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Groundwater Levels in the Denver Basin Bedrock Aquifers of Douglas County, Colorado, 2011–19

Scientific Investigations Report 2020–5076

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

Cover Photograph showing a domestic water well in the foreground and Pikes Peak in the background, taken near Franktown, Colorado, on February 5, 2020, by Helen Malenda, U.S. Geological Survey.

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DAVID BERNHARDT, Secretary

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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)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow Rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F – 32) / 1.8.

Datum

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

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

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

Abbreviations

ARAP	Arapahoe aquifer well, used in the well common names
CDWR	Colorado Division of Water Resources
DENV	Denver aquifer well, used in the well common names
GRNDAW	Grandview Estates, lower Dawson aquifer well, used in the well common names
GRNDEV	Grandview Estates, Denver aquifer well, used in the well common names
LARA	Laramie-Fox Hills aquifer well, used in the well common names
LDAW	lower Dawson aquifer well, used in the well common names
LSD	land-surface datum
M–K	Mann-Kendall
MP	measuring point
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
NWIS	National Water Information System
RWADC	Rural Water Authority of Douglas County
sM–K	seasonal Mann-Kendall
SMWSA	South Metro Water Supply Authority
UDAW	upper Dawson aquifer well, used in the well common names
USGS	U.S. Geological Survey

Groundwater Levels in the Denver Basin Bedrock Aquifers of Douglas County, Colorado, 2011–19

By Helen F. Malenda and Colin A. Penn

Abstract

Municipal and domestic water users in Douglas County, Colorado, rely on groundwater from the bedrock aquifers in the Denver Basin aquifer system as part of their water supply. The four principal Denver Basin bedrock aquifers are, from shallowest to deepest, the Dawson aquifer (divided administratively into “upper” and “lower” Dawson aquifers in Douglas County), the Denver aquifer, the Arapahoe aquifer, and the Laramie-Fox Hills aquifer. Increased groundwater pumping in response to rapid population growth and development has led to declining groundwater levels in Douglas County, where groundwater is a primary water source for densely populated and rural communities. The U.S. Geological Survey, in cooperation with the Rural Water Authority of Douglas County, began a study in 2011 to assess the groundwater resources of the Denver Basin bedrock aquifers within the county. The primary purpose of this report is to present a summary of groundwater levels measured during the study period (2011–19) and present results from statistical analyses of changes in groundwater-level elevations, reported above the land-surface datum, North American Vertical Datum of 1988, through time. During the study period, January 2011 through June 2019, discrete groundwater levels were routinely measured at 36 wells producing from Denver Basin bedrock aquifers within Douglas County. Of the 36 wells, 15 are instrumented with pressure transducers that record groundwater-level measurements at hourly intervals, and these data were temporally aggregated into time-series records. During 2011, wells were added to the monitoring network in phases, so that the start dates of the well records are noncontemporaneous. To keep temporal analysis among wells consistent, the periods of record used in statistical analyses were from February 2012 through February 2019 for the discrete data and from January 2012 through June 2019 for the time-series data.

The upper Dawson, lower Dawson, Denver, and Arapahoe aquifers had some wells with rises in calculated groundwater-level elevations, but most wells showed declines on the basis of statistically significant trends and the relative differences in static groundwater-level elevations between the February 2012 and February 2019 measurements. Neither of the two wells in the Laramie-Fox Hills aquifer showed significant trends in groundwater-level elevations, and these wells had few static discrete measurements, precluding a comparison between 2012 and 2019 static groundwater-level elevations. Of the 13 wells in the upper Dawson, lower Dawson, Denver, and Arapahoe aquifers with significant trends in discrete groundwater-level elevation measurements, the records of 12 wells demonstrated negative trends during the study period. The upper Dawson, lower Dawson, Denver, and Arapahoe aquifers had median significant trends of −0.23, −0.31, −0.92, and −2.26 feet per year, respectively. Although the Arapahoe aquifer had the greatest negative median trend, this median only represents one well with significant trends. Otherwise, the Denver aquifer had the next greatest negative trend, with a median trend of −0.92 foot per year. Significant trends in time-series groundwater-level elevations agreed with significant trends in discrete groundwater-level elevations; for all wells with statistically significant trends in discrete and in time-series groundwater-level elevation data, trend estimates from the two records were within 0.1 foot per year of each other. Potentiometric-surface maps of the upper Dawson, lower Dawson, and Denver aquifers, created using discrete static groundwater levels measured in February 2019, show that groundwater flow direction for the upper Dawson, lower Dawson, and Denver aquifers is generally from south to north. Results of this study could guide future groundwater monitoring in the county and aid in long-term planning of water resources.

Introduction

Douglas County is a rapidly urbanizing county to the south of Denver, Colorado, along the foothills of the Colorado Front Range Mountains, and the county relies on groundwater withdrawals from the bedrock aquifers in the Denver Basin aquifer system (also referred to as the Denver Basin bedrock aquifers) (fig. 1). Douglas County is one of the fastest growing counties in Colorado, according to the U.S. Census Bureau. In 1990, the population of Douglas County was more than 60,000 people (U.S. Census Bureau, 1995). Between 2000 and 2019, the population increased by more than 100 percent from 175,766 to approximately 358,000 residents, and the Douglas County Planning Commission estimates the population will grow to more than 418,000 by 2030 (Douglas County Demographic Summary, 2019; Douglas County Department of Community Development, 2019).

Development of groundwater resources is necessary to meet the growing water needs of Douglas County. Although some water providers in the county have surface-water rights, their allocations do not provide enough water to satisfy the renewable supplies necessary to fulfill the existing water demands of the county (Douglas County, 2019). Therefore, groundwater from the Denver Basin aquifer system, which underlies the northeastern two-thirds of Douglas County (fig. 1), provides a critical component to water supply in the county.

Despite the recent growth of Douglas County, the county retains a mixture of rural and suburban land use, and municipal and domestic (private) water users rely on groundwater from Denver Basin bedrock aquifers. In 2004, 13 local municipalities' water authorities in the south Denver metropolitan area combined to form the South Metro Water Supply Authority (SMWSA). Approximately 80 percent of Douglas County is served by SMWSA (SMWSA, undated), and although domestic groundwater use is less than municipal use, residents in rural parts of the county depend solely on self-supplied groundwater (Paschke, 2011). In October 2008, the Rural Water Authority of Douglas County (RWADC) was created to assist county residents in developing water resources and systems for the benefit of all water users and landowners within the county. The RWADC mission is to assist the more than 8,000 rural water users and local water districts in the county by evaluating current and future water supplies and demand (RWADC, 2019a).

In the late 2000s, SMWSA recognized that regional demand on groundwater resources from the Denver Basin bedrock aquifers was outpacing recharge and, thus, the reliance on groundwater by local municipalities was unsustainable (SMWSA, undated). However, almost one-half of the municipal water supply in the south Denver metropolitan area was still provided by the Denver Basin aquifer system in 2019 (SMWSA, 2020).

In 2011, the U.S. Geological Survey (USGS), in cooperation with the RWADC, began a study to assess the groundwater resources of the Denver Basin bedrock aquifers within the county by establishing and maintaining a groundwater monitoring network (fig. 2) and by analyzing the groundwater levels of the Denver Basin bedrock aquifers throughout Douglas County (Everett, 2014). The establishment of a monitoring network allowed for assessment of the current groundwater resource and provided the basis from which to monitor long-term changes of the hydrologic system. In subsequent years, with cooperation from the RWADC, the USGS has continued routine discrete (manual) measurements of groundwater levels and with additional funding from the Colorado Water Conservation Board equipped and maintained instruments in 15 wells that record groundwater levels on an hourly basis. Continued monitoring improves the ability to assess short- and long-term changes in the groundwater-level elevations and can aid communities in water-resource management.

Purpose and Scope

This report builds upon initial observations made by Everett (2014), who examined groundwater-level elevations measured in Douglas County from 2011 through 2013. This report uses data from a network of 36 groundwater wells where discrete measurements of groundwater levels were made bimonthly from 2012 through 2014 and annually from 2015 through 2019. There were at least two wells in each of the Denver Basin bedrock aquifers. The purpose of this report is to summarize groundwater levels measured during the study period and present results from statistical analyses of changes in groundwater-level elevations through time (trends) in the Denver Basin bedrock aquifers in Douglas County, Colorado, from January 2012 through June 2019. During 2011, wells were added to the monitoring network in phases, so that the start dates of the well records are noncontemporaneous. For this reason, the study period, including summarized groundwater levels, covers 2011–19, whereas the statistical analysis period covers 2012–19. Of the wells added to the monitoring network, 15 were instrumented with pressure transducers that measure and record groundwater-level data on an hourly basis, herein referred to as time-series data (fig. 2). To keep temporal trend analysis among wells consistent, the periods of record used in statistical analyses were from February 2012 through February 2019 for the discrete data and from January 2012 through June 2019 for the time-series data.

Previous Studies

Since the late 1800s, the Denver Basin aquifer system has been the subject of numerous studies examining the geology, structure, and hydrogeology of the basin and its bedrock aquifers. Systematic hydrogeologic characterization of the Denver Basin bedrock aquifers began in the 1970s as part of the development of nontributary groundwater rules established by Colorado Senate Bill 213 (Graham and Van Slyke, 2004). The Colorado Division of Water Resources (CDWR) and the USGS collaborated through the 1970s and 1980s by mapping and characterizing the primary aquifers of the Denver Basin aquifer system. These studies, listed or summarized in Wireman and Romero (1989) and Paschke (2011), were crucial to the development of a groundwater flow model (Robson, 1987) and a fully three-dimensional MODFLOW–2000 groundwater flow model (Paschke, 2011) of the Denver Basin aquifer system. Everett (2014) and Penn and Everett (2019) summarized findings from recent groundwater monitoring in Douglas and Elbert Counties, respectively, and included descriptions of the characterization studies, and Everett (2014) described the principal aquifers' geology in detail. Additional studies have investigated the hydrology and water quality of the Arapahoe aquifer (Hillier and others, 1978) and the Denver Basin aquifer system (Bauch and others, 2014).

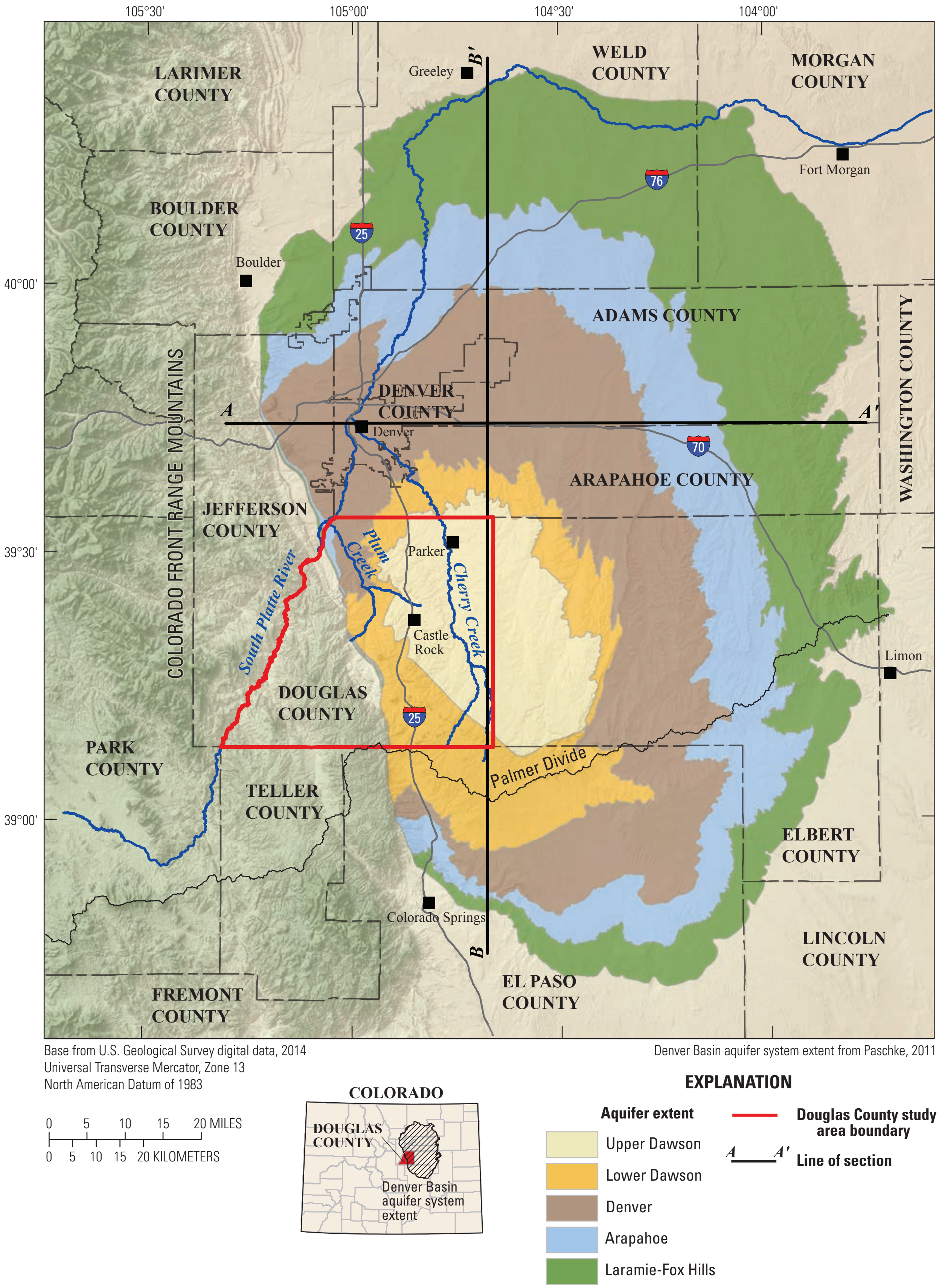

Figure 1. Location of the Denver Basin aquifer system and geologic lines of section *A*, *A*–*A*′ and *B*, *B*–*B*′ near Douglas County, Colorado.

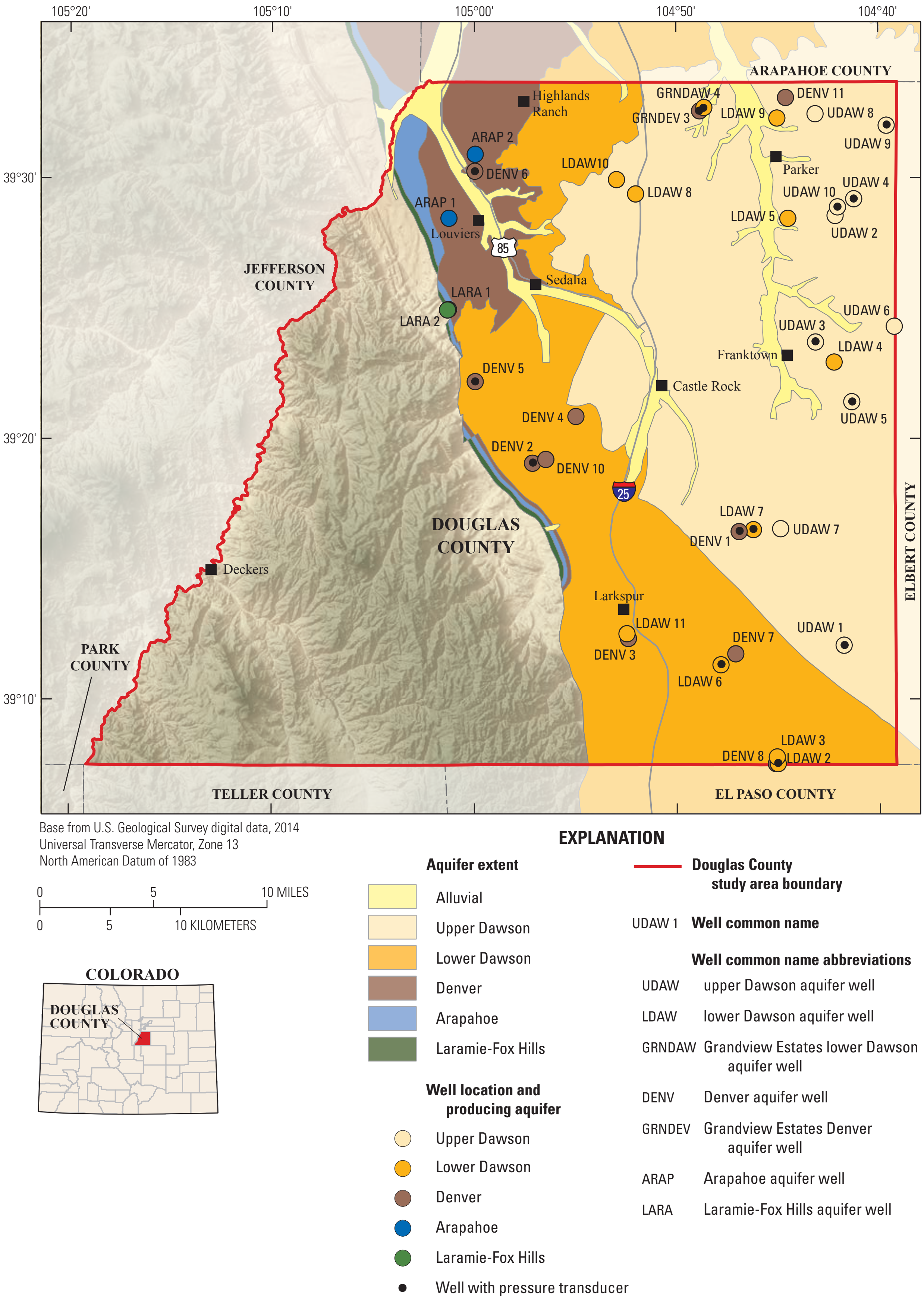

Figure 2. Location of groundwater-level monitoring network wells and producing aquifer, Douglas County, Colorado.

Historically, monitoring of groundwater levels in the Denver Basin bedrock aquifers has been intermittent (Colorado Water Conservation Board, 2004, 2006), with contributions from several entities—the USGS (McConaghy and others, 1964), the Colorado Water Conservation Board (McConaghy and others, 1964), the CDWR (Pottorff and Horn, 2013; Flor, 2017), and local municipalities (Flor, 2017). As of 2017, the CDWR groundwater network monitors groundwater levels in about 89 municipal and domestic wells within the Denver Basin aquifer system on an annual basis (Pottorff and Horn, 2013; Flor, 2017). Recently, Moore and others (2007) assessed groundwater use and population growth and summarized problems associated with groundwater development in Douglas County, an ongoing topic of interest for residents and municipal leaders. In neighboring Elbert County (fig. 1), a groundwater-level monitoring network similar to the Douglas County network presented in this report, has been operating since 2015 (Penn and Everett, 2019). This report builds upon initial observations made by Everett (2014), who summarized groundwater-level elevations measured in Douglas County from 2011 through 2013.

Description of Study Area

Douglas County encompasses an 842-square-mile area at the base of the Colorado Front Range Mountains, midway between Denver and Colorado Springs (fig. 1). The county is bounded by the South Platte River and Jefferson County to the west, Arapahoe County to the north, Elbert County to the east, and Teller and El Paso Counties to the south (fig. 1). Douglas County is mostly rural, although the area is experiencing rapid residential and commercial development (Douglas County Department of Community Development, 2019), expanding outward from the Denver metropolitan area and along Interstate 25 (fig. 1). However, parts of the southeast plains and the mountainous southwest corner of the county, largely designated as national forest, remain relatively unpopulated (Douglas County Department of Community Development, 2019). The topography of the county is varied and includes mountains, foothills, ridgelines, mesas, and plains. Vegetation changes with topography. The mountains are characterized by pine, spruce, and fir trees; the foothills by gamble oak, mountain mahogany, and chokecherry; the riparian zones by cottonwood trees, willows, and lush grasses; and the plains by blue grama, switch grass, and winter wheat grasses (Douglas County Department of Community Development, 2019). The South Platte River and its tributaries, Cherry and Plum Creeks, flow north through the county (fig. 1).

Description of the Denver Basin Aquifer System

The western edge of the Denver Basin aquifer system borders the base of the Colorado Front Range Mountains and extends into the eastern plains of Colorado, covering an area of approximately 7,000 square miles (Bauch and others, 2014) (fig. 1). The northernmost extent ends near the city of Greeley in Weld County, and the southern extent passes under the topographic Palmer Divide and ends southeast of Colorado Springs in El Paso County. The eastern edge runs parallel with the eastern borders of Adams, Arapahoe, and Elbert Counties. The basin's western extent bisects Douglas County, along the base of the Colorado Front Range Mountains (fig. 1). The northeastern two-thirds of the county are underlain by the Denver Basin aquifer system, and private well owners draw from one of the principal bedrock aquifers or the surficial alluvial aquifers (Paschke, 2011). Approximately one-third of Douglas County is west of the Denver Basin aquifer system's western edge, outside the study area, and is underlain by granitic bedrock of the mountains (Tweto, 1979).

The bedrock aquifers in the Denver Basin aquifer system have a synorogenic, bowl-like structure composed of Late Cretaceous to Tertiary-age sandstone bedrock separated by unnamed claystone confining units (Fenneman, 1931; Robson, 1987; Paschke, 2011) and bounded at the base by the Cretaceous-age Pierre Shale (fig. 3, table 1). The four principal bedrock aquifers, from youngest (shallowest) to oldest (deepest), are the Dawson aquifer in the Dawson Formation, Denver aquifer in the Denver Formation, Arapahoe aquifer in the Arapahoe Formation, and Laramie-Fox Hills aquifer in the Laramie Formation and Fox Hills Sandstone (fig. 3). The consolidated sediments comprising these aquifers were deposited during different periods of mountain-building and have physical properties (sediment grain size, porosity, specific yield, and hydraulic conductivity) that differ among aquifers and across the basin. Parts of the basin are overlain by unconsolidated alluvial aquifers (fig. 2). In parts of the Denver Basin aquifer system, the Arapahoe and Dawson aquifers are divided by discontinuous confining units into upper and lower aquifers. Across Douglas County, the Arapahoe aquifer is undivided. The Dawson aquifer is divided into upper and lower aquifers in the northeast part of the county (fig. 1). Outcrops of each bedrock formation are along the outer edge of the associated aquifer extent where the aquifers are generally considered unconfined, whereas confined conditions exist towards the interior of the basin in each aquifer where deeper bedrock aquifers are overlain by younger confining units (fig. 3) (Paschke, 2011).

Many studies have previously investigated the extent, thickness, age, and physical properties of each aquifer. The physical characteristics of the Denver Basin bedrock aquifers are summarized in table 1. Studies from which the information in table 1 was acquired are Romero (1976), Kirkham and Ladwig (1979), Schneider (1980), Robson and others (1981a), Robson and others (1981b), Robson (1987), Crifasi (1992), Raynolds and others (2001), Raynolds (2002, 2004), and Paschke (2011). The reader is referred to Everett (2014) for synopsis of the work completed by the aforementioned authors and descriptions of the hydrostratigraphy and depositional conditions of the aquifers.

