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Generalized Potentiometric-Surface Map and Groundwater Flow Directions in the Madison Aquifer Near Jewel Cave National Monument, South Dakota

Scientific Investigations Report 2019–5098

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

Cover. Wellspring Lake, a subterranean cave lake near Jewel Cave, South Dakota. Photograph courtesy of Dan Austin, National Park Service.

Back cover. Prairie Dog Springs at Jewel Cave National Monument, South Dakota. Photograph by Galen Hoogestraat, U.S. Geological Survey.

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
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	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Datum

Vertical coordinate information is referenced to 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

mya	millions of years ago
NOAA	National Oceanic and Atmospheric Administration
NWIS	National Water Information System
USGS	U.S. Geological Survey

Acknowledgments

The authors wish to thank the South Dakota Department of Environment and Natural Resources for their cooperation and assistance in completing the project. Also, special thanks to the personnel of the Jewel Cave National Monument for their support and contributions with the data collection.

The authors acknowledge Mark T. Anderson and Tim Bartos for providing insightful edits and comments for this report. The authors also acknowledge U.S. Geological Survey personnel who assisted with the collection, processing, and analysis of data.

Cave explorers at the 200th mapped mile of Jewel Cave, South Dakota, December 2017. Photograph courtesy of Dan Austin, National Park Service.

Generalized Potentiometric-Surface Map and Groundwater Flow Directions in the Madison Aquifer Near Jewel Cave National Monument, South Dakota

By Todd M. Anderson,[1] William G. Eldridge,[1] Joshua F. Valder,[1] and Michael Wiles[2]

Abstract

A generalized potentiometric-surface map of the Madison aquifer near Jewel Cave National Monument was constructed using water levels measured from calendar years 1988 to 2019 in 24 groundwater wells and 4 subterranean cave lakes interpreted to be in hydraulic connection with the aquifer. The map indicated that groundwater near Jewel Cave National Monument originates from recharge sources to the Madison aquifer in the higher elevations in the north-central area of the map, flows west to south-southwest through the Jewel Cave network, then southeast.

Hydrographs were constructed using water levels from four observation wells and one subterranean lake (Hourglass Lake) in the Jewel Cave network to evaluate historical and current groundwater recharge to the Madison aquifer in the study area. Hydrographs from 1992 through 2018 indicated water levels were lowest from the early to mid-1990s, increased through the late 1990s, peaked in the early 2000s, decreased until 2010, and then increased to the highest levels during 2016–18. A visual comparison of the Hourglass Lake hydrograph with cumulative precipitation, and quantitative (statistical) comparison of lake-water levels with cumulative precipitation, indicated that lake-water levels increased as cumulative precipitation increased, most likely due to some degree of precipitation recharge to hydraulically connected Madison Limestone outcrops.

Comparing the potentiometric-surface map constructed for this study, with a map by Strobel and others (2000) of the same region and aquifer, indicated similarity and, therefore, provided some validation of map construction. The potentiometric-surface map constructed for this study could be used by park managers and others as a tool to evaluate the hydrogeologic characteristics of the Madison aquifer in the study area.

[1]U.S. Geological Survey.

[2]National Park Service.

Introduction

Jewel Cave National Monument in the Black Hills of southwestern South Dakota (fig. 1) has more than 200 miles (mi) of mapped passages as of 2019, making it one of the longest mapped cave passages in the world (Long and others, 2019). The unique natural features of the cave led U.S. President Theodore Roosevelt to designate the cave as a National Monument in 1908 (KellerLynn, 2009). Jewel Cave was formed in the regionally extensive Madison Limestone characterized as a carbonate karst environment with extensive subterranean cave networks and losing streams at the land surface (Long and others, 2019). The Madison aquifer is present in the water-saturated and more permeable areas of the limestones, siltstones, sandstones, and dolomite of the Madison Limestone (Downey, 1984; Driscoll and others, 2002). The ephemeral surface waters and groundwaters of the area surrounding Jewel Cave National Monument are highly interconnected with fast hydrologic exchanges, resulting in high vulnerability of aquifer contamination from human activities at the surface (Long and others, 2019).

Improved understanding of groundwater flow and stresses of the Madison aquifer allows scientists, Jewel Cave National Monument park managers, and the surrounding communities to better manage, protect, and preserve the site and its unique natural features. The Madison aquifer provides groundwater for municipal, domestic, agricultural, and industrial use (Maupin and others, 2014). Jewel Cave National Monument and the surrounding communities that rely on water from the Madison aquifer are vulnerable to contamination and changes in water levels from cyclical climate conditions. Additionally, the aquifer could become increasingly stressed as regional development for urban and other water uses expands.

Purpose and Scope

The purpose of this report is to present a generalized potentiometric-surface map of the Madison aquifer near Jewel Cave National Monument and to estimate the direction of groundwater flow in the aquifer. A potentiometric surface is a

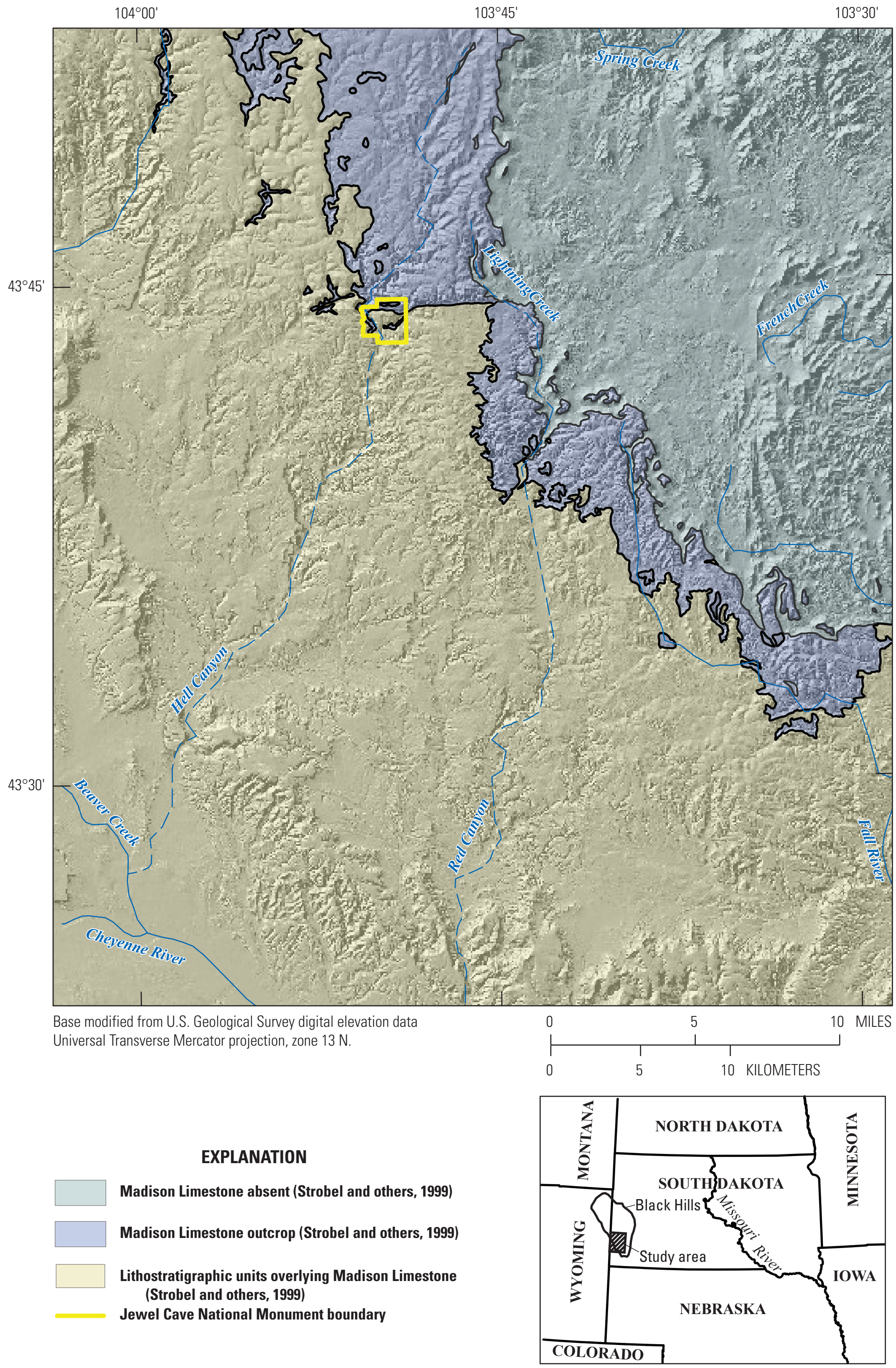


Figure 1. Jewel Cave National Monument in relation to the study area and areas where the Madison Limestone is exposed at land surface, South Dakota.

