Water-Level Changes in the High Plains Aquifer, Predevelopment to 2007, 2005–06, and 2006–07

V. L. McGuire

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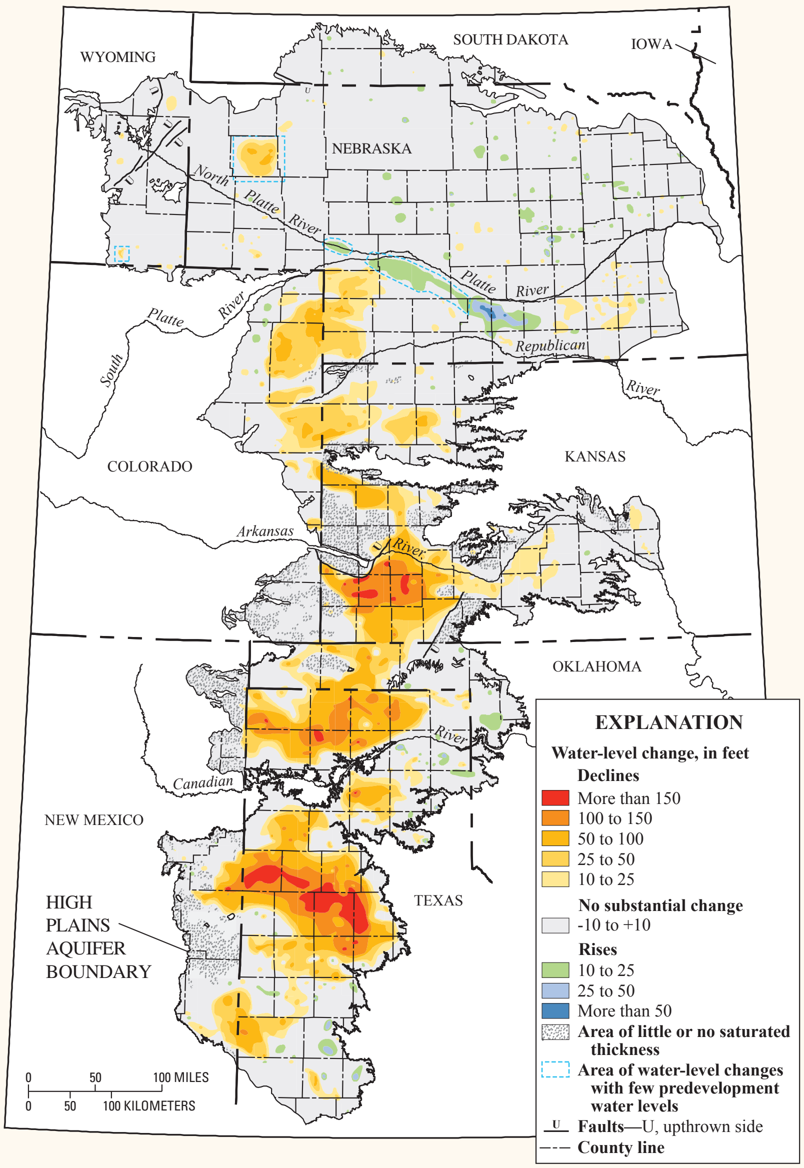

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Front cover. Water-level changes in the High Plains aquifer, predevelopment to 2007 (modified from Gutentag and others, 1984; Lowry and others, 1967; Luckey and others, 1981; and Burbach, 2007).

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U.S. Geological Survey
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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)[a]	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)[a,b]	1,233	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)

[a]There are 640 acres in a square mile (mi^2).

[b]One acre-foot of water is equivalent to the volume of water that would cover one acre (43,560 ft^2) to a depth of 1 foot (325,851 gallons or 43,560 ft^3).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Water-Level Changes in the High Plains Aquifer, Predevelopment to 2007, 2005–06, and 2006–07

By V.L. McGuire

Abstract

The High Plains aquifer underlies 111.6 million acres (174,000 square miles) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Water-level declines began in parts of the High Plains aquifer soon after the beginning of substantial irrigation with ground water in the aquifer area. This report presents water-level changes in the High Plains aquifer from the time before substantial ground-water irrigation development had occurred (about 1950 and termed "predevelopment" in this report) to 2007, from 2005–06, and from 2006–07. The report also presents the percentage change in saturated thickness of the aquifer, from predevelopment to 2007.

