Prepared in cooperation with the Rosebud Sioux Tribe

Trends in Groundwater Levels in and near the Rosebud Indian Reservation, South Dakota, Water Years 1956–2017

Scientific Investigations Report 2020–5119

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DAVID BERNHARDT, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2021

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Suggested citation:
Valseth, K.J., and Driscoll, D.G., 2021, Trends in groundwater levels in and near the Rosebud Indian Reservation, South Dakota, water years 1956–2017: U.S. Geological Survey Scientific Investigations Report 2020–5119, 46 p., https://doi.org/10.3133/sir20205119.

Associated data for this publication:
U.S. Geological Survey, 2019, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN.

ISSN 2328-0328 (online)

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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
mile (mi)	1.609	kilometer (km)
	Area	
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)
million gallons per day (M/gal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day (M/gal/d)	1.54723	cubic foot per second (ft^3/s)

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 National Geodetic Vertical Datum of 1929 (NGVD 29) unless otherwise specified.

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

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

Supplemental Information

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

Abbreviations

LOESS	locally estimated scatterplot smoothing
NWIS	National Water Information System
p-value	probability value
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RST	Rosebud Sioux Tribe
SDDENR	South Dakota Department of Environment and Natural Resources
STP	short-term persistence
τ	tau from Kendall's tau nonparametric test
T_{max}	maximum air temperature
T_{min}	minimum air temperature
USGS	U.S. Geological Survey
WY	water year

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Abstract

The U.S. Geological Survey (USGS), in cooperation with the Rosebud Sioux Tribe, completed a study to characterize water-level fluctuations in observation wells to examine driving factors that affect water levels in and near the Rosebud Indian Reservation, which comprises all of Todd County. The study investigates concerns regarding potential effects of groundwater withdrawals and climate conditions on groundwater levels within an area that includes Todd County and a surrounding area that extends 10 miles north, east, and west of the county border. Characterization of water-level fluctuations in observation wells and relative driving factors was accomplished by statistical trend analysis.

Two statistical methods were used for analysis of temporal trends for climatic and hydrologic data. To determine which trend analysis to use, applicable datasets were tested for statistically significant short-term persistence (STP). In the absence of significant STP, existence of statistical trends was determined using the standard Mann-Kendall test for probability values less than or equal to 0.10 (90-percent confidence level); however, a modified Mann-Kendall test was used for datasets where statistically significant STP was detected. Trend magnitudes were computed using the Sen's slope estimator.

Monthly data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) were aggregated to obtain annual and seasonal datasets for total precipitation, minimum air temperature (T_{min}), and maximum air temperature (T_{max}) for the study area and a surrounding buffer area. Trend tests for total precipitation, T_{min}, and T_{max} were completed for annual and seasonal time series for water years 1956–2017, which is about 2 years before the earliest available water-level measurements. A 2-year offset was arbitrarily selected because scrutiny of water-level and precipitation data indicated that responses of groundwater levels for many of the observation wells lagged major changes in precipitation patterns by about 2 years. Statistically significant upward trends were detected for annual precipitation and annual T_{min} for almost all of the study area and the surrounding buffer area. Statistically significant downward trends in T_{max} were detected for a very small part of the study area; however, the sparse spatial coverage reduces confidence that these are true trends. Spatial distributions of statistically significant trends in seasonal climate data were generally similar to the annual trends, but with substantial differences in the spatial density of the trends.

Groundwater trends for 58 observation wells were analyzed for three separate water-level parameters (minimum, median, and maximum) because wells are measured sporadically and data are biased towards more frequent measurements during periods of heaviest irrigation demand. Trends in the time series of annual precipitation (from PRISM) starting 2 years earlier than for the associated water-level trend also were analyzed for the location of each individual observation well. Sen's slope and Mann-Kendall probability values (*p*-values) were computed for the three water-level parameters and for the annual precipitation time series. Graphs showing results of trend analyses for each observation well also showed changes over time in the sum of licensed groundwater withdrawals within six specified radii (0.5, 1, 2, 3, 4, and 5 miles) of each well as a qualitative indicator of proximal groundwater demand.

Of all 58 observation wells considered, 28 wells had significant upward trends for at least one of the three water-level parameters, 11 wells had significant downward trends for at least one water-level parameter, and 19 wells did not have any significant trends. Significant upward trends in annual precipitation were detected for 48 of the 58 wells.

Results of trend analyses likely show the effects of groundwater withdrawals on water levels in the Ogallala aquifer in areas of substantial demand. Precipitation trends are significantly upward for 43 of the 48 wells completed in the Ogallala aquifer that were analyzed. Of the 48 Ogallala aquifer wells, 24 had significant upward trends for at least one water-level parameter (17 with all 3); however, 10 wells had statistically significant downward trends for at least one water-level parameter (8 with all 3 parameters). All but one of the wells with significant downward trends are located in the south-central part of the study area where licensed irrigation withdrawals are concentrated.

For the eight wells completed in the Arikaree aquifer, three wells had significant upward trends for all three water-level parameters. A single well that is completed in the Arikaree aquifer had significant downward trends for all three water-level parameters. This well is located in the south-central part of the study area where licensed groundwater withdrawal wells are concentrated and where 9 of the 10 Ogallala aquifer wells with statistically significant downward trends for at least one water-level parameter are located. This well is in an area where the hydraulic head in the Arikaree aquifer is artesian and generally similar to that of the Ogallala aquifer. Thus, hydraulic head in the Arikaree aquifer may be affected by withdrawals from the Ogallala aquifer in this vicinity.

For two wells completed in an alluvial aquifer, one well had a significant upward trend for all three water-level parameters and one well had no discernible trends. Withdrawals from the Arikaree and alluvial aquifers generally are much smaller than from the Ogallala aquifer.

Introduction

The Rosebud Indian Reservation comprises all of Todd County in south-central South Dakota (fig. 1). The primary sources of groundwater for the Rosebud Indian Reservation are the Ogallala and Arikaree aquifers (saturated areas of the Ogallala and Arikaree Formations, fig 1), which are part of the High Plains aquifer system that extends as far south as Texas and is the most heavily utilized aquifer system in the United States (Weeks and others, 1988). Large-scale irrigation development from the High Plains aquifer system has substantially decreased groundwater storage and reduced water levels in several States (McGuire, 2011, 2017). In recent years, increasing commodity prices have driven the agricultural industry towards more intensive agricultural practices aimed at increased crop production, which has potential to increase irrigation demand. Increased water demand also has potential to reduce flow in streams and rivers with base flow sourced from the Ogallala and Arikaree aquifers (Long and others, 2003; Long and Putnam, 2010; Davis and Putnam, 2013; Davis and others, 2015). The Rosebud Sioux Tribe (RST) is especially concerned about potential effects of groundwater withdrawals and climate conditions on water levels in the Ogallala and Arikaree aquifers, which are critical for municipal, domestic, and agricultural water supplies within and near the reservation. To help address these concerns, the U.S. Geological Survey (USGS), in cooperation with the RST, completed a study to characterize water-level fluctuations in observation wells to examine driving factors that affect water levels in and near the Rosebud Indian Reservation, which comprises all of Todd County. The results of this study can be used to identify areas of concerning groundwater change that require further investigation and to identify areas with limited data that could be enhanced with data collection tools, such as real-time well recorders.

The State of South Dakota has jurisdiction for issuing water rights for nontribal lands within and beyond the reservation boundaries. The RST has water-rights jurisdiction only for tribal lands within the reservation boundaries.

Purpose and Scope

The purpose of this report is to describe trends in groundwater-level fluctuations in observation wells relative to selected driving factors that affect groundwater levels in and near the Rosebud Indian Reservation. The study area includes Todd County and a surrounding area that extends 10 miles (mi) north, east, and west of Todd County. Driving factors considered that affect groundwater levels include climate conditions and groundwater withdrawals. Temporal trends are analyzed for water-level records during 1957–2017 for 58 observation wells operated by the South Dakota Department of Environment and Natural Resources (SDDENR) or the RST and for selected climatic conditions. Groundwater withdrawals within 5 mi of each observation well are qualitatively compared to water levels. Other factors that may affect water levels, such as groundwater interactions with surface water or ground cover, which can affect recharge, were not considered. Development of quantitative relations among water levels and driving factors is beyond the scope of the study; however, results of the study could inform future efforts to do so.

Description of Study Area

The study area (fig. 1) includes all of Todd County and a surrounding area that extends 10 mi north, east, and west of Todd County. Agriculture is the primary land use within Todd County (Long and others, 2003), with most land used for grazing or hay production for cattle ranching. Approximately 13 percent of land use is for crops, which include wheat, sunflower seeds, corn, and soybeans (U.S. Department of Agriculture, 2017). Most of the cultivated crop land is in south-central Todd County, where there is extensive irrigation from the Ogallala aquifer. Land use in South Dakota counties adjacent to Todd County is generally similar; however, the 2015 reported water use (Dieter and others, 2018) highlights that the irrigated area and the total for all groundwater use in Todd County is larger than in any of the adjacent counties (table 1). More detailed descriptions of land use, physiography, and climate are available from Carter (1998), Long and others (2003), Long and Putnam (2010), Davis and Putnam (2013), and Davis and others (2015).

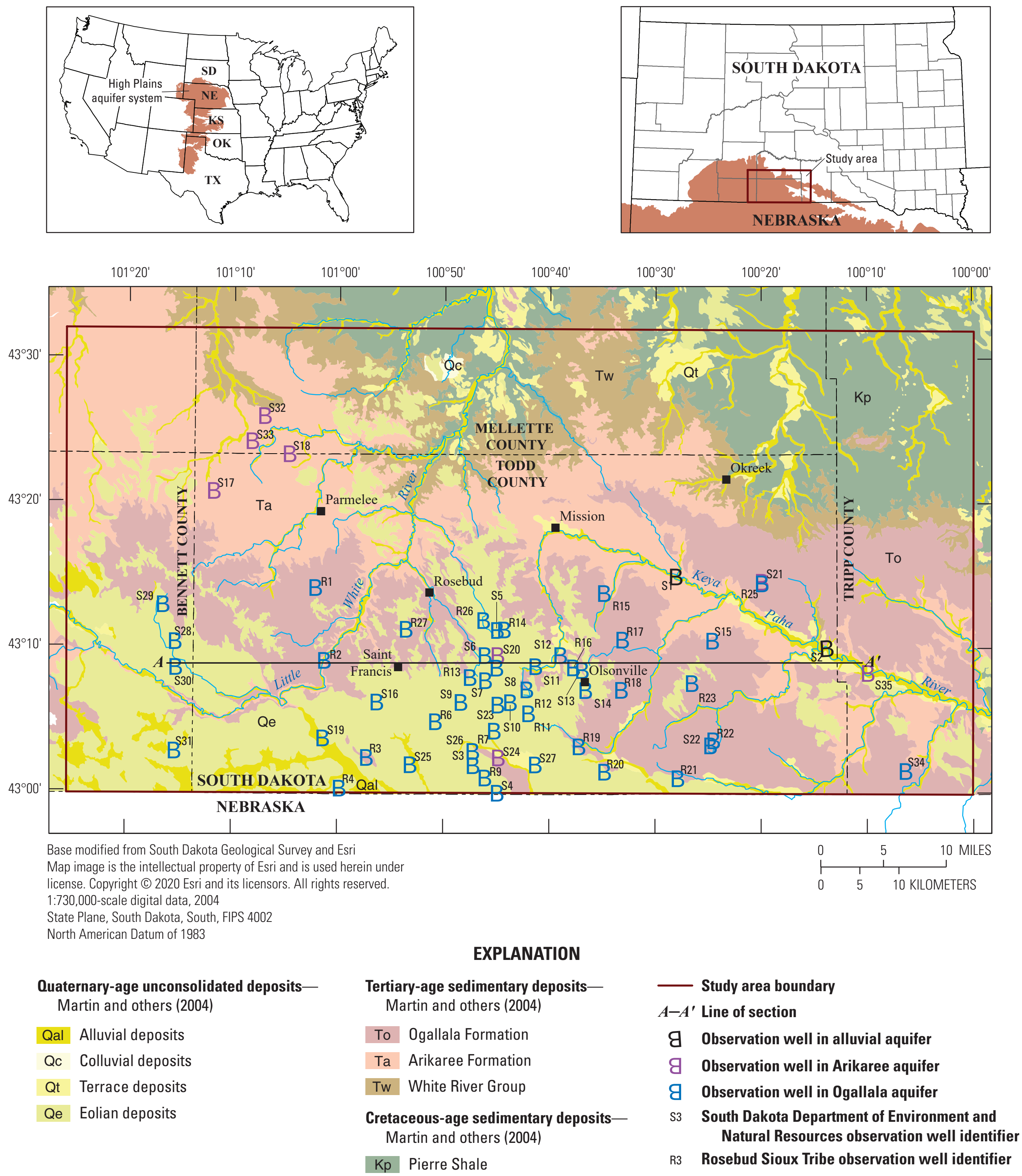


Figure 1. Location of the study area and the Rosebud Indian Reservation in south-central South Dakota.

Table 1. Summary of water use for calendar year 2015 for selected major categories for South Dakota counties in the study area.

[Water use data from Dieter and others (2018); GW, groundwater; SW, surface water; NR, not reported]

County	Total for all GW	GW public supply	GW livestock	Irrigation GW	Irrigation SW	Irrigation total	Irrigated area[a] (thousands of acres)
Water use, in millions of gallons per day							
Bennett	8.90	0.00	0.30	8.60	0.00	8.60	9.04
Mellette	0.26	0.03	0.22	0.01	0.74	0.75	0.67
Todd	12.77	0.00	0.27	12.50	0.30	12.80	7.89
Tripp	1.94	0.49	0.71	0.74	1.56	2.30	1.60
Total	23.87	0.52	1.50	21.85	2.60	24.45	19.20
Water use, in cubic feet per second							
Bennett	13.77	0.00	0.46	13.31	0.00	13.31	13.99
Mellette	0.40	0.05	0.34	0.02	1.15	1.16	1.04
Todd	19.76	0.00	0.42	19.34	0.46	19.81	12.21
Tripp	3.00	0.76	1.10	1.15	2.41	3.56	2.48
Total	36.94	0.80	2.32	33.81	4.02	37.84	29.71

[a]Irrigated area includes groundwater and surface-water sources.

Water resources of Mellette and Todd Counties were described in detail by Carter (1998). Extensive descriptions of the hydrogeology of Todd County and surrounding counties were provided in conjunction with groundwater-flow models developed by several investigators (Long and others, 2003; Long and Putnam, 2010; Davis and Putnam, 2013; Davis and others, 2015). The main rivers in Todd County are the Little White River, which flows through Todd County from southwest to northeast; and the Keya Paha River, which originates in Todd County and flows to the east (fig. 1).

Although the Ogallala and Arikaree aquifers are the primary sources of groundwater in the study area, groundwater also is obtained from several minor aquifers contained in unconsolidated deposits of Quaternary age that include alluvium, eolian deposits, and terrace deposits (fig. 1). The Ogallala aquifer comprises the saturated sandstones and silt of the Tertiary-age Ogallala Formation and is present throughout the southern part of the study area (Long and others, 2003). The Arikaree aquifer comprises the saturated sandstones and siltstones of the Tertiary-age Arikaree Formation, which underlies the Ogallala Formation, where present. The Arikaree aquifer exists throughout all but the northeastern part of study area (Long and others, 2003). The Ogallala and Arikaree aquifers are included in the High Plains aquifer system that underlies parts of eight States and extends from southern South Dakota to Texas (fig. 1). The White River aquifer is present throughout most of the study area and is used as a water source where the Ogallala and Arikaree aquifers are not present (Carter, 1998). The White River aquifer consists primarily of the saturated, poorly consolidated siltstones and claystones and interbedded sand layers within the Tertiary-age White River Group (fig. 1). A thick sequence of Cretaceous-age formations (primarily shale deposits) that include the Pierre Shale (fig. 1) underlie the White River Group.

An example of the bedrock hydrogeology in Todd County is shown in figure 2 (adapted from Long and Putnam, 2010), which shows a hydrogeologic section for line of section *A–A*' on figure 1 (alluvium, eolian deposits, and terrace deposits are not shown on fig. 2). In most areas, the hydraulic head (water-level altitude) in the Arikaree aquifer is above the top of the aquifer, which indicates an artesian (confined) condition in which the water level in a well will rise above the altitude at which the aquifer is penetrated. The Arikaree aquifer is confined where overlain by impermeable materials in the Ogallala Formation, and the deeper part of the Arikaree aquifer is under confined conditions where impermeable material exists in the upper part of the Arikaree Formation (Carter, 1998). Hydraulic heads in the Ogallala and Arikaree aquifers are quite similar in many areas, but the hydraulic head in the Arikaree aquifer is higher than that of the overlying Ogallala aquifer in most areas. Hydraulic heads in the Ogallala and Arikaree aquifers are intercepted by the land surface in the vicinity of several incised river or stream channels.

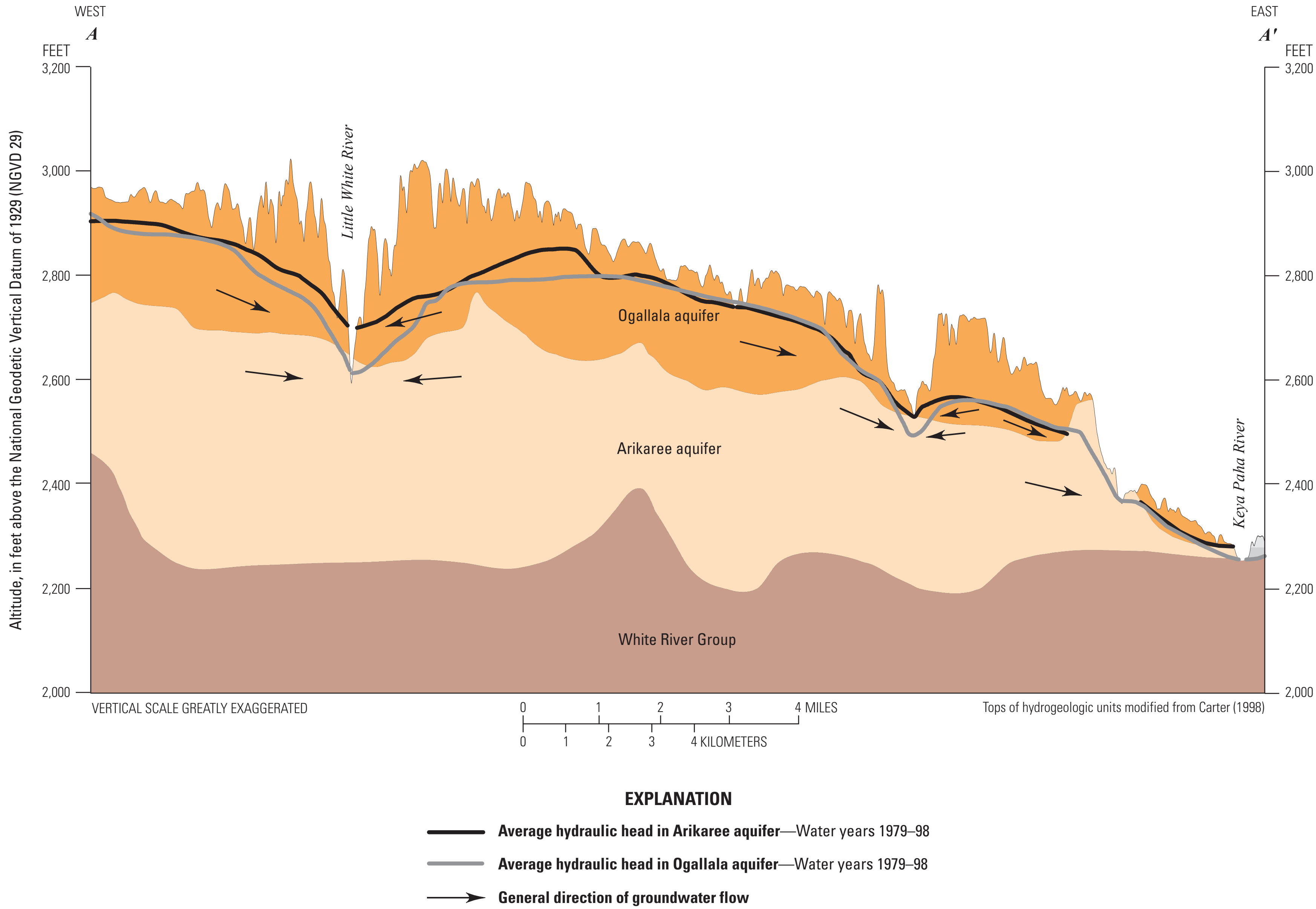


Figure 2. Relations among hydraulic head, bedrock hydrogeologic units, and topographic features in the study area (adapted from Long and Putnam, 2010).