map of groundwater-level elevations (also known as hydraulic heads) represented by the water-table elevation in the unconfined parts of the aquifer, or by the elevation to which water will rise in a properly constructed well in the confined parts of the aquifer (Carter and others, 2002). The scope of the report is limited to water levels measured in 24 groundwater wells and 4 subterranean lakes in the Madison aquifer between 1980 and 2019 and to an area of about 1,000 square miles near Jewel Cave National Monument. The potentiometric-surface map produced for this study provides greater detail than previous potentiometric-surface maps that included the study area, and the map can be used by local managers and others as a tool to characterize the flow and direction of groundwater the Madison aquifer near Jewel Cave National Monument.

Previous Potentiometric Maps

Previous regional and local potentiometric-surface maps of the Madison aquifer included the Jewel Cave National Monument area; however, the maps vary spatially in accuracy and contain inferred potentiometric contours because of sparse or limited water-level data available at the time of publication. Regional maps were published by Downey (1984), and local maps were published by Strobel and others (2000), Carter and others (2002), Putnam and Long (2007, 2009), and Long and Valder (2011).

Study Area

The study area is in the southwestern Black Hills in southwestern South Dakota and includes about 1,000 square miles of the Madison aquifer in and around the boundary of Jewel Cave National Monument (fig. 1). The study area extends about 10 mi north, 20 mi south, 10 mi west, and 15 mi east from Jewel Cave National Monument and was defined to maximize the use of available local water-level data needed to create a potentiometric surface with the most accuracy near the Jewel Cave network. In addition to available water-level data, groundwater levels shown on the potentiometric-surface map by Strobel and others (2000) were considered when the study area was defined.

Physiography and Climate

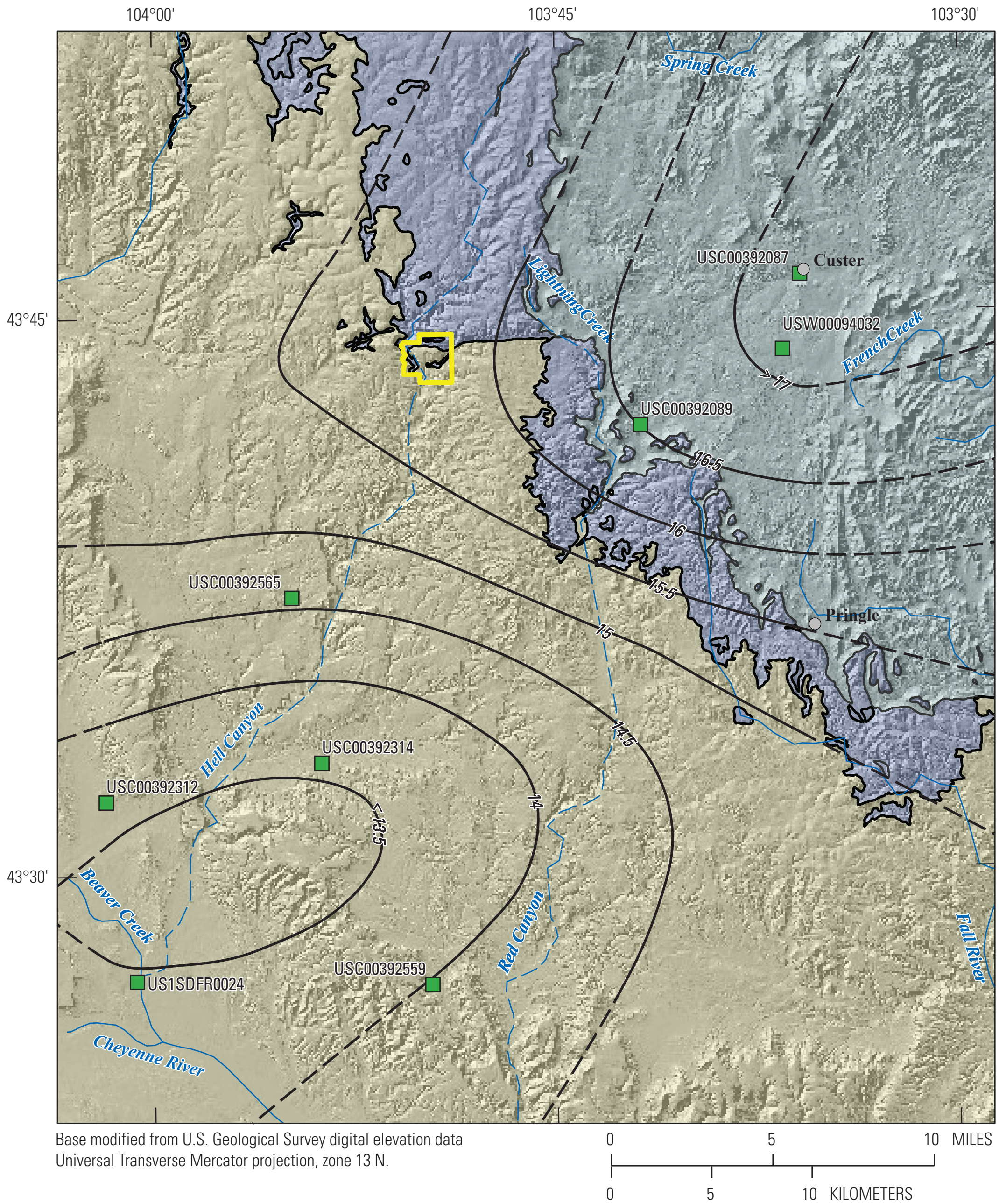
The study area is in the Black Hills section of the Great Plains physiographic province (not shown; Fenneman, 1946), and elevations range from about 3,480 to about 7,220 feet (ft) above the North American Vertical Datum of 1988 (NAVD 88). The Black Hills has a semiarid climate (Keller-Lynn, 2009), and mean annual precipitation for 1981–2010 ranged from about 16 to more than 32 inches (in.; PRISM Climate Group, 2014).

Mean annual precipitation varies with elevation in the study area, and higher elevations receive more precipitation than lower elevations (fig. 2). The mean annual precipitation of the higher elevations, represented by data from National Oceanic and Atmospheric Administration (NOAA) climate station USC00392087 (Custer, SD, US), was 18.45 in. and ranged from 9.27 to 27.76 in. (table 1; period of record 1911–2019 NOAA, 2019). The mean annual precipitation of elevations near the Madison Limestone outcrop, represented by NOAA climate station USC00392089 (Custer 7 SW, SD, US), was 15.26 in. and ranged from 13.22 to 17.71 in. (table 1; period of record 1948–66; NOAA, 2019). The mean annual precipitation at lower elevations in the study area, represented by NOAA climate station USC00392312 (Dewey, SD, US), was 12.55 in. and ranged from 9.79 to 16.13 in. (table 1; period of record 1948–57; NOAA, 2019). Comparing the mean annual precipitation between NOAA climate stations in the study area was considered acceptable because of the long periods of record for each station and because each record included dry and wet seasons even though the period of record differed for each climate station.

Table 1. Summary of precipitation for eight climate stations in the study area, South Dakota.

