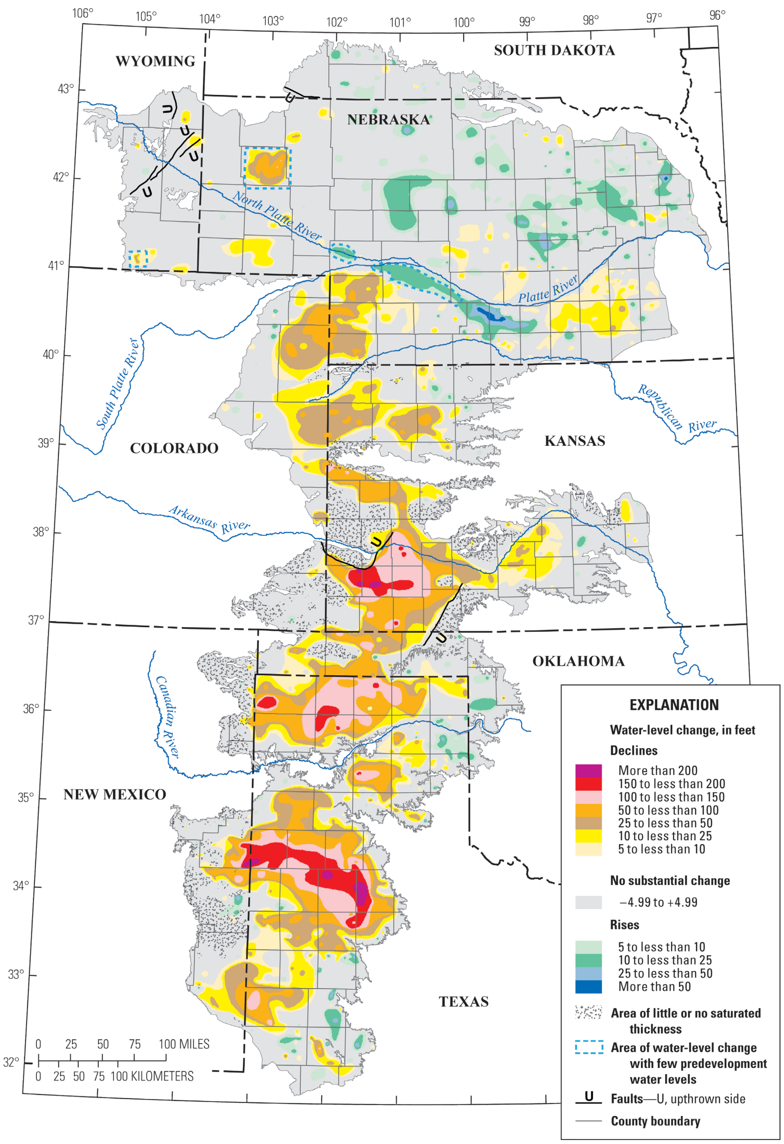
science for a changing world

Groundwater and Streamflow Information Program

Water-Level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2017 and 2015–17



Scientific Investigations Report 2022–5080

U.S. Department of the Interior
U.S. Geological Survey

Water-Level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2017 and 2015–17

By Virginia L. McGuire and Kellan R. Strauch

Groundwater and Streamflow Information Program

Scientific Investigations Report 2022–5080

U.S. Department of the Interior
U.S. Geological Survey

U.S. Geological Survey, Reston, Virginia: 2022

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Suggested citation:
McGuire, V.L., and Strauch, K.R., 2022, Water-level and recoverable water in storage changes, High Plains aquifer, predevelopment to 2017 and 2015–17: U.S. Geological Survey Scientific Investigations Report 2022–5080, 15 p., https://doi.org/10.3133/sir20225080.

Associated data for this publication:
McGuire, V.L., and Strauch, K.R., 2022, Data from maps of water-level changes in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, predevelopment (about 1950) to 2017 and 2015–17: U.S. Geological Survey data release, https://doi.org/10.5066/P9YN7PY3.

U.S. Geological Survey, 2021, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN.

ISSN 2328-0328 (online)

Acknowledgments

Most of the water-level data used in this report were provided to the U.S. Geological Survey by the following State, local, and Federal entities: Colorado—Division of Water Resources (also known as the Office of the State Engineer); Kansas—Department of Agriculture, Division of Water Resources and the Kansas Geological Survey; Nebraska—Central Nebraska Public Power and Irrigation District, Natural Resources Districts, and University of Nebraska–Lincoln, Conservation and Survey Division; New Mexico—Office of the State Engineer; Oklahoma—Water Resources Board; South Dakota—Department of Environment and Natural Resources; Texas—Groundwater Conservation Districts and the Texas Water Development Board; Wyoming—State Engineer's Office; and Federal—Bureau of Reclamation and U.S. Fish and Wildlife Service. The author thanks the above entities for providing the water-level data and for their responsiveness regarding questions about the data.

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
million acre-ft (Macre-ft)	4,047,000,000	square meter-foot (m^2-ft)
million acre-ft (Macre-ft)	1.23348	cubic kilometer (km^3)
billion acre-ft (Bacre-ft)	1,233.48	cubic hectometer (hm^3)

*One acre-foot of water is equivalent to the volume of water that would cover 1 acre (43,560 square feet) to a depth of 1 foot (325,851 gallons or 43,560 cubic feet).

Datum

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

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends.

Abbreviations

NAVD 88	North American Vertical Datum of 1988
NWIS	National Water Information System
USGS	U.S. Geological Survey

Water-Level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2017 and 2015–17

By Virginia L. McGuire and Kellan R. Strauch

Abstract

The High Plains aquifer underlies 111.8 million acres (about 175,000 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 groundwater irrigation (about 1950). This report presents water-level changes and change in recoverable water in storage in the High Plains aquifer from predevelopment (about 1950) to 2017 and from 2015 to 2017.

Water-level changes from predevelopment to 2017, by well, ranged from a rise of 84 feet to a decline of 262 feet; the range for 99 percent of the wells was from a rise of 39 feet to a decline of 200 feet. Water-level changes from 2015 to 2017, by well, ranged from a rise of 41 feet to a decline of 21 feet; the range for 99 percent of the wells was from a rise of 14 feet to a decline of 10 feet. The area-weighted, average water-level changes in the aquifer were an overall decline of 16.8 feet from predevelopment to 2017 and a rise of 0.1 foot from 2015 to 2017. Total recoverable water in storage in the aquifer in 2017 was about 2.91 billion acre-feet, which was a decline of about 291.8 million acre-feet since predevelopment and a rise of 0.1 million acre-feet from 2015 to 2017.

