WATER-LEVEL CHANGES IN THE HIGH PLAINS AQUIFER--PREDEVELOPMENT TO 1990

by Jack T. Dugan and Donald E. Schild

(with State summaries by E.R. Banta; L.J. Combs and B.J. Pabst; J.T. Dugan; R.R. Cruz; J.S. Havens; J.R. Little and K.M. Neitzert; J.B. Ashworth; and K.A. Miller)

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Multiply	*By*	*To obtain*
acre	0.4047	hectare
acre-foot	1,233	cubic meter
foot	0.3048	meter
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

Changes in water levels in the High Plains aquifer underlying parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas result from the variability of precipitation, land use, and ground-water withdrawals. From the beginning of development of the High Plains aquifer to 1980, water levels declined throughout much of the area. These declines exceeded 100 feet in parts of the central and southern High Plains. For 1980 to 1990, patterns of water-level change were more variable. Large areas of intense irrigation development in Kansas, New Mexico, Oklahoma, and Texas had declines ranging from 7.5 feet to more than 15 feet. Additional large areas with 7.5 to 15 feet of decline were present in northeastern Colorado, southwestern Nebraska, and in Box Butte County, Nebraska.

Water levels were either stable or rising in the remainder of the High Plains. Large areas in Texas and eastern Nebraska had rises of more than 7.5 feet. The average area-weighted water-level change from 1980 to 1990 was -1.04 feet compared to -9.9 feet from predevelopment to 1980. This relatively small decline since 1980, in relation to the declines prior to 1980, was associated with a decrease in ground-water application for irrigated agriculture and above-normal precipitation throughout the High Plains from 1981 through 1989. Water-level changes across the High Plains from 1989 to 1990 were a continuation of the variability observed in previous years; however, areas of decline were more prevalent than areas of rise. Declines throughout much of the Northern High Plains were associated with well below-normal precipitation in that area during 1989. Declines also continued throughout much of the intensely developed irrigation areas of the Texas High Plains. Rises associated with above-normal precipitation during 1989, however, occurred in parts of southwestern Kansas where significant long-term declines had occurred. The average area-weighted change from 1989 to 1990 in the High Plains was -0.63 foot, largely attributable to declines in Nebraska and Texas.

INTRODUCTION

(Modified from Dugan and others, 1990)

Report on Water Levels in the High Plains Aquifer is Requested by Congress.

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 that 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 aquifer is necessary to make sound management decisions concerning the use of water, to predict 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, and other Federal agencies. A major study that examined the physical features of the entire aquifer recently has been 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 the 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 were again systematically collected and compiled in an aquifer-wide data base (Kastner and others, 1989). The U.S. Geological Survey and State and local agencies compiled water-level data collected since 1980 at more than 12,000 locations.

This report, the third 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 nonirrigation season of 1989-90 (herein referred to as 1980 to 1990), precipitation patterns from 1981 through 1989 (herein referred to as 1981-89), and water-level changes between the nonirrigation seasons of 1988-89 and 1989-90 (herein referred to as 1989 to 1990), and precipitation patterns for 1989. The changes shown on the subsequent maps are supplemented by hydrographs of long-term water levels in selected wells.

This report differs in several respects from the previous report (Dugan and others, 1990). Sections with accompanying illustrations showing estimated average potential recharge and consumptive irrigation requirements have been added to the discussion of factors affecting water-level changes in the High Plains. In addition, individually authored State sections similar to those in the initial report (Kastner and others, 1989) have been reintroduced to provide more detailed local analyses of water-level changes. The data base of water-level measurements has been expanded considerably in selected areas to add greater definition to water-level changes. Additional data-base management procedures have been instituted to minimize inconsistencies in comparable data.

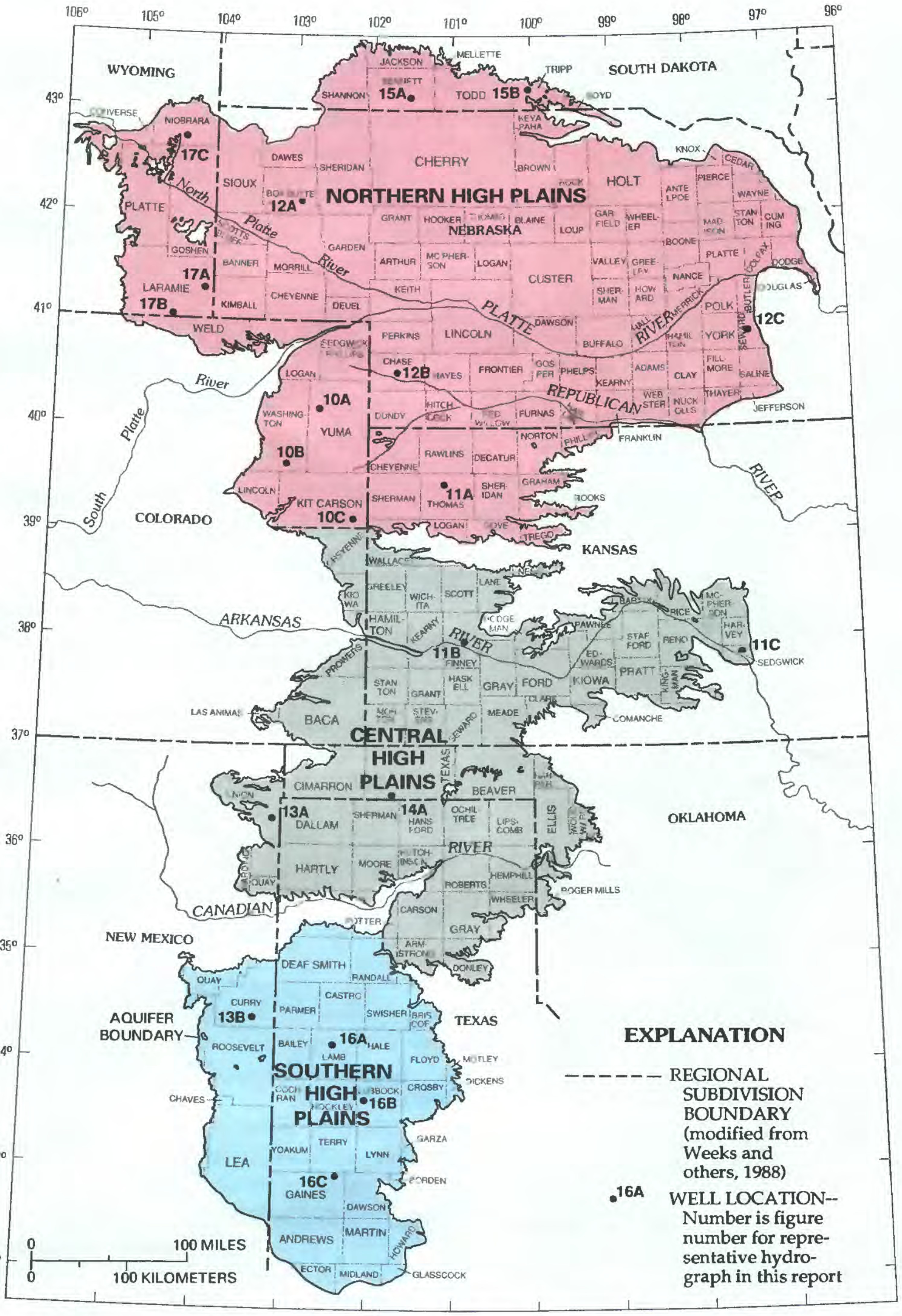

Figure 1. Location and subdivisions of the High Plains aquifer (modified from Dugan and others, 1990).

EXTENT AND DESCRIPTION OF THE HIGH PLAINS AQUIFER

(Modified from Dugan and others, 1990)

High Plains Aquifer Underlies Parts of Eight States--South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas.

The principal source of water in the High Plains is ground water from saturated unconsolidated deposits. This source has been named both the "Ogallala aquifer" and the "High Plains aquifer"; the term "Ogallala aquifer" was used widely in the past. The High Plains aquifer consists mainly of one or more hydraulically connected geologic units of late Tertiary or Quaternary age with the Ogallala Formation normally the principal unit (Gutentag and others 1984, p. 8).

The High Plains aquifer underlies about 174,050 square miles in parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas (table 1). The thickness of the aquifer ranges from less than 1 foot at the edge to as much as 1,300 feet in north-central Nebraska. The average saturated thickness is about 200 feet. The specific yield (the volume of water that will drain by gravity from the aquifer pore spaces) differs throughout the area but averages about 15 percent of the total volume of saturated material. Therefore, the total volume of water that could drain from the aquifer would be about 3,250 million acre-feet (Gutentag and others, 1984). Economic constraints, however, limit the availability of this water.

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 parts of Wyoming. In places, the original plain was dissected; elsewhere new sediments were deposited on the plain.

The oldest formation included in the High Plains aquifer is the Brule Formation (table 2), which 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 and 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 Ogallala Formation was deposited after the Arikaree Group by streams flowing from the ancestral Rocky Mountains. The Ogallala is the dominant formation in the High Plains aquifer over most of the High Plains and is composed of a variety of materials, including clay, silt, sand, and gravel.

Sand dunes were formed on the older High Plains deposits in several areas. The largest of these areas is in the Sand Hills in north-central Nebraska where the deposits exceed 300 feet in thickness, and in Kansas south of the Arkansas River. The dunes are now stabilized by vegetation, but major dune formation continued until about 1,500 years before the present (Swinehart, 1989).

Quaternary streams eroded older formations and re-deposited the sediments as valley-fill material. Present-day streams continue to erode and deposit sediments. Where the sand dunes and stream deposits are saturated and are hydraulically connected to the High Plains aquifer, they are considered to be part of the High Plains aquifer. These deposits are relatively widespread and are locally important sources of water; however, only in Kansas and Nebraska are these Quaternary deposits an areally significant part of the High Plains aquifer.

Table 1. *Characteristics of the High Plains aquifer*

[Source: Gutentag and others, 1984]

			Area of High Plains aquifer							
Characteristic	Units of measurement	Total	South Dakota	Wyoming	Nebraska	Colorado	Kansas	New Mexico	Oklahoma	Texas
Area covered by aquifer	Square miles	174,050	4,750	8,000	63,650	14,900	30,500	9,450	7,350	35,450
Percentage of total aquifer area	Percent	100	2.7	4.6	36.6	8.6	17.5	5.4	4.2	20.4
Percentage of each State covered	Percent	--	7	8	83	14	38	8	11	13
Drainable water in storage	Million acre-feet	3,250	60	70	2,130	120	320	50	110	390

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

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

			Location where the unit is a significant part of the High Plains aquifer							
Geologic unit comprising the aquifer	Age and time before present, in million years	Composition	South Dakota	Wyo-ming	Ne-braska	Colo-rado	Kan-sas	New Mexico	Okla-homa	Texas
Dune sand	Quaternary (Holocene); 0.008 to 0.0015.	Sand, very fine- to medium-grained, windblown.			X		X			
Valley-fill and alluvial deposits	Quaternary (Holocene and Pleistocene); 1.8 to present.	Clay, silt, sand, and gravel, unconsolidated.			X		X			
Ogallala Formation	Tertiary (Miocene); 19 to 5.	Clay, silt, sand, and gravel generally unconsolidated where cemented by calcium carbonate, forms mortar beds.	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				

FACTORS AFFECTING WATER-LEVEL CHANGE--RECHARGE

(Modified from Dugan and others, 1990)

Recharge to the High Plains Aquifer is Affected By Climatic Conditions, Soil Characteristics, Vegetative Cover, and Land Use.

Water-level changes in an aquifer reflect the difference between recharge to and discharge from the aquifer. Almost all recharge to the High Plains aquifer originates naturally as infiltration of local precipitation. In a few isolated areas of the High Plains, however, recharge and rising water-table conditions have resulted from downward seepage of surface-water irrigation or water diverted for hydroelectric-power generation.

Ground-water recharge is a complex, dynamic process, and is dependent on the interaction of several variables. A simplified explanation for the recharge process is that recharge occurs when the amount of water infiltrating the soil exceeds the soil's available water capacity, and the excess water percolates below the root zone. In addition to the amount and seasonal distribution of precipitation, natural recharge is determined by variables that affect water consumption or loss from the soil, including runoff. These include evapotranspiration, soil characteristics, vegetation type, and land use.

Average annual normal precipitation ranges from less than 14 inches along the western boundary of the High Plains to about 30 inches in eastern Nebraska and central Kansas (fig. 2). About 75 percent of the precipitation usually occurs during the growing season, from April to September. Precipitation during this season occurs mainly as local thunderstorms; therefore, irrigation requirements and recharge within a given area during a particular time period may be quite variable.

The amount of water in the soil that becomes available for recharge is dependent on evapotranspiration. Potential evapotranspiration (fig. 2) indicates the amount of atmospheric energy available, theoretically, for the removal of water from the soil either directly as evaporation or as transpiration from vegetation. Potential evapotranspiration represents the maximum water consumption that would occur from a field with complete vegetative cover, provided that an adequate supply of soil water were available at all times to meet the vegetation's demands. Potential evapotranspiration is dependent on various climatic or atmospheric elements, which 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. The actual evapotranspiration or the amount of soil water actually consumed 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 is significant to the recharge process. In the High Plains, actual recharge is most likely to occur during short periods in the non-growing or dormant season when evapotranspiration demand upon the soil water is minimal and precipitation is allowed to accumulate in the root zone and percolate downward. This accumulative process during the dormant season may extend over a period of time, with late autumn precipitation remaining in the soil column during winter and percolating downward only after spring precipitation and winter snowmelt cause the soil's available water capacity to be exceeded. Thus, antecedent soil-water conditions, winter snow, and early spring precipitation prior to the onset of the growing season and the seasonal increase in evapotranspiration are critical to recharge during the dormant season.

The hydrologic characteristics of the soils can have a significant effect on recharge and resultant water-level change. Areas with sandy soil tend to have much higher potential recharge. Under equivalent vegetative and climatic conditions, potential recharge rates are several times higher on sandy soils than on silty clay-loam soils, as a result of sandy soils' lower available water capacities and higher permeabilities. Slope affects the rate at which precipitation infiltrates and becomes soil water. Soils with silty clay-loam textures on steep slopes, common in parts of the High Plains, are

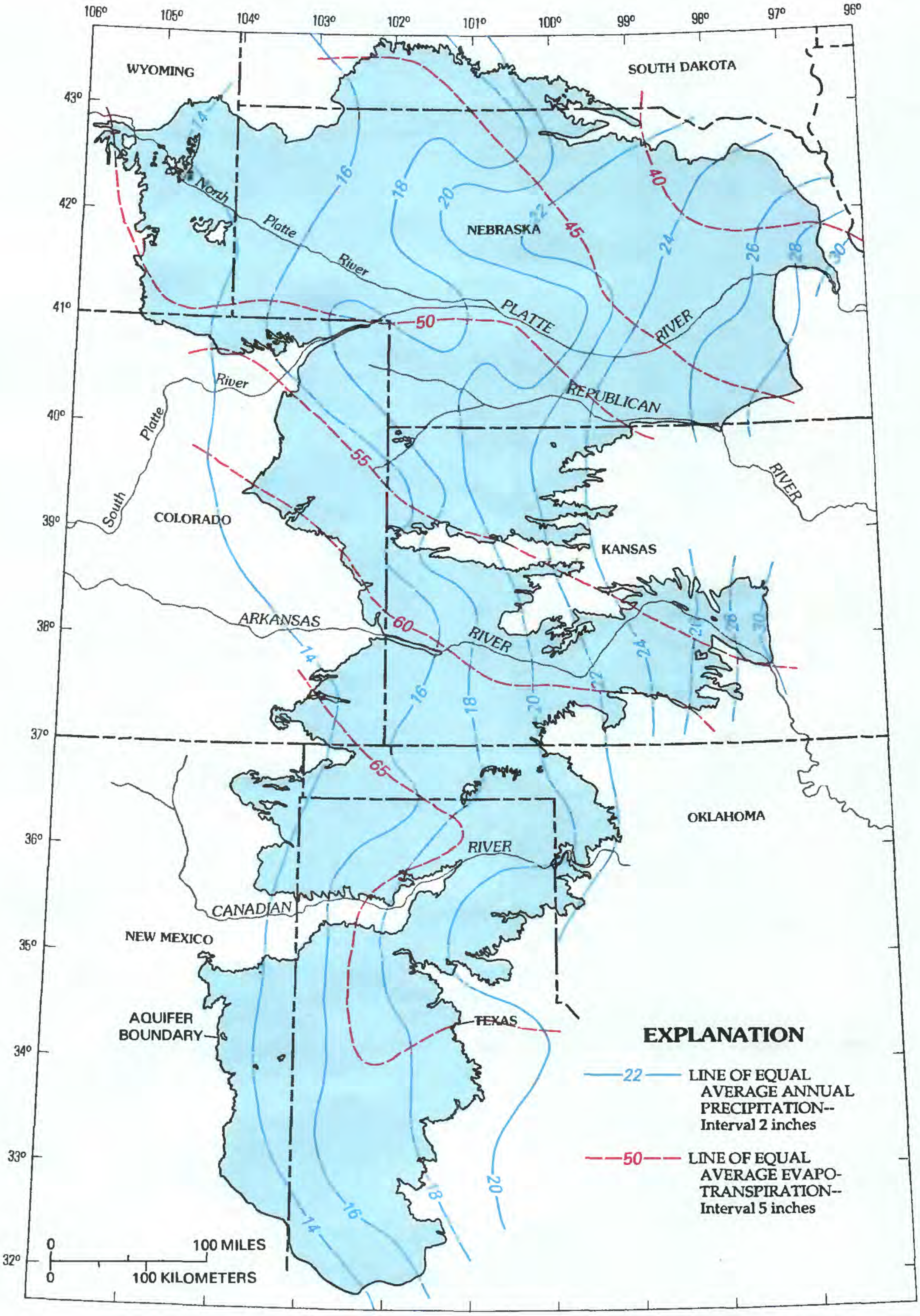

Figure 2. Average annual precipitation and potential evapotranspiration, 1951-80 (Jack T. Dugan and Ronald B. Zelt, U.S. Geological Survey, written commun., 1990).

characterized by high overland runoff and low infiltration during moderate- to high-intensity rainfall. A more complete discussion and generalized map of the hydrologic characteristics of the soils and their relative effects on recharge in the High Plains is found in Dugan and others (1990).

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

Various government programs to remove cropland from production, including the Conservation Reserve Program, which was implemented in 1986 as part of the Food Security Act of 1985, have caused widespread, long-term changes in land-use 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 may result in a decrease in recharge because of the larger water requirement for grasses (Luckey and others, 1981), the subsequent effects on water levels probably will be more than offset by decreases in ground-water withdrawals for irrigation as a result of these land-use changes.

Certain cropping practices in the High Plains can have a significant effect on recharge. The rotation of cropland from winter wheat to fallow in the western High Plains results in more than 25 percent of the land being fallow in any given year in some areas. Fallow conditions increase potential 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 potential 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.