[NOAA, National Oceanic and Atmospheric Administration; NW, northwest; SD, South Dakota; US, United States; ENE, east-northeast; NNW, north-northwest]

NOAA station number	Station name	Precipitation, in inches			Period of record
		Minimum	Maximum	Mean	
US1SDFR0024	Edgemont 14.2 NW, SD, US	10.27	20.46	13.59	1998–2019
USC00392089	Custer 7 SW, SD, US	13.22	17.71	15.26	1948–66
USC00392312	Dewey, SD, US	9.79	16.13	12.55	1948–57
USC00392314	Dewey 8 ENE, SD, US	10.56	14.76	12.71	1948–52
USC00392559	Edgemont 10 N, SD, US	10.77	18.61	13.41	1948–57
USC00392565	Edgemont 23 NNW, SD, US	8.29	26.35	18.11	1989–2019
USW00094032	Custer County Airport, SD, US	12.05	26.57	18.81	1999–2019
USC00392087	Custer, SD, US	9.27	27.76	18.45	1911–2019



EXPLANATION

Madison Limestone absent (Strobel and others, 1999)

Madison Limestone outcrop (Strobel and others, 1999)

Lithostratigraphic units overlying Madison Limestone (Strobel and others, 1999)

Jewel Cave National Monument boundary

14.5 **Mean annual precipitation contour**—Shows annual precipitation, in inches. Dashed where approximately located. Contour interval 0.5 inch. Datum is North American Vertical Datum of 1988

USC00392559 **National Oceanic and Atmospheric Administration climate station and identifier**

Figure 2. Mean annual precipitation in the study area, South Dakota

Hydrogeologic Setting

The Black Hills of southwestern South Dakota and eastern Wyoming is the prominent hydrogeologic feature in the study area. Formed by the Laramide orogeny, the Black Hills are an elongated domal uplift about 125 mi long in the northwest-southeast direction and 60 mi wide in the southwest-northeast direction (Feldman and Heimlich, 1980; Driscoll and others, 2002). The Laramide orogeny was characterized by regional-scale deformation, erosion, and sediment deposition (Dickinson and others, 1988). Precambrian-age (greater than 541 million years ago [mya]; Cohen and others, 2019) igneous and metamorphic rocks and overlying younger sedimentary rocks uplifted during the orogeny and simultaneous and subsequent erosion of the uplift resulted in exposure of the igneous and metamorphic rocks forming the core of the Black Hills surrounded by concentric rings of the remaining once-overlying younger sedimentary rock (Carter and others, 2001a, b).

Precambrian-age igneous and metamorphic rocks forming the core of the Black Hills (Driscoll and others, 2002) reach a maximum elevation of about 7,220 ft. Overlying the Precambrian-age igneous and metamorphic rocks are sedimentary rocks of Cambrian and Ordovician age (about 541 to 444 mya; Cohen and others, 2019), including sandstone, shale, limestone, and dolomite deposited by ancient transgressing and regressing seas (Peterson, 1984). The primary Cambrian- and Ordovician-age formations exposed in the Black Hills area include, from oldest to youngest, the Deadwood, Winnipeg, and Whitewood Formations (Driscoll and others, 2002). Silurian-age (about 444 to 419 mya; Cohen and others, 2019) rocks are present in the subsurface north of the Black Hills but are not exposed in the Black Hills (Gries, 1996). Lying above these formations are rocks included in the Devonian-age (about 419 to 359 mya; Cohen and others, 2019) Englewood Formation and overlying Mississippian-age (about 359 to 323 mya; Cohen and others, 2019) Madison Limestone. Both formations consist of marine carbonates and evaporites from a warm, shallow-sea environment that formed limestone beds with thicknesses as much as 800 ft in the Black Hills region (Downey, 1984; Driscoll and others, 2002). Thickness of the Madison Limestone is about 400 ft within the Jewel Cave National Monument boundary (Dyer, 1961; Fagnan, 2009). The limestone composing much of the Madison Limestone is soluble in water (Morgan, 1991), and karstic sinkhole and cave features are common, especially in the upper part of the formation (Long and others, 2012). In parts of the Black Hills, limestone dissolution is extensive within the Madison Limestone and large cave systems have been mapped in western South Dakota and eastern Wyoming.

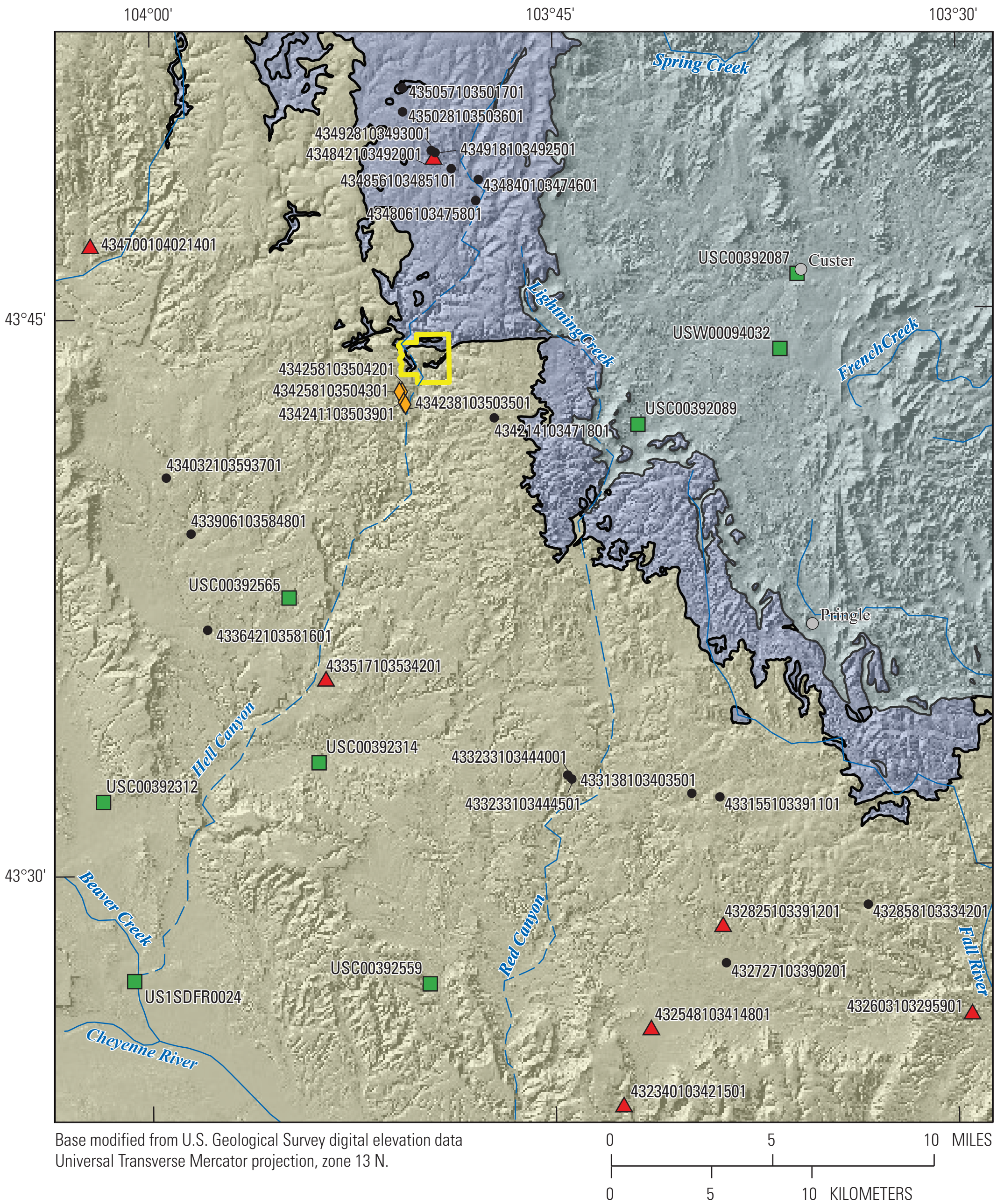
The Madison aquifer is present in the water-saturated and permeable parts of the Madison Limestone (Downey, 1984; Driscoll and others, 2002). Long and Putnam (2002) defined the Madison hydrogeologic unit, which consisted of the karstic Madison aquifer in the upper 100 to 250 ft of the Madison Limestone, and the underlying lower, less-permeable part of the Madison Limestone and underlying Englewood Formation. The upper surface of the Madison Limestone has a weathered karst surface (Putnam and Long, 2009) and is unconformably overlain by the Pennsylvanian- and Permian-age (about 323 to 252 mya; Cohen and others, 2019) Minnelusa Formation. The upper 150 ft of the Madison hydrogeologic unit contains solution openings and fractures which create secondary permeability and are responsible for much of the permeability in the unit (Greene, 1993).