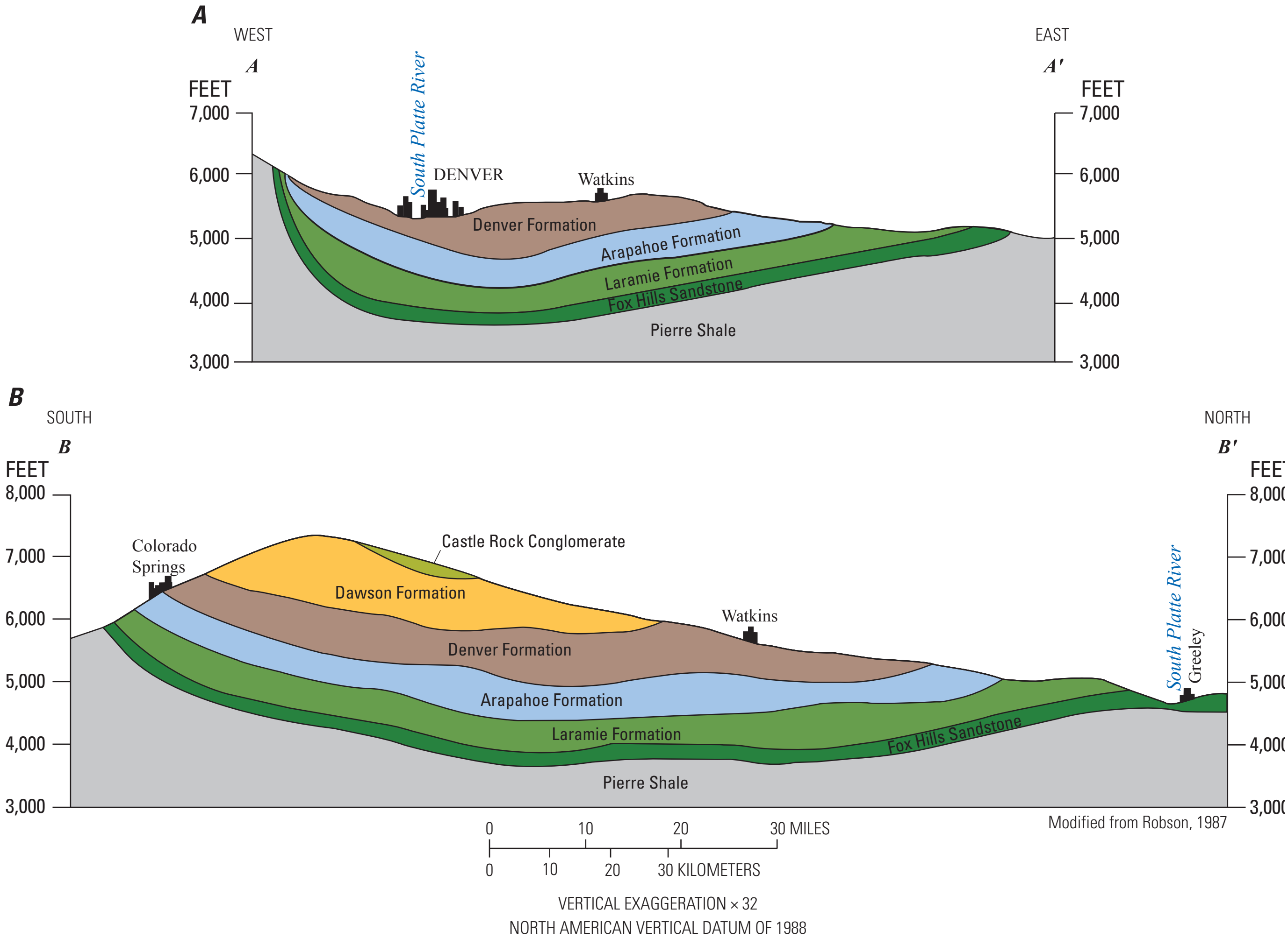

Figure 3. Generalized geologic cross-sections *A*, *A–A′*, west to east, and *B*, *B–B′*, south to north, through the Denver Basin aquifer system. See figure 1 for cross-section locations and table 1 for bedrock aquifer descriptions within each geologic unit.

Study Methods

This section describes how groundwater-level measurements were made and processed, how to access data, the statistical tools used to analyze trends in groundwater-level elevations throughout the county, and how potentiometric-surface and trend maps were created from static groundwater-level elevations.

The Douglas County groundwater monitoring network described in this study was established in the 2011, and the methods related to establishing a groundwater monitoring network—how target areas were identified, study wells were selected, and land-surface elevations were surveyed using a real-time kinetic global positioning system—were described by Everett (2014). All survey data were collected with a common coordinate system, geoid, ellipsoid, and datum. The coordinate system used was Universal Transverse Mercator, zone 13 north, using the horizontal datum North American Datum of 1983 (NAD 83), and the vertical datum North American Vertical Datum of 1988 (NAVD 88), Geoid 03, ellipsoid World Geodetic System.

Groundwater-Level Measurements and Groundwater-Level Elevations

This section presents the methods used for measuring and processing the discrete and time-series groundwater levels analyzed in this study. Groundwater levels are presented as depth to groundwater in feet below land-surface datum (LSD). Calculated groundwater-level elevations are presented in feet above NAVD 88. This report presents data from 36 wells across Douglas County, with at least 2 wells in each of the Denver Basin bedrock aquifers. Well common names include the following abbreviations: UDAW, upper Dawson aquifer well; LDAW, lower Dawson aquifer well; DENV, Denver aquifer well; ARAP, Arapahoe aquifer well; LARA, Laramie-Fox Hills aquifer well; GRNDAW, Grandview Estates Lower Dawson aquifer well; GRNDEV, Grandview Estates, Denver aquifer well.

Table 1. Physical characteristics of bedrock aquifers in the Denver Basin aquifer system.

[See figure 1 for extent and location of aquifers and extent and location of Douglas County. mi^2, square mile; ft, foot; N/A, not applicable]

Bedrock aquifer	Total surface area (mi^2)	Area within Douglas County (mi^2)	Minimum thickness (ft)	Maximum thickness (ft)	Mean water-yielding thickness (ft)	Composition	Age	Top confining layers
Upper Dawson[1]	600	298	100	1,100	100–400	Dawson Formation: interbedded fluvial conglomerate, sandstone, siltstone, shale	Tertiary	N/A—unconfined
Lower Dawson[1]	1,400	488	100	1,100	100–40	Dawson Formation: interbedded fluvial conglomerate, sandstone, siltstone, shale	Tertiary	Clay and shale
Denver[2]	3,200	532	600	1,200	100–300	Denver Formation: interbedded shale, claystone, siltstone, sandstone, coal, and volcanic ash and rocks	Late Cretaceous to early Tertiary	Heterogeneous claystone and shale
Arapahoe[3]	4,700	540	400	700	200–300	Arapahoe Formation: interbedded conglomerate, sandstone, siltstone, shale	Late Cretaceous	Upper Arapahoe Formation fine-grained deposits
Laramie-Fox Hills[4]	7,000	532	10	400	150	Laramie Formation: very fine- to medium-grained sandstone with interstitial silt and clay; Fox Hills Sandstone: very fine-grained silty sandstone and shaly siltstone with interbedded shale	Late Cretaceous	Upper Laramie Formation gray to black shale, coal seams, siltstone, sandstone

[1]Romero, 1976; Robson and others, 1981b; Robson, 1987; Raynolds and others, 2001; Raynolds, 2002; Paschke, 2011.

[2]Romero, 1976; Kirkham and Ladwig, 1979; Robson and others, 1981b; Robson, 1987; Crifasi, 1992; Raynolds and others, 2001; Raynolds, 2002; Paschke, 2011.

[3]Romero, 1976; Robson and others, 1981a; Robson, 1987; Raynolds and others, 2001; Raynolds, 2002; Raynolds, 2004; Paschke, 2011.

[4]Romero, 1976; Schneider, 1980; Robson and others, 1981b; Robson, 1987; Raynolds and others, 2001; Raynolds, 2002; Paschke, 2011.

Discrete Groundwater-Level Measurements and Groundwater-Level Elevations

Groundwater levels were routinely measured in 36 wells during the study period, beginning in April 2011 through June 2019 (table 2). Because of access issues, routine measurements were discontinued recently at three wells (UDAW 1, UDAW 7, and UDAW 8), including one well outfitted with a pressure transducer (UDAW 1) (table 2). For calendar years 2011–14, discrete measurements were made approximately bimonthly (in February, April, June, August, October, and December). Beginning in 2015, measurement frequency was reduced to one measurement per year in February at all wells. The measurement timing in late winter reduces the likelihood of pumping for lawn or garden irrigation. Although this timing does not prevent domestic use, the reduced water use generally decreases stress on the hydraulic system and can provide groundwater-level measurements that are more representative of the system's static conditions. Additional manual measurements were made at 15 wells instrumented with pressure transducers during routine service visits (table 2). The procedures for making discrete groundwater-level measurements are outlined in Cunningham and Schalk (2011), with the exception that a break-away weight was not used because of concerns that the weight could get entangled with pump wiring or piping.

A measuring point (MP) was established on the casing of each well as a consistent point from which to make measurements (fig. 1.1). The height of each MP above the land surface was manually measured. The elevation of each well's MP was determined using the real-time kinetic global positioning system survey, described by Everett (2014). The LSD of each well was calculated by subtracting the well MP height from the MP elevation determined by the survey. Coordinates and elevation of LSD for each well are summarized in table 2. By computing the elevation of LSD for each well with a consistent coordinate system, horizontal datum, and vertical datum, groundwater-level elevations can be calculated and accurately compared across Douglas County.

For most discrete measurements, a calibrated steel tape was lowered down the well to record the depth to groundwater from the well MP (fig. 1.1). In instances where a steel tape could not be used (such as excessive moisture causing fouled readings, erratic levels because of pumping, or difficulties with a well access port), a calibrated electrical tape was used (fig. 1.1). In each instance, the depth to groundwater from the MP was recorded to the nearest 0.01 foot (ft) and corrected for the height of the MP above LSD to give a final reading of measured depth to groundwater below LSD. To determine if the groundwater level measured in the well was static and to follow USGS protocol as a quality-control measure, a second check measurement was made, typically 3–5 minutes after the first measurement. Measurements that differed by 0.02 ft or less were considered static and a reliable measurement.

When the check measurement did not agree with the original measurement, additional measurements were made until the reason for lack of agreement was determined, or results were determined to be reliably representative of field conditions. Subsequent measurements were made to document the status of the groundwater level in the well. If consecutive measurements indicated a rising groundwater level (decreasing depth to groundwater), the well was considered to be recovering from recent pumping, and the highest groundwater level (smallest depth to groundwater) measured during the field visit was assigned a status of "R," indicating recently pumped. Typical reasons for recently pumped wells include water use for lawn irrigation systems, washing machines, or flushing toilets. If consecutive measurements indicated a slowly decreasing groundwater level (increasing depth to groundwater), the well was considered to be affected by one or more wells pumping nearby from the same aquifer, and the highest groundwater level measured during the field visit was assigned a status of "S," indicating nearby pumping. Typical reasons for nearby pumping include agricultural operations or domestic use. If the pump in the well was cycling on and off, the measured depth to groundwater was usually erratic and did not follow a pattern. If the well owners were available, they were asked to temporarily suspend water use during the field visit so that an "R" status could be obtained. If the pump could not be turned off, the highest groundwater level (smallest depth to groundwater) measured during the field visit was given the status of "P," indicating pumping. Static measurements, which were made approximately 80 percent of the time, are ideal for assessing changes and estimating temporal trends— quantified changes through time— in aquifer groundwater levels (appendix 2).

In this report, groundwater-level elevation is calculated from groundwater level below LSD according to the following equation:

$$\begin{aligned} &\textit{Groundwater-level elevation} = \\ &\textit{LSD} - \textit{Water level below LSD} \end{aligned} \tag{1}$$

where

Groundwater-level elevation is groundwater-level elevation, in feet above NAVD 88;

LSD is land-surface datum, in feet above NAVD 88; and

Groundwater level below LSD is measured depth, in feet, to groundwater below land-surface datum.

Time-Series Groundwater-Level Measurements and Groundwater-Level Elevations

Of the 36 wells in the monitoring network, 15 were instrumented with a pressure transducer containing an internal data logger (table 2) (fig. 2). The pressure transducers are vented and rated for a 69-ft range in a freshwater-water column, with a manufacturer accuracy of plus or minus (±) 0.05 percent at 59 degrees Fahrenheit (15 degrees Celsius) (In Situ, Inc., 2020). The transducers are suspended in the well on a vented communication cable that allows the user to download data from the instrument while the transducer remains in place and to use the data directly to calculate depth to water, without needing to correct for barometric pressure. The internal data logger was programmed to record depth to groundwater below LSD every hour, calibrated using a concurrent, static discrete groundwater-level measurement, following the methods described in Cunningham and Schalk (2011).

Each transducer was downloaded, serviced, and calibrated during each site visit. At the time of each discrete groundwater-level measurement, a concurrent instantaneous transducer groundwater-level measurement was recorded. In instances where the transducer measurement had drifted greater than 0.10 ft from the concurrent discrete groundwater-level measurement, the transducer was reset to match the discrete value for depth to groundwater. However, if the groundwater-levels were not static, no attempt was made to reset the transducer. Hourly data were uploaded to the USGS National Water Information System (NWIS) database and processed following USGS guidelines (Freeman and others, 2004). To account for instrument drift, time-series groundwater-level records were corrected to match discrete groundwater-level measurements. To more accurately compare data from different wells, discrete and time-series groundwater-level measurements were converted to groundwater-level elevation using equation 1. Daily mean, minimum, and maximum groundwater-level elevations were computed from the hourly groundwater-level elevation values.

Accessing Data

All discrete and time-series groundwater levels summarized in this report are publicly available through the NWIS database at https://doi.org/10.5066/F7P55KJN (U.S. Geological Survey, 2020) by using the site identification numbers in table 2. The NWIS website provides an interface for accessing site information and data collected by the USGS and is regularly updated to reflect the most current data. Users of the interface can retrieve USGS data by category, region, site number, or many other criteria and can produce tables and graphs for web viewing or export. Data accessible from NWIS can be downloaded in the R statistical software (R Core Team, 2018) using the USGS "dataRetrieval" package (Hirsch and De Cicco, 2015).

Table 2. Well identification and location information and a summary of discrete groundwater-level measurements, April 2011 through June 2019, Douglas County, Colorado.

[Well data can be downloaded using the site identification numbers in the U.S. Geological Survey National Water Information System (NWIS) database https://doi.org/10.5066/F7P55KJN. See figure 2 for well locations. Bold indicates site instrumented with a pressure transducer. NAD 83, North American Datum of 1983; LSD, land-surface datum; ft, foot; NAVD 88, North American Vertical Datum of 1988; bls, below land surface; "R," recently pumped; "S," nearby pumping; "P," pumping; UDAW, upper Dawson aquifer well;°, degrees; ′, minutes; ″, seconds; LDAW, lower Dawson aquifer well; GRNDAW, Grandview Estates, lower Dawson aquifer well; DENV, Denver aquifer well; GRNDEV, Grandview Estates, Denver aquifer well; ARAP, Arapahoe aquifer well; LARA, Laramie-Fox Hills aquifer well]

Site identification number	Well common name	Latitude (NAD 83) (degrees, minutes, seconds)	Longitude (NAD 83) (degrees, minutes, seconds)	Elevation of LSD (ft above NAVD 88)	Well depth (ft bls)	Total measure-ments	Number of static measurements	Number of measurements with status "R"	Number of measurements with status "S"	Number of measurements with status "P"	Mean depth to groundwater below LSD (ft)	Mean groundwater-level elevation (ft above NAVD 88)
391229104421901	UDAW 1[a]	39°12′22.40″	−104°42′18.79″	6,934.52	320	43	35	7	0	1	92.16	6,842.36
392856104424101	UDAW 2	39°28′51.1″	−104°42′41.81″	6,284.27	310	24	18	5	1	0	141.93	6,142.34
392412104434201	UDAW 3	39°24′00.07″	−104°43′41.47″	6,414.87	283	40	34	6	0	0	156.03	6,258.84
392934104414901	UDAW 4	39°29′28.68″	−104°41′45.98″	6,267.98	300	41	35	4	2	0	120.66	6,147.32
392149104415501	UDAW 5	39°21′42.84″	−104°41′53.47″	6,501.66	350	40	22	17	1	0	140.96	6,360.70
392441104394901	UDAW 6	39°24′35.49″	−104°39′46.81″	6,590.31	400	24	24	0	0	0	216.39	6,373.92
391658104453101	UDAW7[b]	39°16′51.02″	−104°45′25.37″	6,808.79	302	22	19	3	0	0	154.55	6,654.24
393252104434701	UDAW 8[c]	39°32′44.61″	−104°43′40.56″	6,195.89	213	22	19	3	0	0	168.79	6,027.21
393226104394401	UDAW 9	39°32′18.18″	−104°40′09.34″	6,285.29	314	43	35	8	0	0	211.31	6,073.98
392916104423601	UDAW10	39°29′10.65″	−104°42′34.58″	6,288.97	320	42	37	5	0	0	114.21	6,174.76
390756104453801	LDAW 2	39°07′50.15″	−104°45′35.11″	7,278.15	180	39	39	0	0	0	68.19	7,209.96
390811104453801	LDAW 3	39°08′05.45″	−104°45′36.86″	7,308.07	300	24	18	6	0	0	124.78	7,183.29
392318104424601	LDAW 4	39°23′13.64″	−104°42′46.06″	6,501.52	723	24	12	12	0	0	565.68	5,935.84
392851104450101	LDAW 5	39°28′44.38″	−104°45′02.28″	6,021.79	530	24	14	10	0	0	207.48	5,814.31
391143104482501	LDAW 6	39°11′37.67″	−104°48′22.89″	7,085.07	205	37	30	7	0	0	41.35	7,043.72
391654104464501	LDAW 7	39°16′48.55″	−104°46′46.54″	6,676.78	345	50	45	3	2	0	87.61	6,589.17
392949104523401	LDAW 8	39°29′41.31″	−104°52′33.56″	6,235.80	468	23	19	4	0	0	386.40	5,849.40
393239104452901	LDAW 9	39°32′34.88″	−104°45′33.98″	5,908.71	285	24	21	3	0	0	165.49	5,743.22
393021104533101	LDAW 10	39°30′14.61″	−104°53′30.83″	6,324.88	620	24	22	1	1	0	480.37	5,844.51
391257104530201	LDAW 11	39°12′49.86″	−104°53′00.55″	6,799.61	240	17	15	2	0	0	89.66	6,709.95
393259104491001	GRNDAW 4	39°32′25″	−104°48′49″	5,816.50	280	47	42	1	4	0	54.11	5,762.39
391656104473001	DENV 1	39°16′43.87″	−104°47′28.54″	6,783.59	600	46	42	4	0	0	151.30	6,632.29
391929104574101	DENV 2	39°19′22.18″	−104°57′40.27″	6,268.94	300	45	29	13	3	0	105.08	6,163.86
391245104525501	DENV 3	39°12′38.72″	−104°52′56.68″	6,822.46	665	22	22	0	0	0	443.17	6,379.29
392115104553501	DENV 4	39°21′09.46″	−104°55′32.44″	6,376.53	480	25	16	9	0	0	230.04	6,146.49
392235105003001	DENV 5	39°22′29.42″	−105°00′30.46″	6,317.29	380	46	19	27	0	0	192.87	6,124.42
393040105003201	DENV 6	39°30′32.91″	−105°00′32.78″	5,716.55	320	40	31	9	0	0	225.12	5,491.43
391212104473801	DENV 7	39°12′02.73″	−104°47′39.07″	7,003.66	900	24	14	10	0	0	408.37	6,595.29
390755104454001	DENV 8	39°07′50.14″	−104°45′40.26″	7,265.13	1,300	23	22	1	0	0	261.84	7,003.29
391936104570101	DENV 10	39°19′31.13″	−104°57′00.44″	6,410.74	404	24	23	1	0	0	234.42	6,176.32
393330104450701	DENV 11	39°33′22.42″	−104°45′07.66″	6,058.29	610	24	22	2	0	0	353.11	5,705.18
393252104492101	GRNDEV 3	39°32′51.83″	−104°49′23.15″	5,864.18	463	48	40	8	0	0	136.28	5,727.90
392853105015001	ARAP 1	39°28′46.00″	−105°01′48.83″	5,789.08	730	23	22	1	0	0	547.11	5,241.97
393120105003101	ARAP 2	39°31′12.83″	−105°00′30.08″	5,750.03	735	23	18	5	0	0	365.42	5,384.61
392522105015001	LARA 1	39°25′15.92″	−105°01′49.28″	6,169.43	601	27	8	19	0	0	120.92	6,048.51
392522105015401	LARA 2	39°25′15.20″	−105°01′53.18″	6,155.85	480	24	10	14	0	0	100.52	6,055.33

[a]Well dropped from routine monitoring in April 2019.

[b]Well dropped from routine monitoring in February 2018.

[c]Well dropped from routine monitoring in February 2017.

Groundwater-Level Elevation Temporal Trend Analysis and Mapping

To evaluate the presence of temporal trends in discrete and time-series groundwater-level elevation data, nonparametric Mann-Kendall (M–K) and nonparametric seasonal Mann-Kendall (sM–K) trend tests were used (Helsel and others, 2020), respectively, using the R statistical software and the “smwrStats” package (Lorenz, 2014) (appendix 3). Trends, quantified changes in groundwater-level elevations through time, were calculated using the Sen slope estimate (Sen, 1968; Hirsch and others, 1982) (appendix 3) with the “smwrStats” package (Lorenz, 2014). These nonparametric statistical methods were chosen because the methods require no assumptions of sample distribution, trend shape, or data continuity when measuring the strength of trends. The reader is referred to appendix 3 for a more detailed description of the statistical methods and the respective equations.

The M–K test (Mann, 1945; Kendall, 1975; Helsel and others, 2020) was applied to discrete winter groundwater-level elevations, manually measured each February at all 36 wells between 2012 and 2019, for a maximum of 8 measurements per site. Only the discrete February measurements were used, herein referred to as “winter measurements,” because measurement frequency at noninstrumented sites (21 out of 36) was reduced to once per year starting in 2015. The measurement timing in late winter reduces the likelihood of pumping for lawn or garden irrigation. Although this timing does not prevent domestic use, the reduced water use generally decreases stress on the hydraulic system and can provide groundwater-level measurements that are more representative of the system’s static state. To reduce bias from recent or nearby pumping, the test was applied to discrete measurements that were determined to be static. Although all 36 wells were measured each winter, some measurements were affected by pumping, which reduced the number of static measurements (n) used in the test (table 3). In two cases, wells LDAW 4 and LARA 1, an insufficient number of static measurements were available to conduct the analysis; therefore, groundwater-level elevations marked with “recently pumped” field notes were included in the trend analysis and noted in the results table (table 3). The Sen slope estimate is referred to as the “trend estimate” or “trend” in groundwater-level elevations (the change in groundwater-level elevations through time) and is reported in feet per year.

Hydrographs (appendix 2) provide a graphical representation of groundwater-level elevations through time. The groundwater-level elevations are denoted by measurement status (static, recently pumped, and pumping) and can be used as a visual comparison to the calculated trends. For the time-series data, the daily maximum elevations were used for reporting (appendix 2), and monthly mean values of these daily maxima were used for trend analysis. The daily maximum groundwater-level elevations were chosen because these elevations tend to best represent periods during the day when pumping is not occurring and has not occurred recently at the well or at nearby wells.

For the time-series measurements, the sM–K test (Hirsch and others, 1982; Helsel and others, 2020) (appendix 3) was utilized to account for seasonal variability in groundwater levels, at the 15 instrumented sites. The sM–K test was applied to the monthly mean values of daily maximum groundwater-level elevations, derived from the time-series data. The sM–K tests account for temporal correlation caused by seasonality by comparing data from a user-defined season only to data from the same season (appendix 3). For the sM–K test, seasons were defined as individual months to minimize effects of temporal correlation among months (for example, January data from one year are only compared to January data from the following years), and the period used in the analysis was January 2012 through June 2019. Trends in time-series data were calculated using seasonal Sen slope estimate, which follows a similar approach to the sM–K test to account for seasonality and was applied to the monthly mean values of groundwater-level elevations.

In addition to statistical tests and estimates of trends in groundwater-level elevations, relative changes in groundwater-level elevations were computed as the difference between the February 2012 and February 2019 groundwater-level elevations for sites with static discrete measurements in both years. These relative differences are not necessarily representative of trends, but the differences indicate relative changes at wells between the beginning and end of the study period and offer a comparison to trend estimates at each well.

For visualization, trend estimates for the upper Dawson, lower Dawson, and Denver aquifers were mapped in the study area by interpolating the trend estimates among wells completed in the same aquifer. These maps are generated solely from the reported data and calculations. An inverse distance weighting function from the Geostatistical Analyst toolbox in ArcMap was applied to interpolate the data (Esri, Inc., variously dated) using default inputs and adding a weight field of $(1-p\text{-value})^2$ to graphically emphasize statistically significant trends. The trend estimate for well LDAW 4 was not included in the interpolation because not enough static measurements were available to calculate a trend estimate reflecting static conditions. Maps of the groundwater-level elevation, also known as potentiometric-surface maps, were created to show the hydraulic head distribution of the different aquifers in the study area. To remove effects of local pumping, only static winter measurements from 2019 were used to produce the maps. The Topo to Raster (default options) and Contour functions in ArcMap Spatial Analyst Toolbox (Esri, Inc., variously dated) were used to derive the hydraulic head distribution and contour lines of equal hydraulic head, respectively.

Table 3. Trend analysis summary of discrete and time-series groundwater-level elevation data, January 2012 through June 2019, Douglas County, Colorado.