Measured water-level changes from predevelopment to 2007 ranged from a rise of 84 feet in Nebraska to a decline of 234 feet in Texas. The area-weighted, average water-level changes in the aquifer were a decline of 14.0 feet from predevelopment to 2007, a decline of 0.4 foot during 2005–06, and a decline of 0.6 foot during 2006–07. Total water in storage in the aquifer in 2007 was about 2.9 billion acre-feet, which was a decline of about 270 million acre-feet since predevelopment.

Introduction

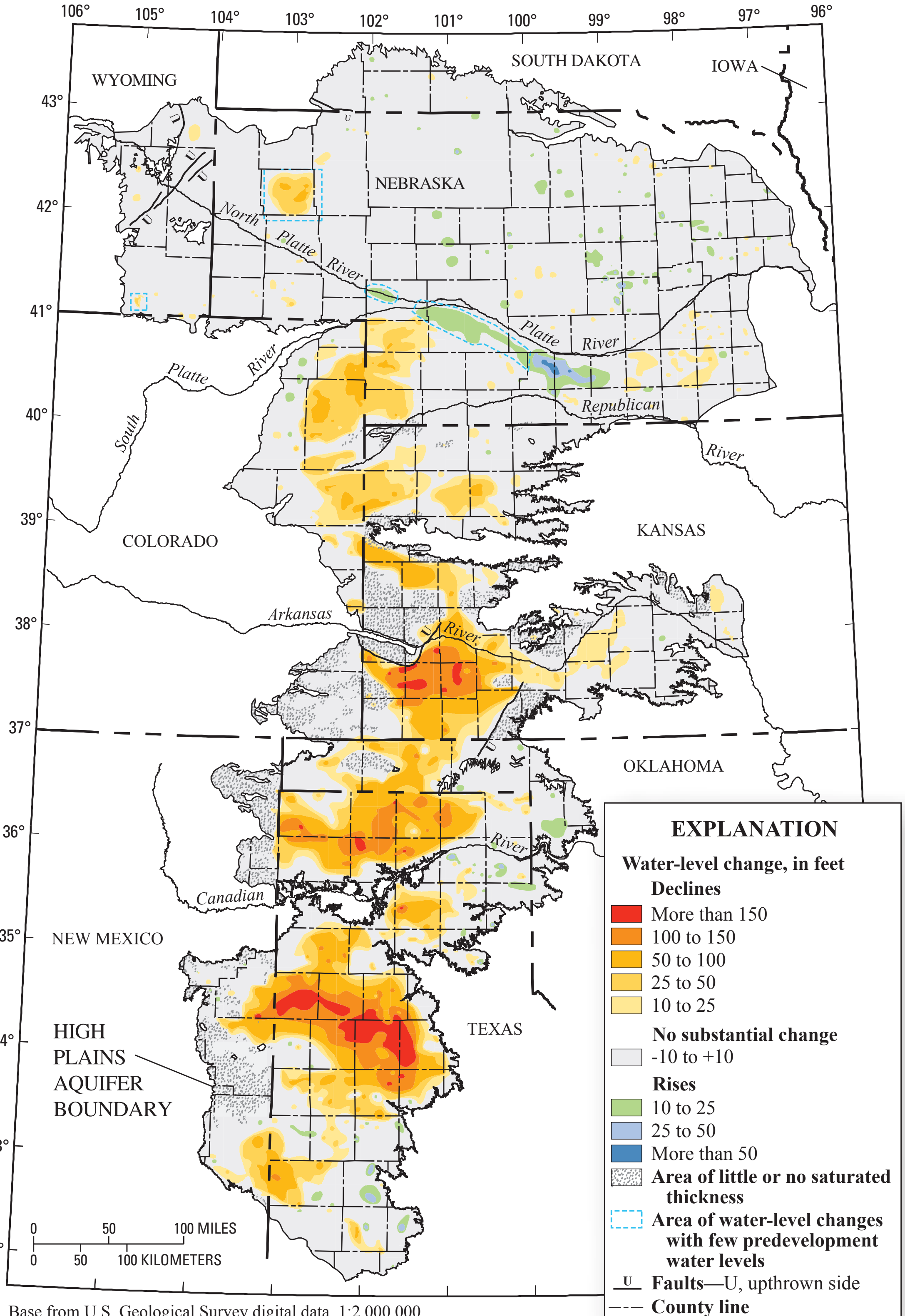
The High Plains aquifer underlies 111.6 million acres (174,000 square miles) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1; Sharon Qi, U.S. Geological Survey, written commun., 2006). The aquifer generally is unconfined; that is, the top of the aquifer is connected to the atmosphere (Weeks and Gutentag, 1981). Gutentag and others (1984) reported that, in a few parts of the aquifer area, the water table is discontinuous; these areas are labeled as "areas of little or no saturated thickness" in figure 1. Wells drilled in areas of little or no saturated thickness (see fig. 8 in Gutentag and others, 1984) likely will not yield water unless the well penetrated saturated sediment in either buried channels or low spots in the bedrock.

