of water levels in nearly 7,000 wells. Observation wells added since 1980 increased the number of observations used to compute changes between 1990 and 1991 to nearly 8,700 (table 4). Although the difference in number of observations between 1980 to 1991 and 1990 to 1991 limits exact comparisons of water-level changes between the two time periods, these differences are not large enough to prevent reasonable comparisons because the vast majority of 1980, 1990, and 1991 water-level measurements were made in the same wells. The additional observation wells used in 1990 and 1991 tend to be located in areas of relatively recent irrigation development.

The observation-well network for water-level change between 1980 and 1991 and between 1990 and 1991 has expanded since the initial report in this series (Kastner and others, 1989). In that report, the network for the 1980-to-1988 changes consisted of 4,719 wells and for the 1987-to-1988 changes consisted of 6,203 wells. Most of the network expansion

Table 4. *Number of observation wells measured in 1980 and 1991 and in 1990 and 1991*

State	Number of observation wells measured	
	1980 and 1991	1990 and 1991
Colorado	572	619
Kansas	1,186	1,690
Nebraska	2,332	3,305
New Mexico	244	245
Oklahoma	233	253
South Dakota	60	77
Texas	2,339	2,459
Wyoming	18	39
Total	6,984	8,687

resulted from acquisition of additional observation-well data from local sources in Texas. Some observation wells, however, have been removed from the network through time because of cutbacks in local monitoring programs and abandonment of nonfunctional wells. Differences in the data base from year to year, however, probably do not affect results significantly.

The density and location of observation wells (fig. 9) are governed principally by the intensity of ground-water irrigation development. Areas with a greater density of observation wells tend to be areas with larger percentages of irrigated land area. In contrast, those areas with less density tend to be areas with limited or no irrigation development. The small density of observation wells in these areas reflects a limited, real or perceived, need for detailed water-level-change information and the unavailability of measurable wells, such as in those areas where the aquifer has little or no saturated thickness.

Most of the observation wells in the network are privately owned irrigation wells with access ports and sufficient diameters to permit ready access with a measuring device. Irrigation wells are especially well suited for monitoring water-table changes because their large diameter and large pumping capacity make them less prone to plugging, which is common in small-diameter, small-capacity wells. A small percentage of the observation wells are specifically designed for water-level monitoring, and some are equipped with recording devices for continuous monitoring of water levels. Few wells designed for municipal, domestic, or livestock uses are suitable for water-level monitoring.

The measurement of water levels is conducted by personnel of numerous Federal, State, and local agencies in the High Plains. Local water and natural resource conservation districts are responsible for the largest number of these water-level measurements. The U.S. Geological Survey is responsible for compiling the water-level data and maintaining the water-level data bases in most States.

Water-level measurements generally are made in the winter and early spring when water levels generally have fully recovered from pumping during the previous irrigation season and represent the highest water-table conditions during the year. Irrigation of winter wheat in the western High Plains in the late winter and early spring occasionally requires selection of alternative measurement periods in those areas. In some areas, particularly in the Northern High Plains, measurements are made only in the fall following the irrigation season because winter and spring weather typically is not conducive to field work. Consistency from year to year in time of measurements is more critical than actual time of measurement because it provides a more meaningful comparison among annual water levels.

METHODS OF DATA ANALYSIS AND PRESENTATION

Areas of equal water-level change and precipitation deviations from normal are defined through the use of Thiessen polygons (Thiessen, 1911). In this method, the area of interest is divided into polygons, each containing one water-level or precipitation measurement site. The sizes and shapes of polygons are governed by the geographic distributions of measurement sites. Where sites are widely spaced, the polygons are large; conversely, where sites are closely spaced, the polygons are small. Although other methods could be used to depict areas of equal water-level change or precipitation deviations, Thiessen polygons were deemed the most suitable for data with wide variances derived from nonuniformly distributed data points.

The use of the polygon method can result in abrupt differences among adjacent polygons, whereas actual water-level change or precipitation deviation between wells or sites could be gradational. The small mapping scale and overall observation-well density, however, generally would not permit gradational differences to be shown.

The patterns of water-level change in the High Plains contain numerous anomalies. A water-level change at a well can represent unique local conditions because of a number of factors, including well construction, local geohydrology, intensity of irrigation in the immediately surrounding area, local soil and

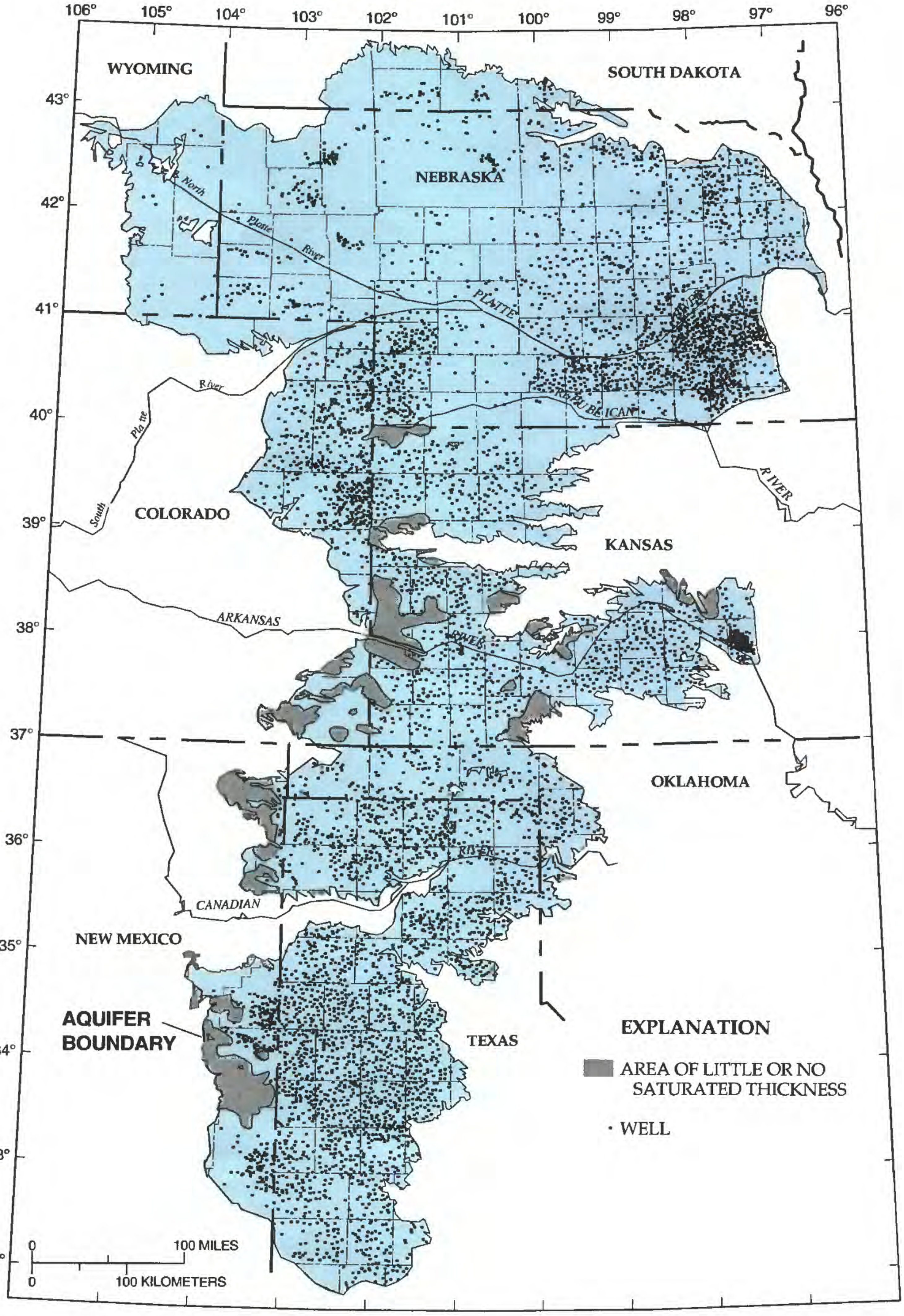

Figure 9. Location of wells with water-level measurements in 1990 and 1991.

vegetation characteristics, and precipitation anomalies. Thus, in the subsequent interpretation of the water-level-change maps, the anomalies likely are a result of unique conditions rather than data uncertainties.

The area-weighted averages by State for water-level change and precipitation deviations presented in tables 5-8 are deemed more appropriate than the arithmetic average of the observation-point data. Where a large number of points represent a small area, an arithmetic average would tend to be strongly affected by changes or deviations in that area. Weighting of values by polygon area gives each unit area equal representation regardless of densities of wells or precipitation stations.

WATER-LEVEL CHANGE AND PRECIPITATION, 1980 to 1991

The geographic pattern of water-level change from 1980 to 1991 (fig. 10) is similar to the pattern from predevelopment to 1980 (fig. 7). The magnitude of change, however, differs substantially between the two time periods. Water-level decline and the depletion of water in storage in the High Plains aquifer is substantially smaller from 1980 to 1991 in nearly all parts of the High Plains (table 5). A few areas with substantial declines from predevelopment to 1980 had water-level rises from 1980 to 1991. The average annual rate of water-level decline from predevelopment (1940) to 1980 was about 0.25 foot per year. The average annual decline from 1980 to 1991 was about 0.13 foot per year.

A comparison of water-level changes since 1980 (fig. 10) with changes prior to 1980 (fig. 7) in areas of substantial ground-water development indicates a decrease in rates of decline in most of the intensely developed areas and reversals in some areas. In the areas of the Southern High Plains in Texas and New Mexico where total declines exceeded 100 feet prior to 1980, the average annual rate of decline from predevelopment (1940) to 1980 was about 2.5 feet. From 1980 to 1991 (fig. 10), the average annual rate of decline in this area has decreased to slightly less than 2 feet, although rates of decline in some observation wells in this area are about the same as the pre-1980 average rate of 2.5 feet per year. In parts of the extreme Southern High Plains in Texas, where water levels declined from 10 to 30 feet from predevelopment (1940) to 1980, water levels rose as much as 20 feet since 1980.

In areas of the Central High Plains where large water-level declines occurred prior to 1980, including parts of southwestern Kansas, the Oklahoma Panhandle, and the north-central Texas Panhandle (fig. 7), declines averaged about 2.5 feet annually from predevelopment (1950) to 1980. Since 1980, declines in these areas averaged about 2 feet annually. The size of the area in southwestern Kansas where water-level declines averaged about 2 feet annually from 1980 to 1991 (fig. 10) appears to be larger than the area where declines exceeded 2.5 feet prior to 1980 (fig. 7). This is probably because ground-water irrigation continued to expand until after 1980 in this area (Kastner and others, 1989).