[See table 2 and figure 2 for well locations. The discrete data record analyzed was from February 2012 through February 2019, and the time-series data analyzed were from January 2012 through June 2019. Only static measurements were used in the discrete dataset, unless noted otherwise. Mann-Kendall trend tests evaluates the significance of a monotonic trend in the data (Mann, 1945; Kendall, 1975; Helsel and others, 2020), whereas the Sen slope estimator (Sen, 1968; Hirsch and others, 1982) calculates the trend, or change in groundwater-level elevations through time. Statistically significant trends—trends were considered significant if the p-value is less than the defined alpha of 0.1. See "Methods" section and appendix 3 for details of field measurement and statistical methods used. Bold, italicized font indicates trend is significant. n, number of observations used in the analysis; tau, rank correlation coefficient, also known as "Kendall's tau" (Kendall, 1975), which measures the strength of the correlation between time and groundwater-level elevations; *p*-value, probability value, which indicates the level of significance; ft/yr, foot per year; UDAW, upper Dawson aquifer well; --, not calculated; LDAW, lower Dawson aquifer well; GRNDAW, Grandview Estates, lower Dawson aquifer well; DENV, Denver aquifer well; GRNDEV, Grandview Estates, Denver aquifer well; ARAP, Arapahoe aquifer well; LARA, Laramie-Fox Hills aquifer well]

Well common name	Hydrograph appendix figure number	Discrete data				Time-series data		
		Mann-Kendall trend test			Sen slope estimator	Seasonal Mann-Kendall trend test		Seasonal Sen slope estimator
		n	tau	*p*-value	Trend (ft/yr)	tau	*p*-value	Trend (ft/yr)
Upper Dawson aquifer								
UDAW 1	2.1	7	−0.05	1.000	0.00	0.29	0.204	0.10
UDAW 2	2.2	7	0.43	0.230	0.23	--	--	--
UDAW 3	2.3	8	***−0.96***	***0.001***	***−0.25***	***−0.89***	***0.001***	***−0.26***
UDAW 4	2.4	7	0.43	0.230	0.20	0.27	0.163	0.30
UDAW 5	2.5	5	−0.50	0.312	−0.32	−0.06	0.597	−0.02
UDAW 6	2.6	8	−0.50	0.105	−0.09	--	--	--
UDAW 7	2.7	4	0.50	0.470	0.06	--	--	--
UDAW 8	2.8	5	−0.20	0.806	−0.13	--	--	--
UDAW 9	2.9	6	***−0.80***	***0.035***	***−0.21***	***−0.87***	***0.001***	***−0.26***
UDAW 10	2.10	6	0.40	0.339	0.43	***0.61***	***0.024***	***0.57***
Lower Dawson aquifer								
LDAW 2	2.11	8	0.11	0.803	0.23	0.19	0.457	0.41
LDAW 3	2.12	6	0.07	1.000	0.20	--	--	--
LDAW 4[a]	2.13	8	−0.50	0.108	−8.55	--	--	--
LDAW 5	2.14	5	−0.40	0.462	−0.44	--	--	--
LDAW 6	2.15	7	−0.14	0.764	−0.08	0.06	0.824	0.04
LDAW 7	2.16	8	***−0.75***	***0.013***	***−0.31***	***−0.46***	***0.030***	***−0.23***
LDAW 8	2.17	5	−0.60	0.221	−0.50	--	--	--
LDAW 9	2.18	5	0.60	0.221	0.45	--	--	--
LDAW 10	2.19	7	***−1.00***	***0.003***	***−0.85***	--	--	--
LDAW 11	2.20	6	***1.00***	***0.009***	***0.71***	--	--	--
GRNDAW 4	2.21	8	0.43	0.174	0.65	0.29	0.239	–0.64
Denver aquifer								
DENV 1	2.22	6	***−0.87***	***0.024***	***−1.11***	***−0.60***	***0.022***	***−1.06***
DENV 2	2.23	7	***−1.00***	***0.003***	***−0.73***	***−0.93***	***0.001***	***−0.67***
DENV 3	2.24	7	***−0.86***	***0.009***	***−0.15***	--	--	--
DENV 4	2.25	5	***−1.00***	***0.027***	***−0.92***	--	--	--
DENV 5	2.26	6	0.33	0.452	0.77	***0.56***	***0.017***	***1.42***
DENV 6	2.27	7	***−1.00***	***0.003***	***−0.48***	***−1.00***	***0.001***	***−0.57***
DENV 7	2.28	4	0.33	0.734	0.38	--	--	--
DENV 8	2.29	7	***−1.00***	***0.003***	***−5.51***	--	--	--
DENV 10	2.30	7	***−1.00***	***0.003***	***−0.92***	--	--	--
DENV 11	2.31	8	0.29	0.386	0.87	--	--	--
GRNDEV 3	2.32	8	−0.32	0.319	−1.12	−0.09	0.705	−0.59
Arapahoe aquifer								
ARAP 1	2.33	8	***−1.00***	***0.001***	***−2.26***	--	--	--
ARAP 2	2.34	7	0.14	0.764	0.73	--	--	--
Laramie-Fox Hills aquifer								
LARA 1[a]	2.35	8	−0.14	0.711	−0.66	--	--	--
LARA 2	2.36	3	−1.00	0.296	−2.03	--	--	--

[a]Insufficient number of static discrete measurements; both measurements determined to be static and affected by recent pumping used in the trend analysis.

Groundwater-Level Elevations in the Denver Basin Bedrock Aquifers of Douglas County

From April 2011 through June 2019, more than 1,100 discrete and 41,000 time-series groundwater-level measurements were made in the Douglas County groundwater monitoring network. Hydrographs showing groundwater-level elevations through time for each well in the network are provided in appendix 2.

Seasonal Patterns in Discrete and Time-Series Groundwater-Level Elevation Data

In general, groundwater-level elevations were lowest during summer and fall and recovered to higher elevations in winter and spring (appendix 2). Seasonal patterns were clearest in wells with pressure transducers and time-series data, but even wells with only discrete measurements showed seasonal fluctuations in groundwater-level elevations in the early years of the study, when discrete measurements were made bimonthly (for example, well UDAW 2, fig. 2.2). Some wells showed strong seasonal fluctuations of several feet (for example, well DENV 1, fig. 2.22), whereas other wells showed minimal seasonality with fluctuations less than 1 ft during the year (for example, well DENV 6, fig. 2.27). In time-series data, groundwater-level elevations generally were highest during winter and spring and lowest during summer and fall, except for well LDAW 6 (fig. 2.15), which did not have strong seasonal patterns. Seasonal variations are caused by natural processes connected to the land surface, including precipitation and evapotranspiration, which affect timing and amount of aquifer recharge in unconfined aquifer zones (Paschke, 2011). Human activities, such as increased irrigation for agriculture (during the growing season) and domestic pumping (for lawns and gardens), also can affect seasonal variations.

Long-Term Trends in Discrete Groundwater-Level Elevations

For the discrete groundwater-level elevations, the significance of trends between 2012 and 2019 were tested using the M–K test, and trend estimates were calculated using the Sen slope estimator (table 3). A negative trend indicates generally declining groundwater-level elevations in the well through time, and a positive trend indicates generally rising groundwater-level elevations in the well through time. Results of the M–K trend test for the winter static groundwater-level elevations indicate that 13 of the 36 wells exhibited statistically significant temporal trends (table 3). Wells LDAW 4 and LARA 1 had insufficient static measurements to assess trend significance, so recently pumped values were included in the analysis (table 3). Of the 13 wells with significant trends, 12 wells had negative trends in groundwater-level elevations. Only well LDAW 11, in the lower Dawson aquifer, had a significant positive trend of +0.71 foot per year (ft/yr). For all aquifers with significant trends in discrete groundwater-level elevations, the median trends for each aquifer were negative, indicating generally declining groundwater-level elevations in each aquifer (table 4).

The upper Dawson aquifer had significant negative trends at two wells (UDAW 3 and 9), with a median trend of −0.23 ft/yr and a maximum negative trend of −0.25 ft/yr. The lower Dawson aquifer had significant trends at three wells (LDAW 7, LDAW 10, and LDAW 11), with a median trend of −0.31 ft/yr, a maximum negative trend of −0.85 ft/yr, and a maximum positive trend of +0.71 ft/yr. Significant negative trends were present at wells LDAW 7 and LDAW 10, whereas a positive trend was present at LDAW 11. The negative trends for wells LDAW 7 and LDAW 10 exceeded −0.30 ft/yr (table 3). The Denver aquifer had 7 wells with significant negative trends (DENV 1, DENV 2, DENV 3, DENV 4, DENV 6, DENV 8, and DENV 10), with a median trend of −0.92 ft/yr and a maximum negative trend of −5.51 ft/yr. In the Arapahoe aquifer, ARAP 1 had a significant trend of −2.26 ft/yr, and the Laramie-Fox Hills aquifer had no wells with significant trends. Of the 12 wells that had significant negative trends in static groundwater-level elevations, 9 wells had negative trends that were less than 1 ft/yr (for example, well UDAW 3 had a negative trend of −0.25 ft/yr). Only three wells, DENV 1 (−1.11 ft/yr), ARAP 1 (−2.26 ft/yr), and DENV 8 (−5.51 ft/yr), showed negative trends exceeding 1 ft/yr (table 4). In the Denver aquifer, the magnitude of negative groundwater-level elevation trends had a larger range than the other aquifers, ranging from −0.15 to −5.51 ft/yr, with five of the seven negative trends exceeding −0.50 ft/yr (table 4).

The magnitude of significant trends is relatively consistent, considering the producing aquifer and well locations throughout Douglas County (fig. 4). An exception is well LDAW 11 along the western edge of the Denver Basin aquifer system, (fig. 4), which had the only positive trend. Otherwise, wells in proximity and producing from the same aquifer generally agree in trend significance and direction. For example, in the Denver aquifer wells DENV 2, DENV 4, and DENV 10, which are less than 3 miles apart, displayed trends of −0.73, −0.92, and −0.92 ft/yr, respectively. Additionally, in the upper Dawson aquifer wells UDAW 3 and UDAW 9, which are 10 miles apart, displayed trends of −0.25 and −0.21 ft/yr, respectively. Both sets of wells show negative trends (with medians of −0.92 and −0.23 ft/yr, respectively) and are in relatively low-density residential areas covered by the RWADC (RWADC, 2019b). The three Denver aquifer wells represent confined aquifer conditions, whereas the upper Dawson aquifer wells represent unconfined aquifer conditions;

although both sets of wells exhibit statistically significant negative trends in groundwater-level elevations. The one Arapahoe well (ARAP 1) with a statistically significant trend (−2.26 ft/yr) is under confined conditions and is in the northwest corner of the county (fig. 4).

Differences in the hydraulic head distribution from two or more points in time can highlight areas where groundwater-level elevations are rising or declining but may or may not have trends that are statistically significant. Relative changes in discrete groundwater-level elevations between the February 2012 and February 2019 static measurements are presented in table 5. The negative changes at 16 wells represent a relative decline in groundwater-level elevation between the two measurements, whereas the 8 wells with a positive change represent a rise in groundwater-level elevation. The largest groundwater-level elevation decline between the 2 years was at well ARAP 1 (−15.61 ft) in the Arapahoe aquifer, but the lower Dawson and the Denver aquifers also had multiple wells with declines in groundwater-level elevation exceeding −5.0 ft. The largest rise between static groundwater-level elevations (+3.26 ft) was at well DENV 5, along the western edge of the Denver aquifer (fig. 2).

Of the four aquifers that had wells with static measurements in February 2012 and February 2019, three aquifers had wells with increases in groundwater-level elevation (upper Dawson, lower Dawson, and Denver aquifers). In each of these aquifers, at least two wells had a positive change and at least three wells had a negative change between the 2012 and 2019 groundwater-level elevations. Both wells in the Arapahoe aquifer had declines in the discrete groundwater-level elevations (table 5). Changes were not computed for wells in the Laramie-Fox Hills aquifer because two static measurements for 2012 and 2019 were not available. Relative changes do not represent statistically significant trends in groundwater-level elevation at a given well but offer a point of comparison for trend results.

Table 4. Statistically significant trends in discrete static groundwater-level elevations, February 2012 through February 2019, Douglas County, Colorado.

[See table 2 and figure 2 for well locations. Only statistically significant trends and results are listed in this table. Mann-Kendall trend tests evaluates the significance of a monotonic trend in the data (Mann, 1945; Kendall, 1975; Helsel and others, 2020), whereas the Sen slope estimator (Sen, 1968; Hirsch and others, 1982) calculates the trend, or change in groundwater-level elevations through time. Trends were considered significant if the p-value is less than the defined alpha of 0.1. See “Methods” section and appendix 3 for details of statistical methods used. tau, rank correlation coefficient, also known as “Kendall's tau” (Kendall, 1975; Helsel and others, 2020), which measures the strength of the correlation between time and groundwater-level elevations; *p*-value, probability value, which indicates the level of significance; ft/yr, foot per year; UDAW, upper Dawson aquifer well; LDAW, lower Dawson aquifer well; DENV, Denver aquifer well; ARAP, Arapahoe aquifer well]

Well common name	Mann-Kendall test		Sen slope estimator
	tau	*p*-value	Trend (ft/yr)
Upper Dawson aquifer (significant trend median, −0.23)			
UDAW 3	−0.96	0.001	−0.25
UDAW 9	−0.80	0.035	−0.21
Lower Dawson aquifer (significant trend median, −0.31)			
LDAW 7	−0.75	0.013	−0.31
LDAW 10	−1.00	0.003	−0.85
LDAW 11	1.00	0.009	0.71
Denver aquifer (significant trend median, −0.92)			
DENV 1	−0.87	0.024	−1.11
DENV 2	−1.00	0.003	−0.73
DENV 3	−0.86	0.009	−0.15
DENV 4	−1.00	0.027	−0.92
DENV 6	−1.00	0.003	−0.48
DENV 8	−1.00	0.003	−5.51
DENV 10	−1.00	0.003	−0.92
Arapahoe aquifer (significant trend median, −2.26)			
ARAP 1	−1.00	0.001	−2.26

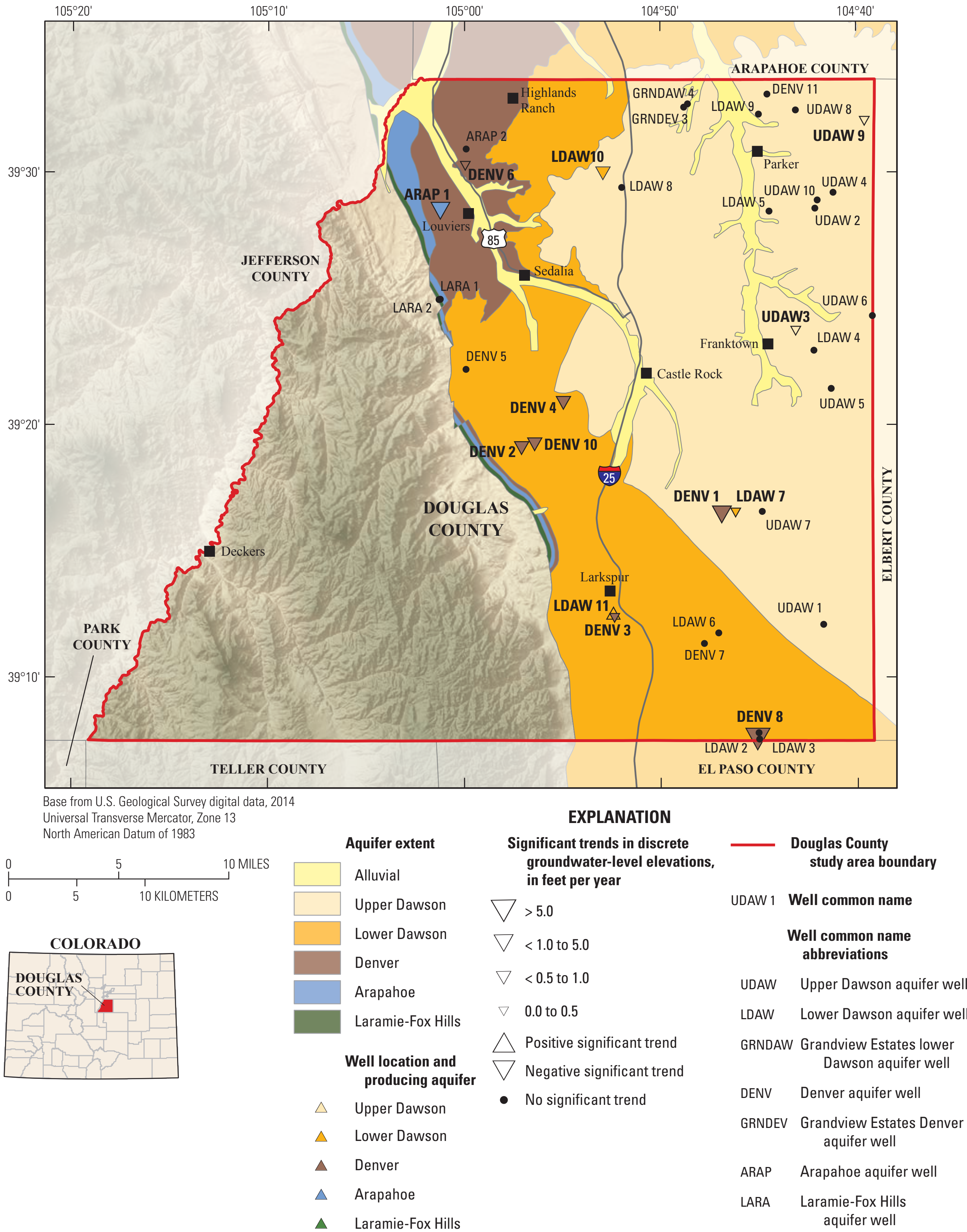

Figure 4. Distribution of significant trends in discrete groundwater-level elevation, by aquifer, Douglas County, Colorado.

Long-Term Trends in Time-Series Groundwater-Level Elevations

Hydrographs of time-series groundwater-level elevations from the 15 instrumented wells were in general agreement with discrete groundwater-level elevations measured at the same well (see hydrograph appendix figure number listed in table 3).

The sM–K test results of the time-series data are compared with the M–K test results from the discrete groundwater-level elevations in table 3, and discrete and time-series measurements are displayed on hydrographs in appendix 2. Significant trends in the time-series groundwater-level elevation data agreed with the significant trends' direction and magnitude calculated from discrete data. If significant trends were indicated in the discrete and in the time-series data for a well, the trend estimates for the two datasets differed by less than 0.1 ft/yr (table 3). Some wells displayed significant trends in the time-series data but not the discrete data (wells UDAW 10 and DENV 5) (table 3). Continued monitoring and more static measurements at these wells may increase the likelihood of significant trend occurrence in discrete datasets at these wells in the future.

Three wells screened in the upper Dawson aquifer had significant trends in the time-series groundwater-level elevation data (wells UDAW 3, UDAW 9, and UDAW 10). Wells UDAW 3 and UDAW 9 had the same trend estimate, −0.26 ft/yr, for time-series data. A spike observed in daily data for UDAW 3 (appendix figure 2.3) in May 2014 was caused by days of continuous pumping but did not greatly affect the monthly mean used in the trend calculation, and thus did not affect the trend's significance or estimate. In contrast, well UDAW 10 had a significant positive trend in the time-series data (+0.57 ft/yr), although the discrete data positive trend for well UDAW 10 was not significant. Only one well screened in the lower Dawson aquifer, LDAW 7, had a statistically significant trend in the time-series data of −0.23 ft/yr. Of the five wells screened in the Denver aquifer with available time-series measurements, four wells displayed significant trends (wells DENV 1, DENV 2, DENV 5, and DENV 6), with the three negative trend estimates exceeding 0.5 ft decline per year (wells DENV 1, DENV 2, and DENV 6) (table 3). Only one well screened in the Denver aquifer (well DENV 5) had a significant positive trend (+1.42 ft/yr) in the time-series data and is approximately 0.5 mile from the western edge of the Denver Basin aquifer system (fig. 2). The discrete data trend at well DENV 5 was also positive but was not statistically significant. No wells in the Arapahoe or Laramie-Fox Hills aquifers have pressure transducers and time-series data (table 3).

Potentiometric-Surface and Trend Maps

Maps of the groundwater-level elevation, also known as the potentiometric-surface maps, were derived from static discrete groundwater levels measured in February 2019 in the upper Dawson, lower Dawson, and Denver aquifers (figs. 5, 6, and 7, respectively). The potentiometric surface can be used to show the general direction of groundwater flow. Groundwater flow is from areas of high hydraulic head (higher groundwater-level elevation) to areas of low hydraulic head (lower groundwater-level elevation); flow direction is assumed to be generally perpendicular to the contours. The February 2019 potentiometric surfaces for the three aquifers are displayed using 100-ft contour intervals, and groundwater-level elevation trends in each aquifer are mapped with spatial weighting that takes trend significance into account.

Based on the derived static potentiometric-surface maps for February 2019, groundwater-level elevations in the upper Dawson aquifer are highest east of Franktown (fig. 5*A*) along the eastern edge of the county, and lower groundwater-level elevations are east of Parker. From the 2019 data, groundwater flow is generally from south to north in the upper Dawson aquifer. In the lower Dawson aquifer, groundwater flow is generally from south to north (fig. 6*A*). Groundwater elevations are highest in the southeast and lowest in the northwest in the Denver aquifer, and groundwater flow is from the southeast to the northwest (fig. 7*A*). General flow direction patterns across the three aquifers are similar to earlier observations across Douglas County (Everett, 2014).

The trends in discrete groundwater-level elevations (2012–19) were mapped for the upper Dawson, lower Dawson, and Denver aquifers (figs. 5, 6, and 7, respectively). Trends of the upper Dawson aquifer show slight negative changes (groundwater-level elevation declines) of less than 0.5 ft/yr to the east of Franktown and slight positive trends of less than 0.5 ft/yr southeast of the town of Parker (fig. 5*B*). These changes show similar patterns to difference maps derived in western Elbert County (Penn and Everett, 2019), which showed relative increases and decreases between April 2015 and 2018 in upper Dawson groundwater levels of less than 1 ft. However, the two sets of derived maps represent different periods of record and times of the year, and the two sets do not overlap in spatial coverage. Trends mapped in the lower Dawson aquifer varied within the county, with the greatest negative trends southeast of Highlands Ranch (fig. 6*B*). Slightly upward trends are indicated at wells in the northern edge of the county and the southwestern edge of the county. The only well with a statistically significant positive trend is in the southwestern edge of the aquifer. Unlike the other wells with positive trends to the north, this well (LDAW 11) is within the unconfined part of the lower Dawson aquifer (fig. 4), and recharge might contribute to the statistically significant upward trend. In the Denver aquifer, negative trends were observed across the county with greater negative trends to the southeast, although the significant negative trend in well DENV 8 has a large effect on the interpolation (fig. 7*B*).

Across Douglas County, proximal locations of wells with and without significant trends may indicate local influences on groundwater-level elevations, such as local water use and management or the presence of localized recharge zones, especially in areas where the aquifers are unconfined and receive greater recharge (Paschke, 2011). For example, three wells with statistically significant positive trends in either the discrete data (LDAW 11) (fig. 4) or the time-series data (DENV 5 and UDAW 10) (table 3) are in areas of potential recharge. Wells LDAW 11 and UDAW 10 are wells producing from unconfined aquifers, and well DENV 5 is less than 1 mile from the western edge of the basin (fig. 2).

Table 5. Values and differences in static discrete groundwater-level elevations, February 2012 and 2019, Douglas County, Colorado.