Subterranean lakes sometimes occur in the Madison Limestone karstic cave systems. Wind Cave National Park, located about 30 miles southeast from Jewel Cave National Monument in the southern Black Hills, South Dakota, has several subterranean lakes in the Madison Limestone, and during 1999 to 2000, two lakes merged into one after a period of increasing groundwater levels in the Madison aquifer (Long and others, 2019). Lake levels at Windy City Lake, a subterranean lake in Wind Cave National Park, increased and decreased concurrently with water levels measured in a nearby groundwater monitoring well completed in the Madison aquifer (Long and others, 2012). Subterranean lakes in the Jewel Cave network in the Madison Limestone were first discovered in 2015, and from 2015 to 2019 several additional subterranean lakes were discovered, mapped, and surveyed as cave explorers reached uncharted parts of the cave (Long and others, 2019). Surveyed water-level elevations of the subterranean lakes in the Jewel Cave network are similar to groundwater levels measured in nearby wells completed in the Madison aquifer; therefore, the subterranean lakes of both Jewel Cave National Monument and Wind Cave National Park likely are hydraulically connected with the regional flow system of the Madison aquifer (Long and others, 2019).

The Madison aquifer is an important source of groundwater for the Black Hills of southwestern South Dakota (Carter and others, 2001b). Long and Putnam (2002) reported that wells completed in the Madison aquifer can produce 5 to 2,500 gallons per minute; most (64 percent) produce 5 to 50 gallons per minute in the area of Rapid City, South Dakota. Depths of wells completed in the Madison aquifer range from 20 to 4,600 ft below land surface; 78 percent of the wells are completed to a depth of less than 1,000 ft (Long and Putnam, 2002).

Data and Methods

This section describes the data and methods used to construct a generalized potentiometric-surface map of the Madison aquifer near the study area, including Jewel Cave. Water levels measured in 24 wells and 4 subterranean cave lakes (fig. 3) were used to construct the map. For this study, groundwater-level elevations are reported in feet above NAVD 88 and are referred to as hydraulic heads.



EXPLANATION

- Madison Limestone absent (Strobel and others, 1999)
- Madison Limestone outcrop (Strobel and others, 1999)
- Lithostratigraphic units overlying Madison Limestone (Strobel and others, 1999)
- Jewel Cave National Monument boundary
- 434241103503901 Jewel Cave lakes and National Water Information System identifier
- 432727103390201 National Water Information System well and identifier added after Strobel and others (2000)
- 432340103421501 National Water Information System well and identifier used in Strobel and others (2000)
- USC00392559 National Oceanic and Atmospheric Administration climate station and identifier

Figure 3. Wells, subterranean cave lakes, and National Oceanic Atmospheric Administration stations in the study area, South Dakota.

Groundwater Wells

Water-level data used to construct the potentiometric-surface map were from groundwater wells completed in the Madison aquifer or subterranean cave lakes in hydraulic connection with the aquifer. Data were compiled from 24 groundwater wells, including 4 observation wells operated by the South Dakota Department of Environment and Natural Resources Water Rights Program (South Dakota Geological Survey, 2019). Water-level data were obtained from the U.S. Geological Survey (USGS) National Water Information System (NWIS) database (USGS, 2019) and were widely distributed in the study area (fig. 3). NWIS data included wells with a single measurement and wells with multiple measurements from calendar years 1980 through 2019: 4 wells had greater than 100 water-level measurements, 1 well had 3 measurements, and the remaining 19 wells in the analyses had 1 measurement (fig. 3; table 2). Hydraulic-head values were calculated by subtracting measured water levels from land-surface elevations recorded in NWIS. An arithmetic mean was calculated for each of the five wells in the study area with multiple measurements. The maximum standard deviation of hydraulic heads calculated for wells with multiple water-level measurements was 19 ft (table 2), about 10 times smaller than the contour interval of 200 ft used for potentiometric-surface map construction, which indicated that the range of groundwater-level fluctuations in these wells would not affect the constructed potentiometric surface because the values were small compared to the 200-ft contour interval.

Subterranean Cave Lakes

In addition to measurements from groundwater wells, discrete and continuous water levels measured at four subterranean cave lakes (Hourglass [USGS station 434258103504201], Piso Mojado [USGS station 434258103504301], Bonus [USGS station 434241103503901], and New Year’s [USGS station 434238103503501]; fig. 4) from 2015 to 2019 were used to construct the generalized potentiometric-surface map. A single discrete water-level measurement was available from Piso Mojado, and multiple discrete water-level measurements were available from Hourglass, Bonus, and New Year’s. Single and multiple water-level measurements of the lake surface elevation were taken during cave exploration using cave surveying techniques that correlated elevation changes measured during exploration with reference elevations from survey markers established within and outside the cave network. Continuous water-level measurements were recorded hourly from March 11, 2018, through July 5, 2019, at Hourglass using an unvented pressure transducer. A Solinst LT F30/M10 Levelogger (transducer) was used to measure water depth and a Solinst Model 3001 Barologger (barometer) was used to measure barometric pressure and air temperature. The transducer was suspended about 6 ft below the cave lake surface, and the barometer was placed above the cave lake. Water depth was recorded hourly, corrected for barometric pressure, and converted to water-level elevation by referencing the starting water depth and subsequent water-depth changes to the surveyed lake-surface elevation recorded when the transducer was installed. The surface elevation at Hourglass Lake used for the generalized potentiometric map was the arithmetic mean of the continuous measurements and nine discrete measurements recorded from October 11, 2015, through July 5, 2019, and had a value of 4,687 ft with a standard deviation of 2 ft (table 2). The standard deviation (2 ft) is small compared to the potentiometric-surface contour interval (200 ft); thus, water-level fluctuations were assumed to not impact the accuracy of the mapped potentiometric surface. Water levels and associated ancillary data for each subterranean cave lake site are available through the USGS NWIS database (USGS, 2019).

Groundwater Conditions

Groundwater conditions in the study area consist of confined and unconfined regions of the Madison aquifer. The Madison aquifer is under artesian pressure over most of its regional extent but without flowing well conditions (potentiometric surface below the land surface). The Madison aquifer is unconfined where the Madison Limestone is exposed at outcrops at the land surface. Water levels measured in wells and the four cave lakes in the study area represent confined and unconfined regions of the Madison aquifer and were used to construct well hydrographs and the generalized potentiometric-surface map.

Well Hydrographs

Hydrographs constructed for selected observation wells (fig. 5) showed water levels were lowest from the early to mid-1990s, increased through the late 1990s, peaked in the early 2000s, decreased until 2010, and then increased to the highest levels during 2016–18. Water levels in two USGS observation wells (434700104021401 [CU–93C] and 433517103534201 [CU–95A]) increased 20 ft from 1995 to 2001. A hydrograph was not constructed for USGS observation well 434842103492001 because of the small number of measurements from 1980 to 1995 (table 2). Hydrographs were compared to the monthly precipitation data for NOAA station USC00392087 (Custer, SD, US; NOAA, 2019) graphed as a monthly cumulative departure from monthly normal for the base period January 1980 through December 2010 (fig. 5). The graph shows generally below-normal cumulative precipitation (downward trending) during 1991–94, 2000–8, and 2012–14; cumulative precipitation generally was above normal (upward trending) during 1995–99, 2009–11, and 2015–19. The groundwater well hydrographs reflect the same pattern showing decreasing water levels during times of below-normal cumulative precipitation and increasing water levels during times of above-normal cumulative precipitation.

Table 2. Water-level data (calendar years 1980–2019) used to construct generalized potentiometric-surface map of the Madison aquifer in the study area, South Dakota.