Introduction

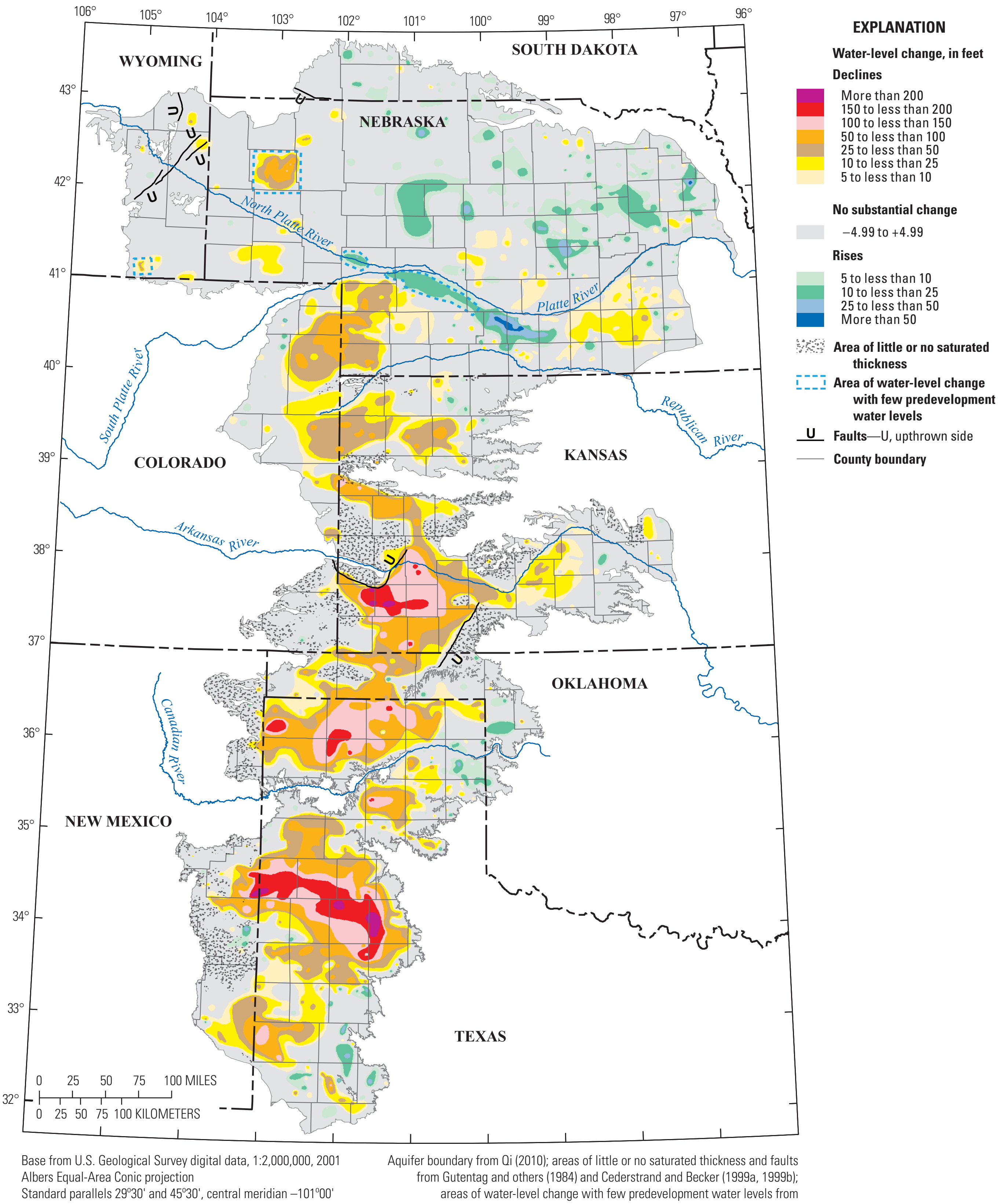
The High Plains aquifer underlies 111.8 million acres (Macres; about 175,000 square miles [mi^2]) in parts of eight States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1; Qi, 2010). In the High Plains aquifer, groundwater generally is under unconfined conditions (Weeks and Gutentag, 1981). The saturated thickness of the aquifer, which is the distance from the water table to the base of the aquifer, ranges from 0 feet (ft) to about 1,200 ft (McGuire and others, 2012). Gutentag and others (1984) reported that a few parts of the aquifer area are discontinuous; these areas total about 6.90 Macres (10,777 mi^2) and are labeled in the figures of this report as "area of little or no saturated thickness." Wells drilled in areas of little or no saturated thickness (fig. 1) likely will not yield water unless the wells penetrated localized saturated sediment in buried channels or depressions in the bedrock surface (Gutentag and others, 1984).

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 groundwater for irrigation in the 1930s and 1940s. Estimated irrigated acreage was 2.1 Macres in 1949, 13.7 Macres in 1980, 13.9 Macres in 1997, 14.7 Macres in 2002, 15.8 Macres in 2005, 15.8 Macres in 2007, 14.9 Macres in 2012, and 14.8 Macres in 2017 (Heimes and Luckey, 1982; Thelin and Heimes, 1987; U.S. Department of Agriculture, 1999; Brown and others, 2019). In 2017, about 14 percent of the aquifer area was irrigated, not including the areas with little or no saturated thickness (Brown and others, 2019).

Estimated groundwater withdrawals from the High Plains aquifer for irrigation increased from 4 to 19 million acre-feet (Macre-ft) from 1949 to 1974; estimated groundwater withdrawals for irrigation in 1980 were 18 Macre-ft (Heimes and Luckey, 1982, 1983). Groundwater withdrawals from the aquifer for irrigation were 19.4 Macre-ft in 2000 (Maupin and Barber, 2005) and 13.0 Macre-ft in 2015 (Lovelace and others, 2020).

Water-level declines began in parts of the High Plains aquifer soon after the onset of substantial groundwater irrigationr (about 1950; Gutentag and others, 1984). From 1938 to 1951, water-level declines of more than 50 ft were documented in the High Plains aquifer in parts of Texas (Gaum, 1953). By 1980, water levels in the High Plains aquifer had declined more than 100 ft in parts of Kansas, New Mexico, Oklahoma, and Texas; more than 50 ft in parts of Colorado; and more than 25 ft in parts of Nebraska and Wyoming. In contrast, by 1980, water-level changes (both rises and declines) in the High Plains aquifer in South Dakota were less than 10 ft (Luckey and others, 1981).

Changes in the static water level of an aquifer result from an imbalance between discharge and recharge; changes in the static water level of an aquifer are derived from changes in static water level in wells screened in the aquifer. The static water level in a well is the water level after substantial recovery from pumping in the measured well or in nearby wells. The static water level in the well may not be the fully



Base from U.S. Geological Survey digital data, 1:2,000,000, 2001
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian −101°00'
North American Datum of 1983

Aquifer boundary from Qi (2010); areas of little or no saturated thickness and faults from Gutentag and others (1984) and Cederstrand and Becker (1999a, 1999b); areas of water-level change with few predevelopment water levels from Lowry and others (1967), Luckey and others (1981), and Young and others (2017)

Figure 1. Water-level changes, High Plains aquifer, predevelopment (about 1950) to 2017.

recovered water level, in that the water level may continue to rise until pumping resumes, but it is assumed to be an acceptable approximation of the fully recovered water level.

In 2015, it was estimated that approximately 95 percent of discharge from the High Plains aquifer was groundwater withdrawals for irrigation, with the remaining discharge for public and domestic water supply and other uses (Lovelace and others, 2020). Discharge from the aquifer also occurs as evapotranspiration, where the water table is near land surface, and seepage to streams, springs, and other surface-water bodies, where the water table intersects the land surface. Discharge as evapotranspiration and seepage primarily occurs in the northern part of the aquifer. Recharge to the aquifer primarily is from precipitation, but other sources of recharge include irrigation return flows and seepage from streams, canals, and reservoirs (Luckey and Becker, 1999; Stanton and others, 2011; Peterson and others, 2020). Water-level declines may result in increased costs to extract groundwater because of increased energy needed for pumping lift and decreased well yields (Taylor and Alley, 2001). Water-level declines also can affect groundwater availability, surface-water flow, and near-stream (riparian) habitat areas (Alley and others, 1999; Peterson and others, 2020).

In response to water-level declines, the U.S. Congress, under the authority of Title III to the Water Resources Research Act (Public Law 98–242 and Public Law 99–662), directed the U.S. Geological Survey (USGS) to monitor water levels in the High Plains aquifer. Since 1987, the USGS, in collaboration with numerous State, local, and Federal water-resources entities, has compiled water levels from wells completed in the High Plains aquifer. Static water levels were measured in 8,938 wells for water year 2015; 8,867 wells for water year 2016; and 8,333 wells for water year 2017. In addition, because New Mexico measured most of their wells on a 5-year rotating schedule, the most recent static water-level measurement from water year 2013 to water year 2016 was retrieved as estimated measurements for 2017 for 63 wells in New Mexico, which were without static water-level measurements in 2017 (table 1). A water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends.

