Prepared in cooperation with the Oglala Sioux Tribe

Conceptual and Numerical Models of Groundwater Flow in the Ogallala and Arikaree Aquifers, Pine Ridge Indian Reservation Area, South Dakota, Water Years 1980–2009

Scientific Investigations Report 2014–5241

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

Cover photograph. West branch of Cottonwood Creek about 4 miles east of Wanblee, South Dakota. Cottonwood Creek is a tributary to the White River and is fed by seeps or springs at originate from the Arikaree aquifer. Photograph taken on September 22, 2010, by Larry Putnam, U.S. Geological Survey.

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SALLY JEWELL, Secretary

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The authors would like to recognize important contributions made by the Oglala Sioux Tribe to the development of the groundwater-flow model described in this report. Development of a calibrated numerical model resulted from the tribe's long-term commitment to obtaining hydrologic information. The lithologic database of the South Dakota Department of Environment and Natural Resources Geological Survey and the Nebraska Statewide Test-hole Database from the University of Nebraska were the primary source of data for interpretation of the hydrogeologic framework. The Water Rights Program of the South Dakota Department of Environment and Natural Resources provided permitting and water-use data and long-term water-level data for their groundwater monitoring network in the study area.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
	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 (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Conductance	
feet squared per day (ft^2/d)	0.0929	Meter squared per day (m^2/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

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

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

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

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

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

NAVD 88	North American Vertical Datum of 1988
NED	National Elevation Dataset
NOAA	National Oceanic and Atmospheric Administration
PEST	Parameter ESTimation (computer code)
UPW	Upstream Weighting (MODFLOW–NWT package)
USGS	U.S. Geological Survey
WY	water year

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Abstract

The Ogallala and Arikaree aquifers are the largest sources of groundwater on the Pine Ridge Indian Reservation and are used extensively for irrigation and public and domestic water supplies. To assess the potential for decreased water levels and discharge to streams in the Pine Ridge Indian Reservation, conceptual and numerical models of groundwater flow in the Ogallala and Arikaree aquifers in southwestern South Dakota were developed by the U.S. Geological Survey in cooperation with the Oglala Sioux Tribe. The study area includes most of the Pine Ridge Reservation in Jackson and Shannon Counties and Indian trust lands in Bennett County in southwestern South Dakota.

The High Plains aquifer, which includes the Ogallala and Arikaree aquifers, generally is less developed in South Dakota compared with other areas underlain by this aquifer; therefore, water levels in the High Plains aquifer in South Dakota generally fluctuated by less than 5 feet (ft) from 1980 to 1999. Despite minimal water-level changes in the High Plains aquifer in South Dakota, extensive withdrawals of groundwater for irrigation have caused water-level declines in many areas and increased concerns about the long-term sustainability of the aquifer; therefore, continued or increased withdrawals from the aquifer or prolonged drought may have the potential to affect water levels within the aquifer and discharge to important streams in the area.

The Ogallala and Arikaree aquifers generally consist of poorly consolidated claystones, siltstones, sandstones, and shale deposited in fluvial and lacustrine environments. Saturated thicknesses ranged from 10 to 314 ft for the Ogllala aquifer and from 10 to 862 ft for the Arikaree aquifer. Previous hydraulic conductivity estimates ranged from less than 1 to 180 feet per day (ft/d) for the Ogallala aquifer and from less than 1 to 13 ft/d for the Arikaree aquifer.

Recharge to the Ogallala and Arikaree aquifers is from precipitation on the outcrop areas, and discharge occurs through evapotranspiration, discharge to streams, and well withdrawals. Evapotranspiration generally occurs in topographically low areas along streams, and maximum evapotranspiration occurs when the water level is at the land surface.

The generalized groundwater-flow direction is to the northeast with local flow towards streams. Precipitation for water years 1980–2009 ranged from about 11 to 39 inches per year (in/yr) and averaged about 19 in/yr. Estimated mean recharge for water years 1980–2009 was about 17.3 percent of precipitation for the Ogallala aquifer and 7.9 percent of precipitation for the Arikaree aquifer. The estimated mean maximum evapotranspiration for water years 1980–2009 was about 35 in/yr. Estimated mean base flow for gaged streams was about 0.06 cubic foot per second (ft^3/s) per square mile of drainage area. Estimated mean total water use for water years 1980–2009 was 5.4 ft^3/s from the Ogallala aquifer and 7.1 ft^3/s from the Arikaree aquifer.

A two-layer numerical groundwater-flow model was constructed using MODFLOW–NWT with a uniformly spaced grid consisting of 166 rows and 288 columns with cells 1,640 ft on a side. The numerical model of the Ogallala and Arikaree aquifers was used to simulate steady-state and transient conditions for water years 1980–2009. Model calibration was accomplished using the Parameter ESTimation (PEST) program that adjusted individual model input parameters and assessed the difference between estimated and model-simulated values of hydraulic head and base flow. Aquifer boundaries were no-flow on the northern and western sides and constant-head on the southern and eastern sides. The mean arithmetic difference was 1.4 ft between the 731 simulated and observed hydraulic heads in the Ogallala aquifer and 9.8 ft between the 2,754 simulated and observed hydraulic heads in the Arikaree aquifer. Simulated mean discharge from the Ogallala and Arikaree aquifers to selected stream reaches was 92.1 ft^3/s compared to estimated discharge of 88.7 ft^3/s.

Calibrated recharge for the transient simulation averaged 3.3 in/yr for the Ogallala aquifer and 1.1 in/yr for the Arikaree aquifer. The mean maximum potential evapotranspiration rate was 35.4 in/yr. Streambed conductance for perennial stream reaches averaged 530 feet squared per day. Horizontal hydraulic conductivity averaged 27 ft/d for the Ogallala aquifer and 1.0 ft/d for the Arikaree aquifer. The vertical hydraulic conductivity averaged 1.4 ft/d for the Ogallala aquifer and 0.004 ft/d for the Arikaree aquifer. Specific yield for the Ogallala aquifer was 0.15 (dimensionless) and averaged 0.02 for

the Arikaree aquifer. Specific storage for the Arikaree aquifer was $1.7x10^{-6}$ per foot. Simulated steady-state model inflow and outflow was 459 ft^3/s. The percentages of inflows were 17 percent from constant-head boundaries, 9 percent from streams, and 74 percent from recharge. Percentages of outflow were 8 percent to constant-head boundaries, 1 percent to wells, 31 percent to streams, and 59 percent to evapotranspiration. Simulated net inflow from the Ogallala aquifer to the Arikaree aquifer ranged from about 22 ft^3/s in dry years to about 37 ft^3/s in wet years.

Two hypothetical future stress scenarios were simulated using input from the 30-year calibrated simulation of water years 1980–2009. The first hypothetical scenario represented an increase in groundwater withdrawals from 50 hypothetical production wells completed in the Arikaree aquifer. At the end of the 30-year hypothetical increased pumping simulation, water levels declined as much as 66 ft in the Arikaree aquifer, decreased discharge to streams accounted for about 26 percent (2.6 ft^3/s) of increased withdrawals, and decreased evapotranspiration accounted for about 53 (5.3 ft^3/s) percent of increased withdrawals.

The second hypothetical scenario represented a 30-year period of decreased recharge (drought) by decreasing recharge 0.2 inch (24 ft^3/s) for each water year. At the end of the hypothetical drought simulation, water levels declined as much as 10.9 ft in the Arikaree aquifer, decreased discharge to streams accounted for about 23 percent (5.5 ft^3/s) of decreased recharge, and decreased evapotranspiration accounted for about 72 percent (17.3 ft^3/s) of decreased recharge.

The numerical model is a tool that could be used to better understand the flow system of the Ogallala and Arikaree aquifers, to approximate hydraulic heads in the aquifer, and to estimate discharge to rivers, springs, and seeps in the Pine Ridge Reservation area in Bennett, Jackson, and Shannon Counties. The model also is useful to help assess the response of the aquifer to additional stress, including potential increased well withdrawals and potential drought conditions.

Introduction

The High Plains aquifer, which includes the Ogallala and Arikaree aquifers, underlies almost 112 million acres in the central United States (Stanton and others, 2011). The High Plains aquifer underlies parts of eight States and extends from southern South Dakota to Texas (fig. 1). The aquifer has been used extensively for irrigation, public water supply, domestic water supply, and stock water use, and is an important water supply for the central United States. About 2 million people rely on the High Plains aquifer for drinking water with total withdrawals for domestic drinking water of 418 million gallons per day (Mgal/d; Dennehy, 2000). The High Plains region supplies approximately one-fourth of the Nation's agricultural production (McMahon and others, 2007).

The High Plains aquifer underlies about 4,750 square miles in south-central South Dakota (fig. 1; Gutentag and others, 1984) including most of the Pine Ridge Indian Reservation area. The Pine Ridge Indian Reservation includes all of Shannon County and part of Jackson County south of the White River (fig.1; fig. 2). Extensive Indian trust lands are in Bennett County. The study area includes most of the Pine Ridge Indian Reservation in Jackson and Shannon Counties and trust lands in Bennett County. The study area is in the Great Plains physiographic division (Fenneman, 1946) in the northern High Plains aquifer region (fig. 1; Luckey and others, 1988).

The High Plains aquifer generally is less developed in South Dakota compared with other parts of the Nation underlain by this aquifer, and thus water levels in the aquifer in South Dakota generally changed less than 5 feet (ft) from 1980 to 1999 (McGuire, 2001). Despite minimal water-level changes in the High Plains aquifer in South Dakota, extensive withdrawals of groundwater for irrigation have caused water-level declines in many parts of the aquifer and increased concerns about the long-term sustainability of the aquifer (Stanton and others, 2011). Since the 1950s, water-level declines of as much as 100 ft have been measured in parts of Kansas, New Mexico, Oklahoma, and Texas (Dennehy, 2000). Discharge from the aquifer through springs and seeps provides base flow for several important streams in the area (Carter, 1998; Carter and Heakin, 2007); therefore, continued or increased withdrawals from the aquifer or prolonged drought may have the potential to affect water levels within the aquifer and discharge to important streams in the area.

The Ogallala and Arikaree aquifers are the largest sources of groundwater on the Pine Ridge Indian Reservation and are used extensively for irrigation and public and domestic water supplies. The Oglala Sioux Tribe has identified a need for scientific information and tools for use in the management, planning, and protection of these important water resources. The U.S. Geological Survey (USGS), in cooperation with the Oglala Sioux Tribe, developed conceptual and numerical models of the Ogallala and Arikaree aquifers to meet this need for scientific information. The numerical model is a water-resource tool used to analyze the groundwater system that can be used to assess water-management issues associated with the High Plains aquifer in the Pine Ridge Indian Reservation area. The model could be used by water managers to evaluate the effects of various hydrologic scenarios, including increased well withdrawals or prolonged drought within the study area.

Purpose and Scope

The purpose of this report is to describe conceptual and numerical models of groundwater flow in the Ogallala and Arikaree aquifers in the Pine Ridge Indian Reservation area. The conceptual model was developed based on hydrologic data for water years (WYs) 1980–2009 (October 1, 1979, through September 30, 2009). A WY is a 12-month period, October 1

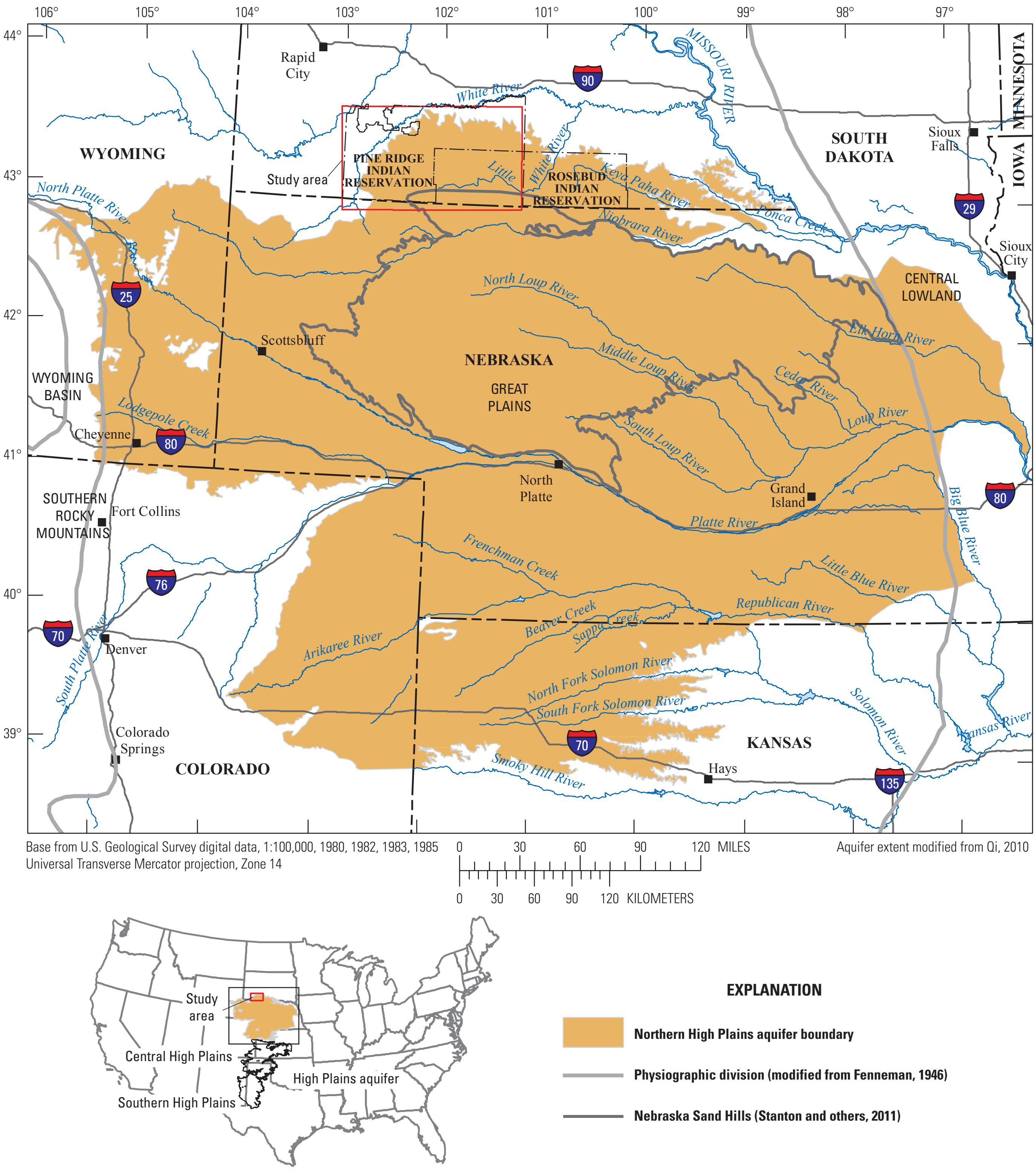


Figure 1. Study area, extent of the northern High Plains aquifer, and location of main physiographic divisions.