[See table 2 and figure 2 for well locations. Only static groundwater-level elevations listed. GW–L, groundwater-level; ft, foot; NAVD 88, North American Vertical Datum of 1988; UDAW, upper Dawson aquifer; --, data not available or unable to be calculated; LDAW, lower Dawson aquifer well; GRNDAW, Grandview Estates lower Dawson aquifer well; DENV, Denver aquifer well; GRNDEV, Grandview Estates, Denver aquifer well; ARAP, Arapahoe aquifer well; LARA, Laramie-Fox Hills aquifer well]

Well common name	2012		2019		Difference (ft)
	Date	GW–L elevation (ft above NAVD 88)	Date	GW–L elevation (ft above NAVD 88)	
Upper Dawson aquifer					
UDAW 1	2/1/2012	6,843.96	--	--	--
UDAW 2	2/10/2012	6,147.56	2/22/2019	6,148.10	0.54
UDAW 3	2/2/2012	6,260.24	2/22/2019	6,258.43	−1.81
UDAW 4	2/2/2012	6,153.61	2/22/2019	6,153.89	0.28
UDAW 5	2/1/2012	6,374.94	2/22/2019	6,372.65	−2.29
UDAW 6	2/2/2012	6,375.05	2/22/2019	6,373.92	−1.13
UDAW 7	2/2/2012	6,654.72	--	--	--
UDAW 8	2/10/2012	6,028.30	--	--	--
UDAW 9	--	--	2/22/2019	6,073.95	--
UDAW 10	2/10/2012	6,176.39	2/22/2019	6,178.19	1.80
Lower Dawson aquifer					
LDAW 2	2/1/2012	7,210.93	2/21/2019	7,210.63	−0.30
LDAW 3	2/1/2012	7,184.53	--	--	--
LDAW 4	2/2/2012	5,921.82	--	--	--
LDAW 5	--	--	2/22/2019	5,823.55	--
LDAW 6	2/1/2012	7,044.88	2/21/2019	7,043.54	−1.34
LDAW 7	2/2/2012	6,592.36	2/21/2019	6,590.12	−2.24
LDAW 8	2/9/2012	5,855.51	2/21/2019	5,844.77	−10.74
LDAW 9	2/10/2012	5,748.35	2/22/2019	5,750.25	1.90
LDAW 10	2/9/2012	5,849.38	2/21/2019	5,842.30	−7.08
LDAW 11	--	--	2/20/2019	6,713.69	--
GRNDAW 4	2/10/2012	5,766.63	2/25/2019	5,768.40	1.77
Denver aquifer					
DENV 1	2/2/2012	6,636.26	2/21/2019	6,629.20	−7.06
DENV 2	2/9/2012	6,167.41	2/20/2019	6,161.98	−5.43
DENV 3	2/1/2012	6,379.57	2/25/2019	6,378.60	−0.97
DENV 4	2/9/2012	6,151.95	2/20/2019	6,145.44	−6.51
DENV 5	2/9/2012	6,134.28	2/20/2019	6,137.54	3.26
DENV 6	2/9/2012	5,492.98	2/20/2019	5,489.69	−3.29
DENV 7	2/1/2012	6,600.99	2/21/2019	6,601.74	0.75
DENV 8	--	--	2/21/2019	6,978.23	--
DENV 10	--	--	2/20/2019	6,171.80	--
DENV 11	2/10/2012	5,719.52	2/22/2019	5,722.24	2.72
GRNDEV 3	2/10/2012	5,741.82	2/25/2019	5,733.06	−8.76
Arapahoe aquifer					
ARAP 1	2/9/2012	5,247.00	2/20/2019	5,231.39	−15.61
ARAP 2	2/9/2012	5,389.08	2/20/2019	5,388.28	−0.80
Laramie-Fox Hills aquifer					
LARA 1	2/9/2012	6,066.15	--	--	--
LARA 2	2/9/2012	6,068.89	--	--	--

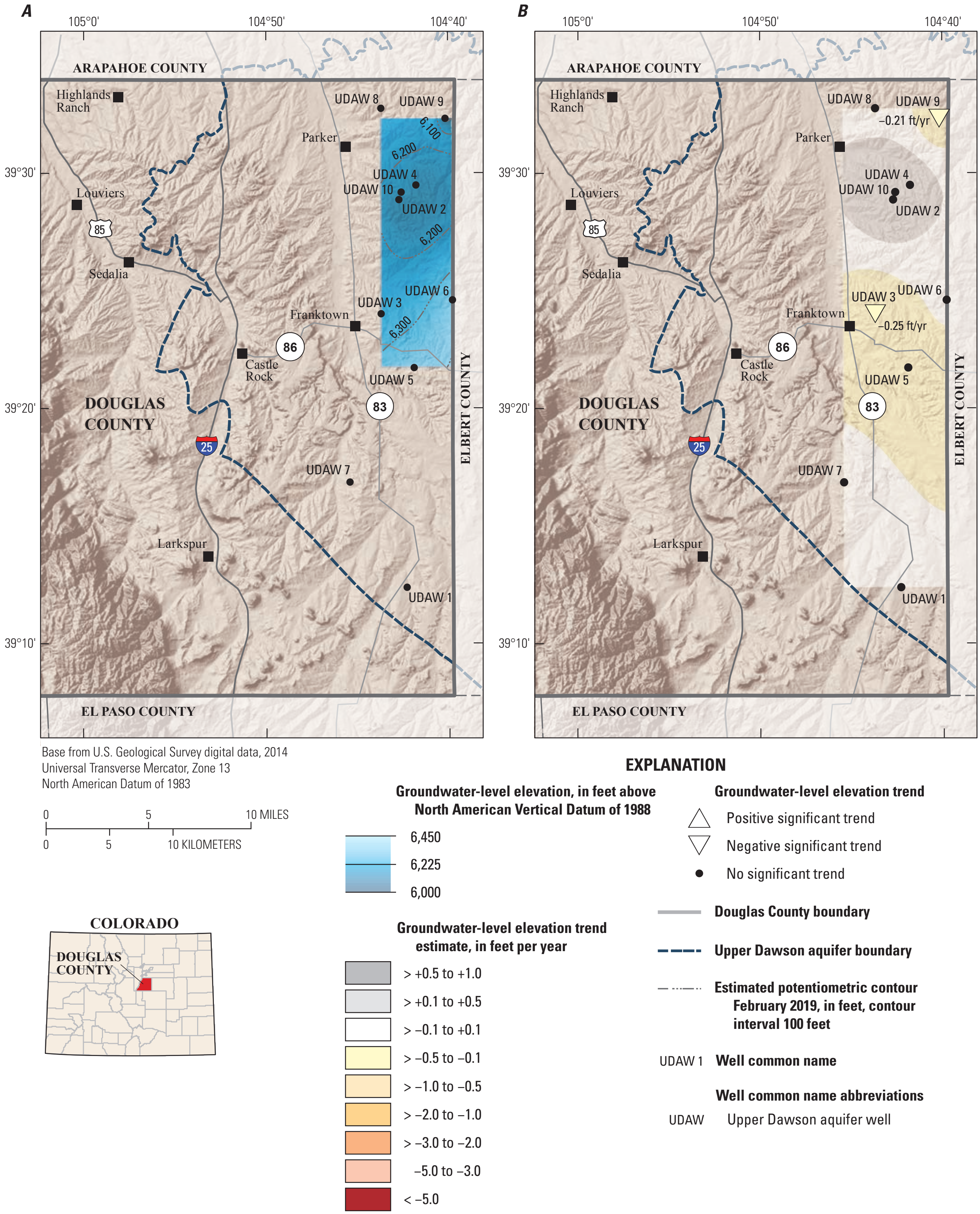

Figure 5. Estimates of potentiometric-surface elevations and groundwater-level elevation trends for the upper Dawson aquifer, Douglas County, Colorado. *A*, estimated potentiometric surface of the upper Dawson aquifer, February 2019. *B*, groundwater-level elevation trend estimates for the upper Dawson aquifer, 2012–19.

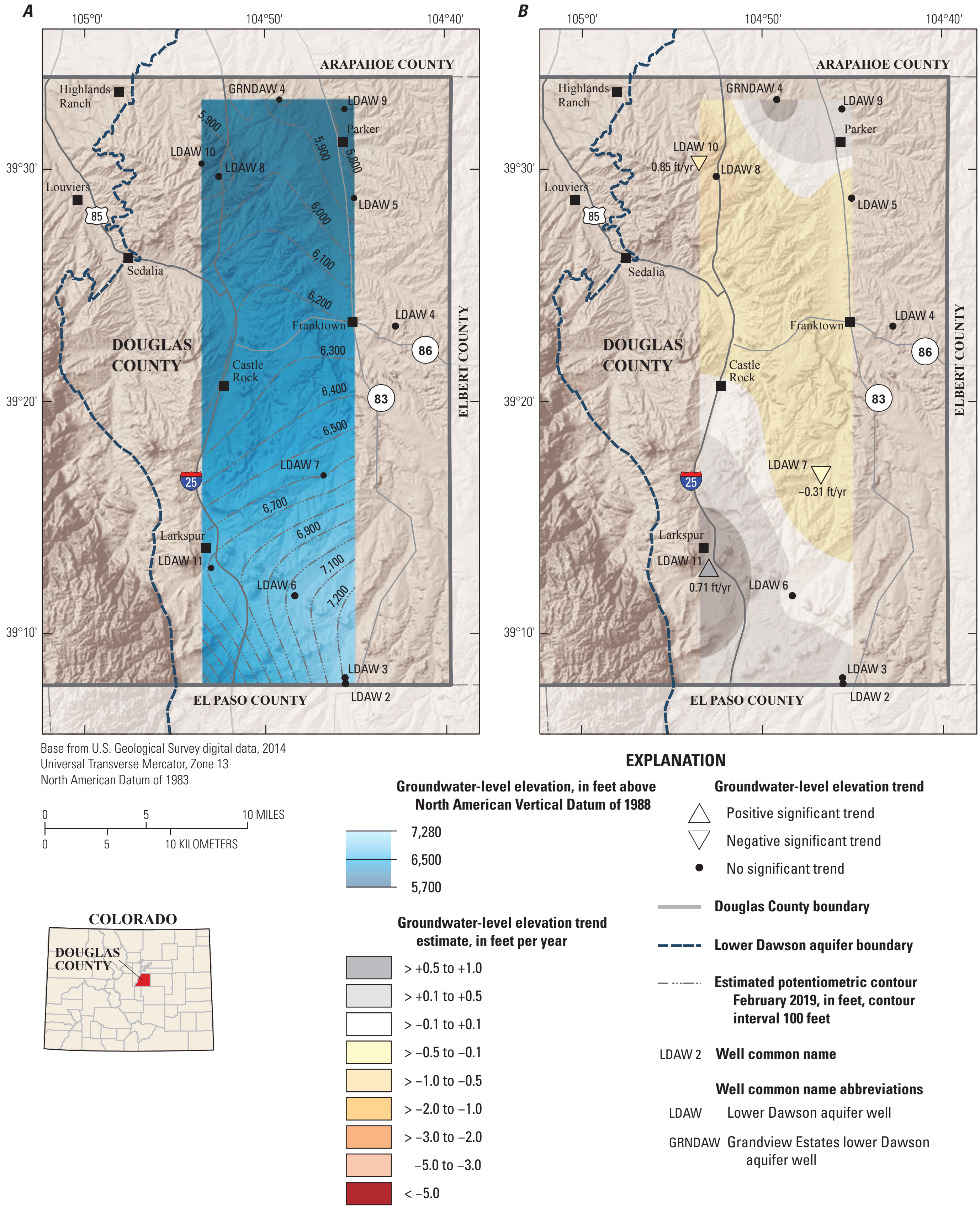

Figure 6. Estimates of potentiometric-surface elevations and groundwater-level elevation trends for the lower Dawson aquifer, Douglas County, Colorado. *A*, estimated potentiometric surface of the lower Dawson aquifer, February 2019. *B*, groundwater-level elevation trend estimates for the lower Dawson aquifer, 2012–19.

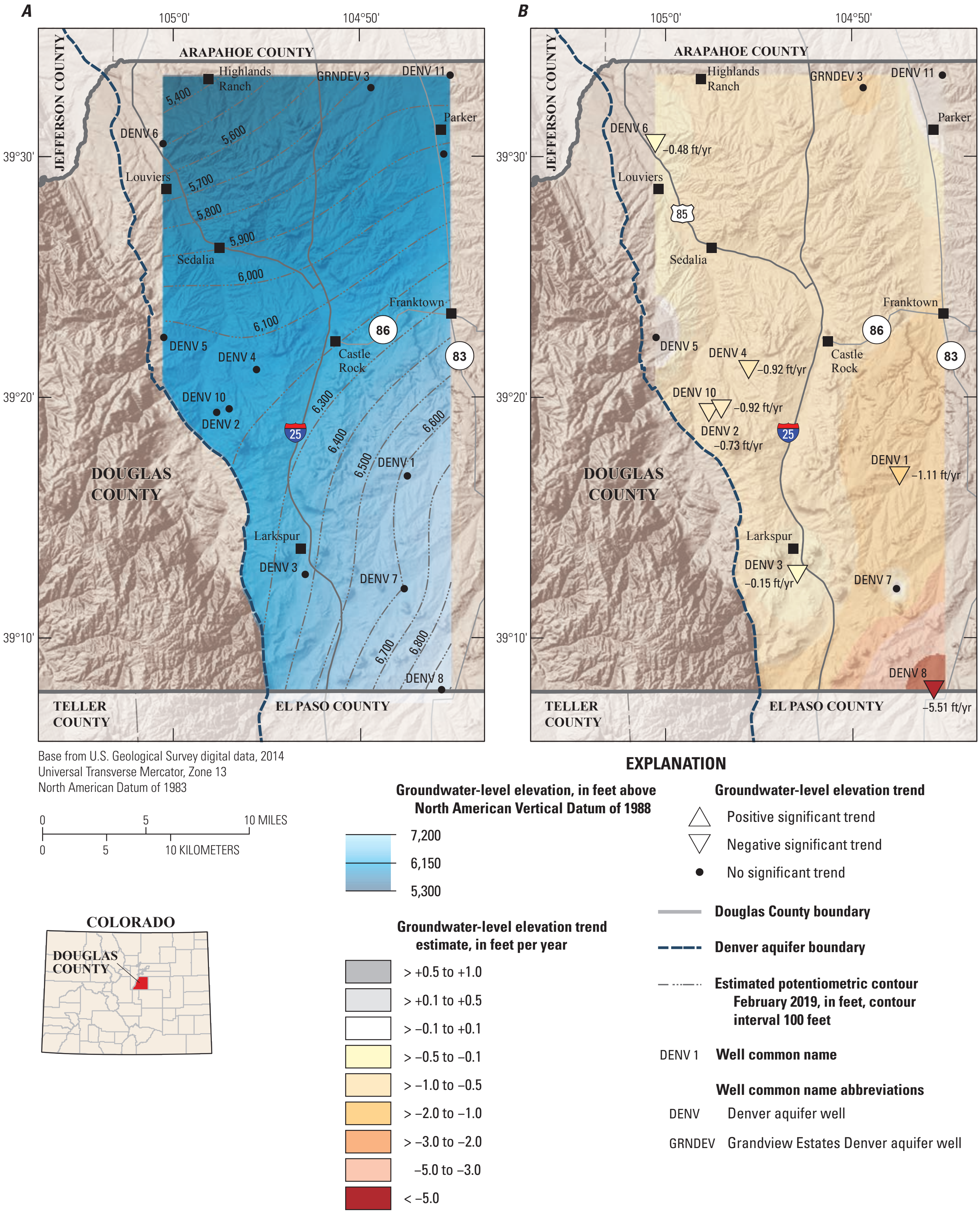

Figure 7. Estimates of potentiometric-surface elevations and groundwater-level elevation trends for the Denver aquifer, Douglas County, Colorado. *A*, estimated potentiometric surface of the Denver aquifer, February 2019. *B*, groundwater-level elevation trend estimates for the Denver aquifer, 2012–19.

Future Research Needs

Changes and trends in groundwater-level elevations are important for informing local water-resource managers and for guiding future monitoring efforts. Continued monitoring and additional static measurements at wells with no significant trends in this study would provide more data points for the trend analysis and may increase the number of wells with statistically significant trends in the future. Additionally, continued monitoring and future analyses of measurements would help elucidate if trends are consistent and persist beyond the study period. Groundwater levels in several wells in this study exhibit interannual periods of rise and decline outside of the normal seasonal variation, for example well LDAW 2 (fig. 2.11). Long-term monitoring at these wells and additional comparisons with water use and recharge patterns may provide insight on the cause of these patterns and if the patterns persist beyond the study period.

A regional study and analysis that combines data from groundwater monitoring networks of the Denver Basin aquifer system in Douglas and Elbert Counties could provide a better understanding of how groundwater levels are changing regionally beyond the Douglas County border. Both counties have had a recent increase in development and have rural areas where residents are reliant on domestic wells. According to the CDWR well permit database (Colorado Division of Water Resources, 2019), from January 2012 through June 2019, within Douglas and Elbert Counties, 626 new domestic water-supply wells were constructed in the upper and lower Dawson aquifers, 264 wells were constructed in the Denver aquifer, 71 wells were constructed in the Arapahoe aquifer, and 23 wells were constructed in the Laramie-Fox Hills aquifer. Continued groundwater monitoring is key to understanding the effect of former and future water-use on aquifer response, recovery, and long-term sustainability (Ruybal and others, 2019a, b). The regional study could produce regional groundwater-level trend maps focusing on monitoring networks with overlapping periods of record. Regional potentiometric-surface and hydraulic-head difference maps from wells with common data collection periods would be more comparable across county boundaries and may provide more insight into the relations among population increase, development, groundwater use, and groundwater-level elevation changes. A regional study and consolidation of available well data could provide additional calibration data to update and improve the Denver Basin groundwater model.

Summary

Douglas County is one of the fastest growing counties in Colorado, and the development of the county, as well as the rapid development of neighboring counties, have generated increased demand on groundwater resources. Groundwater in Douglas County is withdrawn from the four principal Denver Basin bedrock, from shallowest to deepest, the Dawson aquifer (divided administratively into “upper” and “lower” Dawson aquifers in Douglas County), the Denver aquifer, the Arapahoe aquifer, and the Laramie-Fox Hills aquifer. Increases in demand have raised questions about groundwater availability and sustainability. Municipal and domestic water users in Douglas County rely on groundwater from the bedrock aquifers in the Denver Basin aquifer system as part of their water supply. The U.S. Geological Survey, in cooperation with the Rural Water Authority of Douglas County, began a study in 2011 to assess the groundwater resources of the Denver Basin bedrock aquifers within the county. The purpose of the study is to assess the groundwater resources of the Denver Basin bedrock aquifers within the county by establishing and maintaining a groundwater monitoring network and by analyzing the groundwater levels of the Denver Basin bedrock aquifers throughout Douglas County.

The primary purpose of this report is to present a summary of groundwater levels measured during the study period (2011–19) and present results from statistical analyses of changes in groundwater-level elevations, reported above the land-surface datum, North American Vertical Datum of 1988, through time. This report presents data from 36 wells across Douglas County, with at least 2 wells in each of the Denver Basin bedrock aquifers. Of the 36 wells, 15 were instrumented with pressure transducers that record groundwater-level measurements at hourly intervals, and these data were temporally aggregated into time-series records. During 2011, wells were added to the monitoring network in phases, so that the start dates of the well records were noncontemporaneous. To keep temporal analysis among wells consistent, the periods of record used in statistical analyses were from February 2012 through February 2019 for the discrete data and from January 2012 through June 2019 for the time-series data.

Groundwater levels were routinely measured in 36 wells between April 2011 and June 2019. During the analysis period, January 2012 through June 2019, changes and trends in groundwater-level elevations in each well and aquifer were evaluated using a variety of metrics. Trends in static discrete groundwater-level elevations measured in February of each year and monthly mean values of daily maximum groundwater-level elevations in time-series data were tested for significance using the nonparametric Mann-Kendall trend test and seasonal Mann-Kendall trend test, respectively. Trends were calculated in feet per year using the nonparametric Sen slope estimate. In addition to statistical tests, relative changes in groundwater-level elevations were computed as the difference between the February 2012 and February 2019 groundwater-level elevations for sites with static discrete measurements in each period. Maps of the groundwater-level elevation, also known as the potentiometric-surface maps, were derived from static discrete groundwater levels measured in February 2019 in the upper Dawson, lower Dawson, and Denver aquifers.

Four aquifers, the upper Dawson, lower Dawson, Denver, and Arapahoe, had some wells with rises in calculated groundwater-level elevations, but most wells showed water-level declines on the basis of statistically significant trends and the relative differences in static groundwater-level elevations between the February 2012 and February 2019 measurements. Neither of the two wells in the Laramie-Fox Hills aquifer showed significant trends in groundwater-level elevations, and these wells had few static discrete measurements, precluding a comparison between 2012 and 2019 static groundwater-level elevations. Of the 13 wells in the upper Dawson, lower Dawson, Denver, and Arapahoe aquifers with significant trends in discrete groundwater-level elevation measurements, 12 wells demonstrated negative trends during the study period. The upper Dawson, lower Dawson, Denver, and Arapahoe aquifers had median significant trends of −0.23, −0.31, −0.92, and −2.26 feet per year (ft/yr), respectively, in the discrete groundwater-level elevations. Although the Arapahoe aquifer had the greatest negative median trend, this median only represents one well with significant trends. Otherwise, the Denver aquifer had the next greatest negative trend, with a median trend of −0.92 ft/yr. The magnitudes of negative groundwater-level elevation trends were greatest in the Denver aquifer, with one well having a trend of −5.51 ft/yr, and five of the seven wells having significant negative trends greater than −0.50 ft/yr. Significant trends observed in upper Dawson wells indicated declines that were less than −0.30 ft/yr. In the lower Dawson aquifer, two wells had negative trends, and both negative trends exceeded −0.30 ft/yr. However, the only statistically significant positive trend in discrete groundwater-level elevations was observed in the lower Dawson well near the southwest edge of the extent of the aquifer, and this well is under unconfined conditions.

Significant trends in time-series groundwater-level elevations agreed with significant trends in discrete groundwater-level elevations; for all wells with statistically significant trends in discrete and in time-series of groundwater-level elevation data, trend estimates from the two records were within 0.1 ft/yr of each other. However, two wells exhibited significant trends in time-series data but not in static discrete data. A longer study period and more static discrete measurements could increase the frequency of statistically significant trends in discrete data.

Potentiometric-surface maps of the upper Dawson, lower Dawson, and Denver aquifers for February 2019 indicate that groundwater flow is generally from south to north in each aquifer. Relative changes among static groundwater elevations measured in February 2012 and February 2019 were calculated by taking the difference between the two measurements. Of the four aquifers that had wells with static measurements in February 2012 and February 2019, three aquifers had at least two wells with an increase and three wells with a decrease in groundwater-level elevation (upper Dawson, lower Dawson, and Denver aquifers). The two wells in the Arapahoe aquifer showed decreases in groundwater-level elevation, and neither of the two wells in the Laramie-Fox Hills aquifer had enough static measurements to compute a difference. However, relative differences between two measurements are not necessarily representative of trends but, instead, offer a point of comparison to calculated trends.

Results of this study could guide future groundwater monitoring in the county and aid in long-term planning of water resources. Results also could be used for a regional study of groundwater-level elevations in the Denver Basin aquifer system to provide additional calibration data for the Denver Basin groundwater flow model.

References Cited

Bauch, N.J., Musgrove, M., Mahler, B.J., and Paschke, S.S., 2014, The quality of our Nation's waters—Water quality in the Denver Basin aquifer system, Colorado, 2003–05: U.S. Geological Survey Circular 1357, 100 p., accessed September 2019 at https://dx.doi.org/10.3133/cir1357.

Colorado Division of Water Resources, 2019, Colorado Division of Water Resources permit search website, accessed September 30, 2019, at https://dwr.state.co.us/Tools/WellPermits.

Colorado Water Conservation Board, 2004, South Platte Decision Support System ground-water component phase 1, task 44.2—Denver Basin region water level technical memorandum, July 30, 2004: Colorado Water Conservation Board, 27 p.

Colorado Water Conservation Board, 2006, South Platte Decision Support System ground-water component phase 3, task 44.2—Denver Basin region water level technical memorandum, November 28, 2006: Colorado Water Conservation Board, 65 p., accessed April 2, 2020, at https://dnrftp.state.co.us/DWR/HydroGeology/Denver_Basin_Atlases_Complete/SPDSS/spdss44-2_20061128.pdf.

Crifasi, R.R., 1992, Alluvial architecture of Laramide orogenic sediments Denver Basin, Colorado: The Mountain Geologist, v. 29, p. 19–27.

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 September 2019 at https://doi.org/10.3133/tm1A1.

Douglas County, 2019, Water Supply: Douglas County water supply website, accessed September 27, 2019, at https://www.douglas.co.us/water/water-supply/.

Douglas County Demographic Summary, 2019, Douglas County Community Development Department, accessed September 27, 2019, at https://www.douglas.co.us/documents/douglas-county-demographics-summary.pdf/.

Douglas County Department of Community Development, 2019, Douglas County 2040 Comprehensive Master Plan: Douglas County, Colo., Douglas County Department of Community Development, Planning Services Division, 141 p., accessed September 27, 2019, at https://www.douglas.co.us/land/comprehensive-master-plan/.

Esri, Inc., variously dated, ArcGIS desktop 10.5, version 10.5.0.6491: Redlands, Calif., Esri, Inc.

Everett, R.R., 2014, Groundwater levels in the Denver Basin bedrock aquifers of Douglas County, Colorado, 2011–2013: U.S. Geological Survey Scientific Investigations Report 2014–5172, 45 p. [Also available at https://doi.org/10.3133/sir20145172.]

Fenneman, N.M., 1931, Physiography of the western United States: New York, McGraw Hill, 534 p.

Flor, A.D., 2017, Groundwater levels in the Denver Basin bedrock aquifers: Colorado Division of Water Resources, Department of Natural Resources, 10 p., accessed September 27, 2019, at https://dwr.state.co.us/Tools/GroundWater/RunBasinReport?pub=DENVER%20BASIN.

Freeman, L.A., Carpenter, M.C., Rosenberry, D.O., Rousseau, J.P., Unger, R., and McLean, J.C. 2004, Use of submersible pressure transducers in water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 8, chap. A3, 52 p., accessed October 29, 2019, at https://doi.org/10.3133/twri08A3.

Graham, G., and Van Slyke, G., 2004, Development of the regulatory framework for Denver Basin aquifers: The Mountain Geologist, v. 41, no. 4, p. 153–160.

Helsel, D.R., Hirsch, R.M., Ryberg, K.R., Archfield, S.A., and Gilroy, E.J., 2020, Statistical methods in water resources: U.S. Geological Survey Techniques and Methods, book 4, chapter A3, 458 p., accessed June 2020 at https://doi.org/10.3133/tm4a3. [Supersedes USGS Techniques of Water-Resources Investigations, book 4, chapter A3, version 1.1]

Hillier, D.E., Brogden, R.E., and Schneider, P.A., Jr., 1978, Hydrology of the Arapahoe aquifer in the Englewood–Castle Rock area south of Denver, Denver Basin, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I 1043, 2 sheets, accessed September 2019 at https://doi.org/10.3133/i1043.