Purposes of this report are to present (1) water-level changes in the High Plains aquifer from the time before substantial development of groundwater for irrigation (hereinafter referred to as “predevelopment”) to 2017 and from 2015 to 2017; (2) total recoverable water in storage in the High Plains aquifer, 2017; and (3) changes in recoverable water in storage in the High Plains aquifer, predevelopment to 2017 and 2015–17. The raster datasets of water-level changes, from predevelopment to 2017 and 2015–17, and the water-level-change data for the applicable wells are available as a USGS data release (McGuire and Strauch, 2022).

Predevelopment generally is prior to about 1950, but in some areas (for example, in the north-central part of the Texas Panhandle) predevelopment is the late 1990s, and in other areas (for example, in north-central Nebraska), groundwater has not yet (2022) been substantially developed for irrigation. Recoverable 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 to the aquifer material and generally cannot be withdrawn by wells (Meinzer, 1923). Water levels used in this report, referred to as static water levels, generally were measured in winter (October to February) or early spring (March to May), when irrigation wells typically were not pumping, and after water levels generally had recovered from pumping during the previous irrigation season. Irrigation season varies across the High Plains, starting from approximately March to mid-June through approximately July to September.

Table 1. Number of wells used in this report for 2015, 2016, and 2017 static water levels, and for the water-level comparison periods, predevelopment (about 1950) to 2017 and 2015–17, by State and in total for the High Plains aquifer.

State	Wells measured			Wells used in water-level comparison periods	
	2015	2016	2017	Predevelopment to 2017	2015 to 2017
Colorado	444	408	336	97	318
Kansas	1,715	1,705	1,530	497	1,461
Nebraska	3,547	3,362	3,629	1,458	3,363
New Mexico	151	255	103	101*	33
Oklahoma	157	162	155	70	144
South Dakota	99	98	96	67	96
Texas	2,787	2,839	2,445	626	2,245
Wyoming	38	38	39	12	38
High Plains	8,938	8,867	8,333	2,928	7,698

*For 63 wells in the predevelopment to 2017 water-level comparison period, 2013, 2014, 2015, or 2016 water levels were used instead of 2017 water levels because many wells in New Mexico were measured only once every 5 years or because the 2017 water level was not an approximately static water level.

Data and Methods

For this report, geospatial data organized as raster datasets (hereinafter referred to as “rasters”) are used in the following calculations:

Area-weighted, average water-level changes, predevelopment to 2017 and 2015–17;

Total recoverable water in storage in 2017; and

Change in recoverable water in storage, predevelopment to 2017 and 2015–17.

The methods used for these calculations are the same as methods used in McGuire (2013).

Water-Level Data

The water-level data for the High Plains aquifer were largely obtained from measurements in irrigation wells when the water level in the wells had substantially, but not necessarily fully, recovered from pumping in the measured well or nearby wells for the previous irrigation season. Numerous State, local, and Federal water-resources entities measured these wells and provided the water-level data for this report to the USGS or through publicly available websites. The primary water-level data used in this report include predevelopment water levels, water levels for 2015 and 2017, and, for New Mexico only, water levels for 2013–16. The supplemental water-level data were used to substantiate the contours used to control interpolation of the primary water-level data.

Characteristics of Water-Level Data

Water-level data used in this report generally were from measurements collected by an electric tape, steel tape, or transducer using methods similar to those described by Cunningham and Schalk (2011). The wells were measured by numerous State, local, and Federal water-resources agencies, and the measurement results were loaded into the Kansas Geological Survey groundwater database (Kansas Geological Survey, 2020), Texas Water Development Board groundwater database (Texas Water Development Board, 2020), USGS National Groundwater Monitoring Network data portal (U.S. Geological Survey, 2021a), USGS National Water Information System (NWIS; U.S. Geological Survey, 2021b), and Wyoming State Engineer’s Office water database (Wyoming State Engineer’s Office, 2021).

Most of the wells were measured manually one to two times per water year. If a well was measured one time per water year, typically the well was measured in the winter or early spring; if a well was measured two times per water year, in general the well was measured in winter or early spring and in fall. Some wells were measured nearly continuously using instrumentation (data recorders with sensors or floats) that recorded the water level periodically (generally every 15 to 60 minutes) (Cunningham and Schalk, 2011). Available water-level data for each well were reviewed to select a water level that (1) reasonably represented the static water level for each applicable water year, which was generally the minimum depth-to-water measurement for manually measured wells or the minimum mean daily depth-to-water measurement for wells measured continually; and (2) was consistent with water levels in nearby wells. In addition, wells in the same cell in the raster were examined to determine whether the water-level-change values were similar to other wells in the cell. If the water-level change values were not similar, the water-level records for each well were further examined to assess whether the water levels indicated an upward or downward gradient or different hydrogeologic conditions. If the water levels in wells in the same cell were substantially different, generally, the water levels from the shallowest well were used. If it was determined that a water level for a given year should not be used in the water-level-change maps, the use field for the well for that year, which is a field in the well shapefiles (McGuire and Strauch, 2022) was set to a negative number, so subsequent processing would ignore this water level.

Most of the measured wells supply water for irrigation; water-level precision and accuracy in irrigation wells can be adversely affected by lubricating oil floating on the water surface in the well. If there is no oil on the surface of the water in the well, the precision of the water-level measurements generally is 0.01 ft; if there is oil on the surface of the water, the precision of the water-level measurement likely is greater than 0.01 ft. For this study, methods were not used to assess the amount of oil on the surface of the water (Cunningham and Schalk, 2011); therefore, the effect on the water-level accuracy that should be attributed to oil on the water surface cannot be assessed.

Primary Water-Level Data

The primary water-level data used to map water-level changes, predevelopment to 2017, and percentage change in saturated thickness, predevelopment to 2017, include predevelopment water levels, the static water-levels for 2017, and, for New Mexico only, static water levels for 2013–16. In New Mexico, there were 38 wells with a static water level for predevelopment and for 2017 and 63 wells with a static water level for predevelopment and at least 1 year from 2013 to 2016, but not for 2017. The latest available water levels were used for these 63 wells, including water levels from 2 wells measured in 2013, 4 wells measured in 2014, 12 wells measured in 2015, and 45 wells measured in 2016. The primary and only water-level data used to map water-level changes from 2015 to 2017 were from wells with a static water level measured in water years 2015 and 2017.

The predevelopment water levels were compiled by Weeks and Gutentag (1981) and McGuire and others (2003). The predevelopment water level generally is the earliest water-level measurement for a well. Predevelopment water levels were identified for more than 20,000 wells. The median measurement year for these predevelopment water levels was 1957 (McGuire and others, 2003). A predevelopment water level was not available for 5,468 of the wells with 2017 water levels likely because these wells were installed or first measured after substantial irrigation had begun in the area.

The static water level for 2015 and 2017, and, for New Mexico only, static water levels for 2013–16 were provided by the following State, local, and Federal entities through data files or downloads from applicable websites:

Colorado—Division of Water Resources (also known as the Office of the State Engineer) water-level data were retrieved from the National Groundwater Monitoring Network data portal (U.S. Geological Survey, 2021a).

Kansas—Department of Agriculture, Division of Water Resources and the Kansas Geological Survey water-level data were retrieved from the Kansas Geological Survey groundwater database (Kansas Geological Survey, 2020).