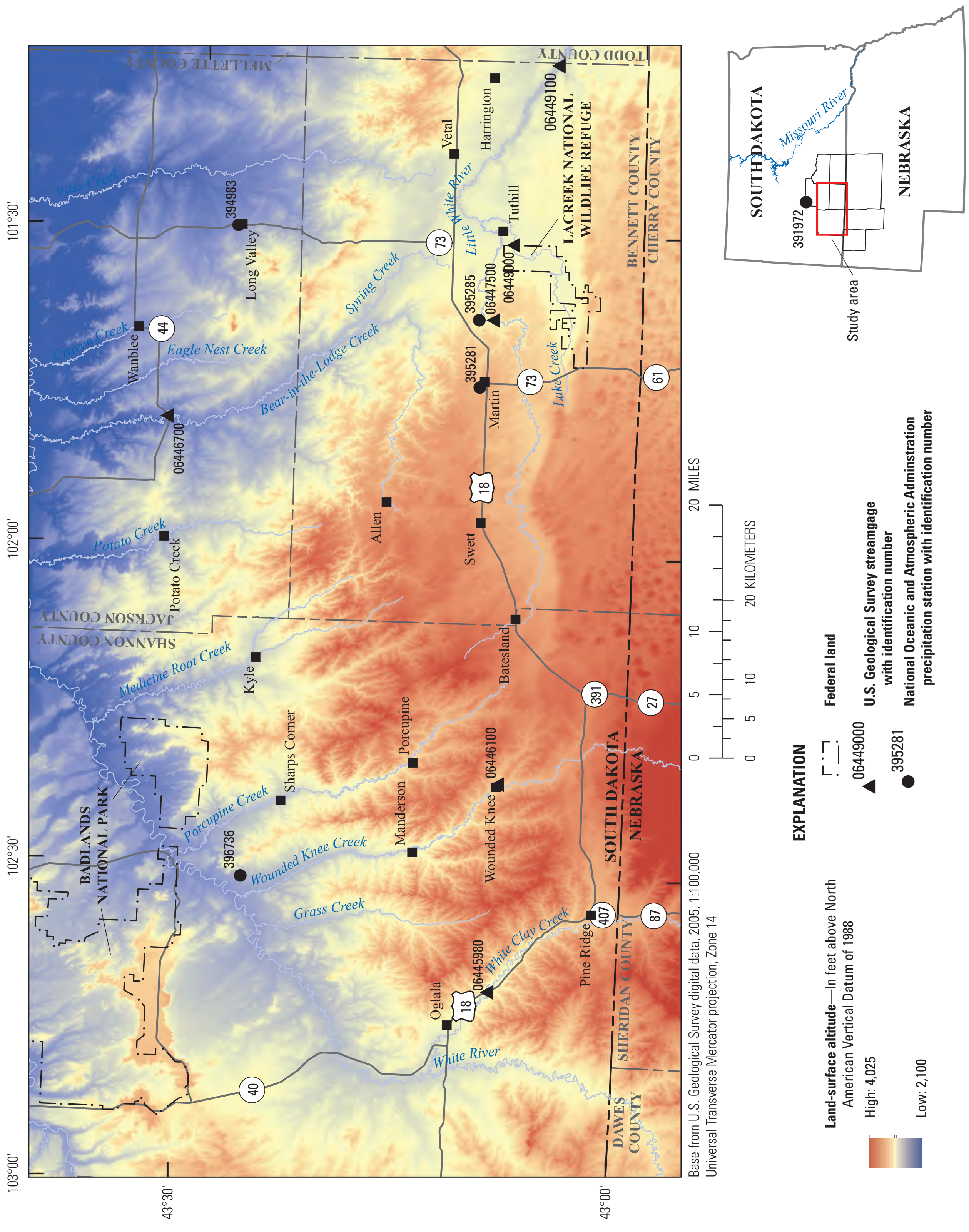


Figure 2. Land-surface altitude, streamgages, and precipitation stations in the study area.

through September 30, and is designated by the calendar year in which it ends. Steady-state and transient numerical simulations for the 30-year period are described in this report. This report also documents numerical simulation of two potential future scenarios. The first scenario represented an increase in groundwater withdrawals from 50 hypothetical production wells, and the second scenario represented a potential 30-year period of decreased recharge (drought).

Previous Investigations

Kolm and Case (1983), Long and others (2003), Long and Putnam (2010), and Davis and Putnam (2013) previously developed groundwater models of the High Plains aquifer near the study area. Kolm and Case (1983) developed a two-dimensional, finite-difference model of the High Plains aquifer within South Dakota. The model included parts of the Pine Ridge Indian Reservation and Bennett County in South Dakota and documented the generalized groundwater flow within the High Plains aquifer in South Dakota and northern Nebraska. Long and others (2003) developed a two-layer model of the Ogallala and Arikaree aquifers in Todd County and the southern part of Mellette County in the Rosebud Indian Reservation area, which is located directly east of the Pine Ridge Indian Reservation and in the central part of the High Plains aquifer in South Dakota (fig. 1). This model simulated groundwater flow of the Ogallala and Arikaree aquifers with a much smaller grid spacing compared to the model produced by Kolm and Case (1983). Long and Putnam (2010) updated the model developed by Long and others (2003) with additional data and simulations of hypothetical drought and increased groundwater withdrawal. Davis and Putnam (2013) developed conceptual and numerical models of groundwater flow for the Ogallala aquifer in Gregory and Tripp Counties, which are located east of Mellette and Todd Counties.

The hydrogeology of Pine Ridge Indian Reservation was described by Ellis and Adolphson (1971) and was further studied in 1987–89 with aquifer tests (Greene and others, 1991). Greene and others (1991) provided hydraulic characteristics of the Arikaree aquifer, including transmissivity, storage, and hydraulic conductivity. Carter and Heakin (2007) published a map of the generalized potentiometric surface of the Arikaree aquifer for the Pine Ridge Indian Reservation area and Bennett County. Filipovic (2011) conducted a hydrogeologic assessment of the High Plains aquifer in Bennett County, which included descriptions and interpretations of additional test hole data. LaBelle (2011) analyzed historical (1985–2009) and projected (2041–70) recharge trends near the Pine Ridge Reservation with a soil-water balance method. For the eastern part of the High Plains aquifer in South Dakota, Filipovic (2004) published a generalized water table and saturated thickness map and developed cross sections for the Ogallala aquifer in Gregory and Tripp Counties.

Description of Study Area

The study area includes most of the Pine Ridge Reservation in Shannon and Jackson Counties, Bennett County, small parts of Mellette and Todd Counties in South Dakota, and the northern edges of Cherry and Sheridan Counties in Nebraska where the Ogallala and Arikaree aquifers are present (fig. 2). The study area was extended southward into Nebraska and eastward into Mellette and Todd Counties in South Dakota to minimize effects of the southern and eastern boundaries in the numerical model.

Physiography, Drainage Features, and Land Use

The study area is located in the Great Plains physiographic division (Fenneman, 1946). The southern part of the study area is overlain by the Nebraska Sand Hills (Stanton and others, 2011; fig. 1). The Great Plains physiographic division is a vast eastward-tilted surface formed by the deposition of sediment from the uplift of the Rocky Mountains during the early Tertiary Period (University of Nebraska–Lincoln, 2011). The Nebraska Sand Hills is the largest field of grass-stabilized sand dunes in the Western Hemisphere (Koch, 1999). The Nebraska Sand Hills was developed on the northern Tertiary-age High Plains deposits and was undergoing dune formation and migration as recently as 700 years ago (Miao and others, 2007).

The topography of the study area is diverse. Gently rolling plains are present throughout the study area. The Badlands, with sharply rising pinnacles, are located in the northwestern corner of the study area. The altitude of the land surface determined from the National Elevation Dataset (NED; U.S. Geological Survey, 2006) ranges from about 4,025 ft above the North American Vertical Datum of 1988 (NAVD 88) at the southern part of the study area to about 2,100 ft above NAVD 88 in the northeastern part of the study area (fig. 2). As intermittent and perennial streams drain north into the White River along the western and northern sides of the study area, the streams become more deeply incised into bedrock. Sand dunes are evident in the southern and southeastern parts of the study area where the Sand Hills are at an altitude of about 3,700 ft above NAVD 88 on the western edge decreasing to about 3,400 ft above NAVD 88 on the eastern side of the study area.

The major streams that drain the study area are the White River and the Little White River. The White River, the Little White River, and their tributaries receive base flow from the Ogallala and Arikaree aquifers (Ellis and Adolphson, 1971; Kolm and Case, 1983). Perennial streamflow in major tributaries to the White River is sustained by a large component of base flow from the Arikaree aquifer (Carter and Heakin, 2007). The minimum monthly mean streamflow for 1960–2011 at USGS streamgage 06449100, which is located on the Little White River near the border of Bennett and Todd Counties (fig. 2), ranged from 12.5 to 33.5 cubic feet per second (ft^3/s; U.S. Geological Survey, 2012).

The altitude of the Little White River ranges from about 3,600 ft above NAVD 88 near its headwaters to about 2,800 ft above NAVD 88 near the eastern edge of the study area (fig. 2). The altitude of Wounded Knee Creek is about 3,800 ft above NAVD 88 at the southern edge of the study area and about 2,700 ft above NAVD 88 near its confluence with the White River.

Agriculture is the primary land use in the study area, and the primary agricultural activities are cattle grazing and hay production (Tetra Tech, Inc., 2005). Cultivated crops are areas used for the production of annual crops, land that is actively tilled, and where crop vegetation accounts for greater than 20 percent of total vegetation (Homer and others, 2004). Cultivated crops cover about 7 percent of the study area, primarily in west-central Bennett County (fig. 3). Pasture and hay cover about 1 percent of the study area. Herbaceous grasslands are any areas dominated by grammanoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management such as tilling, but can be used for grazing (Homer and others, 2004). Herbaceous grasslands accounts for about 76 percent of the land use within the study area. Barren land covers about 7 percent of the study area and exists in and near Badlands National Park in the northwestern part of the study area. Deciduous, evergreen, or mixed forest and shrub or scrubs account for about 4 percent of the land use. The remaining 5 percent of land use is woody wetlands, emergent herbaceous wetlands, open water, or developed areas.

Climate

The climate is arid steppe, with hot summers and cold winters. The arid steppe cold climate is described as a climate with a mean annual temperature less than 64 degrees Fahrenheit (°F) that is too dry to support a forest, but not quite dry enough to be considered a desert, usually consisting of grassland plains (Peel and others, 2007).

Precipitation records were available for four National Oceanic and Atmospheric Administration (NOAA) precipitation stations in the study area (fig. 2): 395281 (Martin), 395285 (Martin 5E), 394983 (Long Valley), and 396736 (Porcupine 11N) (National Climate Data Center, 2011). Precipitation data for NOAA station 395281 (Martin) were combined with NOAA station 395285 (Martin 5E) to create a complete record for WYs 1980–2009. Precipitation for WYs 1980–92 and 1996–98 was from station 395285; precipitation for WYs 1993–95 and 1999–2009 was from station 395281. The combined stations are referred to as station 395281 in this report. The other two stations (394983 and 396736) had records for WYs 1980–2009. Precipitation for WYs 1980–2009 for stations 395281, 394983, and 396736 in the study area ranged from about 11 to 39 inches per year (in/yr; table 1). The mean precipitation in the study area was about 19 in/yr with means for WYs 1980–2009 of 19.8, 19.6, and 17.9 in/yr at stations 395281, 394983, and 396736, respectively. Extended periods of above average precipitation occurred during WYs 1995–99, and below average periods occurred during WYs 1987–90 and WYs 2002–04.

Precipitation generally increases in the spring and early summer, then decreases through the summer and fall with little precipitation in the winter months. Mean monthly precipitation for WYs 1980–2009 for station 395281 (Martin) indicates greater than 3 inches (in.) of precipitation in May and June with less than 2 in. per month in September through March (table 2).

Geologic Setting

The exposed geologic formations in the study area range from sedimentary rocks of Late Cretaceous age to unconsolidated deposits of Quaternary age (Martin and others, 2004; Stoeser and others, 2007; fig. 4). Cretaceous-age deposits are mostly shale, and the exposed units from oldest to youngest include the Carlile Shale, Niobrara Formation, and Pierre Shale (fig. 4). Tertiary-age rocks generally consist of poorly consolidated claystones, siltstones, sandstones, and shale deposited in fluvial and lacustrine environments. These include the Oligocene-age White River Group, the Miocene-age Arikaree Formation and Batesland Formation, and the Pliocene-age Ogallala Formation. Quaternary-age deposits include Holocene-age alluvial deposits and Holocene- and Pleistocene-age eolian deposits. The eolian (windblown) deposits include the Holocene- and Pleistocene-age Sand Hills Formation in the southern part of the study area. The lithology and thickness of mapped units and subdivisions are described in table 3.

The White River Group and older deposits generally are at the surface in the northern and western edges of the study area (fig. 4). The Arikaree Formation is present in most of the study area south and east of the White River. The maximum thickness of the Arikaree Formation ranges from about 800 ft in the southwestern part of the study area (Greene and others, 1991) to about 500 ft in the southeastern part of the study area (Carter, 1998). The five subdivisions within the Arikaree Formation vary substantially in thickness (table 3) and, in many parts of the study area, are undifferentiated. Harksen (1965) described the thicknesses of the subdivisions present in the area near Porcupine and Wounded Knee Creeks as 350 ft for the Sharps Formation, 120 ft for the Monroe Creek Formation, 160 ft for the Harrison Formation, and 235 ft for the Rosebud Formation. The Sharps and Monroe Formations outcrop in south-central Jackson County (Collins, 1960). The Rockyford Ash member of the Sharps Formation caps buttes and tables in the northwestern part of the study area and is widely but discontinuously exposed (Greene and others, 1991). The Arikaree Formation pinches out to the north and northwest where the White River Group is exposed (fig. 4).

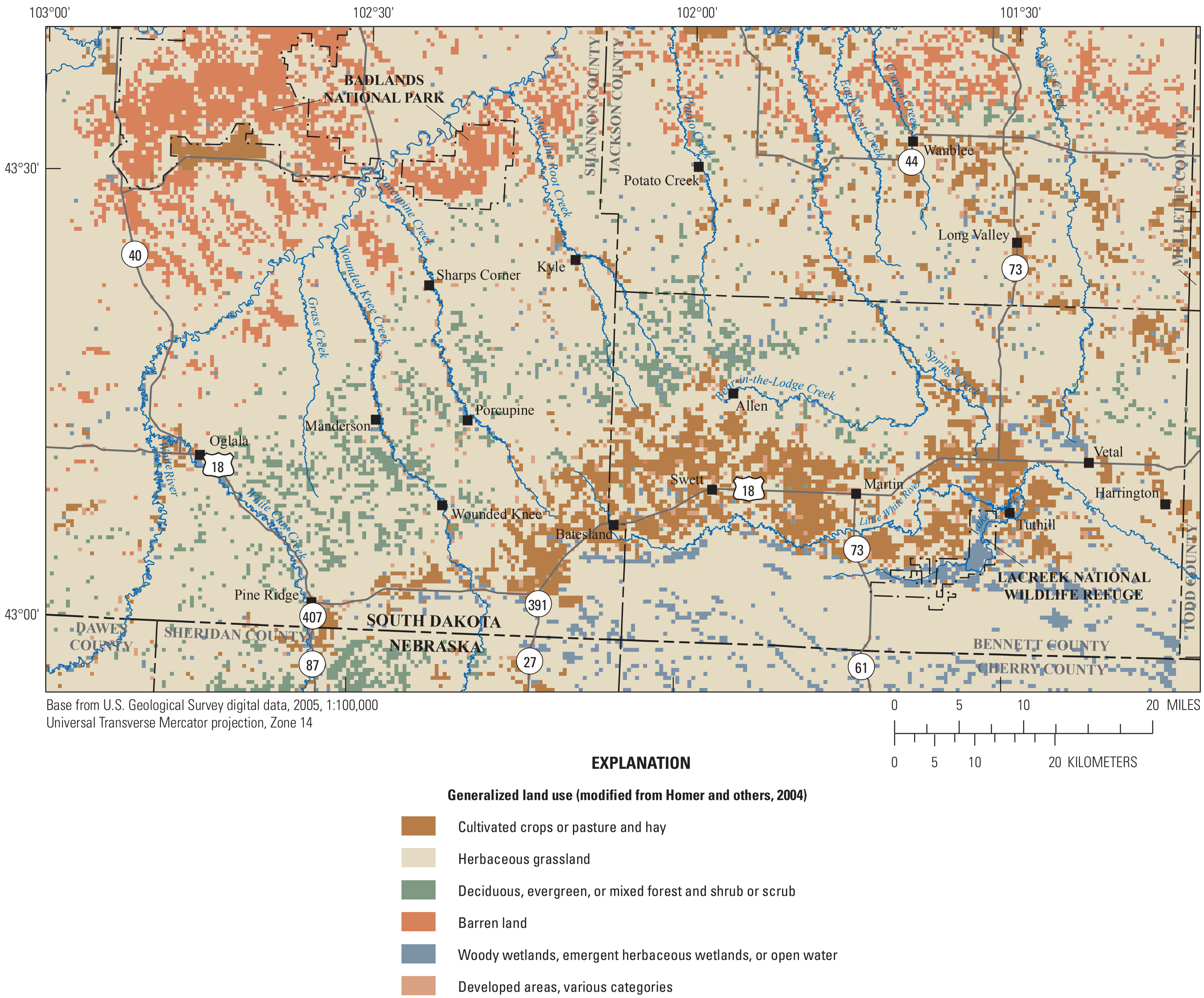


Figure 3. Generalized land use in the study area.

Table 1. Precipitation for water years 1980–2009 for three precipitation stations in the study area.