In most areas of substantial irrigation development in the Northern High Plains, average annual water-level declines also have been smaller since 1980. In parts of northeastern Colorado and southwestern Nebraska declines were about 30 feet from 1965 (predevelopment) to 1980 (fig. 7), or about 2 feet annually. From 1980 to 1991, declines averaged about 1 foot per year in this area (fig. 10). Regulations imposed in the late 1970's in parts of this area, including much of southwestern Nebraska, which limited new well construction and total ground-water withdrawals, appear to have contributed to the smaller declines. Two small areas of decline prior to 1980 in the Northern High Plains in Box Butte County, Nebraska, and Thomas and Sheridan Counties, Kansas, continued to decline at approximately the same rate, slightly more than 1 foot per year from 1980 to 1991. Precipitation was normal or less than normal in 1981-90 in both of these areas. In southeastern Nebraska, where water-level declines averaged slightly more than 20 feet from predevelopment (1955) to 1980, or about 0.8 foot per year, water-level rises averaged about 0.7 foot annually from 1980 to 1991.

Estimated changes in volume of water in storage in the High Plains aquifer, shown in table 5, are based on 15 percent (0.15) average yield of water by gravity drainage from the pore spaces of the saturated material (specific yield) (Gutentag and others, 1984). The rate of decline in storage from predevelopment (1940) to 1980 was about 4.2 million acre-feet per year compared to a rate of decline of about 2.5 million acre-feet per year from 1980 to 1991. Some of the difference in rate of water-level change and change in storage during the two time periods may be due to differences between data bases and methods of computing areas of water-level change. However, the large differences between the two time periods do indicate a substantial decrease in the rate of water-level decline and storage since 1980. The slower rate of removal from storage and subsequently smaller declines in water levels since 1980 are a result of several factors, including:

(1) 1980 to 1991 was a period of generally above-normal precipitation throughout the High Plains, which resulted in conditions favorable for increased recharge and smaller irrigation requirements. For 1981-90, annual precipitation in the High Plains averaged about 1.79 inches greater than the 1951-80 normal (table 6). The largest positive local departures of precipitation from normal occurred in parts of Nebraska, New Mexico, Oklahoma, and Texas (fig. 11). In addition, droughts of the scope and intensity of those of the 1930's and 1950's, which stimulated expansion of irrigated cropland, did not occur in the High Plains during the 1980's.

(2) Advances in irrigation technology, including center-pivot sprinkler irrigation and light-weight gated pipe designed to apply water more evenly and minimize conveyance and field losses, have greatly decreased ground-water pumpage requirements. Irrigation from open ditches, which can result in water losses of as much as 50 percent, is no longer commonly practiced. Recent sprinkler designs, including the low-energy, precise-application (LEPA) method, minimize wind losses from center-pivot irrigation. Although much of the excess applied water by various methods in the past was returned to the underlying aquifer through percolation, substantial volumes of water were lost by runoff and evaporation of ponded water. Prior to 1980, the discharge of some streams in the High Plains during summer months was substantially augmented by irrigation runoff.

(3) Economic considerations have initiated decreases in ground-water withdrawals for irrigation. The decline or stabilization of commodity prices and a continuing rise in production costs, including energy costs for pumping, have caused decreases in withdrawals and irrigation development. In some areas of the High Plains, where large water-level declines have occurred, cropland has been shifted from irrigated to nonirrigated crops because of prohibitive pumping costs caused by decreasing well yields and increased pumping depths. Increased costs of well installations and distribution systems have been a further deterrent to additional development.

(4) Large water-level declines in some areas prior to 1980 prompted local controls on irrigation withdrawals. State and local agencies in some areas were granted the authority to monitor and regulate pumpage volumes from existing wells and to limit new well construction.

(5) Expansion of irrigated cropland peaked by 1980 in much of the High Plains. Few large areas that are well-suited for irrigation on the basis of hydrology, soils, or topography remain to be developed in the High Plains.

A comparison of water-level changes and estimated changes in volume of water in storage by State both before and after 1980 (table 5) indicates that rates of change are not uniform within the High Plains. This variability in rates of change is related to regional differences in (1) intensity of irrigation development, (2) recharge, (3) consumptive irrigation requirements, and (4) the characteristics of the hydrologic environment.

Water-level measurements in the High Plains in 1980 and 1991 indicate certain well-defined areas of water-level declines in the Central and Southern High Plains (fig. 10). Large, continuous areas of decline exceeding 10 feet, with localized areas exceeding 20 feet, are evident in an area of southwestern Kansas extending into the Oklahoma Panhandle, in the northwest and north-central Panhandle of Texas, and in the northern part of the Southern High Plains of Texas extending into east-central New Mexico. Most of these areas have extensive ground-water irrigation development and generally large withdrawal rates (fig. 4). In addition, estimated recharge generally is small (fig. 3), and estimated consumptive irrigation requirements are large (fig. 5) in these areas, which collectively result in relatively large estimated net ground-water withdrawal rates for irrigation (fig. 6).

The large water-level declines in these areas do not appear to be closely related to precipitation during 1981-90. Average annual precipitation during this period generally was greater than normal in nearly all of these areas (fig. 11). In southwestern Kansas, precipitation was mostly 0 to 2 inches greater than normal. In the northwest and north-central Panhandle of Texas, precipitation ranged from near normal to as much as 2 to 4 inches greater than normal, and precipitation in the northern part of the Southern High Plains was generally 2 to 6 inches greater than normal.

In the Northern High Plains, areas of large water-level decline from 1980 to 1991 were relatively small in comparison to the rise of the areas of large declines in the Central and Southern High Plains. Declines exceeding 20 feet, however, occurred in Box Butte County, Nebraska, in parts of northeastern Colorado and southwestern Nebraska, and in Thomas and Sheridan Counties, Kansas. Certain characteristics of these areas are similar to those in the areas of large declines in the Central and Southern High Plains in that (1) ground-water development for irrigation is extensive, (2) ground-water withdrawal rates, by county, exceed 0.10 acre-foot per acre (fig. 4), (3) potential recharge has been small (fig. 3), (4) consumptive irrigation requirements are large (fig. 5), and (5) resultant net ground-water withdrawal rates are large (fig. 6). None of the factors that contribute to large water-level declines, however, are as pronounced in the Northern High Plains as in the Central and Southern High Plains, which probably accounts for the less areally extensive large declines in the Northern High Plains.

Precipitation in the areas of large water-level declines in the Northern Great Plains was variable during 1981-90 and appears to have little apparent relation to the declines. Only in Box Butte County was precipitation substantially less than normal, ranging from 2 to 3 inches less than normal. Precipitation in areas of water-level decline in northeastern Colorado and southwestern Nebraska ranged from about 2 inches less than normal to about 2 inches greater than normal. In the areas of water-level decline in Thomas and Sheridan Counties, Kansas, precipitation ranged from 0 to 2 inches less than normal during 1981-90.

Water-level rises from 1980 to 1991 occurred in three distinct areas of the High Plains; the extreme Southern High Plains in Texas, an area including west-central Oklahoma and the northeast Panhandle of Texas, and in the eastern High Plains of Nebraska and northern Kansas, and an area including southeastern Wyoming, the southern Panhandle of Nebraska, and northeastern Colorado. The size of these areas of water-level rise in some of these areas may be exaggerated by the small number of observation wells (fig. 9) and subsequently large polygons.

The areas of water-level rise from 1980 to 1991 generally had greater than normal precipitation during 1981-90 (fig. 11). The rises in the area extending from east-central to north-central Nebraska coincide with areas where precipitation was generally 2 to 4 inches greater than normal. Water-level rises in west-central Oklahoma, the southern part of the Southern High Plains in Texas, and south-eastern Wyoming generally had precipitation ranging from 2 to 6 inches greater than normal.

Rising water levels in some areas represent hydrologic factors other than precipitation. Water-level rises that have occurred in parts of south-central Nebraska since predevelopment (figs. 7 and 10) are associated with seepage losses from surface-water diversions for irrigation and electrical power generation. The total area of water-level rise has decreased since 1980 as a result of ground-water pumpage for irrigation and for purposely lowering an excessively high water table in certain areas (Peckenpaugh and others, 1987). In areas of the extreme Southern High Plains in Texas, where water-level declines averaged 20 feet, or about 0.5 foot per year from predevelopment (1940) to 1980, water-level rises of more than 20 feet, or nearly 2 feet per year, have occurred since 1980 (fig. 10). These water-level rises, particularly in Dawson and Gaines Counties, Texas, are