Nebraska—Central Nebraska Public Power and Irrigation District (https://www.cnppid.com/), University of Nebraska–Lincoln, Conservation and Survey Division (http://snr.unl.edu/csd/), and the following Natural Resources Districts water-level data were retrieved from USGS NWIS (U.S. Geological Survey, 2021b):

Central Platte (https://cpnrd.org/)

Lewis & Clark (https://lcnrd.nebraska.gov/)

Little Blue (https://www.littlebluenrd.org/)

Lower Big Blue (https://www.lbbnrd.net/)

Lower Elkhorn (http://www.lenrd.org/)

Lower Loup (https://www.llnrd.org/)

Lower Niobrara (https://www.lnnrd.org/)

Lower Platte North (https://www.lpnnrd.org/)

Lower Platte South (https://www.lpsnrd.org/)

Lower Republican (https://www.lrnrd.org/)

Middle Niobrara (https://www.mnnrd.org/)

Middle Republican (https://www.mrnrd.org/)

North Platte (https://www.npnrd.org/)

Papio Missouri River (https://www.papionrd.org/)

South Platte (https://www.spnrd.org/)

Tri-Basin (https://www.tribasinnrd.org/)

Twin Platte (https://www.tpnrd.org/)

Upper Big Blue (https://www.upperbigblue.org/)

Upper Elkhorn (https://www.uenrd.org/)

Upper Loup (https://www.upperloupnrd.org/)

Upper Niobrara White (https://www.unwnrd.org/)

Upper Republican (https://www.urnrd.org/)

New Mexico—Office of the State Engineer (https://www.ose.state.nm.us/) water-level data used in this report were measured by USGS New Mexico Water Science Center and were retrieved from USGS NWIS (U.S. Geological Survey, 2021b).

Oklahoma—Water Resources Board (https://www.owrb.ok.gov/) water-level data were retrieved from USGS NWIS (U.S. Geological Survey, 2021b).

South Dakota—Department of Agriculture and Natural Resources (https://danr.sd.gov) water-level data retrieved from USGS NWIS (U.S. Geological Survey, 2021b).

Texas—The Water Development Board and the following Groundwater Conservation Districts water-level data were retrieved from the Texas Water Development Boards groundwater database (Texas Water Development Board, 2020):

Garza County (https://www.twdb.texas.gov/groundwater/conservation_districts/gcdinfo1.asp)

Gateway (http://www.gatewaygroundwater.com/)

Glasscock (http://glasscock-groundwater.org)

Hemphill County (https://www.twdb.texas.gov/groundwater/conservation_districts/gcdinfo2.asp)

High Plains No. 1(http://www.hpwd.org/)

Llano Estacado (http://www.llanoestacadouwcd.org/)

Mesa (https://www.mesauwcd.org/)

Mesquite (https://www.twdb.texas.gov/groundwater/conservation_districts/gcdinfo2.asp)

North Plains (http://northplainsgcd.org/)

Panhandle (https://www.pgcd.us/)

Permian Basin (http://www.pbuwcd.com/)

Sandy Land (http://www.sandylandwater.com/)

South Plains (http://www.spuwcd.org/)

Wyoming—State Engineer's Office water-level data were retrieved from their water database (Wyoming State Engineer's Office, 2021).

Federal—Bureau of Reclamation (https://www.usbr.gov/gp/nkao/), U.S. Fish and Wildlife Service (https://www.fws.gov/refuge/crescent_lake/ and https://www.fws.gov/refuge/valentine/), and USGS offices in Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming with current and (or) historic water-level data, which were retrieved from USGS NWIS (U.S. Geological Survey, 2021b).

Supplemental Water-Level Data

The supplemental water-level data were used to substantiate contours used to control the interpolation process for the maps of water-level changes, predevelopment to 2017, and percentage change in saturated thickness, predevelopment to 2017, especially in areas with little applicable data. The supplemental data include measured static water levels for wells measured before June 15, 1978; for 1980; and for 2013 to 2017 and published areas of water-level changes without available measured data for predevelopment.

Water-level change and percentage change in saturated thickness values calculated from supplemental data and used in the maps of water-level changes, predevelopment to 2017, and percentage change in saturated thickness, predevelopment to 2017, included the static water levels from wells in all States except New Mexico, which were measured:

In predevelopment and in 2016, but not in 2017,

In predevelopment and in 2015, but not in 2016 or 2017,

In predevelopment and in 2014, but not in 2015, 2016, or 2017, and

In predevelopment and in 2013, but not in 2014, 2015, 2016, or 2017.

Additional water-level-change values calculated from supplemental data and used in the map of water-level changes, predevelopment to 2017, included the following:

The sum of the water-level-change value from wells measured in 1980 and 2017 and the beginning water-level-change value from the contours of water-level change, predevelopment to 1980 (Luckey and others, 1981).

Water-level-change values calculated from water levels in wells measured before June 15, 1978, but not during or before the predevelopment period for the area, and in 2017.

The water levels for 1980 were compiled by Weeks and Gutentag (1981) and Kastner and others (1989). The 1980 water levels were generally measured after the irrigation season in 1979 and before the irrigation season in 1980 (that is, in water year 1980), but some wells were measured 1 or 2 years earlier.

Finally, published areas of water-level change without available measured water levels for predevelopment also were incorporated into the contours used to control the interpolation process for the maps of water-level changes and percentage change in saturated thickness, predevelopment to 2017. These areas are in northwest and central Nebraska and southwest Wyoming (fig. 1; Lowry and others, 1967; Luckey and others, 1981; Young and others, 2017).

Characteristics of Raster Datasets

For this report, rasters were generated for water-level changes and percent changes in saturated thickness, predevelopment to 2017, and for water-level changes, 2015–17. The rasters were generated using two versions of a geographic information system—ArcInfo Workstation, version 9.3, and ArcMap, version 10.3.1 (Environmental Systems Research Institute, 1992, 2010, 2020); the commands used will hereinafter be referred to as “ArcGIS commands.” The rasters were georeferenced to geographic coordinates on an Albers equal-area conic projection using the North American Datum of 1983. The cell size for all rasters was 500 meters (1,640.4 ft) by 500 meters or about 62 acres. Water-level-change values were calculated as feet. Recoverable water in storage was presented as billion acre-feet and changes in recoverable water in storage values were summarized as million acre-feet.

The rasters of water-level changes, predevelopment to 2017 and 2015–17, are available for download in tagged image file format (McGuire and Strauch, 2022). The interpolation process, which was used to generate the rasters, is described in sections “Characterizing Water-Level Changes, Predevelopment to 2017”and “Characterizing Water-Level Changes, 2015–17.” The interpolation process can result in cell values for cells collocated with a measured well, that are generally similar to, but commonly not exactly equal to, the corresponding values based on those water-level measurements. This difference is because the cell values represent the value for the cell area and the measured values are values at specific locations within the area represented by the cell.

Characterizing Water-Level Changes, Predevelopment to 2017

The distribution of water-level changes for predevelopment to 2017 was determined using the same methods used by McGuire (2013) for water-level changes for predevelopment to 2011. A raster was generated using the ArcGIS topogrid command with (1) the water-level-change data from wells measured in predevelopment and measured or, for New Mexico only, estimated for 2017, as the primary source data, and (2) contours of water-level change, predevelopment to 2017, to control the interpolation. An initial set of contours of water-level change were generated by the ArcGIS contour command on the output of the first use of the topogrid command; the contours of water-level change were later manually modified using primary and supplemental water-level-change data. These modified contours were input to subsequent topogrid processing.

The mapped areas between a decline of less than 5 ft and a rise of less than 5 ft were termed areas of no substantial change and were assigned a value of zero water-level change rather than using the interpolation of water-level-change values in these areas. McGuire (2013) discusses the effect of using zero in the areas of no substantial changes instead of the interpolation of water-level-change values. The raster was used to calculate area-weighted, average water-level changes, predevelopment to 2017, by State and for the aquifer using the same methods as McGuire (2013) to calculate area-weighted, average water-level changes, predevelopment to 2011.

Characterizing Water-Level Changes, 2015–17

The distribution of water-level changes, 2015–17, was determined using the same method as McGuire (2013) for the raster of water-level changes, 2009–11. A raster was generated using the ArcGIS command topogrid with 1) the water-level-change data from wells measured in 2015 and 2017 and, 2) the water-level-change contours of declines of less than or equal to 1 ft and rises of less than or equal to 1 ft.

