(200)
Wki
no.95-4208

Introduction

The High Plains aquifer underlies parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. The extensive development of ground-water resources in the High Plains for irrigated agriculture since 1940 has had a significant effect on the underlying High Plains aquifer. About 20 percent of the irrigated land in the United States is in the High Plains, and nearly 30 percent of the ground water used for irrigation in the United States is pumped from the High Plains aquifer (Weeks and others, 1988). The large volume of water withdrawn from the 1940's through 1994 from the aquifer for irrigation purposes has had a substantial effect on water levels.

Water-level changes in the High Plains aquifer, however, have not been uniform. Large regional differences in rates of ground-water recharge and withdrawals for irrigation as a result of regional variability in climate, soil, land use, and historical development of irrigated agriculture have substantially affected the geographical patterns of water-level change in the High Plains.

Jack Dugan, principal author of this report, was also project chief and principal author of the annual High Plains water-level-change reports since 1990. Jack passed away on May 19, 1995.

High Plains Water-Level Monitoring Program

The High Plains regional aquifer-system analysis (RASA), completed in the mid-1980's, indicated that substantial water-level declines had occurred in large parts of the High Plains aquifer (Gutentag and others, 1984). A program by the U.S. Geological Survey (USGS) to monitor water-level changes in the aquifer began in 1988 as a result of a Congressional mandate.

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

An extensive network of observation wells is necessary to monitor water levels in the High Plains (fig. 1). This network is composed of many smaller networks of observation wells measured by numerous Federal, State, and local agencies. Local water and natural resource conservation districts are responsible for most of these smaller networks and the majority of water-level measurements. The total number of wells measured in 1980 and 1994 was 6,143; the total number measured in 1993 and 1994 was 7,130. In most of the High Plains States, the USGS compiles the water-level measurements from these local networks and maintains a statewide data base.

Water-level measurements are usually made in the winter and early spring when water levels generally have recovered fully from pumping during the previous irrigation season. These measurements normally represent the highest water level during the year. Most observation wells are privately owned irrigation wells. The large diameter and high pumping capacity of these wells make them particularly well suited for monitoring water-level changes because they are less prone to plugging, which is common in small-diameter, small-capacity wells.

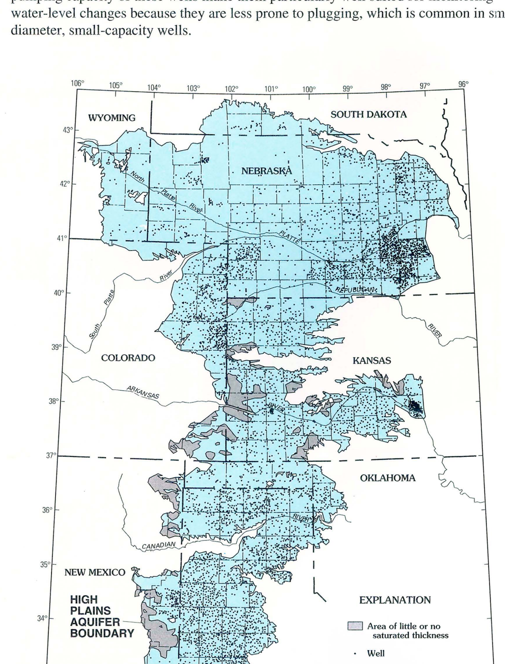


Figure 1. Location of observation wells with water-level measurements in 1980 and 1994.

Extent and Description of the High Plains Aquifer

The High Plains aquifer underlies about 174,050 square miles in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 2). Nearly 37 percent of the area and 66 percent of the volume of the aquifer underlies Nebraska (table 1).

The High Plains aquifer is commonly known as the Ogallala aquifer, but the various geologic units and ages of the deposits constituting the aquifer necessitated a more inclusive designation. In many places, the aquifer consists of one or more geologic units of late Tertiary or Quaternary age; the Ogallala Formation of Tertiary age is generally the principal unit (Gutentag and others, 1984).

The two oldest geologic units included in the High Plains aquifer are the Brule Formation and Arikaree Group of mid-Tertiary age. The Brule and Arikaree, respectively, generally consist of massive well-cemented siltstone and fine-grained sandstone. Only in the northwestern High Plains in parts of northeastern Colorado, the Nebraska Panhandle, south-central South Dakota, and southeastern Wyoming, where the Brule and Arikaree are fractured, are these units important local sources of water, and thus considered part of the High Plains aquifer (Gutentag and others, 1984).

The Ogallala Formation underlies about 134,000 square miles of the High Plains and is the principal water-yielding unit in most of the region (Gutentag and others, 1984). This formation is generally unconsolidated and composed of a variety of materials, including clay, silt, sand, and gravel. The Ogallala Formation is as thick as 700 feet in parts of north-central Nebraska. Irrigation wells completed in the Ogallala can yield about 1,000 gallons per minute of water (Gutentag and others, 1984).

Deposits of Quaternary age, where hydraulically connected to other units of the High Plains aquifer, are considered to be part of the aquifer. These deposits are widespread and are locally important sources of water in Kansas, Nebraska, and New Mexico. The intensive irrigation development of the Platte River Valley of south-central Nebraska depends largely on ground-water pumpage from deposits of Quaternary age (Peckenpaugh and Dugan, 1983; Peckenpaugh and others, 1987).

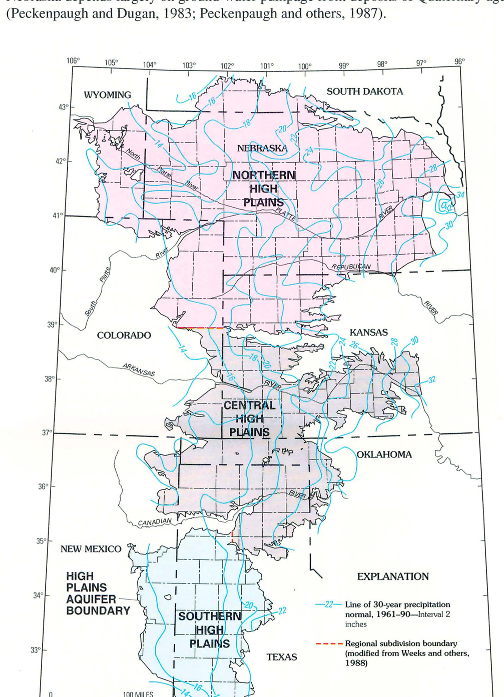


Figure 2. Regional subdivisions of the High Plains and average precipitation, 1961-90 (normal).