[Precipitation data for National Oceanic and Atmospheric Administration (NOAA) stations from National Climate Data Center (2011). Shaded cells indicate an incomplete daily precipitation record for a given water year. Missing values were supplemented with daily precipitation from the nearest precipitation station]

Water year	Precipitation (inches per year)		
	395281[a,b] (Martin)	394983[c] (Long Valley)	396736[c] (Porcupine 11N)
1980	11.9	10.6	10.7
1981	19.8	17.3	12.6
1982	24.1	24.5	20.4
1983	23.7	23.0	17.8
1984	17.1	15.8	15.6
1985	13.0	12.2	12.2
1986	27.1	26.8	21.2
1987	15.7	17.8	14.7
1988	15.4	19.7	15.2
1989	10.7	11.6	12.3
1990	19.2	18.9	14.8
1991	24.1	18.3	17.3
1992	17.4	17.0	20.3
1993	20.4	25.0	24.7
1994	18.9	15.2	16.9
1995	26.5	25.3	22.0
1996	22.2	25.5	20.8
1997	27.9	24.3	25.9
1998	24.4	22.2	15.9
1999	39.4	24.8	28.6
2000	16.7	16.8	17.7
2001	18.2	19.1	19.5
2002	11.9	13.0	15.0
2003	14.0	14.7	12.8
2004	18.2	15.7	15.1
2005	24.1	25.3	21.0
2006	14.5	16.6	18.8
2007	16.5	18.7	16.1
2008	18.8	24.0	20.5
2009	23.2	29.1	20.2
Mean annual	19.8	19.6	17.9

[a]Precipitation for water years 1980–1992 and 1996–1998 was from NOAA station 395285.

[b]Missing daily values were supplemented with daily values from NOAA station 394983.

[c]Missing daily values were supplemented with daily values from NOAA station 396736.

Table 2. Mean monthly precipitation for water years 1980–2009 for National Oceanic and Atmospheric Administration station 395281 (Martin).

[Precipitation data from National Climate Data Center (2011)]

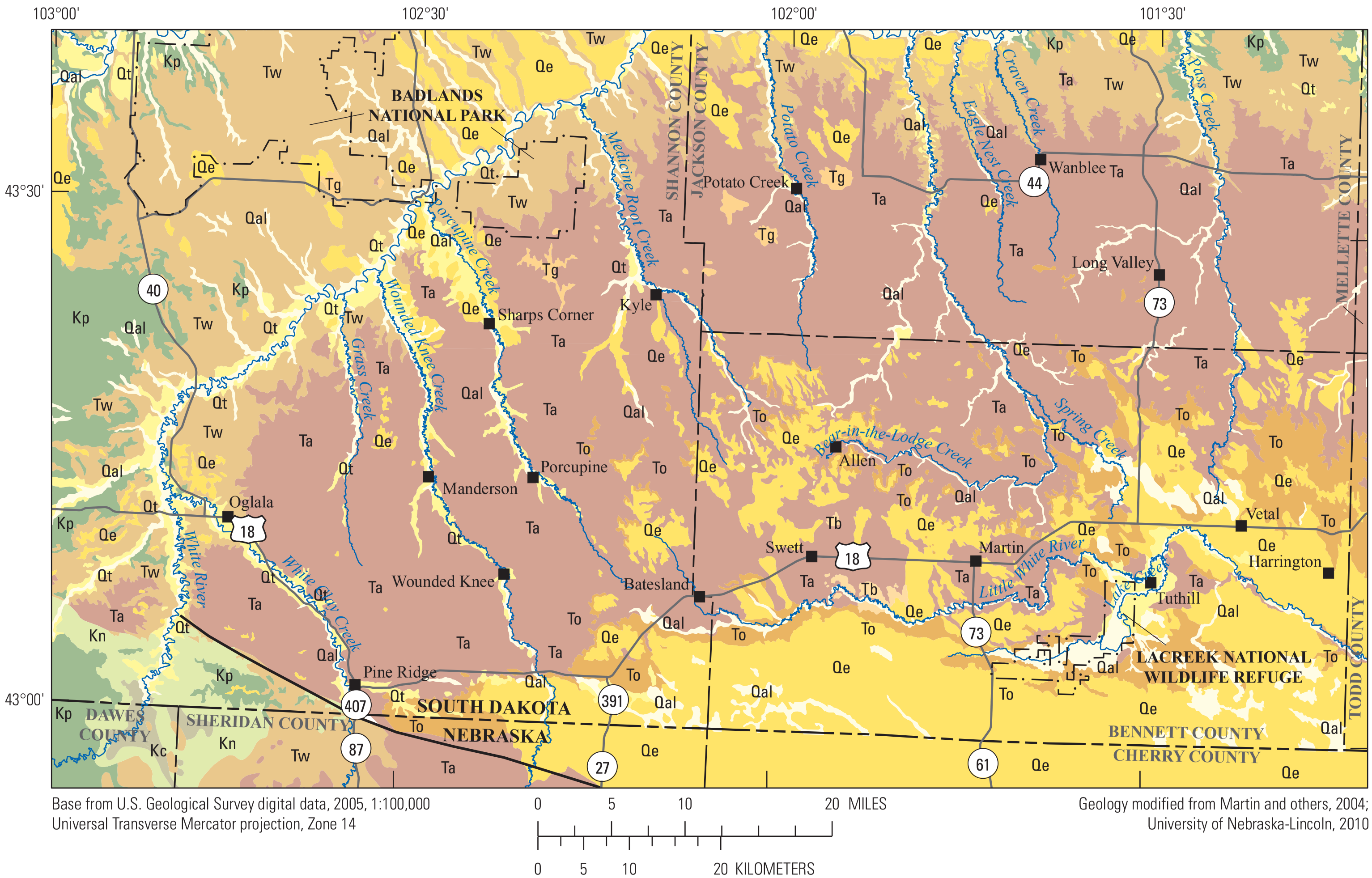
Month	Mean monthly precipitation (inches)
January	0.3
February	0.6
March	1.3
April	2.0
May	3.2
June	3.3
July	2.5
August	2.0
September	1.5
October	1.6
November	1.1
December	0.4

The Batesland Formation is exposed in small areas west of Martin (fig. 4). The Batesland Formation is fill in paleo-valleys that are cut down into the Rosebud Formation. Most of the Batesland Formation has been removed by subsequent erosion (Harksen and Macdonald, 1967).

The Ogallala Formation includes two units: the upper, Ash Hollow Formation, and the lower, Valentine Formation (table 3; Carter and Heakin, 2007). The Ogallala Formation ranges in thickness from 0 to 200 ft in the study area. The Valentine Formation is poorly consolidated and slumps and washes easily. Most of the Valentine Formation is overlain by the eolian deposits with some exposed areas southeast of Martin (Collins, 1959). The Ash Hollow Formation is exposed in the area east of Pine Ridge and is more resistant to erosion than the underlying Rosebud Formation (Harksen, 1965). The Ogallala Formation crops out in the southern and eastern part of the study area, mostly south of the Little White River (fig. 4) where not overlain by the eolian deposits. The Sand Hills Formation (eolian deposits) consists mainly of fine sands derived from the Ogallala Formation and the Rosebud Formation (Harksen, 1965; Collins, 1959). Individual dunes may rise as much as 160 ft above their base and most are 80 to 120 ft in height (Collins, 1959).

Hydrogeologic Setting

The major shallow aquifers from top to bottom include the alluvial, Ogallala, and Arikaree aquifers. These aquifers consist of unconsolidated sand and gravels or poorly consolidated sandstones and siltstones. The White River Group



EXPLANATION

Quaternary-age unconsolidated deposits
- Qal — Alluvial deposits
- Qt — Terrace and landslide deposits
- Qe — Eolian deposits

Tertiary-age sedimentary deposits
- Tg — Gravel deposits
- To — Ogallala Formation
- Tb — Batesland Formation
- Ta — Arikaree Formation
- Tw — White River Group

Cretaceous-age sedimentary deposits
- Kp — Pierre Shale
- Kn — Niobrara Formation
- Kc — Carlile Shale
- **White Clay fault**

Figure 4. Generalized surface geology in the study area.

Table 3. Generalized stratigraphic column with geologic map units and lithology in study area.

[Modified from Ellis and Adolphson (1971), Heakin (2000), Carter and Heakin (2007), and Martin and others (2004). --, not applicable]

System	Series	Mapped unit	Subdivisions	Thickness, in feet	Lithology
Quaternary	Holocene	Alluvial deposits	--	0–60	Light brown to gray, unconsolidated, clay, silt, and fine sand; discontinuous sandy and clayey gravel beds in lower part.
	Holocene and Pleistocene	Landslide deposits	--	0–100	Landslide, slump, and collapsed material composed of chaotically mixed boulders and finer grained rock debris.
		Eolian deposits	--	0–200	Brown, unconsolidated, very fine to medium grained, uniform, quartz sand; characterized by dune topography and blowouts. Includes the Sand Hills Formation.
	Pleistocene	Terrace deposits	--	0–80	Brown, silty clay, sand, and gravel. Commonly, the silty and sandy layers are partly cemented, and the gravel and sand beds are commonly interbedded with laminated silty clay.
Tertiary	Pliocene–Oligocene	Gravel deposits	--	0–60	Clay- to boulder-sized clasts primarily from igneous and metamorphic rocks of the central Black Hills.
	Pliocene	Ogallala Formation	--	0–200	Tan to olive, fine- to medium-grained sandstone with some silty clay. Upper unit of the Ogallala Formation is also known as the Ash Hollow Formation and the lower unit as the Valentine Formation.
	Miocene	Batesland Formation	--	30–50	Light gray to light greenish, fine- to coarse-grained, bedded and cross-bedded, fossiliferous sand with interbedded silts, clays, and marls.[a]
		Arikaree Formation	Unit E (Rosebud Formation)[b]	0–235	Light tan to brown, interbedded calcareous sand, silt, and clay; contains gray to pinkish-gray tabular concretions and small light-brown and greenish clay beds.
			Unit D (Harrison Formation)[b]	0–160	Gray, massive, poorly consolidated, fine to very fine sand; commonly contains layers of light-gray sandy marl, largely pipey concretions, and small spherical concretions. Formation becomes silty toward the east; concretions in the lower part present only in discontinuous zones. Unit is difficult to differentiate from underlying units.
			Unit C (Monroe Creek Formation)[b]	0–120	Buff siltstone and very fine-grained sandstone; sandier toward east. Unit is difficult to distinguish from overlying and underlying units.
			Unit B (unnamed member of Sharps Formation)[b]	0–375	Pinkish-tan, poorly consolidated silt and very fine-grained sand; gray, small (2–4 inches) calcareous concretions are common. Lenses of limestone and channel sand and gravel occur locally throughout the unit in central and western parts of the Pine Ridge Indian Reservation.
			Unit A (Rockyford Ash Member of the Sharps Formation)[b]	0–45	White, tan, buff, and reddish-brown silty volcanic ash; interbedded with thin layers of silt.
	Oligocene	White River Group	Brule Formation	0–450	Yellow to brown, poorly consolidated siltstone and claystone with some beds of fine-grained sand.
			Chadron Formation	0–110	Pale, gray-green bentonite clay alternating with layers of greenish-gray siltstone.
Cretaceous	Upper Cretaceous	Pierre Shale	--	0–1,200	Dark-gray marine shale and mudstone with some layers of bentonite.
		Niobrara Formation	--	0–325	Tan to gray, highly calcareous shale. Commonly described by drillers as “chalk.”
		Carlile Shale	--	100–325	Dark-gray marine shale and mudstone. Middle part of the formation is sandy and contains thin limestone ledges locally.

[a]From Harksen and Macdonald (1967).

[b]Corresponding unit from Harksen and Macdonald (1969).

generally is too impermeable to serve as a source of groundwater; however, local fractured zones and channel sands may yield some water. The Upper Cretaceous units are not a source of groundwater (Carter and Heakin, 2007).

The Ogallala aquifer is composed of the saturated sandstone and siltstone of the Ogallala Formation. The overlying windblown deposits are composed of fine- to medium-grained sands and are similar in composition to the Ogallala Formation. For this reason, the Ogallala Formation and overlying windblown deposits are conceptualized together as a single water-bearing unit. The upper unit of the Ogallala Formation has a relatively low permeability, whereas the lower unit of the Ogallala Formation is water bearing (Ellis and Adolphson, 1971). The water table in the Ogallala aquifer generally is at the base of the windblown sand deposits. Springs commonly exist at the margins of the sand dunes.

The Ogallala aquifer is present throughout about one-half of Bennett County and the southeastern corner of Shannon County, but is not present in the northern or the western part of the study area (fig. 5). The aquifer is thickest in southeastern Bennett County. Seeps and springs exist near the rivers and drainages throughout the study area most commonly at the contact between the Ogallala Formation and the Arikaree Formation. The Ogallala aquifer is considered to be unconfined throughout the study area; however, confined conditions may exist locally within the aquifer. Based on studies in Mellette and Todd Counties, the Ogallala aquifer has the highest yield potential of aquifers in the study area with yields ranging from 1 to 1,250 gallons per minute (gal/min; Carter, 1998). Estimated hydraulic conductivity ranges from 0.2 to 120 feet per day (ft/d; Long and others, 2003). The generalized potentiometric surface of the High Plains aquifer in southern South Dakota, which grouped the Ogallala and Arikaree aquifers, indicates that groundwater flows from drainage divides to the east and toward the Little White River and major streams in Nebraska (Kolm and Case, 1983).

The Arikaree aquifer consists of the saturated siltstones and sandstones of the Arikaree Formation. The upper clayey part of the Arikaree Formation is composed of relativity low-permeability beds, but generally yields water from fractures, joints, and thin silty lenses. The basal sandy and silty part of the formation is moderately permeable. Where not overlain by the Ogallala Formation or not exposed at the land surface, the Arikaree aquifer is overlain by younger unconsolidated deposits including alluvial and eolian deposits. The composition of the younger deposits generally is similar to the composition of the Arikaree aquifer and therefore these units are conceptualized together as a single water-bearing unit. Springs and seeps exist at the contact between the Arikaree Formation and the underlying White River Group and at contacts between impermeable and permeable layers within the Arikaree Formation (Ellis and Adolphson, 1971). The Arikaree aquifer is mostly unconfined but it can be confined where overlain by impermeable layers in the Ogallala Formation in the southern and southeastern parts of the study area (Carter and Heakin, 2007). Confined conditions also may exist locally where impermeable layers are present. Long and others (2003) estimated the horizontal hydraulic conductivity to be in the range of 0.1 to 5.4 ft/d for the Arikaree aquifer in Mellette and Todd Counties.

The Arikaree Formation is present only south and east of the White River except for a small outcrop southwest of the town of Oglala, west of the White River (fig. 4); the small outcrop west of the White River is not included in the extent of the Arikaree aquifer shown in figure 5. Based on lithologic logs from wells that penetrated the White River Group (fig. 5), the Arikaree aquifer is thickest in the southern part of the study area. Water levels in the Arikaree aquifer range from 0 to 200 ft below land surface (Carter and Heakin, 2007). Well yields from the Arikaree aquifer in the study area range from 1 to 1,540 gal/min with the largest yields in Bennett County (Carter and Heakin, 2007) depending on the clay content in the aquifer, consolidation of the materials, and well construction; however, well yields from the Arikaree aquifer generally are less than those from the Ogallala aquifer.

Conceptual Model

The conceptual model describes a hydrogeologic framework, groundwater flow, recharge, evapotranspiration, discharge to streams, water use, and hydraulic properties of the Ogallala and Arikaree aquifers. The conceptual model of the Ogallala aquifer includes the overlying windblown and unconsolidated deposits, and the Arikaree aquifer includes isolated overlying unconsolidated deposits. The hydrogeologic framework describes the physical dimensions and location of the aquifer units. Water budget components were analyzed by WY for the period 1980–2009. Recharge to the Ogallala and Arikaree aquifers is from infiltration of precipitation on outcrop areas. Well withdrawals primarily are for irrigation and public and domestic water supplies. The Ogallala and Arikaree aquifers are assumed to have a hydraulic connection that is limited by the lower vertical hydraulic conductivity of the Arikaree aquifer.

The extents of the Ogallala and Arikaree aquifers were simplified from the extents of the Ogallala and Arikaree Formations (fig. 4) and were used to develop the conceptual model in this report (fig. 5). Thin and intermittently saturated parts near the outer extent of the Ogallala Formation were grouped with the Arikaree aquifer. Thin and intermittently saturated parts of the Arikaree Formation along the northern and western outcrop boundaries were removed. Isolated areas of eolian deposits and the Batesland Formation were grouped with the uppermost underlying Ogallala or Arikaree Formation. The Ogallala and Arikaree aquifers extend about 130 miles (mi) beyond the eastern edge of the study area boundary and about 770 mi beyond the southern edge of the study area boundary. The conceptual model boundaries were extended 3 to 6 mi into Nebraska to the south and 1 to 2 mi into Mellette and Todd Counties to the east to minimize the effect of the boundary conditions in numerical modeling of the Pine Ridge Indian Reservation area. The conceptual model boundaries are coincident with the extent of the Ogallala and Arikaree aquifers shown in figure 5.