The mapped areas between a decline of less than 1 ft and a rise of less than 1 ft were termed areas of no substantial change and were assigned a value of zero water-level change rather than using the interpolation of water-level-change values in these areas. McGuire (2013) discusses the effect of using zero in the areas of no substantial changes instead of the interpolation of water-level-change values. The range of no substantial change for 2015–17 was defined differently than the range used for the predevelopment to 2017 time period because there generally are sufficient data in the 2015–17 time period to map the areas between a decline of less than 1 ft and a rise of less than 1 ft. The raster was used to calculate area-weighted, average water-level changes, 2015–17, by State and for the aquifer using the same methods used in McGuire (2013) to calculate area-weighted, average water-level changes, 2009–11.

Characterizing Specific Yield

Specific yield of the aquifer is needed to calculate recoverable water in storage. Specific yield of a rock or soil, with respect to water, is the ratio of the volume of water, which the saturated rock or soil will yield by gravity, to the rock or soil volume (Meinzer, 1923). A map of specific-yield ranges for the High Plains aquifer was interpolated from point values of depth-interval-weighted specific yield, which was estimated from lithologic logs for selected wells or test holes distributed across the aquifer and generally drilled to the base of the aquifer (Gutentag and others, 1984; Cederstrand and Becker, 1998).

A specific-yield raster was created from the map of specific-yield ranges in the High Plains aquifer (Gutentag and others, 1984; Cederstrand and Becker, 1998) using the ArcMap command polygrid. The raster value, hereafter referred to as “average-mapped specific yield,” was set equal to the average of the assigned range for the associated specific-yield polygons (McGuire and others, 2012). The area-weighted, average specific yield of the aquifer, not including the areas of little or no saturated thickness, ranges by State from 8.1 percent in Wyoming to 18.5 percent in Oklahoma and is 15.1 percent overall for the aquifer (Gutentag and others, 1984; McGuire and others, 2012).

Calculation of Total Recoverable Water in Storage and Change in Recoverable Water in Storage

Total recoverable water in storage for 2017 and changes in recoverable water in storage in the High Plains aquifer for the predevelopment to 2017 and the 2015–17 time periods were calculated by applying “map algebra” techniques (Tomlin and Berry, 1979) to coregistered rasters sharing a common cell size and orientation. Total recoverable water in storage for 2017 was calculated by summing the rasters of saturated thickness for 2009 (McGuire and others, 2012) and the rasters of water-level changes, 2009–11 (McGuire, 2013), 2011–13 (McGuire, 2014), 2013–15 (McGuire, 2017), and 2015–17 (this report), then multiplying the result by the raster of the average-mapped specific yield (McGuire and others, 2012) and by a factor to convert units of square meter-feet to million acre-feet. Changes in recoverable water in storage in the High Plains aquifer for the predevelopment to 2017 and the 2015–17 time periods were calculated by multiplying the raster cell values of water-level changes for each period by the raster cell values of average-mapped specific yield (McGuire and others, 2012) and by a factor to convert units of square meter-feet to million acre-feet. Changes in recoverable water in storage from predevelopment to 2017 and 2015–17, by State and by aquifer, were calculated using the resultant raster.

Characterizing Percentage Change in Saturated Thickness, Predevelopment to 2017

The raster of percentage change in saturated thickness, predevelopment to 2017, was generated using the ArcGIS command topogrid. Inputs to topogrid were

Percentage change in saturated thickness at each well location with a water level measured in predevelopment and measured or estimated for 2017,

Estimated altitude of the aquifer base, relative to the North American Vertical Datum of 1988, and

Contours of percentage change in saturated thickness.

Predevelopment saturated thickness was calculated for each well by subtracting the altitude of the base of aquifer from the predevelopment water-level altitude (North American Vertical Datum of 1988). Percentage change in saturated thickness, predevelopment to 2017, was calculated by dividing water-level change, predevelopment to 2017, by predevelopment saturated thickness.

The contours of percentage change in saturated thickness were used to constrain the interpolation in areas of sparse data; these contours were initially generated by the contour command on the output of the topogrid command. The percentage change in saturated thickness contours was manually modified using the primary and supplemental water-level-change data. The modified percentage change in saturated thickness contours was input to subsequent processing with topogrid.

Water-Level Changes

Water-level changes in the High Plains aquifer are presented for two periods: predevelopment to 2017 and 2015–17. In addition, water-level changes are presented with respect to saturated thickness in predevelopment.

Water-Level Changes, Predevelopment to 2017

The map of water-level changes in the High Plains aquifer, predevelopment to 2017 (fig. 1), is based on water levels from 2,928 wells, including estimated water levels from 63 wells in New Mexico (table 1), and on other published data (Lowry and others, 1967; Luckey and others, 1981; Young and others, 2017). The other published data were used to portray water-level changes in areas in Nebraska and Wyoming with few predevelopment water levels (fig. 1). Water-level changes in wells, predevelopment to 2017, ranged from

- a rise of 84 ft in Nebraska to a decline of 262 ft in Texas,
- a rise of 39 ft to a decline of 200 ft in 99 percent of the wells,
- a rise of 5 ft to a decline of 5 ft in 37 percent of the wells, and
- a rise of 1 ft to a decline of 1 ft in 9 percent of the wells.

The area-weighted, average water-level change from predevelopment to 2017 was a decline of 16.8 ft (table 2). When summarized by State, the area-weighted, average water-level change from predevelopment to 2017 ranged from a decline of 44.0 ft in Texas to a rise of 0.6 ft in South Dakota (table 2). From predevelopment to 2017, not including the areas of little or no saturated thickness, water levels declined 5 ft or more in 35 percent of the aquifer area, 10 ft or more in 27 percent of the aquifer area, 25 ft or more in 19 percent of the aquifer area, and 50 ft or more in 12 percent of the aquifer area. In approximately 57 percent of the aquifer area, water-level changes ranged from a 5-ft decline to a 5-ft rise, which is considered an area of no substantial change. From predevelopment to 2017, water levels rose 5 ft or more in 8 percent of the aquifer area and 10 ft or more in 3 percent of the aquifer area.

Water-Level Changes, 2015–17

The map of water-level changes in the High Plains aquifer, 2015–17 (fig. 2), was based on water levels from 7,698 wells measured before the irrigation season in 2015 and 2017 (table 1). Water-level changes in the measured wells ranged from

- a rise of 41 ft in Colorado to a decline of 21 ft in Kansas,
- a rise of 14 ft to a decline of 10 ft in 99 percent of the wells,

Table 2. Area-weighted, average water-level changes in the High Plains aquifer, not including areas of little or no saturated thickness, predevelopment (about 1950) to 2017 and 2015–17, by State and for the aquifer.

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

State	Area-weighted, average water-level change, in feet	
	Predevelopment to 2017	2015–17
Colorado	−13.2	0.1
Kansas	−28.2	−0.5
Nebraska	−1.1	0.2
New Mexico	−19.1	0.0
Oklahoma	−13.7	−0.3
South Dakota	0.6	0.1
Texas	−44.0	0.2
Wyoming	−0.8	0.2
High Plains aquifer	−16.8	0.1

a rise of 5 ft to a decline of 5 ft in 89 percent of the wells, and

a rise of 1 ft to a decline of 1 ft in 43 percent of the wells.

Water levels declined 3 ft or more in 7 percent of the measured wells and declined 6 ft or more in 2 percent of the measured wells. Water levels rose 3 ft or more in 15 percent of measured wells and rose 6 ft or more in 6 percent of measured wells.

The area-weighted, average water-level change for the aquifer for the period 2015–17 was a rise of 0.1 ft (fig. 2; table 2). Area-weighted, average water-level changes, 2015–17, by State ranged from a 0.5-ft decline in Kansas to a rise of 0.2 ft in Nebraska, Texas, and Wyoming.