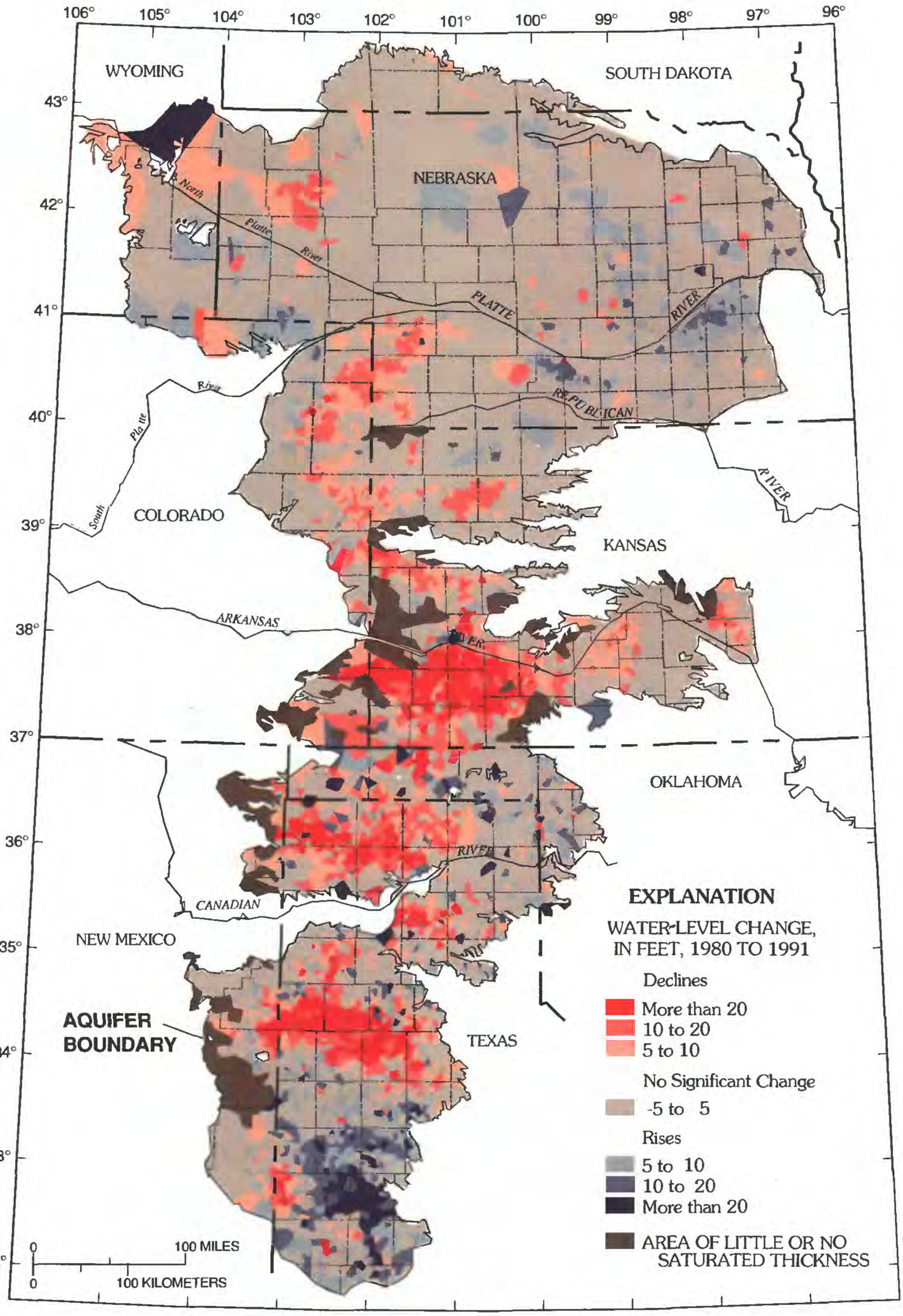

Figure 10. Water-level change in the High Plains aquifer, 1980 to 1991.

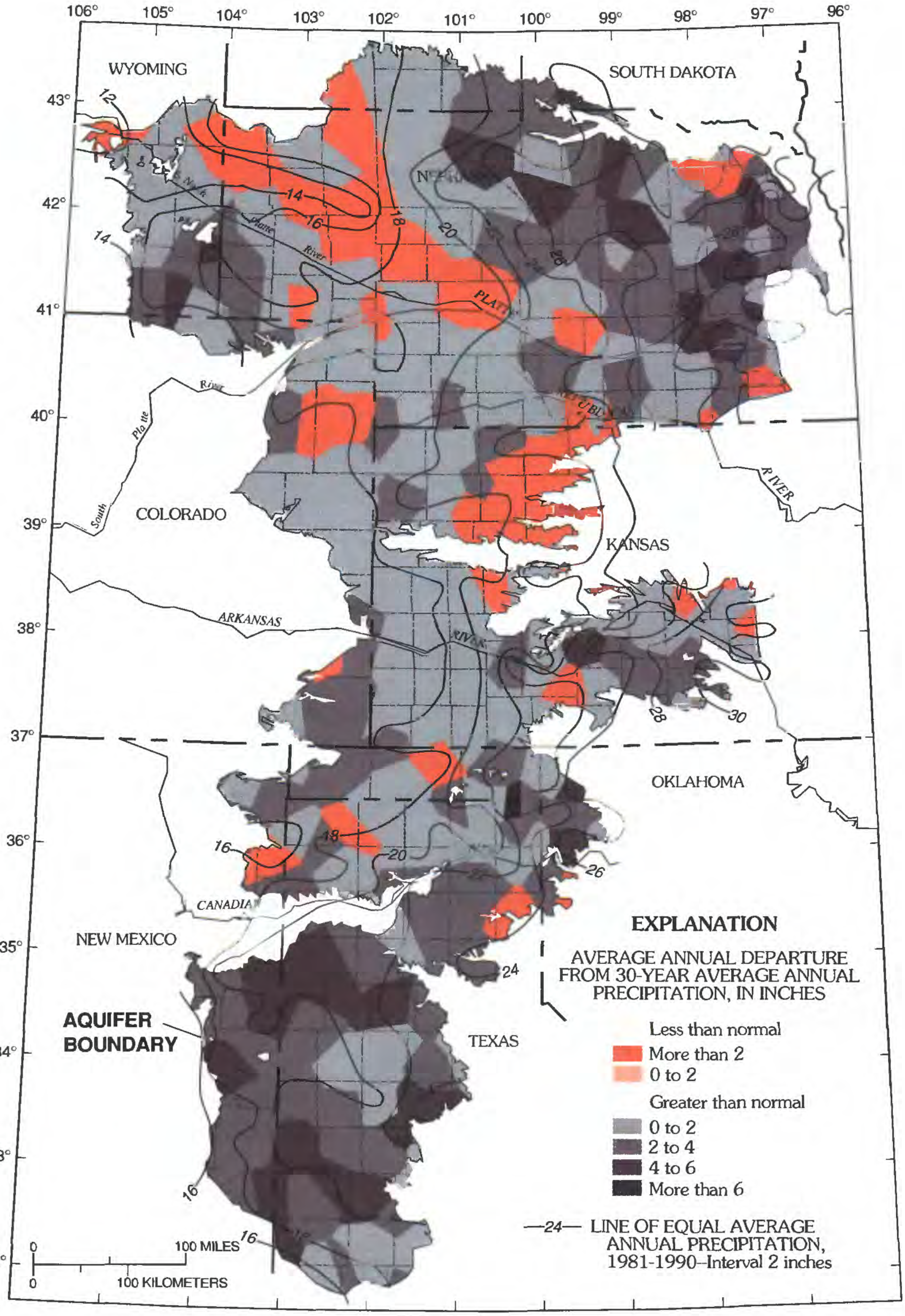

Figure 11. Average annual precipitation, 1981-90, and departures from 30-year normal (1951-80).

Table 5. *Area-weighted water-level changes and estimated changes in volume of water in storage, predevelopment to 1980 and from 1980 to 1991*

State	Area-weighted water-level change (feet)		Estimated changes in volume of water in storage (millions of acre-feet)	
	Predevelopment to [1]1980	1980 to 1991	Predevelopment to [1]1980	1980 to 1991
Colorado	-4.2	-3.15	-6.0	-4.5
Kansas	-9.9	-6.21	-29.0	-18.2
Nebraska	0	+.23	0	+1.4
New Mexico	-9.8	-2.27	-9.0	-2.1
Oklahoma	-11.3	-.11	-8.0	-.1
South Dakota	0	-.74	0	-.3
Texas	-33.7	-1.65	-114.0	-5.6
Wyoming	0	+2.92	0	+2.2
High Plains	-9.9	-1.41	-166.0	-27.2

[1] From Gutentag and others (1984, p. 47).

attributable to several factors in addition to greater than normal precipitation in 1981-90, including a decrease in acres irrigated, improved irrigation management and cultivation practices, and a rise in the potentiometric surface of an aquifer underlying the High Plains aquifer (J.B. Ashworth, *in* Dugan and Schild, 1992, p. 47).

WATER-LEVEL CHANGE AND PRECIPITATION, 1990 to 1991

Water-level declines were evident throughout most of the extensively irrigated areas of the High Plains in 1990 to 1991 (fig. 12). Declines of 1 to 3 feet occurred over large, continuous areas in each subdivision of the High Plains. Several smaller, less continuous areas in the Central and Southern High Plains had water-level declines exceeding 3 feet. Areas of water-level rise were confined to highly localized areas widely scattered throughout the High Plains.

Average area-weighted water-level changes by State in the High Plains (table 7) indicate that from 1990 to 1991 declines were prevalent throughout the High Plains, except in South Dakota. The average decline of 0.42 foot from 1990 to 1991 is about three times larger than the average annual rate of decline from 1980 to 1991 of about 0.13 foot (table 5) and substantially larger than the 0.25-foot average annual rate of decline from predevelopment to 1980. The average decline of 0.42 foot from 1990 to 1991, however, is smaller than the average decline of 0.63 foot from 1989 to 1990 (Dugan and Schild, 1992).

Patterns of water-level decline from 1990 to 1991 do not particularly reflect those of precipitation in the High Plains in 1990 (fig. 13). Although average precipitation in the High Plains in 1990 was 0.27 inch greater than normal (table 8), the average water-level decline for the High Plains (0.42 foot) from 1990 to 1991 was nearly equal to the average declines the previous 2 years, when precipitation was

Table 6. *Average departure of annual precipitation during 1981-90 from 30-year normal (1951-80)*

[Data from U.S. Department of Commerce, National Climatic Data Center, Asheville, North Carolina]

State	Area-weighted average departure, in inches
Colorado	+1.32
Kansas	+1.61
Nebraska	+1.56
New Mexico	+3.09
Oklahoma	+2.21
South Dakota	+1.76
Texas	+2.61
Wyoming	+1.38
High Plains	+1.79

considerably less than normal (Dugan, Schild, and Kastner, 1990; Dugan and Schild, 1992). Precipitation in some States with large average declines, such as New Mexico and Texas (table 7), was less than normal. Other States with substantial water-level declines from 1990 to 1991, including Colorado and Kansas, however, had greater than normal precipitation in 1990.

In the Southern High Plains, the areas with a long-term record of water-level declines continued this trend from 1990 to 1991. In an area in the northern part of the Southern High Plains in Texas and extending into New Mexico, where declines have been nearly continuous since predevelopment (1940), water-level declines averaged nearly 3 feet in 1990 to 1991 (fig. 12). This average decline exceeds the 1980 to 1991 average annual rate of decline about 2 feet per year and is comparable to the average annual rate of decline from predevelopment (1940) to 1980.

The 1990 to 1991 water-level declines in the northern part of the Southern High Plains probably are associated with less than normal precipitation in 1990, which generally was 2 to 5 inches less than normal (fig. 13). Water-level declines of this magnitude, however, are more likely related to large deficiencies in the normal growing-season precipitation than in the slightly less than normal annual precipitation. The much less than normal precipitation in the spring and early summer of 1990 in this area probably required an earlier start of the irrigation season and greater total ground-water withdrawals for the season.

Water-level declines of 1 to 3 feet from 1990 to 1991 were nearly continuous across large parts of the Central High Plains (fig. 12). Declines exceeding 3 feet were widespread in an area extending from southwestern Kansas to the northwestern Panhandle of Texas and northeastern New Mexico. Water-level declines in this extensively irrigated area exceeded both the 1980-to-1991 average annual rate of decline of about 2 feet per year and the pre-1980 average annual rate of decline of about 2.5 feet per year.