The estimated average annual recharge rate in the High Plains ranges from about 0.025 inch to about 6 inches (Weeks and others, 1988). These values compare favorably with simulated potential recharge rates for the 1951-80 period reported by Jack T. Dugan and Ronald B. Zelt of the U.S. Geological Survey (written commun., 1990) of less than 0.10 inch in the drier parts of the western High Plains to more than 6 inches in northeast Nebraska and central Kansas where soils are sandy. These recharge amounts represent from less than 0.5 percent to about 20 percent of the average annual precipitation (Jack T. Dugan and Ronald B. Zelt, U.S. Geological Survey, written commun., 1990).

Recharge throughout in 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, particularly in those areas where average annual precipitation is low. Most of the long-term average recharge may result from a few short wet periods. This process is often cyclical in the High Plains, with 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.

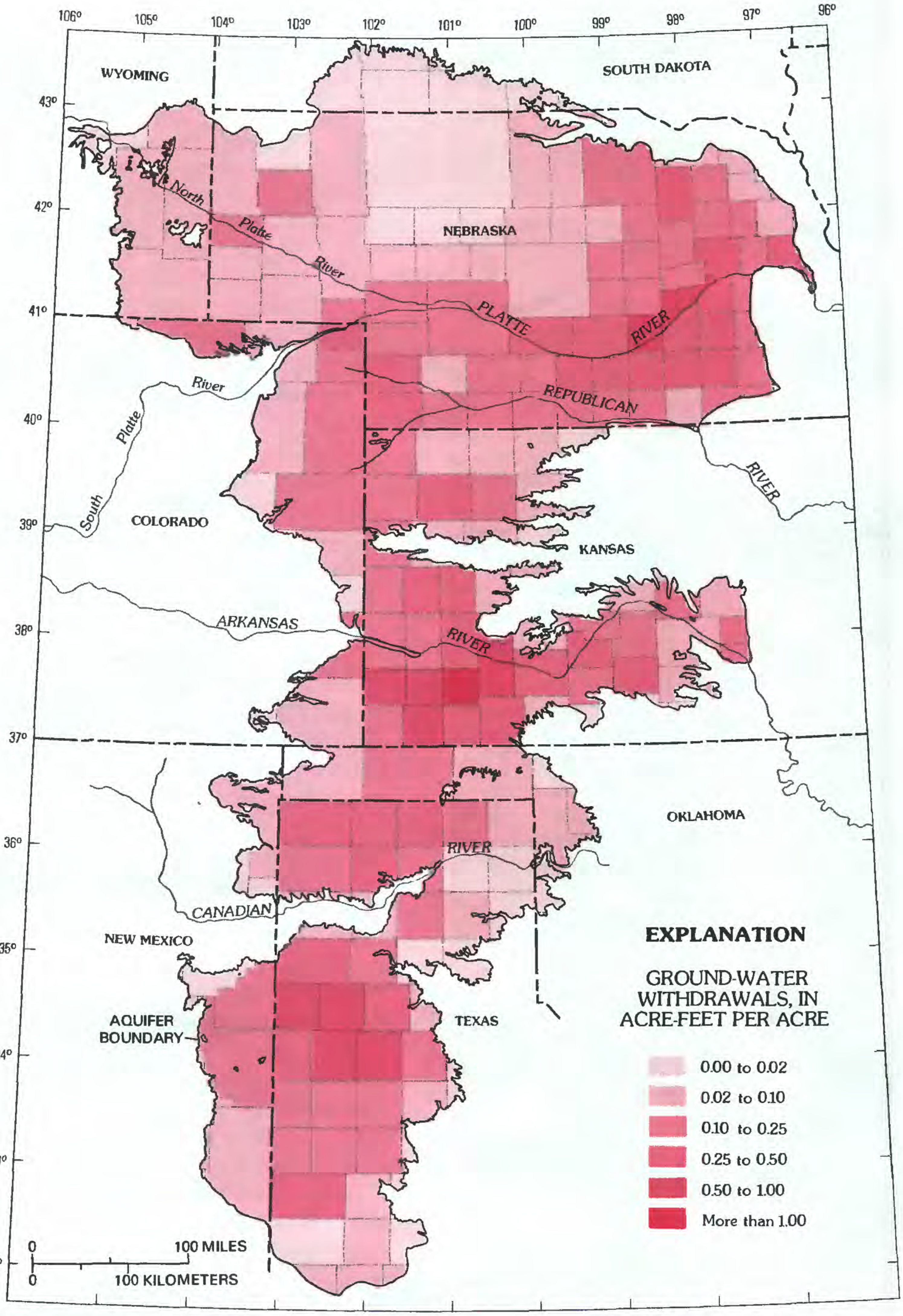

Figure 3. Ground-water withdrawals during 1985, by county. Withdrawals for hydroelectric-power generation and sewage treatment are not included. (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

FACTORS AFFECTING WATER-LEVEL CHANGE--GROUND-WATER WITHDRAWALS FOR IRRIGATION

Ground-Water Withdrawals for Irrigation are Dependent on Both Natural and Human Factors.

Water is lost or discharged from an aquifer both naturally and artificially. Natural discharge occurs as evapotranspiration through plants and soil, where the water table is near the surface, and by seepage from the aquifer through springs or streams. Artificial discharge from an aquifer occurs as pumpage from wells. Wells supply most of the water needs in the High Plains, including agriculture, domestic consumption, mining, and industrial use. About 96 percent of the ground water pumped from the High Plains aquifer is for irrigation and other agricultural uses (Wayne Solley, U.S. Geological Survey, written commun., 1988).

The U.S. Geological Survey, in cooperation with State and local agencies throughout the country, has collected, stored, and published national water-use information at 5-year intervals since 1950. The High Plains data from 1985 were used to compile a map (fig. 3) of ground-water withdrawals by county (U.S. Geological Survey, 1990). The values in figure 3 were derived by dividing the total ground water used in the county by the area of the county.

The estimated total volume of water withdrawn from the High Plains aquifer for 1985 was 17,070,000 acre-feet (Wayne Solley, U.S. Geological Survey, written commun., 1988). This estimate is based on: (1) Extrapolation of metered pumpage, which generally represents a small percentage of the total pumpage; (2) the extrapolation of estimated use per person or per head of livestock; and (3) estimates of the water, supplemental to precipitation, required to raise crops.

Withdrawals of ground water from the High Plains aquifer in 1985 were about 19 percent less than in 1980 (Wayne Solley, U.S. Geological Survey, written commun., 1988). The decrease in ground-water withdrawals was due to several factors:

1. The volume and timing of precipitation during 1985 resulted in a requirement for less irrigation pumpage than in 1980. As an example, the supplemental water needed for raising irrigated crops in Nebraska was estimated to be 22 percent less in 1985 than in 1980 (Steele, 1988).

2. A reduction in agricultural commodity prices and increased irrigation and other production costs by 1985 made irrigation of crops less profitable.

3. Less water was required to fulfill irrigation requirements because of improved agricultural management practices. These practices included widespread use of minimum tillage methods, more precise irrigation scheduling through increased knowledge of soil-water conditions, and improved plant varieties that utilized available soil water more efficiently.

Ground-water withdrawals do not represent the actual consumption or water permanently lost from the aquifer. Only that water consumed by evapotranspiration or that runs off into drainageways is actually lost. Because runoff generally is minimal with most current irrigation systems and because the amount of water applied to crops often exceeds evapotranspiration, a substantial amount of the applied water may infiltrate through the overlying soil and unsaturated zones and return to the aquifer as recharge. Thus, ground-water withdrawals alone will not fully explain water-level changes.

HISTORY OF GROUND-WATER DEVELOPMENT AND WATER-LEVEL CHANGES IN THE HIGH PLAINS, PREDEVELOPMENT TO 1980

(Modified from Dugan and others, 1990)

Irrigation in the High Plains Largely Depends on Ground Water.

A U.S. Army expedition headed by Major Stephen Long crossed part of the High Plains region in 1819-20. In the journals of the expedition the area was described 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). Contrary to this assessment, the High Plains has become one of the major agricultural regions of the United States.

Settlement of the High Plains was encouraged through incentives like the Homestead Act of 1862 and Railroad Land Grants following the Civil War. The subsequent development of railroads allowed settlers easier access to the region and made it easier for them to market their agricultural products. The major impetus for the intensive agricultural development of the region, however, was the availability of water for irrigation. The availability of surface water along some streams, such as the North Platte River, permitted irrigation in limited areas. Widespread irrigation development in the High Plains, however, depended on the availability of ground water for irrigation and readily available low-cost fuel or energy.

Several factors have contributed to the increase in the use of ground water for irrigation in the High Plains. Variability of the climate has been especially important. During droughts, many farmers switched from dryland farming to irrigation in order to stabilize production. During and after the drought of the 1930's, use of ground water for irrigation increased, particularly in the southern High Plains. During the drought of the mid-1950's, irrigation expansion took place principally in the central and northern High Plains.

Fluctuations in the farm economy also have affected ground-water irrigation development. Increases in crop prices and decreases in well-drilling costs have stimulated increases in ground-water withdrawals. Development of natural gas fields and rural electrification in the High Plains during the 1950's provided inexpensive energy for pumping and spurred irrigation development. An increase in energy costs that accompanied the "oil embargo" in the mid-1970's and an increase in pumping costs, caused partly by the lowering of water tables, however, have deterred additional development.

Another important factor in the increased use of ground water for irrigation has been the changes in irrigation technology. Before 1900, withdrawal of ground water was by windmills from shallow wells dug by hand or drilled by horse-powered drill rigs. Improved drilling methods and the availability of gasoline-powered engines by the early 1900's allowed pumping from somewhat greater depths and opened new areas to irrigation with ground water. The development of more efficient turbine pumps by the early 1960's permitted cost-efficient pumping from water tables more than 100 feet below land surface (Weeks and others, 1988, p. A10). Also, in the 1960's, center-pivot irrigation systems were introduced, which made it possible to irrigate areas of sandier soils and steeper topography than could be irrigated with flood irrigation systems. With these advances in technology, ground-water development increased rapidly in the late 1960's and early 1970's, especially in the northern High Plains.

The development of the aquifer for irrigation has affected ground-water levels in most of the High Plains. Water-level changes from predevelopment to 1980 are shown in figure 4. Predevelopment water levels are those estimated to have existed before any effects imposed by human activity. In general, irrigation development had affected water levels in the southern High Plains by 1940, the central High Plains by 1950, and the northern High Plains by 1960. In parts of north-central Nebraska, South Dakota, and Wyoming, ground-water levels still represent predevelopment conditions.

By 1980, the greatest decline in water levels had occurred in the southern High Plains of New Mexico and Texas. Water levels had declined more than 50 feet in a large part of this area with a maximum decline of nearly 200 feet in Texas. Water levels also had declined more than 50 feet in smaller areas of the central High Plains, in northern Texas, in the Oklahoma Panhandle, and in southwestern Kansas. In a few areas, predominantly in Nebraska, water levels rose as the result of increased recharge through surface-water irrigation and leakage from canals and reservoirs (Weeks and others, 1988).

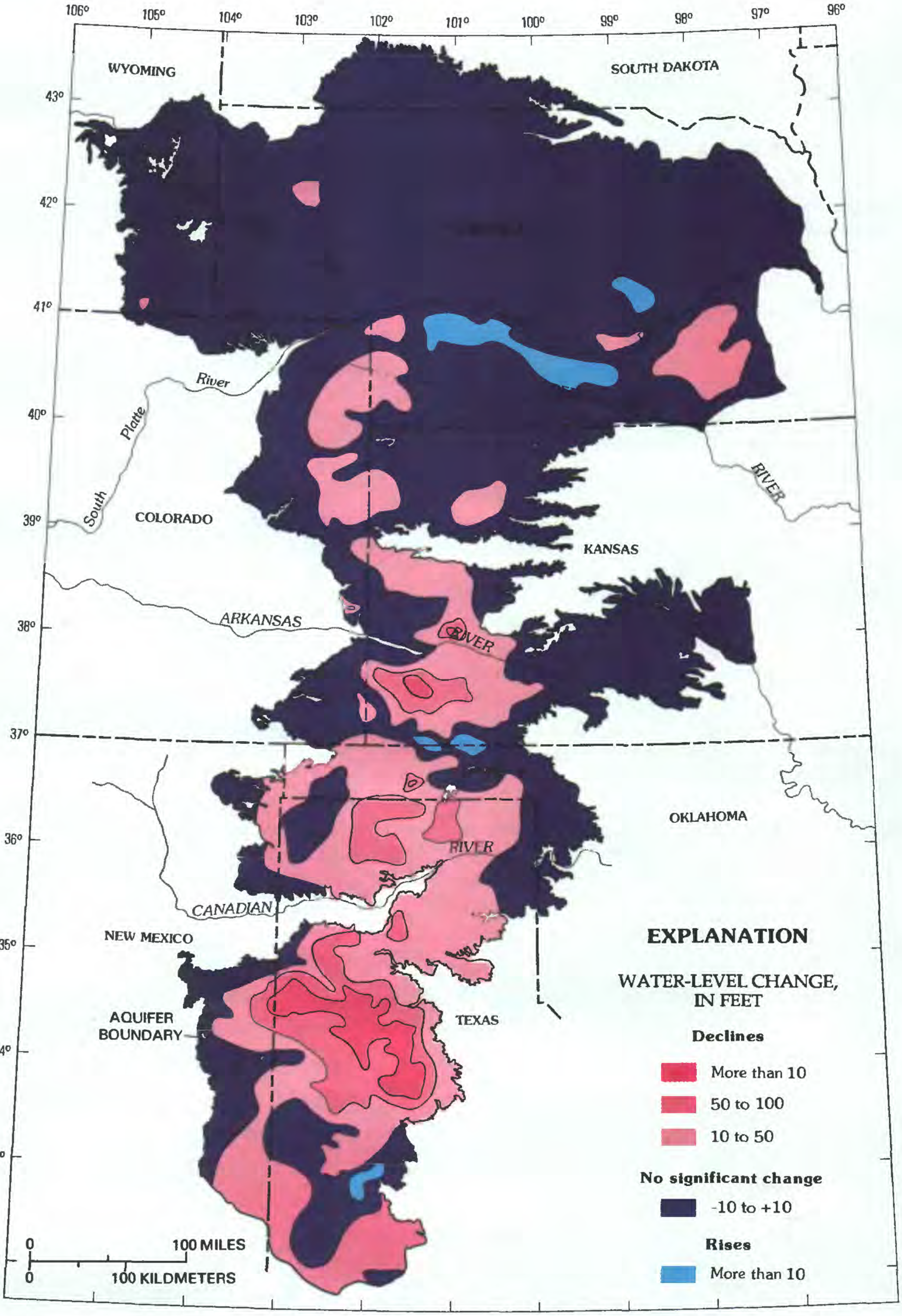

Figure 4. Water-level changes in the High Plains aquifer, predevelopment to 1980 (modified from Weeks and others, 1988).

OBSERVATION-WELL LOCATIONS IN THE HIGH PLAINS AND METHODS OF DATA ANALYSIS AND PRESENTATION

1989-90 Water-Level-Change Patterns Based on Nearly 8,000 Observation Wells.

Water-level changes are based on measurements in 7,085 wells for 1980 to 1990 and 7,988 wells for 1989 to 1990 (table 3). The location of those wells in which water levels were measured in both 1989 and 1990 is shown in figure 5. Most measurements are made in late winter and early spring, although some are made in the fall following the irrigation season.

The density of water-level observation wells is governed principally by the degree of ground-water irrigation development. In those areas of central Nebraska and parts of Texas with dense observation wells, more than 50 percent of all agricultural land, including rangeland, is irrigated. Most areas with low observation-well density are those where ground-water development for irrigation is minimal and there is little perceived need for intensive water-level change information.

Polygons were defined to represent areas of equal water-level change according to the Theissen-polygon method (Theissen, 1911). In this method, the size and shape of a polygon is governed by the distance and location of other observation wells in respect to the well representing a particular polygon or area. Where observation wells are widely spaced, the polygons are large; conversely, where observation wells are closely spaced, the polygons are small. The use of polygons to depict areas of equal water-level change was deemed the most suitable method for short-term, nonuniformly distributed data.

The polygons depicting areas of equal water-level change for the two time periods are shown in figures 6 and 8. Cases where the number of polygons exceed the number of wells in a State (table 3) result from polygons including areas in more than one State and being counted more than once. In Kansas, the number of wells exceed the number of polygons for 1989 to 1990 because there is more than one observation well with the same location; therefore, only one well is selected to represent a polygon.

The area-weighted average by State for both water-level change and precipitation deviations presented in tables in subsequent sections of this report was deemed more appropriate than the simple average of the observation point data. Where a large number of points represent a small area, the simple average would tend to over-represent changes or deviations in that area. The area-weighted value based on polygon size gives each unit area equal representation regardless of observation-well density.