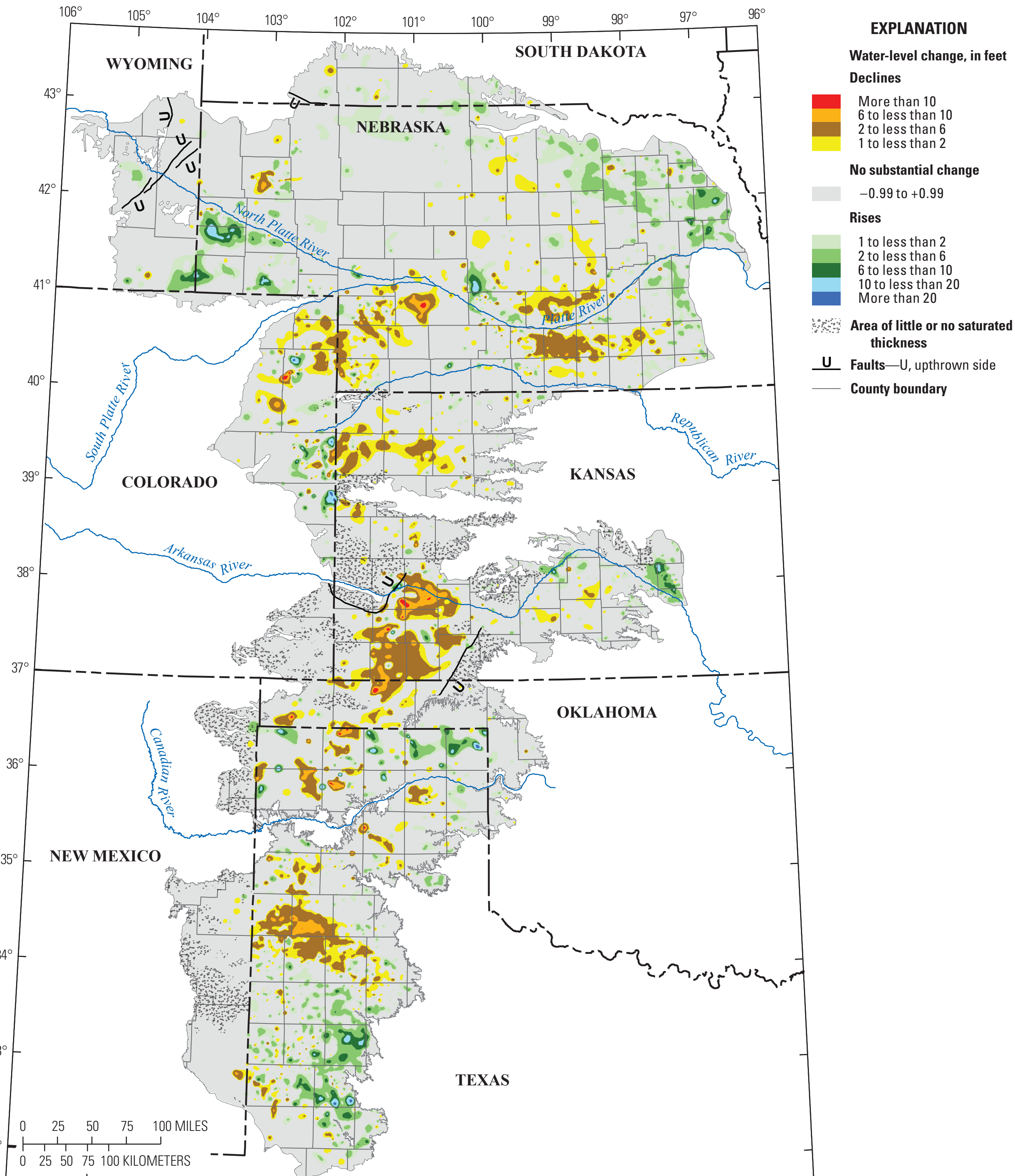
Percentage Change in Saturated Thickness, Predevelopment to 2017

The water-level changes, predevelopment to 2017, as a percentage of predevelopment saturated thickness are shown in figure 3. This map (fig. 3) is similar in some areas to the water-level-change map for the same period (fig. 1); however, a large water-level change would not correspond to a substantial percentage change in saturated thickness if the predevelopment saturated thickness was large relative to the water-level change. Conversely, an area with small water-level change may correspond to a large percentage change in saturated thickness if its predevelopment saturated thickness was small. By 2017, percentage change in saturated thickness as a percent of the aquifer area, not including the areas of little or no saturated thickness, was a decrease of 10 percent or more in 24.4 percent of the area, a decrease of 25 percent or more in 14.8 percent of the area, a decrease of 50 percent or more in 5.5 percent of the area, an increase of 10 percent or more in 1.4 percent of the area, and between a rise of 10 percent and a decline of 10 percent in 74.2 percent of the area.

Change in Recoverable Water in Storage, Predevelopment to 2017 and 2015–17

The recoverable volume of water in storage in the High Plains aquifer was estimated, using various methods, to have been about 3.20 billion acre-feet (Bacre-ft) at predevelopment (McGuire and others, 2012), 3.25 Bacre-ft in 1980 (Gutentag and others, 1984), 2.98 Bacre-ft in 2000 (McGuire and others, 2003), 2.96 Bacre-ft in 2009 (McGuire and others, 2012), and 2.92 Bacre-ft in 2013 (McGuire, 2014). Recoverable water in storage in the High Plains aquifer in 2017 was estimated by this study as 2.91 Bacre-ft.

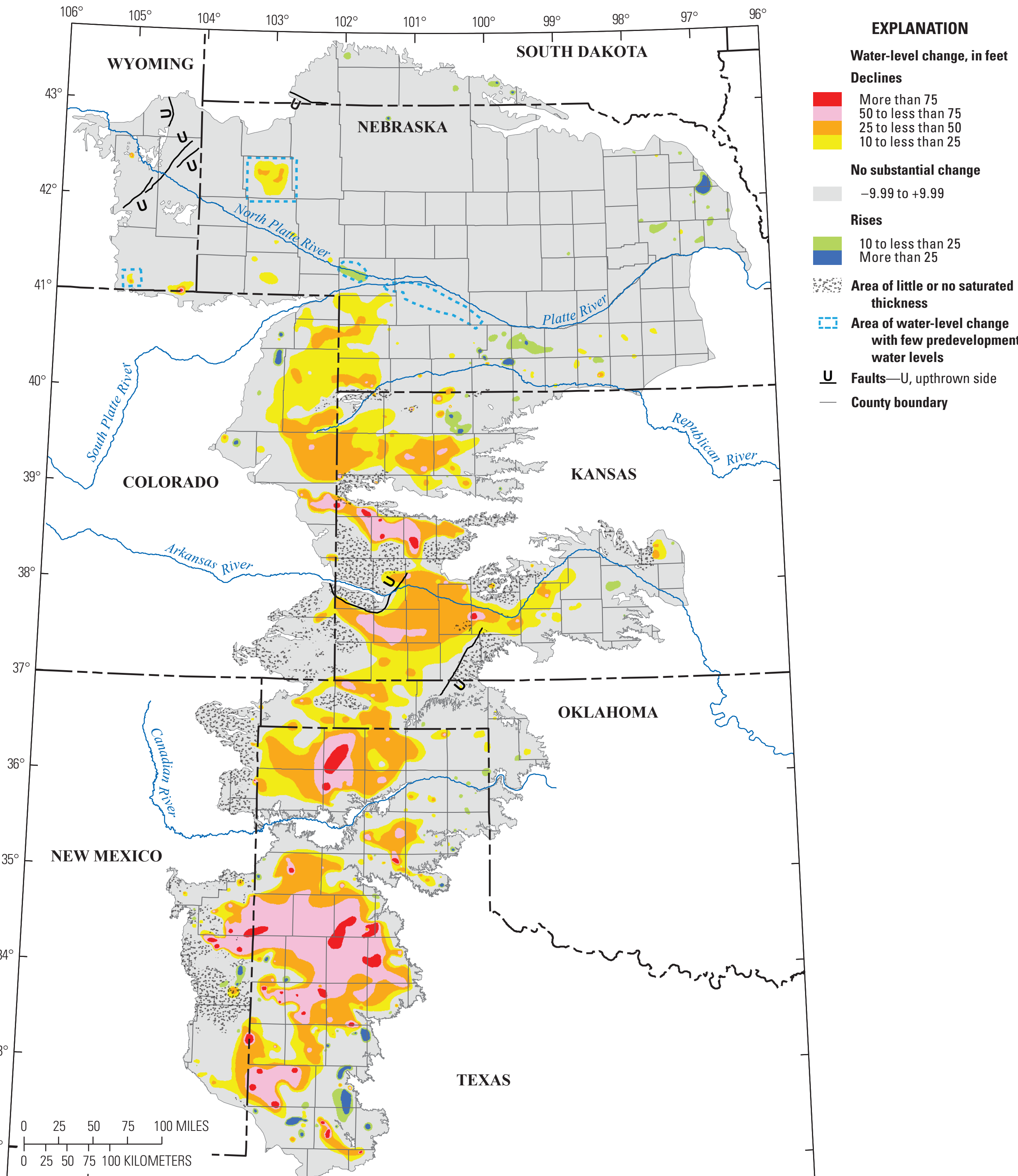
Change in recoverable water in storage, predevelopment to 2017, declined 291.8 Macre-ft for the aquifer overall (table 3) or about a 9-percent decline in storage since predevelopment (McGuire and others, 2012). Changes in storage, predevelopment to 2017, by State, ranged from a decline of 169.1 Macre-ft in Texas to a rise of 0.2 Macre-ft in South Dakota (table 3). Recoverable water in storage, 2015–17, rose 0.1 Macre-ft overall; changes in recoverable water in storage, 2015–17, by State, ranged from a decline of 1.2 Macre-ft in Kansas to a rise of 0.7 Macre-ft in Nebraska (table 3).