Hydrogeologic Framework

The tops and bottoms of the Ogallala and Arikaree Formations were identified from lithologic data (South Dakota Geological Survey, 2012; University of Nebraska-Lincoln, 2012). The contacts between the Ogallala and Arikaree Formations and between the Arikaree and White River Formations were interpreted using descriptions of the geology (Ellis and Adolphson, 1971; Harksen and Macdonald, 1967; Greene and others, 1991; Martin and others, 2004). When a lithologic log included a geologic name with the units described, nearby lithologic logs without identification of geologic units were compared to improve the interpretations. The altitude of land surface near the perimeter where the Ogallala and Arikaree Formations pinched out also was used in the interpolation of the aquifer bottoms.

The top of the Ogallala Formation was coincident with land surface (fig. 2) within the simplified Ogallala aquifer extent (fig. 5). Quaternary-age deposits and Tertiary-age gravel deposits that directly overlie the Ogallala Formation were included with the Ogallala Formation in defining the hydrogeologic framework for the Ogallala aquifer because, in general, these deposits are hydraulically connected to the Ogallala aquifer (Weeks and Gutentag, 1981). The top of the Arikaree Formation within the simplified Arikaree aquifer extent and where the Ogallala aquifer does not exist (fig. 5) was coincident with land surface. Isolated Quaternary-age deposits, Tertiary-age gravel deposits, and thin isolated areas of the Ogallala and Batesland Formations that directly overly the Arikaree Formation were considered hydraulically connected to the underlying Arikaree aquifer.

The bottom of the Ogallala aquifer is coincident with the base of the Ogallala Formation and also is equivalent to the top of the Arikaree Formation. The bottom of the Ogallala aquifer was interpreted from wells and test holes (fig. 6). In addition to test holes or wells that fully penetrated the aquifer, the bottom of the Ogallala aquifer was interpreted from wells that partially penetrated the aquifer and test holes located along hydrologic cross sections of the High Plains aquifer in Bennett County (Filipovic, 2011). The interpolated altitude of the bottom of the Ogallala aquifer ranged from about 3,600 ft above NAVD 88 in the west to about 2,700 ft above NAVD 88 in the east (fig. 6).

The bottom of the Arikaree aquifer is coincident with the bottom of the Arikaree Formation and is equivalent to the top of the White River Group. The bottom of the Arikaree aquifer (fig. 7) was interpreted from sparse lithologic logs that penetrated the White River Group (fig. 5). In addition to test holes or wells that fully penetrated the Arikaree aquifer, the altitude of the bottom of the Arikaree aquifer was interpreted from wells that partially penetrated the aquifer and test holes located along hydrologic cross sections of the High Plains aquifer in Bennett County (Filipovic, 2011). Wells from Carter and Heakin (2007) that partially penetrated the Arikaree aquifer were examined and several were selected to estimate the maximum possible altitude for the bottom of the Arikaree aquifer. Several wells were assumed to be close to fully penetrating the aquifer. The altitude of the bottom of the Arikaree aquifer ranged from about 3,200 ft above NAVD 88 in the southwestern part of the study area to about 2,200 ft above NAVD 88 in the eastern part of the study area (fig. 7).

Groundwater Flow

Generalized potentiometric surfaces of the Ogallala (fig. 8) and Arikaree (fig. 9) aquifers were estimated from water levels from wells screened in the aquifers. The potentiometric surfaces indicate a generalized northeasterly groundwater-flow direction following the topography. Groundwater generally flows from areas of recharge to streams or other topographically low areas where the aquifers discharge either through stream base flow, springs, or evapotranspiration. The general direction of groundwater flow in the Ogallala aquifer is west to east and towards the Little White River (fig. 8). The general direction of groundwater flow in the Arikaree aquifer is towards the north and east with local flow toward streams (fig. 9).

Ogallala Aquifer

The eolian deposits (windblown sand) that overlie the Ogallala aquifer have similar hydrogeologic properties and are in direct hydraulic connection with the Ogallala aquifer; therefore, the two units were conceptualized together as a single water-bearing unit (Weeks and Gutentag, 1981). The generalized potentiometric surface for the Ogallala aquifer was interpreted based on data from 12 long-term observation wells with multiple measurements and 60 wells with single water-level measurements (fig. 8 and table 1–1; U.S. Geological Survey, 2010). For the 12 long-term observation wells, a mean hydraulic head value for the period of record was calculated. The range in water-level fluctuations in the 12 wells with long-term data averaged 8.3 ft. Fluctuations in water levels for 10 of the 12 wells were less than 8 ft. The remaining two wells had water-level fluctuations of 17.8 and 32.1 ft and were close to irrigation wells; therefore, the use of wells with single water-level measurements was assumed to approximate the generalized potentiometric surface for the Ogallala aquifer. The general direction of groundwater flow in the Ogallala aquifer is west to east (fig. 8) and generally follows the topography (fig. 2). Near the South Dakota–Nebraska border, groundwater flow primarily was from west to the east. About 5 mi north of the South Dakota–Nebraska border, the groundwater-flow direction turns north towards the Little White River and Lake Creek. Water-level data were not available in the western part of the aquifer; however, groundwater flow was assumed to be north towards the tributaries flowing to the White River.

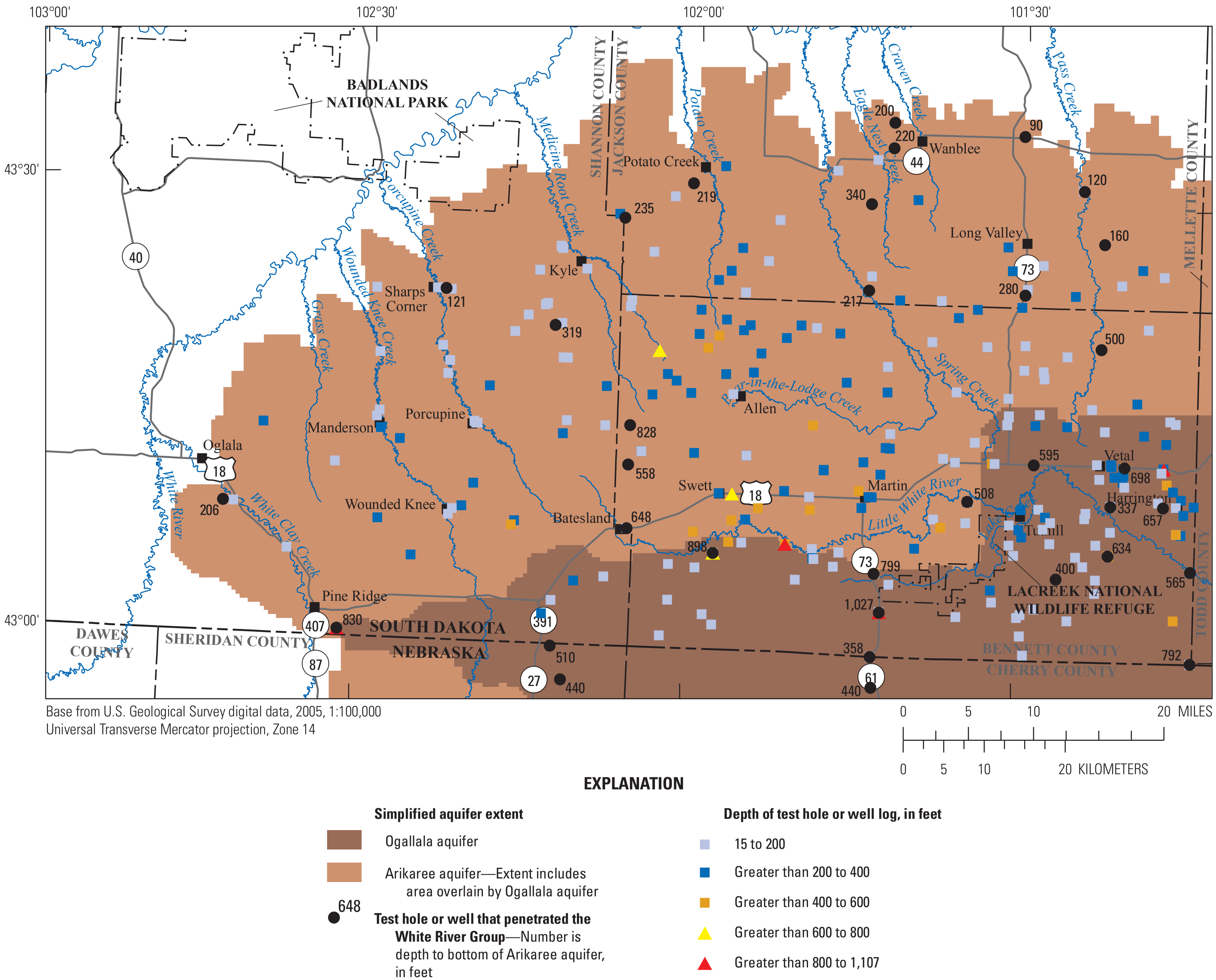


Figure 5. Location of aquifer extents and test holes and wells with lithologic logs in the study area.

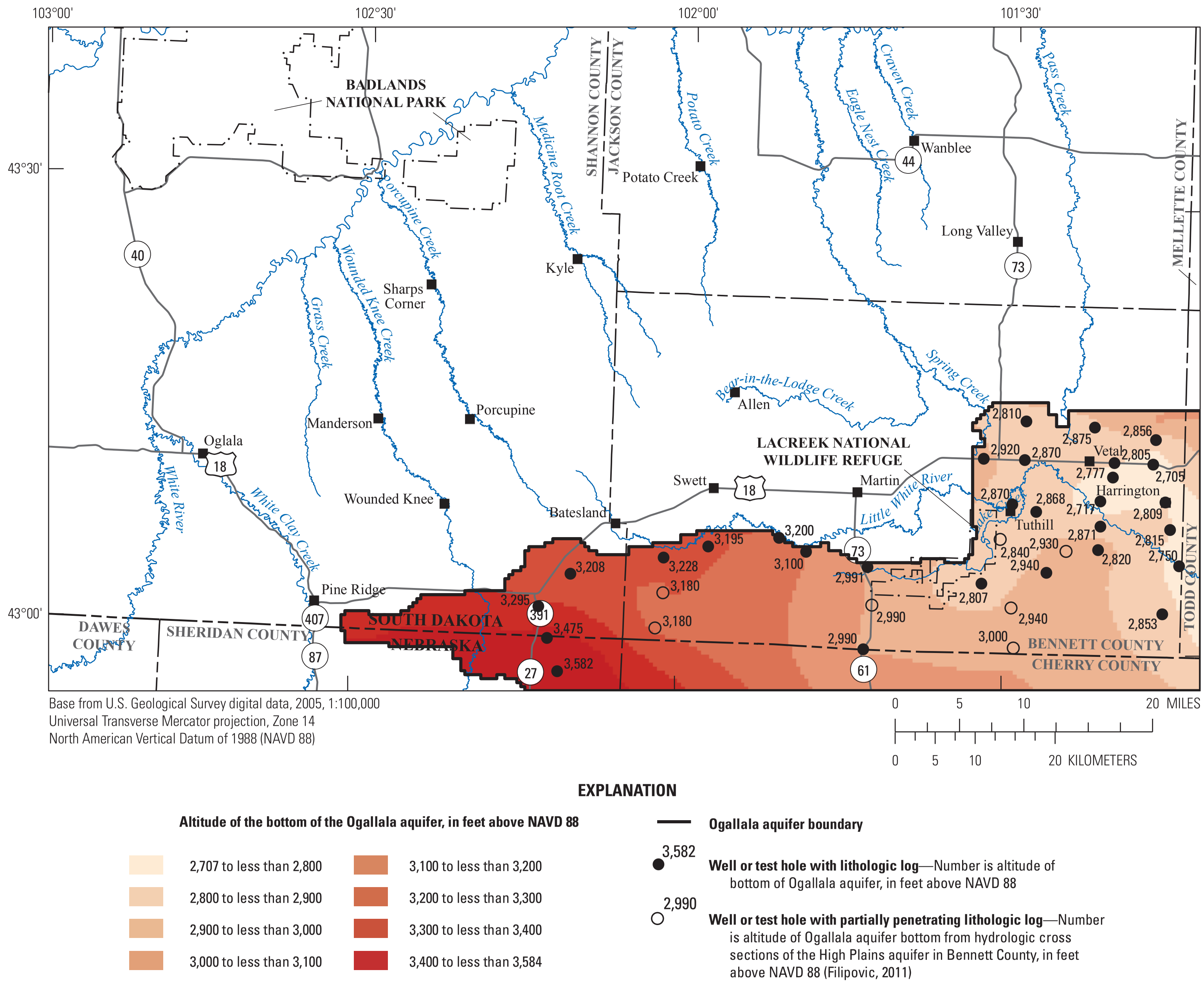


Figure 6. Altitude of the bottom of the Ogallala aquifer in the study area.

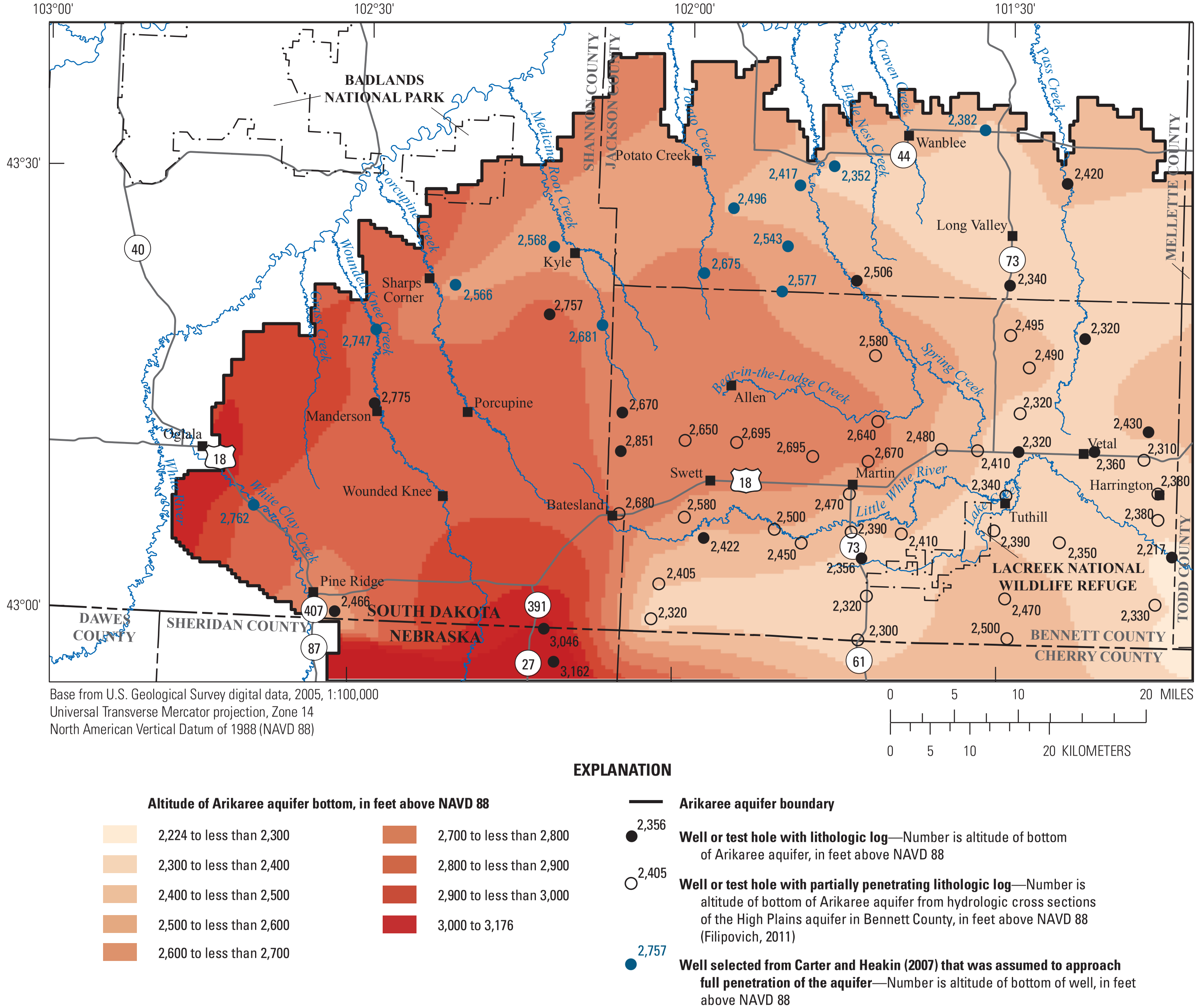
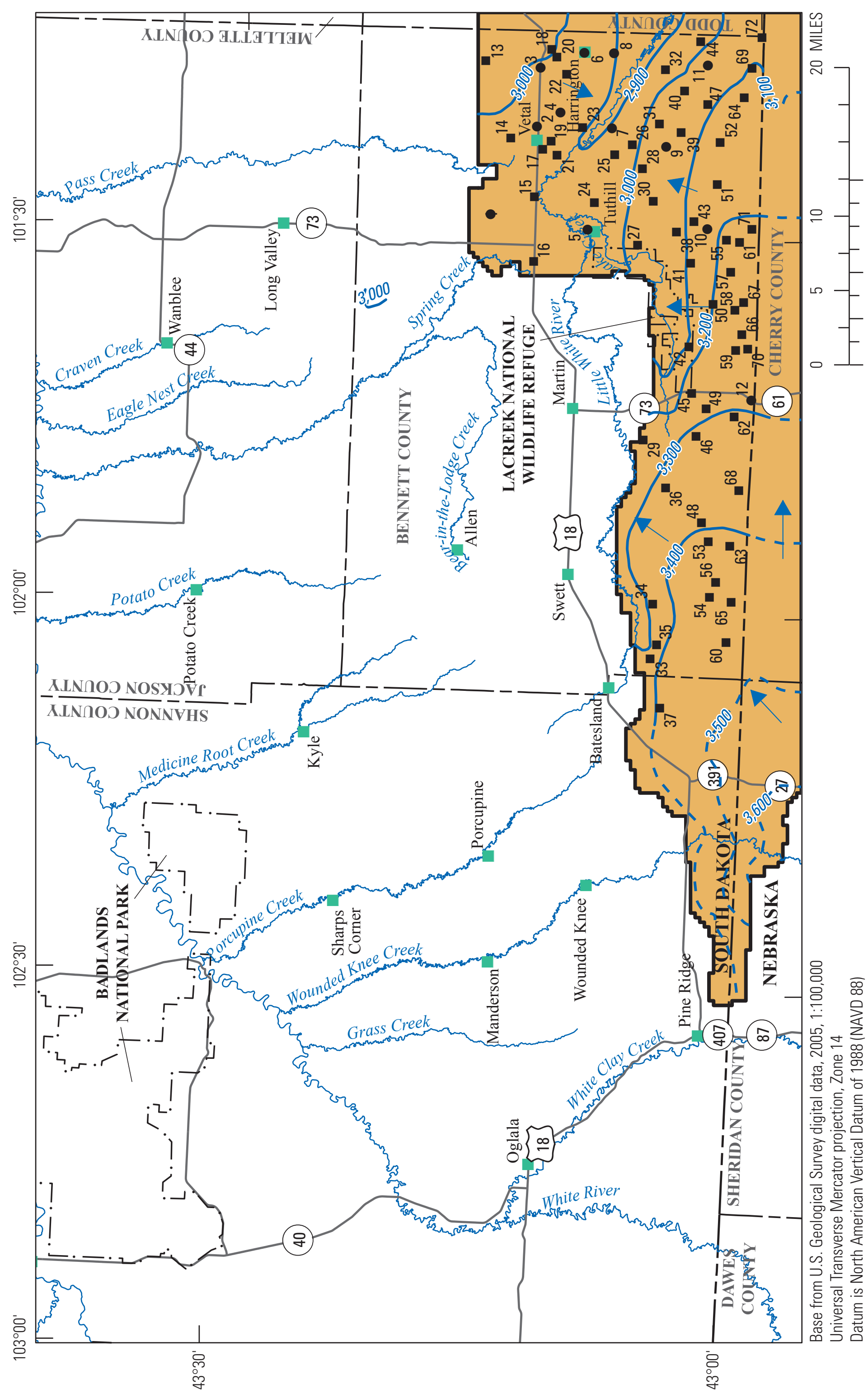