Precipitation departures from normal in 1990 (fig. 13) do not appear to provide an

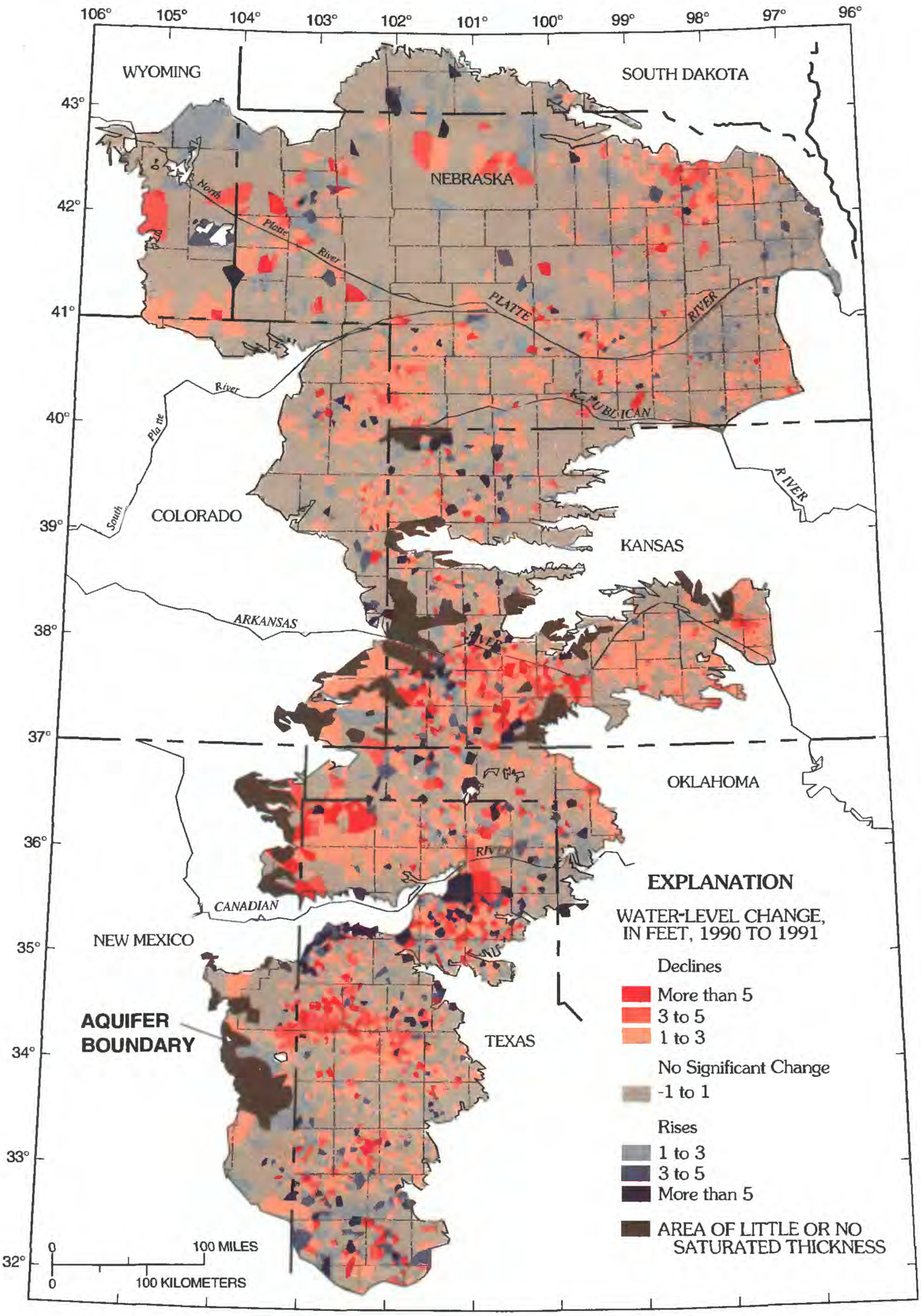

Figure 12. Water-level change in the High Plains aquifer, 1990 to 1991.

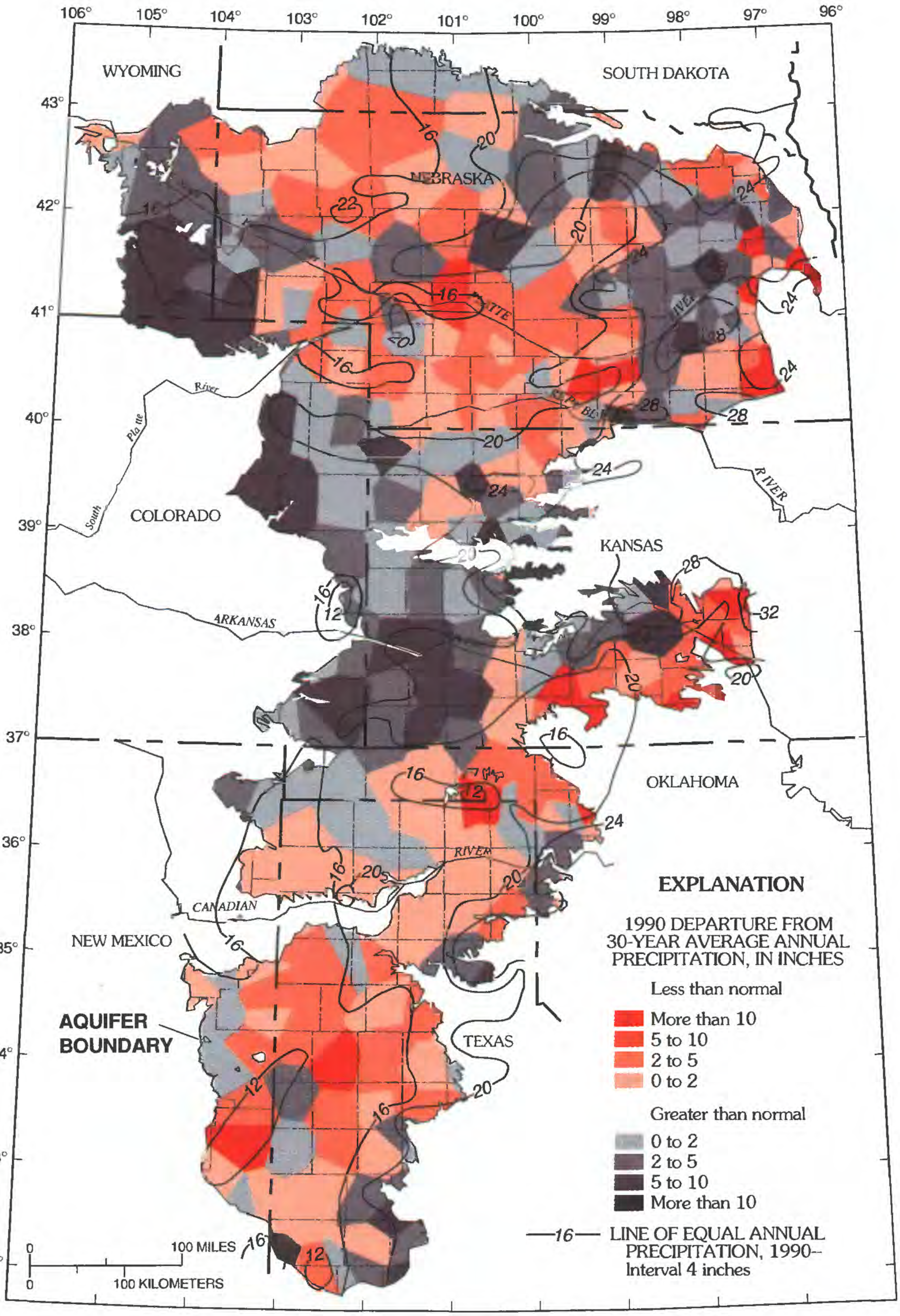

Figure 13. 1990 precipitation and departure from 30-year normal.

Table 7. *Water-level changes from 1990 to 1991*

State	Average area-weighted water-level change (feet)
Colorado	-0.48
Kansas	-.72
Nebraska	-.32
New Mexico	-.70
Oklahoma	-.04
South Dakota	+.45
Texas	-.70
Wyoming	-.06
High Plains	-0.42

Table 8. *Average departure of precipitation in 1990 from 30-year normal (1951-80)*

[Data from U.S. Department of Commerce, National Climatic Data Center, Asheville, North Carolina]

State	Average area-weighted departure of precipitation (inches)
Colorado	+2.87
Kansas	+1.33
Nebraska	-.34
New Mexico	-1.29
Oklahoma	-.57
South Dakota	-.34
Texas	-.93
Wyoming	+3.89
High Plains	+.27

explanation for the large, widespread water-level declines in the Central High Plains between 1990 and 1991 (fig. 12). Precipitation in 1990 generally ranged from near normal in the Oklahoma and Texas Panhandles to 5 to 10 inches greater than normal in southwestern Kansas. Greater than normal precipitation also occurred during the growing season in these areas. Much higher than normal temperatures in early summer could have resulted in a large, early water demand and a consequent increase in ground-water pumpage. June temperatures averaged about 3 to 7 °F above normal. The widespread water-level declines of 1 to 3 feet in parts of south-central Kansas appear to have some association with precipitation, which was generally less than normal in 1990.

In the Northern High Plains, 1990-to-1991 water-level changes were more variable than in the Southern and Central High Plains. Several large, but relatively discontinuous, areas had water-level declines from 1 to 3 feet, and a few smaller areas had declines exceeding 3 feet. The largest and most continuous area of declines extended from northeastern Colorado into southwestern Nebraska. These declines are consistent with the relatively steady pattern of water-level change established in this area from 1980 to 1991, when declines averaged about 1 foot per year. Precipitation in this area in 1990 ranged from slightly less to slightly greater than normal (fig. 13).

Another area of substantial water-level declines in the Northern High Plains from 1990 to 1991 was in northeastern Nebraska, where water levels declined as much as 3 to 5 feet. Substantial declines have occurred in this area each year since 1987 (Kastner and others, 1989; Dugan, Schild, and Kastner, 1990; Dugan and Schild, 1992). Between 1980 and about 1987, however, water levels rose as much as 10 feet (Kastner and others, 1989). The relatively stable water levels from 1980 to 1991 in northeastern Nebraska shown in figure 10 actually obscure two water-level trends; rising water levels from 1980 to 1987 followed by nearly equal declines from 1987 to 1991.

The widespread water-level declines in the 1- to 3-foot range in southeastern and south-central Nebraska from 1990 to 1991 are a continuation of another recent trend. Water levels in this area have declined for 3 consecutive years since 1988 (Dugan, Schild, and Kastner, 1990; Dugan and Schild, 1992). Water-level rises of 10 to 20 feet were common in these areas from 1980 to 1988 (Kastner and others, 1989).