Base from U.S. Geological Survey digital data, 1:2,000,000, 2001
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian –101°00'
North American Datum of 1983

Aquifer boundary from Qi (2010); areas of little or no saturated thickness and faults from Gutentag and others (1984) and Cederstrand and Becker (1999a, 1999b)

Figure 2. Water-level changes, High Plains aquifer, 2015–17.



Base from U.S. Geological Survey digital data, 1:2,000,000, 2001
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian –101°00'
North American Datum of 1983

Aquifer boundary from Qi (2010); change in saturated thickness since predevelopment modified from Luckey and others (1981); areas of little or no saturated thickness and faults from Gutentag and others (1984) and Cederstrand and Becker (1999a, 1999b)

Figure 3. Percentage change in saturated thickness, High Plains aquifer, predevelopment (about 1950) to 2017.

Table 3. Change in recoverable water in storage in the High Plains aquifer, predevelopment (about 1950) to 2017 and 2015–17, by State and for the aquifer.

[Positive values for increases in recoverable water in storage; negative values for decreases in recoverable water in storage]

State	Change in recoverable water in storage, in million acre-feet	
	Predevelopment to 2017	2015–17
Colorado	−17.3	0.2
Kansas	−75.0	−1.2
Nebraska	−6.9	0.7
New Mexico	−11.5	0.0
Oklahoma	−11.7	−0.3
South Dakota	0.2	0.0
Texas	−169.1	0.6
Wyoming	−0.5	0.1
High Plains aquifer	−291.8	0.1

Summary

The High Plains aquifer underlies 111.8 million acres (about 175,000 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 onset of substantial groundwater irrigation (about 1950). In response to the water-level declines, the U.S. Congress directed the U.S. Geological Survey to monitor water levels in the High Plains aquifer. Since 1987, the U.S. Geological Survey, in collaboration with numerous State, local, and Federal water-resources entities, has compiled water levels from wells completed in the High Plains aquifer. Water levels were measured in 8,938 wells for water year 2015 and in 8,333 wells for water year 2017. For 63 wells in New Mexico, water levels were estimated for 2017 using the latest static water level measured from water year 2013 to 2016 if the well had a predevelopment water level but did not have a static water level measured in 2017.

This report presents water-level changes in the High Plains aquifer from predevelopment (about 1950) to 2017 and 2015–17. The water levels used in this report generally were measured in winter or early spring, when irrigation wells typically were not pumping, and after water levels generally had recovered from pumping during the previous irrigation season. The report also presents total recoverable water in storage in 2017 and changes in recoverable water in storage from predevelopment to 2017 and 2015 to 2017. The methods to calculate area-weighted, average water-level changes; change in recoverable water in storage; and total recoverable water in storage used geospatial data layers organized as rasters with a cell size of 500 meters by 500 meters, which is an area of about 62 acres.

The map of water-level changes in the High Plains aquifer from predevelopment to 2017 is based on water levels from 2,928 wells and other published data. Water-level changes from predevelopment to 2017, in individual wells, ranged from a rise of 84 feet (ft) in Nebraska to a decline of 262 ft in Texas; the range for 99 percent of the wells was from a rise of 39 ft to a decline of 200 ft. The area-weighted, average water-level change from predevelopment to 2017 was a decline of 16.8 ft. By 2017, 15 percent of the aquifer area had a decrease in saturated thickness of more than 25 percent from its predevelopment saturated thickness, 6 percent of the aquifer area had more than a 50-percent decrease, and about 1 percent of the aquifer area had more than a 10-percent increase.

Water levels were measured in 7,698 wells before the irrigation season in 2015 and 2017. Water-level changes in the measured wells ranged from a 21-ft decline in Kansas to a 41-ft rise in Colorado; the range for 99 percent of the wells was from a rise of 14 ft to a decline of 10 ft. The area-weighted, average water-level change from 2015 to 2017, was a rise of 0.1 ft.

Total recoverable water in storage in 2017 was about 2.91 billion acre-feet overall, which was a decline of about 291.8 million acre-feet (Macre-ft; or about 9 percent) since predevelopment. Changes in storage, predevelopment to 2017, by State, ranged from a decline of about 169.1 Macre-ft in Texas to a rise of 0.2 Macre-ft in South Dakota. Recoverable water in storage, 2015–17, rose 0.1 Macre-ft overall; changes in recoverable water in storage, 2015–17, by State ranged from a decline of 1.2 Macre-ft in Kansas to a rise of 0.7 Macre-ft in Nebraska.

References Cited

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p. [Also available at https://doi.org/10.3133/cir1186.]

Brown, J.F., Howard, D.M., Shrestha, D., and Benedict, T.D., 2019, Moderate Resolution Imaging Spectroradiometer (MODIS) Irrigated Agriculture Datasets for the Conterminous United States (MIrAD-US): U.S. Geological Survey data release, accessed August 2021 at https://doi.org/10.5066/P9NA3EO8.

Cederstrand, J.R., and Becker, M.F., 1998, Digital map of specific yield for High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Open-File Report 98–414, accessed August 2021 at https://doi.org/10.3133/ofr98414.

Cederstrand, J.R., and Becker, M.F., 1999a, Digital map of geologic faults for the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Open-File Report 99–261, accessed August 2021 at https://doi.org/10.3133/ofr99261.

Cederstrand, J.R., and Becker, M.F., 1999b, Digital map of areas of little or no saturated thickness for the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Open-File Report 99–266, accessed August 2021 at https://doi.org/10.3133/ofr99266.

Cunningham, W.L., and Schalk, C.W., comps., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods, book 1, chap. A1, 151 p., accessed August 2021 at https://doi.org/10.3133/tm1A1.

Environmental Systems Research Institute, 1992, Understanding GIS—The Arc/Info method: Redlands, Calif., Esri, 450 p.

Environmental Systems Research Institute, 2010, ArcDoc version 9.3: Redlands, Calif., Esri software documentation [online documentation and instructions included with GIS software.]

Environmental Systems Research Institute, 2020, ArcMap version 10.8.1: Redlands, Calif., Esri software documentation [online documentation and instructions included with GIS software.]