[All water-level data for these sites are available from the U.S. Geological Survey National Water Information System (NWIS) database (U.S. Geological Survey, 2019); Elevation refers to the distance above the land surface datum, North American Vertical Datum of 1988; --, not applicable]

NWIS identification number	Land-surface elevation, in feet	Water-level depth below land surface, in feet			Standard deviation, in feet	Hydraulic-head elevation,[1] in feet	Well included in Strobel and others (2000)	Water-level measurements			Period of record
		Lowest	Highest	Mean				Total count	Date of first	Date of last	
432340103421501	4,200	680	680	680	--	3,520	Yes	1	05/01/1981	05/01/1981	--
432548103414801	4,175	519	541	525	6	3,650	Yes	166	09/16/1992	09/26/2018	1992–2018
432603103295901	3,715	85	100	89	3	3,626	Yes	151	04/08/1996	10/01/2018	1996–2018
432727103390201	4,156	520	520	520	--	3,636	No	1	05/05/2000	05/05/2000	--
432825103391201	4,369	700	700	700	--	3,669	Yes	1	05/17/1993	05/17/1993	--
432858103334201	4,280	638	638	638	--	3,642	No	1	04/24/1997	04/24/1997	--
433155103391101	4,765	250	250	250	--	4,515	No	1	12/07/1999	12/07/1999	--
433138103403501	4,608	75	75	75	--	4,533	No	1	02/07/2003	02/07/2003	--
433233103444501	4,561	800	800	800	--	3,761	No	1	10/15/2007	10/15/2007	--
433233103444001	4,567	650	650	650	--	3,917	No	1	05/05/2005	05/05/2005	--
433517103534201	4,258	502	540	511	7	3,747	Yes	142	07/24/1995	09/26/2018	1995–2018
433642103581601	4,208	470	470	470	--	3,738	No	1	04/27/2006	04/27/2006	--
433906103584801	4,370	625	625	625	--	3,745	No	1	03/30/2005	03/30/2005	--
434032103593701	4,600	900	900	900	--	3,700	No	1	10/04/2005	10/04/2005	--
434214103471801	5,580	895	895	895	--	4,685	No	1	05/11/2004	05/11/2004	--
[2]434238103503501	5,270	652	679	668	12	4,602	No	3	01/01/2017	10/07/2018	2017–18
[2]434241103503901	5,307	606	607	606	1	4,701	No	2	01/01/2017	10/06/2018	2017–18
[2]434258103504201	5,344	655	660	657	2	4,687	No	Continuous[3]	10/11/2015	07/05/2019	2015–19
[2]434258103504301	5,345	659	659	659	--	4,686	No	1	11/09/2015	11/09/2015	--
434700104021401	4,645	855	909	879	12	3,769	Yes	115	03/21/1994	10/01/2018	1994–2018
434806103475801	6,315	110	110	110	--	6,215	No	1	05/07/2009	05/07/2009	--
434840103474601	6,260	35	35	35	--	6,225	No	1	06/29/1990	06/29/1990	--
434842103492001	6,275	143	182	161	19	6,114	Yes	3	06/19/1980	09/26/1995	1980–95
434856103485101	6,267	125	125	125	--	6,142	No	1	07/07/2010	07/07/2010	--
434918103492501	6,290	174	174	174	--	6,116	No	1	09/22/2006	09/22/2006	--
434928103493001	6,300	137	137	137	--	6,163	No	1	06/27/1998	06/27/1998	--
435028103503601	6,491	133	133	133	--	6,358	No	1	05/18/2006	05/18/2006	--
435057103501701	6,471	145	145	145	--	6,326	No	1	06/08/2006	06/08/2006	--

[1]Average hydraulic-head elevation reported for wells with more than one water-level measurement.

[2]Subterranean cave lake.

[3]Continuous data in hourly increments from 3/11/2018 through 07/05/2019 and nine discrete measurements from 10/11/2015 through 3/11/2018.

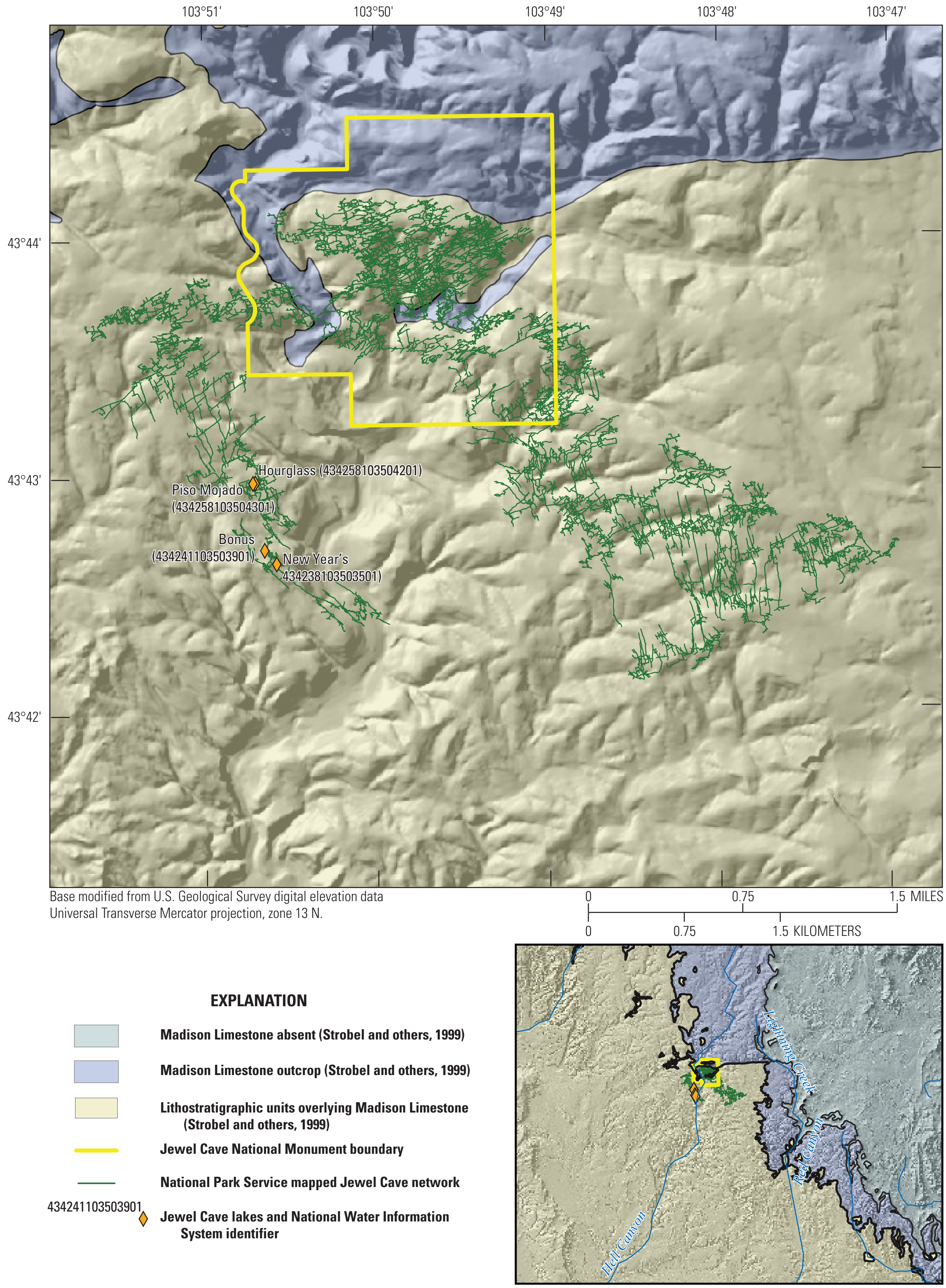


Figure 4. The mapped cave network and subterranean cave lakes near Jewel Cave National Monument, South Dakota.