Climate conditions and groundwater withdrawals are widely recognized as two primary factors that affect water levels for any given aquifer. Climate conditions can affect groundwater levels primarily through changes in recharge conditions. Groundwater discharge from the Ogallala and Arikaree aquifers provides substantial base flow to the Little White River, Keya Paha River, and their tributaries in and near Todd County (Carter, 1998; Long and others, 2003; Long and Putnam, 2010; Davis and Putnam, 2013; Davis and others, 2015). Thus, groundwater levels in these aquifers would decline naturally during prolonged periods of below-mean recharge associated with prolonged drought conditions. Groundwater levels can rise somewhat quickly in response to large episodic recharge associated with periods of above-mean precipitation; however, declines in response to prolonged below-mean precipitation typically are slower. Declining groundwater levels may be further affected by increased groundwater withdrawals during dry periods.

Data Sources and Analytical Methods

Analyses primarily involved (1) temporal trends for measured water levels in observation wells and for estimated precipitation at each observation well, and (2) qualitative consideration of effects of groundwater withdrawals on groundwater levels. All datasets considered are compiled by water year (WY), which is a 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends. Within this report, all references to years involving water-related data are for WYs, unless specifically noted as calendar years.

Data Sources

The primary data sources used in this report are estimated climate data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly and others, 1994, 2002, 2008) and records of water levels in observation wells measured by the SDDENR or RST. Data regarding licensed groundwater withdrawals in and near Todd County, including tribal water-use and SDDENR water-rights information, were also considered. Licensed groundwater withdrawals are used throughout this report and are defined as permitted and licensed withdrawals by the SDDENR and estimated municipal and irrigation water use by the RST (SDDENR, 2017, 2019).

Climate Data

Climate data were estimated using total precipitation, minimum air temperature (T_{min}), and maximum air temperature (T_{max}) outputs from PRISM (Daly and others, 1994, 2002, 2008). PRISM interpolates monthly total precipitation, monthly means of daily T_{min}, and monthly means of daily T_{max} from weather stations to a 2.5-arc-minute grid for the conterminous United States. Monthly PRISM data for total precipitation, T_{min}, and T_{max} were aggregated to obtain datasets of annual total precipitation and annual means of T_{min} and T_{max} for the study area and a surrounding buffer area. These gridded data were used to display spatial distributions of trends in climate data. The time-series data for annual precipitation were used to further evaluate precipitation trends for the study area.

Monthly PRISM data were summed to annual total precipitation for individual well locations for comparisons to water-level records for all observation wells that were considered. Before summing, monthly precipitation for each well was estimated by inverse weighting by distance to cell centers of the four closest cell centers of the 2.5-arc-minute grid cell for each well location. PRISM data generally become progressively less reliable before about 1960 (Gibson and others, 2002) because of decreasing density of source data. This was not considered an issue, however, because precipitation data before 1960 were used only minimally for comparisons with water-level records. PRISM data for total precipitation dating back to 1895, which is the oldest extent of available PRISM data (Gibson and others, 2002), were used to provide a perspective on long-term precipitation trends for the study area.

Water-Level Records

A primary dataset includes publicly available records of measured water levels for 35 observation wells (table 2) monitored by the SDDENR (SDDENR, 2018) that are within 5 mi of Todd County (fig. 1). The 5-mi buffer is used to fill data gaps along the Todd County border and to evaluate potential effects of withdrawals near Todd County. Consideration of observation wells in Nebraska was beyond the scope of the study. Additional water-level records from 23 observation wells in Todd County monitored by the RST also are included (fig. 1). All wells are assigned map numbers in table 2 that identify the wells on figure 1. SDDENR wells generally follow a naming convention that identifies the county, calendar year it was drilled, and a “sequential” letter. For example, well TD-76D (map number S8, fig. 1) is the fourth of 10 wells drilled in Todd County during calendar year 1976. The R in the sequential identifier, such as well TD-57CR, indicates a “replacement” well that was drilled at the same location as the previous well. RST wells are labelled as “RST” followed by a sequential number indicating the sequence of addition to their network. Water-level data for the RST wells were provided to USGS by the RST and are available through the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2019). Additional well-completion information for SDDENR and RST wells can be obtained from the USGS NWIS database using the site identification numbers that are provided in table 2.

Table 2. Selected site information for observation wells within the study area.

[USGS, U.S. Geological Survey; NGVD 29, National Geodetic Vertical Datum of 1929; M, month; D, day; YYYY, year; SDDENR, South Dakota Department of Environment and Natural Resources; NA, not available]

Map number (fig. 1)	Well number	USGS site identification number	Location[a]	Aquifer	Date drilled	Well depth (feet below land surface)	Top of casing elevation (feet above NGVD 29)	First measurement date (M/D/YYYY)
SDDENR wells in Todd (TD) County								
S1	TD-57B	431516100281501	38N27W24CCBC	Alluvial	1/1/1957	18.0	2,428	7/1/1958
S2	TD-57CR	431505100140001	37N25W23ADDA	Alluvial	8/9/1957	62.0	2,299	9/12/1957
S3	TD-59A	430148100471001	35N29W07BBBB	Ogallala	10/5/1959	82.0	2,903	11/22/1959
S4	TD-59BR	425958100445301	35N29W20AADD	Ogallala	11/3/1959	105.0	2,892	11/21/1960
S5	TD-76A	431109100445901	37N29W16AAAA	Ogallala	11/30/1976	185.0	2,857	12/2/1976
S6	TD-76B	430924100460601	37N29W29AAAA	Ogallala	12/2/1976	205.0	2,860	1/18/1977
S7	TD-76C	430748100455601	37N29W33CCCC	Ogallala	11/4/1976	205.0	2,909	1/18/1977
S8	TD-76D	430840100445601	37N29W28DDDD	Ogallala	11/3/1976	195.0	2,858	1/18/1977
S9	TD-76E	430610100481701	36N30W13BBBB	Ogallala	12/6/1976	225.0	2,916	1/18/1977
S10	TD-76F	430609100434201	36N29W16AAAA	Ogallala	12/8/1976	225.0	2,862	1/18/1977
S11	TD-76G	430842100411301	37N28W30CCCB	Ogallala	12/9/1976	185.0	2,770	1/18/1977
S12	TD-76H	430932100390001	37N28W21CCCC	Ogallala	12/9/1976	165.0	2,772	1/18/1977
S13	TD-76I	430839100373801	37N28W27CCCC	Ogallala	12/10/1976	185.0	2,805	1/18/1977
S14	TD-76J	430701100363001	36N28W10BBBB	Ogallala	12/10/1976	185.0	2,823	1/18/1977
S15	TD-79A	431020100243501	37N26W16CCBB	Ogallala[b]	10/12/1979	25.0	2,530	5/6/1980
S16	TD-79B	430613101561701	36N31W14BAAA	Ogallala	10/16/1979	160.0	2,980	11/17/1980
S17	TD-79D	432044101115201	39N33W15DDDD	Arikaree	10/18/1979	360.0	2,800	5/19/1981
S18	TD-80A	432310101045501	39N32W03AAAA	Arikaree	9/23/1980	125.0	2,610	2/18/1981
S19	TD-80B	430340101012301	36N32W25DDDD	Ogallala	9/23/1980	125.0	2,841	2/18/1981
S20	TD-80C	430959100444001	37N29W22CCCC	Arikaree	9/24/1980	265.0	2,881	2/18/1981
S21	TD-80D	431430100195901	38N25W30BBBB	Arikaree	9/25/1980	142.7	2,484	4/21/1981
S22	TD-80E	430310100245501	36N26W31DDAA	Ogallala	9/25/1980	121.5	2,620	2/18/1981
S23	TD-90A	430604100445401	36N29W17AADD	Ogallala	7/10/1990	245.0	2,890	6/16/1992
S24	TD-90B	430226100445201	35N29W04BCCB	Arikaree	7/17/1990	115.0	2,845	6/16/1992
S25	TD-#05[c]	430159100531001	35N30W06DDDD	Ogallala	Unknown	84.5	2,853	11/13/1984
S26	TD-#08[c]	430258100471401	36N30W36DDDD	Ogallala	Unknown	123.0	2,885	11/13/1984
S27	TD-#10[c]	430154100411801	35N29W02DDDD	Ogallala	Unknown	44.4	2,800	11/13/1984

Table 2. Selected site information for observation wells within the study area.—Continued

[USGS, U.S. Geological Survey; NGVD 29, National Geodetic Vertical Datum of 1929; M, month; D, day; YYYY, year; SDDENR, South Dakota Department of Environment and Natural Resources; NA, not available]

Map number (fig. 1)	Well number	USGS site identification number	Location[a]	Aquifer	Date drilled	Well depth (feet below land surface)	Top of casing elevation (feet above NGVD 29)	First measurement date (M/D/YYYY)
SDDENR wells in Bennett (BT) County								
S28	BT-76C	431018101152001	37N33W17CCCC	Ogallala	11/4/1976	185.0	2,998	11/28/1976
S29	BT-78KR	431250101163701	37N34W01AAAA	Ogallala	10/12/2004	259.5	3,115	11/1/1978
S30	BT-80E	430825101151801	37N33W32BBBB	Ogallala	9/18/1980	145.0	2,955	2/19/1981
S31	BT-80F	NA	36N33W31CCCD	Ogallala	9/19/1980	205.0	3,067	4/19/1981
SDDENR wells in Mellette (MT) County								
S32	MT-78A	432554101065601	40N32W21BBBB	Arikaree	10/3/1978	160.0	2,576	11/1/1978
S33	MT-78B	432411101080701	40N32W32BBBB	Arikaree	10/3/1978	260.0	2,640	7/10/1979
South Dakota Department of Environment and Natural Resources wells in Tripp (TR) County								
S34	TR-78E	430133100061501	95N78W20CCCC	Ogallala	5/4/1978	105.0	2,430	6/19/1978
S35	TR-99A	430813100100001	96N79W14BBCB	Arikaree	5/20/1997	49.0	2,240	2/17/1999
Rosebud Sioux Tribe wells								
R1	RST 1	431403101020601	38N31W30CBD	Ogallala	Unknown	Unknown	2,970	1/15/1987
R2	RST 2	430726101033501	36N32W02BAA	Ogallala	Unknown	80.5	2,682	2/15/2000
R3	RST 3	430309100570901	36N31W34DBB	Ogallala	Unknown	91.0	2,920	1/15/1987
R4	RST 4	430017100595101	35N31W17CDC	Ogallala	Unknown	62.0	2,896	1/15/1987
R6	RST 6	430501100504901	36N30W21ADD	Ogallala	Unknown	137.0	2,888	1/15/1987
R7	RST 7	430415100451401	36N29W29ACA	Ogallala	Unknown	133.5	2,870	1/15/1987
R9	RST 9	430100100460501	35N29W18AAA	Ogallala	Unknown	83.8	2,870	1/15/1987
R11	RST 11	430530100422501	36N29W14CDD	Ogallala	Unknown	212.0	2,893	1/15/1987
R12	RST 12	430712100421301	36N29W02CDD	Ogallala	Unknown	200.0	2,850	1/15/1987
R13	RST 13	430755100582301	37N29W31CCB	Ogallala	Unknown	275.0	2,921	1/15/1987
R14	RST 14	431116100422001	37N29W12CCD	Ogallala	Unknown	Unknown	2,810	7/1/1986
R15	RST 15	431342100344101	38N28W36ABD	Ogallala	Unknown	73.0	2,620	1/15/1987
R16	RST 16	430820100371401	37N28W34BDA	Ogallala	Unknown	171.0	2,783	1/15/1987
R17	RST 17	431027100333001	37N27W18DCC	Ogallala	Unknown	53.0	2,609	1/15/1987
R18	RST 18	430702100330501	36N28W12AAA	Ogallala	Unknown	215.0	2,806	1/15/1987
R19	RST 19	430243100371701	36N28W33BDD	Ogallala	Unknown	74.8	2,753	6/15/1999

Table 2. Selected site information for observation wells within the study area.—Continued

[USGS, U.S. Geological Survey; NGVD 29, National Geodetic Vertical Datum of 1929; M, month; D, day; YYYY, year; SDDENR, South Dakota Department of Environment and Natural Resources; NA, not available]

Map number (fig. 1)	Well number	USGS site identification number	Location[a]	Aquifer	Date drilled	Well depth (feet below land surface)	Top of casing elevation (feet above NGVD 29)	First measurement date (M/D/YYYY)
Rosebud Sioux Tribe wells—Continued								
R20	RST 20	430122100344501	35N28W11DBB	Ogallala	Unknown	94.1	2,728	1/15/1987
R21	RST 21	430057100275401	35N27W14BAB	Ogallala	Unknown	84.2	2,690	1/15/1987
R22	RST 22	430335100241401	36N26W32BAA	Ogallala	Unknown	78.4	2,619	1/15/1987
R23	RST 23	430728100135801	36N27W01ACC	Ogallala	Unknown	58.1	2,627	1/15/1987
R25	RST 25	431428100192701	38N25W30BBC	Ogallala	Unknown	145.4	2,499	1/15/1987
R26	RST 26	431158100461002	37N29W08ADB	Ogallala	Unknown	263.0	2,826	1/15/1987
R27	RST 27	431127100532801	37N30W09DDB	Ogallala	Unknown	150.0	2,880	1/15/1987

[a]The well location consists of the township number, followed by "N," the range number followed by "W," and the section number followed by a maximum of four uppercase letters that indicate, respectively, the 160-, 40-, 10-, and 2 1/2-acre tract in which the well is located. These letters are assigned in a counterclockwise direction beginning with "A" in the northeast quarter

[b]Originally completed in the Arikaree aquifer at a depth of 137 feet; however, considered an Ogallala aquifer well after the casing broke at a depth of 28 feet.

[c]Wells TD-#05, TD-#08, and TD-#10 have also been monitored by the Rosebud Sioux Tribe as wells RST 5, RST 8, and RST 10, respectively. However, the SDDENR records are more complete; thus, only the SDDENR records are considered in this report.

SDDENR wells TD-#05, TD-#08, and TD-#10 are owned by RST and have been monitored by RST and SDDENR. However, the SDDENR records are more complete; thus, only the SDDENR records are considered in this report.

The oldest records for SDDENR wells date back to September 12, 1957, for TD-57CR; however, only four wells have records that start before calendar year 1976 (table 2). Records for all RST wells date back to January 15, 1987, with only three exceptions (table 2). The SDDENR and RST datasets consist of sporadic (more or less monthly) measurements of water levels made primarily during or near months of typical irrigation demand, with minimal measurements during nonirrigation months. Water-level records are biased towards more frequent measurements during irrigation periods; thus, to add perspective, trends in water levels were analyzed as three annual datasets (minimum, median, and maximum water level) for each observation well (hereafter referred to as "water-level parameters").

Licensed Groundwater Withdrawals

Licensed groundwater withdrawals primarily include withdrawals for irrigation and municipal use and exclude minor withdrawals for uses such as domestic and stock-water supplies, as described further within this section. The USGS NWIS database (U.S. Geological Survey, 2019) lists a total of 2,177 groundwater withdrawal points (wells) in Todd County as of March 28, 2019. However, only licensed groundwater withdrawals are used in this report for accumulating estimates of withdrawals within specified radii of each observation well.

Locations of licensed groundwater withdrawals in the study area are shown in figure 3, which splits the study area into three sections and provides sufficient resolution to identify locations of licensed groundwater withdrawals, relative to locations of observation wells. Circles with radii of 0.5 and 1.0 mi are plotted around each observation well to provide a perspective on the number of licensed groundwater withdrawals within those radii of each observation well.

Water rights are issued by the State of South Dakota and RST within and beyond Todd County. Locations of State-permitted/licensed groundwater withdrawals and records of (maximum allowable) groundwater usage were obtained from the SDDENR (2017) for consideration in qualitative assessments of potential effects of withdrawals on water-level records for observation wells. The issuance of a groundwater right by SDDENR is a two-step process that consists of initial issuance of a water-right permit that is followed by issuance of a water-right license after a required inspection is performed (SDDENR, 2019). A 5-year period is allowed for development of water-use infrastructure before the inspection is required. In most cases, inspections are performed and licenses are issued before the 5-year period has elapsed; however, inspections and licensing can extend beyond 5 years. Licensed (maximum allowable) withdrawal rates are not necessarily identical to the original permitted rates and usually are somewhat smaller than permitted rates. Thus, licensed withdrawal rates were used for estimation of groundwater withdrawal rates, except for cases where licensing has not yet been completed, which required use of permitted withdrawal rates.

True "starting" dates for permitted or licensed withdrawals cannot be precisely determined from the SDDENR database (SDDENR, 2017) for several reasons. A "priority" date for each permitted water right is established by the filing date of each water-right application, and in some cases, withdrawals may begin within a year or less of the priority date. In other cases, withdrawals may not begin for 5 years or more and only slightly in advance of the licensing date. Another factor is that some of the licensed groundwater withdrawals in the study area substantially predate South Dakota's current permitting/licensing system, and in some cases priority dates precede license dates by one or more decades. Thus, priority dates were used as the starting dates for estimation of groundwater withdrawals.

Licensed groundwater withdrawals for "center-pivot" irrigation systems are the primary sources of groundwater demand in the study area. Pumping rates of about 1 to 2 cubic feet per second (ft^3/s) or about 450 to 900 gallons per minute are typical (SDDENR, 2017) for center-pivot systems that typically irrigate a circular area within a "quarter-section" of land (one-fourth of a square mile). In some cases, a center-pivot system may be served by a single well; however, in many cases, two or more wells may be needed to produce sufficient water. The SDDENR database (SDDENR, 2017) provides individual well locations when multiple wells are used to serve a single irrigation system; however, details regarding production rates for individual wells are not necessarily readily available. Thus, for cases of multiple well locations associated with a single water-right permit or license, an assumption of equal production from each well is used for the qualitative assessments that are performed.

Selected site and production information for 8 irrigation wells and 11 municipal wells that are operated by the RST but are not under the jurisdiction of South Dakota water-right licensing because of tribal sovereignty, is provided in table 3. Locations of those wells are included in figure 3; however, locations are not distinguished from locations of nontribal wells.

The State of South Dakota does not require permitting/licensing for small-scale groundwater withdrawals of less than 25 gallons per minute (0.06 ft^3/s) in most instances (SDDENR, 2019). No attempt was made to account for groundwater withdrawals not reported by the SDDENR or RST. No attempt was made to account for withdrawals in nearby parts of Nebraska, because there are very few center-pivot irrigation systems or other sources of groundwater demand in Nebraska within 5 mi of any of the observation wells considered. An arbitrary maximum distance of 5 mi is used for accumulation of estimated groundwater withdrawal rates.