The area overlying the High Plains aquifer is one of the primary agricultural regions in the Nation; in parts of the area, farmers and ranchers began extensive use of ground water for irrigation in the 1930s and 1940s. Estimated irrigated acreage in the area overlying the High Plains aquifer increased from 1940 to 1980, but did not change greatly from 1980 to 2005: 1949—2.1 million acres, 1980—13.7 million acres, 1997—13.9 million acres, 2002—12.7 million acres, 2005—15.5 million acres (Heimes and Luckey, 1982; Thelin and Heimes, 1987; U.S. Department of Agriculture, 1999, 2004; Joan Kenny, U.S. Geological Survey, written commun., December 2008). In 2005, irrigated acres overlaid 14 percent of the aquifer area, not including the areas with little or no saturated thickness (Joan Kenny, U.S. Geological Survey, written commun., December 2008).

About every 5 years, ground-water withdrawals for irrigation and other uses are compiled from water-use data and reported by the U.S. Geological Survey (USGS) and agencies in each State. Ground-water withdrawals from the High Plains aquifer for irrigation increased from 4 to 19 million acre-feet (acre-ft) from 1949 to 1974; ground-water withdrawals for irrigation in 1980, 1985, 1990, and 1995 were 4 to 18 percent less than withdrawals for irrigation in 1974 (Heimes and Luckey, 1982). Ground-water withdrawals from the aquifer for irrigation were 21 million acre-ft in 2000 (U.S. Geological Survey, 2006; Maupin and Barber, 2005) and 19 million acre-ft in 2005 (Joan Kenny, U.S. Geological Survey, written commun., December 2008).

Water-level declines began in parts of the High Plains aquifer soon after the beginning of substantial irrigation using ground water—about 1950 (Gutentag and others, 1984). Water-level changes in the aquifer result from an imbalance between discharge and recharge. Discharge from the aquifer primarily consists of ground-water withdrawals for irrigation, but also can include evapotranspiration where the water table is near land surface, and seepage to streams, springs, and other surface water where the water table intersects the land surface. Recharge to the aquifer primarily is from precipitation, but other sources of recharge can be seepage from streams, canals, and reservoirs, and irrigation return flows (Luckey and Becker, 1999). By 1980, water levels in the High Plains aquifer in parts of Texas, Oklahoma, and southwestern Kansas had declined more than 100 feet (ft; Luckey and others, 1981).

Water-level declines may result in increased costs for ground-water withdrawals because of increased pumping lift



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

Figure 1. Water-level changes in the High Plains aquifer, predevelopment to 2007 (modified from Gutentag and others, 1984; Lowry and others, 1967; Luckey and others, 1981; and Burbach, 2007).

and decreased well yields (Taylor and Alley, 2001). Water-level declines also can affect ground-water availability, surface-water flow, and near-stream (riparian) habitat areas (Alley and others, 1999).

In response to water-level declines in the High Plains aquifer, the USGS, in collaboration with numerous Federal, State, and local water-resources agencies (see the "Acknowledgments" section), began monitoring water levels in more than 7,000 wells in 1988 to assess annual water-level changes in the aquifer. Water levels for 2005 were based on measurements from 9,068 wells, water levels for 2006 were based on measurements from 9,601 wells, and water levels for 2007 were based on measurements from 9,340 wells (table 1).

This report presents water-level changes in the High Plains aquifer from the time before substantial development of ground water for irrigation to 2007 and during 2005–06 and 2006–07. The time before substantial development of ground water for irrigation is before about 1950 and is termed "predevelopment" in this report. Water-level measurements used in this report generally were measured in winter or early spring, when irrigation wells typically were not pumping and water levels generally had recovered from pumping during the previous irrigation season. The wells generally are measured with an electric or steel tape using methods similar to those described by Stallman (1971).

This report also describes the amount of drainable water in storage in the High Plains aquifer in 2007 and changes in the amount of drainable water in storage in the aquifer from predevelopment to 2007. Drainable water in storage is the fraction of water in the aquifer that will drain by gravity and can be withdrawn by wells. The remaining water in the aquifer is held in the aquifer material by capillary forces and generally cannot be withdrawn by wells. Drainable water in storage is termed "water in storage" in this report.