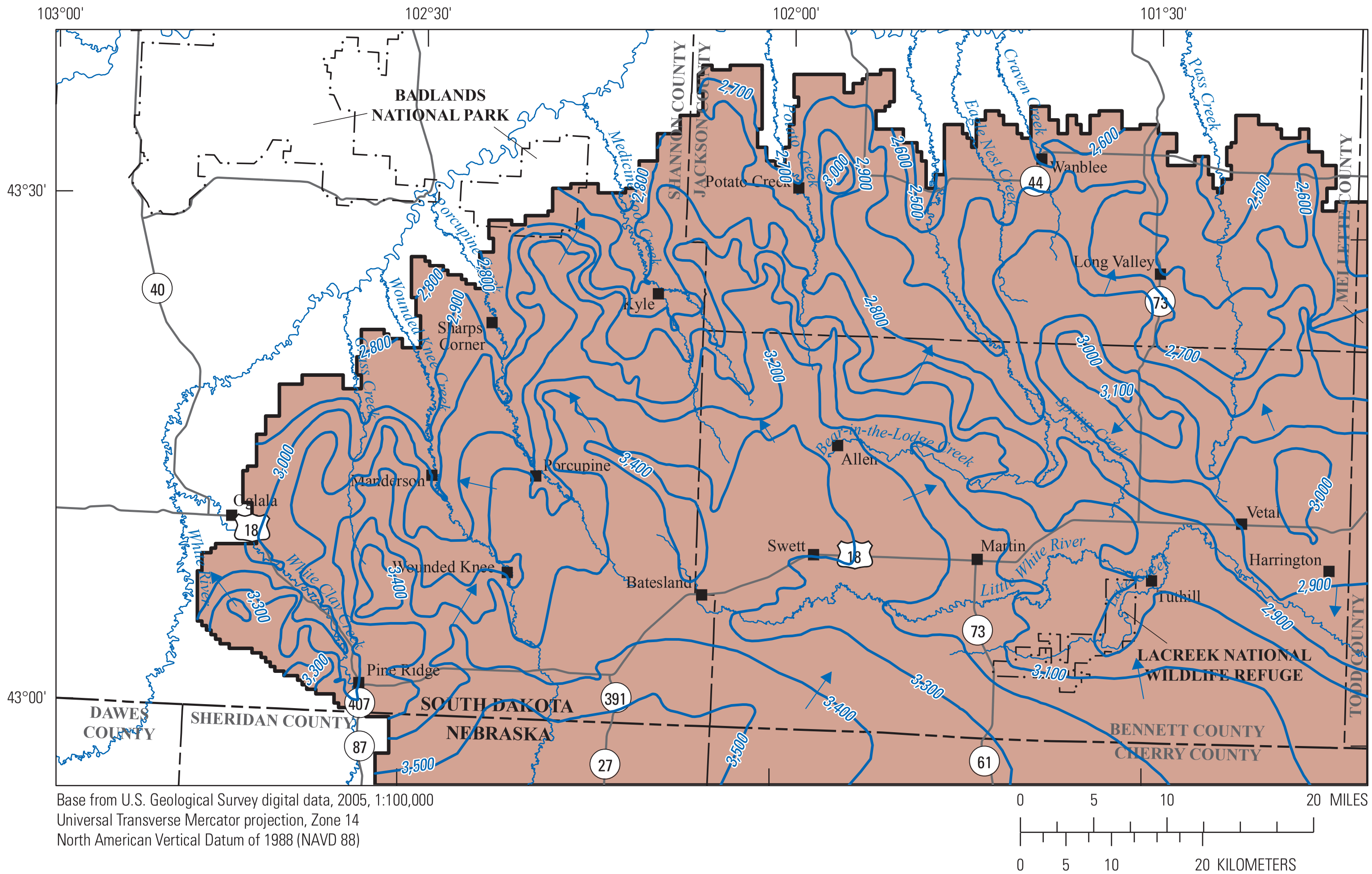
Figure 7. Altitude of the bottom of the Arikaree aquifer in the study area.



EXPLANATION

- **Extent of Ogallala aquifer**
- **Potentiometric contour**—Shows the altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 100 feet. Datum is NAVD 88
- 60 ■ **Well for which single water-level measurement is available**—Number is site identifier in table 1–1
- 12 ● **Well for which long-term water-level data are available**—Number is site identifier in table 1–1
- **Direction of groundwater flow**

Figure 8. Generalized potentiometric surface of the Ogallala aquifer in the study area.



EXPLANATION

Extent of Arikaree aquifer

Potentiometric contour—Shows atlitude at which water level would have stood in tightly cased wells. Contour interval 100 feet. Datum is NAVD 88

Direction of groundwater flow

Figure 9. Generalized potentiometric surface of the Arikaree aquifer in the study area (modified from Carter and Heakin, 2007).

Because the general direction of groundwater flow for the Ogallala aquifer at the southern boundary of the study area was mostly parallel to the boundary, inflow across the southern boundary was assumed to be small. The groundwater-flow direction at the eastern boundary of the study area primarily is towards the Little White River; thus, net flow across the eastern boundary also is assumed to be relatively small.

The generalized potentiometric surface of the Ogallala aquifer (fig. 8) and the bottom of the Ogallala aquifer (fig. 6) were used to calculate the saturated thickness of the aquifer. The saturated thickness of the Ogallala aquifer ranged from 10 to 314 ft (fig. 10). The saturated thickness of the Ogallala aquifer on the northern and western sides and along the downstream part of the Little White River ranged from 10 to 100 ft. The saturated thickness in the south central part of the study area ranged from about 200 to 300 ft.

Arikaree Aquifer

Carter and Heakin (2007) created a generalized potentiometric surface for the Arikaree aquifer using water-level measurements between 1929 and 2006, but most measurements were made between 1980 and 2006. The Arikaree aquifer interpretation included all of subdivisions of the Arikaree Formation listed in table 3. Isolated water levels that are higher than surrounding hydraulic heads may represent groundwater perched on impermeable layers within the Arikaree Formation. Potentiometric contours of 100 ft (fig. 9) were used to interpret groundwater flow in the Arikaree aquifer (Carter and Heakin, 2007).

The general direction of groundwater flow in the Arikaree aquifer is towards the north and east. Locally, groundwater flows downgradient from drainage divides towards major streams, tributaries, and wetlands (Carter and Heakin, 2007). The drainage divides and their relation to major streams and valleys are evident on the shaded relief map of the land surface (fig. 2). The hydraulic gradient generally increases as the Arikaree Formation pinches out towards the northern extent. In the south, the hydraulic gradient is affected by the overlying Ogallala aquifer.

The generalized potentiometric surface of the Arikaree aquifer (fig. 9) and the altitude of the bottom of the Arikaree aquifer (fig. 7) were used to calculate the saturated thickness of the aquifer. The saturated thickness of the Arikaree aquifer ranged from 10 to 862 ft (fig. 11). The saturated thickness of the Arikaree aquifer near the northern and western extents ranged from 10 to 100 ft. The saturated thickness in the southern and central part of the study area ranged from about 500 to 800 ft.

Water Budget Components

Water budget components of recharge and discharge are described in this section. Recharge occurs by infiltration of precipitation in outcrop areas. Discharge occurs through evapotranspiration, discharge to streams, and well withdrawals.

Recharge

Recharge to the Ogallala aquifer occurs by infiltration of precipitation on the outcrop of the Ogallala Formation and the overlying windblown deposits in the southern part of the study area (fig. 4). Recharge to the Arikaree aquifer is from the infiltration of precipitation on the outcrop of the Arikaree Formation in the northern and western parts of the study area.

Previous reports characterizing the High Plains aquifer, which includes the Ogallala and Arikaree aquifers, provide estimates of recharge ranging from approximately 8 percent of annual precipitation or between 1.3 and 1.8 in/yr (Kolm and Case, 1983) to 15 percent of the annual precipitation or between 2.5 and 3 in/yr (Langbein, 1949). Recharge to the Sand Hills of Nebraska was estimated by Rahn and Paul (1975) as about 3 in/yr.

Recharge previously was estimated using a steady-state simulation of groundwater flow in the Ogallala and Arikaree aquifers in the Rosebud Indian Reservation area (Long and others, 2003), located directly east of this study area, and the Pine Ridge Reservation area, as 3.3 and 1.7 in/yr, respectively. Mean recharge rates of 2.91 in/yr for the Ogallala aquifer (or 15 percent of mean precipitation) and 1.45 in/yr for the Arikaree aquifer (or 7 percent of mean precipitation) were estimated after recalibration of the steady-state simulation of the model by Long and others (2003) using additional hydrologic data and enhanced parameter estimation techniques (Long and Putnam, 2010).

Recharge to the Ogallala and Arikaree aquifers was estimated for three zones (fig. 12): (1) the Ogallala aquifer, (2) the eastern part of the Arikaree aquifer, and (3) the western part of the Arikaree aquifer. Recharge to the Ogallala aquifer was represented separate from the Arikaree aquifer because higher precipitation infiltration was expected to occur in the Ogallala aquifer due to the overlying sandy soils derived from the Sand Hills Formation. The lower permeability of the Arikaree aquifer and the greater presence of clay layers were assumed to limit precipitation infiltration in the Arikaree aquifer. The Arikaree aquifer was divided into eastern and western zones based on lower precipitation on the western side of the study area compared to the eastern side.

Mean annual recharge for the three recharge zones (fig. 12) was estimated as a percentage of measured precipitation. Precipitation data from station 395281 (Martin) were used for recharge zone 1 (Ogallala aquifer), station 394983 (Long Valley) was used for recharge zone 2 (eastern part of the Arikaree aquifer), and station 396736 (Porcupine 11N) was used for recharge zone 3 (western part of the Arikaree aquifer; table 4). Mean recharge for WYs 1980–2009 for the Ogallala and Arikaree aquifers was estimated as 15 and 7.5 percent of mean annual precipitation, respectively, determined based on the calibrated recharge values, expressed as a percentage of precipitation, from the model of the adjacent Rosebud Indian Reservation area (Long and Putnam, 2010).

Because of the sandy soil overlying the Ogallala aquifer, and to a lesser extent overlying the Arikaree aquifer,

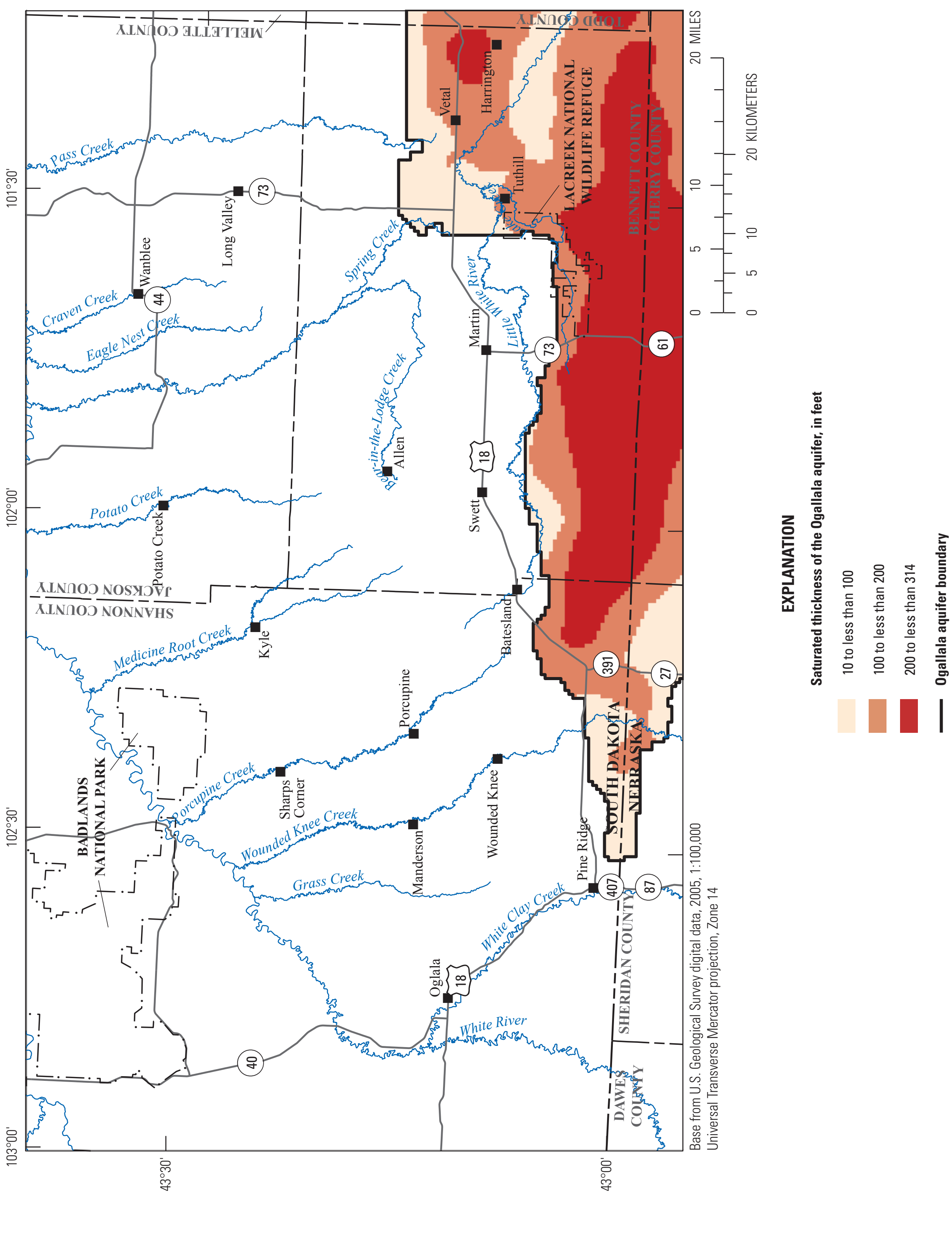


Figure 10. Saturated thickness of the Ogallala aquifer in the study area.