Gaum, C.H., 1953, High Plains, or Llano Estacado, Texas-New Mexico, chap. 6 *of* The physical and economic foundation of natural resources—Volume 4, Subsurface facilities of water management and patterns of supply—Type area studies: Interior and Insular Affairs Committee, House of Representatives, United States Congress, p. 94–104. [Also available at https://babel.hathitrust.org/cgi/pt?id=osu.32435061292421&view=1up&seq=118&skin=2021.]

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. [Also available at https://doi.org/10.3133/pp1400B.]

Heimes, F.J., and Luckey, R.R., 1982, Method for estimating historical irrigation requirements from ground water in the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 82–40, 64 p. [Also available at https://doi.org/10.3133/wri8240.]

Heimes, F.J., and Luckey, R.R., 1983, Estimating 1980 ground-water pumpage for irrigation on the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 83–4123, 40 p. [Also available at https://doi.org/10.3133/wri834123.]

Kansas Geological Survey, 2020, Wizard water well levels database: Lawrence, Kansas Geological Survey digital data, accessed August 2020 at https://www.kgs.ku.edu/Magellan/WaterLevels/index.html.

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 1987-1988: U.S. Geological Survey Water-Resources Investigations Report 89–4073, 61 p. [Also available at https://doi.org/10.3133/wri894073.]

Lovelace, J.K., Nielsen, M.G., Read, A.L., Murphy, C.J., and Maupin, M.A., 2020, Estimated groundwater withdrawals from principal aquifers in the United States, 2015 (ver. 1.2, October 2020): U.S. Geological Survey Circular 1464, 70 p., accessed August 2021 at https://doi.org/10.3133/cir1464.

Lowry, M.E., Crist, M.A., and Tilstra, J.R., 1967, Geology and ground-water resources of Laramie County, Wyoming, with a section on Chemical quality of ground water and of surface water, by J.R. Tilstra: U.S. Geological Survey Water-Supply Paper 1834, 71 p. [Also available at https://doi.org/10.3133/wsp1834.]

Luckey, R.R., and Becker, M.F., 1999, Hydrogeology, water use, and simulation of flow in the High Plains aquifer in northwestern Oklahoma, southeastern Colorado, southwestern Kansas, northeastern New Mexico, and northwestern Texas: U.S. Geological Survey Water-Resources Investigations Report 99–4104, 68 p. [Also available at https://doi.org/10.3133/wri994104.]

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. [Also available at https://doi.org/10.3133/ha652.]

Maupin, M.A., and Barber, N.L., 2005, Estimated withdrawals from principal aquifers in the United States, 2000: U.S. Geological Survey Circular 1279, 46 p. [Also available at https://doi.org/10.3133/cir1279.]

McGuire, V.L., 2013, Water-level and storage changes in the High Plains aquifer, predevelopment to 2011 and 2009–11: U.S. Geological Survey Scientific Investigations Report 2012–5291, 15 p. [Also available at https://doi.org/10.3133/sir20125291.]

McGuire, V.L., 2014, Water-level changes and change in water in storage in the High Plains aquifer, predevelopment to 2013 and 2011–13: U.S. Geological Survey Scientific Investigations Report 2014–5218, 14 p. [Also available at https://doi.org/10.3133/sir20145218.]

McGuire, V.L., 2017, Water-level and recoverable water in storage changes, High Plains aquifer, predevelopment to 2015 and 2013–15: U.S. Geological Survey Scientific Investigations Report 2017–5040, 14 p., accessed August 2021 at https://doi.org/10.3133/sir20175040.

McGuire, V.L., and Strauch, K.R., 2022, Data from maps of water-level changes in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, predevelopment (about 1950) to 2017 and 2015–17: U.S. Geological Survey data release, available at https://doi.org/10.5066/P9YN7PY3.

McGuire, V.L., Johnson, M.R., Schieffer, R.L., Stanton, J.S., Sebree, S.K., and Verstraeten, I.M., 2003, Water in storage and approaches to ground-water management, High Plains aquifer, 2000: U.S. Geological Survey Circular 1243, 51 p. [Also available at https://doi.org/10.3133/cir1243.]

McGuire, V.L., Lund, K.D., and Densmore, B.K., 2012, Saturated thickness and water in storage in the High Plains aquifer, 2009, and water-level changes and changes in water in storage in the High Plains aquifer, 1980 to 1995, 1995 to 2000, 2000 to 2005, and 2005 to 2009: U.S. Geological Survey Scientific Investigations Report 2012–5177, 28 p. [Also available at https://doi.org/10.3133/sir20125177.]

Meinzer, O.E., 1923, Outline of ground-water hydrology, with definitions: U.S. Geological Survey Water-Supply Paper 494, 71 p. [Also available at https://doi.org/10.3133/wsp494.]

Peterson, S.M., Traylor, J.P., and Guira, M., 2020, Groundwater availability of the Northern High Plains aquifer in Colorado, Kansas, Nebraska, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1864, 57 p. [Also available at https://doi.org/10.3133/pp1864.]

Qi, S.L., 2010, Digital map of aquifer boundary for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Data Series 543. [Also available at https://doi.org/10.3133/ds543.]

Stanton, J.S., Qi, S.L., Ryter, D.W., Falk, S.E., Houston, N.A., Peterson, S.M., Westenbroek, S.M., and Christenson, S.C., 2011, Selected approaches to estimate water-budget components of the High Plains, 1940 through 1949 and 2000 through 2009: U.S. Geological Survey Scientific Investigations Report 2011–5183, 79 p. [Also available at https://doi.org/10.3133/sir20115183.]

Taylor, C.J., and Alley, W.M., 2001, Ground-water-level monitoring and the importance of long-term water-level data: U.S. Geological Survey Circular 1217, 68 p. [Also available at https://doi.org/10.3133/cir1217.]

Texas Water Development Board, 2020, Groundwater database: Texas Water Development Board digital data: accessed April 2020 at https://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp.

Thelin, G.P., and Heimes, F.J., 1987, Mapping irrigated cropland from Landsat data for determination of water use from 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–C, 38 p. [Also available at https://doi.org/10.3133/pp1400C.]

Tomlin, C.D., and Berry, J.K., 1979, A mathematical structure for cartographic modeling in environmental analysis, in American Congress on Surveying and Mapping, 39th, Washington, D.C., 1979, Proceedings: Falls Church, Va., American Congress on Surveying and Mapping, p. 269–283.

U.S. Department of Agriculture, 1999, 1997 Census of agriculture, volume 1, geographic area series, part 51: National Agricultural Statistics Service, AC97–CD–VOL1–1B [CD–ROM.]

U.S. Geological Survey, 2021a, National Groundwater Monitoring Network: U.S. Geological Survey well, water-level, and water-quality data portal, accessed March 2021 at https://cida.usgs.gov/ngwmn/.

U.S. Geological Survey, 2021b, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed March 2021, at https://doi.org/10.5066/F7P55KJN.

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 1:2,500,000. [Also available at https://doi.org/10.3133/ha648.]

Wyoming State Engineer’s Office, 2021, Real-time SEO Water Data: Wyoming State Engineer’s Office data, accessed April 2021 at https://seoflow.wyo.gov/.

Young, A.R., Burbach, M.E., Howard, L.M., Waszgis, M.M., Lackey, S.O., and Joeckel, R.M., 2017, Nebraska statewide groundwater-level monitoring report 2017: University of Nebraska–Lincoln, Conservation and Survey Division, Nebraska Water Survey Paper 85, 28 p. [Also available at http://snr.unl.edu/csd-esic/GWMapArchives/GWReports/GW_Level_Report_2017.pdf.]

For more information about this publication, contact:
Director, USGS Nebraska Water Science Center
5231 South 19th Street
Lincoln, NE 68512
402–328–4100

For additional information, visit: https://www.usgs.gov/centers/ne-water

Publishing support provided by the
Rolla and Lafayette Publishing Service Centers

McGuire and Strauch—**Water-Level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2017 and 2015–17**—SIR 2022–5080

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20225080