Abrupt differences in water-level changes that occur among adjacent polygons normally reflect contrasting hydrologic conditions at the

Table 3. *Summary of observation wells measured and water-level change polygons, 1980 to 1990 and 1989 to 1990, by State, in the High Plains*

State	1980 to 1990 Number of wells	1980 to 1990 Number of polygons	1989 to 1990 Number of wells	1989 to 1990 Number of polygons
Colorado	565	633	603	683
Kansas	1,136	1,168	1,470	1,459
Nebraska	2,615	2,658	3,338	3,375
New Mexico	214	275	244	284
Oklahoma	320	395	343	397
South Dakota	59	76	78	87
Texas	2,153	2,216	1,868	1,945
Wyoming	23	30	44	59
Totals	7,085	7,451	7,988	8,289

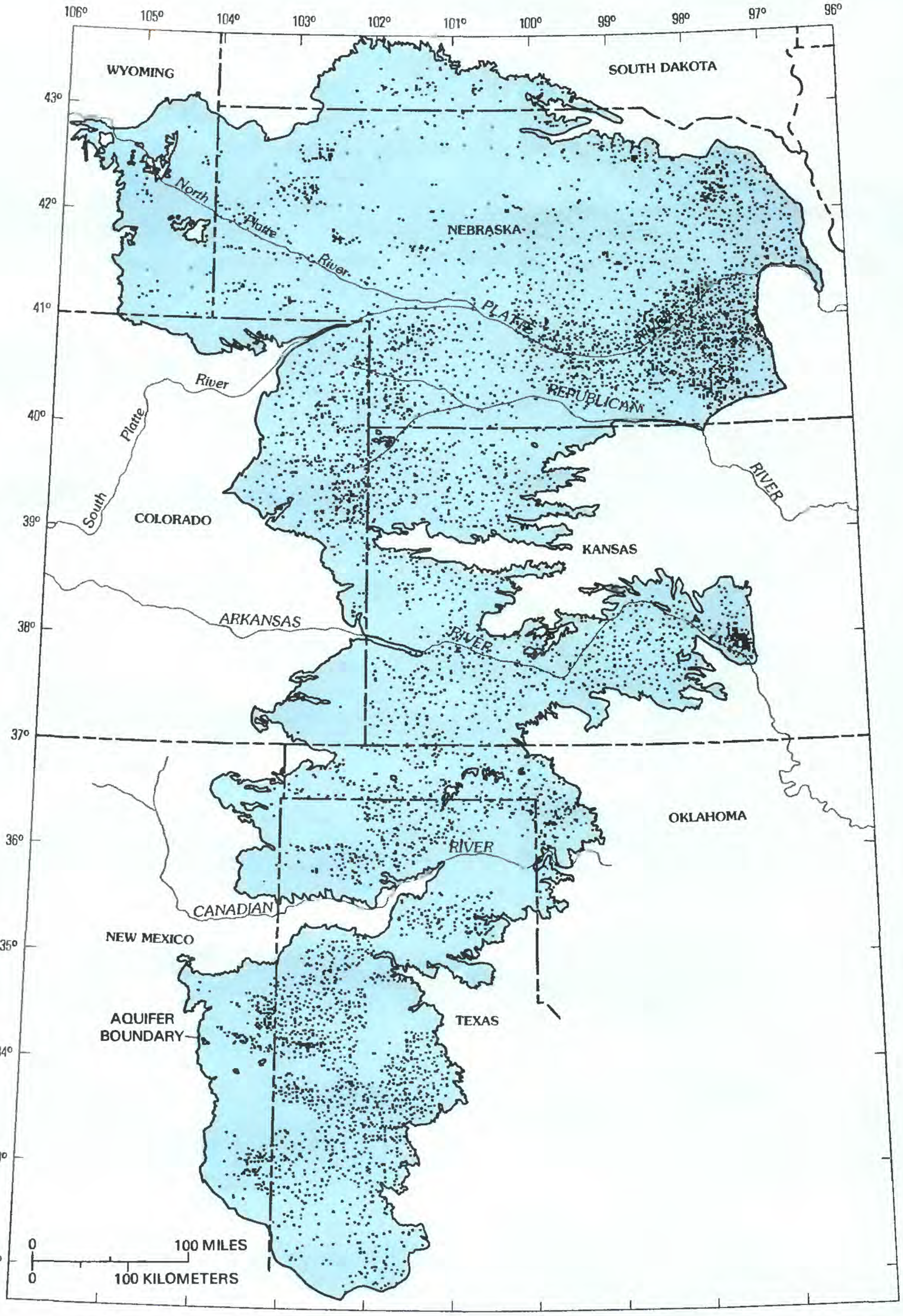

Figure 5. Location of wells with water-level measurements in 1989 and 1990.

observation wells representing each polygon. Variations in precipitation or ground-water withdrawals in the area surrounding an observation well may cause considerable variability in water-level change.

The total number of observation wells used in the analyses for the two time periods represents a significant increase over those used for 1980 to 1989 and 1988 to 1989, as documented in the previous report (Dugan and others, 1990). More than 2,000 wells were added to the 1980 to 1990 data base compared with 1980 to 1989, and nearly 1,800 wells were added to the 1989 to 1990 data base compared with 1988 to 1989. Most of this increase was for Texas, where additional data were acquired. The number of polygons representing areas of water-level change also increased accordingly.

WATER-LEVEL CHANGES IN THE HIGH PLAINS AQUIFER, 1980 to 1990

Dewatering of the High Plains Aquifer has Slowed in Most Areas Since 1980.

Water-level changes in the High Plains from 1980 to 1990 (fig. 6) varied significantly from predevelopment to 1980, as reported by Gutentag and others (1984). In most of the High Plains, dewatering of the aquifer has slowed considerably or has reversed during 1980 to 1990. Several factors have contributed to this overall slower rate of water-level decline since 1980: (1) above-normal precipitation, (2) a decrease in irrigated crop acreages, (3) improved irrigation scheduling, and (4) application of more efficient irrigation technology. These factors will be discussed subsequently in greater detail.

A comparison of water-level changes and estimated changes of water in storage from predevelopment to 1980 with changes from 1980 to 1990 is shown in table 4.

These comparisons are approximate because methods of computing areas of water-level change and the data bases for water-level change differ somewhat between the time periods. Water in storage in the High Plains aquifer for both time periods is based on 15 percent (0.15) average yield of water by gravity drainage from the pore spaces of saturated material (Weeks and others, 1988). Even though the data are not completely comparable, it is apparent that rates of decline of water levels and of water in storage are much smaller from 1980 to 1990 than from predevelopment to 1980. If 1950 is used as an average date for the predevelopment in the High Plains, the average annual rate of water-level change from 1950 to 1980 was -0.33 foot as compared to -0.14 foot during 1980 to 1990. Average annual changes in water in storage would be -5.5 million acre-feet for 1950 to 1980 and -1.7 million acre-feet for 1980 to 1990.

The largest shift in rate of water-level change occurred in Texas where the average annual rate of water-level decline decreased from more than 0.8 foot from predevelopment (1940 for southern High Plains) to 1980 to 0.12 foot from 1980 to 1990. Kansas, however, showed a continued large rate of decline after 1980. If 1950 is assumed to be the beginning of development in Kansas, the average annual predevelopment to 1980 rate of decline was about 0.33 foot and from 1980 to 1990 about 0.5 foot. The contrast between the rates of decline in Texas and Kansas may be the fact that ground-water irrigation peaked in Kansas after 1980; whereas, ground-water irrigation peaked prior to 1980 in the Texas High Plains and subsequently declined after 1980 (Kastner and others, 1989).

A comparison of figures 4 and 6 indicates a more complex relation exists in local areas between predevelopment to 1980 and 1980 to 1990. Some areas with water-level declines from predevelopment to 1980 became areas of water-level rises from 1980 to 1990. The most significant areas of reversal were in the extreme southern High Plains of Texas and New Mexico, where water levels declined more than 50 feet by 1980 but rose by more than 15 feet in some areas from 1980 to 1990. Another area showing a reversal of water-level declines from predevelopment to 1980 was southeastern Nebraska, where rises of 7.5 to 15 feet occurred from 1980 to 1990 following declines of 10 to 50 feet from predevelopment to 1980.

Certain areas that had significant water-level declines from predevelopment to 1980, however, continued to show significant declines from 1980 to 1990. Parts of the central and southern High Plains in southwestern Kansas, the Panhandles of Texas and Oklahoma, and eastern New Mexico, which had declines exceeding 100 feet from predevelopment to 1980, showed some areas of decline exceeding 15 feet from 1980 to 1990. Declines of 10 to 50 feet in a large area of extensive irrigation development in northeastern Colorado and southwestern Nebraska by 1980 showed additional declines of 7.5 to 15 feet by 1990. Other areas of continued significant declines in the northern High Plains include an area in the Nebraska Panhandle (Box Butte County) and in northwestern Kansas (Thomas and Sheridan Counties). These areas had declines of 10 to 50 feet from predevelopment to 1980, with additional declines of 7.5 to 15 feet by 1990.

In most areas of significant water-level declines, both prior to and since 1980, the rate of decline has become slower. In the areas of declines exceeding 100 feet in the southern High

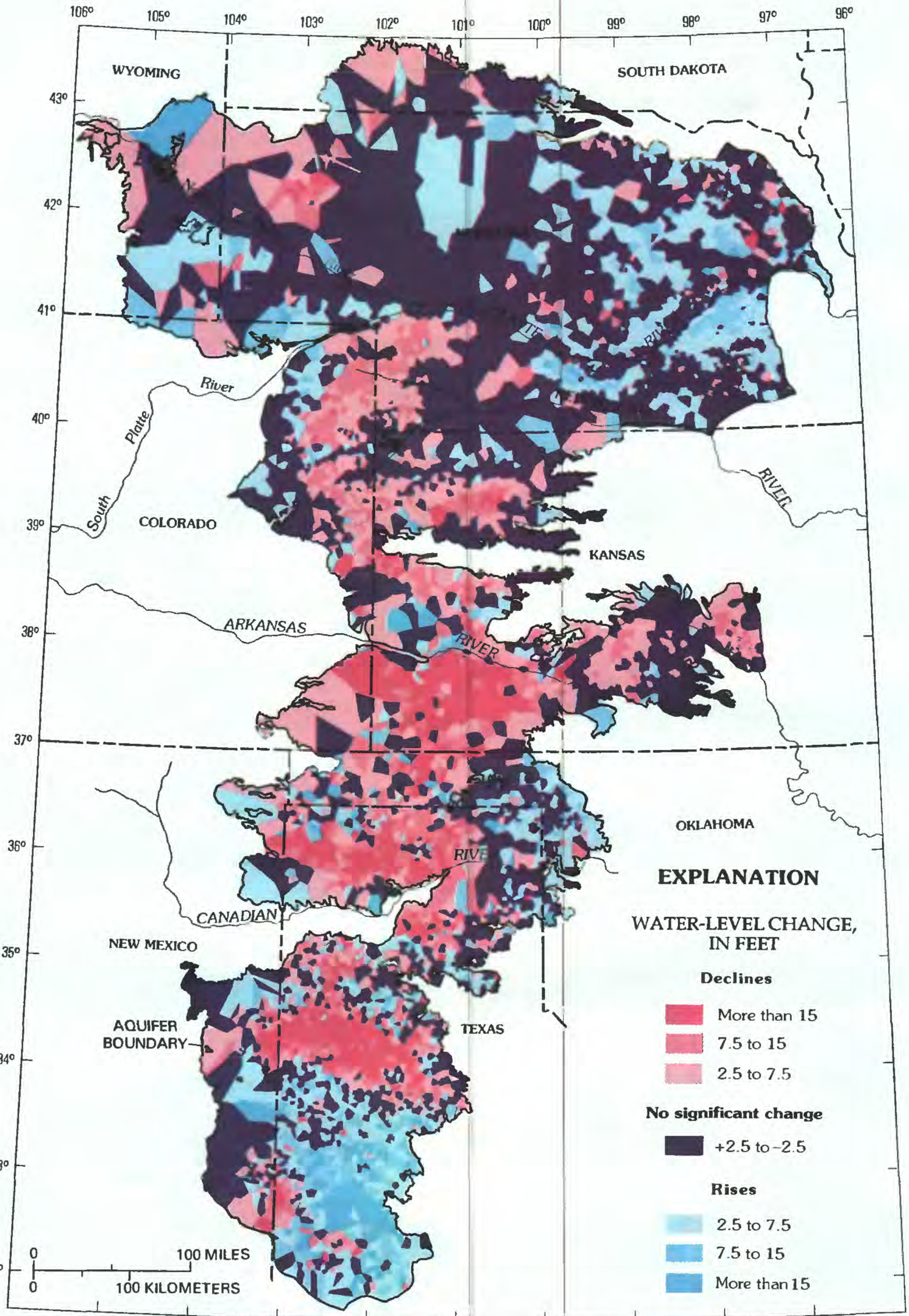

Figure 6. Water-level change, in feet, 1980 to 1990.

Plains of Texas and New Mexico prior to 1980, the average annual rate of decline from predevelopment (1940) to 1980 was more than 2.5 feet. However, from 1980 to 1990 the average annual rate of decline was less than 2 feet.

In those areas of the central High Plains where large water-level declines occurred prior to 1980, which includes parts of southwestern Kansas and the Oklahoma and Texas Panhandles, the rate of decline also has decreased slightly. In these areas, average annual rates of decline decreased from nearly 2.5 feet per year from predevelopment (1950) to 1980 to about 2 feet per year from 1980 to 1990.

In the northern High Plains, average annual rates of decline also generally decreased since 1980. In northeastern Colorado and southwestern Nebraska, declines were approximately 30 feet from 1965 (approximate beginning of development in this area) to 1980, or 2 feet per year. From 1980 to 1990, declines in these areas have averaged less than 1 foot per year. In the two smaller areas of decline in the northern High Plains (Box Butte County, Nebraska, and Thomas and Sheridan Counties, Kansas), 1980 to 1990 annual rates of decline have continued at approximately the same rate as during predevelopment to 1980--slightly more than 1 foot per year.

Several factors contributed to rising water levels or slower rates of decline during 1980-90:

(1) 1980 to 1990 represents a period of generally above-normal precipitation throughout the High Plains, which resulted in conditions favorable for increased recharge and lower irrigation requirements.

(2) Irrigation-management practices that require less water have become more common since 1980. Irrigation scheduling based on soil-water conditions, construction of water-reuse pits to capture runoff, and adoption of more drought-resistant crop varieties have contributed to more efficient use of irrigation. Consequently, withdrawals for irrigation have declined with no decrease in crop yields.

(3) 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 using open ditches, which can result in water losses of as much as 50 percent, is rarely used at the present time. Recent sprinkler designs, including the low-energy precise-application (LEPA) method, minimize wind losses from center-pivot irrigation. While much of the excess applied water in the past would have been returned to the underlying aquifer through seepage, considerable amounts of water were subject to losses by runoff and evaporation of ponded water. Prior to 1980, much of the discharge of some streams in the High Plains during summer

Table 4. *Comparison of water-level changes and estimated changes of water in storage, predevelopment to 1980 and 1980 to 1990, by State*

State	Estimated area-weighted water-level changes, predevelopment to 1980 (feet)[1]	Area-weighted water-level changes, 1980 to 1990 (feet)	Estimated total change in storage, predevelopment to 1980 (millions of acre-feet)[1]	Total change in storage, 1980 to 1990 (millions of acre-feet)
Colorado	-4.2	-3.08	-6.0	-4.4
Kansas	-9.9	-4.91	-29.0	-14.4
Nebraska	0	+.67	0	+4.1
New Mexico	-9.8	-.66	-9.0	-.6
Oklahoma	-11.3	-.32	-8.0	-.2
South Dakota	0	-1.03	0	-.6
Texas	-33.7	-1.17	-114.0	-4.5
Wyoming	0	+3.14	0	+2.4
High Plains	-9.9	-1.04	-166.0	-18.2

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

months was irrigation runoff.

(4) Economic considerations have dictated reduction in ground-water withdrawals for irrigation. The relative 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 formerly have occurred, irrigated cropland has been converted to dryland crops because of prohibitive pumping costs resulting from decreasing well yields. The increasing costs of well installations and distribution systems have been a further deterrent to additional development.

(5) 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 limit new well construction.

(6) 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 addition, long-term regional droughts of the intensity of those of the 1930's and 1950's, which stimulated irrigation of cropland, did not occur in the High Plains during the 1980's.

PRECIPITATION IN THE HIGH PLAINS, 1981-89

Above-Average Precipitation Contributes to Rises or Slower Rates of Decline in Water Levels in Many Parts of the High Plains.

Precipitation throughout the High Plains during 1981-89 was generally well above the 30-year 1951-80 (normals). The High Plains average annual precipitation was nearly 2 inches above normal, with all States exceeding their normals by more than 1 inch (table 5). Large parts of northeastern and north-central Nebraska, central Kansas, and much of the southern High Plains of Texas and New Mexico exceeded their 30-year normals by 4 to 6 inches (fig. 7). Only in a few small areas in the High Plains was precipitation more than 2 to 4 inches below normal for the period, most notably a part of the Nebraska Panhandle.

Average annual precipitation during 1981-89 ranged from less than 14 inches in eastern Wyoming and the Panhandle of Nebraska to more than 30 inches in eastern Nebraska and central Kansas. Precipitation in the normally semiarid southern High Plains averaged more than 20 inches annually as compared to 30-year annual averages of about 16 inches (fig. 2). Only the extreme southern tip of the southern High Plains averaged less than 16 inches annually during the period, which was slightly above normal for that area.

Areas with water-level rises from 1980 to 1990 (fig. 6) correspond closely to areas with greater than normal precipitation during 1981-89 (fig. 7). Those areas of significant water-level rises in the southern High Plains occurred in areas where average annual precipitation during 1981-89 exceeded the 30-year average by 4 to 6 inches. The areas of widespread water-level rises in northeast and north-central Nebraska from 1980 to 1990, ranging from 2.5 to as much as 15 feet (fig. 6), correspond closely to those areas with annual precipitation 4 to 6 inches above normal during 1981-89. Areas of water-level rise of 2.5 to 15 feet in the western part of the northern High Plains, including southeastern Wyoming, parts of northeastern Colorado, and parts of the southern Panhandle of Nebraska correspond to areas of above-normal precipitation (2 to 6 inches).

The areas of significant water-level decline in the High Plains from 1980 to 1990 do not appear to be closely associated with patterns of precipitation. Areas where declines exceeded 7.5 feet in the High Plains tend to coincide closely with those areas of extensive ground-water withdrawals for irrigation, regardless of the precipitation during 1981-89 (fig. 7). Rates of decline, however, were likely affected by precipitation during the period. The slower rates of decline from 1980 to 1990, as compared to pre-

Table 5. *Average annual precipitation departure during 1981-89 from the 30-year normals (1951-80) in the High Plains, by State*

[Source: Compiled from U.S. Department of Commerce, National Climatic Data Center]

State	Average area-weighted departure, in inches
Colorado	+1.15
Kansas	+1.14
Nebraska	+1.77
New Mexico	+3.58
Oklahoma	+2.52
South Dakota	+1.92
Texas	+3.00
Wyoming	+1.11
High Plains	+1.96

1980 rates in several of these areas, tend to correspond closely to areas of above-normal precipitation for the period. Conversely, the few areas of below-normal precipitation where ground-water withdrawals for the period were substantial, such as Box Butte County in the Nebraska Panhandle, tend to show rates of decline similar to those prior to 1980.

Caution should be exercised in interpreting water-level change in direct relation to precipitation. Neither deviations in precipitation from the long-term averages nor actual precipitation amounts directly correspond to variations in ground-water recharge or consumptive-irrigation requirements. Seasonal patterns of precipitation tend to govern ground-water recharge and consumptive-irrigation requirements more than annual precipitation patterns. The complex relations among precipitation, evapotranspiration, vegetation, soils, and the underlying geologic materials need to be taken into consideration in understanding the changes in ground-water storage, particularly in intensively irrigated areas.