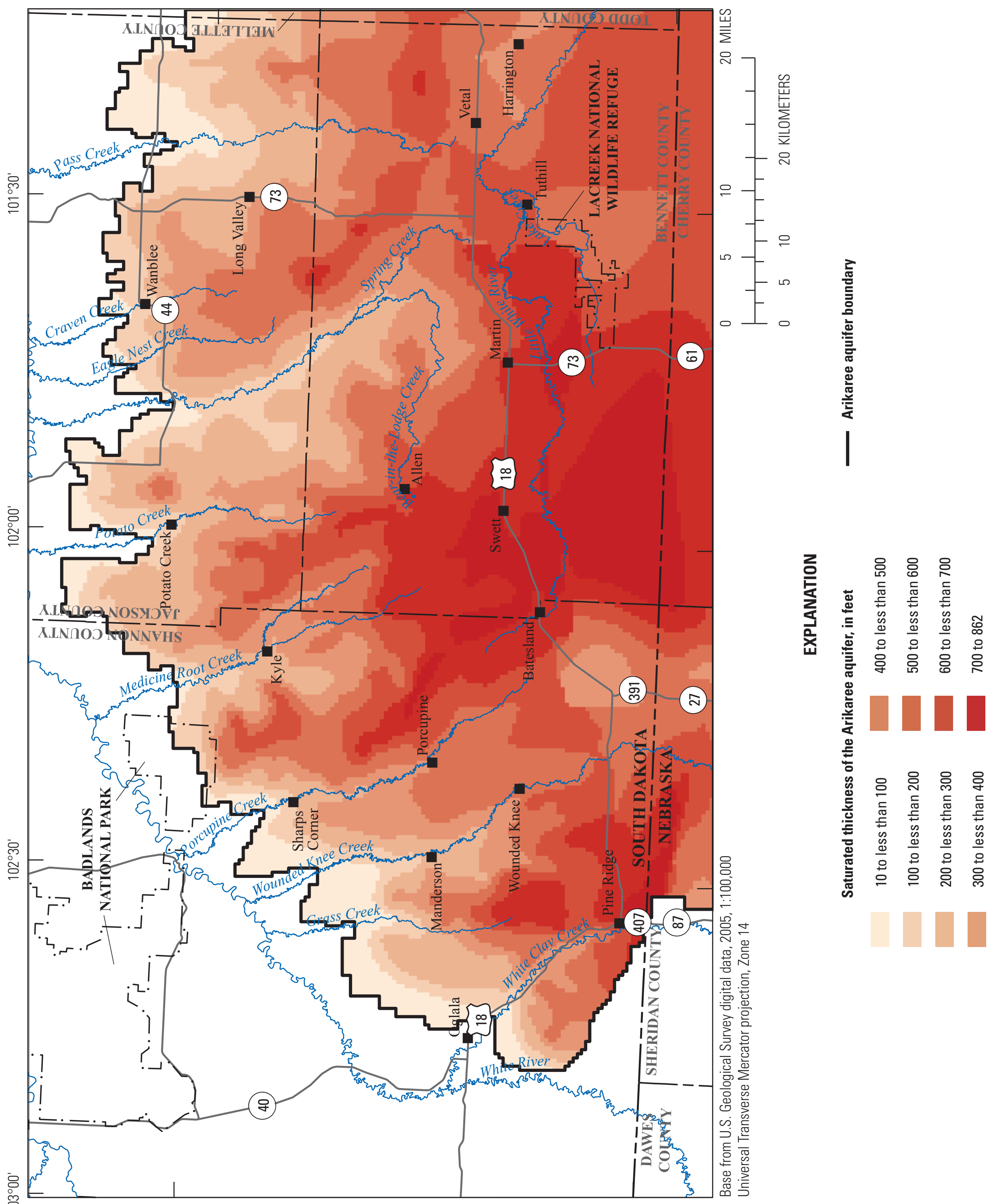


Figure 11. Saturated thickness of the Arikaree aquifer in the study area.

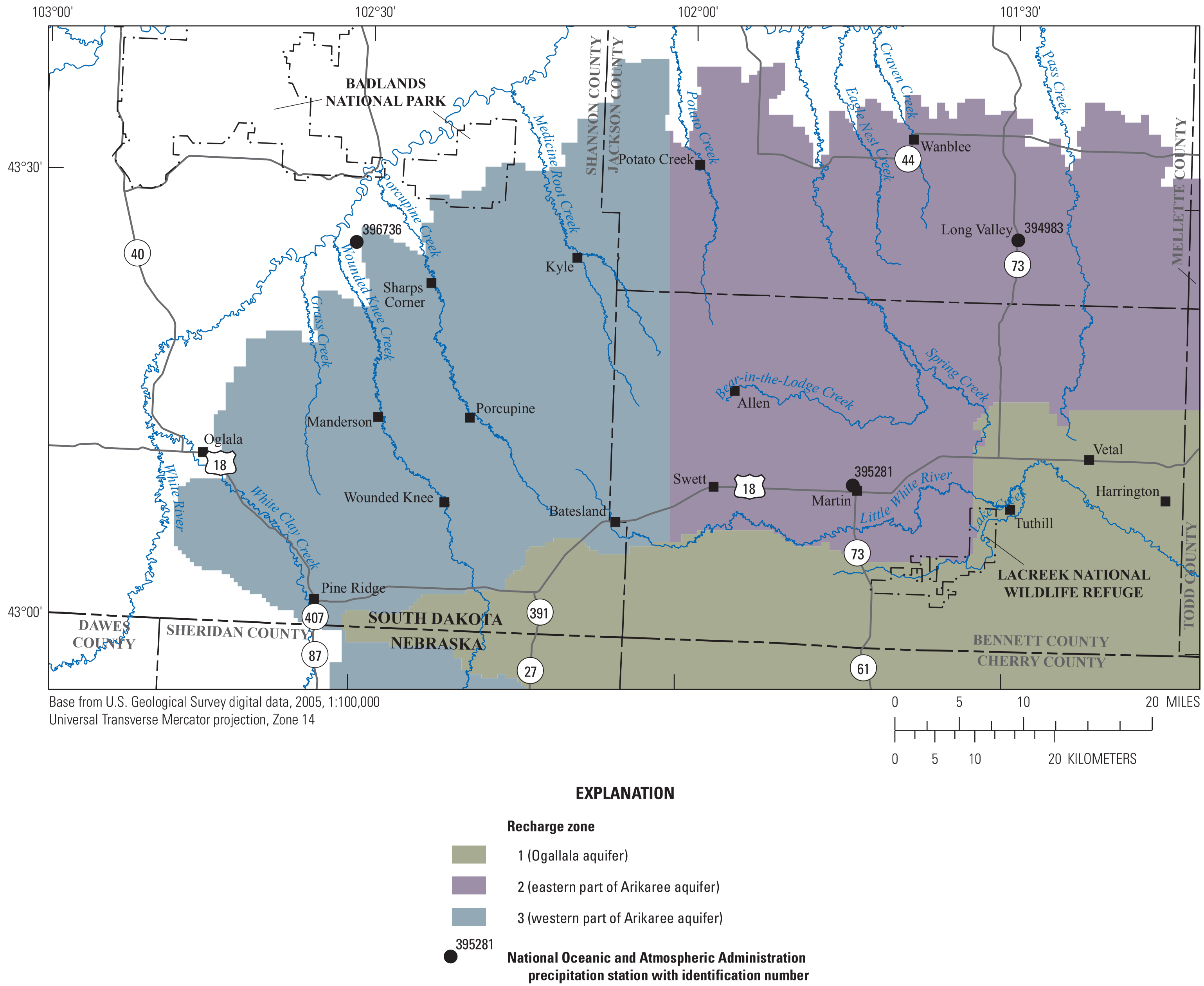


Figure 12. Recharge zones and selected National Oceanic and Atmospheric Administration precipitation stations in the study area.

rainfall that exceeded evapotranspiration losses was assumed to infiltrate to the aquifers. When antecedent soil moisture conditions are dry and soil water is depleted, more of the soil moisture is removed from the soil profile as evapotranspiration. To account for the antecedent soil moisture condition in dry and wet years, recharge as a percentage of precipitation for the transient stress periods was estimated as a linear function of the ratio of the annual precipitation to the mean annual precipitation for WYs 1980–2009 (table 4). For example, the mean annual precipitation at station 395281 (Martin) for WYs 1980–2009 was 19.8 in., and the annual precipitation in WY 1980 was 11.9 in.; therefore, the recharge rate as percentage of precipitation was calculated as 11.9 divided by 19.8 times 15 percent, which equals 9.0 percent of precipitation for WY 1980. This calculation yields an estimated recharge of 1.1 in. (9.0 percent of 11.9 in.) for WY 1980 to the Ogallala aquifer (recharge zone 1). Transient recharge rates were estimated for each WY using this adjusted percentage of annual precipitation for each recharge zone (table 4). Mean annual recharge for WYs 1980–2009 was about 3.3 in/yr to the Ogallala aquifer and 1.5 in/yr to the Arikaree aquifer (mean of annual recharge for recharge zones 2 and 3), or 17.3 and 7.9 percent of the long-term (WYs 1980–2009) mean annual precipitation of 19.1 in/yr for the study area, respectively (mean of annual precipitation for stations 395281, 394983, and 396736; table 4).

Discharge

Discharge from the Ogallala and Arikaree aquifers occurs through evapotranspiration, discharge to streams, and well withdrawals. Discharge by evapotranspiration generally occurs in topographically low areas or where the water table is near land surface. Discharge to streams occurs as flow from springs and seeps and as base flow where the aquifers are hydraulically connected to the streams (river leakage). For the purpose of this analysis, all discharge from springs and seeps was assumed to reach a stream and contribute to base flow. Well withdrawals are from irrigation and public and domestic water supplies.

Evapotranspiration

Maximum potential evapotranspiration is herein defined as the maximum amount of water that could be evapotranspired from an aquifer when the water level is at land surface in an unconfined aquifer. Evapotranspiration decreases with the depth of the water level below land surface and is negligible when the depth to the water table is below the root zone (Long and Putnam, 2010). Generally, the depth of this root zone is assumed to be about 7 to 20 ft with the deeper root penetration (as much as 20 ft) associated with pine and deciduous forests. Most parts of the study area generally are grasslands or agricultural cropland (fig. 3) where the shallower root penetration (as little as 7 ft) is assumed. Evapotranspiration of infiltrating or suspended groundwater in the unsaturated zone was assumed to be accounted for in the estimates of aquifer recharge.

Table 4. Estimated recharge to Ogallala and Arikaree aquifer in the study area for water years 1980–2009 by recharge zone.

[Recharge zone 1 represents the Ogallala aquifer, recharge zone 2 represents the eastern part of the Arikaree aquifer, and recharge zone 3 represents the western part of the Ari-karee aquifer (fig. 12). Precipitation data for National Oceanic and Atmospheric Administration stations from National Climate Data Center (2011). Annual refers to the 12-month period designated by a water year. in/yr, inches per year]

Water year	Station 395281		Recharge zone 1		Station 394983		Recharge zone 2		Station 396736		Recharge zone 3	
	Precipitation (in/yr)	Ratio of annual precipitation to mean annual	Recharge as percentage of precipitation	Recharge rate (in/yr)	Precipitation (in/yr)	Ratio of annual precipitation to mean annual	Recharge as percentage of precipitation	Recharge rate (in/yr)	Precipitation (in/yr)	Ratio of annual precipitation to mean annual	Recharge as percentage of precipitation	Recharge rate (in/yr)
1980	11.9	0.60	9.0	1.1	10.6	0.54	4.1	0.4	10.7	0.60	4.5	0.5
1981	19.8	1.00	15.0	3.0	17.3	0.88	6.6	1.1	12.6	0.70	5.3	0.7
1982	24.1	1.22	18.3	4.4	24.5	1.25	9.4	2.3	20.4	1.14	8.6	1.8
1983	23.7	1.20	18.0	4.3	23.0	1.17	8.8	2.0	17.8	0.99	7.4	1.3
1984	17.1	0.86	12.9	2.2	15.8	0.81	6.1	1.0	15.6	0.87	6.5	1.0
1985	13.0	0.66	9.9	1.3	12.2	0.62	4.7	0.6	12.2	0.68	5.1	0.6
1986	27.1	1.37	20.6	5.6	26.8	1.37	10.3	2.8	21.2	1.18	8.9	1.9

Table 4. Estimated recharge to Ogallala and Arikaree aquifer in the study area for water years 1980–2009 by recharge zone.—Continued

[Recharge zone 1 represents the Ogallala aquifer, recharge zone 2 represents the eastern part of the Arikaree aquifer, and recharge zone 3 represents the western part of the Ari-karee aquifer (fig. 12). Precipitation data for National Oceanic and Atmospheric Administration stations from National Climate Data Center (2011). Annual refers to the 12-month period designated by a water year. in/yr, inches per year]

Water year	Station 395281		Recharge zone 1		Station 394983		Recharge zone 2		Station 396736		Recharge zone 3	
	Precipitation (in/yr)	Ratio of annual precipitation to mean annual	Recharge as percentage of precipitation	Recharge rate (in/yr)	Precipitation (in/yr)	Ratio of annual precipitation to mean annual	Recharge as percentage of precipitation	Recharge rate (in/yr)	Precipitation (in/yr)	Ratio of annual precipitation to mean annual	Recharge as percentage of precipitation	Recharge rate (in/yr)
1987	15.7	0.79	11.9	1.9	17.8	0.91	6.8	1.2	14.7	0.82	6.2	0.9
1988	15.4	0.78	11.7	1.8	19.7	1.01	7.6	1.5	15.2	0.85	6.4	1.0
1989	10.7	0.54	8.1	0.9	11.6	0.59	4.4	0.5	12.3	0.69	5.2	0.6
1990	19.2	0.97	14.6	2.8	18.9	0.96	7.2	1.4	14.8	0.83	6.2	0.9
1991	24.1	1.22	18.3	4.4	18.3	0.93	7.0	1.3	17.3	0.97	7.3	1.3
1992	17.4	0.88	13.2	2.3	17.0	0.87	6.5	1.1	20.3	1.13	8.5	1.7
1993	20.4	1.03	15.5	3.2	25.0	1.28	9.6	2.4	24.7	1.38	10.4	2.6
1994	18.9	0.95	14.3	2.7	15.2	0.78	5.9	0.9	16.9	0.94	7.1	1.2
1995	26.5	1.34	20.1	5.3	25.3	1.29	9.7	2.5	22.0	1.23	9.2	2.0
1996	22.2	1.12	16.8	3.7	25.5	1.30	9.8	2.5	20.8	1.16	8.7	1.8
1997	27.9	1.41	21.2	5.9	24.3	1.24	9.3	2.3	25.9	1.45	10.9	2.8
1998	24.4	1.23	18.5	4.5	22.2	1.13	8.5	1.9	15.9	0.89	6.7	1.1
1999	39.4	1.99	29.9	11.8	24.8	1.27	9.5	2.4	28.6	1.60	12.0	3.4
2000	16.7	0.84	12.6	2.1	16.8	0.86	6.5	1.1	17.7	0.99	7.4	1.3
2001	18.2	0.92	13.8	2.5	19.1	0.97	7.3	1.4	19.5	1.09	8.2	1.6
2002	11.9	0.60	9.0	1.1	13.0	0.66	5.0	0.7	15.0	0.84	6.3	0.9
2003	14.0	0.71	10.7	1.5	14.7	0.75	5.6	0.8	12.8	0.72	5.4	0.7
2004	18.2	0.92	13.8	2.5	15.7	0.80	6.0	0.9	15.1	0.84	6.3	1.0
2005	24.1	1.22	18.3	4.4	25.3	1.29	9.7	2.5	21.0	1.17	8.8	1.8
2006	14.5	0.73	11.0	1.6	16.6	0.85	6.4	1.1	18.8	1.05	7.9	1.5
2007	16.5	0.83	12.5	2.1	18.7	0.95	7.1	1.3	16.1	0.90	6.8	1.1
2008	18.8	0.95	14.3	2.7	24.0	1.22	9.2	2.2	20.5	1.15	8.6	1.8
2009	23.2	1.17	17.6	4.1	29.1	1.48	11.1	3.2	20.2	1.13	8.5	1.7
Mean annual	19.8	1.00	16.4[a]	3.3	19.6	1.00	8.0[a]	1.6	17.9	1.00	7.9[a]	1.4

[a]Does not equal the mean of annual values. Value calculated from mean annual precipitation and mean annual recharge.