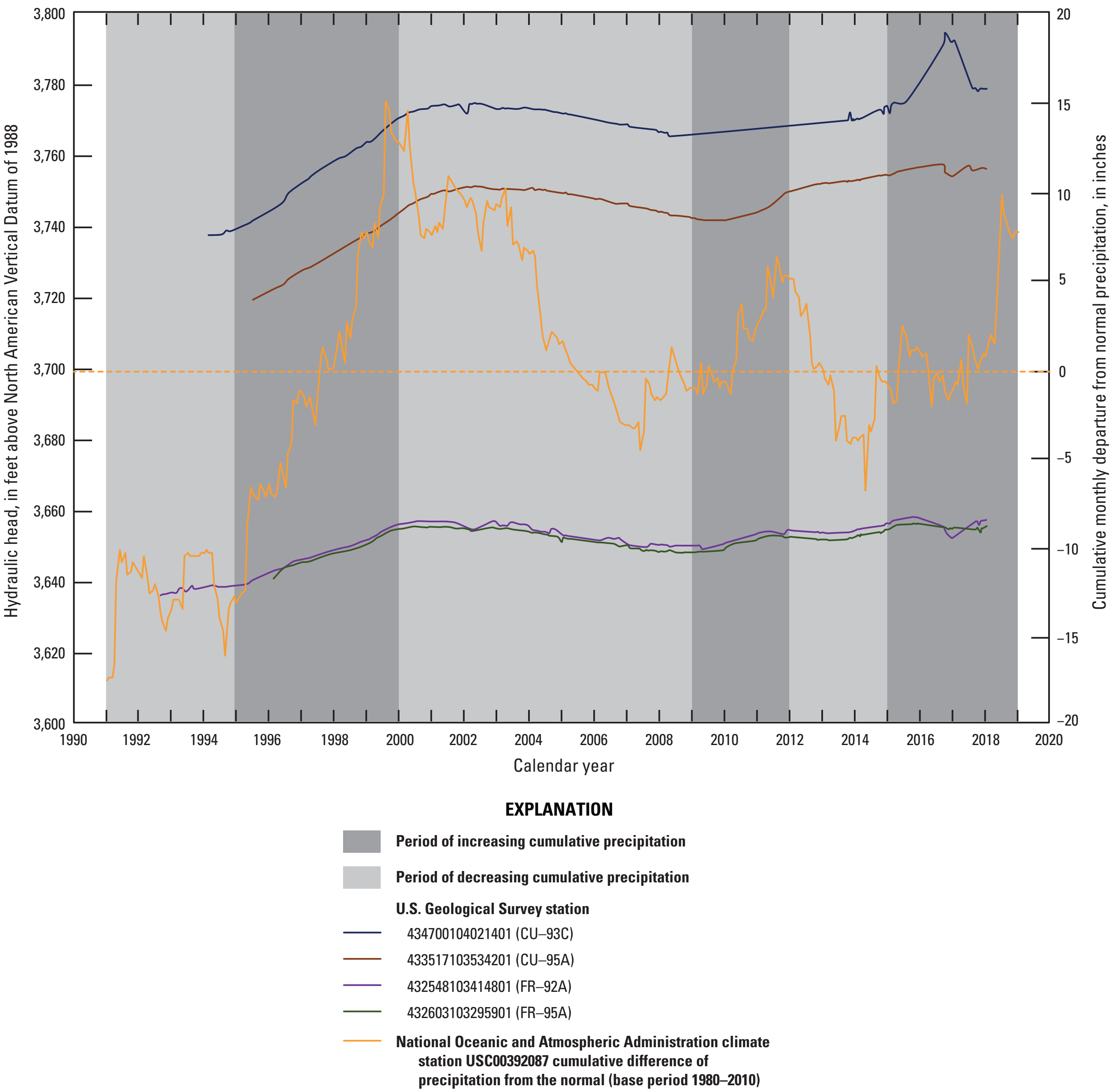
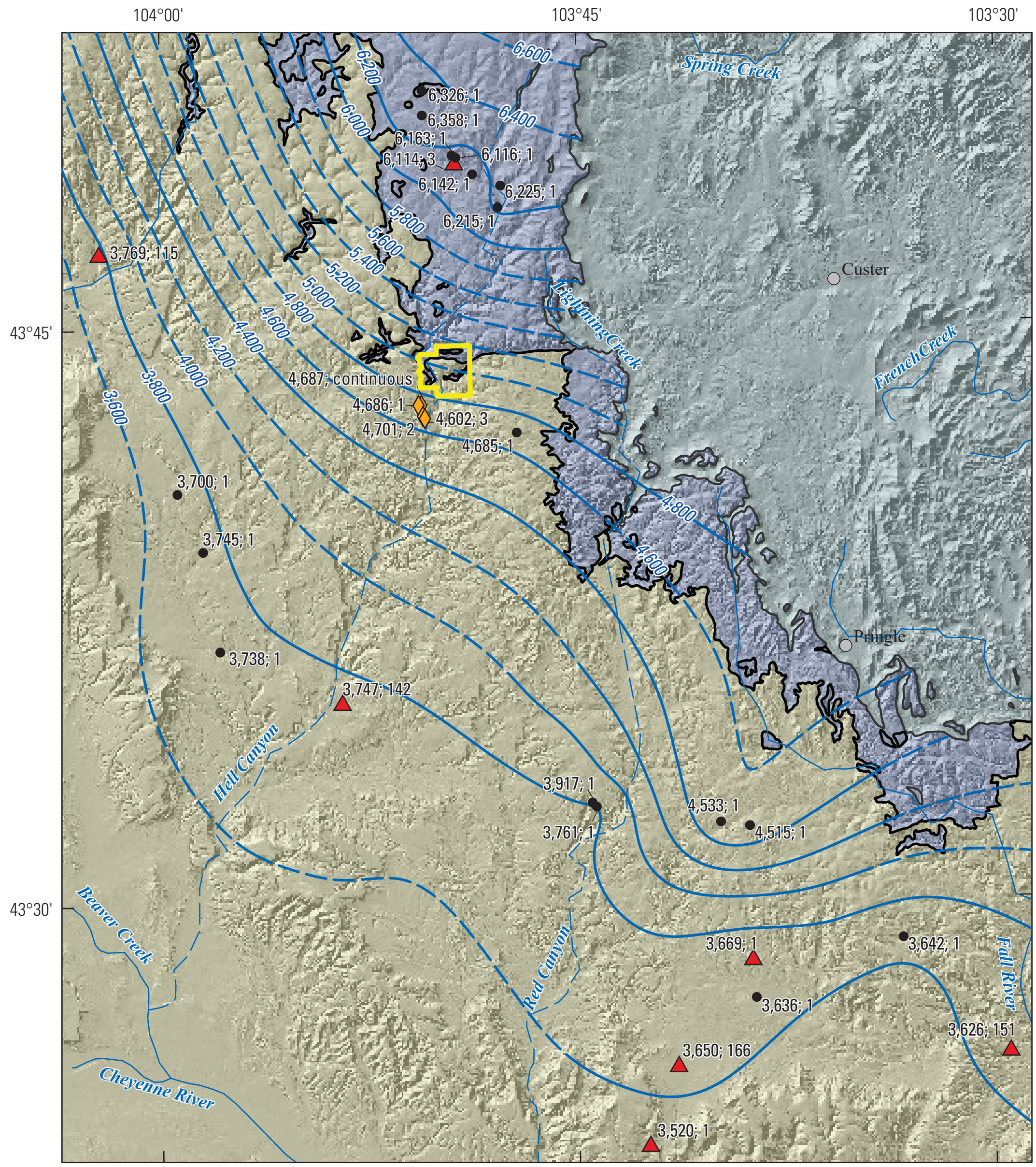


Figure 5. Selected hydrographs of observation wells in the study area, South Dakota.