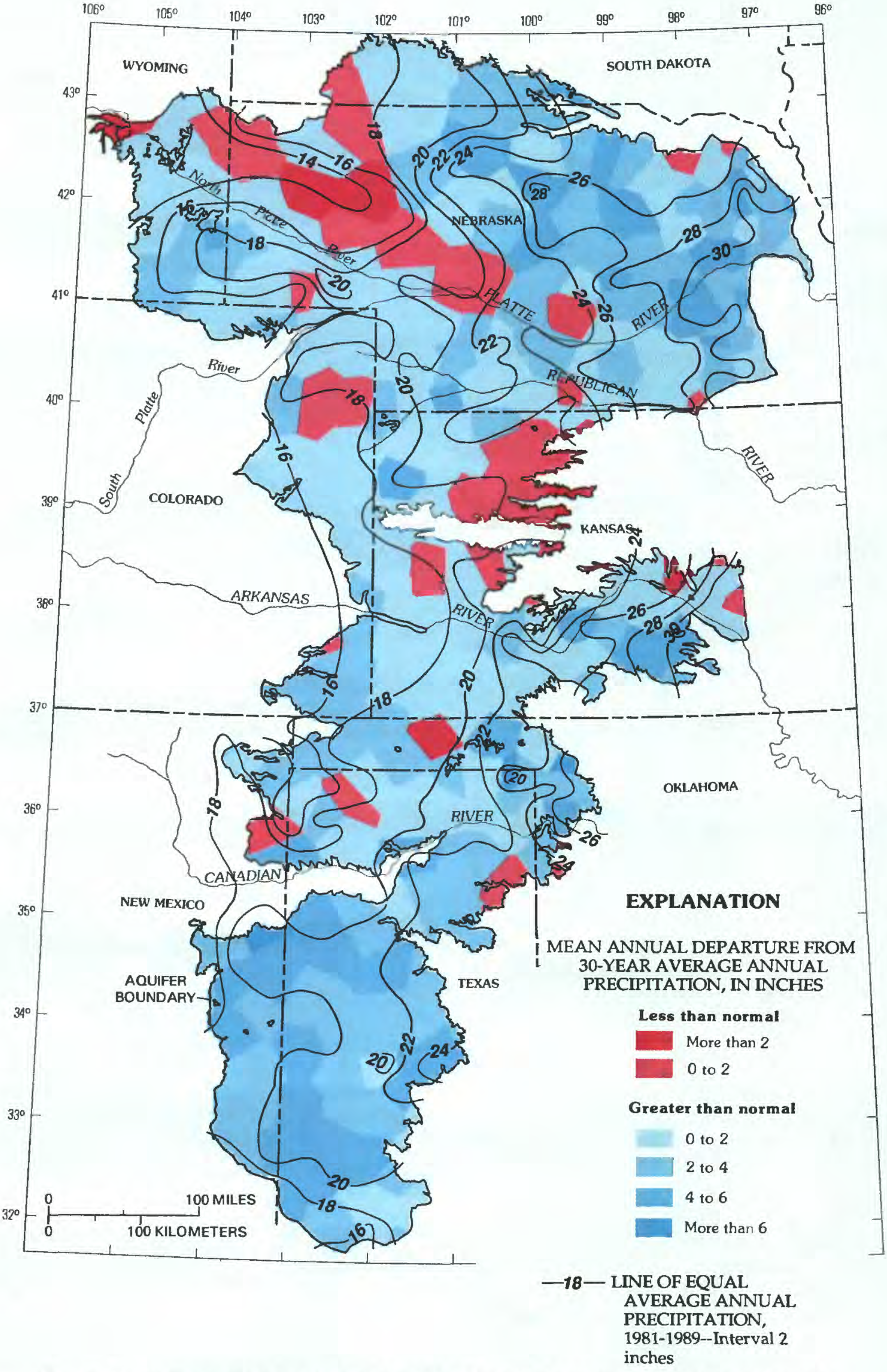

Figure 7. Average annual precipitation, 1981-89, and departure from 30-year normals.

WATER-LEVEL CHANGES IN THE HIGH PLAINS AQUIFER, 1989 TO 1990

Water Levels Decline in Many Parts of the Northern and Southern High Plains but Rise in Parts of the Central High Plains.

Large areas of similar water-level change in the High Plains are not as evident from 1989 to 1990 (fig. 8) as in the previous 2 years (Kastner and others, 1989; Dugan and others, 1990) or from 1980 to 1990. The patterns of water-level change from 1989 to 1990 were mixed, largely because of variability of precipitation in the High Plains during 1989. Areally, most of the High Plains, including some areas with extensive irrigation development, had little change (+1.00 to -1.00 foot). A few small areas, however, had large water-level changes that affected State and regional averages.

Average area-weighted water levels, however, both by State and by region, declined from 1989 to 1990, as indicated in table 6. The Texas High Plains had the largest average change (-1.15 feet), although it is not readily evident in figure 8. The overall decline in Kansas, though relatively small, appears to be the result of substantial declines in a few areas. Numerous small areas of water-level rises are apparent throughout the High Plains of Kansas, which give the perception of an overall rise. For the entire High Plains, the average decline of 0.63 foot from 1989 to 1990 compares closely to the decline of 0.65 foot from 1988 to 1989 (Dugan and others, 1990). The total accumulated decline of 1.28 feet for 1988 to 1990 in the High Plains exceeds the 1980 to 1990 decline of 1.04 feet (table 4).

In the northern High Plains, areas of both rise and decline are evident in figure 8. In northeastern Nebraska, recent water-level declines continued for the third consecutive year, ranging from 1 to 3 feet over much of the area. These declines are in contrast to overall rises of 2.5 to 7.5 feet in that area from 1980 to 1990 (fig. 6). Another area of declines of 1-3 feet in the northern High Plains from 1989 to 1990 was in western Nebraska and eastern Wyoming. Declines occurred over much of northeastern Colorado and southwestern Nebraska in areas of extensive irrigation development, thus continuing the long-term declines in those areas. Another area of 1- to 3-foot declines was in parts of north-central Nebraska (Brown, Rock, and Blaine Counties, and parts of Custer County).

Some areas of substantial water-level rises in the northern High Plains are apparent. Rises of 1 to 3 feet occurred in central Nebraska from 1989 to 1990, where widespread rises occurred from 1980 to 1990. Numerous small areas of water-level rises occurred in parts of northeastern Colorado and northwestern Kansas despite the longer term 1980 to 1990 declines.

In the central High Plains, areas of water-level rise during 1989 to 1990 exceeded areas of decline. In southwestern Kansas, where large declines occurred during the previous 2 years and during 1980 to 1990, numerous areas had rises exceeding 5 feet. Smaller rises of 1 to 3 feet were common in parts of central Kansas and in the eastern Panhandles of Oklahoma and Texas. Water-level rises in parts of the latter area are a continuation of rises during the previous 2 years.

Substantial water-level declines occurred in the western part of the central High Plains, including the western Panhandle of Oklahoma, southeastern Colorado, and the northwestern Panhandle of Texas. In some areas declines exceeded 3 feet from 1989 to 1990.

In the southern High Plains, the pattern of water-level rises and declines, which was evident from 1987 to 1989, continued during 1989 to 1990. Rises of 1 to 3 feet were common over much of the west-central and southern parts of the southern High Plains. A few small areas had rises of more than 5 feet.

A continuing pattern of water-level declines of 1 to 3 feet extended from extreme eastern New Mexico across the northern part of the southern High Plains of Texas from 1989 to 1990. This area had declines of more than 100 feet prior to 1980 (fig. 4) and generally had more than 15 feet of decline from 1980 to 1990 (fig. 6).

Caution should be taken in the interpretation of anomalous 1-year deviations in water levels that are apparent from figure 8. Some of these may represent observation errors but more likely are the result of hydrologic conditions specific to a given area. Among those conditions that may contribute to these anomalies are:

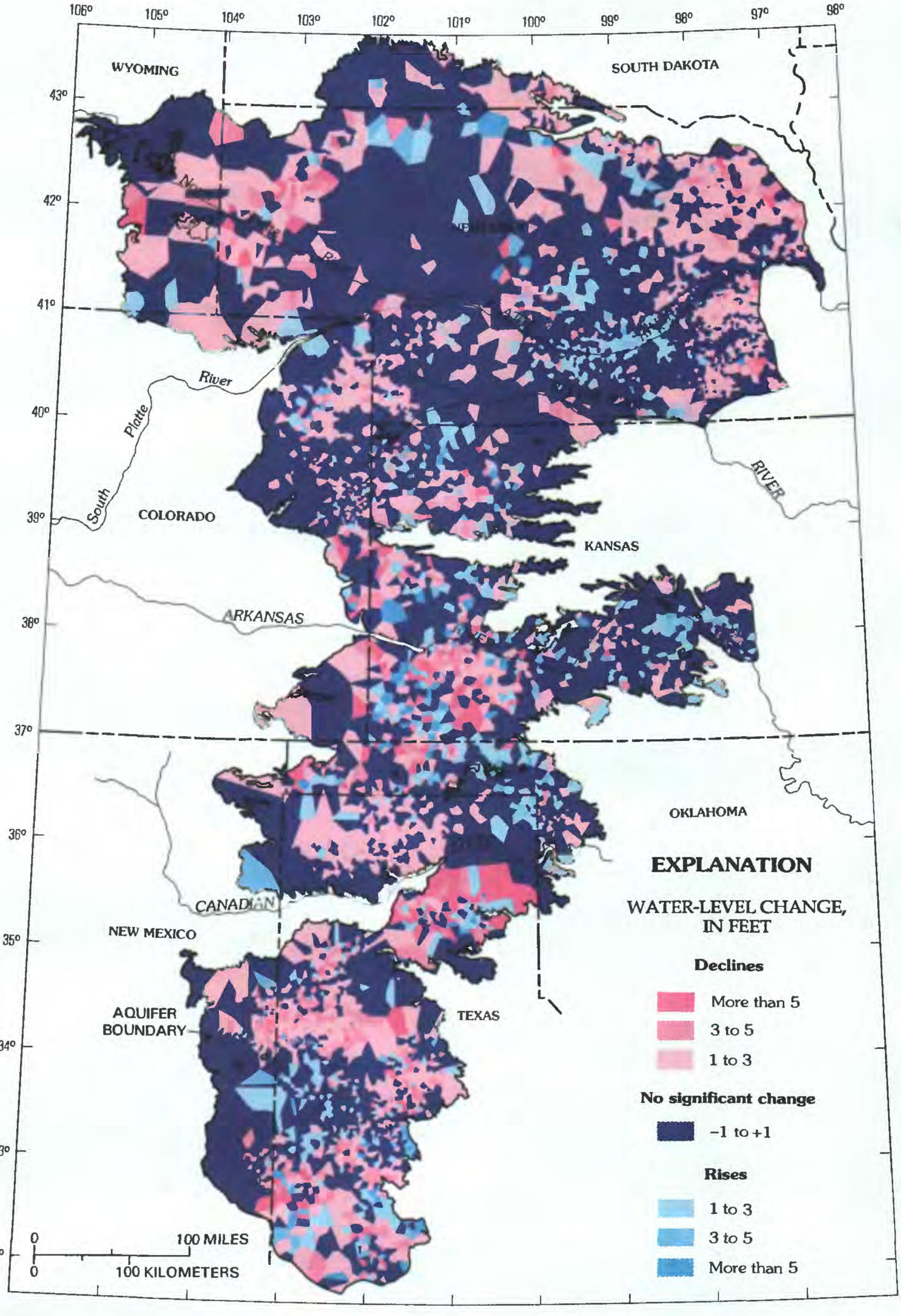

Figure 8. Water-level change, in feet, 1989 to 1990.

(1) Local hydrologic conditions that differ significantly from those of surrounding areas, including confined or semiconfined aquifer conditions.

(2) Intense, local development of irrigation within a larger area of minimal development.

(3) Surface-water irrigation or stream diversions for hydroelectric-power generation, with large seepage losses from canals and reservoirs.

(4) Temporary changes in land-use or cropping patterns, such as substantial areas of irrigated cropland replaced by fallow or dryland crops.

These conditions may result in temporary deviations in regional water-level patterns of change but also could indicate the initial phase of a developing trend in a given area. More detailed discussion of the 1989 to 1990 water-level changes are presented in the State summaries in this report.

Table 6. *Water-level changes from 1989 to 1990, by State*

State	Average area-weighted change (feet)
Colorado	-0.62
Kansas	-.24
Nebraska	-.59
New Mexico	-.29
Oklahoma	-.27
South Dakota	-.63
Texas	-1.15
Wyoming	-.93
High Plains	-.63

PRECIPITATION IN THE HIGH PLAINS, 1989

Precipitation Was Well Below Normal in the Northern High Plains But Well Above Normal in the Central High Plains.

Regional precipitation patterns across the High Plains were variable in 1989. As indicated by State area-weighted averages in table 7 and by figure 9, precipitation in the northern High Plains was considerably below the 30-year normals, the central High Plains was well above normal, and the southern High Plains was slightly below normal. For the entire High Plains, precipitation averaged slightly more than 2 inches below normal.

Precipitation in the northern High Plains was generally well below the 1951-80 30-year normals (fig. 9). In a large area of northeastern and north-central Nebraska, precipitation was from 5 to 10 inches below normal and more than 10 inches below normal in smaller areas. Over most of the remainder of the northern High Plains, precipitation was 2 to 5 inches below normal. In absolute amounts, precipitation in the northern High Plains ranged from less than 10 inches in an area extending from eastern Wyoming to north-central Nebraska to more than 28 inches in a small area in central Nebraska. Precipitation was less than 16 inches over more than one-half of the northern High Plains during 1989 (fig. 9).

Table 7. *Average departure of precipitation in 1989 from the 30-year normals (1951-80), by State*

[Source: Compiled from U.S. Department of Commerce, National Climatic Data Center]

State	Average area-weighted departure (inches)
Colorado	-0.30
Kansas	+.80
Nebraska	-5.22
New Mexico	-1.35
Oklahoma	+3.89
South Dakota	-5.24
Texas	-.49
Wyoming	-1.43
High Plains	-2.01

In contrast, precipitation amounts in the central High Plains were generally greater than the 30-year normals. Large areas in the central High Plains had precipitation amounts from 5 to 10 inches above normal, with a small area centered in the eastern Panhandle of Oklahoma that received more than 10 inches above normal. In absolute amounts, precipitation in the central High Plains ranged from about 12 inches in a few areas of the extreme west to more than 32 inches in south-central Kansas and the eastern Panhandle of Oklahoma. Precipitation exceeded 20 inches over most of the central High Plains during 1989 (fig. 9).

Precipitation across the southern High Plains during 1989 ranged from well above to well below normal. The area with above-normal precipitation in the central High Plains extended into the northern part of the southern High Plains; precipitation was about 2 inches above normal, with a small area receiving 5 to 10 inches above normal. Precipitation in the southern part, however, generally was 2 to 5 inches below normal. In the extreme south, precipitation was 5 to 10 inches below normal. In absolute amounts, precipitation in the southern High Plains during 1989 ranged from less than 8 inches in the extreme south to more than 24 inches in the northeast. Precipitation averaged slightly less than 16 inches over most of the southern High Plains (fig. 9).

The possible effects of 1989 precipitation on 1989 to 1990 water-level changes are apparent from a comparison of figures 8 and 9. Widespread declines ranging from 1 to 3 feet correspond to well below-normal precipitation in parts of the northern High Plains, particularly in northeastern Nebraska, northern Panhandle of Nebraska, and eastern Wyoming, where extensive ground-water withdrawals occur. Water-level rises in parts of central Nebraska correspond to small areas of above-normal precipitation in parts of Buffalo and Hall Counties. Some areas of rise in south-central Nebraska (Gosper, Phelps, and Kearney Counties), however, are more closely associated with surface-water irrigation seepage.

In the central High Plains, water-level rises exceeding 5 feet in some small areas are associated with precipitation that exceeded the normal by 5 to more than 10 inches. This association is most apparent in an area extending from southwestern Kansas across the Oklahoma Panhandle into the extreme northeastern Panhandle of Texas. An area of rise in the extreme southeastern central High Plains coincides with an area of well above-normal precipitation during 1989.

In the southern High Plains, a comparison of figures 8 and 9 shows little apparent relation between 1989 precipitation and 1989 to 1990 water-level changes. The areas of water-level rise evident in the central and southern sections of the southern High Plains prior to 1990 (fig. 6) continued to show rises, although precipitation was well below normal during 1989. The areas of declines in the northern part of the southern High Plains are a continuation of the trends existing prior to and since 1980 (figs. 6 and 8), even though precipitation was near normal or above in 1989. Other factors, including longer term precipitation patterns and intensive irrigation development, are apparently factors in the continuation of these established trends in water-level changes.

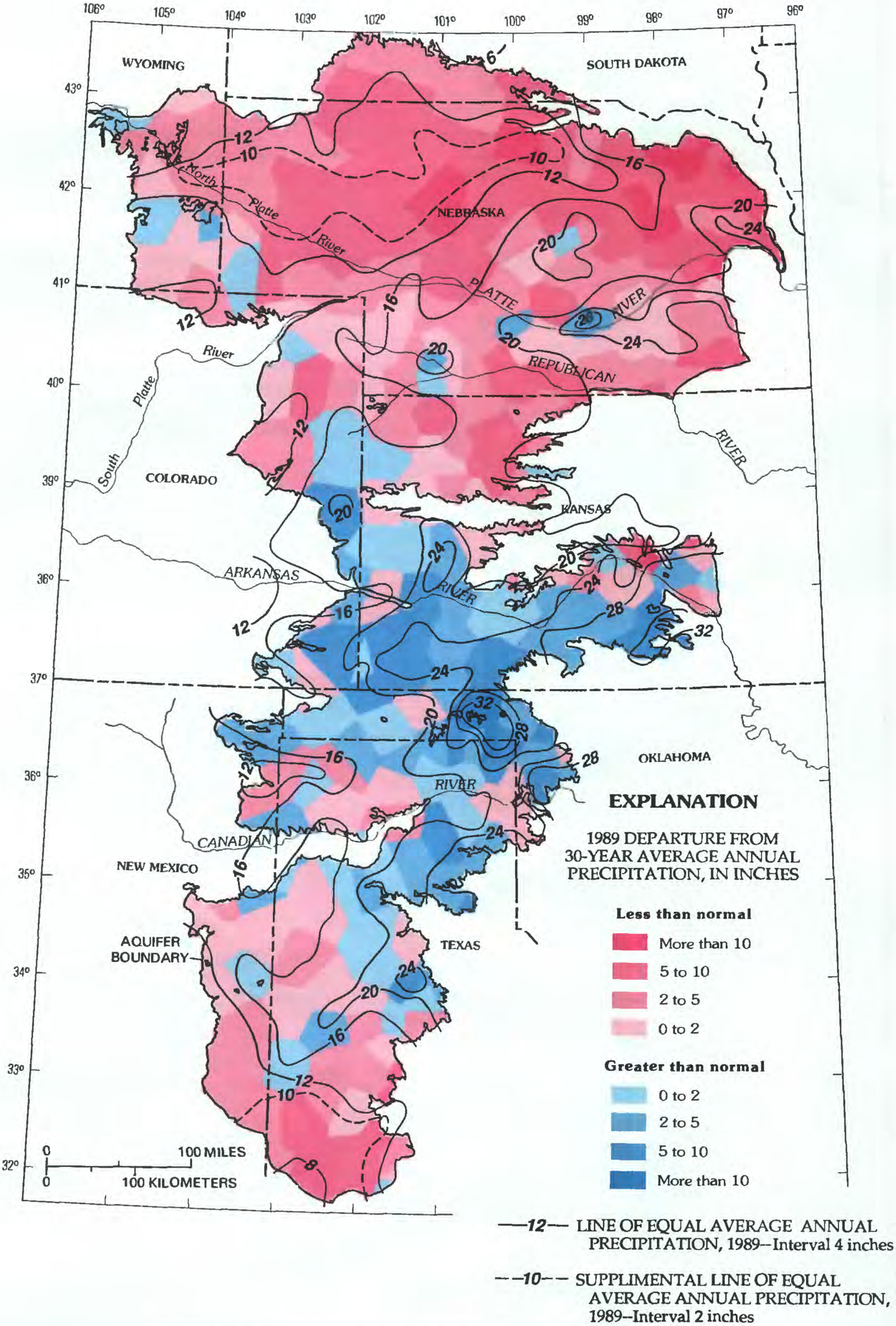

Figure 9. 1989 precipitation and departure from 30-year normals.