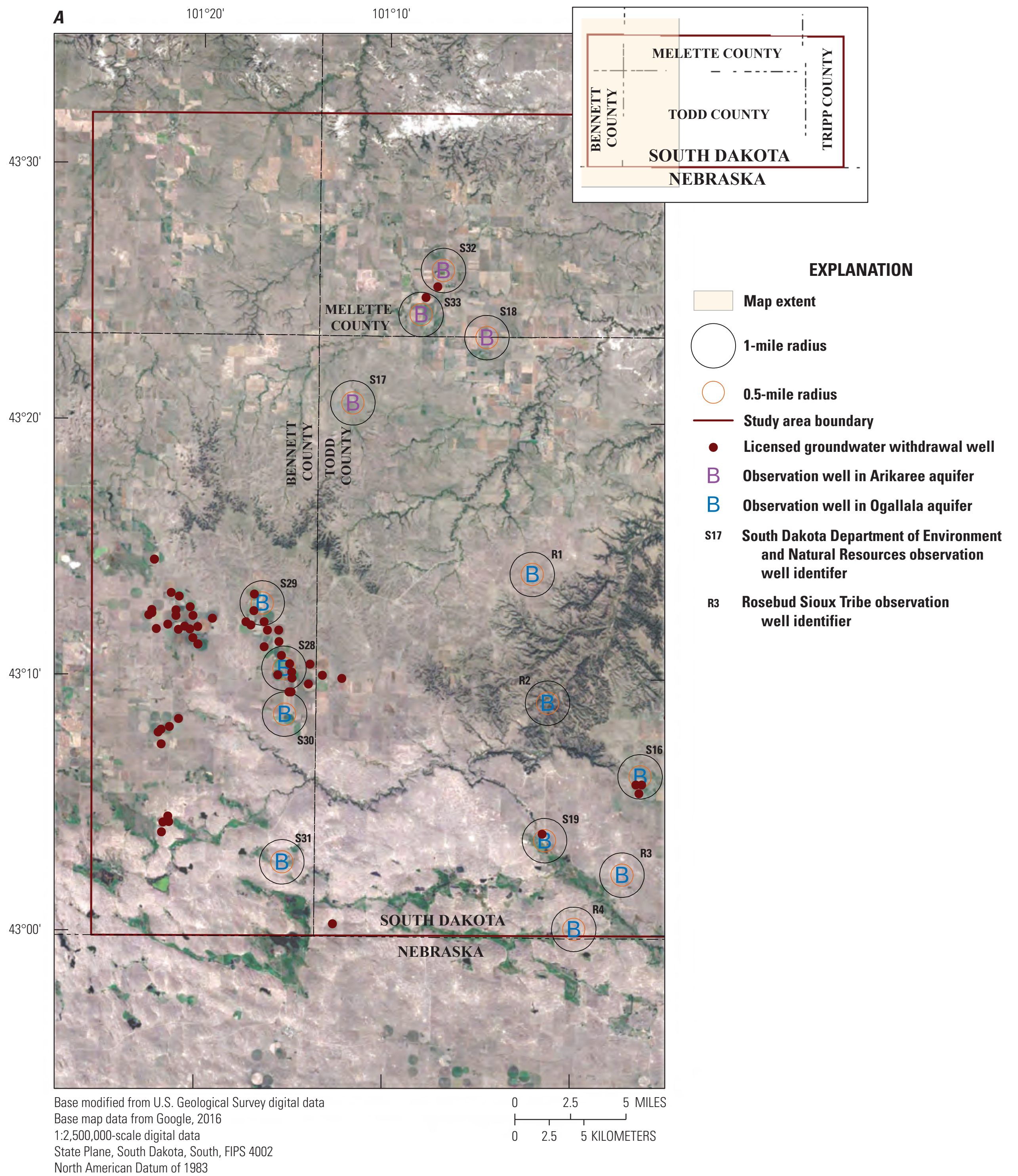
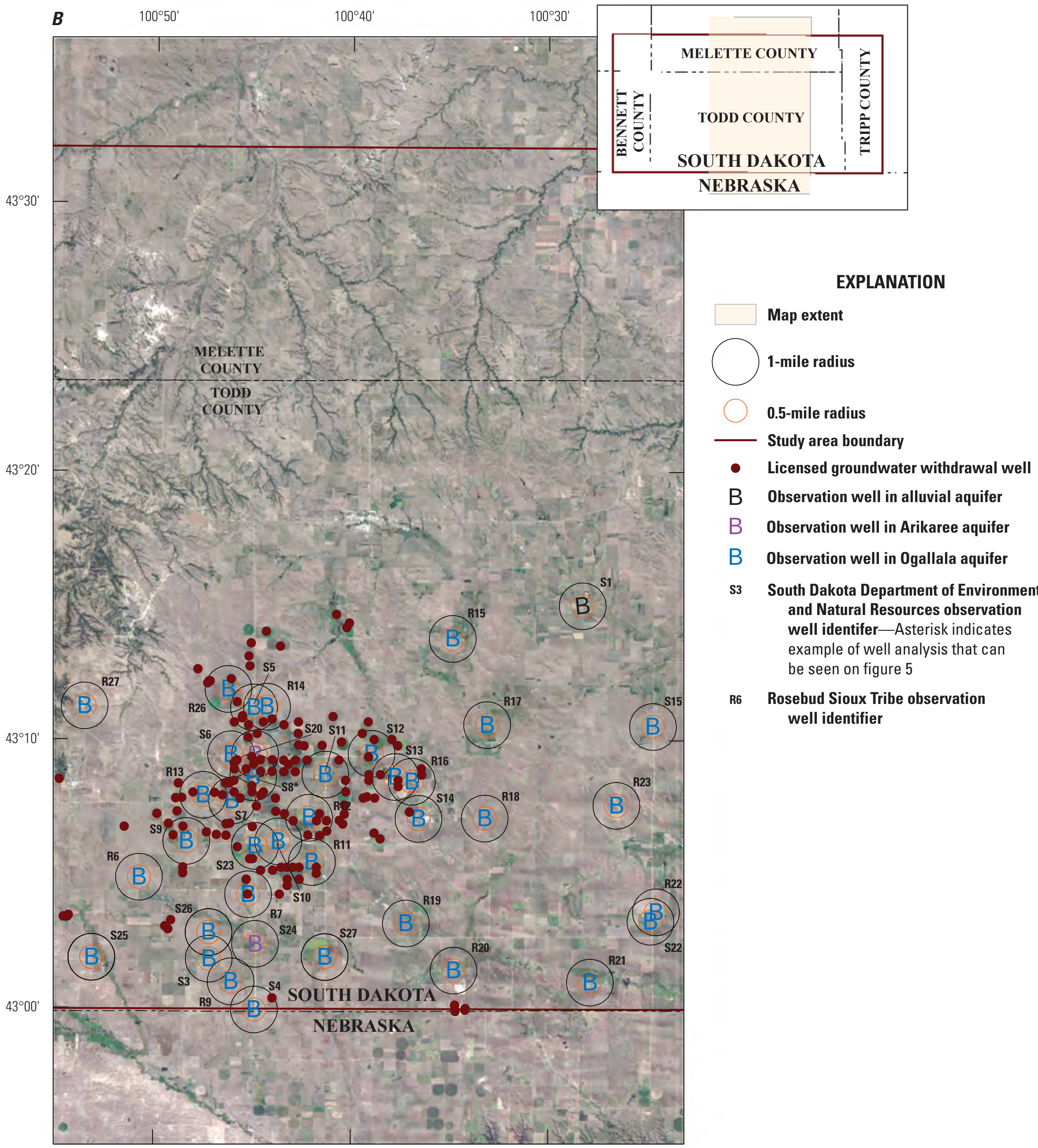


Figure 3. Locations of licensed groundwater withdrawals within the study area, relative to locations of observations wells. *A*, Licensed groundwater withdrawals in western part of study area. *B*, Licensed groundwater withdrawals in central part of study area. *C*, Licensed groundwater withdrawals in eastern part of study area.



Base modified from U.S. Geological Survey digital data
Base map data from Google, 2016
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State Plane, South Dakota, South, FIPS 4002
North American Datum of 1983

Figure 3. —Continued

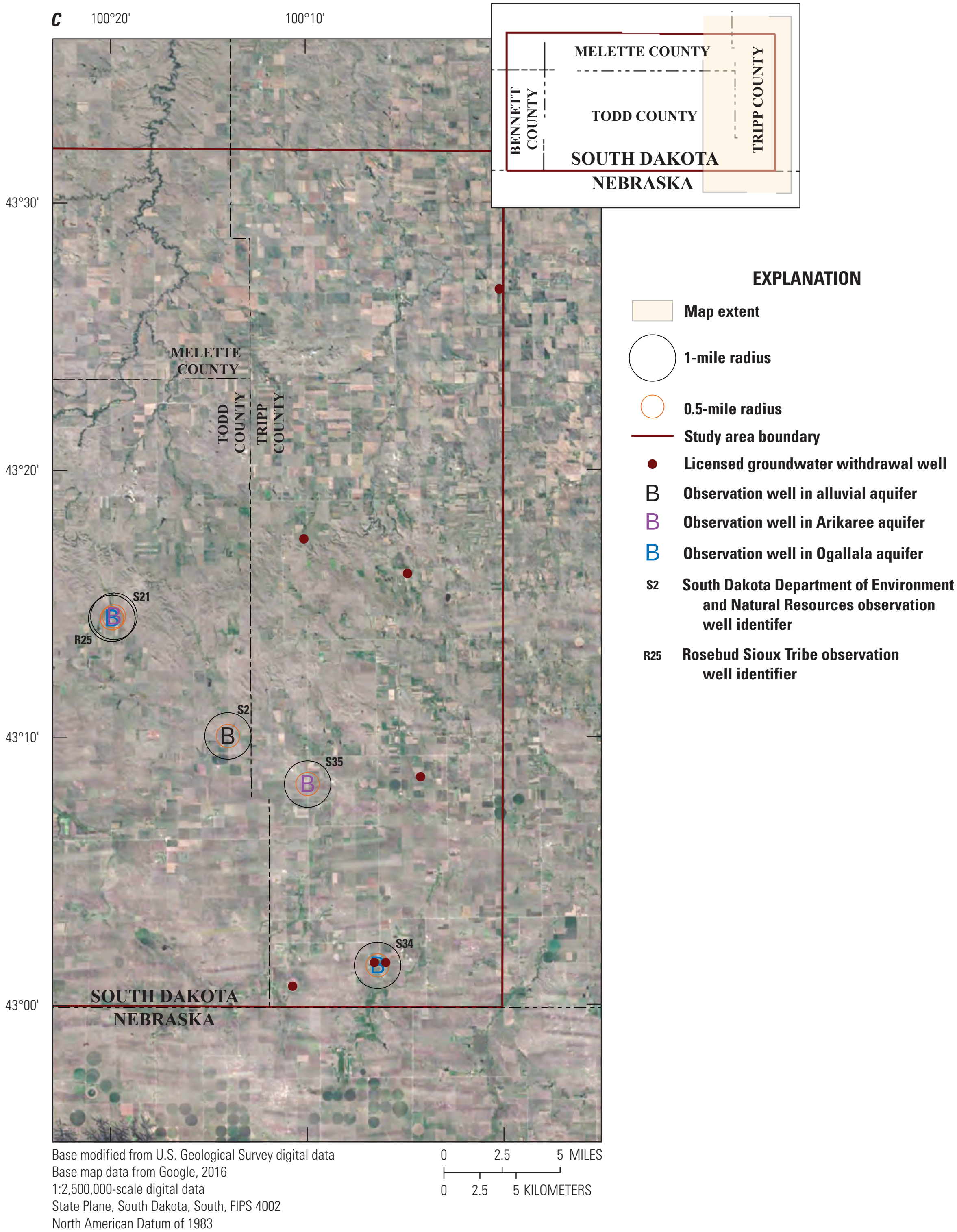

Figure 3. —Continued

Table 3. Selected site and production information for licensed groundwater withdrawal wells operated by Rosebud Sioux Tribe.

[M, month; D, day; YYYY, year; gal/min, gallon per minute; ft^3/s, cubic feet per second; Withheld, latitude and longitude withheld for security purposes]

Well name	Latitude	Longitude	Date drilled (M/D/YYYY)	Estimated start date for withdrawals (M/D/YYYY)	Depth	Tested production rate (gal/min)	Estimated mean production rate (gal/min)	Estimated mean production rate (ft^3/s)
Irrigation wells								
Irrigation-5	43.22694	−100.752	8/7/1984	1/1/1985	Unknown	420	420	0.936
Irrigation-6	43.21861	−100.754	8/8/1984	1/1/1985	Unknown	550	550	1.225
Irrigation-7	43.2125	−100.753	8/8/1984	1/1/1985	Unknown	370	370	0.824
Irrigation-15	43.13389	−100.783	7/24/1984	1/1/1985	Unknown	650	650	1.448
Irrigation-16	43.1325	−100.776	7/23/1984	1/1/1985	Unknown	450	450	1.003
Irrigation-17	43.10778	−100.781	8/1/1984	1/1/1985	Unknown	500	500	1.114
Irrigation-18	43.1075	−100.773	8/2/1984	1/1/1985	Unknown	550	550	1.225
Irrigation-23	43.07083	−100.754	8/9/1984	1/1/1985	Unknown	200	200	0.446
Municipal wells								
Rosebud 84-1	Withheld	Withheld	Unknown	1/1/1984	Unknown	Unknown	200	0.446
Rosebud 84-2	Withheld	Withheld	1984	1/1/1984	Unknown	Unknown	200	0.446
Rosebud 84-3	Withheld	Withheld	1984	1/1/1984	Unknown	Unknown	200	0.446
Rosebud 98-1	Withheld	Withheld	7/8/1998	1/1/1999	262.8	300	200	0.446
Rosebud 98-2	Withheld	Withheld	6/29/1998	1/1/1999	210.1	450	300	0.668
Saint Francis 90-1	Withheld	Withheld	1989	1/1/1990	Unknown	150	100	0.223
Casino 94-1	Withheld	Withheld	7/8/1994	1/1/1995	185.0	30	20	0.045
Casino 94-2	Withheld	Withheld	7/22/1994	1/1/1995	165.0	55	40	0.089
Casino 98-1	Withheld	Withheld	5/2/1998	1/1/1999	134.5	Unknown	30	0.067
Casino 03-1	Withheld	Withheld	9/25/2003	1/1/2004	138.0	40	30	0.067
Casino 03-2	Withheld	Withheld	9/30/2003	1/1/2004	140.0	50	30	0.067

A summary of estimated licensed groundwater withdrawals over time throughout study area is shown in figure 4 and shows (1) minimal withdrawals before 1975, (2) sudden increases in withdrawals between about 1975–78 and 1984–86, (3) somewhat minor increases during about 1986–2005, and (4) somewhat slow but steady increases since about 2005. By the end of WY 2017, cumulative licensed groundwater withdrawals throughout the study area totaled about 195 ft^3/s. Cumulative licensed groundwater withdrawals are defined throughout this report as the sum of licensed groundwater withdrawals from 1958 to 2017 and include the total withdrawals from the Arikaree and Ogallala aquifers. Actual cumulative withdrawal rates (table 1), reported by Dieter and others (2018) are much smaller than shown in figure 4 because (1) the estimated withdrawals in the current study are based on maximum permitted/licensed withdrawal rates, which typically are approached only during particularly dry years; and (2) the irrigation season typically includes less than 6 months of each year.

Statistical and Analytical Methods

Various statistical methods are used for analysis of temporal trends for climatic and hydrologic data. For all trend analyses in this report, the independent (x) variable is time (annual or seasonal), and the dependent (y) variable is a climate or hydrologic variable (precipitation, temperature, or water levels in wells). Seasons, where applicable, are defined throughout this analysis as October–December, January–March, April–June, and July–September.

Some of the statistical analyses involve determination of trend magnitude, or the mean change over time for an analysis period. Trend magnitudes are computed using the Sen's slope estimator (Sen, 1968) using the modifiedmk R package developed by Patakamuri (2018). Sen's slope, also referred to as the Kendall-Theil robust line (Helsel and others, 2020), is a nonparametric estimator of trend magnitude per time interval (slope) for a univariate time series when the time interval is constant (equally spaced). For use in correlations, a time-weighted trend magnitude also is calculated for the water-level data with at least one statistically significant water-level parameter by multiplying the annual median Sen's slope value by the number of years in the period of record for each well.

Two statistical analyses were used to test for statistical significance of temporal trends. The nonparametric Mann-Kendall test (Helsel and others, 2020; Kendall, 1938) is the primary method used to determine statistical significance of trends. The null hypothesis for this method is "(H_0) is rejected if the value of S is statistically significantly different from zero" (Helsel and others, 2020, p. 332), where H_0 is no change and S is Kendall's τ of y versus time variable; alternatively, a monotonic trend is assumed. Trends are considered statistically significant for probability values (p-values) less than or equal to 0.10 (90-percent confidence level) for the null hypothesis that Kendall's tau (τ) equals zero. Kendall's tau measures the degree of correspondence between two variables, with τ ranging from −1 to 1. If τ=−1, the data have a perfect negative correlation or downward trend. If τ=1, the data have a perfect positive correlation or upward trend. If τ=0, there is no correlation or trend.

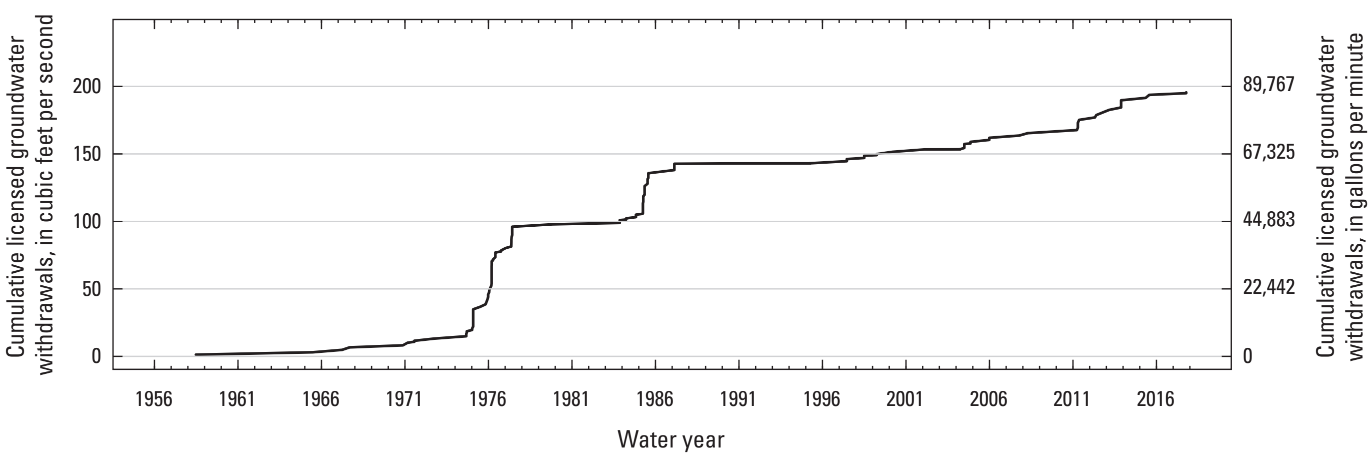

Figure 4. Summary of licensed groundwater withdrawals over time for the study area.

An issue for trend analysis of hydroclimatic datasets has been potential effects of serial correlation within time-series data (Cohn and Lins, 2005). There are two types of serial correlation: short-term persistence and long-term persistence. Short-term persistence (STP) is when past measurements affect the subsequent measurements in a short timeframe, and long-term persistence is when past measurements affect the subsequent measurements in a long timeframe or infinite timeframe (Koutsoyiannis and Montanari, 2007). A standard Mann-Kendall test is appropriate only for time-series data that are identically distributed, independent, and have no short- or long-term persistence (Wilks, 2011). If these assumptions are violated, for example when series are autocorrelated, the standard Mann-Kendall *p*-values can decrease, causing Type I errors. Type I errors are the false acceptance of a trend as statistically significant when, in fact, no trend exists. Long-term persistence typically can be observed only in periods of record more than 50–100 years (Hodgkins and Dudley, 2011). However, long-term persistence was not considered a concern because the oldest well records date back to calendar years 1957–60 for only 4 of 58 wells (table 2), with all other records starting in calendar year 1976 or later. In contrast, STP was of potential concern, because both the precipitation and groundwater measurements are consecutive timeseries.

To determine which Mann-Kendall test to use for statistical significance and magnitudes of temporal trends, applicable data were tested for statistically significant STP using the Autocorrelation Function (Venables and Ripley, 2002) from the R stats package (R Core Team, 2017). The autocorrelation values were calculated and plotted for the annual cumulative precipitation and the annual median water level for observation wells, and the plots were visually inspected for STP. STP was identified by a gradual tapering of the autocorrelation value below a conditional probability of 0.05.

The standard version of the nonparametric Mann-Kendall test (Kendall, 1938; Helsel and others, 2020) was used to determine statistical significance of trends for datasets that showed little or no STP. Various methods can be used to modify the Mann-Kendall test to minimize effects of STP (Hamed and Rao, 1998; Hamed, 2008; Önöz and Bayazit, 2012; Bayazit, 2015); however, such methods typically make the Mann-Kendall test less sensitive to trends. For datasets with substantial STP, the Modified Mann-Kendall Test from the modifiedmk R package (Patakamuri, 2018) was used. The function uses the Hamed and Rao (1998) variance correction approach, wherein a trend-free time series is constructed by calculating Sen's slope and Auto Correlation coefficients to calculate a new *p*-value. The *p*-value was not reported if the modified Mann-Kendall method induced an error owing to negative variance in the constructed time series.

A locally estimated scatterplot smoothing (LOESS) curve with a span of 0.8 was used to aid in the visualization of trends for some datasets. The 0.8 span was selected because it provided a generalized visual representation of the trend within the data. The LOESS curve is a multivariate and single variate smoothing procedure (Cleveland and Devlin, 1988; Cleveland and others, 1992) that can be applied to a time series. The Local Polynomial Regression Fitting function from the stats R package (R Core Team, 2017) was used to calculate the LOESS curve values for single variates to be plotted.