Hirsch, R.M., and De Cicco, L.A., 2015, User guide to exploration and graphics for RivEr Trends (EGRET) and data retrieval—R packages for hydrologic data (version 2.0, February 2015): U.S. Geological Survey Techniques and Methods, book 4, chap. A10, 93 p. [Also available at https://doi.org/10.3133/tm4A10.]

Hirsch, R.M., Slack, J.R., and Smith, R.A., 1982, Techniques of trend analysis for monthly water quality data: Water Resources Research, v. 18, no. 1, p. 107–121. [Also available at https://doi.org/10.1029/WR018i001p00107.]

In-Situ, Inc., 2020, Level TROLL® 400, 500 & 700 Data Loggers spec sheet: Fort Collins, Colo., In-Situ, Inc., 2 p., accessed June 2, 2020, at https://in-situ.com/pub/media/support/documents/LevelTROLL_SS.pdf.

Kendall, M.G., 1975, Rank correlation methods, 4th ed.: London, Charles Griffen, p. 272.

Kirkham, R.M., and Ladwig, L.R., 1979, Coal resources of the Denver and Cheyenne Basins, Colorado: Colorado Geological Survey Resource Series 5, 70 p., 5 pls.

Lorenz, D.L., 2014, General tools for hydrologic data and trend analysis: U.S. Geological Survey, accessed October 29, 2019, at https://github.com/USGS-R/smwrStats.

Mann, H.B., 1945, Nonparametric tests against trend: Econometrica, v. 13, no. 3, p. 245–259. [Also available at https://doi.org/10.2307/1907187.]

McConaghy, J.A., Chase, G.H., Boettcher, A.J., and Major, T.J., 1964, Hydrogeologic data of the Denver Basin, Colorado: Colorado Water Conservation Board, Basic-Data Report no. 15, 224 p.

Moore, J.E., Raynolds, R.G., and Dechesne, M., 2007, Bedrock aquifers and population growth in the Denver Basin, Colorado, USA: Episodes, v. 30, no. 2, p. 115–118. [Also available at https://doi.org/10.18814/epiiugs/2007/v30i2/006.]

Paschke, S.S., ed., 2011, Groundwater availability of the Denver Basin aquifer system, Colorado, U.S. Geological Survey Professional Paper 1770, 274 p. [Also available at https://doi.org/10.3133/pp1770.]

Penn, C.A., and Everett, R.R., 2019, Groundwater-level elevations in the Denver Basin bedrock aquifers of Elbert County, Colorado, 2015–18: U.S. Geological Survey Scientific Investigations Report 2019–5014, 50 p. [Also available at https://doi.org/10.3133/sir20195014.]

Pottorff, E.T., and Horn, A., 2013, Groundwater levels in the Denver Basin bedrock aquifers, 2013: Colorado Division of Water Resources, 198 p, accessed June 2, 2020, at https://dnrweblink.state.co.us/dwr/ElectronicFile.aspx?docid=2769885&dbid=0.

R Core Team, 2018, R—A language and environment for statistical computing: Vienna, Austria, R Foundation for Statistical Computing, accessed August 1, 2018, at https://www.R-project.org/.

Raynolds, R.G., 2002, Upper Cretaceous and Tertiary stratigraphy of the Denver Basin, Colorado: Rocky Mountain Geology, v. 37, no. 2, p. 111–134. [Also available at https://doi.org/10.2113/gsrocky.37.2.111.]

Raynolds, R.G., 2004, Stratigraphy and water levels in the Arapahoe aquifer, Douglas County area, Denver Basin, Colorado: The Mountain Geologist, v. 41, no. 4, p. 195–210.

Raynolds, R.G., Johnson, K.R., Arnold, L.R., Farnham, T.M., Fleming, R.F., Hicks, J.F., Kelley, S.A., Lapey, L.A., Nichols, D.J., Obradovich, J.D., and Wilson, M.D., 2001, The Kiowa core—A continuous drill core through the Denver Basin bedrock aquifers at Kiowa, Elbert County, Colorado: U.S. Geological Survey Open-File Report 01–0185, 72 p. [Also available at https://doi.org/10.3133/ofr01185.]

Robson, S.G., 1987, Bedrock aquifers in the Denver Basin, Colorado—A quantitative water-resources appraisal: U.S. Geological Survey Professional Paper 1257, 73 p. [Also available at https://doi.org/10.3133/pp1257.]

Robson, S.G., Romero, J.C., and Zawistowski, S., 1981a, Geologic structure, hydrology, and water quality of the Arapahoe aquifer in the Denver Basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA–647, scale 1:500,000, 3 sheets. [Also available at https://doi.org/10.3133/ha647.]

Robson, S.G., Wacinski, A., Zawistowski, S., and Romero, J.C., 1981b, Geologic structure, hydrology, and water quality of the Laramie–Fox Hills aquifer in the Denver Basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas, HA–650, Scale 1:500,000, 3 sheets. [Also available at https://doi.org/10.3133/ha650.]

Romero, J.C., 1976, Ground-water resources of the bedrock aquifers of the Denver Basin: Denver, Colo., Colorado Division of Water Resources Report, 109 p.

Rural Water Authority of Douglas County [RWADC], 2019a, Rural Water Authority of Douglas County mission: Rural Water Authority of Douglas County, Colorado, web page, accessed September 30, 2019, at http://www.rwadc.org/.

Rural Water Authority of Douglas County [RWADC], 2019b, Rural water authority of Douglas County service area, water providers and wells: Rural Water Authority of Douglas County, Colorado, web page, accessed September 30, 2019, at http://www.rwadc.org/images/Rural-Water-Providers-Esize.2.pdf.

Ruybal, C.J., Hogue, T.S., and McCray, J.E., 2019a, Evaluation of groundwater levels in the Arapahoe aquifer using spatiotemporal regression kriging: Water Resources Research, v. 55, no. 4, p. 2820–2837. [Also available at https://doi.org/10.1029/2018WR023437.]

Ruybal, C.J., Hogue, T.S., and McCray, J.E., 2019b, Assessment of groundwater depletion and implications for management in the Denver Basin Aquifer System: Journal of the American Water Resources Association, v. 55, no. 5, p. 1130–1148. [Also available at https://doi.org/10.1111/1752-1688.12755.]

Schneider, P.A., Jr., 1980, Water-supply assessment of the Laramie–Fox Hills aquifer in parts of Adams, Boulder, Jefferson, and Weld Counties, Colorado: U.S. Geological Survey Open-File Report 80–327, 21 p. [Also available at https://doi.org/10.3133/ofr80327.]

Sen, P.K., 1968, Estimate of the regression coefficient based on Kendall's tau: Journal of the American Statistical Association, v. 63, no. 324, p. 1379–1389. [Also available at https://doi.org/10.1080/01621459.1968.10480934.]

South Metro Water Supply Authority [SMWSA], undated, Master plan overview—2016 regional master plan update: South Metro Water Supply Authority, 20 p., accessed September 27, 2019, at https://southmetrowater.org/application/files/9615/7867/2371/MP-Publication-Final.pdf.

South Metro Water Supply Authority [SMWSA], 2020, Strength through partnerships: South Metro Water Supply Authority web page, accessed April 2, 2020, at https://southmetrowater.org/.

Tweto, O., 1979, MI–16 Geologic Map of Colorado: Denver, Colo., Miscellaneous Investigations, Colorado Geological Survey, Department of Natural Resources, Scale 1:500,000, 1 sheet. [Also available at https://coloradogeologicalsurvey.org/publications/tweto-geologic-map-colorado-1979.]

U.S. Census Bureau, 1995, Population of Counties by Decennial Census: 1900 to 1990. U.S. Census Bureau, accessed June 2, 2020, at https://www.census.gov/population/cencounts/co190090.txt.

U.S. Geological Survey, 2020, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed January 8, 2020, at https://doi.org/10.5066/F7P55KJN.

Wireman, M., and Romero, J.C., 1989, Bibliography of geology and ground water geology for the Denver Basin, Colorado: Denver, Colo., Colorado Division of Water Resources Office of the State Engineer, 12 p.

Appendix 1. Groundwater-Well Measurement Diagram

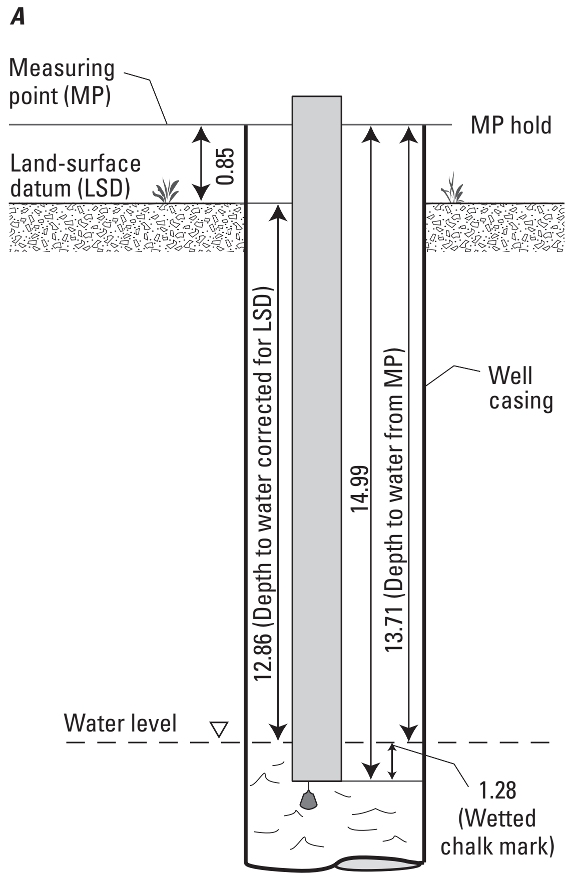

Figure 1.1. Diagram showing example measurement point and groundwater-level measurement using *A*, a calibrated steel tape with chalk, and *B*, a calibrated electrical tape. Modified from Cunningham and Schalk, 2011 (values are in feet).

Reference Cited

Cunningham, W., 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 September 2019 at https://doi.org/10.3133/tm1A1.

Appendix 2. Hydrographs Showing Groundwater-Level Elevation Through Time for Wells in the Douglas County Groundwater-Level Monitoring Network

Hydrographs showing groundwater-level elevation through time for each well in this study are presented in this appendix (figs. 2.1 through 2.36). Measurement periods differ but are generally from April 2011 through June 2019 for discrete measurements and are during summer or fall 2011 through June 2019 for time-series measurements. Daily maximum groundwater-level elevation, in feet above North American Vertical Datum of 1988, is plotted for time-series measurements. Daily median and minimum values were not plotted, but data are available; see the “Accessing Data” section. Discrete measurement symbols differ by measurement status; see “Study Methods” section for a description of the status codes. Well common names include the following abbreviations: UDAW, upper Dawson aquifer well; LDAW, lower Dawson aquifer well; DENV, Denver aquifer well; ARAP, Arapahoe aquifer well; LARA, Laramie-Fox Hills aquifer well; GRNDAW, Grandview Estates lower Dawson aquifer well; GRNDEV, Grandview Estates, Denver aquifer well.

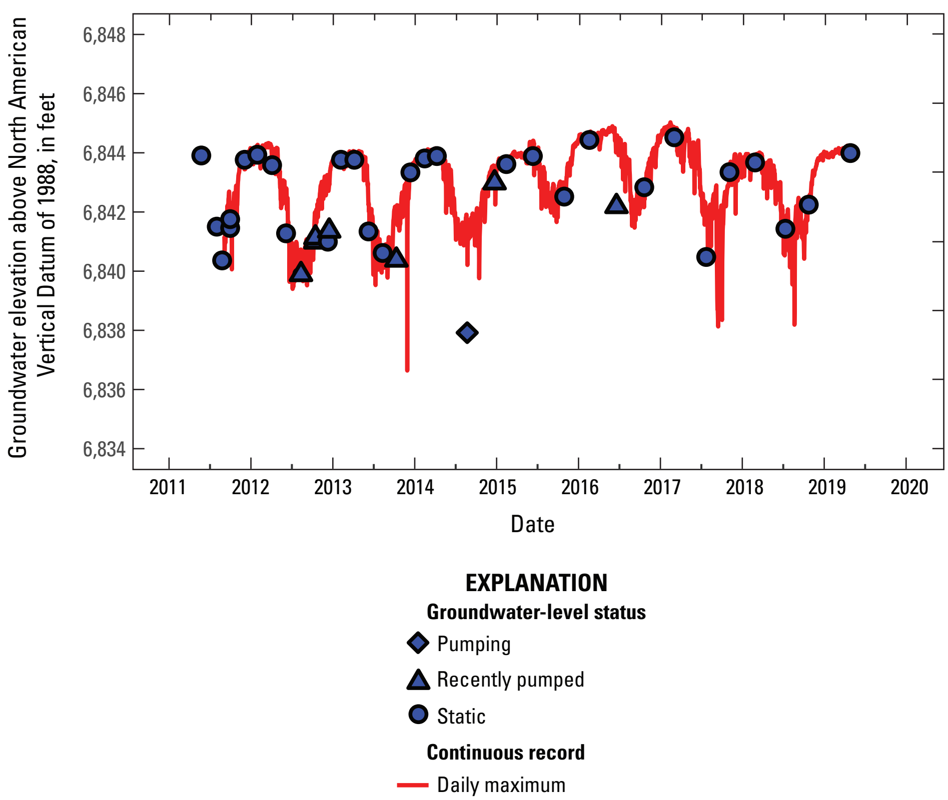

Figure 2.1. Groundwater-level hydrograph for well UDAW 1, U.S. Geological Survey site number 391229104421901, Douglas County, Colorado.

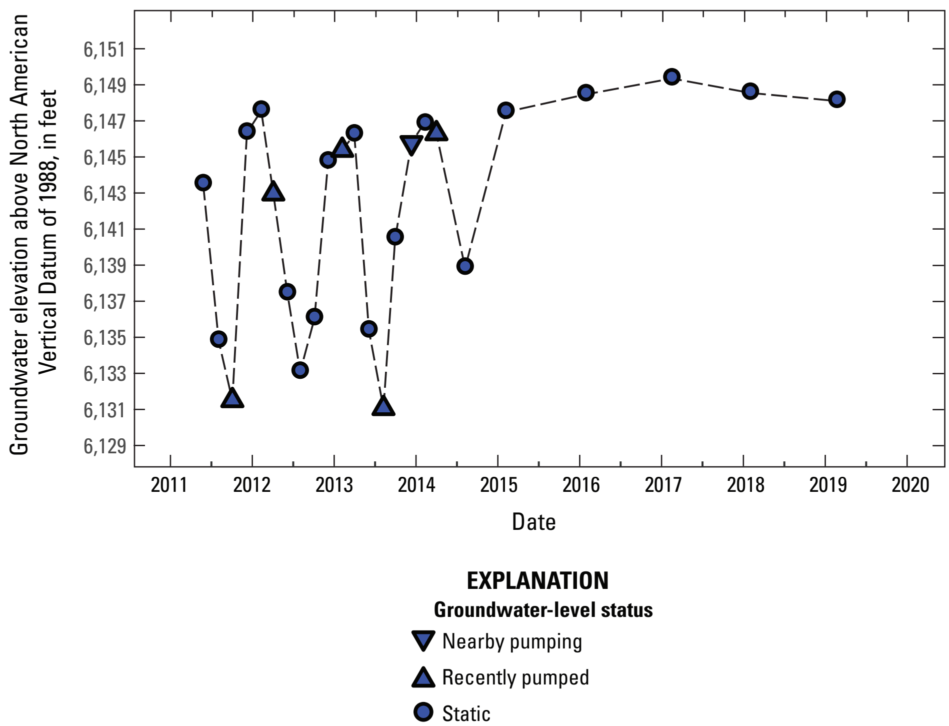

Figure 2.2. Groundwater-level hydrograph for well UDAW 2, U.S. Geological Survey site number 392856104424101, Douglas County, Colorado.

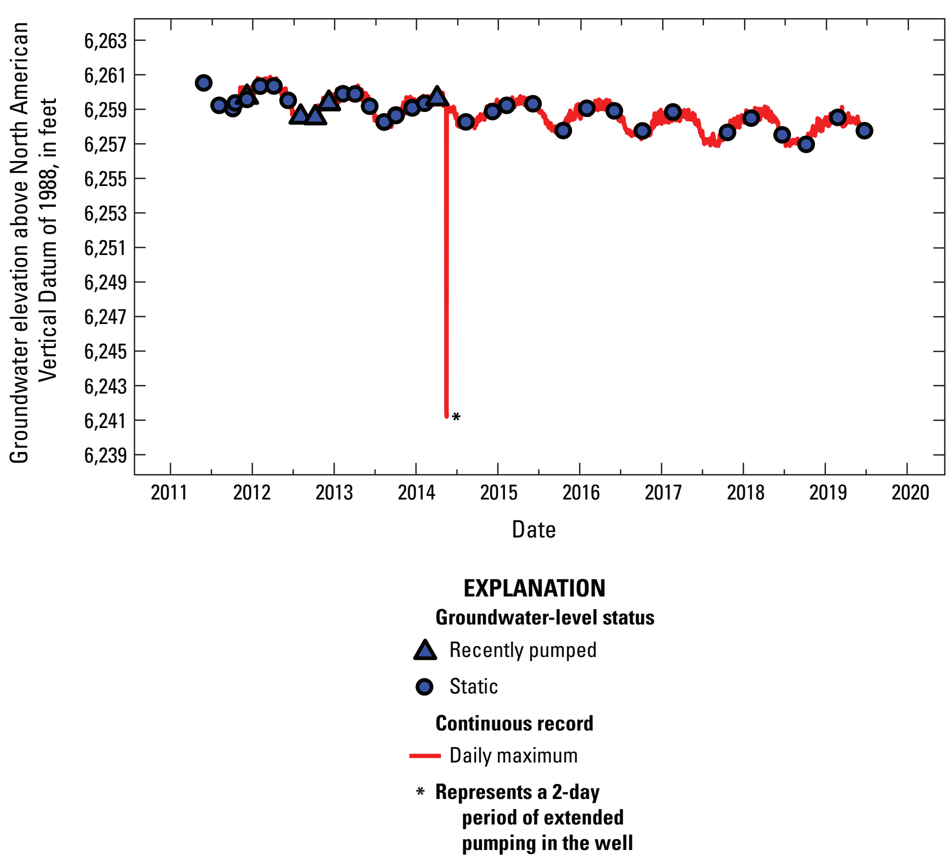

Figure 2.3. Groundwater-level hydrograph for well UDAW 3, U.S. Geological Survey site number 392412104434201, Douglas County, Colorado.

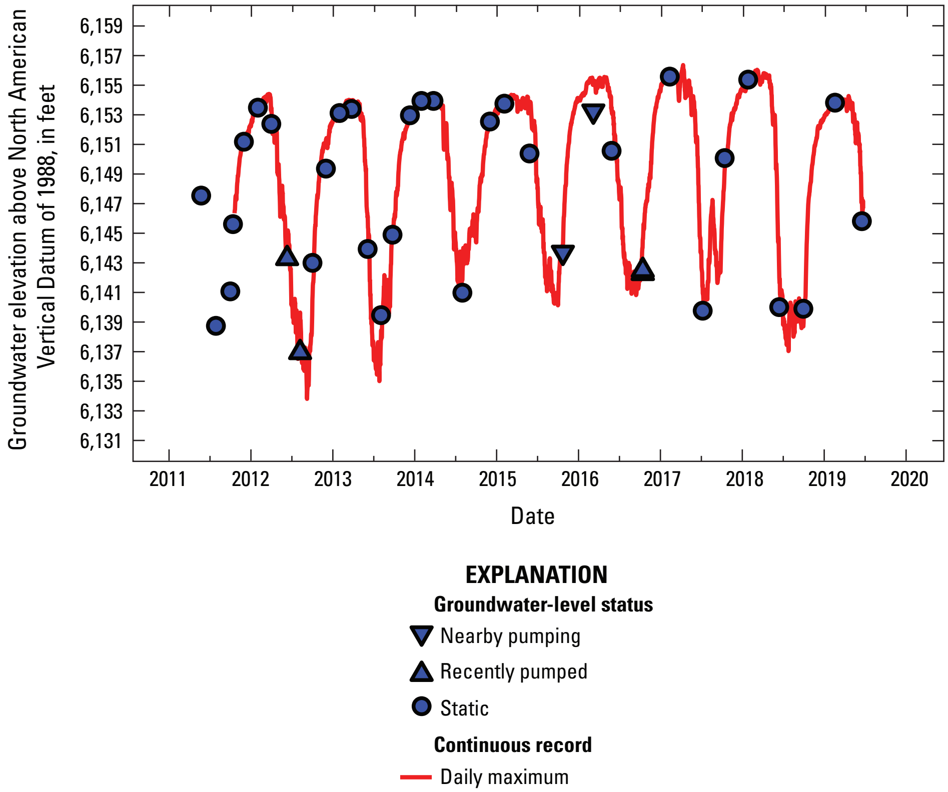

Figure 2.4. Groundwater-level hydrograph for well UDAW 4, U.S. Geological Survey site number 392934104414901, Douglas County, Colorado.

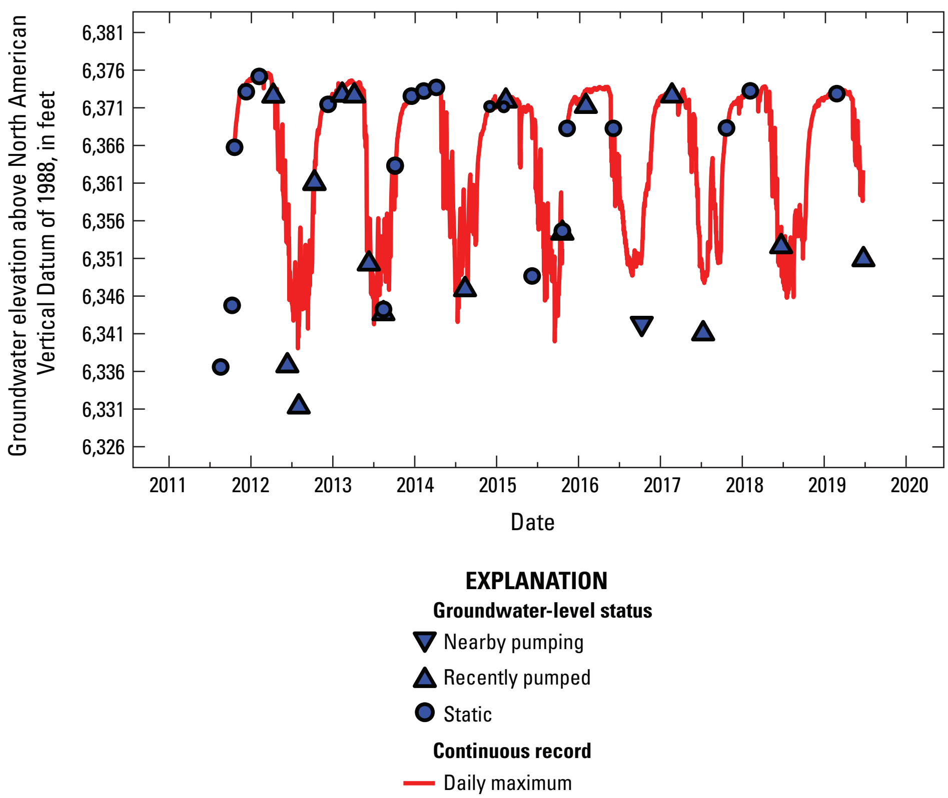

Figure 2.5. Groundwater-level hydrograph for well UDAW 5, U.S. Geological Survey site number 392149104415501, Douglas County, Colorado.