Methods

The map of water-level changes from predevelopment to 2007 (fig. 1) was developed initially by using a geographic information system (GIS) to generate a grid of the water-level changes using the GIS function, inverse weighted distance (IDW), and then converting the IDW output grid into polygons using the "reclass" and "gridpoly" GIS commands (Environmental Systems Research Institute, 1992). The data inputs to the GIS function used in the initial step were the water-level-change values from wells measured in both predevelopment and 2007. The initial water-level-change polygons generated by the GIS function were modified manually, where appropriate, using supplemental water-level-change data from:

1. wells measured in predevelopment and in 2004–06, but not in 2007;
2. wells measured before June 15, 1978 (but not during or before the predevelopment period for the area) and in 2007;
3. wells measured in 1980 and 2007 and the published maps of water-level changes, predevelopment to 1980 (Luckey and others, 1981); and
4. published maps of water-level changes since predevelopment (Lowry and others, 1967; Luckey and others, 1981; Burbach, 2007) for parts of the aquifer in Nebraska and Wyoming with few predevelopment water levels (fig. 1).

The area-weighted, average water-level change values for predevelopment to 2007 (table 2) were computed by making a grid of the map of water-level change, predevelopment to 2007, using 500-square-meter (m^2) square cells (0.124-acre

Table 1. Number of wells used in this report for 2005, 2006, and 2007 water levels, and number of wells used for the water-level comparison periods—predevelopment to 2007, 2005–06, and 2006–07.

State	Wells measured			Wells used in water-level comparison periods		
	2005	2006	2007	Predevelopment to 2007	2005–06	2006–07
Colorado	501	486	503	363	455	453
Kansas	1,208	1,753	1,758	666	1,025	1,681
Nebraska	3,997	3,832	3,957	1,624	3,704	3,725
New Mexico	74	306	108	[a]119	56	69
Oklahoma	161	145	115	76	141	110
South Dakota	94	133	113	72	87	102
Texas	2,983	2,887	2,729	703	2,585	2,481
Wyoming	50	59	57	20	48	56
High Plains (Total)	**9,068**	**9,601**	**9,340**	**3,643**	**8,101**	**8,677**

[a]Includes 2003 to 2006 water levels, instead of 2007 water levels, for 92 wells in the predevelopment-to-2007 comparison period because many wells in New Mexico are measured only once every 5 years.

Table 2. Area-weighted, average water-level changes in the High Plains aquifer, not including the areas of little or no saturated thickness—predevelopment to 2007, 2005–06, and 2006–07.

[Positive values indicate water-level rises; negative values indicate water-level declines]

State	Area-weighted, average water-level change (feet)		
	Predevelopment to 2007	2005–06	2006–07
Colorado	-12.8	-1.0	-0.8
Kansas	-22.7	-.5	-1.1
Nebraska	-1.0	-.1	-.2
New Mexico	-15.7	-.3	-.8
Oklahoma	-12.4	-.5	-.5
South Dakota	0	.2	-.2
Texas	-36.9	-.6	-.7
Wyoming	-.4	-.4	-.5
High Plains aquifer	**-14.0**	**-.4**	**-.6**

square cells); multiplying the cell area for each cell times one of the following: the midrange of the associated water-level-change polygon, -150 ft in areas where declines are more than 150 ft, 50 ft in areas with rises of more than 50 ft, or 0 ft in areas of little or no saturated thickness; summing the result; and then dividing the sum by the aquifer area, excluding the areas with little or no saturated thickness.

Maps of generalized annual water-level changes, 2005–06 and 2006–07, were created with computer-generated Thiessen polygons (Thiessen, 1911). Thiessen polygons apportion the water-level change in each well to an area around the well; the size of each polygon depends on the proximity of neighboring wells. The area-weighted, average water-level change values for 2005–06 and 2006–07 (table 2) were computed by summing the quantity equal to the area of each Thiessen polygon multiplied by the actual water-level change value for the well, and then dividing the result by the aquifer area, excluding areas with little or no saturated thickness. The maps of generalized water-level change for 2005–06 and 2006–07 are not included in this report because this report emphasizes long-term water-level trends; however, the associated area-weighted, average water-level-change and storage-change values are given in tables 2 and 3.

Annual area-weighted, average water-level changes since 1988 were calculated using Thiessen polygons because a large number of spatially distributed wells are available with water levels measured in the both the current and prior report years and, therefore, the Theissen polygon method results in a reasonable value for annual area-weighted, average water-level change. In contrast, area-weighted, average water-level changes since predevelopment were calculated using a grid with 500-m^2 cells of the map of water-level changes from predevelopment to the report year instead of with Thiessen polygons because a smaller number of wells are available with water levels measured in both predevelopment and the current report year.