Table 1. Characteristics of the High Plains aquifer

[Modified from Gutentag and others, 1984]

Characteristic	Unit of measurement	Total	Colorado	Kansas	Nebraska	New Mexico	Oklahoma	South Dakota	Texas	Wyoming
Area underlain by aquifer	Square miles	174,050	14,900	30,500	63,650	9,450	7,350	4,750	35,450	8,000
Percentage of total aquifer area	Percent	100	8.6	17.5	36.6	5.4	4.2	2.7	20.4	4.6
Percentage of each state underlain by aquifer	Percent	--	14	38	83	8	11	7	13	8
Average area-weighted saturated thickness in 1980	Feet	190	79	101	342	51	130	207	110	182
Volume of drainable water in storage in 1980	Million acre-feet	3,250	120	320	2,130	50	110	60	390	70
Percentage of total volume of drainable water in storage in 1980	Percent	100	3.7	9.9	65.5	1.5	3.4	1.8	12.0	2.2

Climate and the High Plains Aquifer

The climate of the High Plains has a significant effect on the High Plains aquifer. The climatic characteristic with the greatest apparent effect on the High Plains aquifer is precipitation, which affects both natural recharge and irrigation requirements. Total area-weighted normal precipitation (1961–90) is nearly 20 inches per year in the High Plains but ranges from 14 inches in parts of the northwestern and extreme southern High Plains to more than 30 inches in eastern parts of the High Plains in Kansas and Nebraska (fig. 2). About 75 percent of the precipitation occurs during the warm season, April through September. Precipitation in the High Plains in any given year tends to be quite variable both in time and location.

Potential evapotranspiration (PET) in the High Plains varies from less than 40 inches in the northeastern part to more than 65 inches in the southwestern part (Dugan and Cox, 1994).

Factors Affecting Water-Level Change

Water-level change in the High Plains aquifer results from an imbalance between recharge and discharge. Human activities such as pumpage from wells, stream diversions, and agricultural practices have disturbed this balance in many parts of the High Plains and resulted in substantial water-level change through time.

Recharge

Precipitation is the principal source of natural ground-water recharge to the High Plains aquifer. Several additional factors also affect natural recharge to the High Plains aquifer. These include topography, soil texture and thickness, vegetation or crop type, PET, and the lithology and thickness of the unsaturated zone.

Recharge to the High Plains aquifer usually results from conditions present during the nongrowing season when evapotranspiration is minimal and soil water can accumulate in the root zone and percolate downward. In the drier western High Plains, the recharge process may only occur as an isolated event every several years. In the wetter eastern High Plains, the recharge process is more frequent because the soil water in the root zone reaches its capacity more often (Dugan and Zelt, in press).

Estimated average annual potential ground-water recharge to the High Plains aquifer during 1951–80 is illustrated in figure 3. Values shown in figure 3 are not observed amounts of water entering the aquifer but are values for the potential surplus soil water available as recharge as determined by climatic, soil, and vegetation characteristics (Dugan and Cox, 1994). Calculation of estimated potential ground-water recharge is explained in more detail in Dugan and Zelt (in press). Estimated average annual potential ground-water recharge to the High Plains aquifer ranges from less than 0.25 inch in the western High Plains to more than 6 inches in parts of eastern Nebraska and central Kansas. Expressed as a percentage of average annual precipitation, estimated ground-water recharge ranges from less than 0.5 percent in western parts of the High Plains to about 25 percent in eastern Nebraska where soils are sandy (Dugan and Zelt, in press).

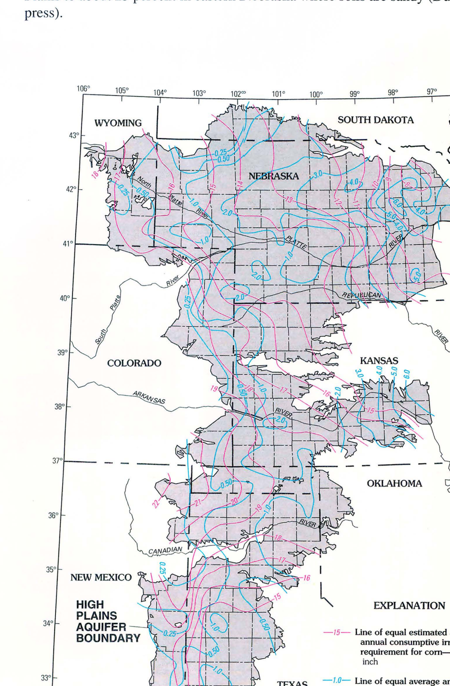


Figure 3. Estimated average annual potential ground-water recharge and consumptive irrigation requirement for corn, 1951–80 (modified from Dugan and Zelt, in press).

Discharge

Natural discharge from the High Plains aquifer occurs as evapotranspiration where the water table is near the land surface and as seepage from the aquifer where the water table intersects the land surface. Under natural conditions, this type of discharge would tend to balance long-term natural recharge. Water is discharged artificially from the aquifer predominantly by pumping of wells. Where pumpage exceeds recharge, water is removed from storage, and the water table declines. Part of this loss to storage is alleviated by decreases in natural discharge or induced recharge from streams caused by lowering of the water table.

Nearly 95 percent of the ground-water withdrawals from the High Plains aquifer in 1990, more than 15.6 million acre-feet, were for irrigated agriculture (table 2). Total ground-water withdrawals from the High Plains aquifer, however, decreased nearly 20 percent from 1980 (20.5 million acre-feet) to 1990 (16.5 million acre-feet). Most of this decline (about 17 percent) was between 1980 and 1985 (Wayne Solley, U.S. Geological Survey, oral commun., 1988; Carr and others, 1990; Solley and others, 1993). Although comparable statistics for ground-water irrigation withdrawals are not available for 1980 and 1985, the decline in total withdrawals by 1990 appears to be largely attributable to declines in irrigation (table 2). Declines in irrigation withdrawals since 1980 have been associated with (1) wetter-than-normal conditions across most of the High Plains—average annual precipitation for the High Plains from 1981–93 was 1.40 inches above normal (National Climatic Data Center, 1981–93), (2) a long-term decrease in irrigated cropland acreage in parts of the Central and Southern High Plains in areas where consumptive irrigation requirements (fig. 3) are among the highest in the High Plains, and (3) advances in irrigation technology and management practices that have reduced pumpage requirements to meet water needs (Dugan and Cox, 1994).