Discontinuous areas of water-level declines, some exceeding 5 feet, occurred in parts of north-central and western Nebraska and parts of Wyoming from 1990 to 1991 (fig. 12). Some of these declines have little apparent relation to precipitation in 1990. Precipitation in 1990 in these areas ranged from only slightly less than normal in north-central Nebraska to much greater than normal in the High Plains of Wyoming. The sparsity of observation wells in these areas tends to exaggerate the size of the areas of change. Furthermore, these declines may be related to localized hydrologic conditions.

Rising water levels occurred only in a few isolated areas of the High Plains from 1990 to 1991. Areas of long-term rise between 1980 and 1991 (fig. 10) in the extreme Southern High Plains in Texas had smaller areas of rises of 1 to 5 feet from 1990 to 1991, and static or declining water levels over the remaining areas. Precipitation ranged from 5 to 10 inches greater than normal to 5 inches less than normal in the extreme Southern High Plains in 1990. A small area of 1- to 3-foot water-level rise in west-central Oklahoma and the northeastern Panhandle of Texas from 1990 to 1991 appears to be associated with slightly greater than normal precipitation. Rises in water levels in east-central Nebraska are associated with an area where precipitation was as much as 5 to 10 inches greater than normal in 1990.

Discontinuous areas of water-level rise in an area extending from northeastern Cherry County in north-central Nebraska to western Bennett County in south-central South Dakota do not appear to be related to 1990 precipitation patterns. Water-level rises of 3 to 5 feet from 1990 to 1991 in southern Goshen County in southeastern Wyoming, however, correspond closely to an area where precipitation was from 5 to 10 inches greater than normal in 1990. Water levels have risen from 5 to 10 feet in southern Goshen County between 1980 and 1991 (fig. 10).

An area of water-level rises of 1 to 3 feet from 1990 to 1991 in southwestern Niobrara County, Wyoming, is in an area where water levels have risen more than 20 feet between 1980 and 1991. This area of rising water levels, however, appears to represent local hydrologic conditions rather than above-normal precipitation (figs. 11 and 13).

HYDROGRAPHS OF REPRESENTATIVE OBSERVATION WELLS

The hydrographs in this report illustrate water-level changes over time in selected observation wells in the High Plains. These observation wells generally are located in areas of substantial ground-water development and water-level change. Criteria for specific observation-well selection include: (1) wells that represent water-table conditions, (2) long-term observation wells that reflect, as close as possible, water-level changes that are due to long-term ground-water development from predevelopment to 1991, and (3) observation wells at which multiple water-level measurements are made each year. Many of these wells have continuous water-level recorders. Observation-well locations are shown in figure 1.

The different responses in the various observation wells generally represent the local pattern of ground-water development of an area. The hydrographs of some observation wells, however, may indicate certain characteristics of the observation well itself or highly localized properties of the aquifer that are not entirely typical of the area.

Colorado

The hydrograph for an observation well in Yuma County (fig. 14A) is representative of the relatively large water-level declines that have occurred in an area of substantial irrigation development in northeast Colorado since the mid-1960's. Water-level declines began in this well in the mid-1960's and have been continuous except for a brief period of rise in the late 1980's. Water-level declines from 1964 to 1991 were nearly 40 feet. From 1968 to 1980, water levels declined about 2 feet per year. Between 1980 and 1991, the rate of decline has averaged about 1 foot per year, the decrease in rate of decline likely is a result of an increase in precipitation and a decrease in the rate of withdrawals for irrigation.

The hydrograph for the well in Washington County (fig. 14B) indicates that long-term water-level changes were small in this area of the High Plains, with the relatively large year-to-year changes resulting from large yearly differences in precipitation and pumpage. The observation well is located in an area where saturated thickness is less than 50 feet, well yields are relatively small (less than 500 gallons per minute), and irrigation development is limited. The fluctuations in the hydrograph indicate that irrigation may be intermittent in this area. The slight general rise in water levels in this well from 1980 to 1991 probably is attributable to greater than normal precipitation during this period.

The hydrograph of the well in Kit Carson County (fig. 14C), is typical of wells used for winter irrigation of wheat, a practice common throughout much of the western High Plains. The downward spikes are indicative of pumpage just prior to late-December or January measurements. From 1970 to 1991, the water level in this well has declined nearly 10 feet or approximately 0.5 foot per year (E.R. Banta, *in* Dugan and Schild, 1992, p. 31-32).

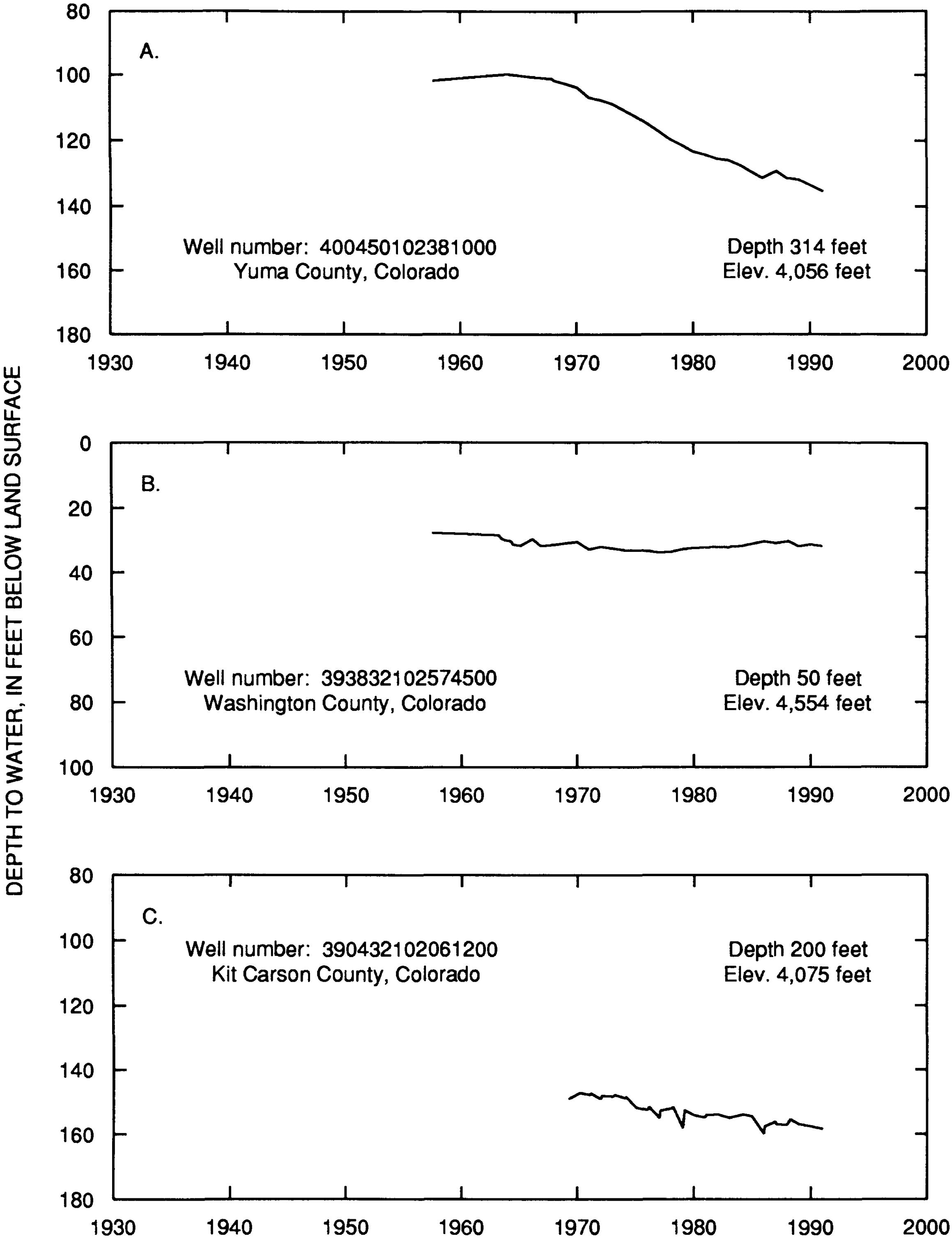

Figure 14. Observation wells: A, Yuma County; B, Washington County; C, Kit Carson County, Colorado.

Kansas

The hydrograph of the well in Thomas County (fig. 15A) shows a continual decline in water levels that corresponds to an increase in irrigation in the county following the drought of 1953-57. Total declines from about 1955 to 1991 were slightly more than 15 feet or slightly less than 0.5 foot per year. The water levels were nearly stable from about 1981 to the mid-1980's in response to above-normal precipitation and a decline in the rate of irrigation development. From 1987 to 1991, water levels again declined rapidly as a result of increased irrigation withdrawals during a period of below-normal precipitation.

The hydrograph of the well in Finney County (fig. 15B) is indicative of the overall decline of water levels in the area since the early 1950's. Following World War II and the introduction of large-capacity turbine pumps, irrigation developed rapidly in this part of southwestern Kansas until the mid-1970's. From the early 1950's until the early 1980's, water levels in this well declined more than 40 feet, an average decline of nearly 1.5 feet per year. Since the early 1980's, however, above-average precipitation, decreases in irrigated acres, and declines in pumpage rates have resulted in additional water-level declines of only about 5 feet in this well or about 0.5 foot per year.

The well located in Sedgwick County (fig. 15C) is completed in the unconsolidated *Equus* beds, which is principally Pleistocene in age. This formation, which constitutes the eastern extension of the High Plains aquifer in south-central Kansas, is used extensively for public-water supplies in this area. Rapid rates of long-term natural recharge (fig. 4) in this area contribute to the relative stable long-term water levels in this well (L.J. Combs and B.J. Pabst, *in* Dugan and Schild, 1992, p. 34-36).