An advantage of the Thiessen polygon method for calculating area-weighted, average water-level changes is that the Thiessen polygon area is multiplied by the actual water-level change value for the associated well, whereas the grid method, which is used to calculate area-weighted, average water-level changes from predevelopment to the report year, multiplies the cell area times a specified value for the associated polygon. The specified values for the associated polygon depends on the water-level-change range of the polygon—50 for areas of rises greater than 50 feet, -150 for areas of declines greater than 150 feet, 0 for areas of little or no saturated thickness, and, in all other areas, the midrange of associated water-level change polygon. A disadvantage of the grid method is that if the actual average water-level change for a given polygon is different than the polygon's specified value, it would affect the accuracy of the area-weighted, average water-level change calculation.

Change in water in storage in the High Plains aquifer for each period (table 3 and fig. 2) was calculated using the specific yield of the High Plains aquifer and change in the saturated volume of the High Plains aquifer for the period from the corresponding water-level-change map. Specific yield is an estimate of the ratio of the volume of water that an unconfined aquifer will yield by gravity drainage to the aquifer volume (Meinzer, 1923). The area-weighted, average specific yield of the High Plains aquifer is 0.15; specific yield of the High Plains aquifer ranges from near 0 to 0.30 (Gutentag and others, 1984). In this report and to be consistent with previous reports (Kastner and others, 1989; McGuire, 2006), calculations of water in storage used the area-weighted, average specific yield of the aquifer. The change in saturated aquifer

Table 3. Change in water in storage in the High Plains aquifer, predevelopment to 2007, 2005–06, and 2006–07.

[Positive values indicate increases in water in storage; negative values indicate decreases in water in storage]

State	Change in water in storage (million acre-feet)		
	Predevelopment to 2007	2005–06	2006–07
Colorado	-17.4	-1.1	-0.9
Kansas	-63.0	-1.3	-2.8
Nebraska	-21.4	-.6	-1.4
New Mexico	-10.3	-.2	-.4
Oklahoma	-12.2	-.4	-.3
South Dakota	-.6	.1	-.1
Texas	-140.1	-2.2	-2.5
Wyoming	-2.3	-.3	-.4
High Plains aquifer	**-267.5**	**-6.0**	**-8.9**

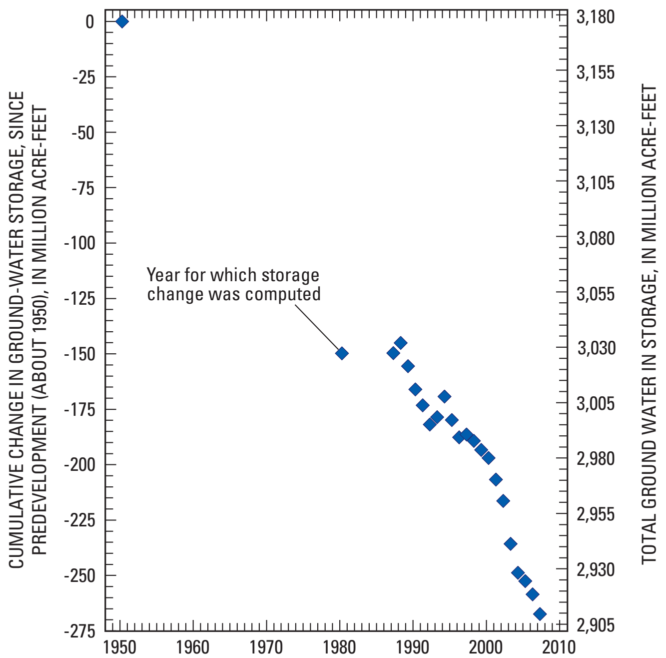


Figure 2. Cumulative change and total ground water in storage in the High Plains aquifer, predevelopment to 2007 (modified from McGuire, 2006).

volume, predevelopment to 2007, was calculated by summing change in saturated aquifer volume, predevelopment to 2000 (McGuire and others, 2003), and the annual changes in saturated aquifer volume from 2000 to 2005 (McGuire, 2003, 2004a, 2004b, 2006) and from 2005–06 and 2006–07.