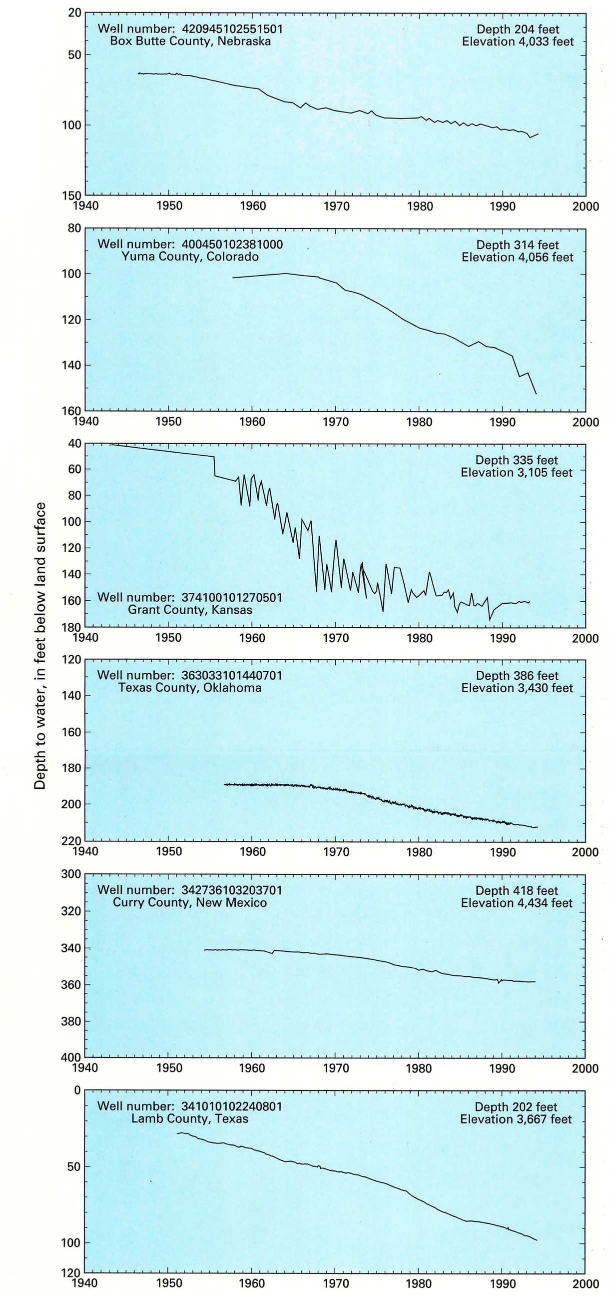
Ground-water withdrawal rates by county, shown in figure 4, largely represent irrigation development in the High Plains. Withdrawal rates are largely a function of both irrigated acreages and withdrawal rates per irrigated acre. The large withdrawal rates per county in parts of southwestern Kansas and the Texas Panhandle reflect, in part, the large withdrawal rates per irrigated acre in these areas. Some counties in south-central Nebraska have among the largest percentage of land area irrigated in the High Plains, but withdrawal rates per irrigated acre are relatively small (Dugan and Zelt, in press).

The rate of withdrawals per irrigated acre is largely determined by consumptive irrigation requirements (CIR). The average annual CIR for corn (fig. 3) is a function largely of both solar radiation (a factor controlling PET) and precipitation. The large CIR in the western parts of the Central and Southern High Plains—exceeding 22 inches in northeastern New Mexico—reflects small average annual precipitation (fig. 2) and intense solar radiation (Dugan and Zelt, in press). CIR less than 10 inches in eastern Nebraska reflects nearly double the average annual precipitation and substantially less intense solar radiation, particularly during the growing season. It is assumed that any water applied in excess of the CIR becomes runoff (usually negligible) or infiltrates back to the aquifer. A more detailed explanation of CIR and its relation to actual water use in the High Plains is given in Dugan and Cox (1994).

Table 2. Ground-water withdrawals from the High Plains aquifer in 1990 and 1985 by type of use

[Data from Carr and others (1990) and Solley and others (1993). Withdrawals in thousands of acre-feet]

State	Year	Nonagricultural use: Domestic (public and private water supplies)	Nonagricultural use: Mining, industrial, commercial, and thermoelectric-power generation	Agricultural use: Livestock	Agricultural use: Irrigation	Total
Colorado	1990	11.6	5.5	8.6	989.5	1,015.2
	1985	6.2		877.1		883.3
Kansas	1990	54.4	19.4	51.6	3,936.6	4,062.0
	1985	92.7		4,324.0		4,416.7
Nebraska	1990	167.7	19.7	101.4	4,736.4	5,025.2
	1985	197.1		5,598.5		5,795.6
New Mexico	1990	29.0	22.5	4.2	738.4	794.1
	1985	50.0		603.0		653.0
Oklahoma	1990	17.3	.9	13.0	375.3	406.5
	1985	8.0		270.0		278.0
South Dakota	1990	2.9	0	1.2	18.3	22.4
	1985	3.0		21.7		24.7
Texas	1990	106.5	194.0	47.9	4,702.4	5,050.8
	1985	188.8		4,531.7		4,720.5
Wyoming	1990	11.8	.5	1.3	145.0	158.6
	1985	33.0		266.7		299.7
Total	**1990**	**401.2**	**262.5**	**229.2**	**15,641.9**	**16,534.8**
	1985	**578.8**		**16,492.7**		**17,071.5**



Hydrographs of Representative Observation Wells

The following observation-well hydrographs illustrate water levels through time at selected locations in the High Plains where either development of ground-water resources or other activities have had a significant effect on the aquifer. The hydrographs represent unconfined conditions.

Box Butte County, Nebraska

Irrigation development began in this area in about 1950, and the water level steadily declined about 44 feet from 1951 to 1994, or 1 foot per year. The rate of decline was largest in the early and mid-1960's when the water level declined about 2 feet per year. Average annual precipitation in this area is about 16 inches.

Yuma County, Colorado

Substantial irrigation development began in the mid-1960's in this area, and the water level steadily declined except for brief recoveries in 1986 and 1992. From 1964 to 1994, the decline was 43.5 feet or about 1.4 feet per year. The water level at this location has declined almost 7 feet from 1991 to 1994.

Grant County, Kansas

The water level at this location declined nearly 9 feet from 1943 to 1955 and more than 100 feet from 1955 to 1980, about 4 feet per year. After 1980, the water level declined only an additional 6 feet and essentially stabilized at 160 feet since 1990, which possibly indicates the cessation of irrigation pumpage in the immediate area.

Texas County, Oklahoma

The water level at this location remained relatively steady until 1967. From 1967 to 1994, the water level steadily declined about 24 feet or nearly 0.9 foot per year. Irrigated acreage has decreased in Texas County since the early 1980's, which probably contributed to the smaller rate of decline from 1990 to 1994 of about 0.5 foot per year.