STATE SUMMARIES OF WATER-LEVEL CHANGES IN THE HIGH PLAINS AQUIFER, 1980 TO 1990 AND 1989 TO 1990

The purpose of the following State summaries of water-level changes in the High Plains aquifer is to provide greater in-depth analyses of local conditions contributing to these changes. Each State summary follows approximately the same format, varying according to local concerns and emphases.

From one to three hydrographs of observation wells were selected to represent long-term water-level trends in different parts of the High Plains in each State. The length of record of each hydrograph differs because the entire historical record of each well is presented. The following information is indicated on each hydrograph: (1) Well number indicates the latitude and longitude of the well; (2) depth is the total depth of the well; and (3) elevation is the elevation of the land surface at the well. The location of the wells are shown in figure 1.

Certain differences among the well hydrographs result from the method of observation. Some hydrographs that show relatively smooth patterns are from wells measured manually on an annual basis at about the same time each year. Others are from wells equipped with continuous recorders, which show substantial seasonal water-level changes, particularly if the well is located near active irrigation wells. Long-term water-level trends on hydrographs produced from continuous recorders can best be interpreted by examining the annual high points or peaks, which generally represent spring water levels.

COLORADO

Water-Level Declines Widespread in Colorado High Plains

by Edward R. Banta

The High Plains aquifer underlies about 14,900 square miles in eastern Colorado. Water levels in a network of wells in the Colorado part of the aquifer are monitored by personnel of the U.S. Geological Survey and the Colorado Office of the State Engineer. The network includes 565 wells where depth to water was measured during the nonirrigation seasons of 1980 and 1990; depth to water was measured in 603 wells during the nonirrigation seasons of 1989 and 1990.

The rate of ground-water withdrawal in Colorado probably was greatest in the 1970's (Van Slyke and Joliat, 1990). In some areas, primarily near the edge of the aquifer where saturated thickness and well yields are small and generally are getting smaller, pumpage from some wells was reduced during the 1980's, and some wells have been used only on an intermittent basis, in efforts to maintain well yields. These decreases in ground-water withdrawals contributed to decreased rates of water-level decline and to water-level rises in some areas during the 1980's.

Water levels declined between 1980 and 1990 in 78 percent of the wells monitored. The most widespread areas of decline included southeastern Phillips, most of Yuma, eastern Kit Carson, and part of eastern Cheyenne Counties (fig. 6). The largest recorded decline of 42 feet occurred in southeastern Kiowa County. Water levels rose in the remaining 22 percent of the monitored wells. Areas of generally rising water levels included southeastern Logan, central Washington, and northern Lincoln Counties. The largest water-level rise occurred in eastern Logan County and measured about 11 feet. The median water-level change for the 565 wells was a decline of 4.7 feet (area-weighted change, -3.08 feet). On an annual basis, this is a decline of 0.47 feet per year.

Precipitation for the period 1981 to 1989 was above normal in most areas (fig. 7); the general water-level rise in central Washington County likely was due in part to well above-normal precipitation (2-4 inches), which probably resulted in less irrigation pumpage and increased recharge. Slightly below-normal precipitation in Yuma and extreme eastern Washington Counties caused water-level declines in that area.

The widespread water-level declines generally are in areas that have the most irrigation wells. The largest concentrations of irrigation wells, in terms of number of wells per township, are found in southeastern Phillips, northern Yuma, and eastern Kit Carson Counties (Van Slyke and Joliat, 1990). Pumpage from these wells likely is the primary factor in producing the large water-level declines.

Between 1989 and 1990 (fig. 8), water levels declined in 74 percent of the wells monitored; water-level declines and rises generally were more mixed with respect to geographic location than they were for the 1980 to 1990 period (fig. 6). However, some trends are discernible. Water levels generally declined in southeastern Phillips, northern Yuma, eastern Kit Carson, eastern Cheyenne, and Baca Counties. The largest decline, about 15 feet, was recorded in northeastern Prowers County. Water levels were unchanged or rose in 26 percent of the monitored wells; scattered water-level rises were recorded in all counties. The largest water-level rise, about 6 feet, occurred in southeastern Kiowa County. The median water-level change for the 603 wells was a decline of 0.63 foot (area-weighted change, -0.62 foot). This is a larger rate of decline than during 1980 to 1990 (0.47 foot per year), despite the fact that water levels declined in a smaller percentage of wells during 1989 to 1990 than during 1980 to 1990.

Areas with the most ground-water development, such as southeastern Phillips, northern Yuma, and eastern Kit Carson Counties tended to have the largest water-level declines from 1989 to 1990; however, many individual wells in these areas had either small declines or water-level rises. How much and how recently an individual well was used during 1989 may have affected the amount and direction of water-level change. Such factors have a greater relative effect on year-to-year water-level changes than they have on long-term water-level changes. The practice by farmers of using some wells in some years but not in others may have contributed to the scattered pattern of water-level declines and rises that are evident in many areas.

Precipitation in 1989 in the southern half of the Colorado High Plains generally was above normal (fig. 9). In the northern half of the area, precipitation generally was below normal except in eastern Kit Carson and southern Yuma Counties. The dry conditions in northern Yuma County likely resulted in increased water-level declines in that area because of reduced recharge and increased need for irrigation.

Rates and patterns of ground-water withdrawals and rates of recharge from precipitation are the primary factors that affect water-level changes in the aquifer over time. The hydrograph for a well in Yuma County is representative of wells in that part of the aquifer (fig. 10A). It shows a substantial decline nearly every year since about 1970, but the rate of decline lessened since about 1980, probably as a combined result of an increase in precipitation and a decrease in pumpage. The rate of water-level decline in this well for 1970 to 1980 was about 2 feet per year; whereas, the rate of decline for 1980 to 1990 was about 1 foot per year. The relatively large overall rate of decline is due mainly to the relatively intensive withdrawal of ground water for irrigation in northern Yuma County.

The hydrograph for a well in Washington County (fig. 10B) is representative of wells that have had a relatively small long-term water-level change but which have had substantial year-to-year water-level changes. This well is in an area where saturated thickness is less than 50 feet and where farmers may use some wells on an intermittent basis; such a pattern of pumpage would result in the erratic appearance of the hydrograph. Above-normal precipitation in the area of this well for 1981-89 likely helped cause the generally rising trend apparent in the hydrograph during that period.

For the High Plains monitoring program, water-level measurements generally are made each winter in late December or January in an attempt to obtain data representative of the nonirrigation season. However, farmers in Colorado increasingly have been pumping their wells to irrigate winter wheat in the winter months. The downward spikes apparent in the hydrograph for a well in Kit Carson County are typical for a well used for winter irrigation (fig. 10C). In 1977, 1979, and 1986 two winter measurements were made, separated by intervals of 1 week to 1 month; water-level recoveries ranged from 2.2 to 5.5 feet. Measurements that seem to have been affected by winter pumpage were not used in preparing data for the Colorado part of the water-level change maps (figs. 6 and 8).

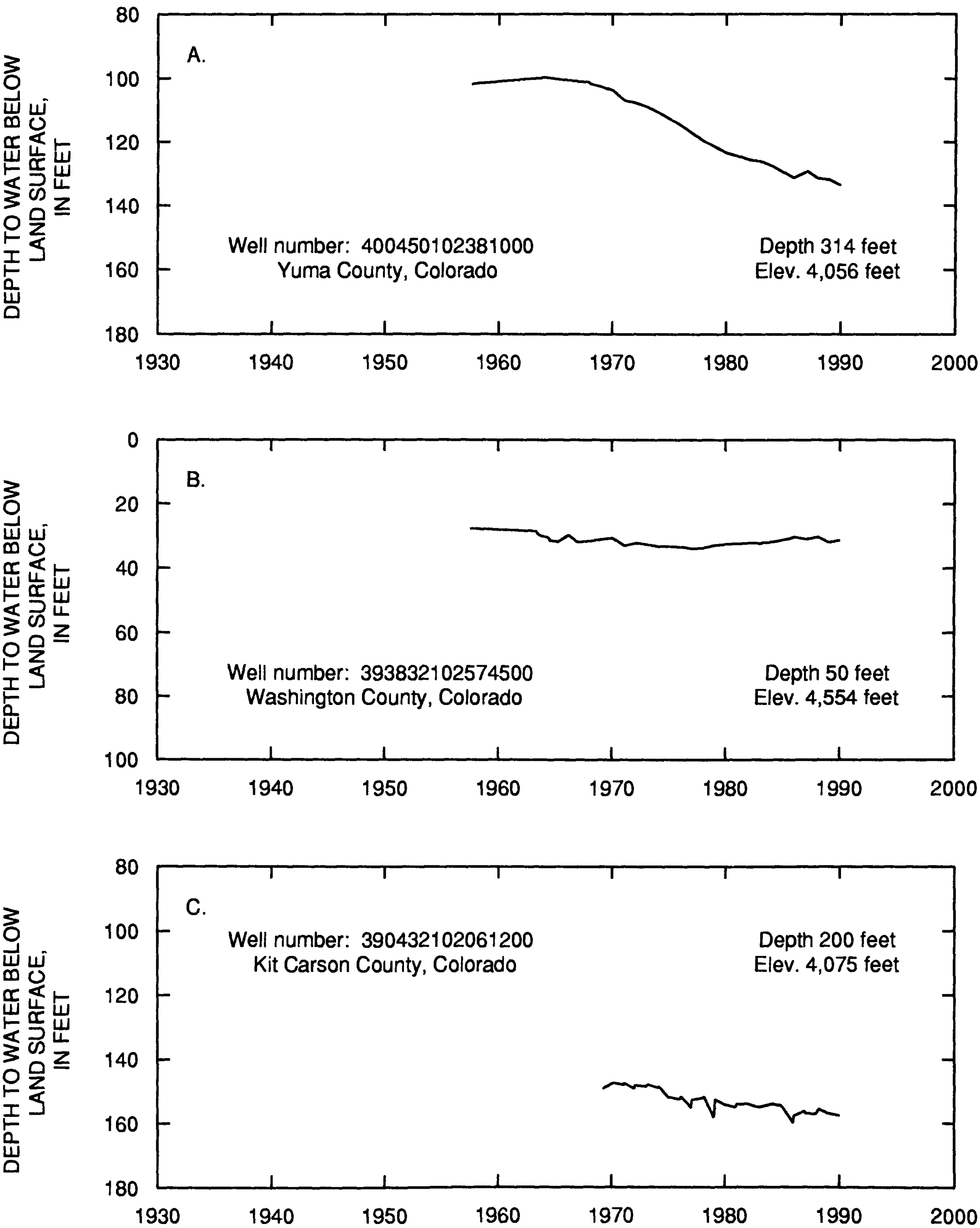

Figure 10. Observation wells: A, Yuma County; B, Washington County; C, Kit Carson County, Colorado.

KANSAS

Water-Level Changes in the High Plains Aquifer in Kansas Varied Markedly During 1989

by L.J. Combs and B.J. Pabst

The High Plains aquifer underlies about 30,500 square miles of western and south-central Kansas and consists of stream and wind-laid deposits of unconsolidated clay, silt, sand, and gravel of the Ogallala Formation and similar associated Tertiary and Quaternary deposits. The aquifer is replenished primarily by infiltration from precipitation and is depleted primarily by ground-water pumpage for irrigation.

Hansen (1991) estimated that the mean annual rate of potential natural recharge to the High Plains aquifer ranges from less than 0.5 inch in extreme western Kansas where average annual precipitation is about 16 inches to about 3 inches in the eastern part of south-central Kansas where average annual precipitation is about 30 inches.

The number of irrigation wells in the area of Kansas underlain by the High Plains aquifer has increased from fewer than 500 in 1940 to more than 20,000 in 1989. The largest development of irrigation is in west-central and northern parts of southwest Kansas, where nine townships had an average of more than three irrigation wells per square mile (Stullken and others, 1985). Estimated total withdrawals from the High Plains aquifer were 3,580 million gallons per day in 1989, 96 percent of which was used for irrigation (Joan F. Kenny, U.S. Geological Survey, written commun., 1991).

As a result of the typical irrigation practices used in the High Plains of Kansas, which consist of pre-watering in the spring and irrigation in the summer, water levels in wells commonly will rise during the winter, decline slightly in the spring, perhaps rise slightly during early summer, decline to their lowest annual levels in late summer, and then rise again during the fall and winter. When pumpage exceeds recharge, water levels in the High Plains aquifer never fully recover to the height achieved during the previous winter. The result is continual removal of ground water from storage.

Significant water-level declines occurred between 1940 and 1980, with large areas of the High Plains aquifer in Kansas experiencing declines of 10 to 150 feet during the 41-year period (Luckey and others, 1981). The average water-level decline from predevelopment to 1980 over the entire Kansas High Plains was nearly 10 feet (table 4).

The average annual rate of decline has decreased since 1980. The average rate of water-level decline for northwestern Kansas was 0.8 foot per year from 1966 to 1980 and 0.1 foot per year from 1980 to 1989. In west-central Kansas, the average rate of decline was 1.7 feet per year from 1966 to 1980 and about 0.7 foot per year from 1980 to 1989. Average water-level declines in southwestern Kansas slowed from a rate of 2.2 feet per year from 1966 to 1980 to about 1.7 feet per year from 1980 to 1989. In south-central Kansas, average water-level declines were 0.7 foot per year from 1974 to 1980 and 0.2 foot per year from 1980 to 1989 (M.E Pabst, U.S. Geological Survey, unpublished data, 1981; Geiger and others, 1990).

The rate of water-level decline appears to have decreased, particularly since 1985. In general, water levels in western and south-central Kansas have declined at a rate of about 0.1 foot less per year during the past 5 years (1985-89) compared to the previous 5 years (1980-84) (Geiger and others, 1990).

Rates of ground-water withdrawals in the Kansas High Plains have decreased in recent years as a result of increased energy cost, decreasing well yields, and improved ground-water management. For example, the number of acres irrigated by ground water in southwestern Kansas has remained fairly stable from 1975 to 1985 at about 1.4 million acres (Gutentag and others, 1981; Kansas Agricultural Statistics, 1987), but annual water-level declines slowed from an average of 5.6 feet in 1975 (Pabst and Jenkins, 1976) to 0.6 foot in 1985 (Dague, 1986).

From 1986 through 1990, more than 1.6 million acres of irrigated and nonirrigated land has been taken out of production in counties underlain by the High Plains aquifer in Kansas as part of the U.S. Department of Agriculture's Conservation Reserve Program (C.K. Bradford, Soil Conservation Service, written commun., April 1991). It is premature, however, to define the full effects of this program on water levels in the High Plains aquifer.

Since the mid-1970's, five ground-water management districts, largely within the High Plains, have been organized in western and south-central Kansas. Each district was required to develop a management program and could recommend regulations to the Chief Engineer (Kansas State Board of Agriculture, Division of Water Resources), who then could sanction policies and regulations related to the conservation and management of ground water. Examples of policies and regulations adopted within the districts include mandatory metering, well-spacing restrictions, water-use and water-wastage restrictions, and programs related to protecting the quality of ground water.

Water-level changes in the High Plains aquifer during the past decade, based on 1,136 wells measured in both 1980 and 1990, varied considerably throughout western and south-central Kansas. The largest declines, ranging from 7.5 to more than 15 feet for the period, occurred in southwestern Kansas in parts of Finney, Grant, Gray, Haskell, and Stanton Counties (fig. 6). These large declines occurred despite normal to above-normal precipitation for the 1981-89 period (fig. 7). A few isolated areas of water-level increases did occur, however, most notably in west-central Kansas.

The slower rates of water-level decline and the water-level rises in much of the High Plains aquifer in Kansas in recent years are due, in part, to above-normal precipitation in most of the area (fig. 7) and, therefore, a decreased need for irrigation and increased recharge. Precipitation during 1988 in the High Plains of Kansas, however, averaged about 4 inches below normal (Geiger and others, 1989; 1990). Consequently, there was an increase in ground-water pumpage for irrigation during 1988, and water levels declined considerably during 1989 (Dugan and others, 1990).

The rate of water-level change relates primarily to such variable factors as climate and agricultural economics. Average annual precipitation in the High Plains of Kansas for the 1981-89 period ranged from 4 to 6 inches above normal in parts of south-central Kansas to 0 to 2 inches above normal over most of the remainder of the Kansas High Plains. Precipitation in parts of northwest Kansas, however, was at or below normal (fig. 7).

Water-level changes in the High Plains aquifer from 1989 to 1990 in Kansas were determined from a monitoring network of about 1,470 observation wells measured in midwinter by personnel from the Kansas State Board of Agriculture and the U.S. Geological Survey (fig. 5). Support for this cooperative effort is also provided by the Kansas Geological Survey.

The map of water-level changes from 1989 to 1990 (fig. 8) shows only scattered areas of substantial decline (more than 3 feet). In northwestern Kansas, the mean measured water level declined 0.2 foot during 1989. In southwestern Kansas (area south of the Scott-Finney County line), the mean measured water level declined 0.3 foot. The most substantial declines were in areas of intensive irrigation-well development. In south-central Kansas, the mean measured water level rose 0.2 foot (Geiger and other, 1990). Because annual measurements of water-level change generally are affected by temporary conditions, trends are more accurately identified from long-term records.

Precipitation during 1989 averaged 0.65 inch above normal (area-weighted average, +0.80 inch above normal in table 7) for the entire High Plains area in Kansas (Geiger and others, 1990, 1991). Precipitation in northwestern Kansas averaged 2.39 inches below normal; west-central Kansas, 1.72 inches below; southwestern Kansas, 3.76 inches above; and south-central Kansas, 2.96 inches above normal. As a result of an overall increase in precipitation and less pumpage during 1989, water-level declines slowed, and in some areas water levels rose from 1989 to 1990 (fig. 8).

The hydrograph of the well in Thomas County (fig. 11A) shows a continual decline of water levels that corresponds to an increase in the total acres irrigated in the county following the drought of 1953-57. Many areas in the High Plains of Kansas experienced a rapid increase in the number of wells drilled for irrigation during and after the 1953-57 drought. The decline in the water levels stabilized from about 1981 to the mid-1980's in response to above-normal precipitation and a reduced rate of increase in the number of acres irrigated. In 1987-90, water levels again declined rapidly as a result of increased irrigation pumpage during drought conditions.

The hydrograph of the well in Finney County (fig. 11B) indicates an overall continual decline of water levels in response to an increase in total acres irrigated starting in 1949. The rapid increase in irrigation in Finney County began after World War II when large-capacity turbine pumps were introduced. Increases in natural recharge to and decreases in natural discharge from the aquifer in this area normally are exceeded by the ground-water pumpage for irrigation; consequently, there has been continual removal of ground water from storage. As in the well in Thomas County (fig. 11A), water-level declines have slowed somewhat since about 1981. Since 1986, the amount of land taken out of production in Finney County through the Conservation Reserve Program has totaled 58,028 acres and may be responsible in part for the recent slowing of declines shown by the Finney County hydrograph. However, water-level declines in much of southwestern Kansas during the 1980's exceeded 15 feet (fig. 6).