Plots and trends over time for groundwater levels and for annual precipitation for the 58 observation wells are presented in figures 1.1 through 1.58 in the appendix. Analyses for the 35 SDDENR observation wells are presented in figures 1.1 through 1.35 and the 23 RST observation wells are presented in figures 1.36 through 1.58. Data regarding groundwater withdrawals, if present, within specified radii of each observation well are also included in figures 1.1 through 1.58. Trends in withdrawals over time are not analyzed for any of the wells.

An example of the data and analyses that are presented in the appendix figures 1.1 through 1.58 is provided in figure 5, which is identical to figure 1.8 in the appendix. This example is for SDDENR well TD-76D (map number S8, table 2) which is situated in eolian (windblown sand) deposits (fig. 1) about 7 mi southeast of Rosebud, South Dakota. This well is completed in the Ogallala aquifer, which underlies the windblown sand deposits (fig. 2). The individual measurements of water levels for well TD-76D that date back to January 18, 1977 (table 2) and estimated annual total precipitation from PRISM data (inverse weighted for the four closest 2.5-arc-minute grid cells) beginning in WY 1956 are shown in figure 5*A*. The 1956–2017 precipitation period is shown in appendix figures 1.1 through 1.58 so that a common time scale can be used for the x-axis for all figures. This period starts about 2 years before the earliest available water-level measurements. A 2-year offset was arbitrarily selected because scrutiny of water-level and precipitation data indicated that responses of groundwater levels for many of the observation wells lagged major changes in precipitation patterns by about 2 years.

Results of time-trend analyses are shown at the top of figure 5*A* for three annual water-level parameters (minimum, median, and maximum) for WYs 1977–2017 and for the annual totals of precipitation for WYs 1975–2017, which reflect the 2-year offset that is used for precipitation data. A LOESS curve is also included on figure 5*A* that is fit to the time series for the total annual precipitation starting in WY 1975. The LOESS curve aids in visualizing the statistically significant upward trend for annual precipitation (Mann-Kendall *p*-value=0.038, Sen’s slope=0.119), which means that annual precipitation has increased by 0.119 inch per year, or about 5.1 inches (in.) between WYs 1975 and 2017. Results indicate statistically significant downward trends for all three annual water-level parameters.

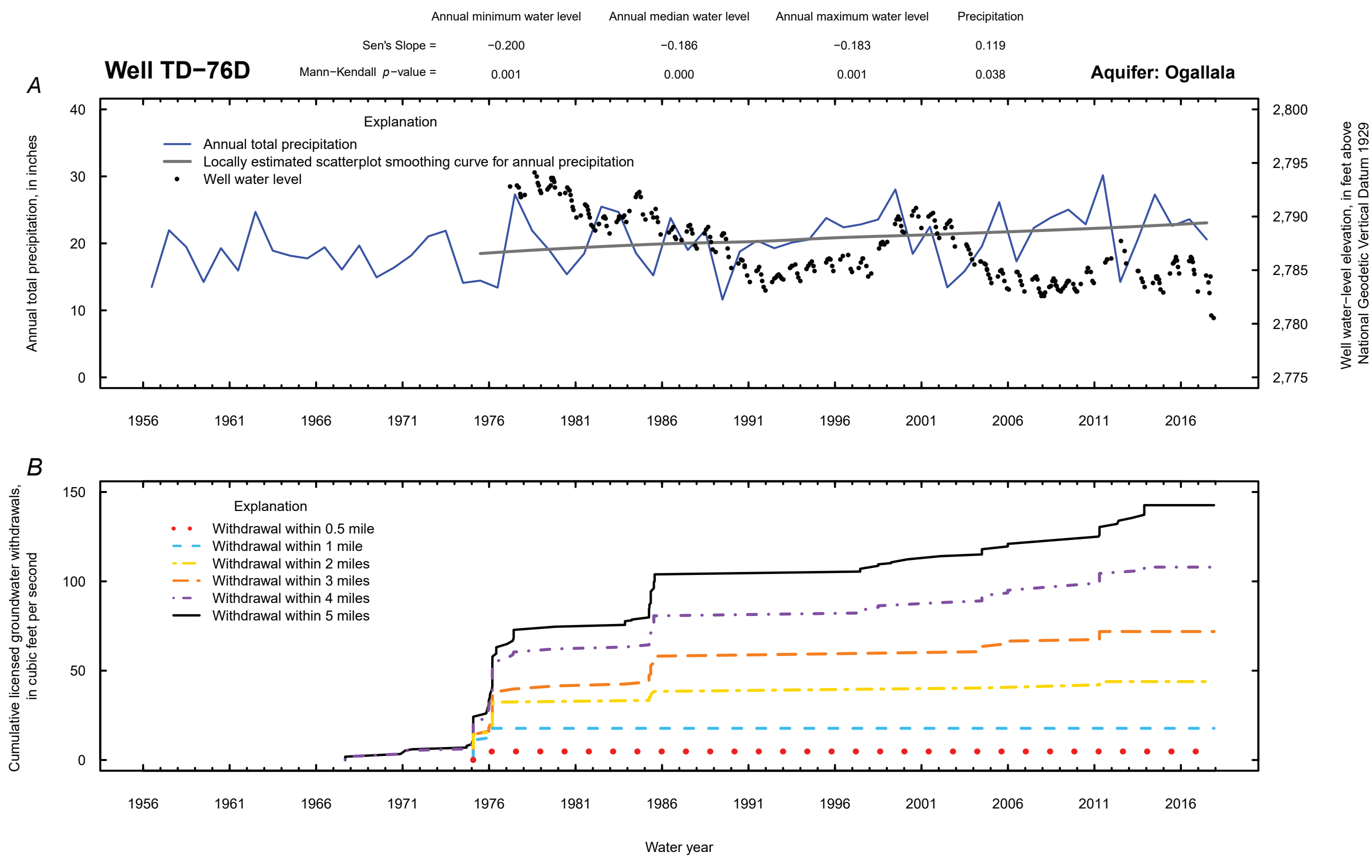

Figure 5. Example analysis that includes two graphs showing trends in measured groundwater levels and annual precipitation totals, and proximal groundwater withdrawals for South Dakota Department of Environment and Natural Resources observation well TD-76D (fig. 1, map number S8). *A*, groundwater levels and annual total precipitation; and *B*, sum of groundwater withdrawals within specified radii of observation well.

Licensed groundwater withdrawals, by year, within six specified radii (0.5, 1, 2, 3, 4, and 5 mi) of observation well TD-76D are shown on figure 5*B*. If a specified radius is not plotted, then there were no records of licensed groundwater withdrawals within that specified radius. As described in the "Licensed Groundwater Withdrawals" section, the licensed groundwater withdrawals primarily represent maximum allowable withdrawal rates for wells permitted or licensed by SDDENR, but also may include withdrawals for wells owned and operated by the RST (table 3). In cases where there are no known licensed groundwater withdrawals within 5.0 miles of the observation well graph *B* is not included.

Analysis of Trends

Trends in groundwater levels for selected observation wells in the study area are analyzed in this section. Climate conditions are a primary driver of trends in groundwater levels; thus, trends in climate data are presented first. It should be noted that the precipitation and water-level trends presented in this report are applicable only for the specific periods of record that are analyzed and should not be construed as forecasts of future conditions.

Climate Trends

The spatial distribution of statistically significant trends for annual PRISM climate data (total precipitation, T_{min}, and T_{max} from aggregated PRISM data) for WYs 1956–2017, which reflects the offset of about 2 years before the earliest available water-level measurements (table 2) are shown in figure 6. The trends in annual climate data provide a qualitative perspective regarding potential effects on groundwater levels, because (1) increased precipitation has potential to increase recharge rates and (2) increased temperature has potential to increase evapotranspiration, which could cause decreased recharge and increased irrigation demand. Statistically significant upward trends are shown for annual precipitation (fig. 6*A*) and for annual T_{min} (fig. 6*B*) for almost all of the study area and the surrounding buffer area. Statistically significant downward trends in T_{max} are shown for a very small part of the study area (fig. 6*C*); however, the sparsity of the spatial coverage reduces confidence that these are true trends for 1956–2017, relative to the near-completeness of the spatial coverage in upward trends for T_{min} (fig. 6*B*).

The spatial distribution of statistically significant trends in seasonal climate data are shown in figures 7–10, which are generally similar to the annual trends, but with substantial differences in the spatial density of the trends. These figures show that the generally upward trends in annual precipitation (fig. 6*A*) are driven more heavily by upward trends for October–December (fig. 7*A*) and January–March (fig. 8*A*), which have somewhat dense spatial coverage, than by upward trends for April–June (fig. 9*A*) and July–September (fig. 10*A*), which have sparser spatial coverage. The generally upward trends for annual T_{min} (fig. 6*B*) are driven primarily by upward seasonal trends for January–March (fig. 8*B*) and July–September (fig. 10*B*). Seasonal trends for T_{max} are downward for much of the study area for April–June (fig. 9*C*) and for parts of the study area for October–December (fig. 7*C*) and July–September (fig. 10*C*). However, with offsetting (upward) T_{max} trends for much of the study area for January–March (fig. 8*C*), the net effect is a general absence of statistically significant trends for annual T_{max} (fig. 6*C*).

Trend magnitudes were not calculated for the spatial climate data derived from PRISM (total precipitation, T_{min}, and T_{max}), because of the large number of grid cells involved. STP was tested for the annual climate time series for data shown in figure 6 and was not detected for any of the three datasets (fig. 2.1). Thus, statistical significance was determined using the standard Mann-Kendall test. The seasonal climate data were not tested for STP because statistically significant STP was not detected for any of the three annual datasets that were tested.

Additional information regarding long-term precipitation patterns for the study area are provided in figure 11. Annual total precipitation from PRISM for WYs 1956–2017 are shown in figure 11*A*, and the long-term mean for this period is 19.89 in. The annual departure from the mean, shown in figure 11*B*, has essentially the same pattern. The cumulative annual departure from the mean, shown in figure 11*C*, clearly indicates multiyear periods of above- or below-mean precipitation. Years before 1976 constitute an extended period of generally below-mean precipitation, as indicated by the generally downward slope during 1956–76. Years since 1994 have been generally above the mean, with the general exception of several years between 1998 and 2003.

The annual total precipitation data for the study area, shown in figure 12, is similar to that of figure 11, but for a time period of 1896–2017, which is the earliest availability of data from PRISM. The 1896–2017 mean is 19.23 in., which is 0.66 in. less than the mean for 1956–2017. Especially dry conditions from the early 1920s through 1940 and moderately dry conditions from 1951 through 1976 are shown in figure 12*C*. Precipitation has been predominantly above the mean since 1976, with especially wet conditions dominating since about 1994.

Annual total precipitation within the study area was tested for trend magnitude and statistical significance for WYs 1975–2017, which includes the entire period of record for all but four of the observation wells considered (table 2) and, with consideration of the 2-year offset, matches the period of record for the 10 SDDENR wells drilled during calendar year 1976 (wells TD-76A through TD-76J). Results are summarized in table 4, along with results for the time periods considered in figures 11 and 12. The standard Mann-Kendall test was used for all three periods because statistically significant STP was not detected for any of the periods (table 4; fig. 2.2). Statistically significant upward trends were indicated for all three time periods. Mean annual precipitation during 1975–2017 was 20.59 in., which is larger than the mean annual precipitation for 1956–2017 (19.89 in.) and 1896–2017 (19.23 in.). The computed trend magnitude for 1975–2017 is almost as large as for 1956–2017, which is almost twice as large as for 1896–2017. In contrast, the mean for 1975–2017 is only 1.36 in. larger than for 1896–2017. Comparison of the statistical results of the three different time periods indicates (1) the sensitivity of the Sen's slope estimator to the period of record that is considered and (2) that caution needs to be exercised in applying the results of testing for trend magnitudes.

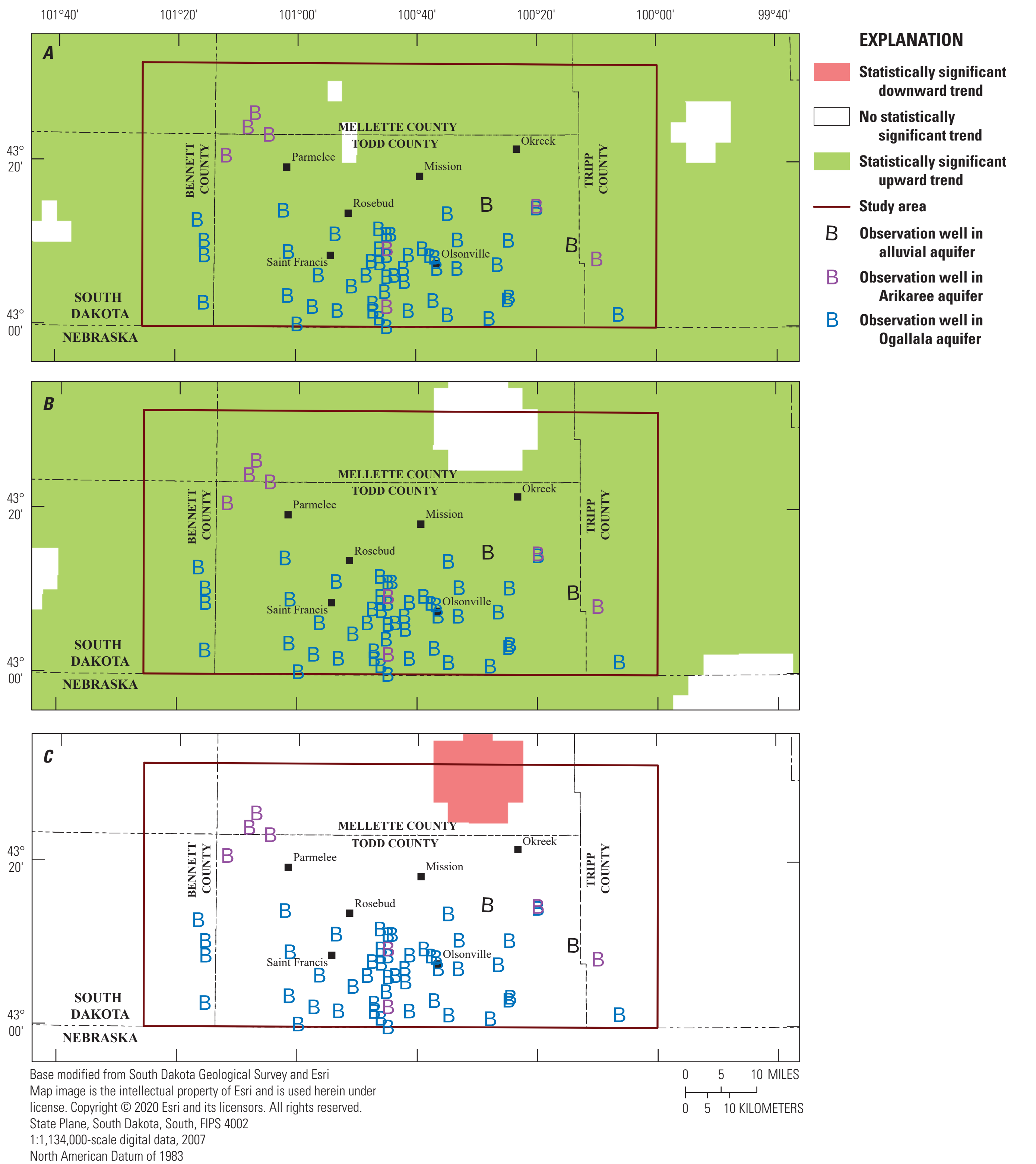

Figure 6. Spatial distribution of statistically significant trends in annual climate data within the study area, water years 1956–2017. *A*, total precipitation; *B*, monthly means of daily minimum air temperature; and *C*, monthly means of daily maximum air temperature.

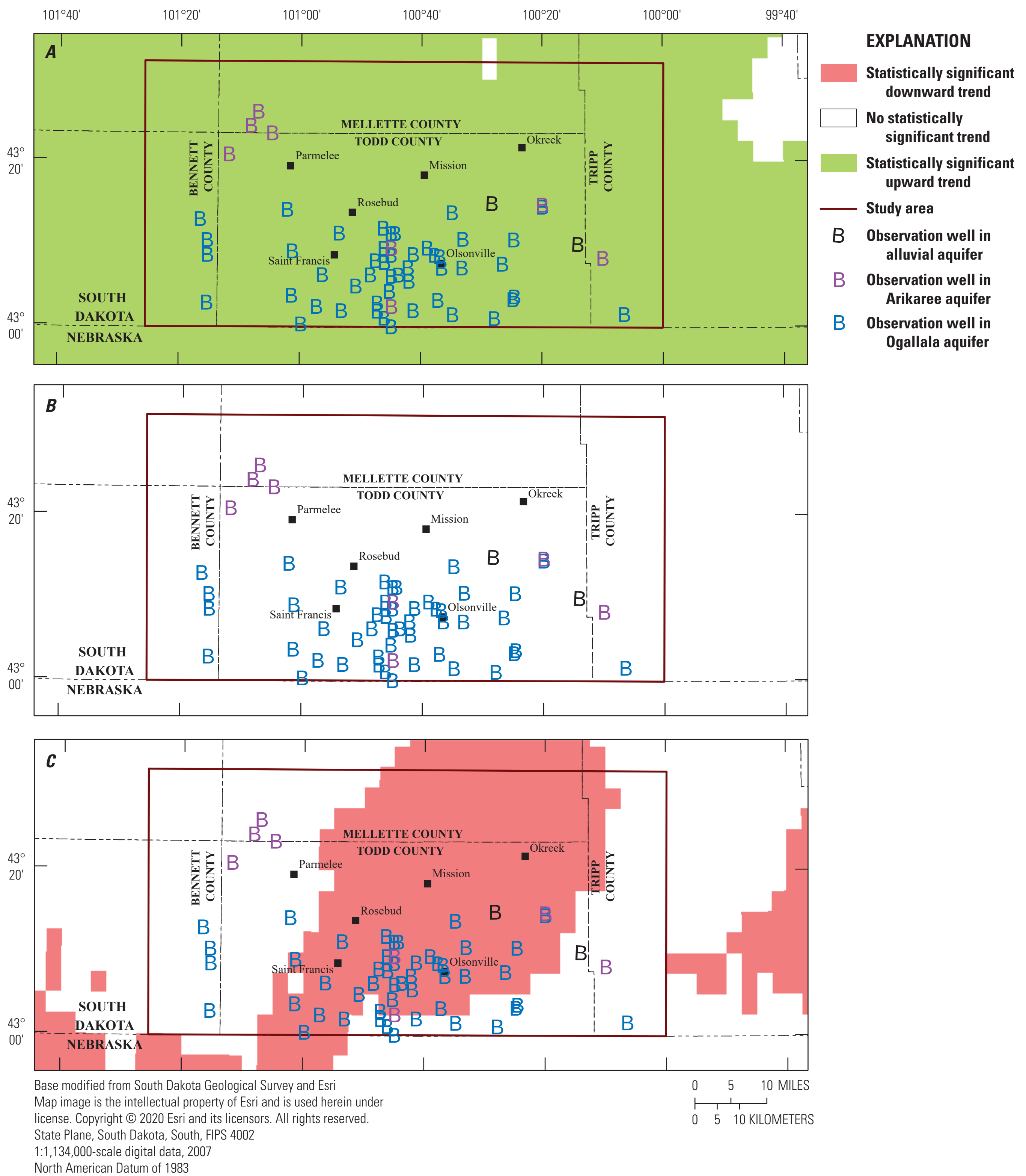

Figure 7. Spatial distribution of statistically significant trends in seasonal (October–December) climate data within the study area, water years 1956–2017. *A*, total precipitation; *B*, monthly means of daily minimum air temperature; and *C*, monthly means of daily maximum air temperature.