Curry County, New Mexico

The well is located just west of the intensively irrigated area in the northern part of the Southern High Plains of Texas and New Mexico. The 1993–94 section of the hydrograph shows moderate seasonal fluctuations.

Lamb County, Texas

The hydrograph of this observation well illustrates the nearly constant rate of depletion of the aquifer by intensive irrigation withdrawals since the early 1950's in the northern part of the Southern High Plains. Water levels in this well declined nearly 70 feet from 1951 to 1994, an average of about 1.6 feet per year. More than 35 percent of the 1951 saturated thickness was depleted by 1994.

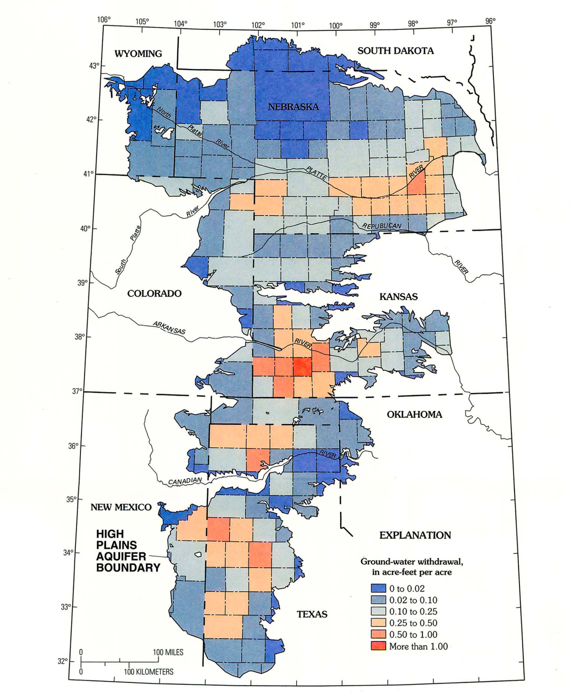


Figure 4. Ground-water withdrawal rates by county during 1990 (data from U.S. Geological Survey National Water-Data Storage and Retrieval System).

Ground-Water Irrigation Development and Water-Level Change, Predevelopment to 1980

Technological developments, including rotary drills, turbine pumps, and efficient powerplants to run the turbine pumps, served important roles in the development of ground-water resources for irrigation in the High Plains after 1940. These advances permitted cost-efficient pumping from depths exceeding 100 feet in upland areas. Subsequent technological advances in irrigation such as lightweight aluminum pipe (including gated pipe) in the 1950's, and center-pivot irrigation systems in the 1960's, permitted even greater irrigation expansion in the uplands of the High Plains.

The availability of low-cost energy sources, including electricity, natural gas (including propane), and diesel fuel, was perhaps as important as technology for irrigation development in the High Plains. However, the large increase in energy prices after 1974 became a significant factor in limiting later irrigation expansion.

Ground-water irrigation expanded rapidly in the High Plains after 1940: 1949—2.1 million acres (Texas—1.6 million acres); 1959—6.1 million acres (Texas—4.0 million acres); 1969—9.0 million acres (Texas—4.5 million acres); and 1978—12.9 million acres (Texas and Nebraska—4.5 million acres each) (Gutentag and others, 1984). With the northward expansion of ground-water irrigation from the Texas High Plains, the Texas proportion of ground-water irrigated acres decreased from 76 percent in 1949 to 35 percent in 1978.

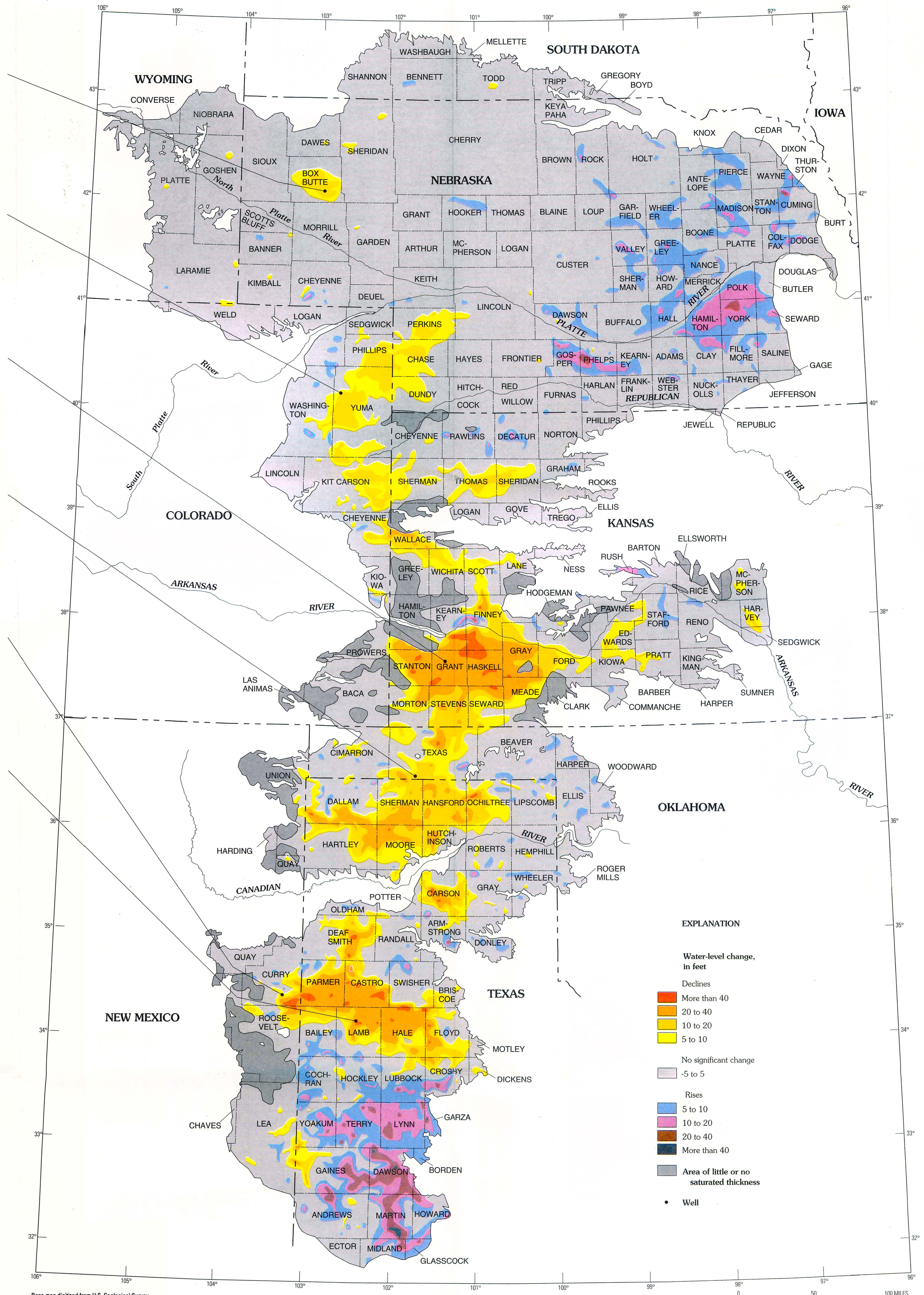


Figure 6. Water-level change in the High Plains aquifer, 1980 to 1994.