Recent above-normal precipitation and subsequent natural recharge to the High Plains aquifer in south-central Kansas resulted in more stable water levels as evidenced by the hydrograph from a well in Sedgwick County (fig. 11C). This observation well is completed in unconsolidated deposits of the *Equus* beds, which range in age from Pliocene to Holocene, but are principally Pleistocene. The *Equus* beds, a local term used for the easternmost extension of the High Plains aquifer, is used extensively for public water supplies. The relatively stable water levels since about 1958 are primarily the result of decreased pumpage due to increased use of surface water for public supplies (Bevans and others, 1985).

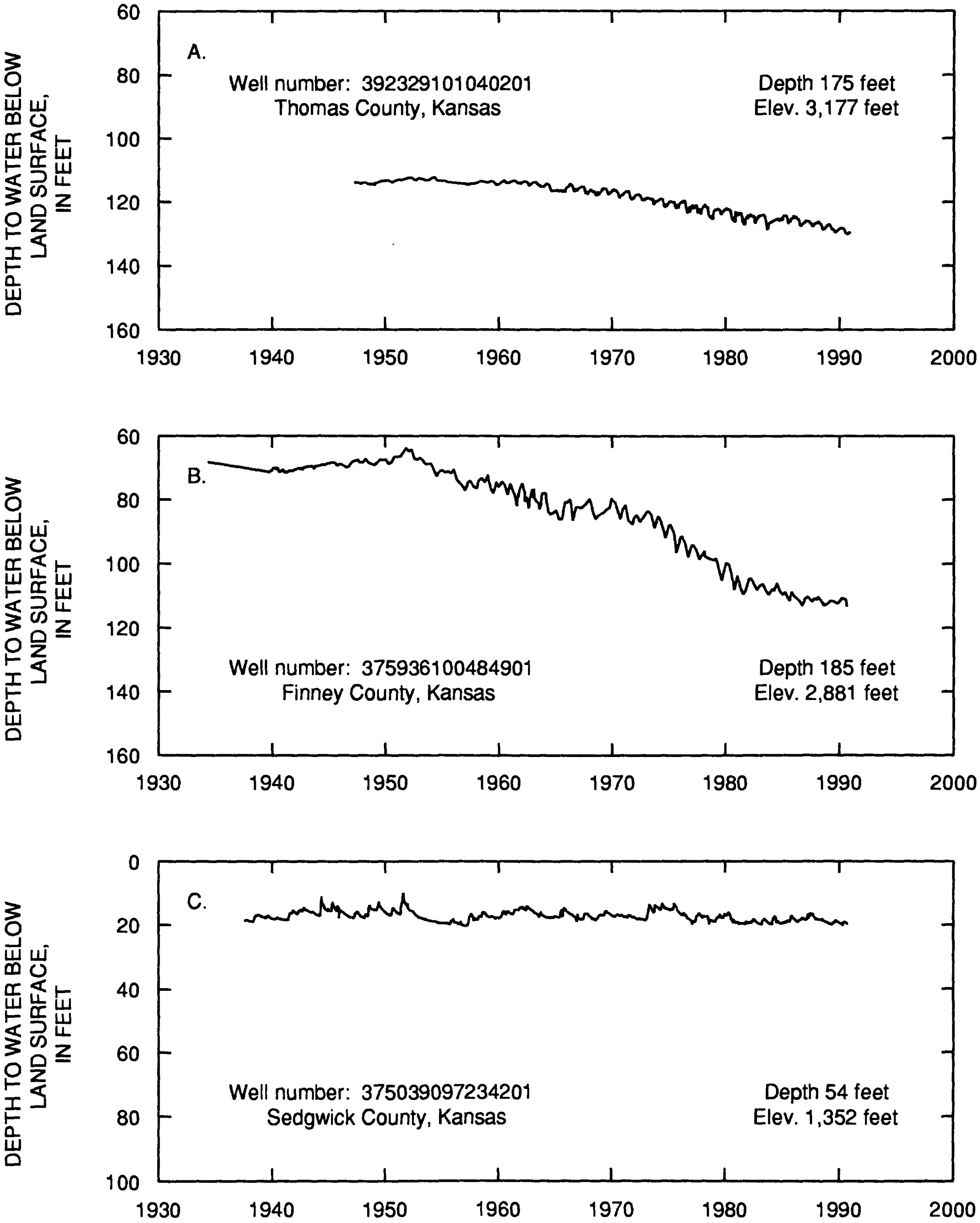

Figure 11. Observation wells: A, Thomas County; B, Finney County; C, Sedgwick County, Kansas.

NEBRASKA

Water-Level Declines Occur During 1989-90 As a Result of Widespread Severe Drought in 1989

by J.T. Dugan

The High Plains aquifer in Nebraska underlies about 63,650 square miles, with saturated thicknesses averaging 340 feet (Gutentag and others, 1984). More than 7 million acres in the High Plains of Nebraska are presently irrigated. Approximately 1 million acres are irrigated from surface-water sources, principally in the North Platte and Platte River basins; and the remaining approximately 6 million acres are irrigated by ground water from nearly 69,000 wells.

The development of ground-water irrigation in Nebraska following the drought of the mid 1950's was very rapid. In 1953, less than 600,000 acres in the State were irrigated from ground-water sources. By 1965 there were more than 2 million ground-water irrigated acres and by 1975 nearly 5 million acres. The present ground-water irrigated acreage was reached by 1985 and has actually declined slightly in some parts of the High Plains of Nebraska (Nebraska Department of Agriculture, 1989; Ellis and others, 1990).

Much of the growth in ground-water irrigation in Nebraska since the late 1960's has been associated with the development of center-pivot irrigation systems, which has permitted land not well suited for gravity-flow irrigation (such as sandy soils and rolling topography) to be irrigated. More than 3.5 million acres are irrigated by center pivots in Nebraska or approximately 50 percent of the total irrigated acreage (Conservation and Survey Division, 1990).

The somewhat later development of ground-water irrigation in Nebraska contributed to the smaller declines in water levels prior to 1980 (fig. 4) compared to water-level changes in parts of the central and southern High Plains where development began much earlier. Since 1980, relatively favorable climatic conditions, particularly precipitation, and more efficient irrigation management, including center-pivot irrigation, has minimized water-level declines over most of the High Plains in Nebraska (fig. 6).

Substantial water-level declines from 1980 to 1990 have been limited to a few areas in the Nebraska High Plains (fig. 6). A large area of decline occurred in southwestern Nebraska, particularly in Chase and Perkins Counties, where widespread declines ranged from 2.5 to 7.5 feet and averaged about 0.5 foot per year. Declines in smaller areas ranged from 7.5 to 15 feet from 1980 to 1990, averaging approximately 1 foot per year. Another area of substantial declines occurred in Box Butte County and adjoining counties in the central Panhandle where declines ranged from 7.5 to 15 feet. A few observation wells in these areas show declines exceeding 20 feet, an average of 2 feet per year since 1980. These declines in the central Panhandle generally coincide with an anomalous area of below-normal precipitation during 1981-89, which averaged less than 14 inches annually during the period.

Water levels in the remaining parts of Nebraska generally represented stable to rising conditions from 1980 to 1990. Large areas in eastern and south-central Nebraska had substantial water-level rises ranging from 2.5 to 15 feet (fig. 6) inspite of extensive irrigation development. These rises can be attributed, in part, to annual precipitation 4 to 6 inches above normal during 1981-89 (fig. 7). However, much of the rise in water levels in parts of south-central Nebraska, including Gosper, Phelps, and Kearney Counties are associated with seepage from surface-water irrigation.

In parts of north-central Nebraska where the soils are generally sandy and minimal ground-water development has occurred, water levels rose from 2.5 to 7.5 feet during the period. These areas generally received above-normal precipitation during 1981-89 (fig. 7). The limited number of observation wells in these areas (fig. 5) and the resultant large polygons representing areal change, however, may exaggerate the areal extent of some water-level rises (fig. 6).

Discontinuous areas of water-level rise in the southern and west-central Panhandle from 1980 to 1990 also are associated with above-normal precipitation during the period (fig. 7). Average annual precipitation was as much as 4 inches above the 30-year average in this area during 1981-89.

Water-level changes from 1980 to 1990, however, are not reflective of the short-term changes that occurred from 1989 to 1990 (fig. 8). These differences principally reflect weather conditions in 1989, which was one of the driest in recent years. Precipitation in much of the High Plains of Nebraska was from 5 to 10 inches below normal in 1989 (area-weighted average, -5.22 inches), with some parts of northeast and north-central Nebraska more than 10 inches below normal (fig. 9). In absolute amounts, precipitation ranged from less than 10 inches over large areas of the Panhandle and north-central Nebraska to more than 24 inches in an isolated area of south-central Nebraska. At several north-central locations, less than 9 inches were recorded, which is about 50 percent of normal for these areas. In a few anomalous areas in south-central and southeastern Nebraska was 1989 precipitation normal to slightly above normal, with much of it occurring late in the growing season.

These extremely dry conditions extended from the dormant season of 1988-89 into the early growing season of 1989 over most of the High Plains in Nebraska. Thus, resultant soil moisture was not adequate for ground-water recharge or for crops during the 1989 growing season. As a result, widespread water-level declines of 1 to 3 feet were common in many irrigated areas of the High Plains of Nebraska during 1989-90. In some cases declines of 3 to 5 feet or more occurred in the central Panhandle, and in the southwestern and northeastern parts of the State declines coincided closely with areas of well below-normal precipitation (fig. 9).

In a few areas of the Nebraska High Plains, water levels rose during 1989 to 1990. In the south-central area, rises continued in Gosper, Phelps, and Kearney Counties in those areas of surface-water irrigation. Widespread rises also occurred in Buffalo, Hall, and southeastern Custer Counties, probably as a result of substantial amounts of precipitation late in the growing season. Other areas of rise appear to be localized and not readily explainable. Some of these rises may represent delayed recharge as a result of antecedent conditions.

Three well hydrographs were selected to represent long-term trends in selected areas of the Nebraska High Plains. The hydrographs represent areas of major ground-water irrigation development, but each illustrates a distinct pattern of water-level change. Because hydrographs show water-level changes in a specific well, they do not necessarily represent average changes in a given area.

The first hydrograph represents long-term changes in a well in Box Butte County in the central Panhandle since 1946, just prior to major irrigation development (fig. 12A). Precipitation in this area averages approximately 16 inches annually. Beginning in 1951, water-levels declined at a relatively steady rate of about 1 foot per year to about 40 feet by 1990.

The second hydrograph (fig. 12B) represents water-level changes in a well in Chase County in southwestern Nebraska since 1964, soon after significant ground-water irrigation development began in the area. Precipitation averages approximately 19 inches annually in this area. Water levels declined 35 feet in 27 years, an average of 1.3 feet per year. Only during 1980 to 1984, when precipitation was well above normal, did water levels stabilize and actually rise. The effects of irrigation withdrawals during the growing season are evident from the seasonal pattern of drawdowns. These seasonal drawdowns were greatest in the late 1970's, perhaps as a result of larger pumping rates in the surrounding area.

The third hydrograph (fig. 12C) represents water-level conditions at a well in Seward County in the extreme eastern High Plains of Nebraska, from shortly after significant irrigation development began in the area in the mid-1950's. Precipitation in this area averages about 27 inches annually. Since 1959, water levels have exhibited little long-term change with a net change of about +1 foot. The hydrograph, however, shows a relatively steady decline in water levels of about 9 feet between 1963 and 1982. From 1982 to 1988, water levels rose more than 12 feet but then declined approximately 4 feet from 1988 to 1990. The water-level rises during 1982 to 1988 occurred during a 6-year period when annual precipitation averaged nearly 33 inches, or 6 inches above normal. In 1988 and 1989, however, annual precipitation averaged only about 21 inches, or 6 inches below normal, for the 2-year period.

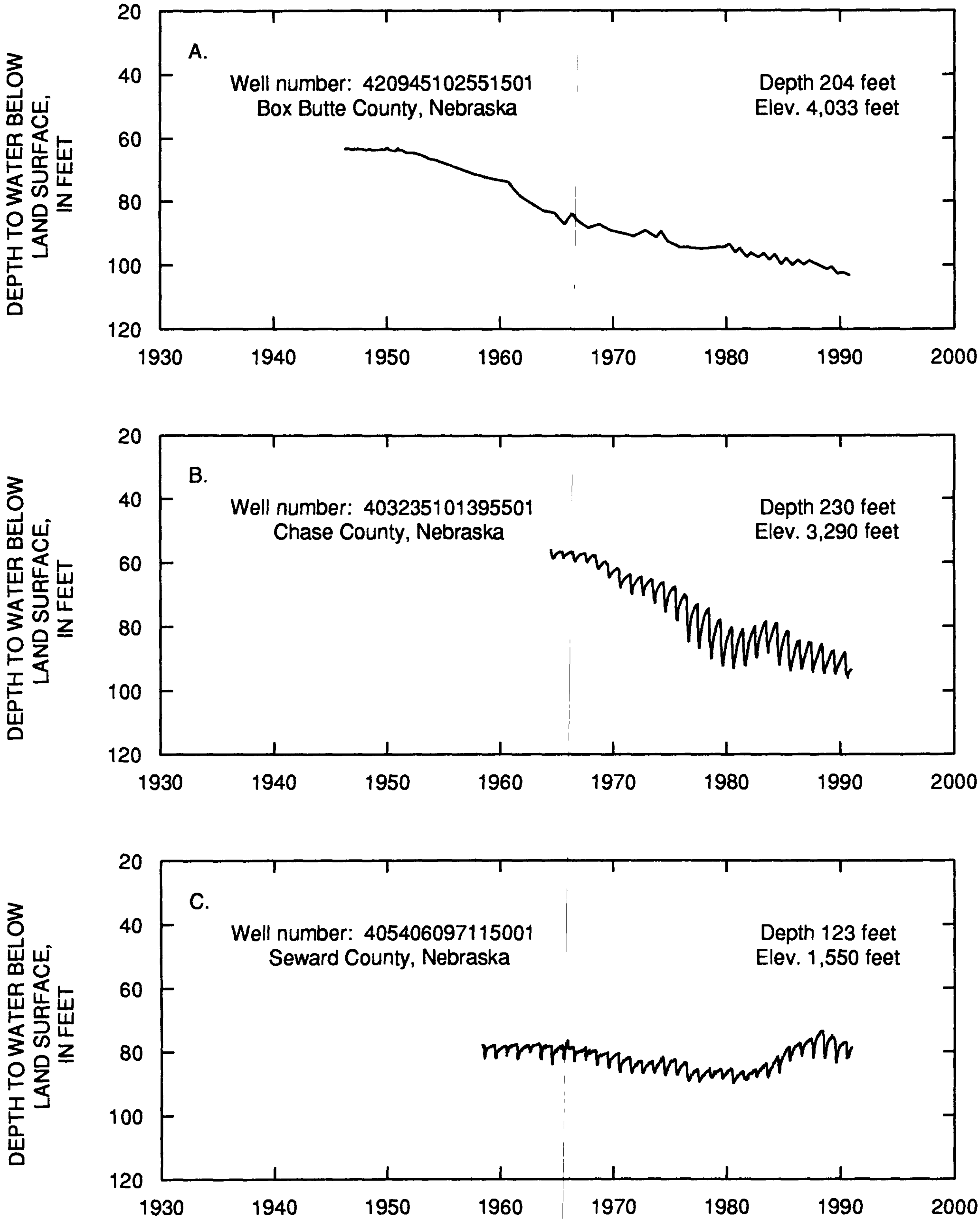

Figure 12. Observation wells: A, Box Butte County; B, Chase County; C, Seward County, Nebraska.

NEW MEXICO

Water Levels Continue to Decline Throughout the High Plains of New Mexico

by Roy R. Cruz

The High Plains aquifer underlies about 9,450 square miles in eastern New Mexico. Estimates on 1989 pumpage from the entire High Plains aquifer in New Mexico are not yet available. Preliminary 1989 pumpage estimates for two representative areas, however, indicate an increase since 1985 (Wilson, 1986; New Mexico State Engineer, Frank Bradley, Portales Basin Supervisor, and Johnny Hernandez, Lea County Supervisor, oral commun., 1991). Total irrigated acres increased from 1988 to 1989 in east-central and southeastern New Mexico by 60,800 acres in Curry County, 21,500 acres in Roosevelt County, and 1,020 acres in Lea County (Lansford and others, 1990).

Ground-water data in New Mexico are collected by personnel of the U.S. Geological Survey and the New Mexico State Engineer as part of a continuing Federal-State cooperative observation-well program. Mass water-level measurements (water-level measurements made in a large number of wells at approximately the same time) are made in winter at 1-year and 5-year intervals to monitor water-level changes in the High Plains aquifer.

Few water-level measurements are made each year in northeastern New Mexico; therefore, limited data are available for this area. In east-central New Mexico, however, a large number of water-level measurements are made to determine the ground-water depletion allowance permitted by the U.S. Internal Revenue Service. These annual water-level changes then are computed and mapped by the U.S. Geological Survey (Cruz, 1990).

Five of the six continuous water-level recorders used in the High Plains monitoring network in New Mexico were added to the observation-well program in 1988. These recorders aid in defining seasonal fluctuations in water levels. The degree of irrigation development generally determines seasonal water-level fluctuations. In the areas of lesser irrigation development, the highest water levels usually occur in late April or early May, and the lowest water levels occur in September. In areas of greater irrigation development, the highest water levels occur in mid to late March, and the lowest water levels generally occur in late July.

Water levels in irrigated areas of the High Plains aquifer have had a net decline since ground-water development began. In those areas of less irrigation development, however, declines generally are much smaller, and in a few cases, water levels have risen since predevelopment. Much of the decline was prior to 1980 (area-weighted average is -9.8 feet prior to 1980 and -0.66 foot since 1980). The declines generally increase from west to east and exceed 80 feet along the New Mexico-Texas border in areas of intense irrigation development in east-central New Mexico (fig. 4).

In some areas water levels rose from 1980 to 1990 (fig. 6), and in others the rate of decline was smaller than from predevelopment to 1980 (fig. 4). This can be attributed to: (1) A decrease in irrigation requirements and increased recharge because of above-normal precipitation (average annual area-weighted precipitation was 3.58 inches above normal during 1981-89); (2) a decrease in irrigated acreage because of unfavorable agricultural economics and government incentives to reduce cultivated acreage; and (3) a change in water-management practices. Recharge may have increased along ephemeral streams because of the increased precipitation and resultant increase in surface-water runoff.

For the High Plains aquifer in New Mexico, the area-weighted water-level change from 1989 to 1990 was a decline of 0.29 foot (table 6). The area-weighted precipitation during 1989 was 1.35 inches below normal (table 7).