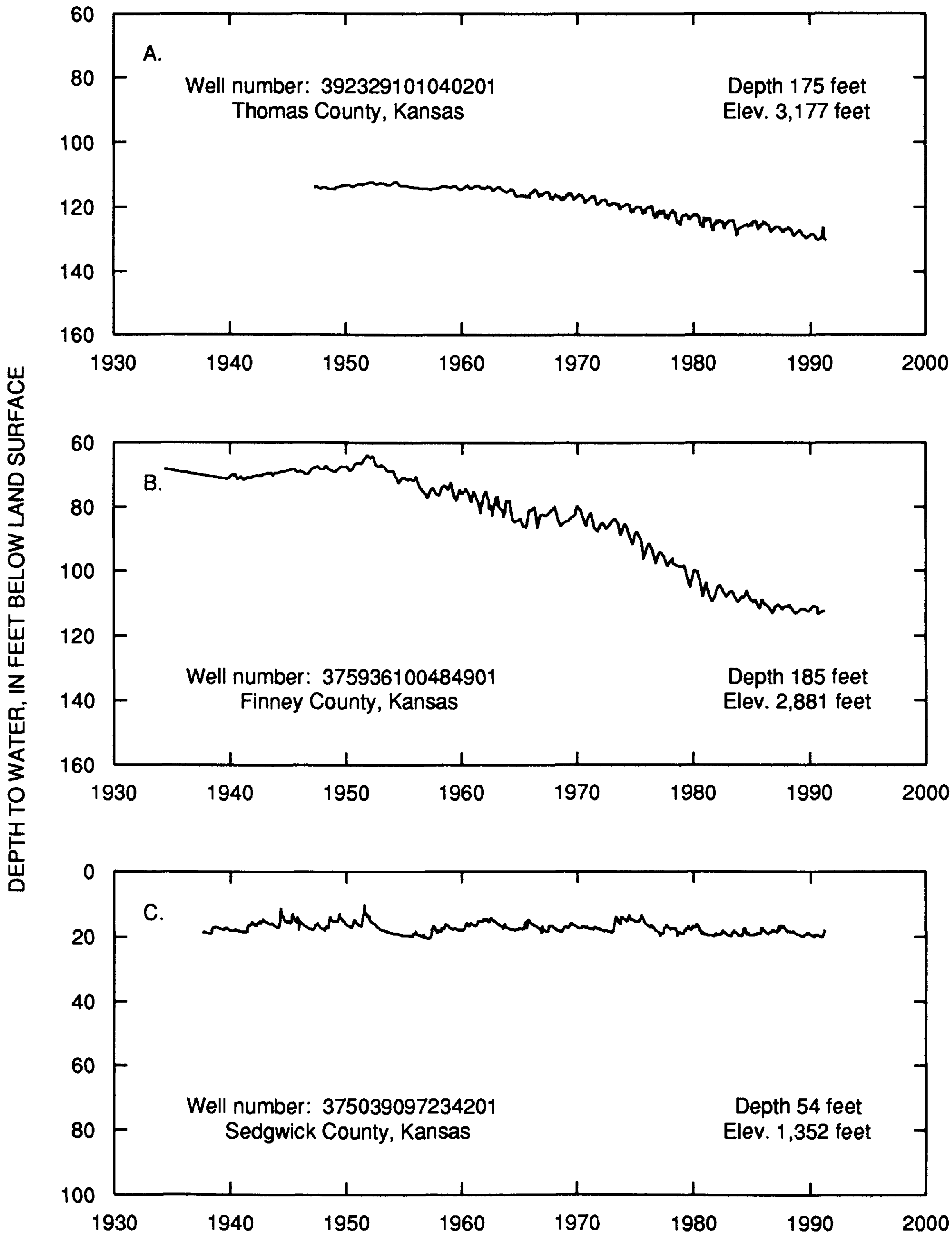

Figure 15. Observation wells: A, Thomas County; B, Finney County; C, Sedgwick County, Kansas.

Nebraska

The hydrograph of the well in Box Butte County (fig. 16A) represents the long-term water-level declines that have occurred in this area since the early 1950's. Water-level declines exceeded 40 feet from 1951 to 1991 or about 1 foot per year in this well, which is located in an area of intensive irrigation development. Limited recharge (fig. 3) and relatively large consumptive irrigation requirements (fig. 5) as a result of small average annual precipitation (16 inches) in the area have contributed to these long-term declines.

The hydrograph of the well in Chase County (fig. 16B) represents the decline in water levels soon after substantial irrigation development began in southwestern Nebraska in the mid-1960's. Water levels declined nearly 37 feet from 1964 to 1991 or about 1.4 feet per year. Water levels rose slightly from 1980 to 1984 during a period of increased recharge and smaller consumptive irrigation requirements associated with much-above-normal precipitation. Strict controls on annual irrigation-withdrawal rates and on the development of additional irrigated land were implemented in southwestern Nebraska in the late 1970's and apparently have contributed to slower rates of water-level decline since the early 1980's. The hydrograph indicates the seasonal drawdown patterns of the water table associated with irrigation pumpage from nearby wells during the growing season. There are eight irrigation wells within 1 mile of the observation well. Seasonal drawdowns appear to have been greatest in the late 1970's, perhaps indicating the period of maximum pumpage in the surrounding area prior to implementation of ground-water controls.

The hydrograph of a well in Seward County (fig. 16C) represents water-level conditions in the extreme eastern High Plains of Nebraska from shortly after irrigation development began in the area in the mid-1950's. From 1963 to 1982, water levels declined about 9 feet followed by water-level rises of about 12 feet from 1982 to 1988 when annual precipitation averaged about 32 inches or 6 inches above normal. Since 1988, annual precipitation in the area has averaged slightly more than 20 inches or nearly 7 inches below normal, and water levels have declined nearly 4 feet. The water level in this well, however, declined less than 1 foot from 1989 to 1991, indicating relatively large recharge (fig. 3) and the small average consumptive irrigation requirements (fig. 5) during this period in this area. Seven irrigation wells are within 1 mile of the observation well, which contributes to the pattern of seasonal drawdowns (J.T. Dugan, *in* Dugan and Schild, 1992, p. 38-40).

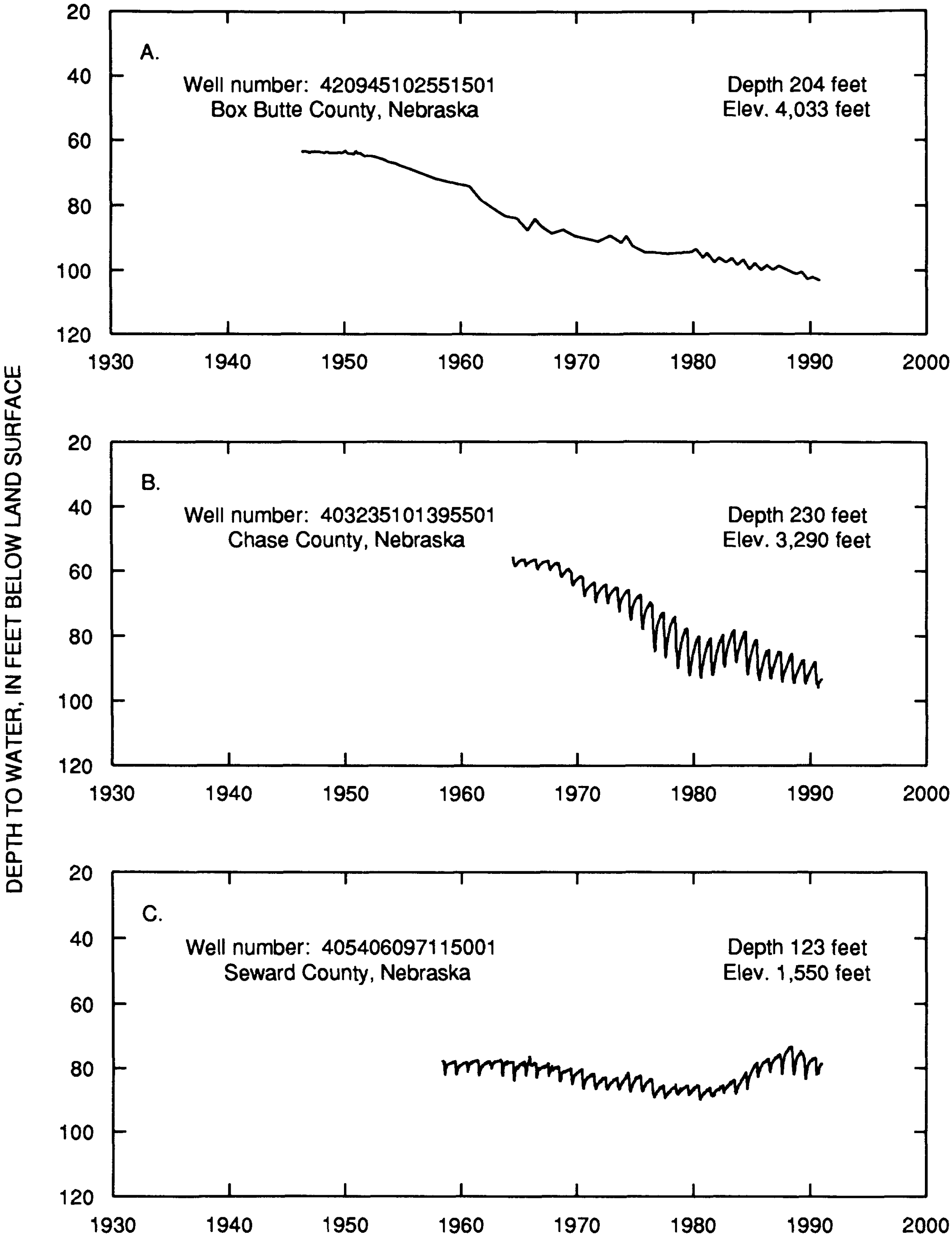

Figure 16. Observation wells: A, Box Butte County, B, Chase County; C, Seward County, Nebraska.

New Mexico

The hydrograph of an observation well in Union County in northeastern New Mexico (fig. 17A) represents an area of moderate irrigation development but very small average recharge (fig. 3) and large average consumptive irrigation requirements (fig. 5), which apparently have contributed to a steady decline in water levels in the area. Water levels declined more than 15 feet since 1969. Substantial declines probably occurred in this area prior to the installation of this well (see fig. 7).

The hydrograph in figure 17B represents an observation well in Curry County, just west of the intensively irrigated area of the northern part of the Southern High Plains in Texas and New Mexico. Water levels have declined steadily a total of 15 feet in this well from 1961 to 1991--an average of 0.5 foot per year (R.R. Cruz, *in* Dugan and Schild, 1992, p. 41-42).