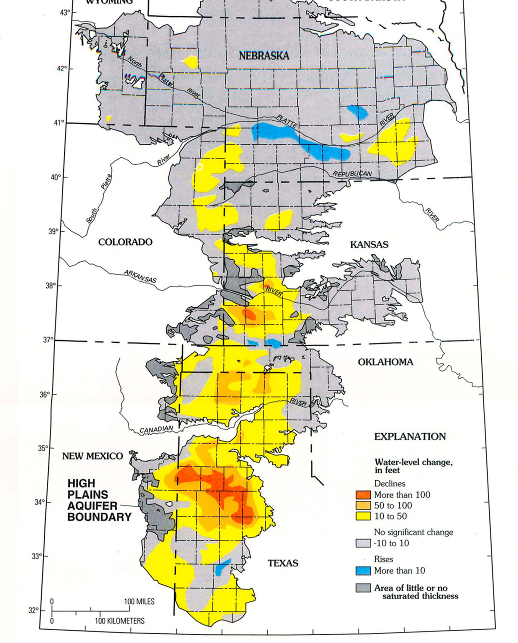


Figure 5. Water-level change in the High Plains aquifer, predevelopment to 1980 (modified from Luckey and others, 1981).

Water-level declines began in the Southern High Plains soon after ground-water development began in upland areas in about 1940. These declines generally followed the northward migration of irrigation development. Water-level declines became evident in the Central High Plains early in the 1950's and in the Northern High Plains in the 1960's.

Water-level declines from predevelopment to 1980 exceeded 100 feet in a substantial area of the Southern High Plains and a smaller area of southwestern Kansas (fig. 5). Declines exceeding 10 feet by 1980 were widespread in the Southern High Plains and substantial areas of the Central and Northern High Plains. Area-weighted average water levels declined nearly 10 feet in the High Plains and nearly 34 feet in the Texas High Plains (Gutentag and others, 1984). Area-weighted average water levels in the High Plains declined at a rate of about 0.25 foot per year from 1940 to 1980. The large areas of water-level rise exceeding 10 feet in south-central Nebraska from predevelopment to 1980 resulted from seepage losses from surface-water diversions for irrigation and power generation.

Water-Level Change, 1980 to 1994

Water-level change in the High Plains aquifer from 1980 to 1994 (fig. 6) reflects variable patterns in comparison to the patterns of change observed from predevelopment to 1980 (fig. 5). Substantial declines have continued in the Central High Plains in southwestern Kansas, the Oklahoma and Texas Panhandles, and the northern part of the Southern High Plains in New Mexico and Texas. Some areas of substantial water-level declines from predevelopment to 1980 in the Northern High Plains, however, have generally had considerably slower rates of decline, or rising water levels, since 1980.

The average area-weighted water level in the High Plains declined 1.54 feet from 1980 to 1994 compared to 9.9 feet from predevelopment to 1980 (table 3). Considering 1940 as the time of initial irrigation development, the area-weighted average annual rate of decline decreased from nearly 0.25 foot per year from 1940 to 1980 to 0.11 foot per year from 1980 to 1994. Much of the reduction in the area-weighted average annual rate of decline since 1980 can be attributed to an area-weighted average water-level rise in Nebraska of 1.88 feet or 0.13 foot per year.

The smaller rate of decline for the High Plains after 1980 can also be attributed, in part, to a significantly smaller rate of decline in Texas from 1980 to 1994; water levels that declined an area-weighted average of 33.7 feet or 0.84 foot per year from 1940 to 1980 declined an area-weighted average of 3.02 feet from 1980 to 1994 or 0.22 foot per year. The area-weighted average rate of decline in Texas slowed after 1980 due to (1) substantial reductions in the number of acres irrigated since the 1970's in those areas of the Texas High Plains prone to large rates of water-level decline and (2) widespread water-level rises in the southern part of the Southern High Plains. Irrigated land in the Texas High Plains decreased by 1.39 million acres, or about 31 percent between 1979 and 1991 (Gutentag and others, 1984; Dugan and Schild, 1992, p. 44).

The rate of water-level decline in Kansas, however, increased after 1980. Considering 1950 as the beginning of irrigation development in Kansas, water levels declined an area-weighted average of 9.9 feet from 1950 to 1980 or 0.33 foot per year. From 1980 to 1994, the area-weighted average water level declined 6.12 feet or 0.44 foot per year. The increase in the rate of decline in Kansas from 1980 to 1994 can be attributed, in part, to the continued expansion of irrigation in the late 1970's and early 1980's.

Table 3. Average area-weighted water-level changes and estimated changes in volume of water in storage in the High Plains aquifer, predevelopment to 1980 and 1980 to 1994

State	Area-weighted water-level change (feet): Predevelopment to [1]1980	Area-weighted water-level change (feet): 1980 to 1994	Estimated changes in volume of water in storage (millions of acre-feet): Predevelopment to 1980	Estimated changes in volume of water in storage (millions of acre-feet): 1980 to 1994
Colorado	-4.2	-3.39	-6.0	-4.8
Kansas	-9.9	-6.12	-29.0	-17.9
Nebraska	0	+1.88	0	+11.9
New Mexico	-9.8	-2.31	-9.0	-2.1
Oklahoma	-11.3	-1.81	-8.0	-1.3
South Dakota	0	+1.47	0	+1.7
Texas	-33.7	-3.02	-114.0	-10.3
Wyoming	0	-2.52	0	-1.9
High Plains	**-9.9**	**-1.54**	**-166.0**	**-24.7**

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

The overall rate of water-level decline in the High Plains since 1980 probably would have exceeded the predevelopment-to-1980 rate if acres irrigated were the only determining factor. An average of 6 million acres were irrigated annually in the High Plains during the predevelopment to 1980 period and about 14 million acres after 1980 (Gutentag and others, 1984; Weeks, J.B., *in* Sun, 1986). The following factors, however, appear to have contributed to a reduction in the rate of decline.