In northeastern New Mexico, the water-level changes from 1989 to 1990 were variable, ranging from declines of 1 to 3 feet in central Union County to rises of 3 to 5 feet in southern Union, northern Quay, and eastern Harding Counties (fig. 8). Precipitation in northeastern New Mexico in 1989 ranged from 2 to 5 inches above normal to 2 to 5 inches below normal (fig. 9) but appears to have little correlation with water-level changes from 1989 to 1990 (fig. 8).

In east-central and southeastern New Mexico, water-level measurements in 1989 and 1990 indicate declines in most of the areas of intensive irrigation development. Water levels rose in localized areas of less irrigation development in southeastern Roosevelt and northeastern Curry Counties (fig. 8). Precipitation generally was below normal in east-central and southeastern New Mexico during 1989 (fig. 9) but showed little correlation with the 1989 to 1990 water-level changes.

The hydrographs (fig. 13) showing the water-level changes in observation wells in Union (A) and Curry (B) Counties generally are representative of water-level changes in the High Plains aquifer of New Mexico. Both wells are located in areas of moderate irrigation development in their respective counties and show declines of approximately 15 feet since 1970.

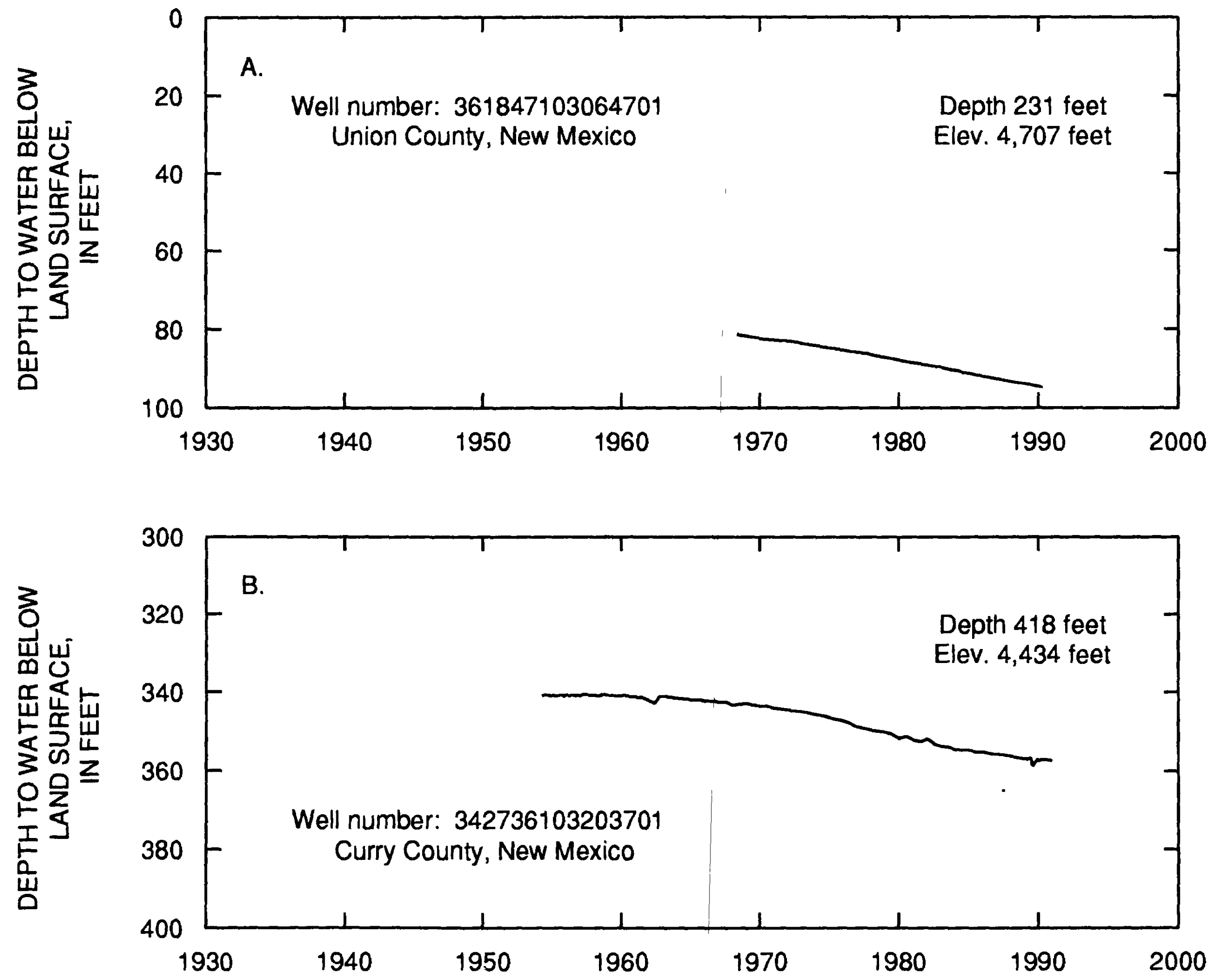

Figure 13. Observation wells: A, Union County; B, Curry County, New Mexico.

OKLAHOMA

Increased Precipitation and Decreased Irrigation Lands Have Slowed Water-Level Declines

by John S. Havens

The High Plains aquifer underlies about 7,350 square miles of western Oklahoma and the Panhandle. Water pumped from the High Plains aquifer in Oklahoma during 1989 is estimated to have been about 197 million gallons per day (220,670 acre-feet). In 1985, 97 percent of the water pumped from this aquifer was used for irrigation (Wayne Solley, U.S. Geological Survey, written commun., 1988).

In general, irrigated acreage has decreased since the late 1970's in the High Plains of Oklahoma. Because of the unstable economy and low commodity prices, some cropland is no longer irrigated, and considerable cropland has been entirely removed from production as a result of the Conservation Reserve Program. Irrigated acres in the High Plains of Oklahoma decreased from 220,595 acres in 1989 to 186,190 acres in 1990. In addition, increased fuel costs (particularly for natural gas) have caused irrigators to make more efficient use of fuel, with a consequent decrease in the amount of water pumped from the aquifer.

Annual water-level measurements in the High Plains of Oklahoma were made cooperatively by the U.S. Geological Survey and the Oklahoma Water Resources Board during 1989 and by the Oklahoma Water Resources Board during 1990. Each year about 400 wells are measured during January when water levels are assumed to have reached maximum recovery from the previous pumping season. Data from 320 wells measured during January 1980 and January 1990 are available.

Water levels in the High Plains aquifer of Oklahoma declined only slightly from January 1980 through January 1990. The average area-weighted water-level change was a decline of 0.32 foot (table 4). The mean area-weighted precipitation for 1981 through 1989 was 2.52 inches above normal (table 5).

The average area-weighted water-level change for the 343 wells measured during January 1989 and January 1990 was a decline of 0.27 foot. Water levels in a majority of wells measured in west-central Oklahoma rose; whereas, water levels in the Panhandle were variable, with a majority of wells in Texas and Cimarron Counties declining slightly (fig. 8).

Precipitation during 1989 was above normal throughout most of the High Plains in Oklahoma, particularly in the west-central part (fig. 9). Average area-weighted precipitation exceeded the normal during 1989 by 3.89 inches in the Oklahoma High Plains (table 7). This above-normal precipitation is reflected in water-level rises from January 1989 to January 1990 in large parts of the aquifer in Oklahoma.

The largest historical water-level declines in the High Plains of Oklahoma have occurred in the central Panhandle. The hydrograph of an observation well in Texas County shows a continual water-level decline totaling nearly 30 feet since about 1965 (fig. 14), reflecting withdrawals for irrigation from the High Plains aquifer. Annual variability of precipitation does not greatly affect water levels in this observation well. The slope of the hydrograph steepens, beginning in the early 1970's, reflecting the increase in acres irrigated through 1982. This observation well is located on the southwestern edge of a large cone of depression south of Guymon in Texas County. Water levels in the center of the cone declined about 100 feet during 1940-80. A marked decrease in acres irrigated since 1981 and slight increases in precipitation may have caused a slight decrease in the rate of water-level decline during the last several years. Irrigated acres in Texas County have decreased from a peak of nearly 190,000 acres in 1981 to less than 110,000 acres in 1990.

The data used to prepare the well hydrograph are from the files of the U.S. Geological Survey. Estimates of acres irrigated with ground water are derived from unpublished data obtained from the Oklahoma Department of Agriculture, Oklahoma Crop and Livestock Reporting Service for 1980-87 and from the Oklahoma Water Resources Board for 1988-90. The data, which include acres irrigated for selected crops, have been adjusted to include all crops irrigated with ground water.

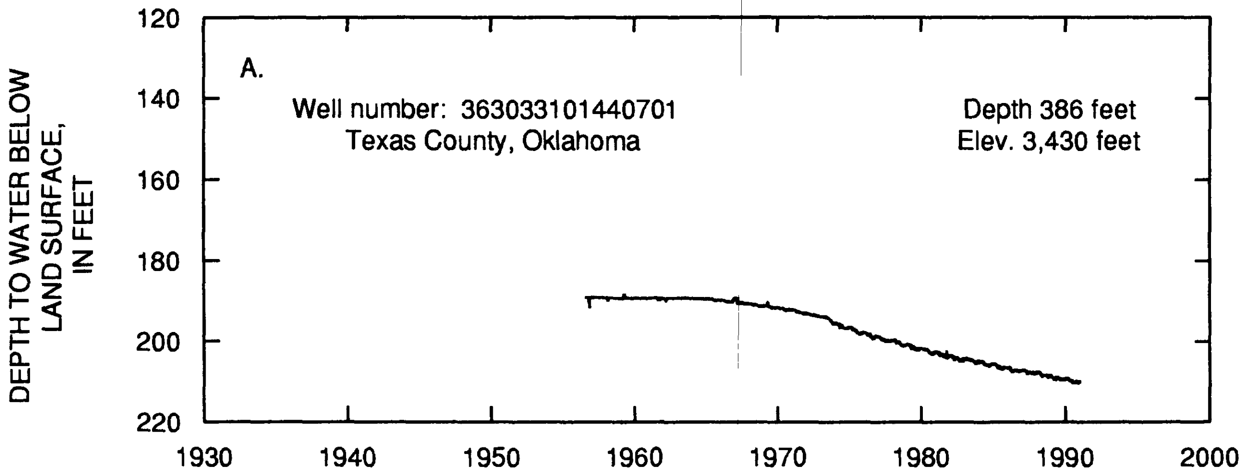

Figure 14. Observation well: A, Texas County, Oklahoma.

SOUTH DAKOTA

Water Levels Decline in the High Plains of South Dakota During 1989-90

by J.R. Little and K.M. Neitzert

The High Plains aquifer underlies about 4,750 square miles in all or parts of seven counties in south-central South Dakota. The aquifer is not as intensively developed in South Dakota as it is in other States of the High Plains. During 1985, an estimated 24,480 acre-feet of water (21.84 million gallons per day) was pumped from the aquifer (Wayne Solley, U.S. Geological Survey, written commun., 1988). Agricultural use accounted for about 88 percent of this pumpage; the remainder was used for public supply, domestic, and commercial purposes. Withdrawals, however, are not uniform throughout the area.

In general, withdrawals of water from the aquifer for irrigation have remained relatively constant since the end of the drought of the mid-1970's, although a few areas have shown slight increases in irrigated acres since 1980. For example, ground-water irrigated acres in Bennett County increased from about 4,600 acres in 1980 to about 6,600 acres in 1988, with a maximum of about 7,100 acres in 1985 (Del Brosz, South Dakota Department of Environment and Natural Resources, oral commun., 1990).

The South Dakota Department of Environment and Natural Resources, Division of Water Rights, operates a statewide network of more than 1,500 observation wells, 78 of which are in the High Plains area. These wells are measured monthly in cooperation with the U.S. Geological Survey, and data are available from either agency. The U.S. Geological Survey also operates continuous recorders in two wells in the area (fig. 1), which are represented by the hydrographs in figure 15.

Between spring of 1980 and spring of 1990, water levels in the High Plains aquifer in South Dakota fluctuated, but no major trends developed (fig. 6). From 1981 through 1989, precipitation ranged from about 2 inches below normal (30-year average) in the western part of the area to about 6 inches above normal in the eastern part (fig. 7). Selected hydrographs from wells in Bennett County in the west (fig. 15A) and Tripp County in the east (fig.15B) reflect this precipitation pattern. Of the 59 wells that were measured in the spring of 1980 and again in the spring of 1990, 34 indicated water-level rises or declines of 2.5 feet, or less (14 rose and 20 declined). Eleven wells indicated rises of more than 2.5 feet, and 11 indicated declines of more than 2.5 feet during the period, with the maximum rise being 5.6 feet and the maximum decline being 9.8 feet. All of the wells that indicated declines of more than 5 feet were in areas of ground-water irrigation development, and much of the overall decline occurred during 1989.

Water levels generally declined in the High Plains aquifer in South Dakota between April 1989 and April 1990, because the precipitation over the area during 1989 ranged from 2 to 10 inches below normal. Of the 78 wells that were measured during April 1989 and again during April 1990, 40 wells indicated rises or declines of 1 foot or less. One well indicated a rise of 4.4 feet, and 36 wells indicated declines of more than 1 foot, with the maximum decline being 3.9 feet.

The two hydrographs shown in figure 15 represent two climatically different areas of the South Dakota High Plains aquifer. The observation well in Bennett County in south-central South Dakota shows that water levels have been generally unchanged since 1960. Water levels in the Tripp County well in the eastern part of the South Dakota High Plains have risen nearly 5 feet since the early 1980's.

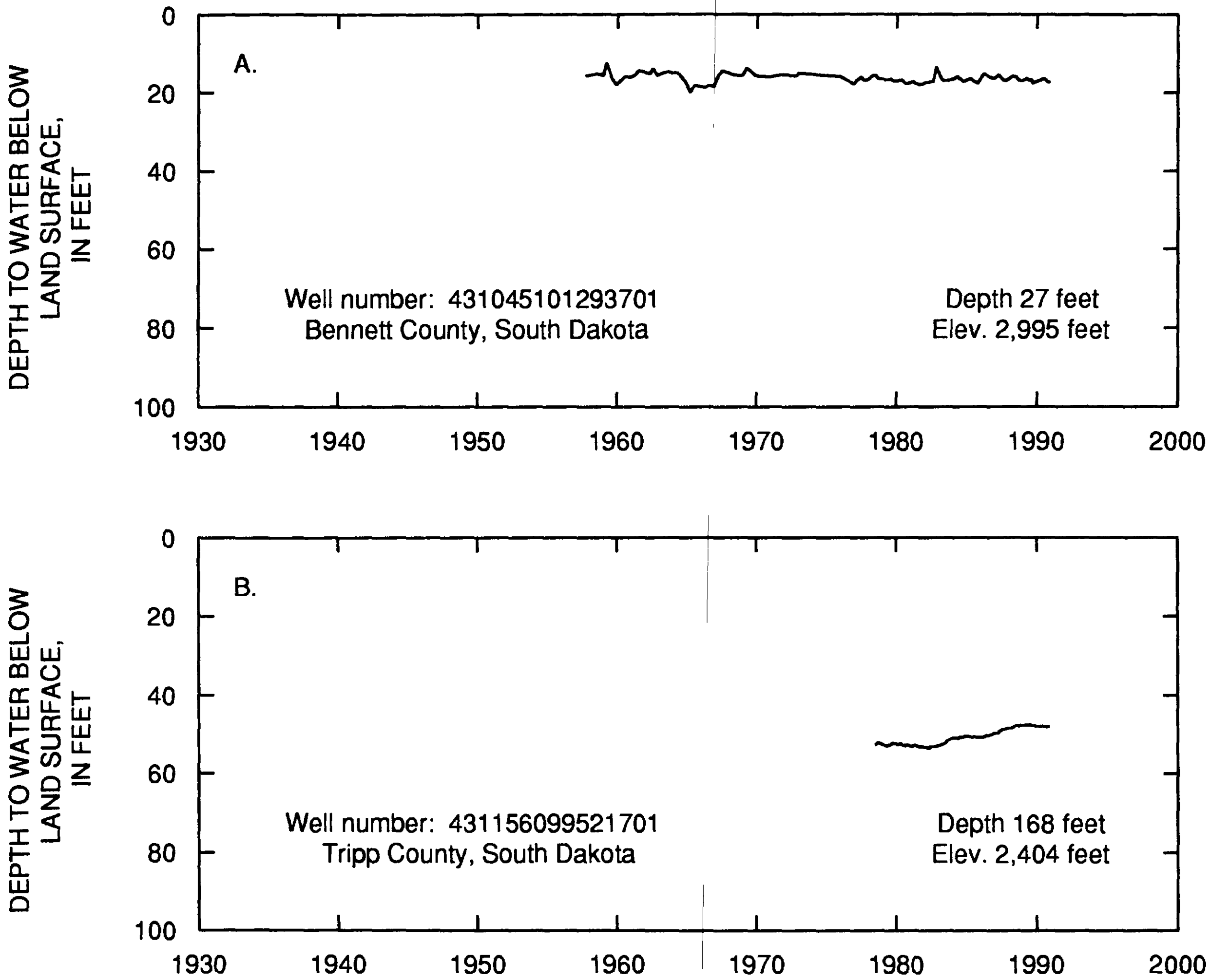

Figure 15. Observation wells: A, Bennett County; B, Tripp County, South Dakota.

TEXAS

Water-Level Declines Slowing or Reversing in Much of the Texas High Plains

by John B. Ashworth (Texas Water Development Board)

The High Plains aquifer underlies approximately 35,450 square miles of the Texas Panhandle and West Texas. In 1989, approximately 3.95 million acres were irrigated on the Texas High Plains. This represents about 65 percent of the irrigated acreage in the State (83 percent of the acres irrigated with ground water) and is a reduction of about 1.39 million irrigated acres since 1979. Similarly, about 4.69 million acre-feet of ground water were pumped for irrigation from the High Plains aquifer in 1989, which is a reduction of about 0.98 million acre-feet from 1979 pumpage. Higher energy costs, declining well yields, unavailability of labor, and depressed prices for farm products account for this reduction in irrigated acreage (Texas Water Development Board, 1991). Water levels are measured annually in more than 3,100 wells in the High Plains aquifer by the Texas Water Development Board and the area underground water conservation districts; 1,868 of the wells were included in the 1989 to 1990 water-level analyses (fig. 5).

Water-level changes in the High Plains aquifer in Texas from 1980 to 1990 (fig. 6) varied substantially from the generally declining trend prior to 1980 (fig. 4). In approximately 40 percent of the area, the pre-1980 declines were reversed, and water-level rises were observed (Ashworth, 1991). This reversal was primarily due to decreased pumpage as a result of an increase in precipitation in recent years, improved irrigation-management practices, and a decrease in irrigated acreage.

During 1980 to 1990, the largest area of water-level rise (in excess of 15 feet) occurred in the southern part of the region and was centered in Dawson and eastern Gaines Counties (fig. 6). The maximum rise observed was more than 60 feet in a small area in Dawson County (Ashworth, 1991). Water-level conditions in this southern region may be affected by a rise in the potentiometric surface of the underlying Cretaceous aquifer. Other areas of significant water-level rise in excess of 15 feet occurred in Dallam, Martin, and Swisher Counties.