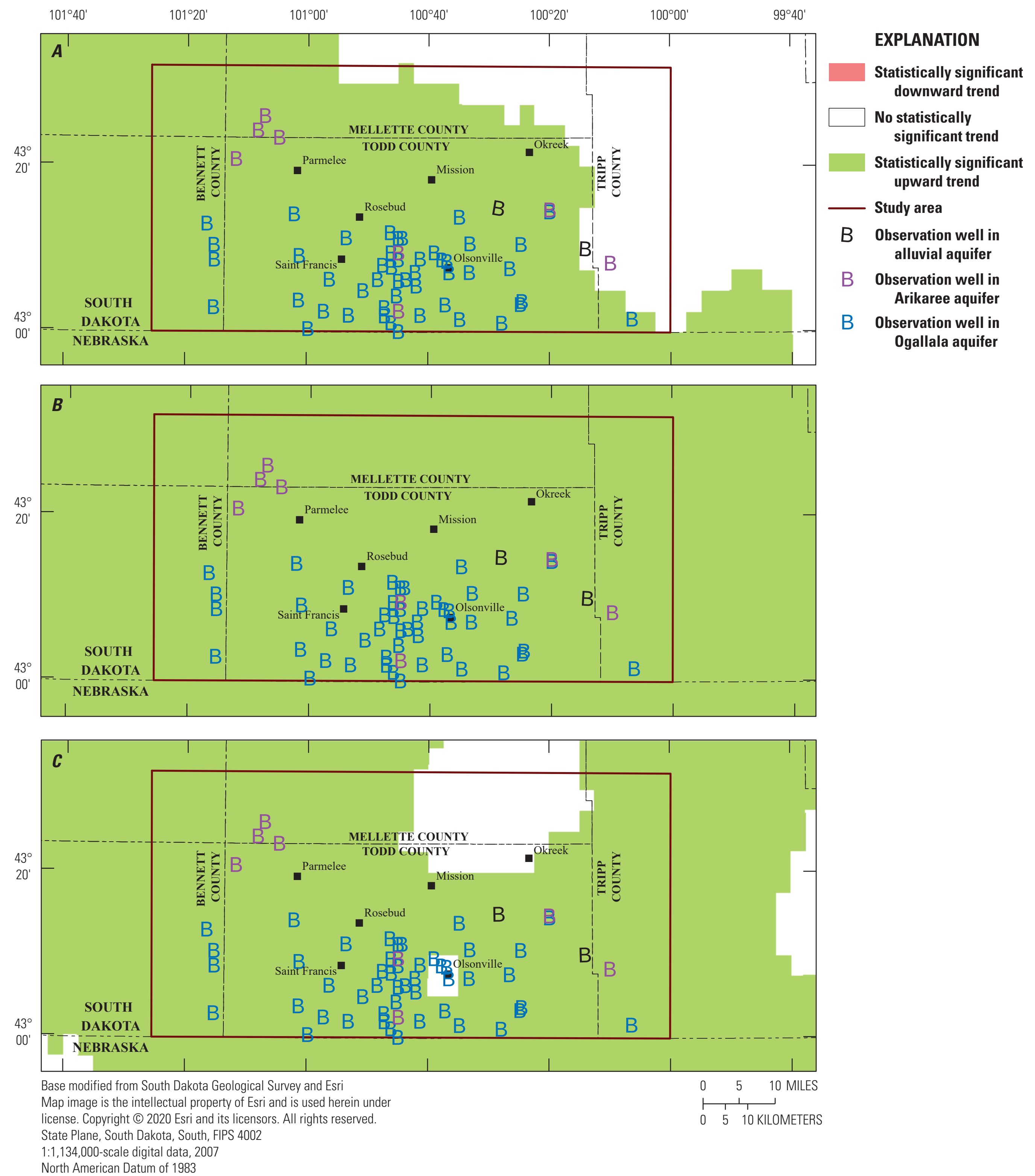

Figure 8. Spatial distribution of statistically significant trends in seasonal (January–March) climate data within the study area, water years 1956–2017. *A*, total precipitation; *B*, monthly means of daily minimum air temperature; and *C*, monthly means of daily maximum air temperature.

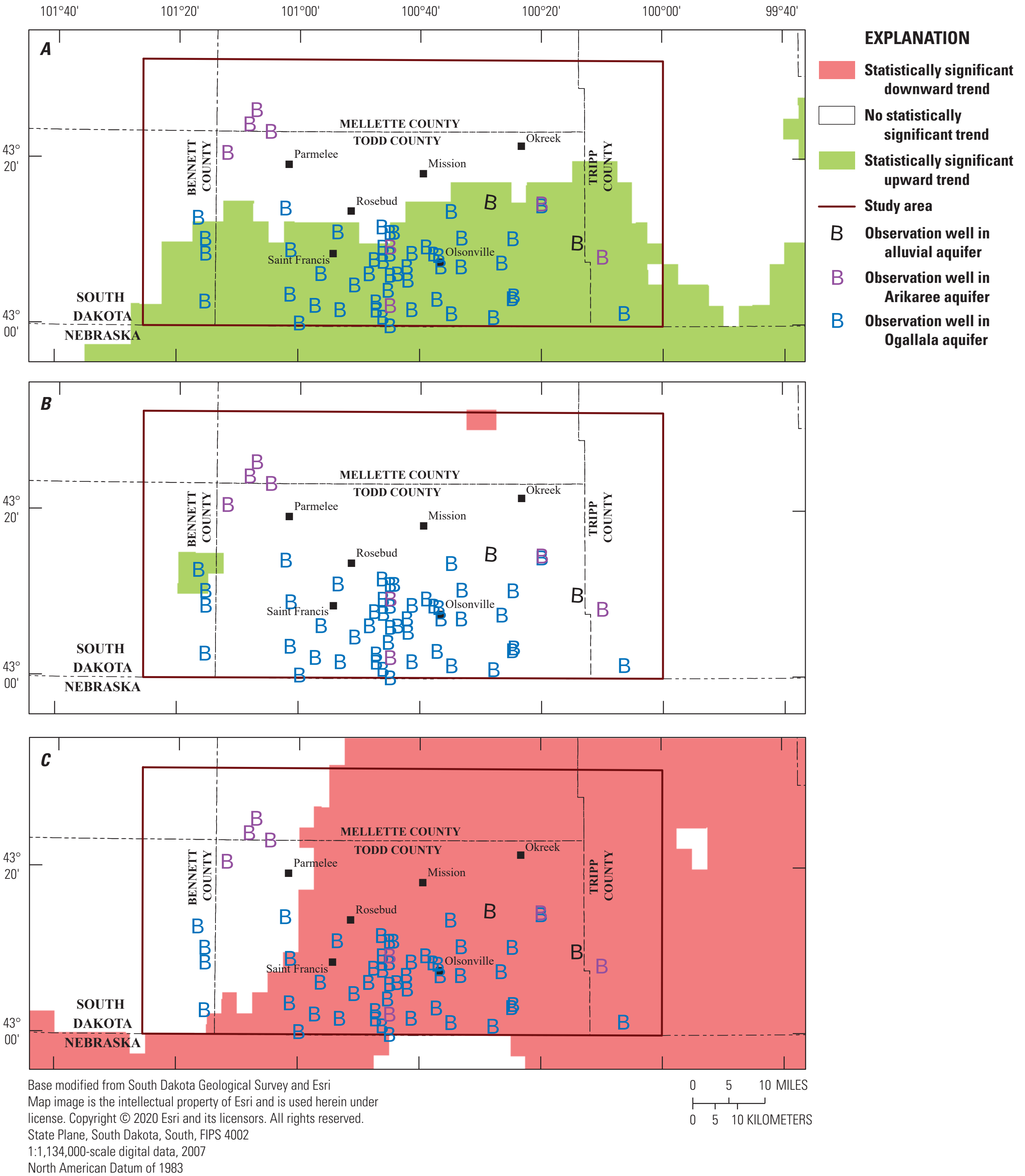

Figure 9. Spatial distribution of statistically significant trends in seasonal (April–June) climate data within the study area, water years 1956–2017. *A*, total precipitation; *B*, monthly means of daily minimum air temperature; and *C*, monthly means of daily maximum air temperature.

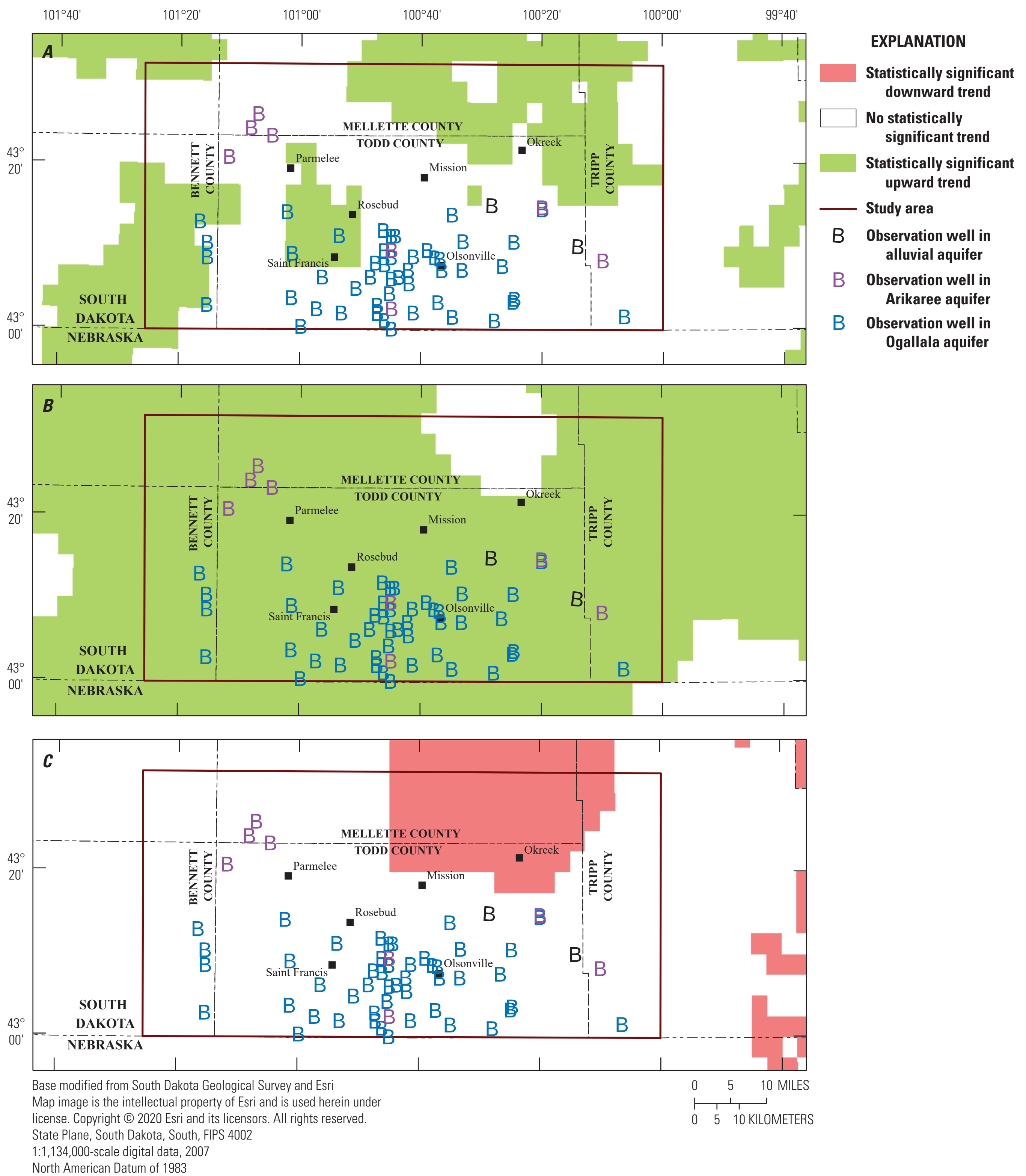

Figure 10. Spatial distribution of statistically significant trends in seasonal (July–September) climate data within the study area, water years 1956–2017. *A*, total precipitation; *B*, monthly means of daily minimum air temperature; and *C*, monthly means of daily maximum air temperature.

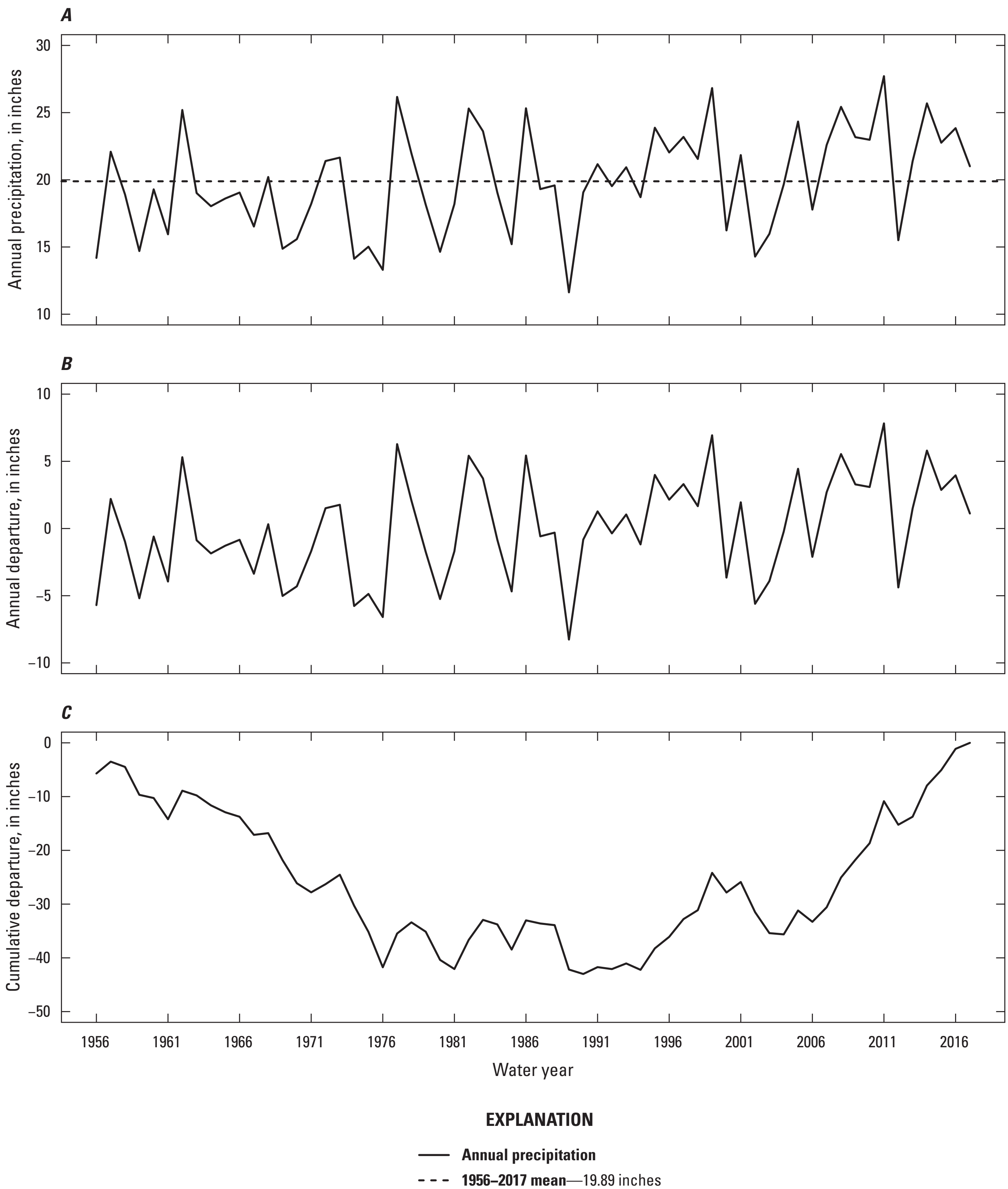

Figure 11. Annual total precipitation and departures from mean for the study area, water years 1956–2017. *A*, annual total precipitation for study area; *B*, annual departure from 1956 to 2017 mean; *C*, cumulative departure from 1956 to 2017 mean.

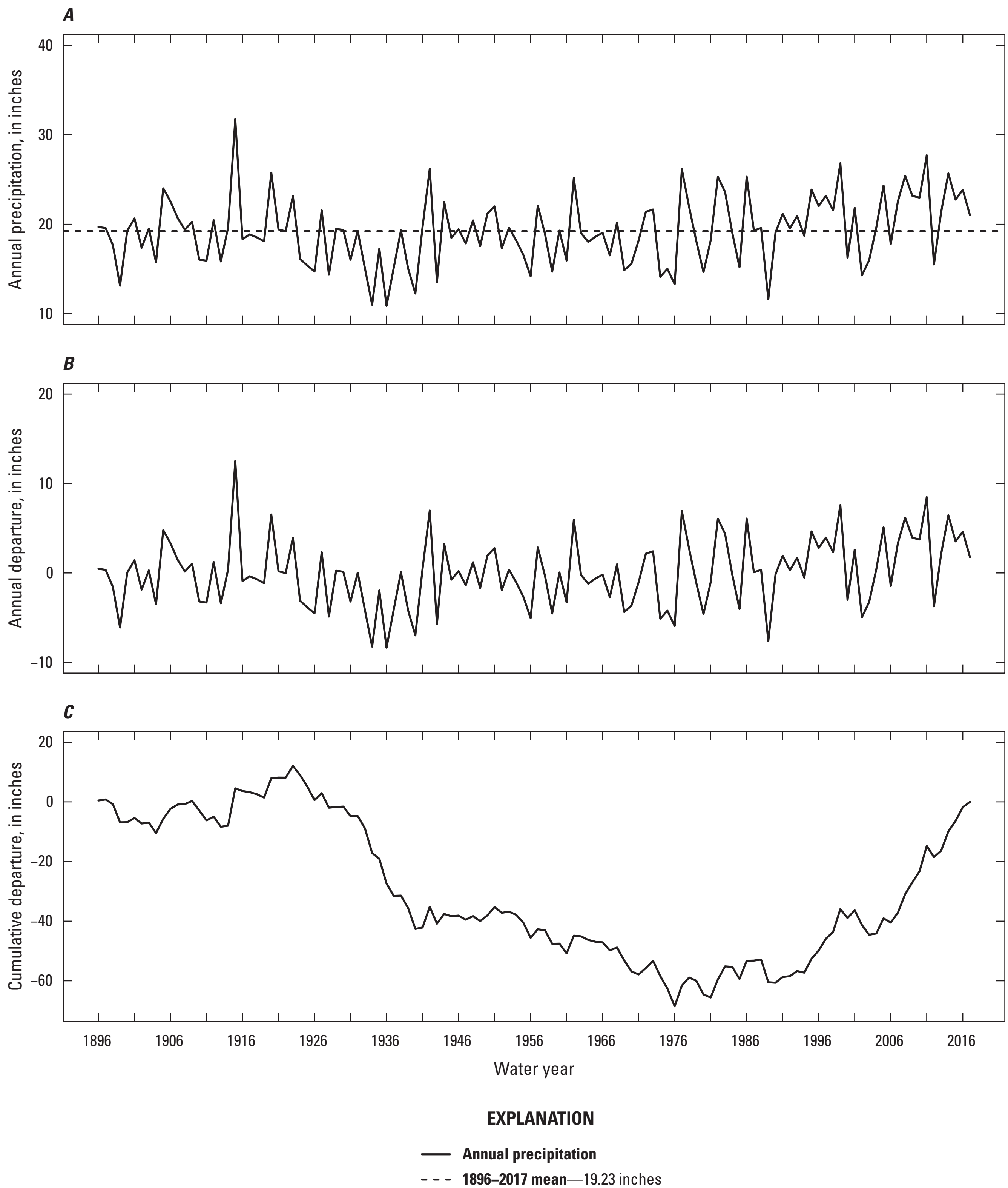

Figure 12. Annual total precipitation and departures from mean for the study area, water years 1896–2017. *A*, annual total precipitation for study area; *B*, annual departure from 1896 to 2017 mean; *C*, cumulative departure from 1896 to 2017 mean.

Table 4. Results of trend analyses for annual total precipitation for the study area for three time periods.

[STP, short-term persistence; *p*-value, probability value]

Period, in water years	STP present (yes/no)	Sen's Slope (inches per year)	Mann-Kendall *p*-value	Mann-Kendall tau (τ)	Mean annual precipitation for period (inches)	Number of years	Trend magnitude, in inches
1975–2017	No	0.118	0.029	0.231	20.59	43	5.07
1956–2017	No	0.088	0.002	0.276	19.89	62	5.46
1896–2017	No	0.025	0.015	0.149	19.23	122	3.05

Groundwater Trends

Trends over time for groundwater levels and annual precipitation for the 58 observation wells considered are presented in figures 1.1 through 1.58 in appendix 1. These figures also show licensed groundwater withdrawals over time within six specified radii for each well that has associated groundwater withdrawal data. Complete results of statistical trend analyses for the 58 observation wells are presented in table 2.1. The modified Mann-Kendall test was used for testing of all three water-level parameters because statistically significant STP was detected for most of the water-level datasets (table 2.2, figs. 2.3–2.60). Table 2.1 also includes results of statistical analyses for annual total precipitation for the location of each observation well. The standard Mann-Kendall test was used for testing of precipitation trends because statistically significant STP was not detected in any of the precipitation datasets.