(1) Precipitation from 1980 to 1994 was generally well above normal throughout the High Plains (fig. 7). Area-weighted average annual precipitation during 1981–93 was 21.18 inches or 1.40 inches above normal (table 4).

(2) Later phases of irrigation development in the High Plains shifted geographically from areas of larger potential rates of aquifer depletion to areas of smaller potential rates of depletion. From predevelopment to 1980, most irrigated land was in the Southern and Central High Plains where recharge tends to be small and consumptive irrigation requirements large (fig. 3). After 1980, more than half of the 14 million acres irrigated were in the Northern High Plains, mainly in Nebraska, where recharge is generally larger and consumptive irrigation requirements are smaller than in the Central and Southern High Plains.

(3) Significant advances in irrigation technology have substantially reduced the ground-water pumpage needed to meet consumptive irrigation requirements. These include center-pivot sprinkler irrigation, lightweight gated pipe, surge irrigation, and the low-energy, precise application method, which reduces wind loss from center-pivot irrigation.

(4) Irrigation management practices, including irrigation scheduling based on soil-water conditions and crop growth stages and the conversion to crops or varieties with smaller consumptive irrigation requirements, have further reduced ground-water pumpage.

(5) Water-level declines in some areas prior to 1980 prompted local regulation of ground-water withdrawals for irrigation and development of irrigated land.

(6) Declining or stable commodity prices, increased production costs (including higher energy and fertilizer prices) and various agricultural programs of the Federal government have contributed to the removal of marginally profitable land from irrigated production and stimulated more efficient irrigation practices on remaining irrigated land.

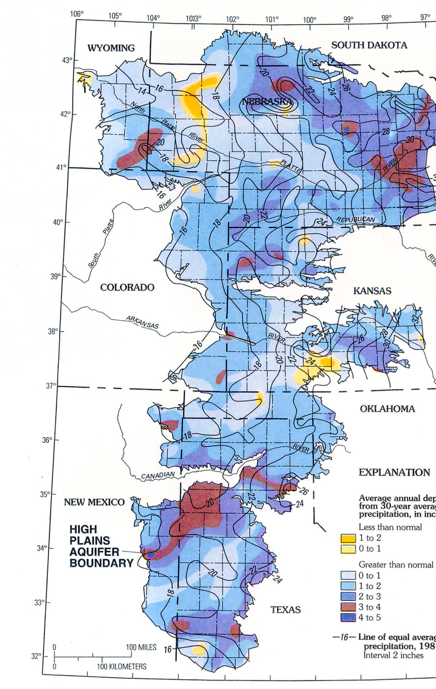


Figure 7. Average annual precipitation, 1981–93, and departure from 30-year normal (1961–90) (precipitation data from U.S. Department of Commerce, National Climatic Data Center, Asheville, North Carolina).

Table 4. Average annual area-weighted precipitation in the High Plains during 1981–93, departure from 30-year normal (1961–90), and percentage of normal

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

State	Average annual area-weighted precipitation (inches)	Departure from 30-year normal (inches)	Percentage of normal
Colorado	17.42	+1.13	107
Kansas	22.64	+1.15	105
Nebraska	22.87	+1.36	106
New Mexico	18.48	+2.19	113
Oklahoma	20.68	+.99	105
South Dakota	20.32	+1.62	109
Texas	20.59	+1.66	109
Wyoming	15.79	+1.37	110
High Plains	**21.18**	**+1.40**	**107**

Southern High Plains

Water-level change from 1980 to 1994 in the Southern High Plains of New Mexico and Texas presents two contrasting patterns. In the northern half, water levels in a relatively continuous 25- to 40-mile-wide belt from eastern Curry and Roosevelt Counties, New Mexico, to western Floyd County, Texas, have declined more than 20 feet. In isolated locations within this belt declines have exceeded 40 feet (fig. 6). The area of 20-foot declines closely approximates the area of declines exceeding 100 feet from predevelopment to 1980. The rate of decline of about 3 feet annually in this area from predevelopment (1940) to 1980, however, decreased to less than 2 feet annually since 1980.

Water levels in the southern half of the Southern High Plains have risen substantially over a large area. Rises exceeding 20 feet extended over much of Dawson and eastern Gaines Counties, Texas.

Central High Plains

Water-level declines from 1980 to 1994 were largest, both in area and magnitude of decline, in the Central High Plains. A nearly continuous area of decline exceeding 10 feet includes much of southwestern Kansas, part of the Panhandle of Oklahoma, and much of the northern Panhandle of Texas. The area of declines exceeding 20 feet from 1980 to 1994 (fig. 6) also is much larger than the area of decline exceeding 50 feet from predevelopment (1950) to 1980 (fig. 5). Declines exceeded 40 feet in some areas of southwestern Kansas. The area-weighted average annual rate of decline in this part of Kansas since 1980 is as large or larger than the predevelopment-to-1980 rate of decline, about 2.5 feet. Development of irrigation continued in much of the Central High Plains into the early 1980's, which may account for the continued large rate of decline after 1980. Precipitation, which averaged about 2 inches above normal from 1981–93 in the Central High Plains, appeared to have had a minimal effect on this large rate of water-level decline.

Northern High Plains

The Northern High Plains presents a strong contrast to the Central High Plains and northern part of the Southern High Plains. Areas of water-level decline are relatively small and more than offset by areas of equivalent water-level rise. Patterns of water-level decline after 1980 also differ considerably from those prior to 1980. Water levels did continue to decline in northeastern Colorado, the central Panhandle and southwestern areas of Nebraska, and northwestern Kansas. Declines in these areas, however, averaged about 10 feet from 1980 to 1994, or less than 1 foot per year compared to about 1.5 feet per year from predevelopment (1965 in this area) to 1980.

Water-level rises exceeding 5 feet were widespread throughout the eastern High Plains of Nebraska (fig. 6). Water-level rises of 10 to 20 feet occurred in an area of eastern Nebraska that had water-level declines exceeding 20 feet from predevelopment (1955 to 1960 in the area) to 1980. Precipitation was as much as 4 to 5 inches above normal in this area from 1981–93 (fig. 7).