Maximum potential evapotranspiration during June–September periods was estimated as 70 percent of total annual pan evaporation based on the relation between pan evaporation and evapotranspiration data described by Farnsworth and others (1982). Pan evaporation rates were assumed to be similar to those at an NOAA climatological data station at Cottonwood (National Climatic Data Center, 2010; station 391972), which is located about 20 mi north of the study area (fig. 2). Pan evaporation records at station 391972 were available for the months of June through September for the 30 WYs included in the analysis. The estimated potential evapotranspiration for the 30 June–September periods (table 5) for WYs 1980–2009 ranged from 20.4 to 30.7 in., with a mean of 26.0 in. Sparse pan evaporation data were available for October through May. The mean pan evaporation was estimated to be 4.25 in. for the October–February period and 8.5 in. for the March–May period, based on sparse available pan evaporation rates for the October–February and March–May periods. To estimate the maximum potential evapotranspiration rate for the October–February and March–May periods for each WY, the mean annual maximum potential evapotranspiration rate of 35 in/yr was multiplied by the ratio of the monthly mean temperature for October–May in each WY divided by the mean monthly temperature for October–May in WYs 1980–2009 (National Climatic Data Center, 2010; station 391972). Based on these estimates and an assumption that maximum potential evapotranspiration was 70 percent of pan evaporation (Farnsworth and others, 1982), the mean maximum potential evapotranspiration was 3.0 in for the October–February period and 6.0 in for the March–May period. These estimates were then added to the values for the June–September period to estimate the maximum potential evapotranspiration rate for WYs 1980–2009 (table 5).

Discharge to Streams

Groundwater discharges to streams where streams are incised to an altitude below the hydraulic head (altitude of the potentiometric surface) in the Ogallala and Arikaree aquifers. Long and Putnam (2010) calculated a steady-state discharge to streams from the Ogallala and Arikaree aquifers of about 75 ft^3/s in the adjacent Rosebud Indian Reservation area.

The daily base-flow contribution to streamflow at six streamgages (table 6; fig. 2) was estimated using HYSEP (Sloto and Crouse, 1996), a computer program that uses automatic hydrograph separation methods on daily mean streamflow data (U.S. Geological survey, 2012). The HYSEP program uses three methods for hydrograph separation: fixed interval, sliding interval, and local minimum. Descriptions of the three hydrograph separation methods are available in the HYSEP documentation (Sloto and Crouse, 1996). The local minimum method resulted in the smallest base-flow values and was assumed to minimize the effects of bank storage in the final estimates.

Mean base-flow rates for WYs 1980–2009 for the six streamgages ranged from 3.5 to 52.2 ft^3/s (table 7). The mean base flow for gaged streams was about 0.06 ft^3/s per square mile of drainage area. Base flow expressed in inches per year over the contributing drainage area for the Little White River upstream from streamgage 06449100 was 1.1 in/yr. The Little White River drainage basin includes most of the outcrop of the Ogallala Formation. Base flow for Bear-in-the-Lodge Creek for the contributing drainage area upstream from streamgage 06446700 (fig. 2) was 0.4 in/yr. Most of the Bear-in-the-Lodge Creek drainage area includes the outcrop of the Arikaree Formation.

For streamgages with incomplete periods of record, base flow was estimated with equations developed by linear regression of the base flow for the existing period of record with the base flow calculated for streamgage 06447500 (Little White River near Martin, South Dakota [fig. 2]) for the same period for each streamgage. This procedure was completed using the method documented by Riggs (1972). The coefficient of determination for each of the linear regressions was 0.99. For streamgage 06446700 (Bear-in-Lodge Creek near Wanblee, S. Dak. [fig. 2]), base flow was 0.72 times base flow for streamgage 06447500; for streamgage 06446100 (Wounded Knee Creek at Wounded Knee, S. Dak. [fig. 2]), base flow was 0.21 times base flow for streamgage 06447500; and for streamgage 06445980 (White Clay Creek near Oglala, S. Dak. [fig. 2]), base flow was 0.50 times base flow for streamgage 06447500.

Water Use

Water use from the Ogallala and Arikaree aquifers was primarily for irrigation and public supplies but also for domestic and stock use. Most production wells (fig. 13) that were used for irrigation were located in the southern part of the study area where the Ogallala aquifer is present (fig. 5) and the saturated thickness of the Arikaree aquifer is the greatest (fig. 11). Irrigators report their water use to the South Dakota Department of Environment and Natural Resources; these data were used to compile well withdrawals by aquifer for WYs 1980–2009 (table 8). The mean irrigation water-use rates for WYs 1980–2009 were 5.4 ft^3/s for the Ogallala aquifer and 5.2 ft^3/s for the Arikaree aquifer.

The Arikaree aquifer is used extensively for public supplies. Water use for public supplies was compiled based on estimated community population and per capita water use. Public-supply wells were inventoried during a water-quality sampling program conducted by Heakin (2000) that identified 27 communities including schools, housing authorities, and small towns. Population equivalents were estimated for these communities based on 2010 census data for census-designated places (U.S. Census Bureau, 2013). Per capita water use was assumed to average 93 gallons per population equivalent per day based on estimated public-supply domestic water deliveries for South Dakota (table 9; Amundson, 1998; Amundson, 2002; Carter and Neitzert, 2008). Population was assumed to uniformly increase 0.4 percent per year based on population changes for Bennett, Jackson, and Shannon Counties (table 9).

Table 5. Estimated maximum potential evapotranspiration rate in the study area, water years 1980–2009.

Water year	Estimated maximum potential evapotranspiration for June–September[a] (inches)	Estimated maximum potential evapotranspiration for October–May[b] (inches)	Maximum potential evapotranspiration rate (inches per water year)
1980	29.1	9.0	38.1
1981	24.4	9.9	34.3
1982	22.0	8.5	30.5
1983	28.3	9.1	37.4
1984	26.6	8.5	35.1
1985	27.8	8.8	36.6
1986	25.3	8.4	33.7
1987	27.7	9.4	37.1
1988	30.7	8.8	39.5
1989	29.5	8.7	38.2
1990	28.4	9.2	37.6
1991	26.5	9.0	35.5
1992	21.6	9.7	31.3
1993	20.4	8.1	28.5
1994	26.2	8.6	34.8
1995	25.3	9.0	34.3
1996	27.7	8.1	35.8
1997	22.5	7.9	30.4
1998	21.9	9.2	31.1
1999	22.4	9.6	32.0
2000	27.2	9.9	37.1
2001	24.8	8.4	33.2
2002	28.4	9.1	37.5
2003	28.4	9.1	37.5
2004	25.6	9.3	34.9
2005	27.2	9.8	37.0
2006	28.1	9.8	37.9
2007	28.4	9.4	37.8
2008	23.0	8.9	31.9
2009	25.6	8.9	34.5
Mean	26.0	9.0	35.0

[a]Potential evapotranspiration during June–September periods was estimated as 70 percent of pan evaporation on the basis of the relation between pan evaporation and evapotranspiration described by Farnsworth and others (1982).

[b]Potential evapotranspiration estimates for the October–May period were estimated on the basis of sparse pan evapotranspiration records.

Table 6. Streamgages in study area.

[USGS, U.S. Geological Survey]

USGS streamgage	Station name	Drainage area (square miles)	Period of record available for water years 1980–2009
06445980	White Clay Creek near Oglala, S. Dak.	376	1988–1999
06446100	Wounded Knee Creek at Wounded Knee, S. Dak.	73.5	1993–1997
06446700	Bear-in-Lodge Creek near Wanblee, S. Dak.	423	1996–2009
06447500	Little White River near Martin, S. Dak.	313	1980–2009
06449000	Lake Creek below Refuge near Tuthill, S. Dak.	121	1980–2009
06449100	Little White River near Vetal, S. Dak.	619	1980–2009

Table 7. Estimated base-flow contribution to streamflow at streamgages in the study area.

Water year	Base-flow rate for U.S. Geological Survey streamgages (cubic feet per second)					
	06445980	06446100	06446700	06447500	0644900	06449100
1980	5.0	2.1	7.2	10.0	13.7	40.5
1981	5.3	2.3	7.7	10.7	6.5	25.8
1982	7.4	3.2	10.7	14.9	17.3	46.7
1983	8.5	3.7	12.3	17.1	9.3	44.0
1984	7.9	3.4	11.5	16.0	16.9	52.0
1985	5.4	2.3	7.8	10.9	6.1	29.2
1986	7.6	3.3	11.1	15.4	18.6	47.1
1987	8.6	3.7	12.5	17.3	21.6	48.3
1988	7.5	3.3	10.9	15.2	19.6	48.0
1989	5.3	2.3	7.8	10.8	8.6	32.4
1990	6.1	2.6	8.9	12.3	11.4	41.3
1991	7.2	3.1	10.5	14.6	22.8	59.3
1992	5.9	2.6	8.6	12.0	13.8	44.5
1993	8.5	3.7	12.4	17.2	22.2	55.8
1994	10.6	4.6	15.3	21.3	30.2	66.9
1995	12.0	5.2	17.4	24.1	26.7	69.9
1996	9.9	4.3	14.4	20.0	30.5	70.3
1997	13.4	5.8	19.4	27.0	37.2	85.2
1998	11.0	4.7	15.9	22.1	31.7	82.6
1999	12.0	5.2	17.4	24.1	29.2	81.6
2000	10.9	4.7	15.9	22.1	16.2	56.4
2001	10.5	4.6	15.3	21.2	28.2	65.3
2002	6.9	3.0	10.0	13.9	21.6	47.7
2003	6.7	2.9	9.7	13.5	18.0	46.9
2004	5.4	2.3	7.8	10.8	14.8	39.9
2005	7.6	3.3	11.1	15.4	22.2	64.4
2006	6.9	3.0	10.1	14.0	10.7	37.4
2007	5.0	2.2	7.3	10.1	11.5	40.3
2008	6.5	2.8	9.5	13.2	21.6	48.3
2009	9.3	4.0	13.5	18.7	19.9	49.2
Mean	8.0	3.5	11.7	16.2	19.3	52.2
Mean per square mile of drainage area	0.02	0.05	0.03	0.05	0.16	0.08

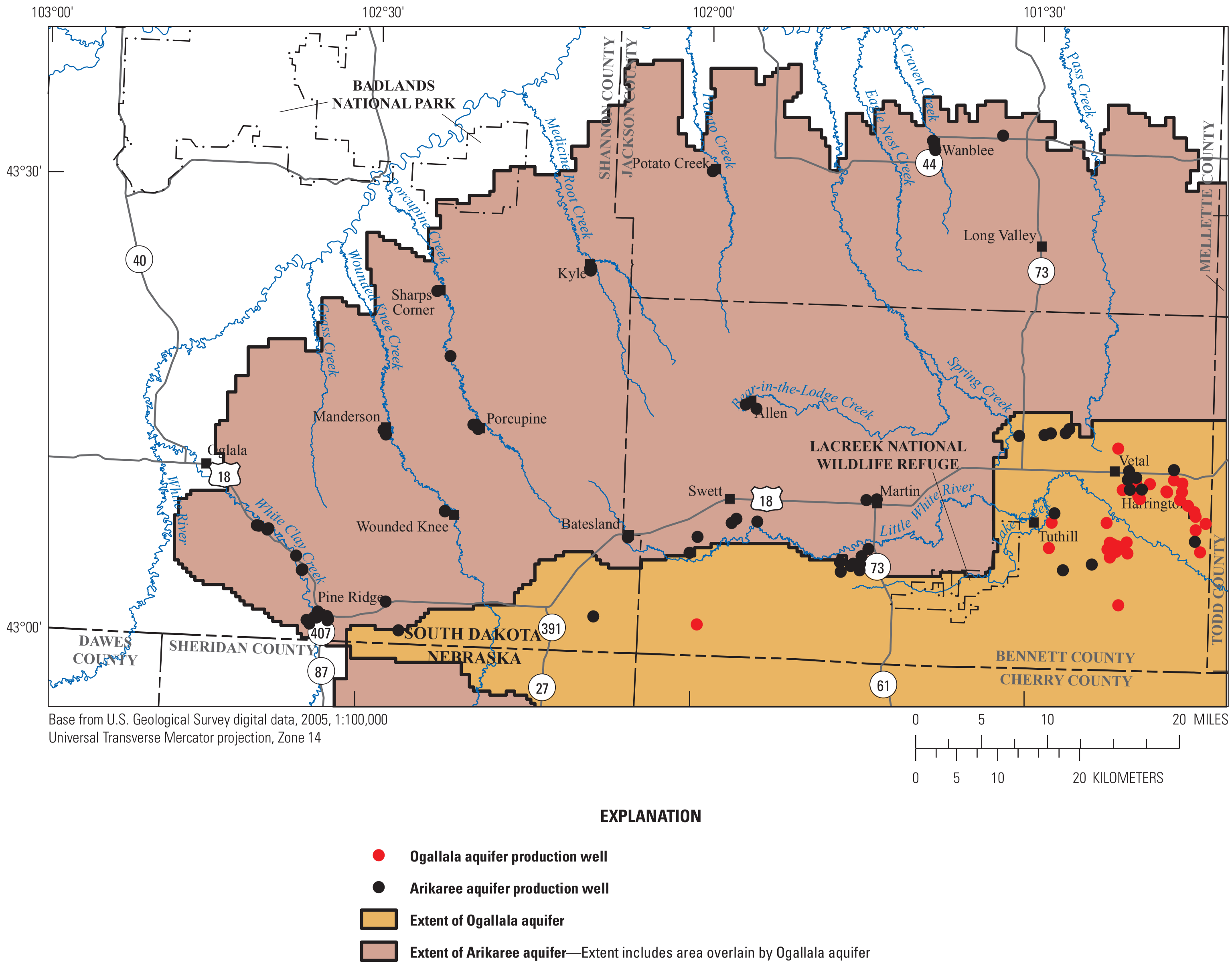


Figure 13. Location of production wells completed in the Ogallala and Arikaree aquifers in the study area.

Table 8. Estimated groundwater withdrawals for water years 1980–2009 in the study area.

Water year	Water-use rate (cubic feet per second)				
	Irrigation		Public supplies	Total water use	
	Ogallala aquifer	Arikaree aquifer	Arikaree aquifer	Ogallala aquifer	Arikaree aquifer
1980	1.2	4.6	1.7	1.2	6.3
1981	1.2	3.9	1.7	1.2	5.6
1982	1.6	2.4	1.7	1.6	4.1
1983	3.2	3.8	1.7	3.2	5.5
1984	3.2	4.1	1.8	3.2	5.9
1985	5.8	8.3	1.8	5.8	10.1
1986	2.8	3.8	1.8	2.8	5.6
1987	4.1	4.2	1.8	4.1	6.0
1988	5.4	4.9	1.8	5.4	6.7
1989	8.9	8.6	1.8	8.9	10.4
1990	5.7	5.3	1.8	5.7	7.1
1991	5.7	4.1	1.8	5.7	5.9
1992	5.8	2.8	1.8	5.8	4.6
1993	4.1	2.5	1.8	4.1	4.3
1994	6.8	3.3	1.8	6.8	5.1
1995	5.7	3.9	1.8	5.7	5.7
1996	5.6	6.5	1.8	5.6	8.3
1997	5.6	4.7	1.8	5.6	6.5
1998	5.7	3.7	1.9	5.7	5.6
1999	4.7	4.8	1.9	4.7	6.7
2000	7.0	5.0	1.9	7.0	6.9
2001	4.6	6.6	1.9	4.6	8.5
2002	6.3	7.7	1.9	6.3	9.6
2003	6.1	5.5	1.9	6.1	7.4
2004	7.5	6.8	1.9	7.5	8.7
2005	6.7	6.5	1.9	6.7	8.4
2006	8.7	8.0	1.9	8.7	9.9
2007	8.0	7.3	1.9	8.0	9.2
2008	7.3	6.8	1.9	7.3	8.7
2009	7.0	6.4	1.9	7.0	8.3
Mean	5.4	5.2	1.8	5.4	7.1

Consequently, estimated water use for public supplies from the Arikaree aquifer for WYs 1980–2009 averaged 1.8 ft^3/s (table 8).