Total water in storage in the High Plains aquifer in 2007 was calculated by summing water in storage in 2000 and the annual change in water in storage, 2000 to 2007 (McGuire, 2003, 2004a, 2004b, 2006; fig. 2). Water in storage in 2000 was derived by multiplying the saturated aquifer volume in 2000 by the area-weighted, average specific yield of the aquifer (0.15). The saturated aquifer volume in 2000 was calculated by first making a grid of saturated thickness in 2000, using 500-m^2 square cells; then multiplying the cell area for each cell times the midrange of the associated saturated thickness contour interval; and summing the results. For example, the aquifer volume of a 500-m^2 cell in the 100-to-200-ft saturated-thickness contour interval is 807,320 cubic feet (ft^3; or 18.5 acre-ft), which is calculated by multiplying 500 m^2 by 1/0.09290 ft^2/m^2 times 150 ft. Saturated thickness in 2000 was mapped as the difference between superimposed contours of the altitude of the water table in 2000 and contours of the altitude of the base of the aquifer (McGuire and others, 2003). Annual change in water in storage for 2000–01, 2001–02, 2002–03, 2003–04, 2004–05, 2005–06, and 2006–07 were computed for each time period by multiplying the associated annual area-weighted, average water-level change by the aquifer area and area-weighted, average specific yield of the aquifer (0.15).

The map of the percentage change in saturated thickness, predevelopment to 2007 (fig. 3), was generated by contouring water-level change as a percentage of the predevelopment saturated thickness using predevelopment and 2007 water-level data from available wells, areas of water-level changes from previous reports (Lowry and others, 1967; Luckey and others, 1981; Burbach, 2007), and data on the base of the aquifer (Weeks and Gutentag, 1981). The contours were generated initially by using IDW, a GIS function, and then converting the IDW output grid into polygons using the "reclass" and "gridpoly" GIS commands (Environmental Systems Research Institute, 1992). The data inputs to IDW were the percentage change in saturated thickness from wells measured in both predevelopment and 2007. The initial percentage change in saturated-thickness polygons generated by the GIS function were modified manually, where appropriate, using supplemental data on estimated percentage changes in saturated thickness for many wells that were not measured in both predevelopment and 2007 and for parts of the aquifer with sparse predevelopment data (fig. 1). These supplemental data were estimated using water-level changes from:

1. selected wells measured in predevelopment and in 2004–06, but not in 2007;
2. selected wells not measured during or before the predevelopment period of the area but measured before June 15, 1978, and in 2007;
3. selected wells measured in 1980 and 2007 and published maps of water-level changes, predevelopment to 1980 (Luckey and others, 1981); and
4. published maps of water-level changes (Lowry and others, 1967; Luckey and others, 1981; Burbach, 2007) for parts of the aquifer with few predevelopment water levels (fig. 1).

Water-Level Changes, Predevelopment to 2007

The map of water-level changes in the High Plains aquifer from predevelopment to 2007 (fig. 1) is based on water levels from 3,643 wells (table 1) and on other published data (Lowry and others, 1967; Luckey and others, 1981; Burbach, 2007). The other published data were used in areas in Nebraska and Wyoming with few predevelopment water levels (fig. 1). Water-level changes from predevelopment to 2007 ranged from a rise of 84 ft in Nebraska to a decline of 234 ft in Texas. The area-weighted, average water-level change from predevelopment to 2007 was a decline of 14.0 ft; the area-weighted, average water-level change from predevelopment to 2007 ranged from a decline of 36.9 ft in Texas to no change in South Dakota (table 2). From predevelopment to 2007, water levels declined more than 10 ft in about 26 percent of the