Primary results of trend testing for the 58 observation wells are summarized in table 5, which is sorted by aquifer to facilitate characterizations of results by aquifer. For each well, statistically significant upward trends for any of the three water-level parameters are denoted with **bold-faced font** and statistically significant downward trends are denoted with *italicized font*. Of all 58 wells considered, 39 wells have statistically significant trends for at least one of the three water-level parameters (28 upward and 11 downward) and 19 wells had no significant water-level trends. Significant upward trends in annual precipitation are indicated for 48 of the 58 wells.

Results for 48 wells that are completed in the Ogallala aquifer are listed in table 5, all of which are in the southern part of the study area (fig. 1). The table is sorted to first show 17 wells with statistically significant upward trends for all three water-level parameters. Three additional wells have significant upward trends for two of the three water-level parameters, and four more wells have significant upward trends for only a single water-level parameter. All but 2 of these 24 wells have significant upward trends for annual precipitation. Licensed groundwater withdrawals within 0.5 and 1.0 mi radii of each observation well are shown in figure 3 and are summarized in table 5, along with withdrawals within a 5.0-mi radius. A complete summary of licensed groundwater withdrawals is listed table 2.3 in appendix 2 for radii of 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 mi. Of these 24 wells, only 6 have licensed groundwater withdrawals within 0.5 mi and only 9 have licensed groundwater withdrawals within 1.0 mi. Considering the largest radius, 17 of the 24 wells have licensed groundwater withdrawals within 5 mi and 11 wells have withdrawals exceeding 10 ft^3/s within 5 mi. Magnitudes of water-level trends in table 5 were computed as the product of the applicable period of record and the Sen's slope for the median value for all wells having statistically significant trends for at least one of the three water-level parameters. For the 24 wells with significant upward trends, trend magnitudes range from 0.7 foot for well TD-80B to 19.3 feet for well RST 27.

Sorted next in table 5 are 10 wells completed in the Ogallala aquifer with significant downward trends for at least one water-level parameter. Of these 10 wells, 8 have significant downward trends for all three water-level parameters and all but 1 have significant upward trends for annual precipitation. For the 10 wells having significant downward trends for at least one of the three water-level parameters, trend magnitudes range from −0.8 foot for well TD-76G to −15.2 feet for well RST 26. Of these 10 wells, 9 have licensed groundwater withdrawals within a 1-mi radius that range from 4.3 to 17.7 ft^3/s. The maximum cumulative withdrawal rate of 142.6 ft^3/s within a 5-mi radius of well TD-76D represents about 73 percent of the cumulative withdrawals of about 195 ft^3/s for Todd County (fig. 4). Well TD-76D (map number S8) is located near the center of the heaviest concentration of withdrawals in south-central Todd County (fig. 3*B*).

Fourteen of the wells completed in the Ogallala aquifer did not have statistically significant trends for any of the three water-level parameters. All but 2 of these 14 wells have significant upward trends for annual precipitation. Of these 14 wells, 1 has no licensed groundwater withdrawals within a 5-mi radius, 6 have generally small withdrawals (between 1.3 and 7.0 ft^3/s) within a 5-mi radius, and 7 have withdrawals within a 5-mi radius that range from 11.5 to 95.5 ft^3/s.

Table 5. Summary of results of trend analyses for water levels and annual total precipitation at observation wells.

[Start year, first water year for statistical analysis; ft/yr, foot/year; Mod M-K, modified Mann-Kendall; *p*-value, probability value; M-K, Mann-Kendall; in/yr, inch per year; Years, years of water-level record; <, less than; NA, not analyzed; Up, number of statistically significant upward trends; --, not applicable; Down, number of statistically significant downward trends; NR, not reported. Statistically significant upward trends (positive Sen's slope with *p*-value less than or equal to 0.10) are noted with **bold-face font**, and statistically significant downward trends (negative Sen's slope) are noted with *italics*]

Map number	Well number	Start year	Annual minimum water level		Annual median water level		Annual maximum water level		Start year	Annual total precipitation		Licensed groundwater withdrawals, in cubic feet per second, within specified radius of well, in miles			Time weighted trend magnitude for median water level (ft)
			Sen's Slope (ft/yr)	Mod M-K *p*-value	Sen's Slope (ft/yr)	Mod M-K *p*-value	Sen's Slope (ft/yr)	Mod M-K *p*-value		Sen's Slope (in/yr)	M-K *p*-value	0.5	1.0	5.0	
Observation wells monitoring Ogallala aquifer															
S3	TD-59A	1960	0.033	0.001	0.030	0.001	0.030	<0.001	1958	0.089	0.002	0.0	0.0	18.7	1.7
S4	TD-59BR	1961	0.091	0.004	0.100	0.003	0.100	0.001	1959	0.098	0.001	0.0	1.8	2.2	5.7
S13	TD-76I	1977	0.038	0.055	0.046	0.013	0.050	0.002	1975	0.105	0.057	1.3	2.7	70.7	1.9
S14	TD-76J	1977	0.141	<0.001	0.137	<0.001	0.133	<0.001	1975	0.124	0.035	1.8	1.8	50.3	5.6
S15	TD-79A	1980	0.078	0.038	0.104	0.023	0.116	0.028	1978	0.120	0.009	0.0	0.0	0.0	4.0
S29	BT-78KR	1979	0.046	0.014	0.065	0.002	0.063	0.004	1977	0.075	0.286	0.0	7.0	76.6	2.5
S30	BT-80E	1981	0.050	0.009	0.061	<0.001	0.063	<0.001	1979	0.131	0.082	0.0	0.0	42.4	2.3
R1	RST 1	1987	0.239	<0.001	0.234	<0.001	0.229	<0.001	1985	0.179	0.029	0.0	0.0	0.0	7.3
R2	RST 2	2000	0.135	0.002	0.123	0.029	0.117	0.077	1998	0.233	0.163	0.0	0.0	0.0	2.2
R3	RST 3	1987	0.165	0.001	0.163	0.021	0.169	0.036	1985	0.197	0.011	0.0	0.0	9.8	5.0
R6	RST 6	1987	0.112	<0.001	0.112	<0.001	0.123	<0.001	1985	0.162	0.019	0.0	0.0	41.9	3.5
R16	RST 16	1987	0.090	0.001	0.082	0.002	0.102	0.012	1985	0.145	0.049	0.0	4.5	55.5	2.6
R18	RST 18	1987	0.322	<0.001	0.308	0.001	0.298	0.001	1985	0.188	0.005	0.0	0.0	12.4	9.5
R20	RST 20	1987	0.162	<0.001	0.158	<0.001	0.173	<0.001	1985	0.189	0.005	0.0	0.0	0.3	4.9
R21	RST 21	1987	0.131	0.001	0.122	0.008	0.119	0.008	1985	0.141	0.031	0.0	0.0	0.0	3.8
R23	RST 23	1987	0.194	0.007	0.189	0.011	0.259	0.001	1985	0.173	0.003	0.0	0.0	0.0	5.9
R27	RST 27	1987	0.619	<0.001	0.621	<0.001	0.607	<0.001	1985	0.196	0.009	0.0	0.0	0.2	19.3
S16	TD-79B	1981	0.064	0.072	0.058	0.041	0.042	0.112	1979	0.164	0.007	4.7	7.0	11.1	2.2
S25	TD-#05	1985	0.017	0.169	0.031	0.062	0.031	0.071	1983	0.167	0.018	0.0	0.0	4.3	1.0
R22	RST 22	1987	0.087	0.076	0.072	0.152	0.070	0.018	1985	0.153	0.034	0.0	0.0	0.0	2.2
R25	RST 25	1987	0.091	<0.001	0.087	0.079	0.070	0.169	1985	0.136	0.034	0.0	0.0	0.0	2.7
S19	TD-80B	1981	0.022	0.130	0.018	0.069	0.022	0.148	1979	0.153	0.016	1.3	1.3	5.9	0.7
R11	RST 11	1987	0.272	0.003	0.174	0.136	0.132	0.159	1985	0.164	0.029	1.0	4.7	98.2	5.4
R13	RST 13	1987	0.073	0.091	0.061	0.136	0.056	0.428	1985	0.134	0.091	1.9	5.3	109.4	1.9

Table 5. Summary of results of trend analyses for water levels and annual total precipitation at observation wells.—Continued

[Start year, first water year for statistical analysis; ft/yr, foot/year; Mod M-K, modified Mann-Kendall; *p*-value, probability value; M-K, Mann-Kendall; in/yr, inch per year; Years, years of water-level record; <, less than; NA, not analyzed; Up, number of statistically significant upward trends; --, not applicable; Down, number of statistically significant downward trends; NR, not reported. Statistically significant upward trends (positive Sen's slope with *p*-value less than or equal to 0.10) are noted with **bold-face font**, and statistically significant downward trends (negative Sen's slope) are noted with *italics*]

Map number	Well number	Start year	Annual minimum water level		Annual median water level		Annual maximum water level		Start year	Annual total precipitation		Licensed groundwater withdrawals, in cubic feet per second, within specified radius of well, in miles			Time weighted trend magnitude for median water level (ft)
			Sen's Slope (ft/yr)	Mod M-K *p*-value	Sen's Slope (ft/yr)	Mod M-K *p*-value	Sen's Slope (ft/yr)	Mod M-K *p*-value		Sen's Slope (in/yr)	M-K *p*-value	0.5	1.0	5.0	
S5	TD-76A	1977	−0.100	0.005	−0.100	0.012	−0.095	0.018	1975	0.110	0.049	0.0	9.3	90.2	−4.1
S6	TD-76B	1977	−0.178	<0.001	−0.166	0.001	−0.153	0.002	1975	0.107	0.057	1.8	6.5	116.0	−6.8
S7	TD-76C	1977	−0.123	0.002	−0.107	0.010	−0.104	0.016	1975	0.112	0.060	2.8	10.1	134.0	−4.4
S8	TD-76D	1977	−0.200	0.001	−0.186	<0.001	−0.183	0.001	1975	0.119	0.038	4.8	17.7	142.6	−7.6
S10	TD-76F	1977	−0.178	<0.001	−0.165	<0.001	−0.164	<0.001	1975	0.117	0.049	0.0	0.0	126.0	−6.8
S23	TD-90A	1992	−0.156	0.002	−0.153	0.013	−0.141	0.005	1990	0.132	0.128	0.0	6.5	112.8	−4.0
R12	RST 12	1987	−0.112	<0.001	−0.123	<0.001	−0.105	<0.001	1985	0.149	0.027	5.2	14.0	136.7	−3.8
R26	RST 26	1987	−0.449	0.007	−0.491	0.001	−0.442	<0.001	1985	0.129	0.091	0.7	4.3	76.4	−15.2
S28	BT-76C	1977	−0.044	0.063	−0.044	0.067	−0.036	0.124	1975	0.114	0.086	5.6	9.2	56.9	−1.8
S11	TD-76G	1977	−0.024	0.049	−0.020	0.131	−0.012	0.396	1975	0.115	0.031	0.0	5.1	139.9	−0.8
S9	TD-76E	1977	0.004	0.707	0.009	0.347	0.013	0.260	1975	0.116	0.044	0.0	5.0	75.6	NA
S12	TD-76H	1977	0.000	0.949	0.015	0.429	0.012	0.476	1975	0.104	0.044	1.4	7.5	90.0	NA
S22	TD-80E	1981	0.042	0.223	0.037	0.283	0.046	0.114	1979	0.122	0.042	0.0	0.0	0.0	NA
S26	TD-#08	1985	0.019	0.418	0.030	0.164	0.032	0.133	1983	0.129	0.057	0.0	0.0	33.6	NA
S27	TD-#10	1985	0.033	0.181	0.033	0.210	0.050	0.130	1983	0.154	0.027	0.0	0.0	14.1	NA
S31	BT-80F	1981	0.032	0.259	0.035	0.214	0.044	0.103	1979	0.168	0.029	0.0	0.0	2.2	NA
S34	TR-78E	1978	0.043	0.385	0.047	0.189	0.045	0.165	1976	0.108	0.104	1.3	1.3	3.6	NA
R4	RST 4	1987	0.015	0.333	0.015	0.590	0.023	0.322	1985	0.209	0.019	0.0	0.0	1.3	NA
R7	RST 7	1987	0.028	0.652	0.027	0.513	0.047	0.435	1985	0.145	0.042	0.4	2.5	72.6	NA
R9	RST 9	1987	−0.017	0.630	−0.019	0.355	−0.015	0.475	1985	0.148	0.034	0.0	0.0	9.6	NA
R14	RST 14	1986	−0.013	0.527	0.001	0.986	0.026	0.604	1984	0.136	0.058	0.0	3.7	95.5	NA
R15	RST 15	1987	−0.005	0.870	−0.021	0.656	−0.015	0.470	1985	0.154	0.034	0.0	0.0	1.3	NA
R17	RST 17	1987	−0.007	0.786	−0.007	0.844	0.001	0.949	1985	0.154	0.029	0.0	0.0	11.5	NA
R19	RST 19	1999	0.249	0.182	0.179	0.301	0.107	0.187	1997	0.242	0.139	0.0	0.0	7.0	NA

Table 5. Summary of results of trend analyses for water levels and annual total precipitation at observation wells.—Continued

[Start year, first water year for statistical analysis; ft/yr, foot/year; Mod M-K, modified Mann-Kendall; *p*-value, probability value; M-K, Mann-Kendall; in/yr, inch per year; Years, years of water-level record; <, less than; NA, not analyzed; Up, number of statistically significant upward trends; --, not applicable; Down, number of statistically significant downward trends; NR, not reported. Statistically significant upward trends (positive Sen's slope with *p*-value less than or equal to 0.10) are noted with **bold-face font**, and statistically significant downward trends (negative Sen's slope) are noted with *italics*]

Map number	Well number	Start year	Annual minimum water level		Annual median water level		Annual maximum water level		Start year	Annual total precipitation		Licensed groundwater withdrawals, in cubic feet per second, within specified radius of well, in miles			Time weighted trend magnitude for median water level (ft)
			Sen's Slope (ft/yr)	Mod M-K *p*-value	Sen's Slope (ft/yr)	Mod M-K *p*-value	Sen's Slope (ft/yr)	Mod M-K *p*-value		Sen's Slope (in/yr)	M-K *p*-value	0.5	1.0	5.0	
Totals for trend analyses		Up	22	--	21	--	19	--	--	43	--	--	--	--	--
		Down	10	--	9	--	8	--	--	0	--	--	--	--	--
		No trend	16	--	18	--	21	--	--	5	--	--	--	--	--
Observation wells monitoring Arikaree aquifer															
S17	TD-79D	1981	0.243	<0.001	0.243	<0.001	0.248	<0.001	1979	0.086	0.255	0.0	0.0	0.0	9.0
S18	TD-80A	1981	0.382	<0.001	0.410	<0.001	0.438	<0.001	1979	0.079	0.127	0.0	0.0	2.7	15.2
S32	MT-78A	1979	0.143	0.017	0.140	0.037	0.100	NR[a]	1977	0.039	0.598	0.0	1.3	2.7	5.5
S20	TD-80C	1981	−0.292	<0.001	−0.217	<0.001	−0.171	<0.001	1979	0.114	0.066	4.8	15.1	136.0	-8.0
S21	TD-80D	1981	0.050	0.158	0.053	0.139	0.046	0.217	1979	0.117	0.037	0.0	0.0	0.0	NA
S24	TD-90B	1992	0.008	0.814	0.025	0.717	0.022	0.627	1990	0.146	0.079	0.0	0.0	26.1	NA
S33	MT-78B	1979	−0.035	0.101	−0.033	0.283	−0.024	0.344	1977	0.032	0.629	0.0	1.3	2.7	NA
S35	TR-99A	1999	−0.044	0.084	<0.001	0.972	0.020	0.354	1997	0.219	0.194	0.0	0.0	2.4	NA
Totals for trend analyses		Up	3	--	3	--	3	--	--	3	--	--	--	--	--
		Down	1	--	1	--	1	--	--	0	--	--	--	--	--
		No trend	4	--	4	--	4	--	--	5	--	--	--	--	--
Observation wells monitoring an alluvial aquifer															
S1	TD-57B	1958	−0.007	0.132	<0.001	0.956	0.007	0.260	1956	0.091	0.001	0.0	0.0	0.0	NA
S2	TD-57CR	1957	0.025	<0.001	0.025	0.002	0.028	0.002	1956	0.091	0.002	0.0	0.0	0.0	1.5
Totals for trend analyses		Up	1	--	1	--	1	--	--	2	--	--	--	--	--
		Down	0	--	0	--	0	--	--	0	--	--	--	--	--
		No trend	1	--	1	--	1	--	--	1	--	--	--	--	--

[a]Not reported because of a square-root error due to negative variance in the constructed time series.

The spatial distribution of wells completed in the Ogallala aquifer with statistically significant trends for at least one water-level parameter are shown in figure 13. Well S28, which is in an area of somewhat concentrated groundwater withdrawals on the east side of Bennett County (fig. 3*A*), is 1 of the 10 Ogallala aquifer wells with significant downward trends for at least one of the three water-level parameters (table 5). All nine of the other Ogallala aquifer wells with significant downward trends are located in the south-central part of the study area where licensed groundwater withdrawal wells are concentrated (fig. 3*B*). However, many other Ogallala aquifer wells with significant upward trends and wells without significant trends also are quite common around the periphery of the area of concentrated downward trends. In many cases the effects of groundwater withdrawals may be overshadowing the upward precipitation trends.

Results for eight wells that are completed in the Arikaree aquifer are also listed in table 5. Well TD-80C (map number S20), which has statistically significant downward trends for all three of the water-level parameters, is located in the south-central part of the study area where licensed groundwater withdrawal wells are concentrated (fig. 3*B*) and where 9 of the 10 Ogallala aquifer wells with statistically significant downward trends for at least one water-level parameter are located. This well is in an area where the hydraulic head in the Arikaree aquifer is artesian and generally similar to that of the Ogallala aquifer (fig. 2). Thus, hydraulic head in the Arikaree aquifer may be affected by withdrawals from the Ogallala aquifer in this vicinity.

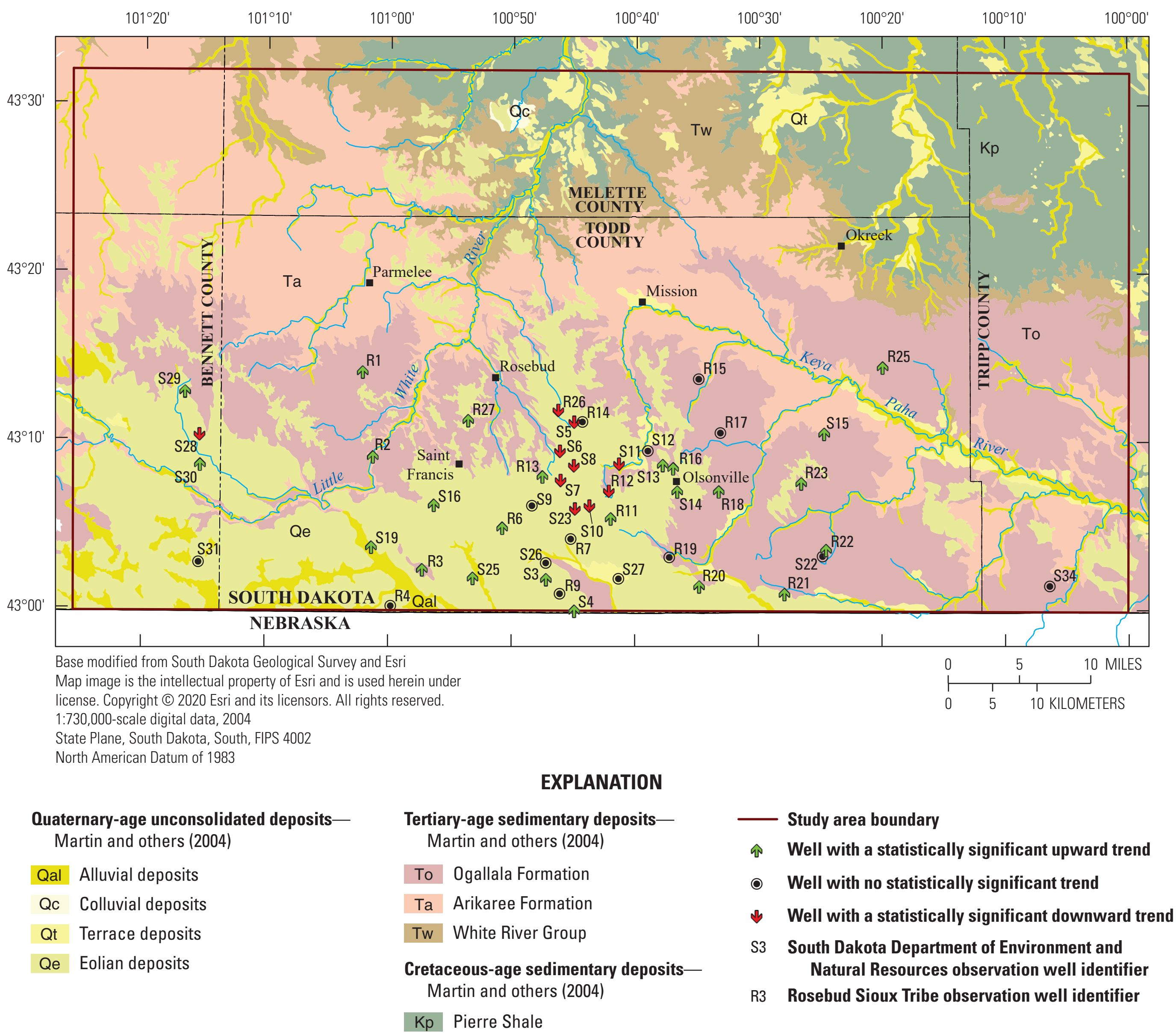

Figure 13. Wells completed in the Ogallala aquifer with statistically significant trends for at least one water-level parameter.