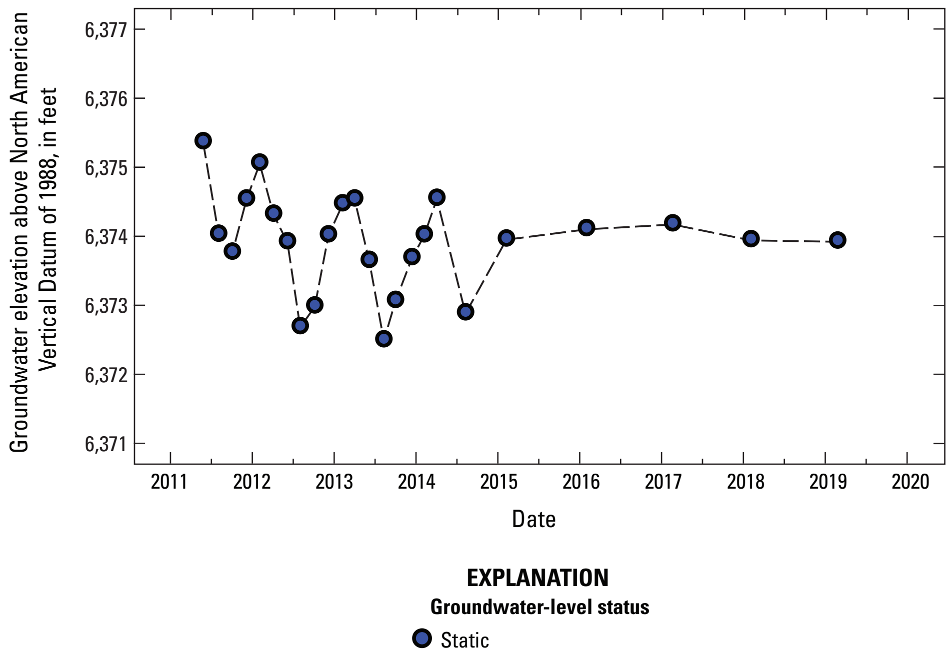

Figure 2.6. Groundwater-level hydrograph for well UDAW 6, U.S. Geological Survey site number 392441104394901, Douglas County, Colorado.

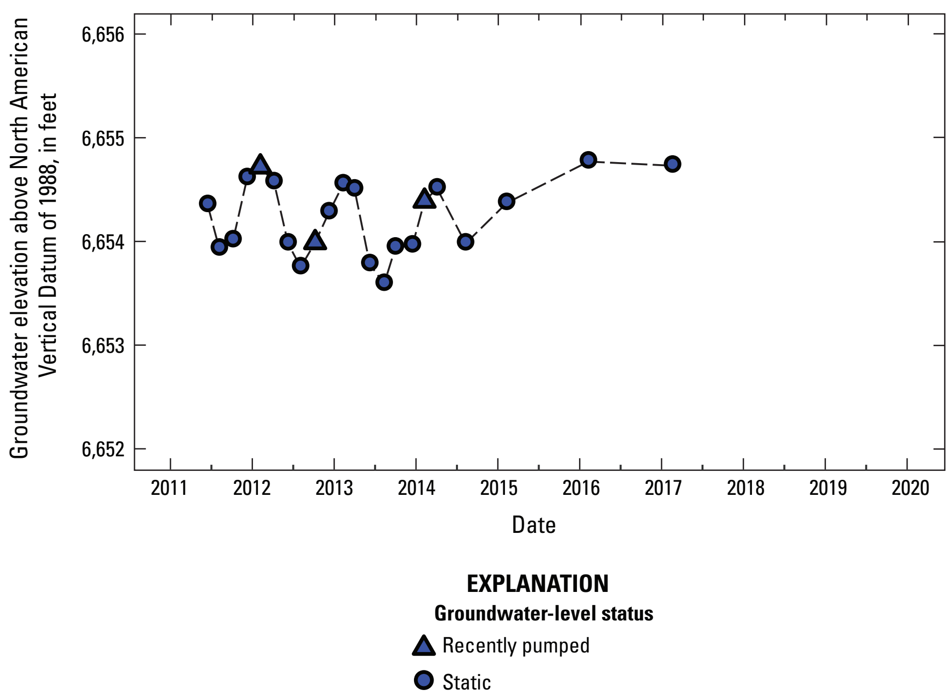

Figure 2.7. Groundwater-level hydrograph for well UDAW 7, U.S. Geological Survey site number 391658104453101, Douglas County, Colorado.

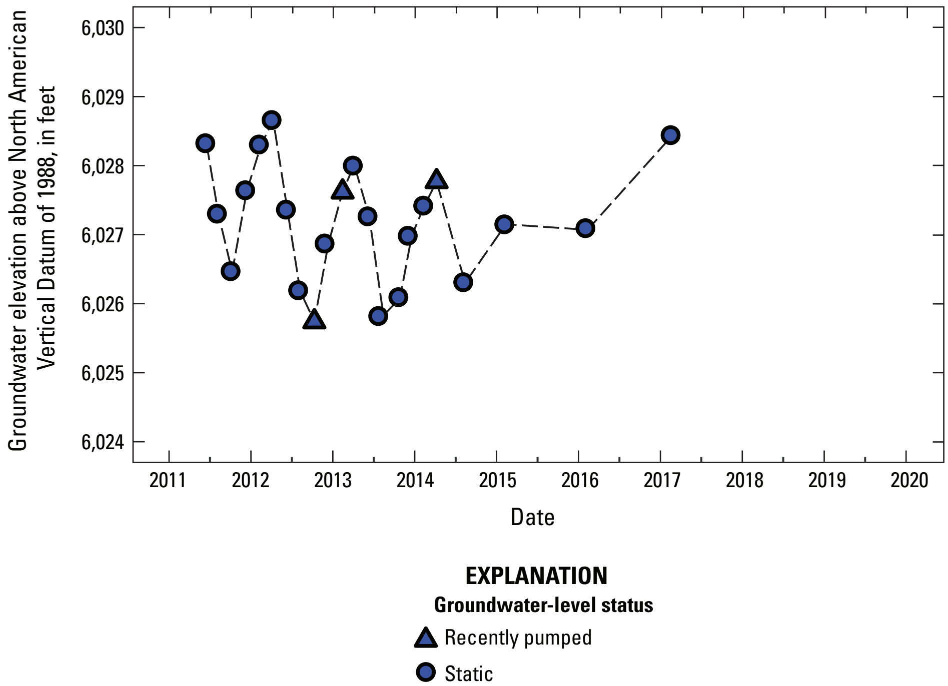

Figure 2.8. Groundwater-level hydrograph for well UDAW 8, U.S. Geological Survey site number 393252104434701, Douglas County, Colorado.

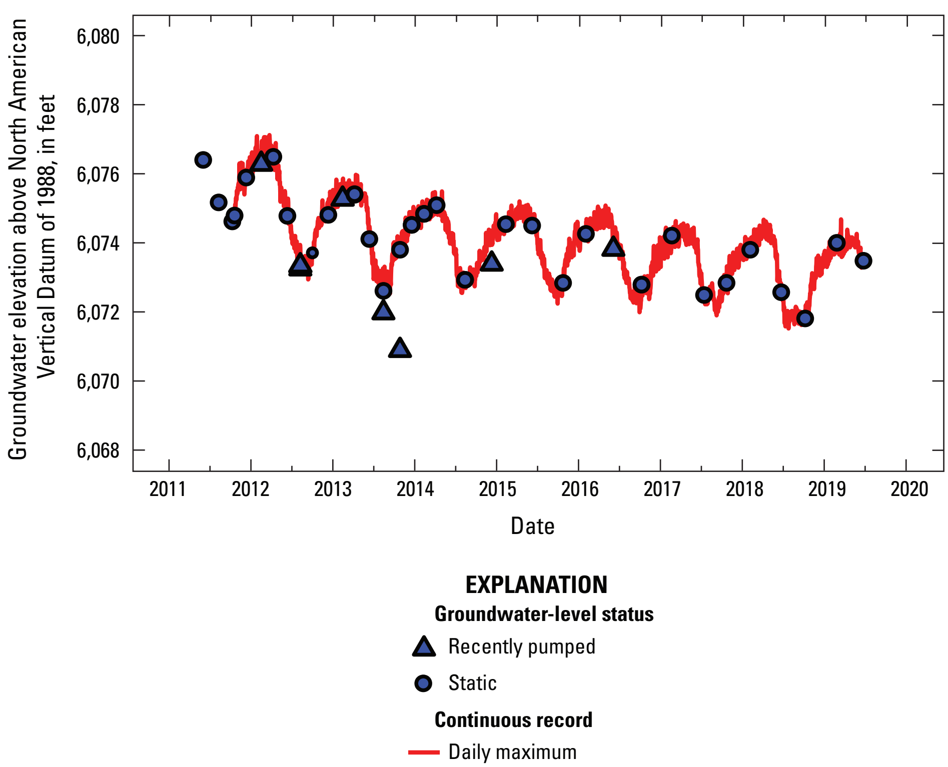

Figure 2.9. Groundwater-level hydrograph for well UDAW 9, U.S. Geological Survey site number 393226104394401, Douglas County, Colorado.

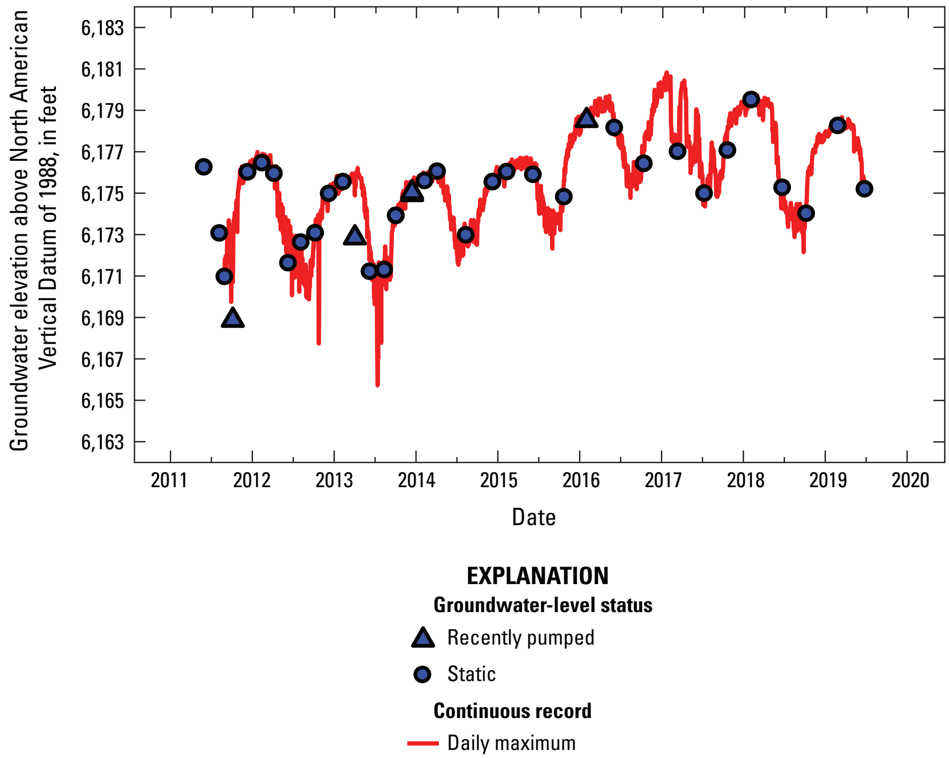

Figure 2.10. Groundwater-level hydrograph for well UDAW 10, U.S. Geological Survey site number 392916104423601, Douglas County, Colorado.

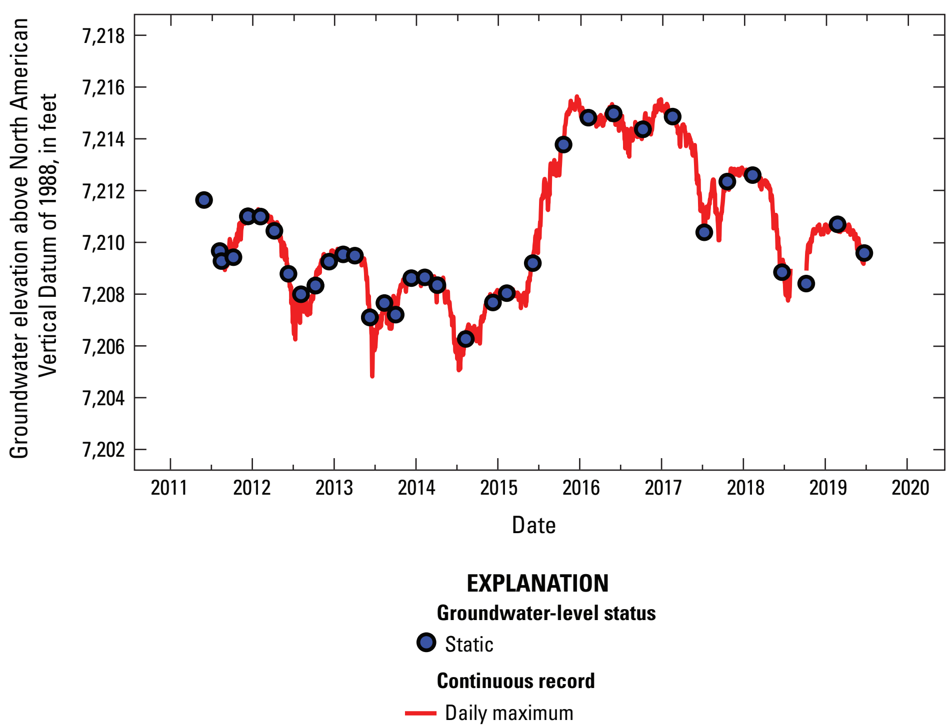

Figure 2.11. Groundwater-level hydrograph for well LDAW 2, U.S. Geological Survey site number 390756104453801, Douglas County, Colorado.

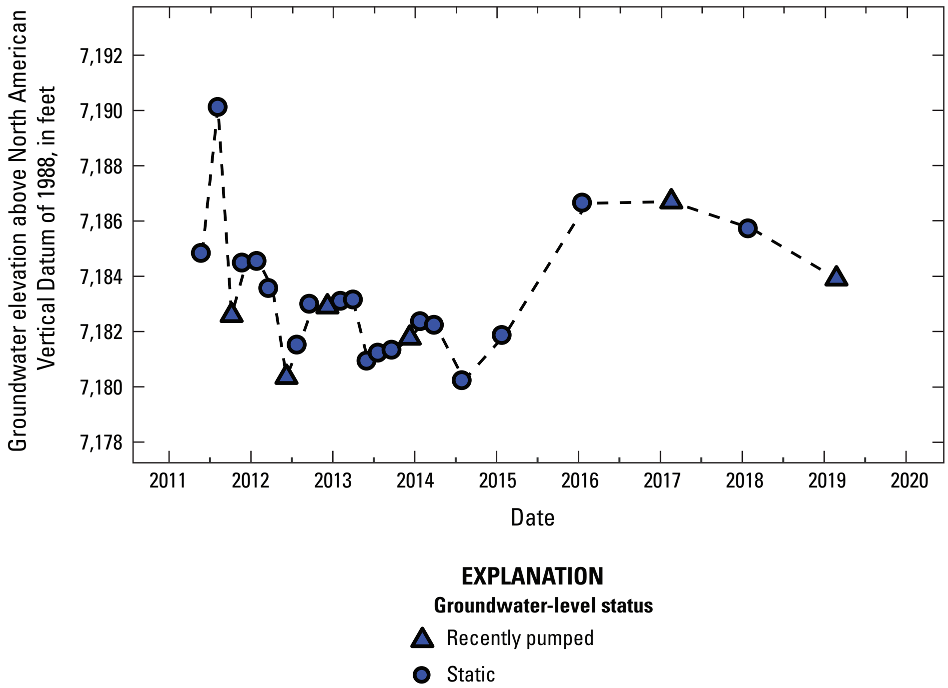

Figure 2.12. Groundwater-level hydrograph for well LDAW 3, U.S. Geological Survey site number 390811104453801, Douglas County, Colorado.

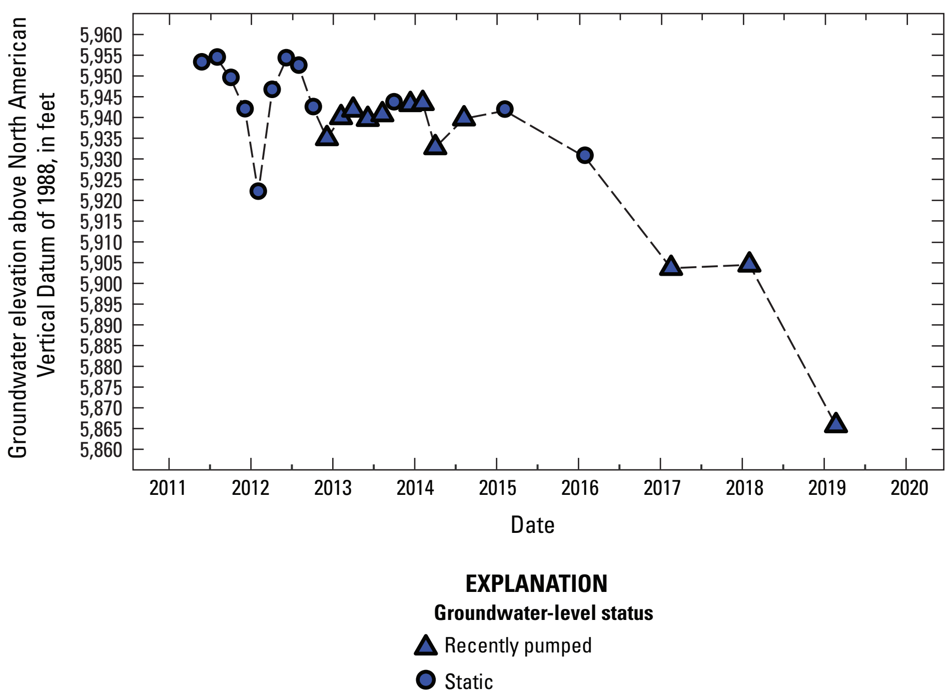

Figure 2.13. Groundwater-level hydrograph for well LDAW 4, U.S. Geological Survey site number 392318104424601, Douglas County, Colorado.

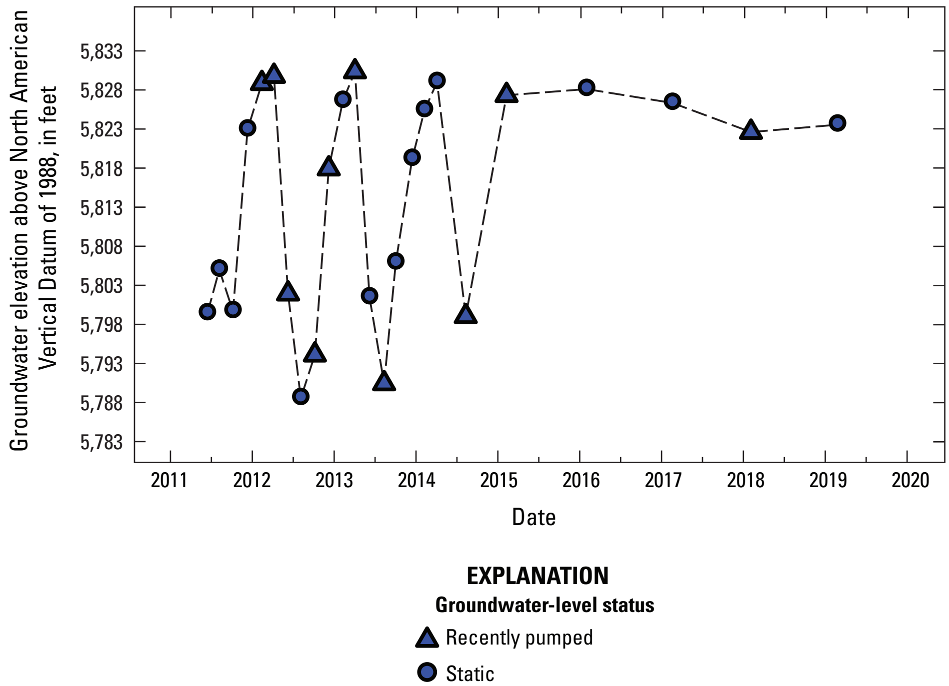

Figure 2.14. Groundwater-level hydrograph for well LDAW 5, U.S. Geological Survey site number 391924104374101, Douglas County, Colorado.

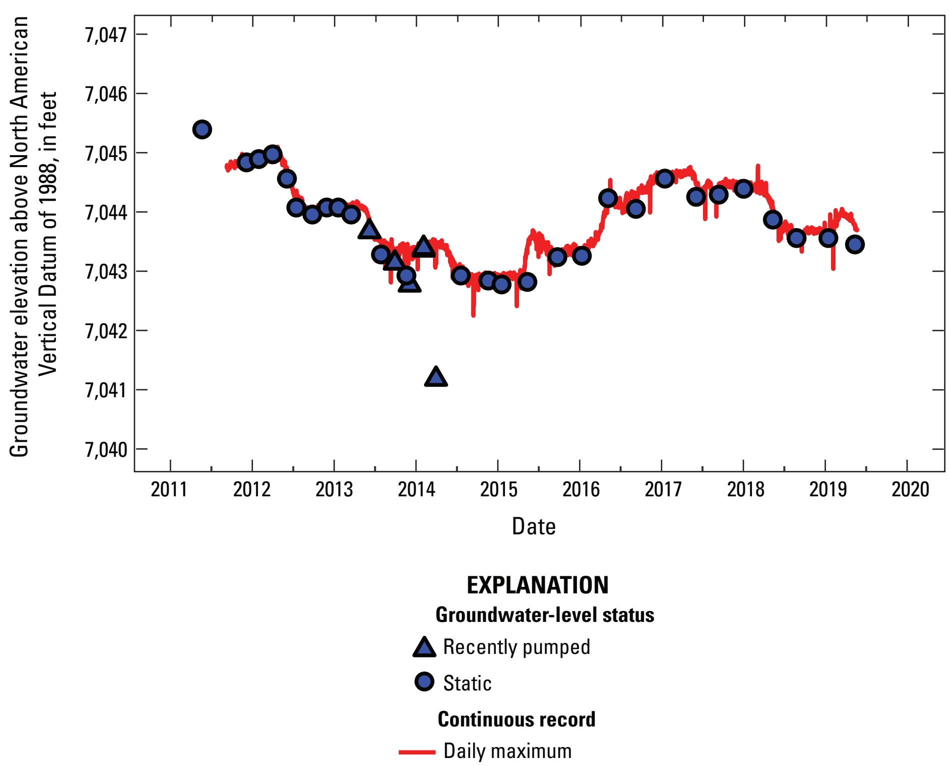

Figure 2.15. Groundwater-level hydrograph for well LDAW 6, U.S. Geological Survey site number 391143104482501, Douglas County, Colorado.

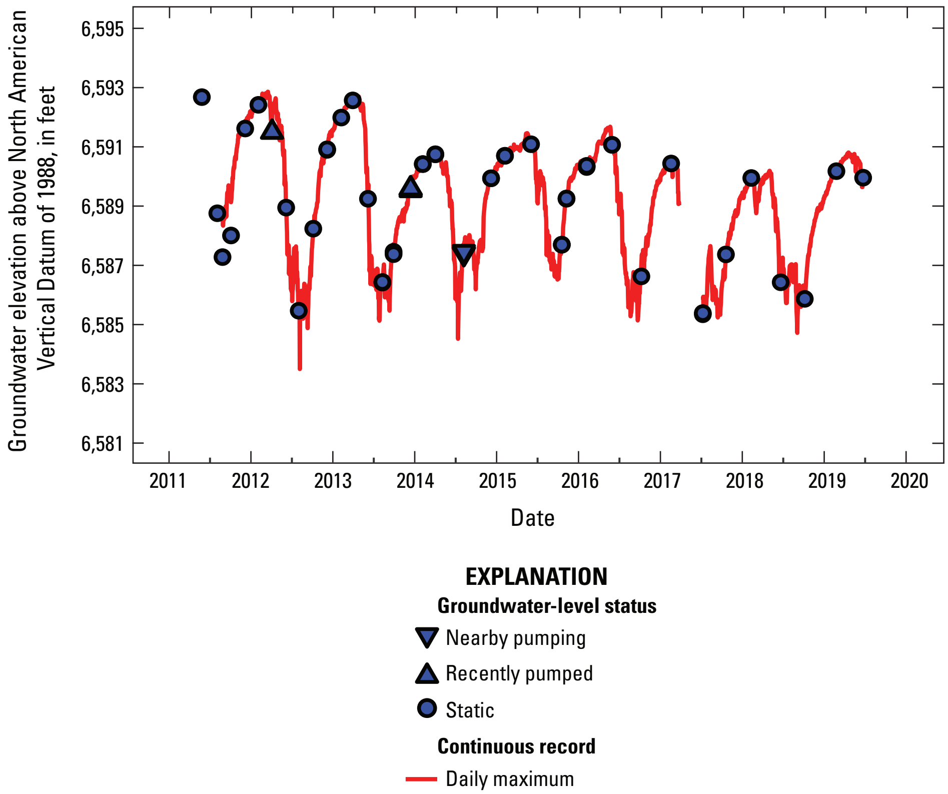

Figure 2.16. Groundwater-level hydrograph for well LDAW 7, U.S. Geological Survey site number 391654104464501, Douglas County, Colorado.