Generalized Potentiometric-Surface Map

Water-level data from calendar years 1980 to 2019 were used to construct a generalized potentiometric-surface map of the Madison aquifer. Potentiometric contours were generated using geographic information system software (ArcGIS Pro; Esri, 2019) to interpolate hydraulic-head values of wells completed in the Madison aquifer in the study area (fig. 6). Well locations and hydraulic-head values were mapped using the "XY Table to Point" tool within the software in ArcGIS Pro before interpolating hydraulic head. Hydraulic-head values were interpolated using the "Topo to Raster" tool in ArcGIS Pro to map the potentiometric surface. The Topo to Raster tool was designed specifically for creating elevation surfaces using an iterative finite-difference interpolation method that combines the efficiency of local interpolation methods with the surface continuity of global interpolation methods (Esri, 2019). Hydraulic heads were then contoured using a 200-ft contour interval to represent the potentiometric surface. Contour lines were manually edited to correct for extremes in high and low water-level elevations and in regions of sparse data within the study area.



Base modified from U.S. Geological Survey digital elevation data
Universal Transverse Mercator projection, zone 13 N.

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

Madison Limestone absent (Strobel and others, 1999)

Madison Limestone outcrop (Strobel and others, 1999)

Lithostratigraphic units overlying Madison Limestone (Strobel and others, 1999)

Jewel Cave National Monument boundary

3,600 **Potentiometric contour**—Shows average observed elevation at which water level would have stood in tightly cased well, in feet. Dashed where approximately located. Contour interval 200 feet. Datum is North American Vertical Datum of 1988 (NAVD 88)

4,700; 1 **Jewel Cave lake site**—Numbers are hydraulic head, in feet above land surface datum NADV 88; and number of water-level measurements (table 2).

3,636; 1 **National Water Information System well added after Strobel and others (2000)**—Numbers are hydraulic head, in feet above land surface datum NADV 88; and number of water-level measurements (table 2).

3,520; 1 **National Water Information System well used in Strobel and others (2000)**—Numbers are hydraulic head, in feet above land surface datum NADV 88; and number of water-level measurements (table 2).

Figure 6. A generalized potentiometric-surface map of the Madison aquifer in the study area, South Dakota.

Groundwater Flow

The generalized potentiometric-surface map (fig. 6) was used to characterize groundwater-flow directions in the study area. Groundwater-flow directions were assumed to be perpendicular to the potentiometric contours (fig. 7); however, groundwater flow might not actually be perpendicular to generalized potentiometric contours because of the anisotropic permeability arising from cave and fracture orientations in the karstic Madison aquifer (Greene and Rahn, 1995). The map indicates that groundwater near Jewel Cave National Monument originates from recharge to the Madison aquifer in the higher elevations in the north-central area of the map, flows west to south-southwest through the Jewel Cave network, and then southeast (fig. 7). The groundwater-flow pattern is similar to the flow directions mapped by previous investigations also concluding that Madison aquifer groundwater near Jewel Cave National Monument originates from recharge sources in the Madison Limestone on the south-western side of the Black Hills, initially flows southwest, and then turns southeast (Galloway, 2000; Strobel and others, 2000; Long and Valder, 2011; Long and others, 2019).

The generalized potentiometric-surface map constructed for this study was compared to a potentiometric-surface map of the Madison aquifer by Strobel and others (2000). A visual comparison indicates that contours in both maps are similar in locations, and the direction of groundwater flow is comparable (fig. 7). However, potentiometric-contour elevations differ by about 50 ft at similar locations likely because the water-level data recorded from 1995 to 2019 at 17 wells and 4 subterranean cave lakes (table 2) used to construct the generalized potentiometric-surface map were not available to Strobel and others (2000) at the time of their publication.

Groundwater Recharge

The Madison aquifer in the Black Hills generally receives recharge in areas where the Madison Limestone is exposed at the land surface (Putnam and Long, 2009; fig. 1). Sources of recharge to the Madison aquifer include precipitation infiltration and streamflow losses where streams cross formation outcrops. Putnam and Long (2009) estimated mean annual recharge (water years 1988–1997) to the Madison aquifer in the eastern Black Hills to be 16.1 cubic feet per second from precipitation infiltration and 38.8 cubic feet per second from streamflow losses at 10 streams crossing Madison Limestone outcrops.

Visual comparison of a hydrograph of Hourglass Lake water levels with cumulative precipitation at NOAA climate station USW00094032 (Custer County Airport, SD, US) for March 11, 2018, through July 5, 2019, indicates cave lake-water-level elevations increased as cumulative precipitation increased but after some time delay (fig. 8). The linear relation between cave lake-water level and cumulative precipitation was evaluated quantitatively using the Pearson correlation coefficient (Wright, 1921). The Pearson correlation coefficient assumes that pairs of data are related linearly; a coefficient value of positive 1 indicates the data correlate positively, a value of negative 1 indicates the data correlate negatively, and a value of zero indicates the data are weakly linearly correlated. The correlation coefficient was calculated for the data by pairing Hourglass Lake water levels at 12:00 p.m. each day with the cumulative precipitation at Custer County Airport for the same day. The calculated Pearson correlation coefficient (0.91) indicated a strong positive correlation between increasing water-level elevations and increasing cumulative precipitation. However, visual examination of a plot of water-level elevations and cumulative precipitation indicated the relation was only loosely linear, most likely because of a delay between the time of precipitation and the time at which cave lake-water levels began to increase. Increasing offset times (measured in days) were applied to the precipitation data, and the Pearson correlation coefficient was calculated for each offset to determine the number of offset days with the highest correlation coefficient (Kuniansky, 2002). An offset of 41 days optimized the correlation coefficient and resulted in a larger Pearson correlation coefficient (0.97). In addition, visual examination of a plot of water-level elevations and cumulative precipitation with the 41-day offset indicated a more linear relation and could be interpreted to indicate that Hourglass Lake is hydraulically connected to precipitation recharge occurring to Madison Limestone outcrops at land surface. Additionally, the response of water levels at Hourglass Lake is about 41 days after precipitation is recorded at Custer County Airport. However, the correlation is not exact; Hourglass Lake water levels began to increase on about March 22, 2019, but the rate of cumulative precipitation did not begin to increase until early May 2019, indicating that sources of recharge other than precipitation from the Custer County Airport area also could contribute to Hourglass Lake recharge. An additional source of recharge that explains the relation between precipitation and Hourglass Lake water levels in March is early spring snowmelt. Snow melting at the higher elevations of Madison Limestone outcrops during spring months could recharge the aquifer and contribute to increasing water levels at cave lakes without corresponding increases in measured precipitation at weather stations.

Data and Interpretive Limitations

The data and data interpretation used to construct the generalized potentiometric-surface map have limitations. Much of the data used to construct the map consisted of a single water-level measurement taken by a well driller at the time of well installation. Driller's measurements could be from uncalibrated instruments subject to errors, or from a well in which the water level had not fully recovered after well completion and development. Additionally, single water-level measurements were from different years (1980–2018),