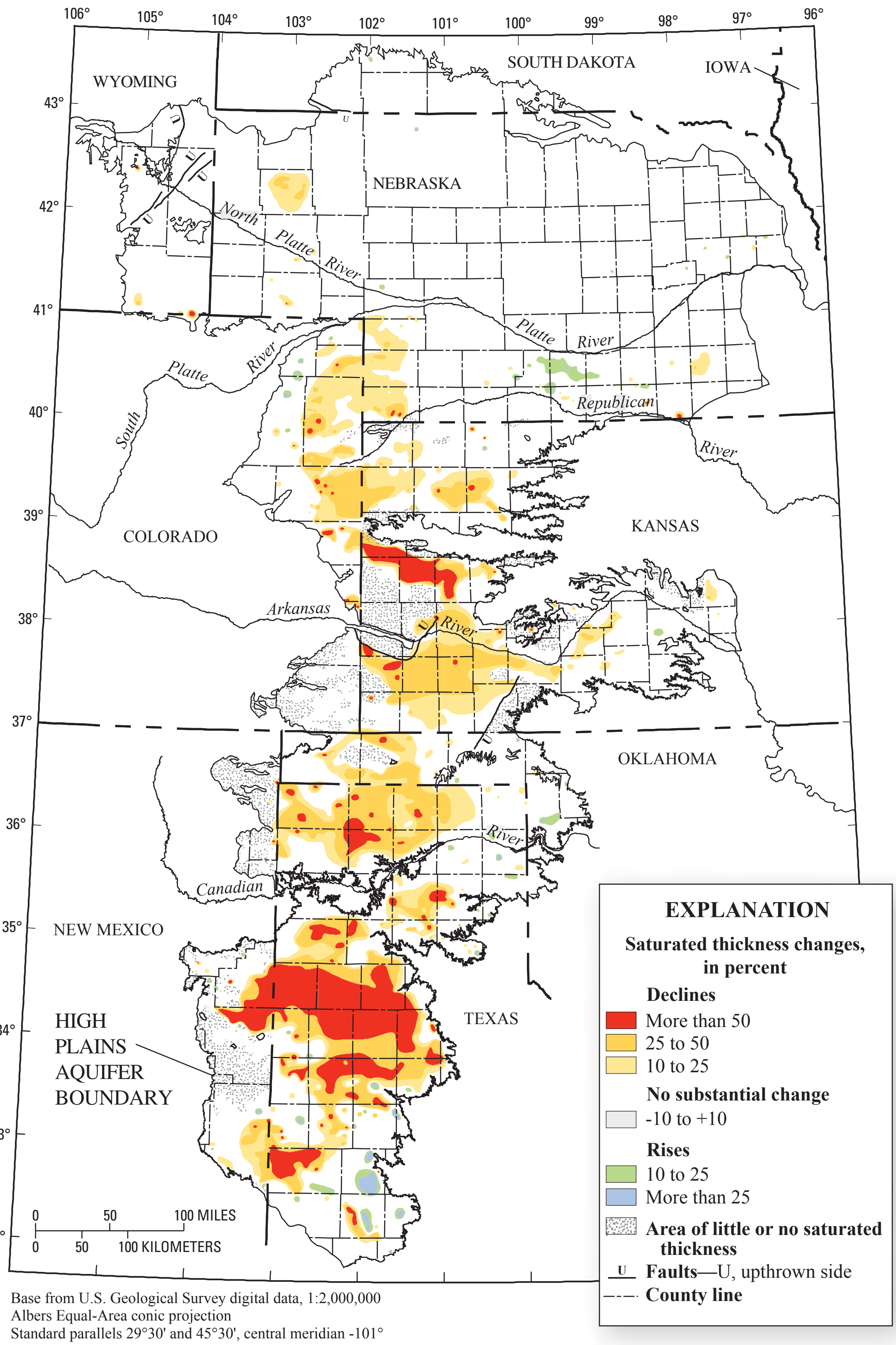


Figure 3. Percentage change in saturated thickness of the High Plains aquifer, predevelopment to 2007 (modified from Gutentag and others, 1984; Luckey and others, 1981).

aquifer area, more than 25 ft in about 18 percent of the aquifer area, and more than 50 ft in about 11 percent of the aquifer area. In approximately 72 percent of the aquifer area, water-level changes ranged from a 10-ft decline to a 10-ft rise. In approximately 2 percent of the aquifer area, water levels rose more than 10 ft from predevelopment to 2007.

Water-Level Changes, 2005–06

Water levels were measured in 8,101 wells before the irrigation season in both 2005 and 2006 (table 1); the irrigation season generally begins in May, but the actual dates depend on location. Water-level changes in the measured wells ranged from a 10-ft rise in Texas to a 12-ft decline in Texas. Water-level declines of 3 ft or greater occurred in 7 percent of the measured wells. The area-weighted, average water-level change in the High Plains aquifer from 2005 to 2006 ranged from a 1.0-ft decline in Colorado to a 0.2-ft rise in South Dakota (table 2); overall, the area-weighted, average water-level change in the High Plains aquifer during 2005–06 was a 0.4-ft decline (table 2).

Water-Level Changes, 2006–07

Water levels were measured in 8,677 wells before the irrigation season in both 2006 and 2007 (table 1); water-level changes in the measured wells ranged from a 10-ft rise in Texas to a 16-ft decline in Kansas. Water-level declines of 3 ft or greater occurred in 9 percent of the measured wells. The area-weighted, average water-level change from 2006–07 ranged from a 1.1-ft decline in Kansas to a 0.2-ft decline in both Nebraska and South Dakota (table 2); overall, the area-weighted, average water-level change in the High Plains aquifer during 2006–07 was a 0.6-ft decline (table 2).