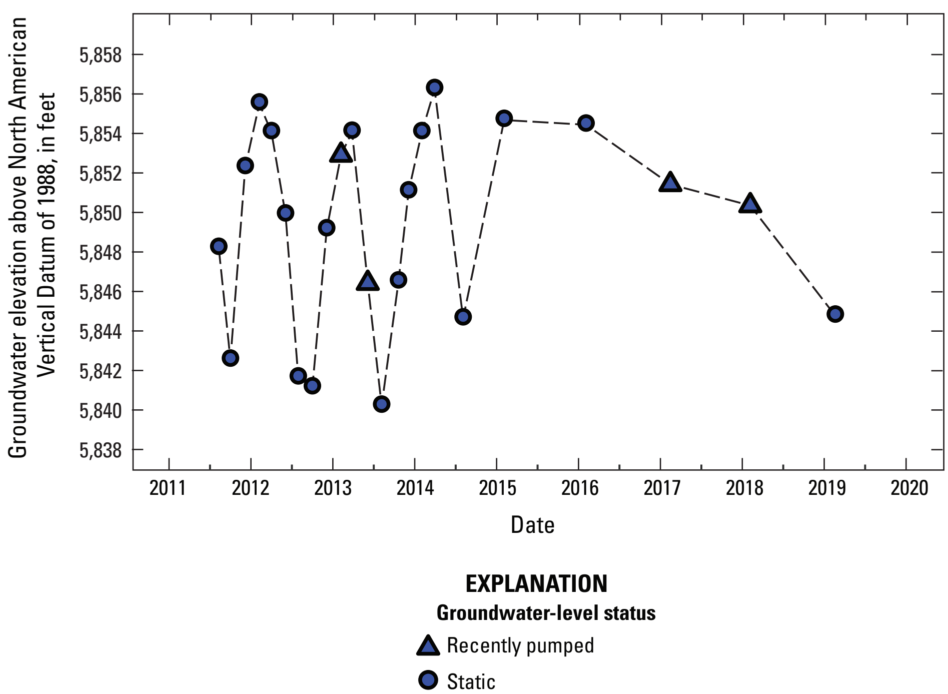

Figure 2.17. Groundwater-level hydrograph for well LDAW 8, U.S. Geological Survey site number 392949104523401, Douglas County, Colorado.

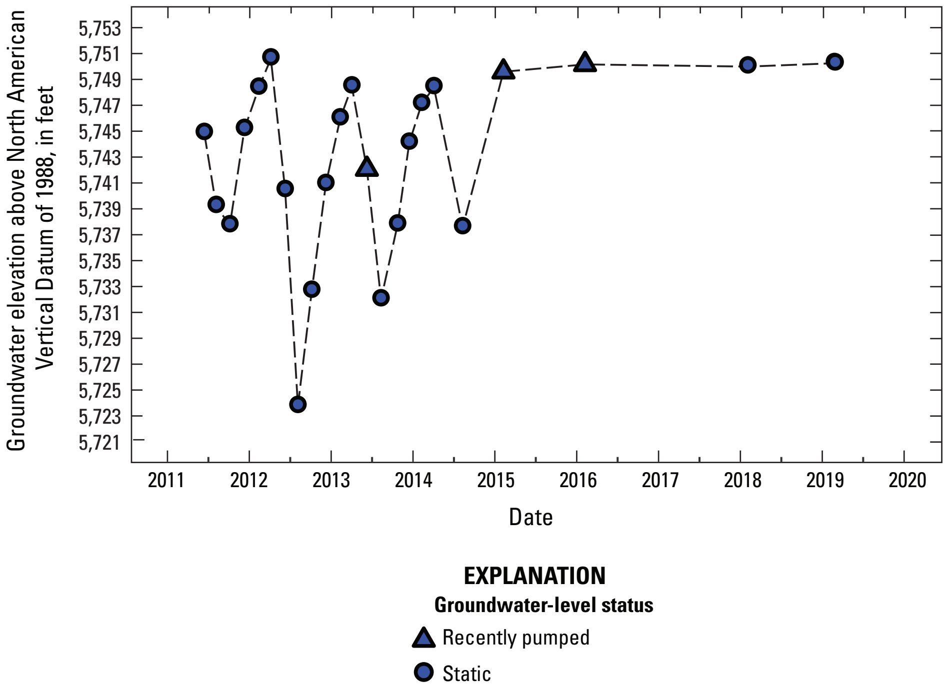

Figure 2.18. Groundwater-level hydrograph for well LDAW 9, U.S. Geological Survey site number 393239104452901, Douglas County, Colorado.

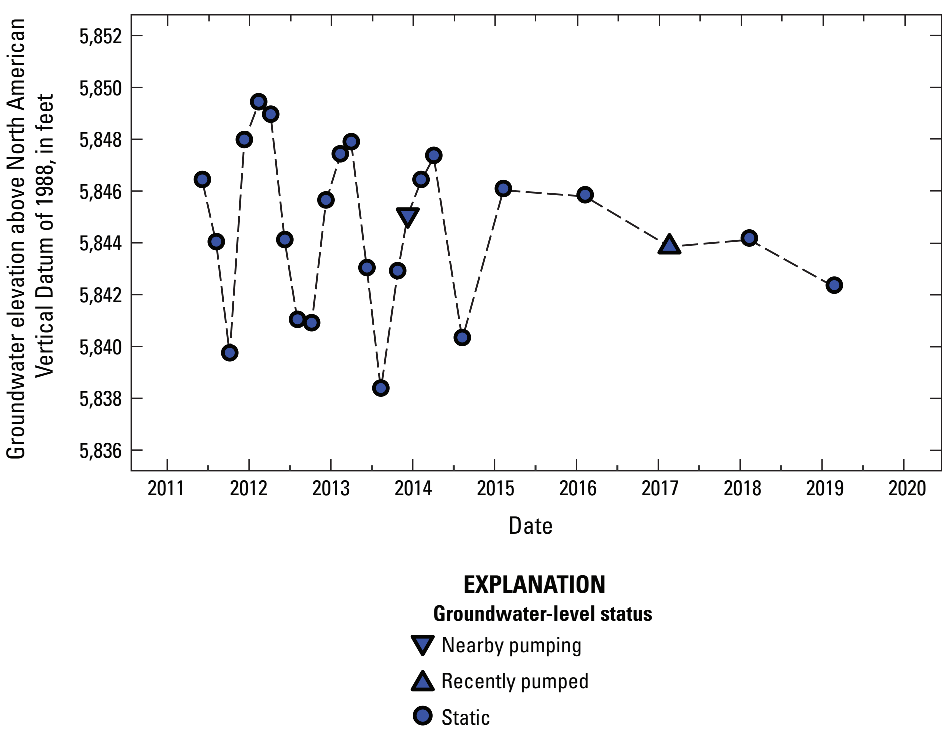

Figure 2.19. Groundwater-level hydrograph for well LDAW 10, U.S. Geological Survey site number 393021104533101, Douglas County, Colorado.

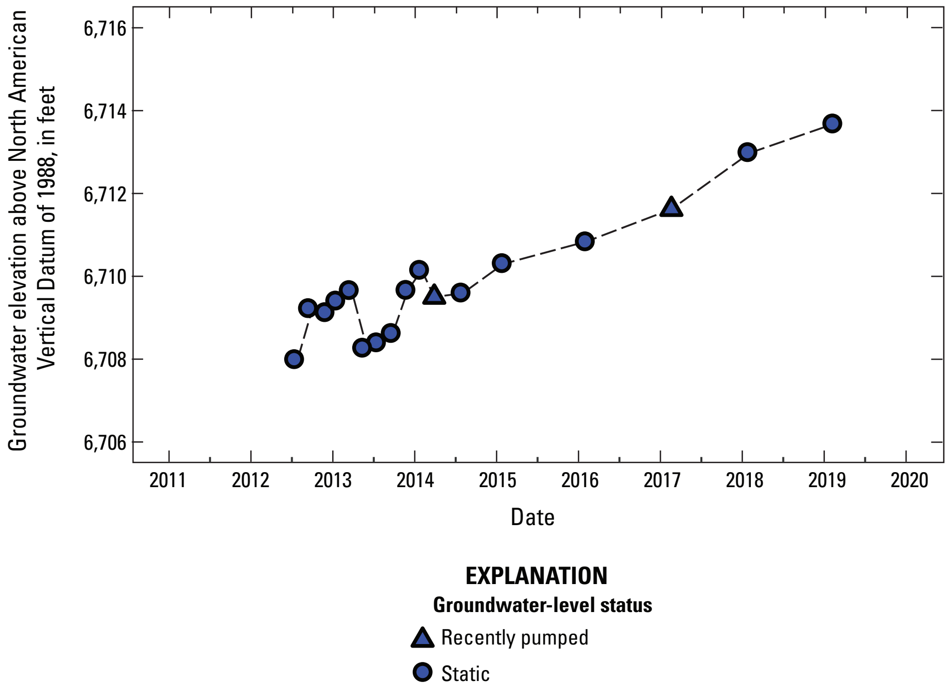

Figure 2.20. Groundwater-level hydrograph for well LDAW 11, U.S. Geological Survey site number 391257104530201, Douglas County, Colorado.

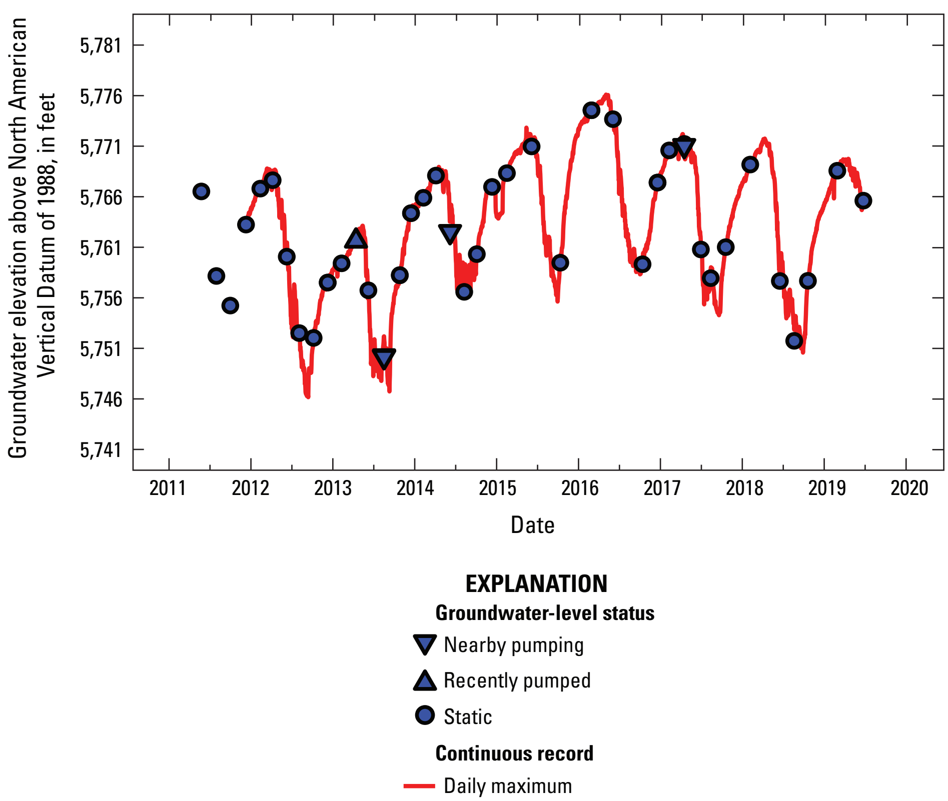

Figure 2.21. Groundwater-level hydrograph for well GRNDAW 4, U.S. Geological Survey site number 393259104491001, Douglas County, Colorado.

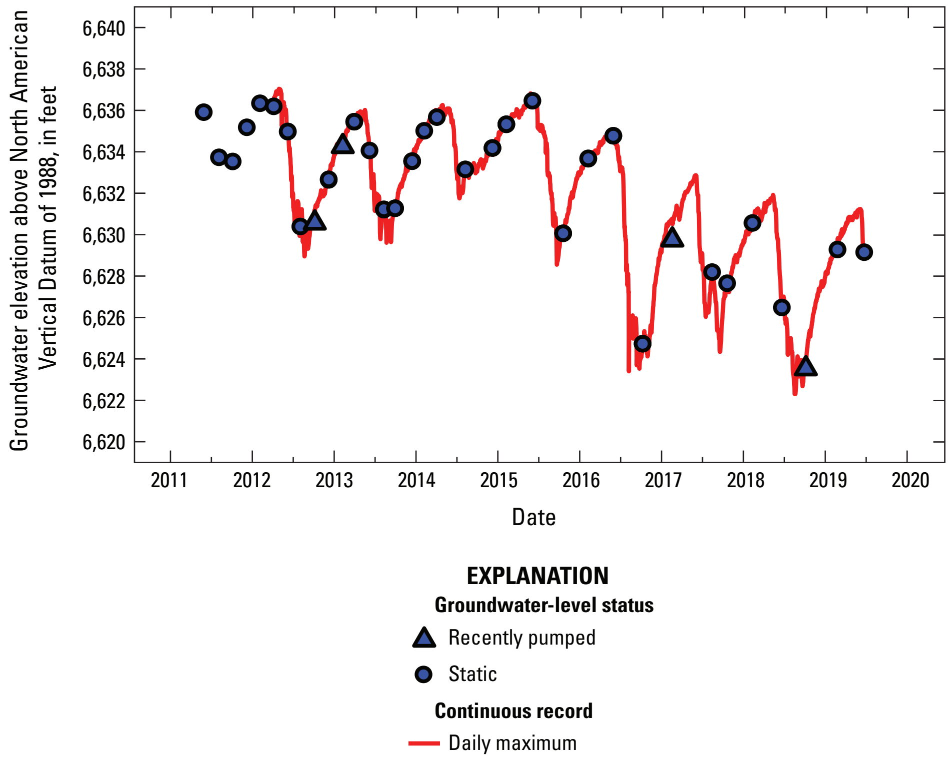

Figure 2.22. Groundwater-level hydrograph for well DENV 1, U.S. Geological Survey site number 391656104473001, Douglas County, Colorado.

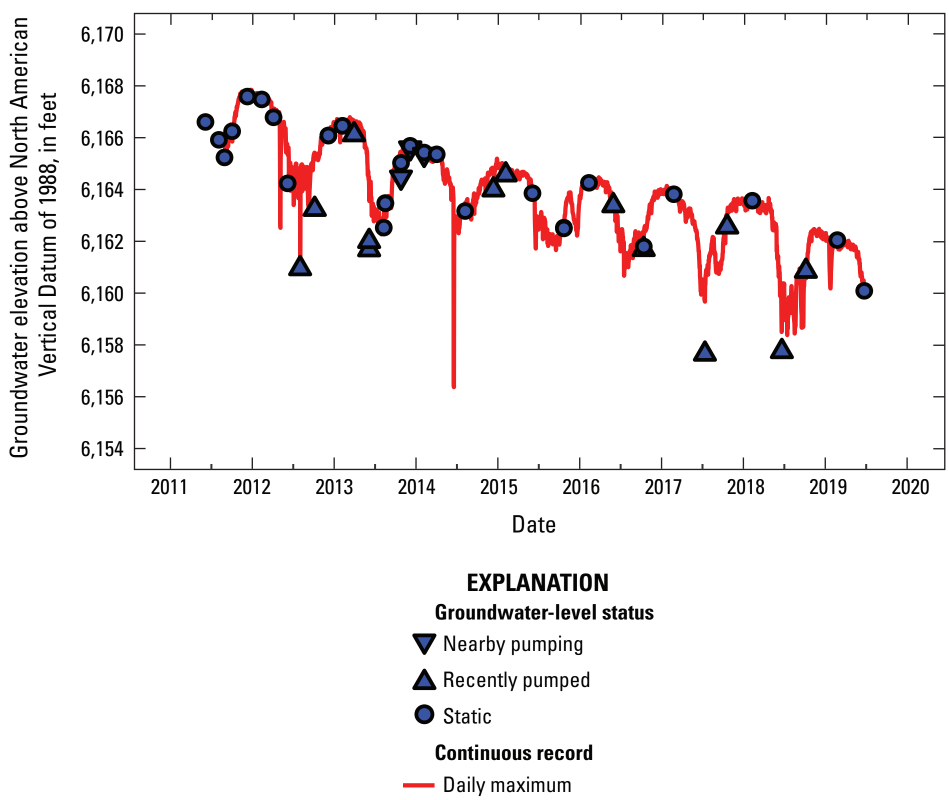

Figure 2.23. Groundwater-level hydrograph for well DENV 2, U.S. Geological Survey site number 391929104574101, Douglas County, Colorado.

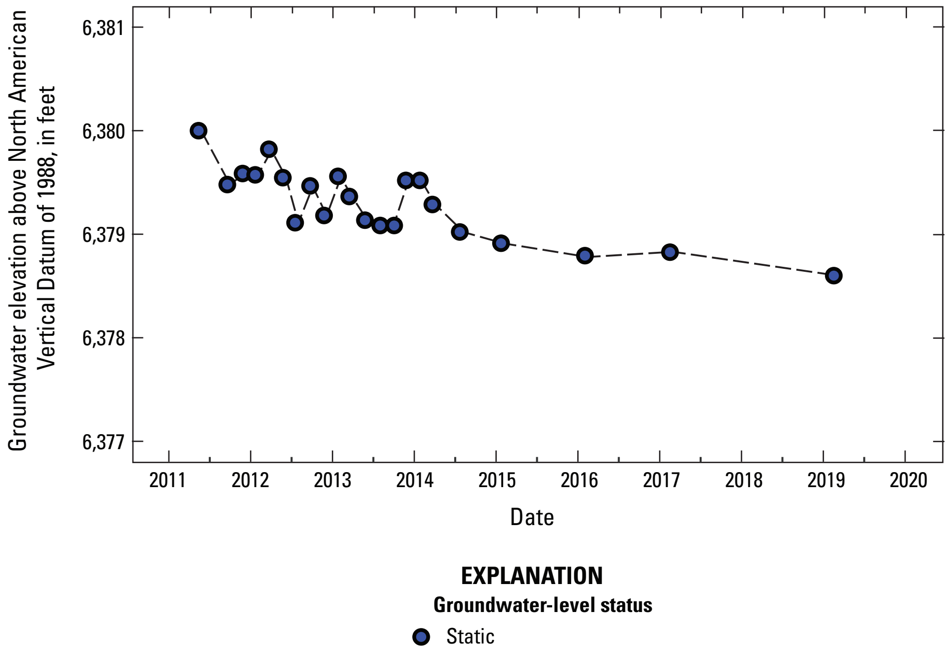

Figure 2.24. Groundwater-level hydrograph for well DENV 3, U.S. Geological Survey site number 391245104525501, Douglas County, Colorado.

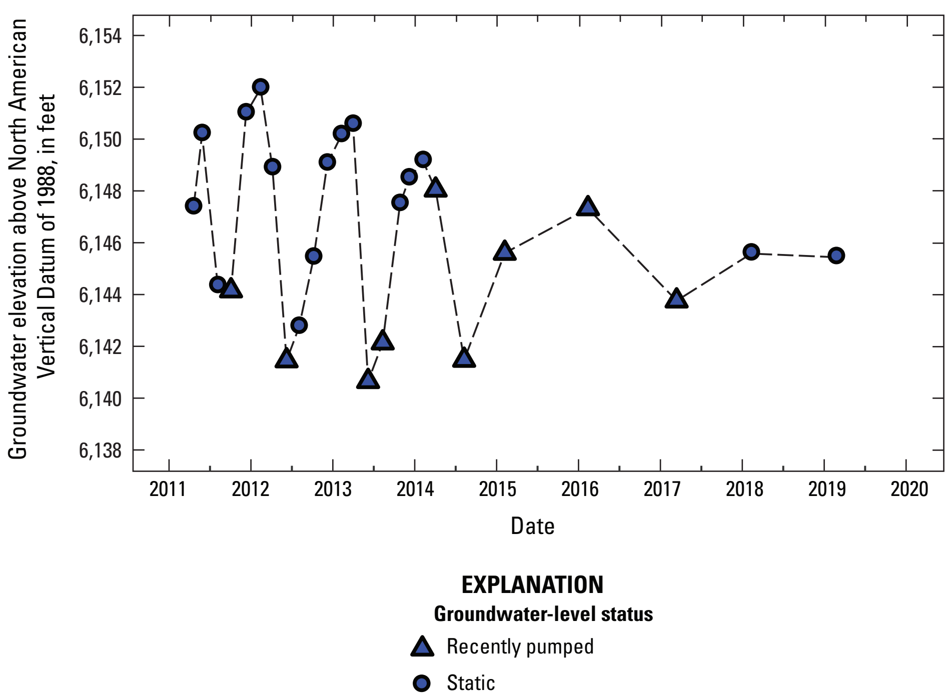

Figure 2.25. Groundwater-level hydrograph for well DENV 4, U.S. Geological Survey site number 392115104553501, Douglas County, Colorado.

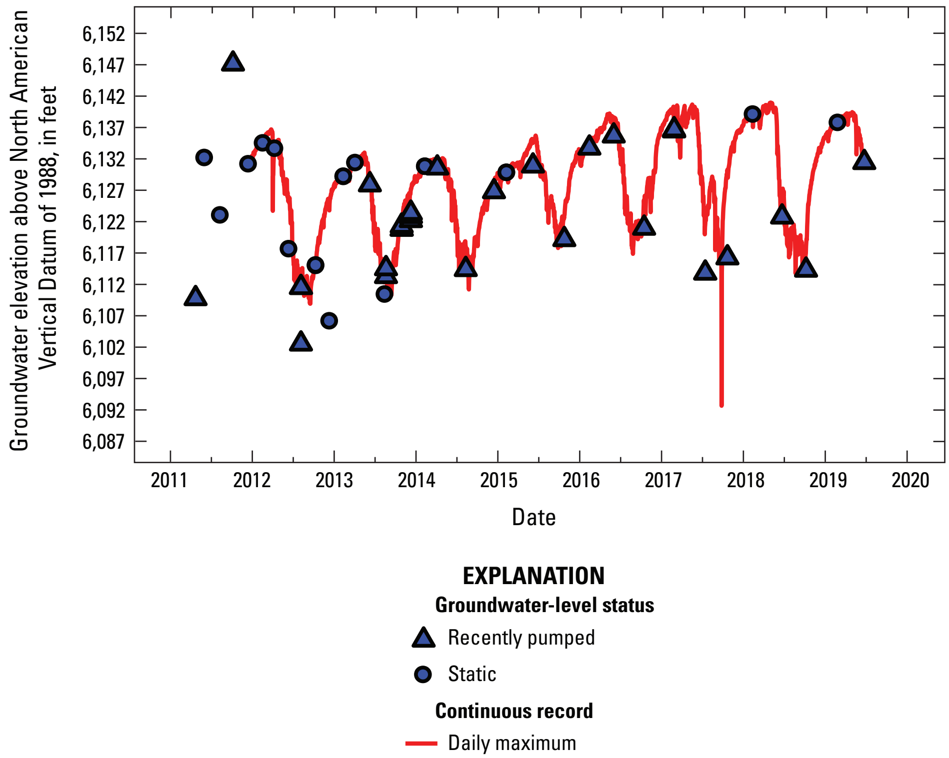

Figure 2.26. Groundwater-level hydrograph for well DENV 5, U.S. Geological Survey site number 392235105003001, Douglas County, Colorado.

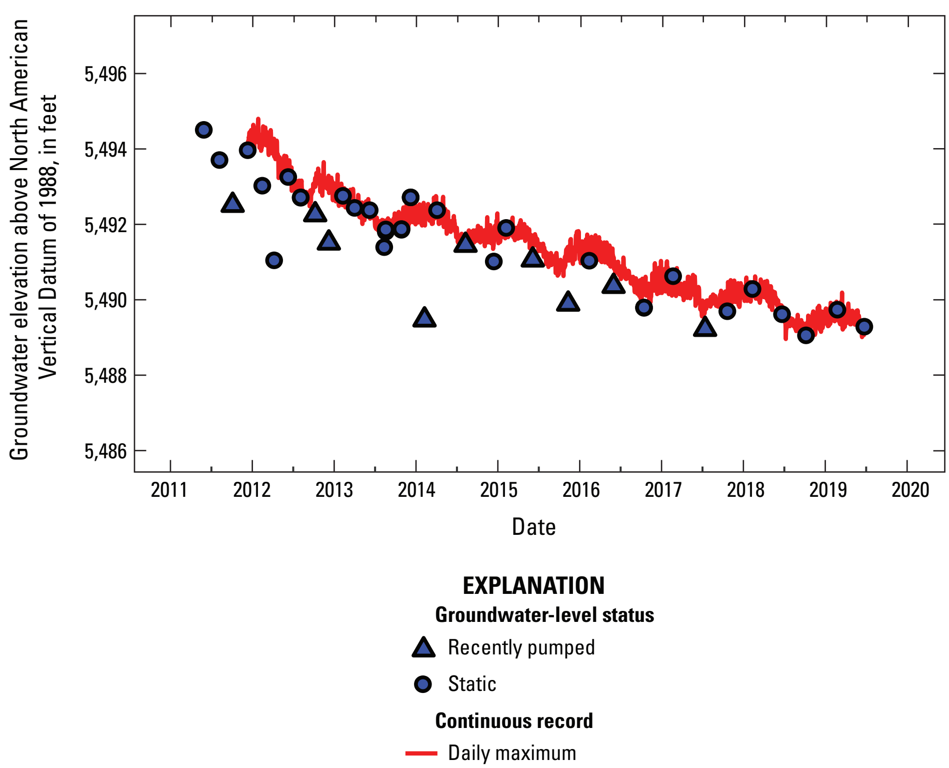

Figure 2.27. Groundwater-level hydrograph for well DENV 6, U.S. Geological Survey site number 393040105003201, Douglas County, Colorado.