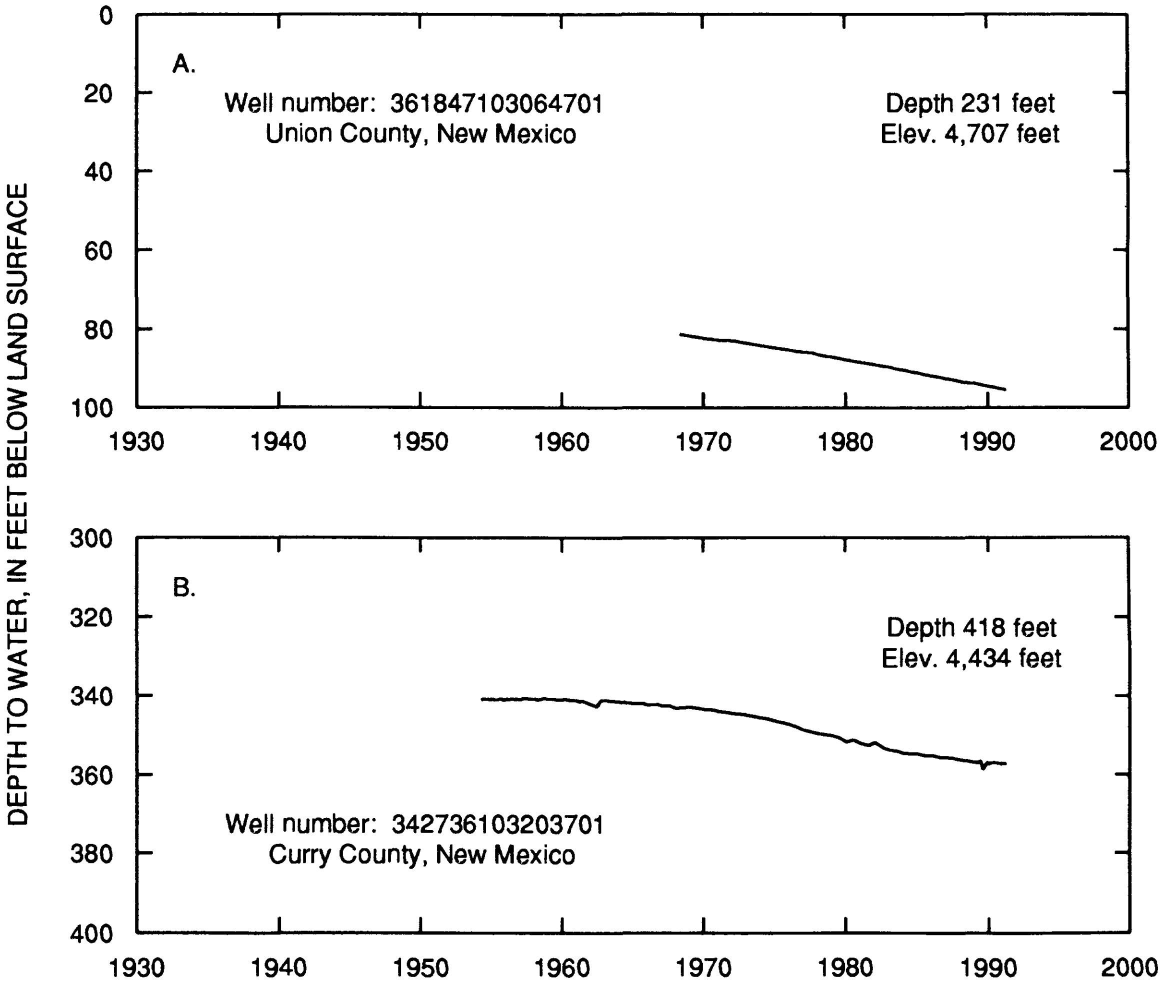

Figure 17. Observation wells: A, Union County; B, Curry County, New Mexico.

Oklahoma

The hydrograph of an observation well in Texas County (fig. 18) shows a continual water-level decline totaling about 25 feet since the mid-1960's. Most of this decline has occurred since about 1974. This observation well is located on the southwestern edge of a large cone of depression in Texas County. Water levels in the center of this cone declined about 100 feet from 1940 to 1980 (fig. 7). Declines in this well largely reflect the effect of long-term withdrawals for irrigation rather than short-term variability of precipitation in the surrounding area. The rate of decline of the water levels in the well began to increase in the early 1970's, reflecting an increase in acres irrigated that continued through 1981. A decrease in irrigated cropland since 1981 and a possible decrease in rates of withdrawals for irrigation in the 1980's as a result of above-normal precipitation appear to have slowed the rate of water-level decline in recent years. Irrigated acreage in Texas County decreased from a peak of nearly 190,000 acres in 1981 to less than 110,000 acres in 1990 (J.S. Havens, *in* Dugan and Schild, 1992, p. 43).

South Dakota

Net water-level change in an observation well in Bennett County (fig. 19A) was minimal from 1960 to 1991. These stable water-level conditions are indicative of the minimal irrigation development in this area. The upturn in the hydrograph in 1990 probably is related to above-normal precipitation in 1990 in this area (fig. 13).

Water levels in an observation well in Tripp County in the eastern High Plains of South Dakota rose about 5 feet between the early 1980's and 1991 (fig. 19B). This rise may be attributable to above-normal precipitation in 1981-90, which averaged about 23 inches annually or 3 inches above normal. Irrigation development is minimal in this area (J.R. Little and K.M. Neitzert, *in* Dugan and Schild, 1992, p. 45).

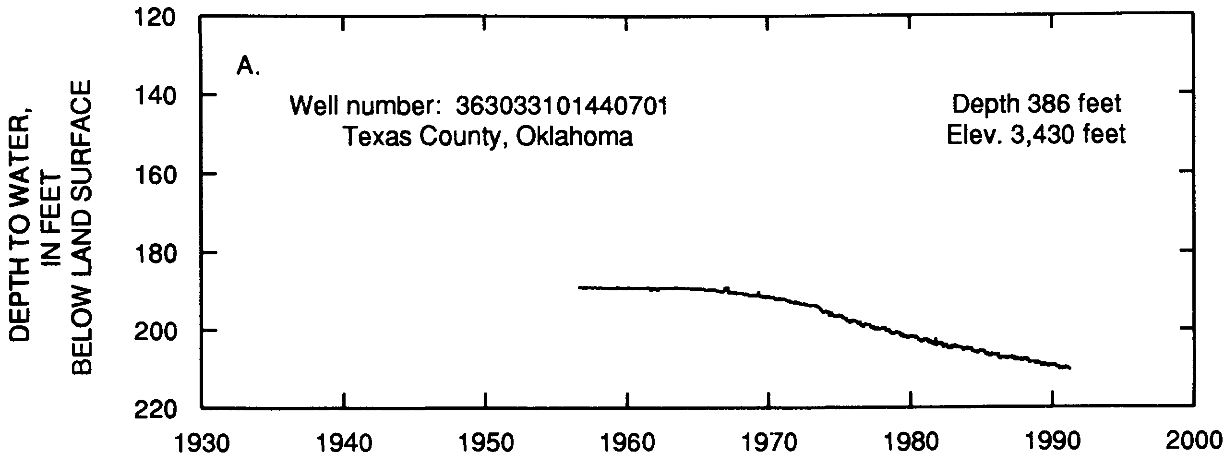

Figure 18. Observation well: A, Texas County, Oklahoma.

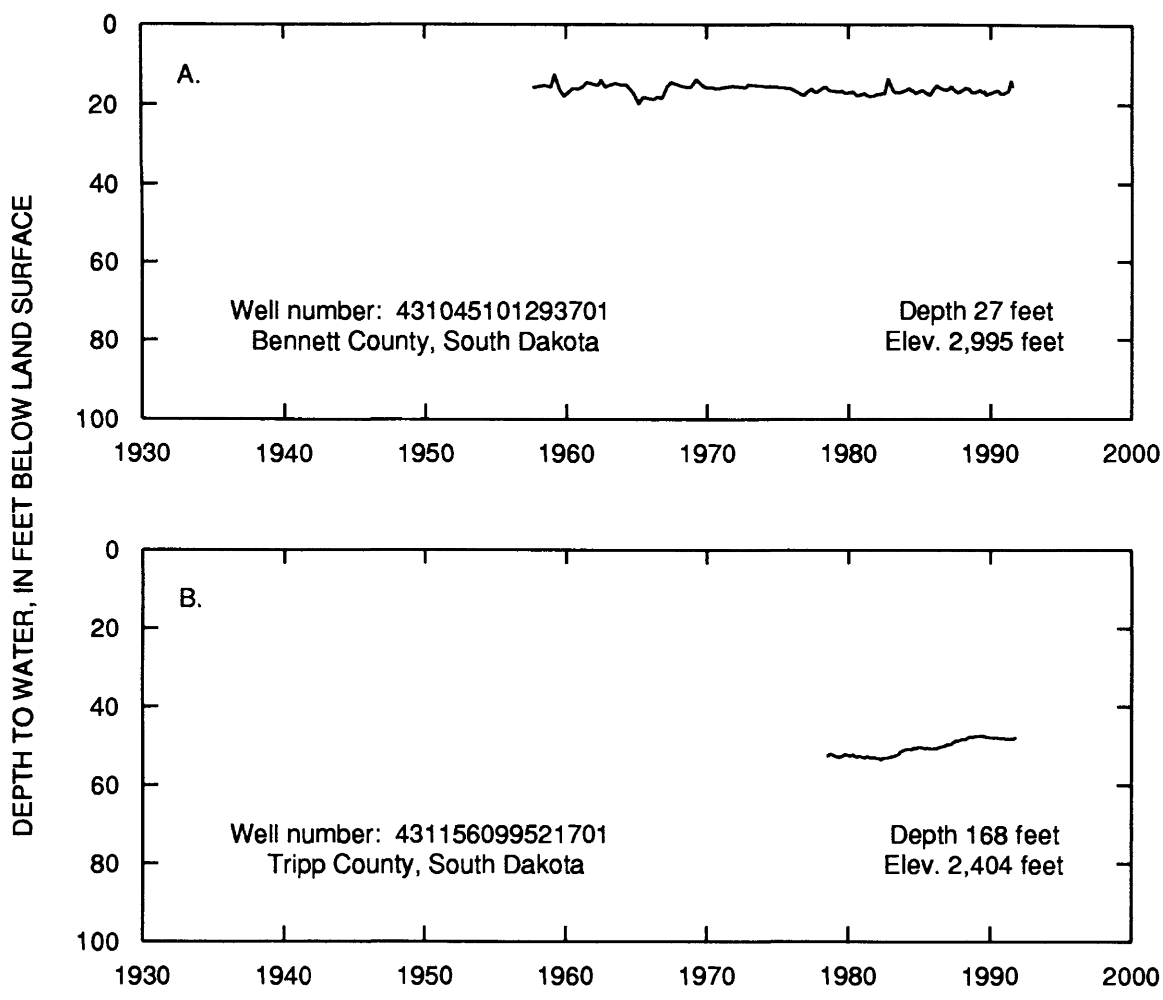

Figure 19. Observation wells: A, Bennett County; B, Tripp County, South Dakota.