Regional Variability of Remaining Saturated Thickness

Changes in saturated thickness associated with predevelopment, 1980, and 1994 further indicate large regional differences in the rate of aquifer depletion (table 5). In Texas and New Mexico, about 74 and 80 percent, respectively, of predevelopment saturated thickness remains. In Kansas, Oklahoma, and Colorado, about 86 and 91 percent, respectively, remains, and nearly 100 percent remains in Nebraska, South Dakota, and Wyoming. In those areas where water-level declines exceed 140 feet since predevelopment (figs. 5 and 6), remaining saturated thickness is often less than 50 percent.

Table 5. Average area-weighted saturated thickness of the High Plains aquifer, predevelopment, 1980, and 1994

State	Predevelopment (feet)	1980 (feet)	1980 as a percentage of predevelopment	1994 (feet)	1994 as a percentage of predevelopment
Colorado	83.2	79.0	95	75.6	91
Kansas	110.9	101.0	91	95.9	86
Nebraska	342.0	342.0	100	344.0	101
New Mexico	60.8	51.0	84	48.7	80
Oklahoma	141.3	130.0	92	128.2	91
South Dakota	207.6	207.0	100	208.5	100
Texas	143.7	110.0	77	107.0	74
Wyoming	182.0	182.0	100	179.5	99
High Plains	**199.9**	**190.0**	**95**	**188.5**	**94**

Water-Level Change, 1993 to 1994

This was the second consecutive 1-year period of average area-weighted water-level rise in the High Plains (table 6). The average area-weighted 0.56-foot rise from 1993 to 1994 (table 7), however, was considerably larger than the rise of 0.21 foot from 1992 to 1993 (Dugan and Cox, 1994). The larger magnitude of the 1993 to 1994 rise may be largely attributed to precipitation in the High Plains that had an area-weighted average of 4.24 inches above normal in 1993 compared to 2.03 inches above normal in 1992 (table 6). The cumulative effect of 3 consecutive years of above-normal precipitation also may have contributed to the large 1993 to 1994 rise. Precipitation in the High Plains from 1991–93 had an area-weighted average of 2.49 inches above normal.

Whereas the area-weighted average water level rose in the High Plains from 1993 to 1994 and area-weighted average precipitation was well above normal in 1993, these conditions were not uniform across the High Plains. Both water-level changes and precipitation presented strongly contrasting regional patterns within the High Plains (figs. 8 and 9).

Water-level declines of at least 1 foot were common throughout the Southern High Plains and southwestern half of the Central High Plains. Declines exceeding 3 feet extended in a nearly continuous arc from Roosevelt and Curry Counties, New Mexico, to Swisher and Hale Counties, Texas (fig. 8). The average area-weighted water level declined nearly 1 foot in the High Plains of Texas and 0.27 foot in New Mexico from 1993 to 1994 (table 7). Precipitation was generally below normal in 1993 in those parts of the Southern and Central High Plains with widespread water-level declines from 1993 to 1994 (figs. 8 and 9, table 8).

In contrast, water-level rises of 1 to 3 feet were widespread throughout much of the Northern High Plains and northeastern half of the Central High Plains from 1993 to 1994. The average area-weighted water level rose 1.81 feet in the Nebraska High Plains and 0.55 foot in the Kansas High Plains (table 7) from 1993–94.

The widespread water-level rises throughout the Northern High Plains and parts of the Central High Plains from 1993 to 1994 were associated with one of the wettest years on record in those areas. Precipitation in each of the High Plains States of Kansas, Nebraska, and South Dakota averaged about 7 inches or more above normal in 1993 (table 8). Precipitation was 10 inches above normal over large parts of eastern and south-central Nebraska and was more than 20 inches above normal (nearly 200 percent of normal) at two locations in south-central Nebraska (fig. 9).

Table 6. Average annual area-weighted water-level changes in the High Plains aquifer and annual area-weighted precipitation and departures from normal, 1988 to 1994

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

Water-level change period	Average annual area-weighted water-level change (feet)	Precipitation year	Area-weighted precipitation (inches)	Average area-weighted departure of precipitation from normal (inches)
1988 to 1989	-0.65	1988	18.84	-0.94
1989 to 1990	-.63	1989	17.00	-2.78
1990 to 1991	-.42	1990	19.28	-.50
1991 to 1992	-.55	1991	20.99	+1.21
1992 to 1993	+.21	1992	21.81	+2.03
1993 to 1994	+.56	1993	24.02	+4.24
Annual average	**-.25**	**1988-93**	**20.32**	**+.54**

Table 7. Average area-weighted water-level change from 1993 to 1994

State	Area-weighted water-level change (feet)
Colorado	-0.13
Kansas	+.55
Nebraska	+1.81
New Mexico	-.27
Oklahoma	+.10
South Dakota	+.38
Texas	-.99
Wyoming	+.13
High Plains	**+.56**

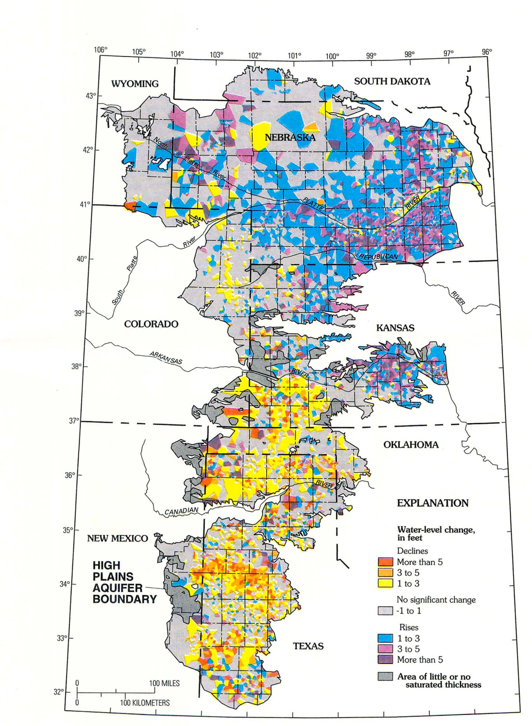


Figure 8. Water-level change in the High Plains aquifer, 1993 to 1994.