Change in Water in Storage, Predevelopment to 2007

Water in storage in the High Plains aquifer in 2007 was about 2.9 billion acre-ft (fig. 2), which was a decline of about 270 million acre-ft since predevelopment (fig. 2 and table 3). Predevelopment water in storage was estimated from water in storage in 2000 and water-level changes from predevelopment to 2000 (McGuire and others, 2003). Although changes in storage may have occurred before “predevelopment,” these changes in storage were not estimated for this report.

The apparent effect of a given change in the volume of water in storage in an area depends partly on the predevelopment saturated thickness of the aquifer. The map of percentage change in saturated thickness (fig. 3) presents predevelopment to 2007 water-level changes, as a percentage of predevelopment saturated thickness. This map (fig. 3) is similar in some areas to the water-level-change map (fig. 1); however, an area of large water-level change would not show up on this map (fig. 3) if predevelopment saturated thickness was large and the change did not substantially alter the saturated thickness. Conversely, an area with small water-level change may result in a large percentage change in saturated thickness because of small predevelopment saturated thickness. By 2007, 13 percent of the aquifer area had more than a 25-percent decrease in saturated thickness since predevelopment, 5 percent of the aquifer area had more than a 50-percent decrease in saturated thickness, and less than 1 percent of the aquifer area had more than a 10-percent increase in saturated thickness.

Summary

The High Plains aquifer underlies 111.6 million acres (174,000 square miles) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Water-level declines began in parts of the High Plains aquifer soon after the beginning of substantial irrigation with ground water. In response to the water-level declines in the High Plains aquifer, the U.S. Geological Survey, in collaboration with numerous Federal, State, and local water-resources agencies, began monitoring water levels in more than 7,000 wells in 1988 to assess annual water-level changes in the aquifer. Water levels for 2005 were based on measurements from 9,068 wells; water levels for 2006 were based on measurements from 9,601 wells; and water levels for 2007 were based on measurements from 9,340 wells. This report presents water-level changes in the High Plains aquifer from the time before substantial ground-water irrigation development (about 1950) to 2007, 2005–06, and 2006–07. The water-level measurements used in this report generally were measured in winter or early spring, when irrigation wells typically were not pumping and water levels generally had recovered from pumping during the previous irrigation season.

The map of water-level changes in the High Plains aquifer from predevelopment to 2007 is based on water levels from 3,643 wells and other published data. The water-level changes from predevelopment to 2007 ranged from a rise of 84 ft in Nebraska to a decline of 234 feet in Texas. The area-weighted, average water-level change from predevelopment to 2007 was a decline of 14.0 feet.

Water levels were measured in 8,101 wells before the irrigation seasons in both 2005 and 2006; water-level changes ranged between a 10-foot rise in Texas and a 12-foot decline in Texas. The area-weighted, average water-level change in the High Plains aquifer during 2005–06 was a decline of 0.4 foot.

Water levels were measured in 8,677 wells before the irrigation seasons in both 2006 and 2007; water-level changes ranged between a 10-foot rise in Texas and a 16-foot decline in

Kansas. The area-weighted, average water-level change in the High Plains aquifer during 2006–07 was a decline of 0.6 foot.

Total water in storage in 2007 was about 2.9 billion acre-feet, which was a decline of about 270 million acre-feet since predevelopment. Predevelopment water in storage was estimated from water in storage in 2000 and water-level changes from predevelopment to 2000. The apparent effect of a given percent change in the volume of water in storage in an area depends partly on the predevelopment saturated thickness of the aquifer. By 2007, 13 percent of the aquifer area had sustained more than a 25-percent decrease in predevelopment saturated thickness, 5 percent of the aquifer area had more than a 50-percent decrease, and less than 1 percent of the aquifer area had more than a 10-percent increase.

Acknowledgments

The water-level data used in this report were provided by the following local, State, and Federal entities:

- Colorado: State Engineer's Office;
- Kansas: Department of Agriculture—Division of Water Resources and Kansas Geological Survey (Kansas Geological Survey, 2008);
- Nebraska: Central Nebraska Public Power and Irrigation District, Natural Resources Districts, and University of Nebraska—Lincoln, School of Natural Resources, Conservation and Survey Division;
- New Mexico: Office of the State Engineer;
- Oklahoma: Water Resources Board;
- South Dakota: Department of Environment and Natural Resources;
- Texas: Water Development Board (Texas Water Development Board, 2008) and Groundwater Conservation Districts;
- Wyoming: State Engineer's Office; and
- Federal: Bureau of Reclamation, U.S. Fish and Wildlife Service, and U.S. Geological Survey offices in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (U.S. Geological Survey, 2008).

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