Texas

The hydrograph for an observation well in Lamb County illustrates the continuous depletion of the aquifer in the northern part of the Southern High Plains (fig. 20A). As a result of intensive irrigation withdrawals since the early 1950's, water levels had declined nearly 65 feet by 1991. Declines averaged about 3 feet per year from 1978 to 1986 and 2 feet per year after a period of stable water levels in 1986.

The hydrograph for an observation well in Lubbock County illustrates a unique condition (fig. 20B). Water levels began to rise in this well in the late 1960's after the City of Lubbock curtailed ground-water withdrawals and began to import water from outside the county. Ground-water withdrawals were further curtailed by a decrease in irrigation caused by the expansion of the city into previously irrigated farmland. Substantial amounts of recharge to the aquifer occur locally as a result of storm runoff, which collects in a large surface depression located in the southwestern part of the city.

The hydrograph for the well in Gaines County illustrates the rise in water levels in the southeastern part of the Southern High Plains (fig. 20C). Water levels in this well rose nearly 35 feet from 1969 to 1991, about 30 feet of this rise occurring since 1982. Precipitation in this area averaged 4 to 6 inches above normal in 1981-90 (fig. 11). In addition, water levels in this area may have been affected by a rise in the potentiometric surface of the aquifer underlying the High Plains aquifer (J.B. Ashworth, *in* Dugan and Schild, 1992, p. 47-48).

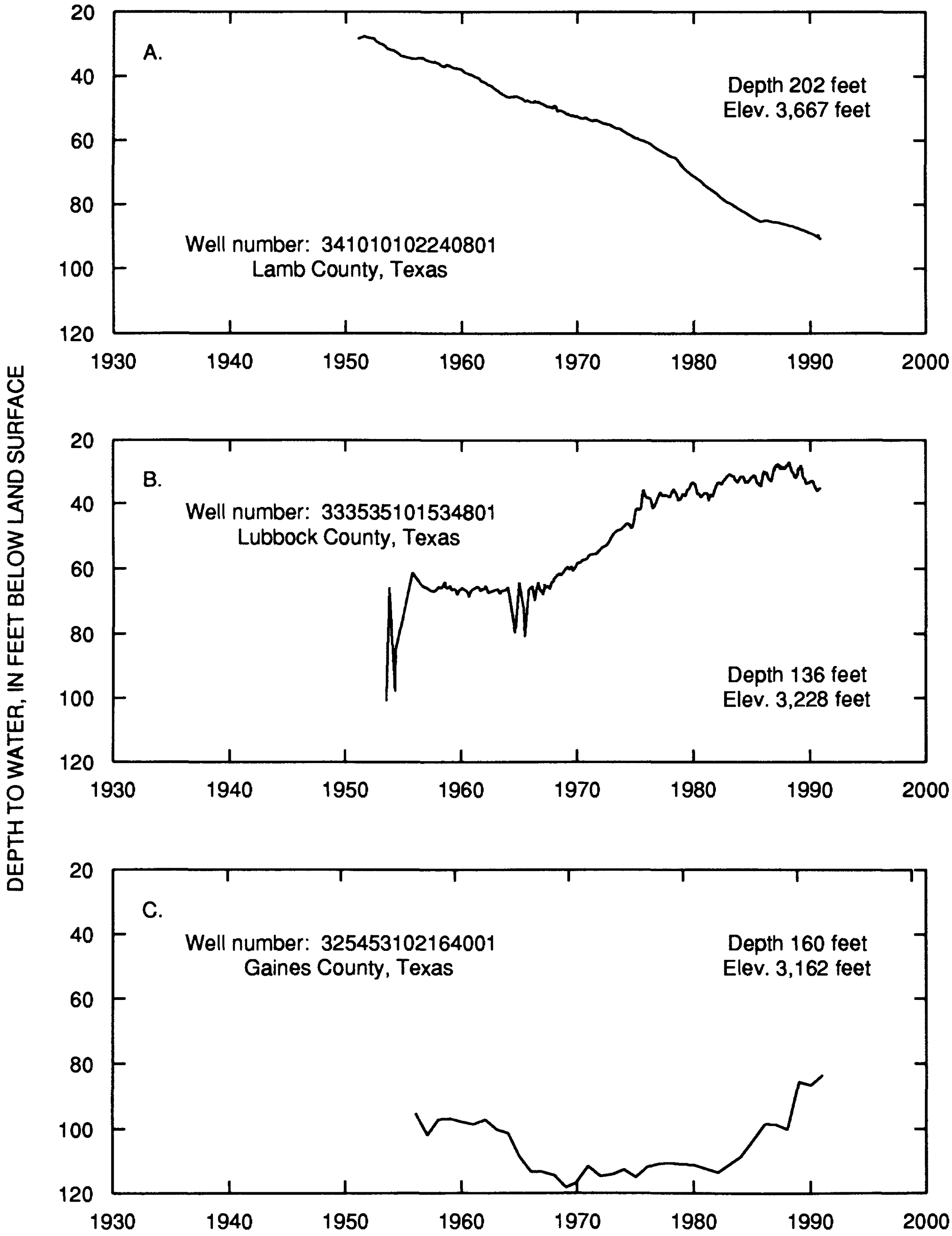

Figure 20. Observation wells: A, Lamb County; B, Lubbock County; C, Gaines County, Texas.

Wyoming

The hydrograph for a well in eastern Laramie County, near the Nebraska border, shows a rise of about 5 feet in the early 1980's but a decline totalling nearly 5 feet from 1985 to 1991 (fig. 21A). Precipitation during 1981-90 averaged 2 to 4 inches above normal (fig. 11). The decline does not appear to be closely related to precipitation but to a possible increase in ground-water withdrawals in the surrounding area. The hydrograph indicates the well is very responsive to pumping of nearby wells, characterized by large, rapid drawdowns and recoveries.

Water levels in a well in southern Laramie County declined nearly 20 feet from 1974 to 1980, rose nearly 15 feet from 1980 to 1986, and declined about 5 feet from 1985 to 1991 (fig. 21B). The rise from 1980 to 1985 occurred during a period when precipitation averaged nearly 6 inches above normal. The declines from 1985 to 1991, however, probably are related to an increase in pumpage in the surrounding area. From 1985 to 1991, precipitation in the area averaged slightly above normal.

Water levels in a well in southern Niobrara County declined nearly 15 feet between 1973 and 1991, an average decline of about 0.8 foot per year (fig. 21C). The rate of decline was about 1.2 feet per year between 1973 and 1982, but only about 0.3 foot per year between 1982 and 1991. Precipitation from 1981 to 1990 was near normal or about 14 inches annually (fig. 11) (K.A. Miller, *in* Dugan and Schild, 1992, p. 50-51).

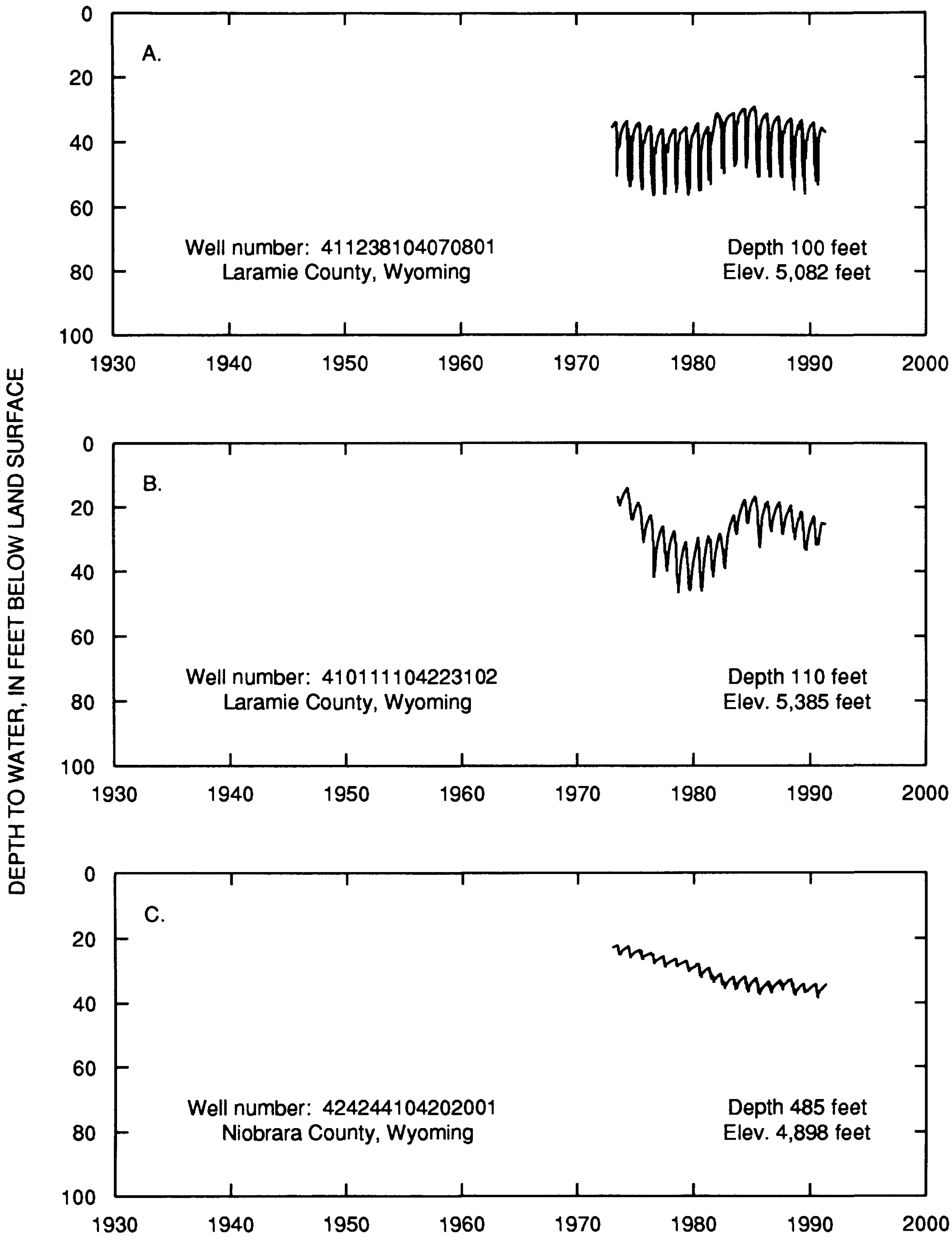

Figure 21. Observation wells: A, eastern Laramie County; B, southern Laramie County; C, Niobrara County, Wyoming.

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