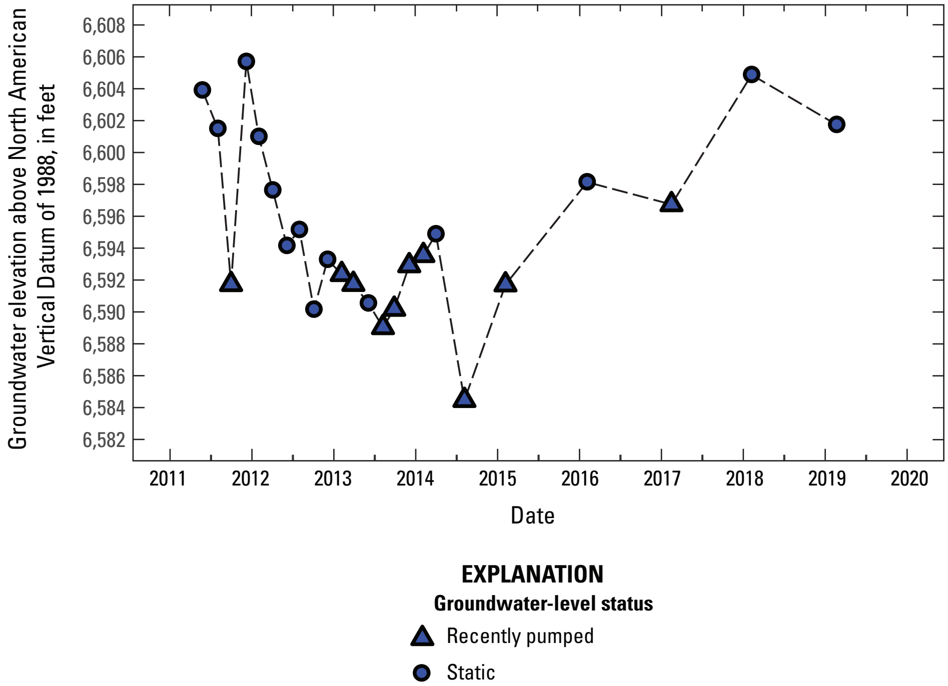

Figure 2.28. Groundwater-level hydrograph for well DENV 7, U.S. Geological Survey site number 391212104473801, Douglas County, Colorado.

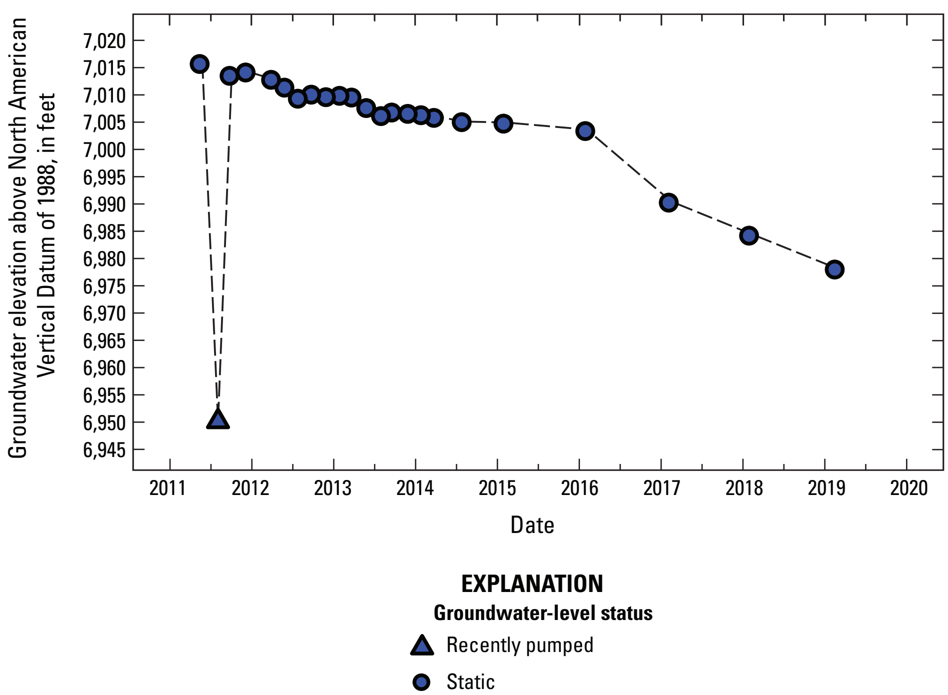

Figure 2.29. Groundwater-level hydrograph for well DENV 8, U.S. Geological Survey site number 390755104454001, Douglas County, Colorado.

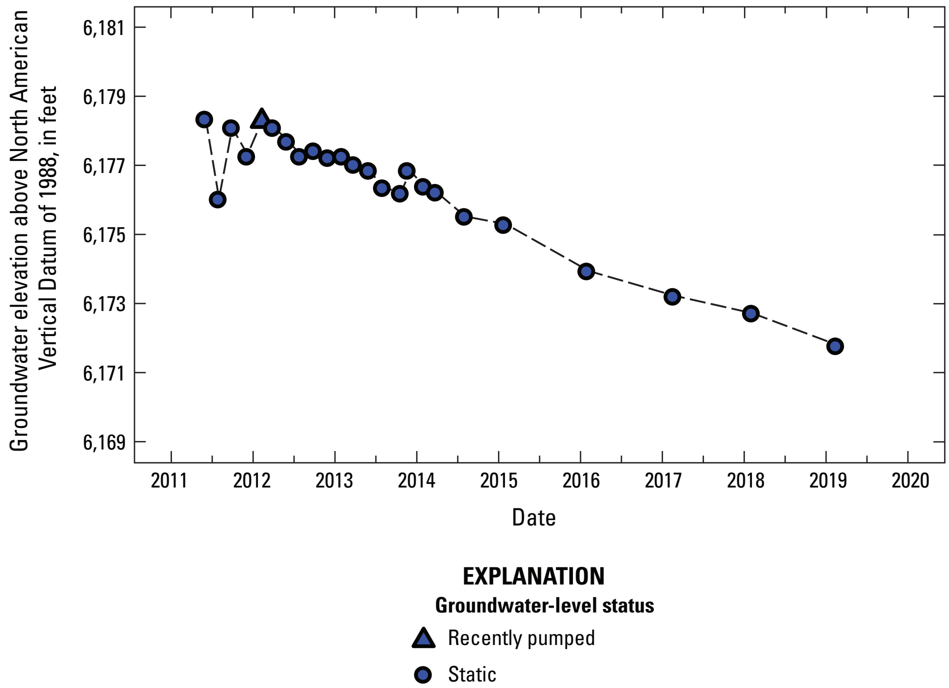

Figure 2.30. Groundwater-level hydrograph for well DENV 10, U.S. Geological Survey site number 391936104570101, Douglas County, Colorado.

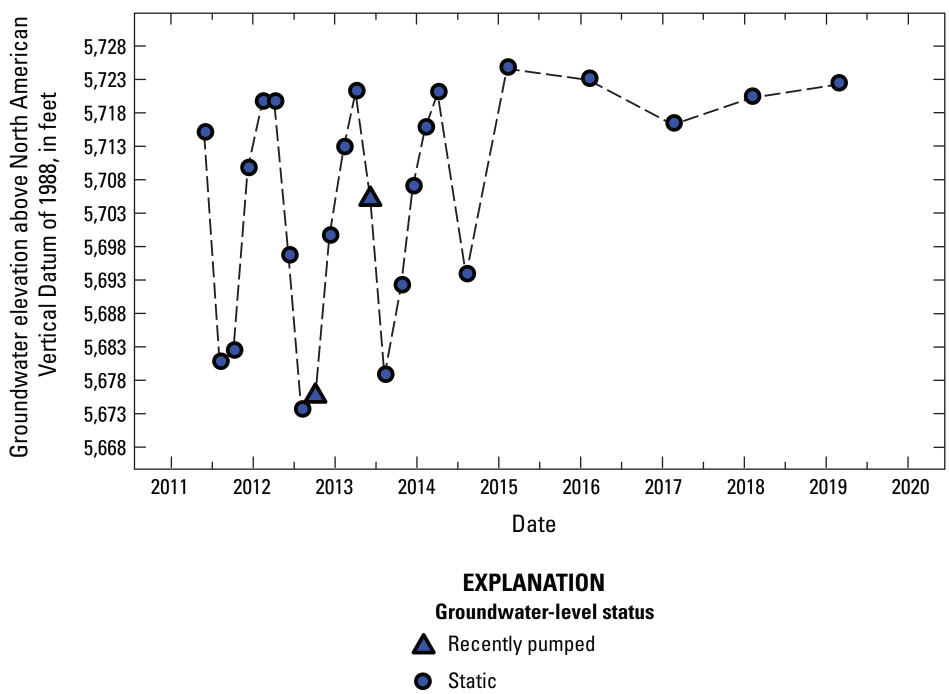

Figure 2.31. Groundwater-level hydrograph for well DENV 11, U.S. Geological Survey site number 393330104450701, Douglas County, Colorado.

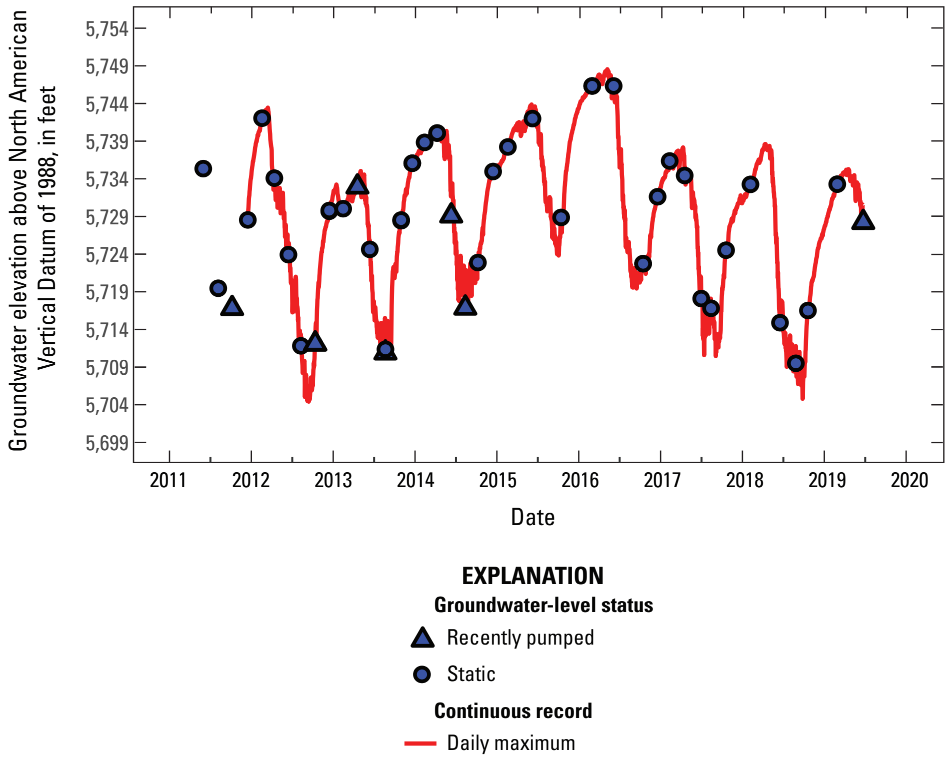

Figure 2.32. Groundwater-level hydrograph for well GRNDEV 3, U.S. Geological Survey site number 393252104492101, Douglas County, Colorado.

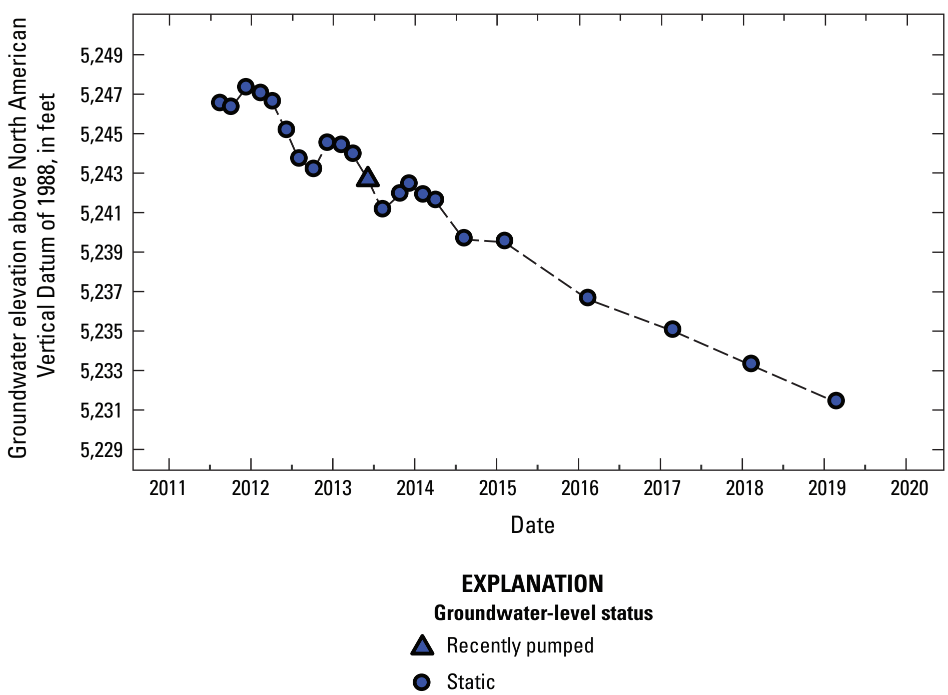

Figure 2.33. Groundwater-level hydrograph for well ARAP 1, U.S. Geological Survey site number 392853105015001, Douglas County, Colorado.

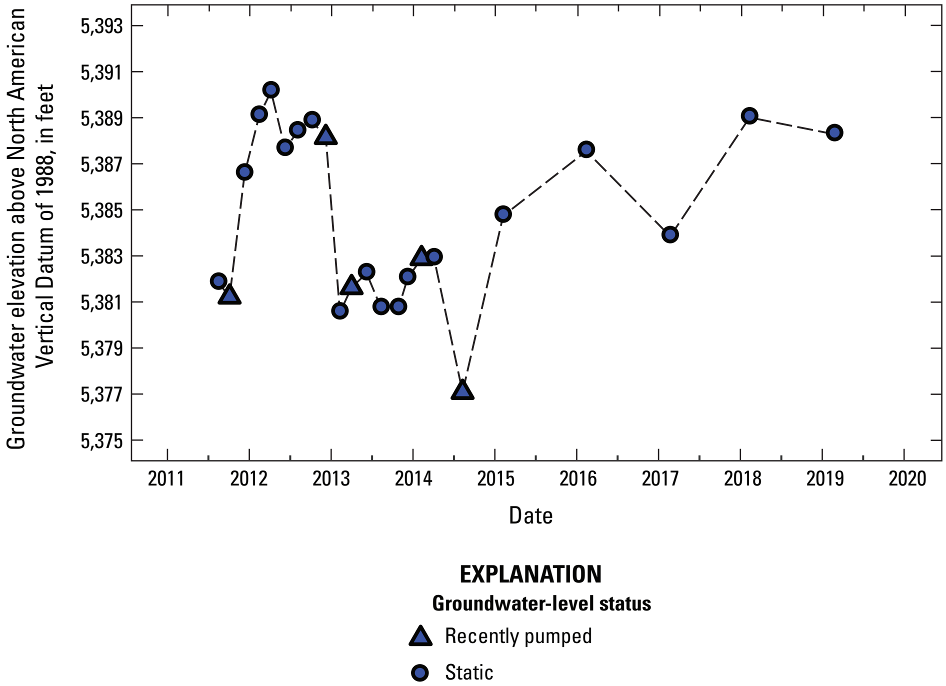

Figure 2.34. Groundwater-level hydrograph for well ARAP 2, U.S. Geological Survey site number 393120105003101, Douglas County, Colorado.

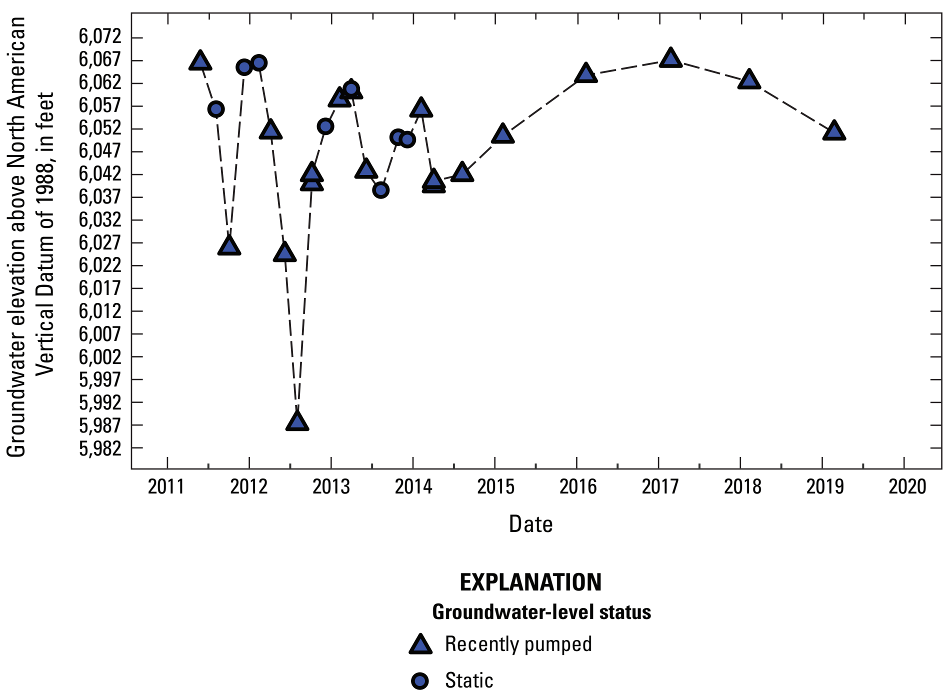

Figure 2.35. Groundwater-level hydrograph for well LARA 1, U.S. Geological Survey site number 392522105015001, Douglas County, Colorado.

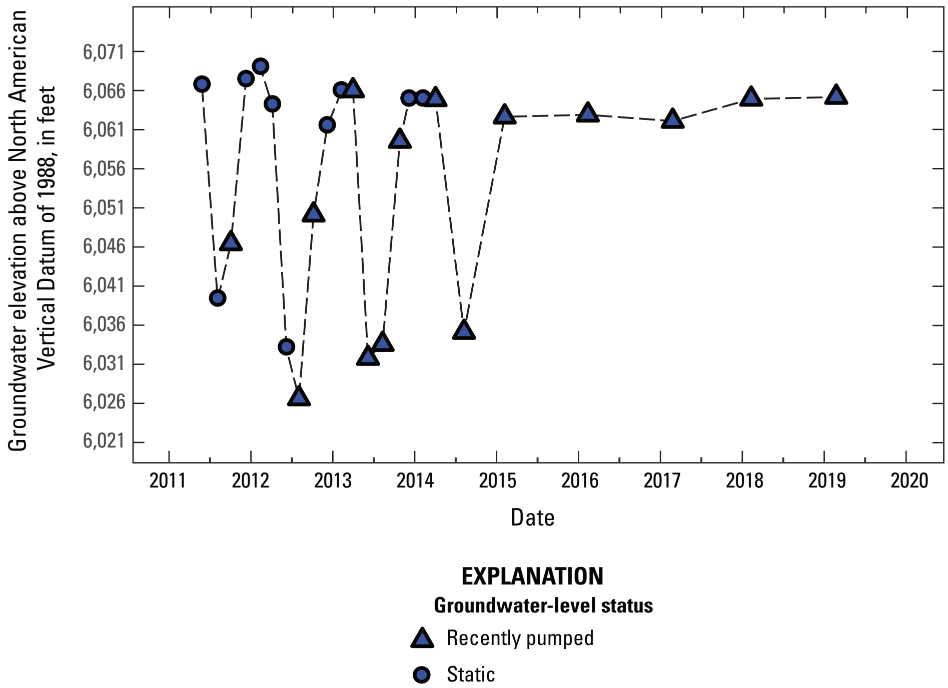

Figure 2.36. Groundwater-level hydrograph for well LARA 2, U.S. Geological Survey site number 392522105015401, Douglas County, Colorado.

Appendix 3. Descriptions and Equations of Mann-Kendall Test, Seasonal Mann-Kendall Test, and Sen Slope Estimate

The Mann-Kendall (M–K) trend test evaluates the strength of the monotonic association between two vectors, in this case groundwater-level elevations (y) and time (x). The nonparametric M–K test requires no assumptions of sample distribution, trend shape, or data continuity when measuring the strength of the relation. The M–K test compares the number of times y decreases as x increases (“discordant” pairs) to the number of times y increases as x increases (“concordant” pairs) (Helsel and others, 2020):

$$S = \sum_{i<j} (sign(x_j - x_i) * sign(y_j - y_i)) \quad (3.1)$$

where

- S is the test statistic, which estimates the monotonic dependence of y on x;
- x is the rank of time variable, from least to most recent; and
- y is the measured groundwater-level elevation, in feet above North American Vertical Datum of 1988.

The strength of the correlation is then estimated by Kendall’s tau (τ), also known as the rank correlation coefficient (Helsel and others, 2020). Kendall’s tau is analogous to the linear correlation coefficient and compares the S test statistic to the maximum possible value of S:

$$\tau = \frac{S}{n(n-1)/2} \quad (3.2)$$

where

- τ is the rank correlation coefficient and
- n is the number of data pairs.

The range of τ is from –1 (where all y values decrease with increasing x values) to +1 (where all y values increase with increasing x values). A τ value close to zero indicates a weak dependence of y on x, or lack of trend. Absolute τ values greater than 0.7 are considered to indicate strong correlation (Helsel and others, 2020). A probability value (p-value) can be calculated or estimated (depending on the sample size) using the S statistic and its distribution (Helsel and others, 2020). Although the M–K test is preferred rather than parametric methods in scenarios where residuals’ distributions are nonnormal or the correlation between x and y is nonlinear (Hirsch and others, 1991), the M–K test evaluates monotonic (consistently negative or positive) trends. Datasets with repeated negative and positive correlations will result in a nonsignificant trend. This condition means that standard M–K tests are not suitable for data with cyclical seasonality, unless the applied method accounts for periodicity.

To account for seasonality, the seasonal Mann-Kendall (sM–K) test was used, which conducts M–K tests for each season separately (for example, January data are compared only to January data in other years). The S test statistics are calculated for each month (eq. 3.1), and then the individual months’ S statistics are summed for an overall S test statistic (Sk) (Helsel and others, 2020). Subsequently, an overall τ and the p-value can be calculated from Sk values for each record.

To evaluate trend significance, a hypothesis test and the derived p-value were used. The null hypothesis of no monotonic trend and an alpha (α) of 0.10 were used. Therefore, when the p-value was less than or equal to 0.10, the null hypothesis was rejected, and a trend in groundwater-level elevations was considered statistically significant.

The Sen slope estimate is referred to as the “trend estimate” or “trend” in groundwater-level elevations in the report (tables 3 and 4). The Sen slope estimate was used to calculate the trend in groundwater-level elevations by using the same pairs of x and y data used to compute S in the Mann-Kendall test. The Sen slope is calculated by taking the median of the slope of each pair as follows:

$$\beta_{ss} = median\left(\frac{y_j - y_i}{x_j - x_i}\right) \quad (3.3)$$

where

- β_{ss} is the Sen slope estimate, in feet per year.

References Cited

Helsel, D.R., Hirsch, R.M., Ryberg, K.R., Archfield, S.A., and Gilroy, E.J., 2020, Statistical methods in water resources: U.S. Geological Survey Techniques and Methods, book 4, chapter A3, 458 p., accessed June 2020 at https://doi.org/10.3133/tm4a3. [Supersedes USGS Techniques of Water-Resources Investigations, book 4, chapter A3, version 1.1]

Hirsch, R.M., Alexander, R.B., and Smith, R.A., 1991, Selection of methods for the detection and estimation of trends in water quality: Water Resources Research, v. 27, no. 5, p. 803–813. [Also available at https://doi.org/10.1029/91WR00259.]

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