Certain areas that had significant water-level declines from predevelopment to 1980 continued to show declines from 1980 to 1990 (fig. 6). In approximately 45 percent of the Texas High Plains, the aquifer continued to decline between 1980 and 1990 as a result of pumpage in excess of recharge (Ashworth, 1991). In the central part of the Panhandle, water-level declines in parts of Castro, Floyd, Hale, Lamb, Parmer, and Swisher Counties exceeded 15 feet, even though some of these areas recorded rises in 1986 and 1987. Farther north, water-level declines in smaller areas of Carson, Dallam, Hartley, Hutchinson, Moore, and Sherman Counties also exceeded 15 feet from 1980 to 1990. The average rate of decline in some of these areas was about 2 feet per year.

Annual precipitation was considerably above normal during 1981-89 in the Texas High Plains, resulting in conditions favorable for increased recharge and lower irrigation requirements. The greatest increase occurred south of the Canadian River where annual precipitation was 4 to 6 inches above the 30-year average over approximately 50 percent of this area (fig. 7). The remainder of this area received as much as 4 inches above-normal precipitation. This above-normal precipitation during the period can largely be attributed to abundant precipitation during 1985-87.

Although some of the decline in irrigation pumpage in Texas can be attributed to above-normal precipitation, improved irrigation management practices also have contributed significantly. Conservation education is a primary goal of the underground water conservation districts that serve much of the Texas High Plains. As a result of their efforts, many irrigators are reporting water savings of as much as 50 percent. In particular, the High Plains Underground Water Conservation District No. 1 reports that water levels within their 15-county area, which occupies the north-central two-thirds of the southern High Plains in Texas (fig. 1), stabilized in 1985 for the first time in the 40-year history of the District. Net water-level rises were recorded in 1986 and 1987, followed by 2 years of slight net declines (High

Plains Underground Water Conservation District No. 1, 1990). This marks a significant improvement over the 1960's when water-level declines of 3 to 4 feet per year were common.

Water-level changes during 1989 to 1990 (fig. 8) in the High Plains aquifer in Texas continued to show the same general trends exhibited by the 1980 to 1990 changes. Much of the central and southern parts of the aquifer experienced a water-level rise of 1 to 3 feet, with some isolated areas of rises of more than 5 feet. Although 1989 was a relatively dry year, water levels in this area are still rising as a result of the abundant precipitation that occurred between 1985 and 1987. Elsewhere in Texas, the High Plains aquifer remained relatively stable or declined slightly. Water levels in the most intensively irrigated areas in the central and northern parts of the aquifer generally declined from 1 to 3 feet. The High Plains Underground Water Conservation District No. 1 recorded a 1-foot average water-level decline in 1,018 wells measured in their service area in 1989. The District reported that drier than normal pre-plant soil-moisture conditions and below-normal precipitation during the growing season caused increased pumpage from the aquifer in 1989 (High Plains Underground Water Conservation District No. 1, 1990). Similarly, the irrigated region north of the Canadian River experienced water-level declines primarily due to dry conditions during the pre-planting period.

Hydrographs illustrating water-level changes in the High Plains aquifer were prepared from data in the files of the Texas Water Development Board (fig. 16). The hydrograph of the Lamb County well illustrates the continuous depletion of the aquifer in this area since the early 1950's due to irrigation withdrawals. The water level in the Lamb County well declined at a rate of 3 feet per year from 1978 to 1985, remained static during 1986 due to increased precipitation, and then continued to decline at a slower rate of about 2 feet per year.

The Lubbock County well hydrograph differs from that previously described in that a water-level rise began in the late 1960's when the City of Lubbock started importing water from outside of the county. An additional slight rise can be seen in 1987, which was a particularly wet year. Also affecting the water level is a decline in irrigated acreage in the vicinity of the well due to the expansion of the city into previously irrigated farmland. A substantial amount of recharge to the aquifer occurs where storm runoff collects at a large surface depression or playa lakebed located in the southwestern part of the city.

The hydrograph of the Gaines County well shows that the water level rose about 30 feet since 1982, after remaining relatively constant for the previous 16 years. This well is located in an area that received a substantial increase in average annual precipitation during 1981-89 (4 to 6 inches above normal, fig. 7).

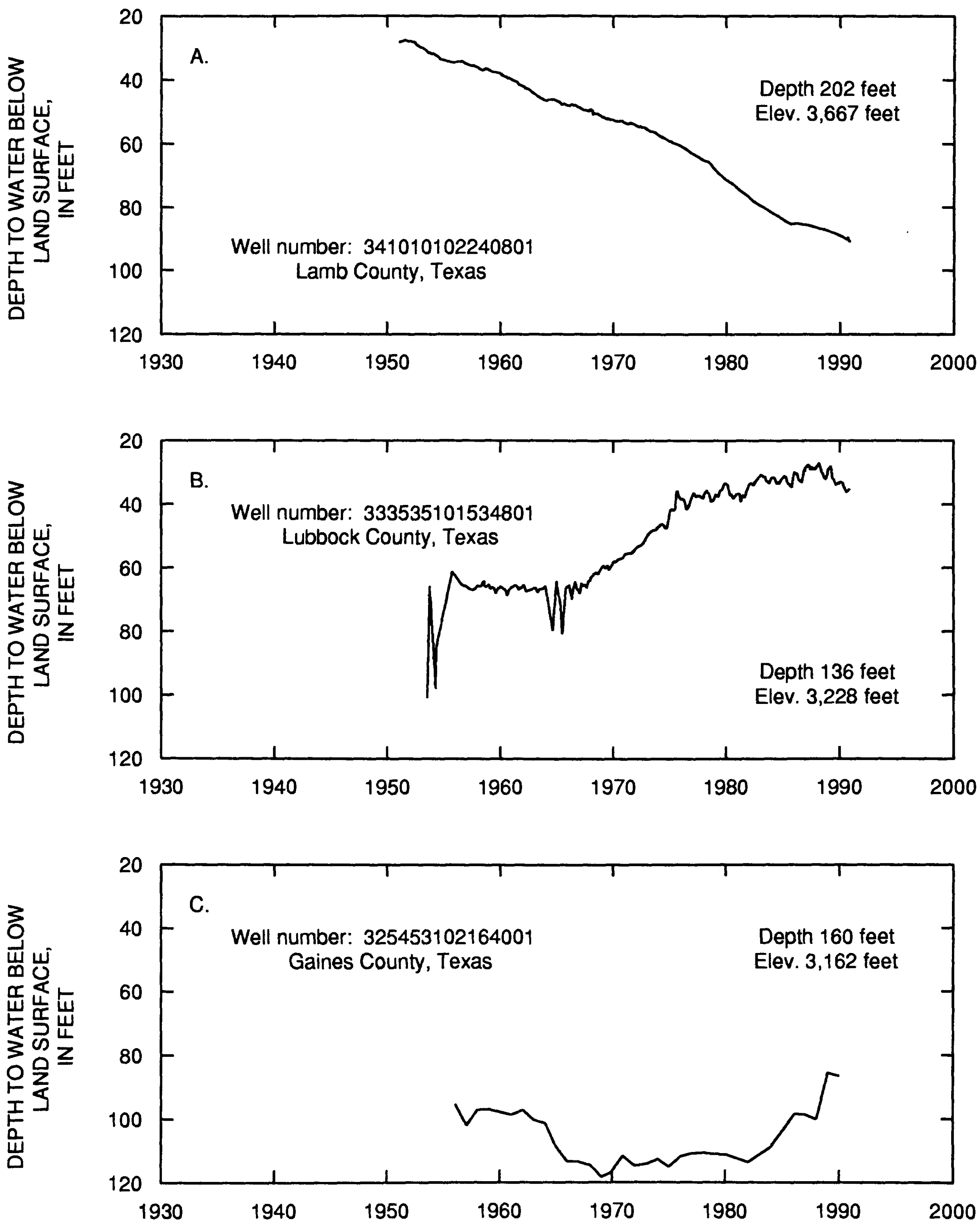

Figure 16. Observation wells: A, Lamb County; B, Lubbock County; C, Gaines County, Texas.

WYOMING

Widespread Water-Level Declines Occur During 1989-90 in the High Plains Aquifer in Wyoming

by K.A. Miller

The High Plains aquifer underlies approximately 8,000 square miles of southeast Wyoming (Kastner and others, 1989). Ground-water withdrawals from the High Plains averaged about 260 million gallons per day in 1985, with irrigation accounting for approximately 89 percent of the total use (Schuetz, 1990). Ground-water levels in Wyoming are monitored most intensively in those areas where ground water is used in large quantities for irrigation and municipal water supply (Kennedy and Green, 1990). Variability in water-level changes often are related to the location of these withdrawal wells.

The plains of southeastern Wyoming are semiarid, receiving an average of between 10 and 18 inches of precipitation per year. Most precipitation occurs during late spring and early summer (May and June) in the form of localized, intense thunderstorms (Martner, 1986). Precipitation over most of southeast Wyoming during 1981-89 was greater than the 30-year average (fig. 7). Average departures ranged from 0 to 2 inches above normal for most of the area to 4 to 6 inches above normal in southeastern Goshen County. Areas where precipitation averaged below normal were northeastern Goshen and southeastern Niobrara Counties (0 to -2.00 inches) and southeastern Converse County (-2.00 to -4.00 inches).

Precipitation for 1989 was generally less than the 30-year average (fig. 9). Departures ranged from 0 to 5 inches below normal for most of southeastern Wyoming. A notable exception to these departures was southeastern Goshen County, where precipitation departures were 2 to 5 inches above normal.

Recharge of the High Plains aquifer in southeastern Wyoming is derived both from precipitation and surface-water seepage. Estimates from several previous studies suggest recharge ranges from about 5.5 percent (Morgan, 1946); Rapp and others, 1953) to 6.5 percent (Lines, 1976) of the mean annual precipitation in southeastern Wyoming.

Recharge in certain areas is derived from surface-water bodies. Seepage from irrigation canals is one significant source of recharge (Crist, 1983). In the North Platte project area of central Goshen County, it has been estimated that over 200,000 acre-feet of water recharges the High Plains aquifer annually by seepage from canals and irrigated fields (Morris and Babcock, 1960). Some recharge of the aquifer in southeastern Wyoming occurs from storm runoff carried by ephemeral streams. Many catchment ponds and reservoirs in that area also contribute recharge. Some areas, however, do not contain substantial surface-water bodies. This is particularly true in such areas as the uplands of southern Niobrara County underlain by the Arikaree Formation of the High Plains aquifer and where stream channel development is poor (Whitcomb and Cummings, 1965).

The ground-water level program is conducted by the U.S. Geological Survey in cooperation with the Wyoming State Engineer. Water-level data from 23 observation wells were used to calculate water-level changes in the High Plains aquifer from 1980 to 1990, and data from 44 wells were used to calculate changes from 1989 to 1990 (fig. 5).

Water levels in the High Plains aquifer varied significantly in Laramie County from 1980 to 1990. Water levels rose between 7.5 and 15 feet in parts of southern Laramie County during that period (fig. 6). Much of the rise occurred in 1983 and 1984 during successive years of above-normal precipitation. The rises in the southwestern parts of the county may be due in part to a decrease in pumpage of ground water by the City of Cheyenne. The net rise in water levels in southern Laramie County during 1980 to 1990, however, is not indicative of the trend in water levels since 1985, which is one of decline.

Another significant area of water-level rise in Laramie County was in the northwest quarter, where rises of 2.5 to 7.5 feet occurred from 1980 to 1990. Large declines (-7.5 to -15.0 feet), however, occurred in the northeast corner of the county. Declines of lesser amounts (-2.5 to -7.5

feet) were noted in parts of south-central Laramie County. Precipitation over much of Laramie County during 1981-89 averaged between 2 and 4 inches above the 30-year average. Precipitation in the northwest and southeast corners of the county was only slightly above normal (fig. 7).

Water levels in much of Laramie County from 1989 to 1990 did not change significantly (fig. 8). Exceptions were the northwestern and southeastern parts of the county where declines between 1 and 3 feet were measured, and the southwestern part of the county where water levels continue to rise. Precipitation over most of Laramie County for 1989 was slightly below the 30-year average, except in the southeast corner where precipitation was between 2 and 5 inches below normal. Precipitation in the northwest corner of the county was slightly above normal.

Water levels in the High Plains aquifer in Goshen County from 1980 to 1990 also were variable. In northern Goshen County, water levels declined between 2.5 and 7.5 feet; whereas, rises between 2.5 and 7.5 feet occurred in the southern part of the county (fig. 6). Average precipitation in the southern part of the county during 1981-89 was between 2 and 6 inches greater than the 30-year average (fig. 7). Precipitation over much of the remainder of Goshen County was just slightly above normal, except in the northeastern corner, which was slightly below normal.

From 1989 to 1990, water levels declined in the High Plains aquifer in much of Goshen County. These declines were variable, ranging from 3 to 5 feet along the North Platte River in east-central Goshen County to 1 to 3 feet in most of northern and parts of southern Goshen County. Water levels in the remainder of the county did not change significantly, with the exception of the southeast corner, where water levels rose between 3 and 5 feet.

Precipitation in the southeast corner of Goshen County during 1989 was between 2 and 5 inches above the 30-year average (fig. 9). Precipitation for much of the rest of Goshen County for 1989 was below normal (-2.0 to -5.0 inches). Precipitation in the southwest corner of the county was only slightly below normal.

Water levels in the High Plains aquifer for much of Platte County did not change significantly from 1980 to 1990. An exception was the western third of the county where declines of 2.5 to 7.5 feet were measured. Precipitation in Platte County during 1981-89 was slightly greater than the 30-year average.

From 1989 to 1990, significant water-level declines of 3.0 to more than 5.0 feet were measured in western Platte County. Water levels for the remainder of Platte County did not change significantly. Precipitation departures from the 30-year average varied in Platte County in 1989. Precipitation in the southern part of the county was slightly above normal. Over the remainder of the county precipitation ranged from slightly below normal in the central part to 2 to 5 inches below normal in the northeastern and northwestern parts of the county.

Water levels in the High Plains aquifer in southeastern Niobrara County generally declined from 1980 to 1990, although water-level data in this area are sparse. In southwestern Niobrara County, water levels in an observation well have risen, which may be due partly to decreased pumping of municipal wells. Precipitation over much of southern Niobrara County during 1981-89 was slightly above the 30-year average, with the exception of the southeast corner, where precipitation was slightly below normal.

Water levels in southern Niobrara County from 1989 to 1990 did not change significantly. Precipitation in parts of southern Niobrara County in 1989 varied from 2 to 5 inches below the 30-year average to slightly below normal in south-central Niobrara County.

The variability of water-level change in the High Plains aquifer of southeastern Wyoming is indicated in the representative hydrographs in figure 17. Water levels in the well in northeastern Laramie County (fig. 17A) rose from approximately 1980 to the mid-1980's and have declined since. Water levels in the well in southeastern Laramie County (fig. 17B) rose nearly 10 feet from 1979 to 1985 but declined nearly 5 feet since. Water levels in the well in southeastern Niobrara County (fig. 17C) have declined nearly 10 feet at a steady rate since 1973.

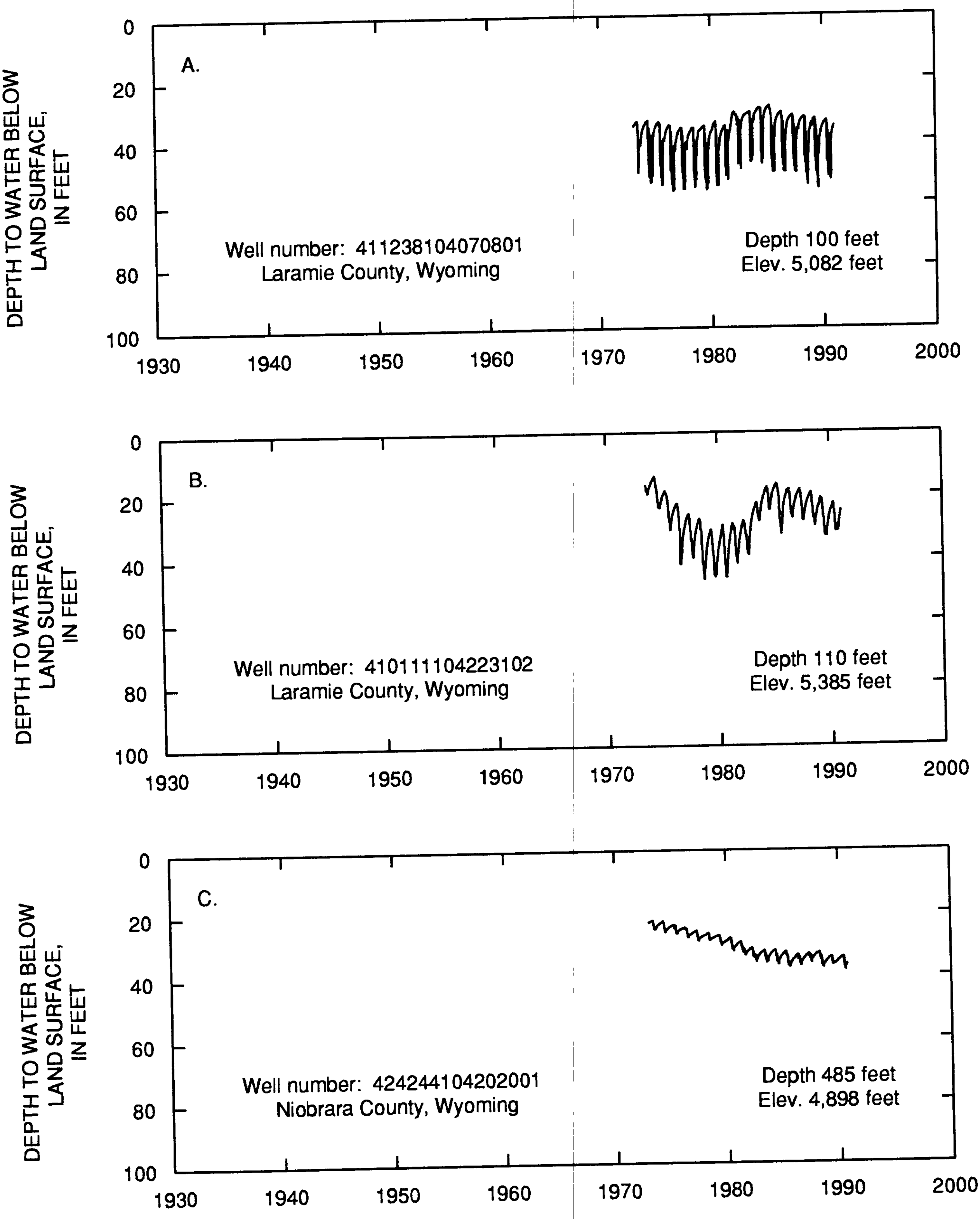

Figure 17. Observation wells: A, northeastern Laramie County; B, southeastern Laramie County; C, Niobrara County, Wyoming.

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