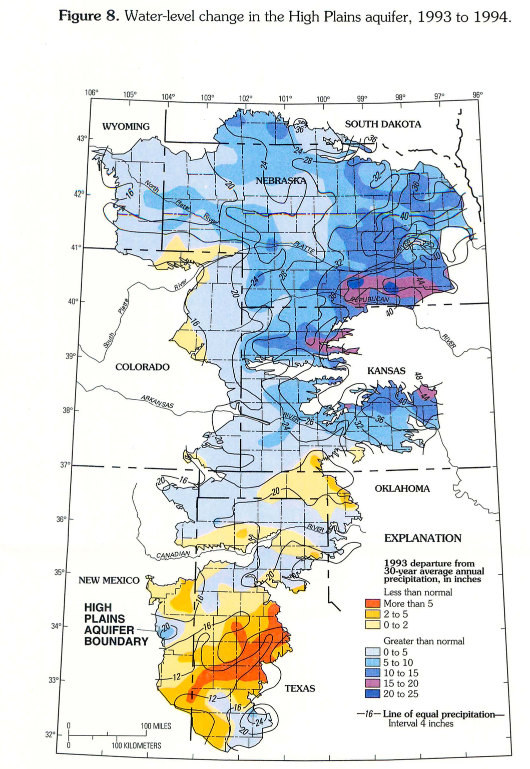


Figure 9. 1993 precipitation and departure from 30-year normal (1961–90) (precipitation data from U.S. Department of Commerce, National Climatic Data Center, Asheville, North Carolina).

Table 8. Average area-weighted precipitation in the High Plains in 1993, departure from 30-year normal (1961–90), and percentage of normal

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

State	Average area-weighted precipitation (inches)	Average area-weighted departure from 30-year normal (inches)	Percentage of normal
Colorado	17.42	+1.14	107
Kansas	28.75	+7.26	134
Nebraska	29.38	+7.87	137
New Mexico	15.10	-1.28	92
Oklahoma	19.44	-.25	99
South Dakota	25.69	+6.98	137
Texas	17.56	-1.37	93
Wyoming	18.01	+3.67	126
High Plains	**24.02**	**+4.24**	**121**

Selected References

Ashworth, J.B., 1991, Water-level changes in the High Plains aquifer of Texas: Texas Water Development Board Hydrologic Atlas No. 1, 1 sheet, scale 1:250,000.

Carr, J.E., Chase, E.B., Paulson, R.W., and Moody, D.W., 1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 552 p.

Dugan, J.T., and Cox, D.A., 1994, Water-level changes in the High Plains aquifer—Predevelopment to 1993: U.S. Geological Survey Water-Resources Investigations Report 94–4157, 60 p.

Dugan, J.T., McGrath, T.S., and Zelt, R.B., 1994, Water-level changes in the High Plains aquifer—Predevelopment to 1992: U.S. Geological Survey Water-Resources Investigations Report 94–4027, 56 p.

Dugan, J.T., and Schild, D.E., 1992, Water-level changes in the High Plains aquifer—Predevelopment to 1990: U.S. Geological Survey Water-Resources Investigations Report 91–4165, 55 p.

Dugan, J.T., Schild, D.E., and Kastner, W.M., 1990, Water-level changes in the High Plains aquifer underlying parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas—Predevelopment through nonirrigation season 1988–89: U.S. Geological Survey Water-Resources Investigations Report 90–4153, 29 p.

Dugan, J.T., and Zelt, R.B., (in press), Simulation and analysis of soil-water conditions in the Great Plains and adjacent areas, Central United States, 1951–80: U.S. Geological Survey Water-Supply Paper 2427.

Emry, R.J., Bjork, P.R., and Russell, L.S., 1987, The Chadronian, Orellan, and Whitneyan North American land mammal ages, *in* Woodburne, M.O., ed., Cenozoic mammals of North America: Berkeley and Los Angeles, University of California Press, p. 118–152.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–B, 63 p.

Kastner, W.M., Schild, D.E., and Spahr, D.S., 1989, Water-level changes in the High Plains aquifer underlying parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas—Predevelopment through nonirrigation season, 1987–88: U.S. Geological Survey Water-Resources Investigations Report 89–4073, 61 p.

Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980 in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–652, 2 sheets, scale 1:2,500,000.

McGrath, Timothy, and Dugan, J.T., 1993, Water-level changes in the High Plains aquifer—Predevelopment to 1991: U.S. Geological Survey Water-Resources Investigations Report 93–4088, 53 p.

Peckenpaugh, J.M., and Dugan, J.T., 1983, Hydrogeology of parts of Central Platte and Lower Loup Natural Resources Districts, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 83–4219, 100 p.

Peckenpaugh, J.M., Dugan, J.T., Kern, R.A., and Schroeder, W.J., 1987, Hydrogeology of the Tri-Basin and parts of the Lower Republican and Central Platte Natural Resources Districts, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 87–4176, 117 p.

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1993, Estimated use of water in the United States in 1990: U.S. Geological Survey Circular 1081, 76 p.

Sun, R.J., ed., 1986, Regional Aquifer-System Analysis Program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, 264 p.

Swinehart, J.B., 1989, Wind-blown deposits, *in* Bleed, Ann, and Flowerday, Charles, eds., An atlas of the Sand Hills: University of Nebraska-Lincoln, Institute of Agriculture and Natural Resources, Conservation and Survey Division, Resource Atlas 5, p. 45–46.

Tedford, R.H., Galusha, Theodore, Skinner, M.F., Taylor, B.E., Fields, R.W., Macdonald, J.R., Rensberger, J.M., Webb, S.D., and Whistler, D.P., 1987, Faunal succession and biochronology of the Arikareean through Hemphillian interval (late Oligocene through the earliest Pliocene Epochs) in North America, *in* Woodburne, M.O., ed., Cenozoic mammals of North America: Berkeley and Los Angeles, University of California Press, p. 153–210.

U.S. Department of Commerce, National Climatic Data Center, 1951–93, Climatological data by State, monthly and annual summaries: Asheville, N.C.

Weeks, J.B., and Gutentag, E.D., 1981, Bedrock geology, altitude of base, and 1980 saturated thickness of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–648, 2 sheets, scale 1:250,000.

Weeks, J.B., Gutentag, E.D., Heimes, F.J., and Luckey, R.R., 1988, Summary of the High Plains regional aquifer-system analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–A, 30 p.

CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot	1,233	cubic meter
acre-foot per acre	0.3048	cubic meter per square meter
foot	0.3048	meter
gallon per minute	0.06309	decimeter per second
inch	25.4	millimeter
mile	1.609	kilometer
million gallons per day	0.003785	million cubic meters per day
square mile	2.590	square kilometer

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$°C=5/9\ (°F-32)$$
$$°F=9/5\ (°C)+32.$$

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 the United States and Canada, formerly called Sea Level Datum of 1929.

U.S. GEOLOGICAL SURVEY
DENVER
SEP 16 1996
LIBRARY
GEOLOGIC DIVISION

WATER-LEVEL CHANGES IN THE HIGH PLAINS AQUIFER—PREDEVELOPMENT TO 1994

By
Jack T. Dugan and Jennifer B. Sharpe

1996