Two of the Arikaree aquifer wells have statistically significant upward trends for all three of the water-level parameters (table 5) and one well has significant upward trends for two of the three water-level parameters. All three wells are in the northwest part of the study area where licensed groundwater withdrawals are minimal (fig. 3*A*; map numbers S17, S18, and S32). Significant trends are not identified for the other four Arikaree aquifer wells. Significant upward trends in annual precipitation are identified for only three of the eight Arikaree aquifer wells, which have shorter periods of records than most of the Ogallala aquifer wells.

Two wells (map numbers S1 and S2) are completed in an alluvial aquifer (table 5) along the Keya Paha River in the eastern part of the study area (fig. 1). Both wells have statistically significant upward trends in annual precipitation but only one of the wells has a significant upward water-level trend (all three parameters).

Several water-level measurements reported by SDDENR (Jeanne Goodman, SDDENR, written commun., 2020) at the end of WY 2017 are considered suspect data by SDDENR. The suspect data were not specifically identified by the SDDENR, so visually identified outlier data points from 13 observation wells (map numbers S5, S6, S8, S13, S17, S23, S26, S28, S29, S31, S32, S33, and S35) from WY 2017 were removed and statistically reanalyzed to determine how the suspect data affected the results of the study. Most wells had slight changes in Sen's slope (trend magnitude); however, three observation wells (map numbers S26, S31, S35) did have a change from significant upward trend to not significant trend or vice versa in one or two water-level parameters. Statistically, the suspect water-level data did not substantially change the results of the study, and because the suspect water-level data were publicly available (as of 2020), the date ranges and data were not changed or censored in any way for this study.

The three graphs on figure 14 were developed for the 34 wells completed in the Ogallala aquifer having a statistically significant trend, whether upward or downward, for at least one of the three water-level parameters considered (table 5). A correlation plot between the Sen's slope values for the annual median water levels and the Sen's slope values for annual total precipitation for the 34 observation wells is shown on figure 14*A*. The positive correlation ($r=0.523$) is consistent with the overwhelming predominance of wells with upward precipitation trends but is somewhat weak because of the proximal groundwater withdrawals that contribute to downward trends in water levels. A correlation plot between the Sen's slope values for the annual median water levels and cumulative withdrawals within 5 mi of each observation well is shown on figure 14*B*. The inverse correlation ($r=-0.612$) is physically realistic and somewhat stronger than for the correlation of figure 14*A*. A correlation plot between the time-weighted magnitudes of water-level trends and cumulative withdrawals within 5 mi of each well is shown on figure 14*C*. The time weighting results in a slightly stronger correlation ($r=-0.640$) than for figure 14*B*.

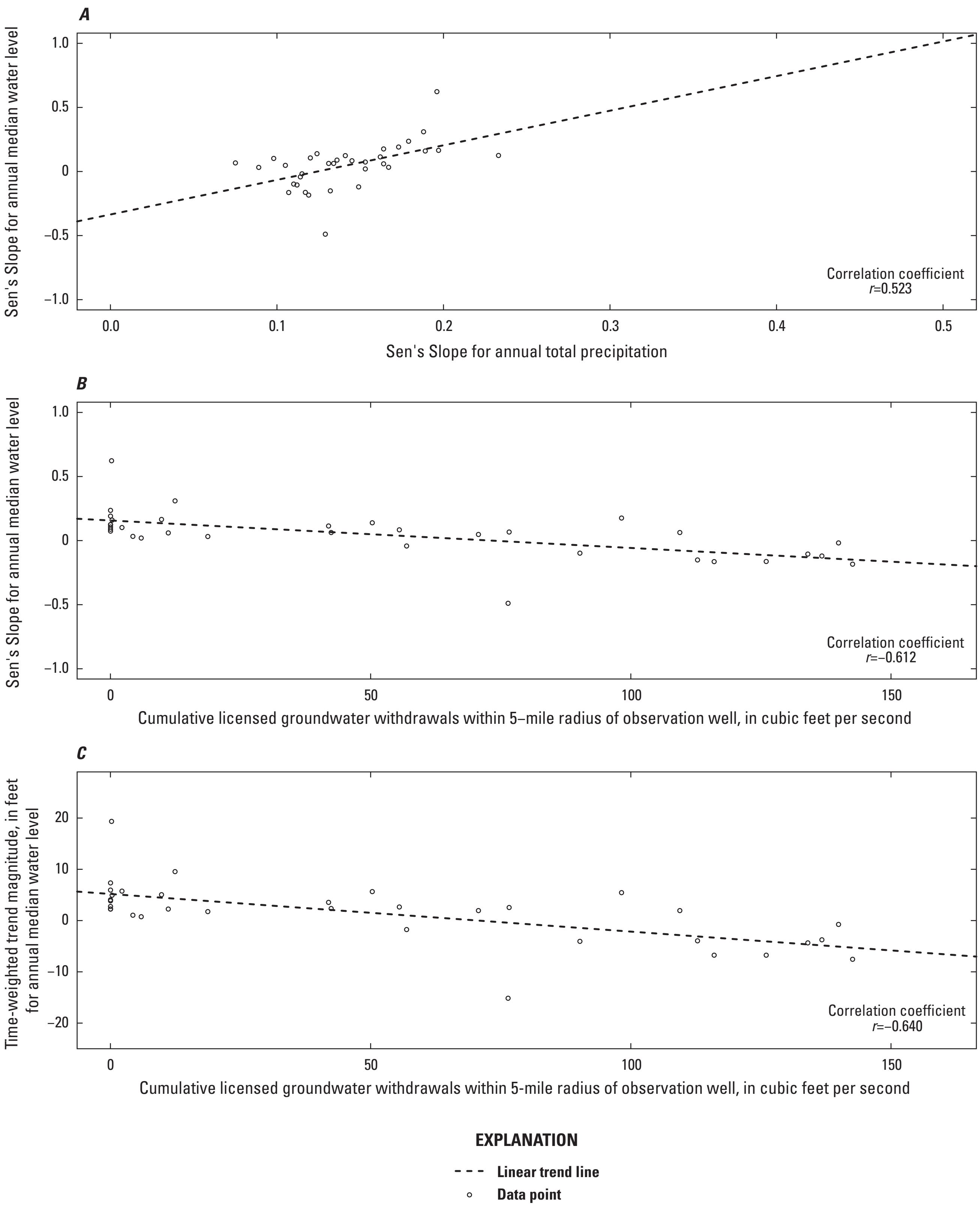

Figure 14. Correlation analyses for 34 observation wells completed in the Ogallala aquifer having statistically significant trends in at least one of three water-level parameters considered. *A,* Sen's slope for annual median water level and Sen's slope for annual total precipitation; *B,* Sen's slope for annual median water level and cumulative licensed groundwater withdrawals within 5-mile radius of an observation well; and *C,* time-weighted trend magnitude and cumulative licensed groundwater withdrawals within 5-mile radius of an observation well.

Summary

The U.S. Geological Survey, in cooperation with the Rosebud Sioux Tribe, completed a study to characterize water-level fluctuations in observation wells to examine driving factors that affect water levels in and near the Rosebud Indian Reservation, which comprises all of Todd County. The study investigates concerns regarding potential effects of groundwater withdrawals and climate conditions on groundwater levels within an area that includes Todd County and a surrounding area that extends 10 miles north, east, and west of the county border. Driving factors considered include precipitation, minimum temperature, maximum temperature, and groundwater withdrawals. Trends over time are analyzed for water-level records during 1957–2017 for 58 observation wells operated by the South Dakota Department of Environment and Natural Resources or Rosebud Sioux Tribe and for estimated precipitation at the well locations. Groundwater withdrawals within a 5-mile radius of each observation well are qualitatively compared to water levels.

Analyses primarily involved (1) trends over time for measured water levels in observation wells and for estimated precipitation at each observation well, and (2) qualitative consideration of effects of groundwater withdrawals on groundwater levels. Water-level records were analyzed for 35 observation wells monitored by the South Dakota Department of Environment and Natural Resources, with the earliest records beginning in water year (WY) 1957 and for 23 wells monitored by the Rosebud Sioux Tribe with the earliest records beginning in water year WY 1987. All climate data considered (primarily annual precipitation) were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM).

Most of the statistical analyses involved trend testing in annual time steps for statistical significance and trend magnitude. Before trend testing, applicable datasets were tested for statistically significant short-term persistence (STP). In the absence of significant STP, statistical significance was determined using the standard Mann-Kendall test for probability values less than or equal to 0.10 (90-percent confidence level); however, a modified Mann-Kendall test was used for datasets where statistically significant STP was detected. Trend magnitudes were computed using the Sen's slope estimator.

Monthly PRISM data were aggregated to obtain annual and seasonal datasets for total precipitation, minimum air temperature (T_{min}), and maximum air temperature (T_{max}) for the study area and a surrounding buffer area. Trend tests for total precipitation, T_{min}, and T_{max} were completed for annual and seasonal time series for WYs 1956–2017, which is about 2 years before the earliest available water-level measurements. Statistically significant upward trends were detected for annual precipitation and annual T_{min} for almost all of the study area and the surrounding buffer area. The near-completeness of the spatial coverage in upward trends provides high confidence that these are true trends for WYs 1956–2017. Statistically significant downward trends in T_{max} were detected for a very small part of the study area; however, the sparse spatial coverage reduces confidence that these are true trends. Spatial distributions of statistically significant trends in seasonal climate data were generally similar to the annual trends, but with substantial differences in the spatial density of the trends. Estimates of annual total precipitation for the study area for three different time periods were examined in greater detail to obtain additional perspectives on precipitation patterns. Mean annual precipitation during WYs 1975–2017 was 20.59 in., which is larger than the mean annual precipitation for 1956–2017 (19.89 in.) and 1896–2017 (19.23 in.). Statistically significant upward trends were indicated for all time periods.

Groundwater trends for observation wells were analyzed for three separate water-level parameters (minimum, median, and maximum) because wells are measured sporadically and data are biased towards more frequent measurements during periods of heaviest irrigation demand. Trends in the time series of annual precipitation (from PRISM), starting 2 years earlier than for the associated water-level trend, also were analyzed for the location of each individual observation well. Sen's slope and Mann-Kendall *p*-values were computed for the three water-level parameters and for the annual precipitation time series. Graphs showing results of trend analyses for each observation well also showed changes over time in the sum of groundwater withdrawals within six specified radii (0.5, 1, 2, 3, 4, and 5 miles) of each well as a qualitative indicator of proximal groundwater demand.

Of all 58 wells considered, 28 wells had significant upward trends for at least one of the three water-level parameters, 11 wells had significant downward trends for at least one parameter, and 19 wells did not have any significant trends. Significant upward trends in annual precipitation are indicated for 48 of the 58 wells.

Results of trend analyses likely show the effects of groundwater withdrawals on water levels in the Ogallala aquifer in areas of substantial demand. Precipitation trends are significantly upward for 43 of the 48 wells that were analyzed. Of the 48 wells completed in the Ogallala aquifer, 24 had significant upward trends for at least one water-level parameter (17 with all 3); however, 10 wells had statistically significant downward trends for at least one water-level parameter (8 with all 3 parameters). All but one of the wells with significant downward trends are located in the south-central part of the study area where licensed groundwater withdrawals are concentrated.

For the eight wells completed in the Arikaree aquifer, three wells had significant upward trends for all three water-level parameters. A single well that is completed in the Arikaree aquifer had significant downward trends for all three water-level parameters. This well is located in the south-central part of the study area where licensed groundwater withdrawal wells are concentrated and where 9 of the 10 Ogallala aquifer wells with statistically significant downward trends for at least one water-level parameter are located. This well is in an area where the hydraulic head in the Arikaree aquifer is artesian and generally similar to that of the Ogallala aquifer. Thus, hydraulic head in the Arikaree aquifer may be affected by withdrawals from the Ogallala aquifer in this vicinity.

For the two wells completed in an alluvial aquifer, one well had a significant upward trend for all three water-level parameters and one well has no discernible trends. Withdrawals from the Arikaree and alluvial aquifers generally are much smaller than from the Ogallala aquifer.

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Appendix 1

Graphs showing trends in measured water levels for the 58 observation wells considered are shown in figures 1.1 through 1.58 (available at https://doi.org/10.3133/sir20205119). Graphs for South Dakota Department of Environment and Natural Resources observation wells are presented in figures 1.1 through 1.35, and graphs for Rosebud Sioux Tribe observation wells are presented in figures 1.36 through 1.58. Either one or two graphs are presented for each observation well. Graph *A* shows individual measurements of groundwater levels for each well and annual total precipitation from Parameter-elevation Regressions on Independent Slopes Model, which is estimated for the location of the observation well. Graph *A* includes a locally estimated regression scatterplot smoothing curve that is fit to the time series for annual total precipitation starting 2 years before the first year of water-level record for each well, which is used as the first year for trend analyses for the precipitation data. Results of time-trend analyses (Sen's slope and Mann-Kendall *p*-values) are shown above graph *A* for three annual water-level parameters (minimum, median, and maximum). Graph *B* shows licensed groundwater withdrawals, by year, within six specified radii (0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 miles) of each well. Graph *B* is not included in cases where there are no known licensed groundwater withdrawals within 5.0 miles.

Appendix 2

Complete results of the modified Mann-Kendall statistical trend tests for water-level measurements and standard Mann-Kendall trend tests for precipitation measurements at observation wells are listed in table 2.1. Two statistical methods were used for analysis of temporal trends for climatic and hydrologic data. To determine which trend analysis to use for statistical significance and magnitudes of temporal trends, applicable datasets were tested for statistically significant short-term persistence (STP) as described in the "Statistical and Analytical Methods" section in the body of the report. The standard version of the nonparametric Mann-Kendall test was used to determine statistical significance of trends for datasets that showed little or no STP. For datasets with substantial STP, a modified Mann-Kendall test was used. Results of testing for STP for applicable datasets are summarized in table 2.2. Graphs showing autocorrelation function values for annual total precipitation, annual mean maximum temperature, and annual mean minimum temperature for the study area are shown in figure 2.1. Graphs showing autocorrelation function values for annual total precipitation for the study area from 1896 to 2017, 1956 to 2017, and 1975 to 2017 are shown in figure 2.2. Graphs showing autocorrelation function values for annual total precipitation and annual median water levels for the 58 observation wells considered are shown in figures 2.3 through 2.60 (available at https://doi.org/10.3133/sir20205119).

Table 2.1. Results of statistical trend analyses for groundwater levels estimates at observation wells.

[Start year, start year for statistical analysis; ft/yr, foot per year; Mod M-K, modified Mann-Kendall; *p*-value, probability value; in/yr, inch per year; <, less than]

Map number	Well number	Aquifer	Start year	Water levels								
				Minimum water level			Median water level			Maximum water level		
				Sen's slope (ft/yr)	Mod M-K *p*-value	Mod M-K tau	Sen's slope (ft/yr)	Mod M-K *p*-value	Mod M-K tau	Sen's slope (ft/yr)	Mod M-K *p*-value	Mod M-K tau
Wells operated by South Dakota Department of Environment and Natural Resources												
S1	TD-57B	Alluvium	1958	−0.007	0.132	−0.153	<0.001	0.956	−0.007	0.007	0.260	0.101
S2	TD-57CR	Alluvium	1957	0.025	<0.001	0.422	0.025	0.002	0.396	0.028	0.002	0.360
S3	TD-59A	Ogallala	1960	0.033	0.001	0.544	0.030	0.001	0.515	0.030	<0.001	0.521
S4	TD-59BR	Ogallala	1961	0.091	0.004	0.575	0.100	0.003	0.625	0.100	0.001	0.650
S5	TD-76A	Ogallala	1977	−0.100	0.005	−0.499	−0.100	0.012	−0.452	−0.095	0.018	−0.434
S6	TD-76B	Ogallala	1977	−0.178	<0.001	−0.602	−0.166	<0.001	−0.574	−0.153	0.002	−0.523
S7	TD-76C	Ogallala	1977	−0.123	0.002	−0.533	−0.107	0.010	−0.448	−0.104	0.016	−0.409
S8	TD-76D	Ogallala	1977	−0.200	0.001	−0.605	−0.186	<0.001	−0.550	−0.183	0.001	−0.527
S9	TD-76E	Ogallala	1977	0.004	0.707	0.039	0.009	0.347	0.102	0.013	0.260	0.112
S10	TD-76F	Ogallala	1977	−0.178	<0.001	−0.746	−0.165	<0.001	−0.713	−0.164	<0.001	−0.691
S11	TD-76G	Ogallala	1977	−0.024	0.049	−0.213	−0.020	0.131	−0.161	−0.012	0.396	−0.098
S12	TD-76H	Ogallala	1977	0.000	0.949	0.009	0.015	0.429	0.100	0.012	0.476	0.100
S13	TD-76I	Ogallala	1977	0.038	0.055	0.273	0.046	0.013	0.340	0.050	0.002	0.338
S14	TD-76J	Ogallala	1977	0.141	<0.001	0.645	0.137	<0.001	0.674	0.133	<0.001	0.673
S15	TD-79A	Ogallala	1980	0.078	0.038	0.400	0.104	0.023	0.417	0.116	0.028	0.425
S16	TD-79B	Ogallala	1981	0.064	0.072	0.236	0.058	0.041	0.294	0.042	0.112	0.251
S17	TD-79D	Arikaree	1981	0.243	<0.001	0.665	0.243	<0.001	0.671	0.248	<0.001	0.673
S18	TD-80A	Arikaree	1981	0.382	<0.001	0.671	0.410	<0.001	0.704	0.438	<0.001	0.725
S19	TD-80B	Ogallala	1981	0.022	0.130	0.180	0.018	0.069	0.150	0.022	0.148	0.155
S20	TD-80C	Arikaree	1981	−0.292	<0.001	−0.623	−0.217	<0.001	−0.553	−0.171	<0.001	−0.462
S21	TD-80D	Arikaree	1981	0.050	0.158	0.192	0.053	0.139	0.179	0.046	0.217	0.156
S22	TD-80E	Ogallala	1981	0.042	0.223	0.240	0.037	0.283	0.215	0.046	0.114	0.260
S23	TD-90A	Ogallala	1992	−0.156	0.002	−0.618	−0.153	0.013	−0.569	−0.141	0.005	−0.575
S24	TD-90B	Arikaree	1992	0.008	0.814	0.046	0.025	0.717	0.068	0.022	0.627	0.092
S25	TD-#05	Ogallala	1985	0.017	0.169	0.153	0.031	0.062	0.195	0.031	0.071	0.235
S26	TD-#08	Ogallala	1985	0.019	0.418	0.153	0.030	0.164	0.231	0.032	0.133	0.244
S27	TD-#10	Ogallala	1985	0.033	0.181	0.167	0.033	0.210	0.157	0.050	0.130	0.210
S28	BT-76C	Ogallala	1977	−0.044	0.063	−0.304	−0.044	0.067	−0.277	−0.036	0.124	−0.241
S29	BT-78KR	Ogallala	1979	0.046	0.014	0.383	0.065	0.002	0.414	0.063	0.004	0.388
S30	BT-80E	Ogallala	1981	0.050	0.009	0.479	0.061	<0.001	0.536	0.063	<0.001	0.485

Table 2.1. Results of statistical trend analyses for groundwater levels estimates at observation wells.—Continued