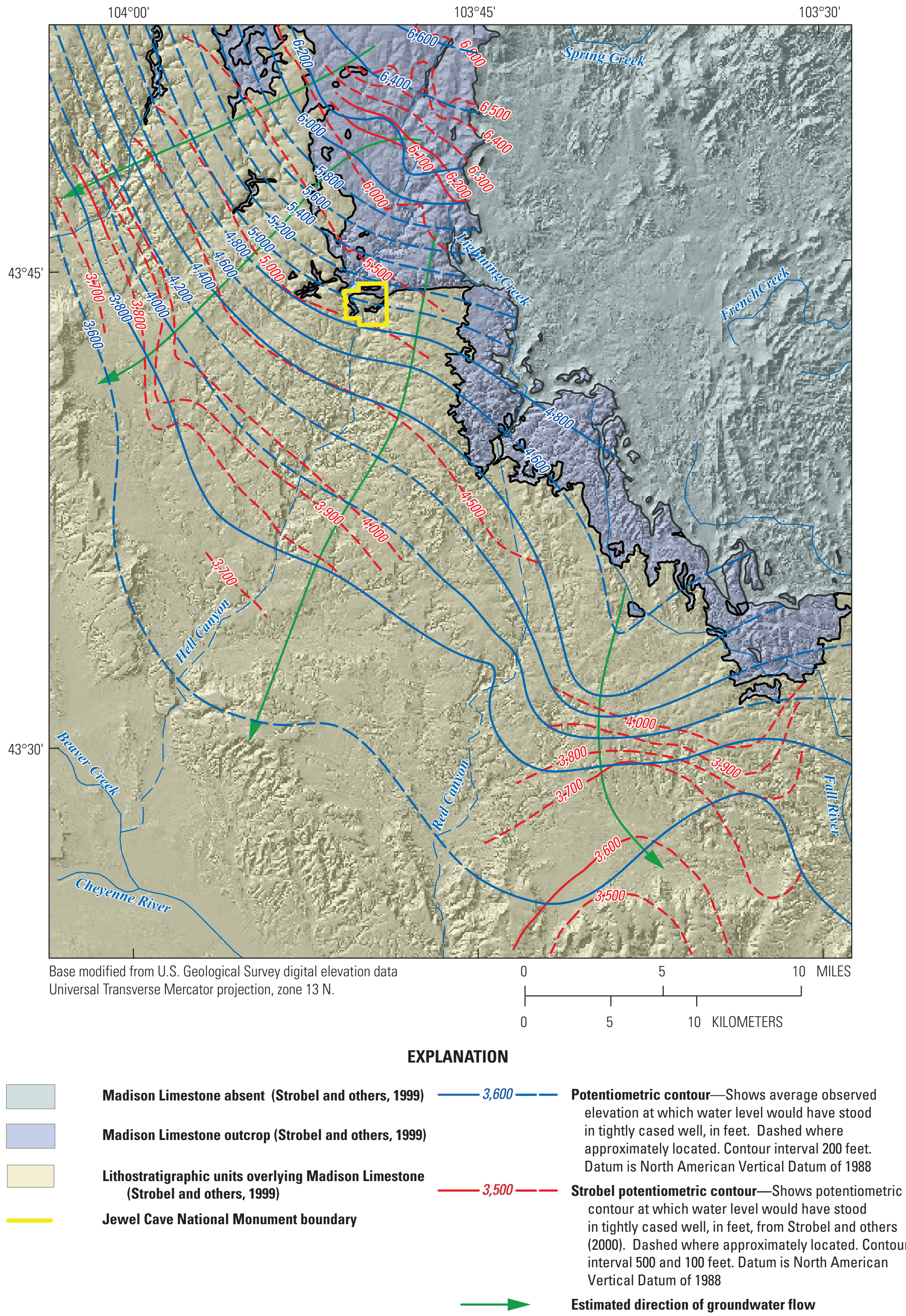


Figure 7. The generalized direction of groundwater flow in the study area, South Dakota. Potentiometric-surface map of Strobel and others (2000) provided for comparison.

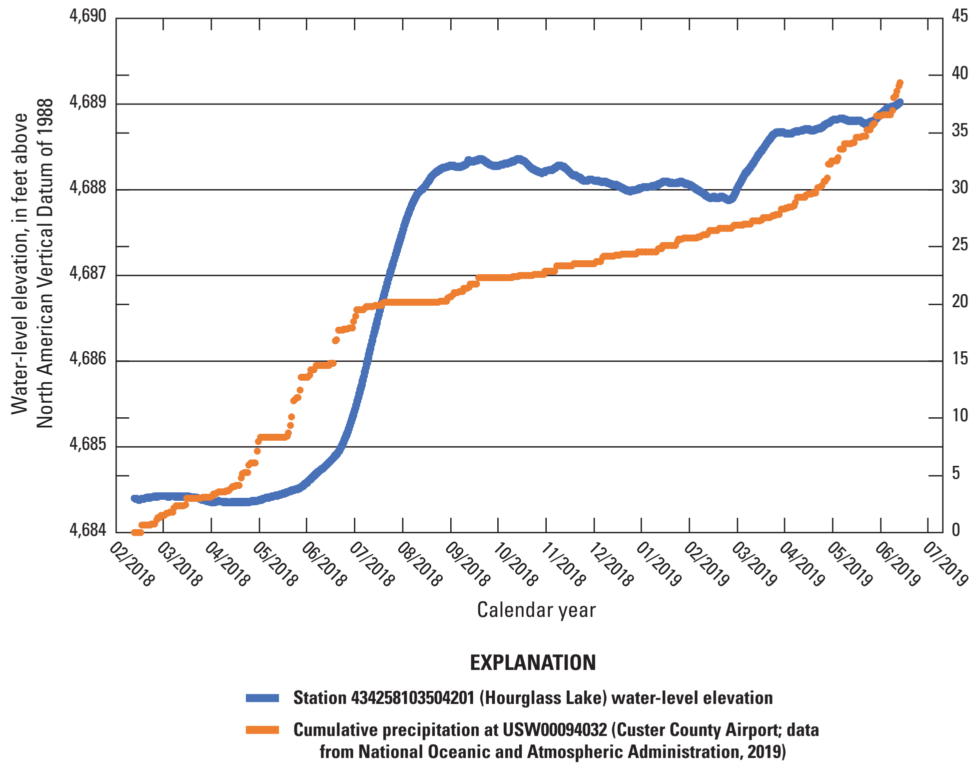


Figure 8. Hourglass Lake water-level elevations in relation to cumulative precipitation at Custer County Airport, South Dakota.

different times of year, and different depth intervals within the aquifer; therefore, the potentiometric surface is general and not specific. In some cases, inferred potentiometric contours may pass through unsaturated zones of the Madison Limestone because of interpolation or data gaps. Data interpretation also had limitations primarily because potentiometric contours are nonunique numeric approximations of a dynamic and complex system. Contour interpretations are affected by the availability and location of groundwater-level measurements and the interpolation method. Taylor and Alley (2001) highlighted the importance of long-term groundwater-level monitoring and the effects of data gaps when spatially interpolating water-level data. Areas without water-level data potentially create regions in the potentiometric-surface map with less accurate interpolation, highly inferred contours, or both.

Comparing the generalized potentiometric-surface map constructed for this study with a previously published map (Strobel and others, 2000) indicated similarity and provided some validation of map construction. The potentiometric-surface map constructed for this study could be used as a tool to evaluate the hydrogeologic characteristics of the Madison aquifer in the study area, including groundwater-flow directions and hydraulic gradients.

Summary

Jewel Cave National Monument in the Black Hills of southwestern South Dakota contains one of the longest mapped cave passages in the world. Previous studies indicated that the Madison aquifer is in hydraulic connection with subterranean cave lakes in the Jewel Cave network. A generalized potentiometric-surface map of the Madison aquifer near Jewel Cave National Monument was constructed using water levels measured from calendar years 1980 to 2019 in 24 groundwater wells and 4 subterranean cave lakes interpreted to be in hydraulic connection with the aquifer. The map indicated that groundwater near Jewel Cave National Monument originates from recharge to the Madison aquifer in the higher elevations in the north-central area of the map, flows west to south-southwest through the Jewel Cave network, and then southeast.

Hydrographs were constructed using water levels from four observation wells and one subterranean lake (Hourglass Lake) in the Jewel Cave network to evaluate historical and current groundwater recharge to the Madison aquifer in the study area. All four observation-well hydrographs indicated Madison aquifer water levels were lowest from the early to mid-1990s, increased through the late 1990s, peaked in the early 2000s, decreased until 2010, and then increased to the highest levels during 2016–18. A visual comparison of the Hourglass Lake hydrograph with cumulative precipitation, and a statistical comparison of lake water levels with cumulative precipitation, indicated that lake-water levels increased as cumulative precipitation increased, most likely due to precipitation recharge to hydraulically connected Madison Limestone outcrops. Other studies in the Black Hills indicated that recharge to the Madison aquifer is mostly from precipitation recharge and streamflow losses to aquifer outcrop areas.

Comparing the potentiometric-surface map constructed for this study with one constructed from an earlier study indicated similarity and, therefore, provided some validation of map construction. However, potentiometric-contour elevations between studies differed by about 50 ft at similar locations, most likely due to inclusion of water-level data from 17 additional wells and 4 subterranean cave lakes collected from 1995 to 2019 that were not available in the earlier study. The generalized potentiometric-surface map constructed for this study could be used by park managers and others as a tool to evaluate the hydrogeologic characteristics of the Madison aquifer in the study area, including groundwater-flow directions and hydraulic gradients.

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