[Start year, start year for statistical analysis; ft/yr, foot per year; Mod M-K, modified Mann-Kendall; *p*-value, probability value; in/yr, inch per year; <, less than]

Map number	Well number	Aquifer	Water levels									
			Start year	Minimum water level			Median water level			Maximum water level		
				Sen's slope (ft/yr)	Mod M-K *p*-value	Mod M-K tau	Sen's slope (ft/yr)	Mod M-K *p*-value	Mod M-K tau	Sen's slope (ft/yr)	Mod M-K *p*-value	Mod M-K tau
Wells operated by South Dakota Department of Environment and Natural Resources—Continued												
S31	BT-80F	Ogallala	1981	0.032	0.259	0.254	0.035	0.214	0.260	0.044	0.103	0.318
S32	MT-78A	Arikaree	1979	0.143	0.017	0.204	0.140	0.038	0.181	0.100	NR	0.151
S33	MT-78B	Arikaree	1979	−0.035	0.101	−0.154	−0.033	0.283	−0.131	−0.024	0.344	−0.113
S34	TR-78E	Ogallala	1978	0.043	0.385	0.154	0.047	0.189	0.194	0.045	0.165	0.181
S35	TR-99A	Arikaree	1999	−0.044	0.084	−0.257	0.000	0.972	−0.023	0.020	0.354	0.129
Wells operated by Rosebud Sioux Tribe												
R1	RST 1	Ogallala	1987	0.239	<0.001	0.886	0.234	<0.001	0.858	0.229	<0.001	0.634
R2	RST 2	Ogallala	2000	0.135	0.002	0.463	0.123	0.029	0.397	0.117	0.077	0.324
R3	RST 3	Ogallala	1987	0.165	0.001	0.363	0.163	0.021	0.416	0.169	0.036	0.391
R4	RST 4	Ogallala	1987	0.015	0.333	0.124	0.015	0.590	0.076	0.023	0.322	0.124
R6	RST 6	Ogallala	1987	0.112	<0.001	0.432	0.112	<0.001	0.524	0.123	<0.001	0.487
R7	RST 7	Ogallala	1987	0.028	0.652	0.067	0.027	0.513	0.090	0.047	0.435	0.117
R9	RST 9	Ogallala	1987	−0.017	0.630	−0.103	−0.019	0.355	−0.193	−0.015	0.475	−0.137
R11	RST 11	Ogallala	1987	0.272	0.003	0.453	0.174	0.136	0.266	0.132	0.159	0.259
R12	RST 12	Ogallala	1987	−0.112	<0.001	−0.457	−0.123	<0.001	−0.492	−0.105	<0.001	−0.480
R13	RST 13	Ogallala	1987	0.073	0.091	0.237	0.061	0.136	0.193	0.056	0.428	0.166
R14	RST 14	Ogallala	1986	−0.013	0.527	−0.091	0.001	0.986	0.007	0.026	0.604	0.105
R15	RST 15	Ogallala	1987	−0.005	0.870	−0.023	−0.021	0.656	−0.069	−0.015	0.470	−0.108
R16	RST 16	Ogallala	1987	0.090	<0.001	0.402	0.082	0.002	0.379	0.102	0.012	0.356
R17	RST 17	Ogallala	1987	−0.007	0.786	−0.055	−0.007	0.844	−0.034	0.001	0.949	0.016
R18	RST 18	Ogallala	1987	0.322	<0.001	0.772	0.308	<0.001	0.699	0.298	0.001	0.639
R19	RST 19	Ogallala	1999	0.249	0.182	0.353	0.179	0.301	0.275	0.107	0.187	0.275
R20	RST 20	Ogallala	1987	0.162	<0.001	0.432	0.158	<0.001	0.455	0.173	<0.001	0.471
R21	RST 21	Ogallala	1987	0.131	<0.001	0.395	0.122	0.008	0.434	0.119	0.008	0.434
R22	RST 22	Ogallala	1987	0.087	0.076	0.278	0.072	0.152	0.244	0.070	0.018	0.324
R23	RST 23	Ogallala	1987	0.194	0.007	0.474	0.189	0.011	0.448	0.259	0.001	0.467
R25	RST 25	Ogallala	1987	0.091	<0.001	0.343	0.087	0.079	0.260	0.070	0.169	0.205
R26	RST 26	Ogallala	1987	−0.449	0.007	−0.532	−0.491	0.001	−0.714	−0.442	<0.001	−0.772
R27	RST 27	Ogallala	1987	0.619	<0.001	0.852	0.621	<0.001	0.926	0.607	<0.001	0.894

Table 2.2. Results of statistical trend analyses for annual total precipitation estimates at observation wells.

[Start year, start year for statistical analysis; *p*-value, probability value; M-K, Mann-Kendall; in/yr, inch per year]

Map number	Well number	Aquifer	Annual total precipitation			
			Start year	Sen's slope (in/yr)	M-K *p*-value	M-K tau
Wells operated by South Dakota Department of Environment and Natural Resources						
S1	TD-57B	Alluvium	1956	0.091	0.001	0.280
S2	TD-57CR	Alluvium	1956	0.091	0.002	0.267
S3	TD-59A	Ogallala	1958	0.089	0.002	0.271
S4	TD-59BR	Ogallala	1959	0.098	0.001	0.285
S5	TD-76A	Ogallala	1975	0.110	0.049	0.209
S6	TD-76B	Ogallala	1975	0.107	0.057	0.203
S7	TD-76C	Ogallala	1975	0.112	0.060	0.200
S8	TD-76D	Ogallala	1975	0.119	0.038	0.220
S9	TD-76E	Ogallala	1975	0.116	0.044	0.214
S10	TD-76F	Ogallala	1975	0.117	0.049	0.209
S11	TD-76G	Ogallala	1975	0.115	0.031	0.229
S12	TD-76H	Ogallala	1975	0.104	0.044	0.214
S13	TD-76I	Ogallala	1975	0.105	0.057	0.203
S14	TD-76J	Ogallala	1975	0.124	0.035	0.225
S15	TD-79A	Ogallala	1978	0.120	0.009	0.287
S16	TD-79B	Ogallala	1979	0.164	0.007	0.304
S17	TD-79D	Arikaree	1979	0.086	0.255	0.128
S18	TD-80A	Arikaree	1979	0.079	0.127	0.171
S19	TD-80B	Ogallala	1979	0.153	0.016	0.271
S20	TD-80C	Arikaree	1979	0.114	0.066	0.206
S21	TD-80D	Arikaree	1979	0.117	0.037	0.233
S22	TD-80E	Ogallala	1979	0.122	0.042	0.228
S23	TD-90A	Ogallala	1990	0.132	0.128	0.206
S24	TD-90B	Arikaree	1990	0.146	0.079	0.238
S25	TD-#05	Ogallala	1983	0.167	0.018	0.281
S26	TD-#08	Ogallala	1983	0.129	0.057	0.227
S27	TD-#10	Ogallala	1983	0.154	0.027	0.264
S28	BT-76C	Ogallala	1975	0.114	0.086	0.183
S29	BT-78KR	Ogallala	1977	0.075	0.286	0.117
S30	BT-80E	Ogallala	1979	0.131	0.082	0.196

Table 2.2. Results of statistical trend analyses for annual total precipitation estimates at observation wells.—Continued

[Start year, start year for statistical analysis; *p*-value, probability value; M-K, Mann-Kendall; in/yr, inch per year]

Map number	Well number	Aquifer	Annual total precipitation			
			Start year	Sen's slope (in/yr)	M-K *p*-value	M-K tau
Wells operated by South Dakota Department of Environment and Natural Resources—Continued						
S31	BT-80F	Ogallala	1979	0.168	0.029	0.244
S32	MT-78A	Arikaree	1977	0.039	0.598	0.059
S33	MT-78B	Arikaree	1977	0.032	0.629	0.054
S34	TR-78E	Ogallala	1976	0.108	0.104	0.175
S35	TR-99A	Arikaree	1997	0.219	0.194	0.210
Wells operated by Rosebud Sioux Tribe						
R1	RST 1	Ogallala	1985	0.179	0.029	0.269
R2	RST 2	Ogallala	1998	0.233	0.163	0.232
R3	RST 3	Ogallala	1985	0.197	0.011	0.314
R4	RST 4	Ogallala	1985	0.209	0.019	0.288
R6	RST 6	Ogallala	1985	0.162	0.019	0.288
R7	RST 7	Ogallala	1985	0.145	0.042	0.250
R9	RST 9	Ogallala	1985	0.148	0.034	0.261
R11	RST 11	Ogallala	1985	0.164	0.029	0.269
R12	RST 12	Ogallala	1985	0.149	0.027	0.273
R13	RST 13	Ogallala	1985	0.134	0.091	0.208
R14	RST 14	Ogallala	1984	0.136	0.058	0.230
R15	RST 15	Ogallala	1985	0.154	0.034	0.261
R16	RST 16	Ogallala	1985	0.145	0.049	0.242
R17	RST 17	Ogallala	1985	0.154	0.029	0.269
R18	RST 18	Ogallala	1985	0.188	0.005	0.345
R19	RST 19	Ogallala	1997	0.242	0.139	0.238
R20	RST 20	Ogallala	1985	0.189	0.005	0.348
R21	RST 21	Ogallala	1985	0.141	0.031	0.265
R22	RST 22	Ogallala	1985	0.153	0.034	0.261
R23	RST 23	Ogallala	1985	0.173	0.003	0.364
R25	RST 25	Ogallala	1985	0.136	0.034	0.261
R26	RST 26	Ogallala	1985	0.129	0.091	0.208
R27	RST 27	Ogallala	1985	0.196	0.009	0.322

Table 2.3. Results of short-term persistence analyses for annual total precipitation and annual median groundwater levels estimates at observation wells.

[Start year, start year for statistical analysis; STP, short-term persistence]

Map number	Well number	Aquifer	Annual total precipitation		Annual median water levels	
			Start year	STP present (yes/no)	Start year	STP present (yes/no)
Wells operated by South Dakota Department of Environment and Natural Resources						
S1	TD-57B	Alluvium	1956	No	1958	No
S2	TD-57CR	Alluvium	1956	No	1957	Yes
S3	TD-59A	Ogallala	1958	No	1960	Yes
S4	TD-59BR	Ogallala	1959	No	1961	Yes
S5	TD-76A	Ogallala	1975	No	1977	Yes
S6	TD-76B	Ogallala	1975	No	1977	Yes
S7	TD-76C	Ogallala	1975	No	1977	Yes
S8	TD-76D	Ogallala	1975	No	1977	Yes
S9	TD-76E	Ogallala	1975	No	1977	Yes
S10	TD-76F	Ogallala	1975	No	1977	Yes
S11	TD-76G	Ogallala	1975	No	1977	Yes
S12	TD-76H	Ogallala	1975	No	1977	Yes
S13	TD-76I	Ogallala	1975	No	1977	Yes
S14	TD-76J	Ogallala	1975	No	1977	Yes
S15	TD-79A	Ogallala	1978	No	1980	Yes
S16	TD-79B	Ogallala	1979	No	1981	Yes
S17	TD-79D	Arikaree	1979	No	1981	Yes
S18	TD-80A	Arikaree	1979	No	1981	Yes
S19	TD-80B	Ogallala	1979	No	1981	Yes
S20	TD-80C	Arikaree	1979	No	1981	Yes
S21	TD-80D	Arikaree	1979	No	1981	Yes
S22	TD-80E	Ogallala	1979	No	1981	Yes
S23	TD-90A	Ogallala	1990	No	1992	Yes
S24	TD-90B	Arikaree	1990	No	1992	Yes
S25	TD-#05	Ogallala	1983	No	1985	Yes
S26	TD-#08	Ogallala	1983	No	1985	Yes
S27	TD-#10	Ogallala	1983	No	1985	Yes
S28	BT-76C	Ogallala	1975	No	1977	Yes
S29	BT-78KR	Ogallala	1977	No	1979	Yes
S30	BT-80E	Ogallala	1979	No	1981	Yes
S31	BT-80F	Ogallala	1979	No	1981	Yes
S32	MT-78A	Arikaree	1977	No	1979	Yes
S33	MT-78B	Arikaree	1977	No	1979	Yes
S34	TR-78E	Ogallala	1976	No	1978	Yes
S35	TR-99A	Arikaree	1997	No	1999	No
Wells operated by Rosebud Sioux Tribe						
R1	RST 1	Ogallala	1985	No	1987	Yes
R2	RST 2	Ogallala	1998	No	2000	Yes
R3	RST 3	Ogallala	1985	No	1987	Yes
R4	RST 4	Ogallala	1985	No	1987	Yes

Table 2.3. Results of short-term persistence analyses for annual total precipitation and annual median groundwater levels estimates at observation wells.—Continued

[Start year, start year for statistical analysis; STP, short-term persistence]

Map number	Well number	Aquifer	Annual total precipitation		Annual median water levels	
			Start year	STP present (yes/no)	Start year	STP present (yes/no)
Wells operated by Rosebud Sioux Tribe—Continued						
R6	RST 6	Ogallala	1985	No	1987	Yes
R7	RST 7	Ogallala	1985	No	1987	Yes
R9	RST 9	Ogallala	1985	No	1987	Yes
R11	RST 11	Ogallala	1985	No	1987	Yes
R12	RST 12	Ogallala	1985	No	1987	Yes
R13	RST 13	Ogallala	1985	No	1987	Yes
R14	RST 14	Ogallala	1984	No	1986	Yes
R15	RST 15	Ogallala	1985	No	1987	Yes
R16	RST 16	Ogallala	1985	No	1987	Yes
R17	RST 17	Ogallala	1985	No	1987	Yes
R18	RST 18	Ogallala	1985	No	1987	Yes
R19	RST 19	Ogallala	1997	No	1999	Yes
R20	RST 20	Ogallala	1985	No	1987	Yes
R21	RST 21	Ogallala	1985	No	1987	Yes
R22	RST 22	Ogallala	1985	No	1987	Yes
R23	RST 23	Ogallala	1985	No	1987	Yes
R25	RST 25	Ogallala	1985	No	1987	Yes
R26	RST 26	Ogallala	1985	No	1987	Yes
R27	RST 27	Ogallala	1985	No	1987	Yes

Table 2.4. Summary of licensed groundwater withdrawals within a specified radius of an observation well.

Map number	Well number	Aquifer	Licensed groundwater withdrawals, in cubic feet per second, within specified radius of well, in miles					
			0.5	1.0	2.0	3.0	4.0	5.0
Wells operated by South Dakota Department of Environment and Natural Resources								
S1	TD-57B	Alluvial	0.0	0.0	0.0	0.0	0.0	0.0
S2	TD-57CR	Alluvial	0.0	0.0	0.0	0.0	0.0	0.0
S3	TD-59A	Ogallala	0.0	0.0	0.0	2.7	7.7	18.7
S4	TD-59BR	Ogallala	0.0	1.8	1.8	1.8	1.8	2.2
S5	TD-76A	Ogallala	0.0	9.3	17.9	49.8	72.9	90.2
S6	TD-76B	Ogallala	1.8	6.5	36.0	63.1	94.8	116.0
S7	TD-76C	Ogallala	2.8	10.1	37.6	68.5	105.0	134.0
S8	TD-76D	Ogallala	4.8	17.7	43.9	71.9	108.0	142.6
S9	TD-76E	Ogallala	0.0	5.0	16.7	35.2	55.7	75.6
S10	TD-76F	Ogallala	0.0	0.0	28.8	53.9	89.3	126.0
S11	TD-76G	Ogallala	0.0	5.1	34.8	74.2	108.6	139.9
S12	TD-76H	Ogallala	1.4	7.5	25.9	40.0	67.1	90.0
S13	TD-76I	Ogallala	1.3	2.7	21.6	34.1	50.2	70.7
S14	TD-76J	Ogallala	1.8	1.8	6.2	16.5	33.3	50.3
S15	TD-79A	Ogallala	0.0	0.0	0.0	0.0	0.0	0.0
S16	TD-79B	Ogallala	4.7	7.0	7.0	7.2	8.8	11.1
S17	TD-79D	Arikaree	0.0	0.0	0.0	0.0	0.0	0.0
S18	TD-80A	Arikaree	0.0	0.0	0.0	0.0	2.7	2.7
S19	TD-80B	Ogallala	1.3	1.3	1.3	1.3	1.3	5.9
S20	TD-80C	Arikaree	4.8	15.1	48.6	69.3	96.7	136.0
S21	TD-80D	Arikaree	0.0	0.0	0.0	0.0	0.0	0.0
S22	TD-80E	Ogallala	0.0	0.0	0.0	0.0	0.0	0.0
S23	TD-90A	Ogallala	0.0	6.5	24.8	51.0	92.8	112.8
S24	TD-90B	Arikaree	0.0	0.0	0.0	4.7	18.4	26.1
S25	TD-#05	Ogallala	0.0	0.0	0.0	1.6	4.3	4.3
S26	TD-#08	Ogallala	0.0	0.0	2.7	6.7	17.9	33.6
S27	TD-#10	Ogallala	0.0	0.0	0.0	1.8	5.9	14.1
S28	BT-76C	Ogallala	5.6	9.2	27.8	40.8	45.1	56.9
S29	BT-78KR	Ogallala	0.0	7.0	20.7	26.5	54.8	76.6
S30	BT-80E	Ogallala	0.0	0.0	12.7	20.4	30.0	42.4
S31	BT-80F	Ogallala	0.0	0.0	0.0	0.0	2.2	2.2
S32	MT-78A	Arikaree	0.0	1.3	2.7	2.7	2.7	2.7
S33	MT-78B	Arikaree	0.0	1.3	2.7	2.7	2.7	2.7
S34	TR-78E	Ogallala	1.3	1.3	1.3	1.3	3.6	3.6
S35	TR-99A	Arikaree	0.0	0.0	0.0	0.0	0.0	2.4
Wells operated by Rosebud Sioux Tribe								
R1	RST 1	Ogallala	0.0	0.0	0.0	0.0	0.0	0.0
R2	RST 2	Ogallala	0.0	0.0	0.0	0.0	0.0	0.0
R3	RST 3	Ogallala	0.0	0.0	0.0	1.6	3.9	9.8
R4	RST 4	Ogallala	0.0	0.0	0.0	0.0	0.0	1.3
R6	RST 6	Ogallala	0.0	0.0	1.5	12.8	21.1	41.9

Table 2.4. Summary of licensed groundwater withdrawals within a specified radius of an observation well.—Continued

Map number	Well number	Aquifer	Licensed groundwater withdrawals, in cubic feet per second, within specified radius of well, in miles					
			0.5	1.0	2.0	3.0	4.0	5.0
Wells operated by Rosebud Sioux Tribe—Continued								
R7	RST 7	Ogallala	0.4	2.5	9.8	20.0	39.4	72.6
R9	RST 9	Ogallala	0.0	0.0	1.8	1.8	4.9	9.6
R11	RST 11	Ogallala	1.0	4.7	18.4	37.1	59.4	98.2
R12	RST 12	Ogallala	5.2	14.0	24.0	63.5	106.7	136.7
R13	RST 13	Ogallala	1.9	5.3	26.7	49.5	77.6	109.4
R14	RST 14	Ogallala	0.0	3.7	21.5	54.8	74.4	95.5
R15	RST 15	Ogallala	0.0	0.0	0.0	0.0	0.0	1.3
R16	RST 16	Ogallala	0.0	4.5	15.5	27.8	35.9	55.5
R17	RST 17	Ogallala	0.0	0.0	0.0	0.0	5.0	11.5
R18	RST 18	Ogallala	0.0	0.0	0.0	0.0	5.6	12.4
R19	RST 19	Ogallala	0.0	0.0	0.0	0.0	0.8	7.0
R20	RST 20	Ogallala	0.0	0.0	0.3	0.3	0.3	0.3
R21	RST 21	Ogallala	0.0	0.0	0.0	0.0	0.0	0.0
R22	RST 22	Ogallala	0.0	0.0	0.0	0.0	0.0	0.0
R23	RST 23	Ogallala	0.0	0.0	0.0	0.0	0.0	0.0
R25	RST 25	Ogallala	0.0	0.0	0.0	0.0	0.0	0.0
R26	RST 26	Ogallala	0.7	4.3	11.9	24.8	46.3	76.4
R27	RST 27	Ogallala	0.0	0.0	0.0	0.0	0.2	0.2

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Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Rolla and Sacramento Publishing Service Centers

Valseth and Driscoll—**Trends in Groundwater Levels in and near the Rosebud Indian Reservation, South Dakota, Water Years 1956–2017**—SIR 2020–5119

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20205119