Private domestic and stock wells that exist within the study area were not included in the analysis because the total withdrawals from domestic and stock wells were assumed to account for a small fraction of the total water budget for the study area. Mean total water use for WYs 1980–2009 was 5.4 ft^3/s from the Ogallala aquifer and 7.1 ft^3/s from the Arikaree aquifer (table 8).

Hydraulic Properties

Previously published hydraulic properties (table 10) determined based on aquifer tests, specific capacity tests, and numerical modeling near the study area indicate heterogeneity in aquifer properties. Transmissivity in the Ogallala aquifer ranged from 2 to about 7,000 feet squared per day (ft^2/d) and from 2 to 2,000 ft^2/d for the Arikaree aquifer. Horizontal hydraulic conductivity ranged from less than 1 to 180 feet per day (ft/d) for the Ogallala aquifer and from less than 1 to 13 ft/d for the Arikaree aquifer. Vertical hydraulic conductivity ranged from 4.18×10^{-4} to 18 ft/d for the Ogallala aquifer and

Table 9. Total population for Bennett, Jackson, and Shannon Counties and estimated public-supply domestic water deliveries for South Dakota per capita per day, 1995, 2000, and 2005.

Year	Total population by county			Estimated public-supply domestic water deliveries for South Dakota per capita (gallons per day)
	Bennett	Jackson	Shannon	
1995[a]	3,310	2,870	11,680	89
2000[b]	3,570	2,930	12,470	90
2005[c]	3,590	2,860	13,660	99

[a]Amundson (1998).

[b]Amundson (2002).

[c]Carter and Neitzert (2008).

from $8.77x10^{-5}$ to 3.66 ft/d for the Arikaree aquifer (Long and Putnam, 2010; Davis and Putnam, 2013). Specific yield ranged from 0.02 (dimensionless) to about 0.06 for the Ogallala aquifer and was 0.03 for the Arikaree aquifer. Gutentag and others (1984) estimated a specific yield of less than 0.1 for the High Plains aquifer based on lithologic descriptions from drillers logs. Storage coefficients for the Ogallala aquifer ranged from 0.003 to 0.06 and from 0.0003 to 0.007 for the Arikaree aquifer.

Numerical Model

The numerical model of the Ogallala and Arikaree aquifers described in this report includes analysis of WYs 1980–2009 with 31 simulation stress periods, and was developed from the data included in the conceptual model. The numerical model was used to simulate steady-state and transient historical conditions and potential future scenarios. Stress period 1 was a steady-state simulation with the mean of aquifer stresses applied for WYs 1980–2009. The hydraulic heads calculated from this simulation were used as starting heads in the transient simulation for stress periods 2–31, with each stress period representing a water year. The groundwater modeling program, MODFLOW–NWT (Niswonger and others, 2011) was used for the numerical simulation of groundwater flow. Zonebudget (Harbaugh, 1990), a program that calculates subregional water budgets from MODFLOW–NWT results, was used to compute selected water budgets for individual model layers.

Simulation Methods

MODFLOW–NWT is a Newton formulation variant of MODFLOW–2005 (Harbaugh, 2005), which is a numerical, three-dimensional, finite-difference groundwater modeling program. The Newton formulation described in this report extends the applicability of MODFLOW–2005, especially to those problems representing unconfined aquifers and surface-water/groundwater interaction (Niswonger and others, 2011). The model includes two layers: the upper layer represented the Ogallala aquifer and the overlying unconsolidated deposits, and the lower layer represented the Arikaree aquifer and grouped sediments.

Assumptions

Using MODFLOW–NWT to simulate groundwater-flow systems through finite-difference solution techniques implies many assumptions (Harbaugh, 2005); the primary assumptions are listed:

1. Flow in the Ogallala and Arikaree aquifers in the study area is assumed to be predominantly horizontal where the aquifers are unconfined within the study area; therefore, each aquifer is represented appropriately with a single model layer.
2. The spatial variability in aquifer properties is adequately represented at the scale of a uniform grid with cells that are 1,640 by 1,640 ft in size, and aquifer properties are uniform within the area of each cell. Sediments of the Ogallala and Arikaree aquifers are fluvial in origin and have a greater degree of vertical and horizontal heterogeneity than is represented by the scale of the model. It is recognized that actual hydraulic properties at individual sites could differ widely from those represented in the model. Nevertheless, a 1,640-ft grid spacing was assumed to be an appropriate discretization of the model to represent the heterogeneity of the Ogallala and Arikaree aquifer properties for the scale of the groundwater-flow model, given the intended purpose and study objectives. Additionally, a 1,640-ft spacing was similar to that used by Long and Putnam (2010) to simulate groundwater flow in the High Plains aquifer in Mellette and Todd Counties directly to the east of the study area.
3. Sources and sinks of water that have an important effect on the groundwater-flow system, such as streams, well withdrawals, and recharge, can be adequately simulated using a grid spacing of 1,640 by 1,640 ft. Streams in the study area actually are much less than 1,640 ft wide, but as stated in assumption 2, the 1,640-ft spacing is sufficient discretization for the scale of the groundwater-flow model and the study objectives.
4. Starting conditions for the 30-year transient simulation can be appropriately estimated with a steady-state stress period, during which the mean of aquifer stresses for WYs 1980–2009 was applied.
5. Sources and sinks of water that have an important effect on the groundwater-flow system were appropriately represented by stress periods of one WY in length. It is recognized that aquifer stresses exist at a higher degree of

Table 10. Previously published horizontal hydraulic properties for the Ogallala and Arikaree aquifers in or near the study area.

[ft^2/d, feet squared per day; ft/d, feet per day; --, no data]

Method	Transmissivity (ft^2/d)	Horizontal hydraulic conductivity (ft^2/d)	Storage coefficient (dimensionless)	Specific yield (dimensionless)	Location	Source
			Ogallala aquifer			
Time drawdown aquifer test	7,005	[a]70	0.003	0.057	Todd County	Rahn and Paul, 1975
Distance drawdown aquifer test	3,234	132	0.06	--	Todd County	Rahn and Paul, 1975
Aquifer test	2,995	21.6	--	0.02	Todd County	Kremlin-Smith, 1984
Aquifer test	1,644	7.9	--	0.03	Todd County	Kremlin-Smith, 1984
Aquifer test	3,088	17.5	--	0.02	Todd County	Kremlin-Smith, 1984
Specific capacity	180–3,476	1.2–25.2	--	--	Todd County	Kremlin-Smith, 1984
Specific capacity	2–2,400 average 600	--	--	--	Todd County	Carter, 1998
Numerical model	--	0.2–120	--	--	Mellette and Todd Counties	Long and others, 2003
Numerical model	--	0.2–84	--	--	Mellette and Todd Counties	Long and Putnam, 2010
Numerical model	--	1.0–180	--	--	Gregory and Tripp Counties	Davis and Putnam, 2013
			Arikaree aquifer			
Specific capacity	2–2,000 average 90	--	--	--	Todd County	Carter, 1998
Aquifer test	1,250	13	0.007	0.03	Shannon County 35N44W17	Greene and others, 1991
Aquifer test	300	1	0.0003	--	Shannon County 35N44W17	Greene and others, 1991
Aquifer test	310	1.0	0.0004	--	Shannon County 35N44W	Sipe, 1989
Time drawdown (single well)	298	1.0	0.0004	--	Shannon County 35N44W	Sipe, 1989
Time recovery (single well)	326	1.0	--	--	Shannon County 35N44W	Sipe, 1989
Numerical model	--	0.1–5.4	--	--	Mellette and Todd Counties	Long and others, 2003
Numerical model	--	0.1–4.3	--	--	Mellette and Todd Counties	Long and Putnam, 2010

[a]Calculated from transmissivity based on saturated thickness of 100 feet.

variability than is represented by the temporal discretization of the model. Temporally varied stresses, such as well withdrawals, are smoothed and averaged compared with what may exist in reality. Nevertheless, as with assumptions 2 and 3, the degree of discretization used is appropriate for the scale of this groundwater-flow model and the study objectives.

Model Design

The MODFLOW–NWT (Niswonger and others, 2011) was used to simulate groundwater flow for the Ogallala and Arikaree aquifers in the study area. MODFLOW–NWT is a numerical, three-dimensional, finite-difference groundwater modeling program that uses many of the packages distributed with MODFLOW–2005. Additional packages used by MODFLOW–NWT are either modified MODFLOW–2005 packages or new packages. The MODFLOW–NWT and

MODFLOW–2005 packages that were incorporated into the model were documented in Niswonger and others (2011) and Harbaugh (2005), and included the Well, Drain, Evapotranspiration, River, Recharge, and Upstream Weighting (UPW) packages.

The MODFLOW–2005 solver packages can have convergence problems if parts of the model domain become dewatered during a simulation. The UPW package is a new package that can be used in conjunction with the NWT solver in MODFLOW–NWT to provide a robust representation of dry cells in the model. The UPW package is useful for simulating flow in unconfined aquifer systems because it does not deactivate and subsequently reactivate dry cells during a simulation like other MODFLOW–2005 solver packages would. Instead, the UPW package reduces the conductance between a dry cell and an adjoining wetted cell to zero. This reduction of conductance to zero keeps a dry cell active while not allowing water to flow out of a dry cell (Niswonger and others, 2011).

The Well package is the only MODFLOW–2005 package that was modified for MODFLOW–NWT for this study. The modified Well package has the ability to reduce the pumping rate of a well located in a cell that is dewatered during a simulation. This prevents water from being removed from a dewatered cell.

Finite-Difference Grid and Boundary Conditions

The model grid consisted of two layers made up of 166 rows oriented east to west and 288 columns oriented north to south. The boundaries of the model were represented by constant-head or no-flow cells (fig. 14). The southern and eastern boundaries of model layer 1, where the Ogallala aquifer existed beyond the study area boundary, were simulated by constant-head cells. The constant-head cells were used to represent groundwater flow into and out of the model domain. The hydraulic heads for the constant-head cells were assigned based on the generalized potentiometric surface of the Ogallala aquifer (fig. 8). For layer 1, the northern and western model boundaries were represented by no-flow cells where the Ogallala aquifer pinches out. The boundary was simplified to eliminate isolated and intermittently saturated areas of the aquifer. In general, areas with less than 10 ft of saturated thickness were removed from the model.

The southern and eastern boundaries of model layer 2, where the Arikaree aquifer existed beyond the study area boundary, were simulated by constant-head cells. The constant-head cells were used to represent groundwater flow into and out of the model domain. The hydraulic heads for the constant-head cells were assigned based on the generalized potentiometric surface of the Arikaree aquifer (fig. 9) and were used to represent groundwater flow into and out of the model domain. For model layer 2, the northern and western model boundaries were represented by no-flow cells where the Arikaree aquifer pinches out. The northern and western boundaries were simplified to eliminate thin or intermittently saturated areas of the aquifer. In general, areas with less than 10 ft of saturated thickness were removed from the model.

Hydrogeologic Representation

The thickness of model cells for layers 1 and 2 was determined based on the aquifer tops and bottoms described in the "Hydrogeologic Framework" section of this report. Cells representing the Ogallala and Arikaree aquifers were simulated as potentially being able to convert between confined and unconfined conditions. Although the Ogallala and Arikaree aquifers generally are unconfined within the study area, confined conditions exist within the Arikaree aquifer where overlain by the Ogallala aquifer in the southwestern part of the model area (fig. 14).

Hydraulic Properties

Previously published values (table 10) were used as general indicators for hydraulic conductivity, but parameter estimation of hydraulic conductivity using the Parameter ESTimation (PEST) computer code (Doherty, 2010) was used to adjust the final values and distributions in the study area. Values for horizontal hydraulic conductivity were estimated using pilot-point parameterization, which is described further in the "Model Calibration" section of this report. In contrast to subdividing the model into a subset of zones representing uniform hydraulic conductivity, pilot-point parameterization allowed a smooth variation of hydraulic conductivity over the model domain.

Hydraulic conductivity for model layers 1 and 2 was simulated using pilot points (Doherty and others, 2010), which served as the "parameters" seen by the parameter estimation process. During each forward model run, the values of the pilot-point parameters are spatially interpolated to two-dimensional arrays that are subsequently used by the model as inputs (Doherty, 2010; Doherty and others, 2010). Kriging is the method typically used to interpolate values of hydraulic conductivity estimated at the pilot points to the model grid cells. Kriging assumes that the parameters vary in a continuous manner from one pilot-point location to the next; thus, points that are near each other have a certain degree of spatial correlation, as would be expected given the proximity, but values kriged at points that are widely separated are more independent. Kriging requires specification of the correlation function, typically represented by a semivariogram, which defines the expected correlation between any two points, given the separation distance. For this study, an exponential variogram was defined for each model layer to facilitate interpolating pilot-point values to the model input arrays.

Pilot points for model layer 1 were distributed diagonally at cell centers every 10 cells, except east of the town of Pine Ridge where an additional point was added. Pilot points for model layer 2 were evenly distributed at cell centers every 20 cells throughout the model domain (fig. 15). Additional pilot points were added along the northern and eastern edges

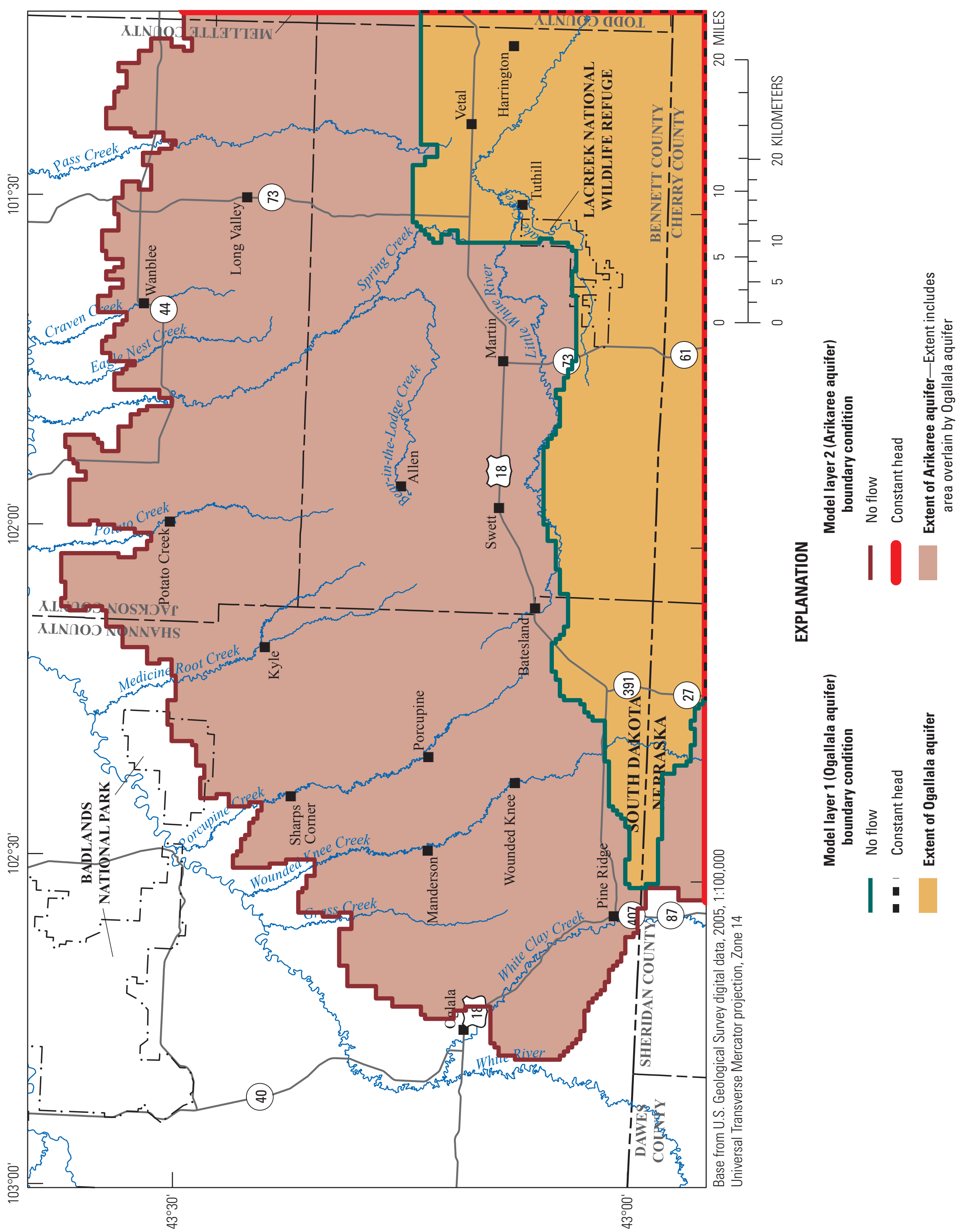


Figure 14. Boundary conditions for model layers 1 and 2 in the study area.

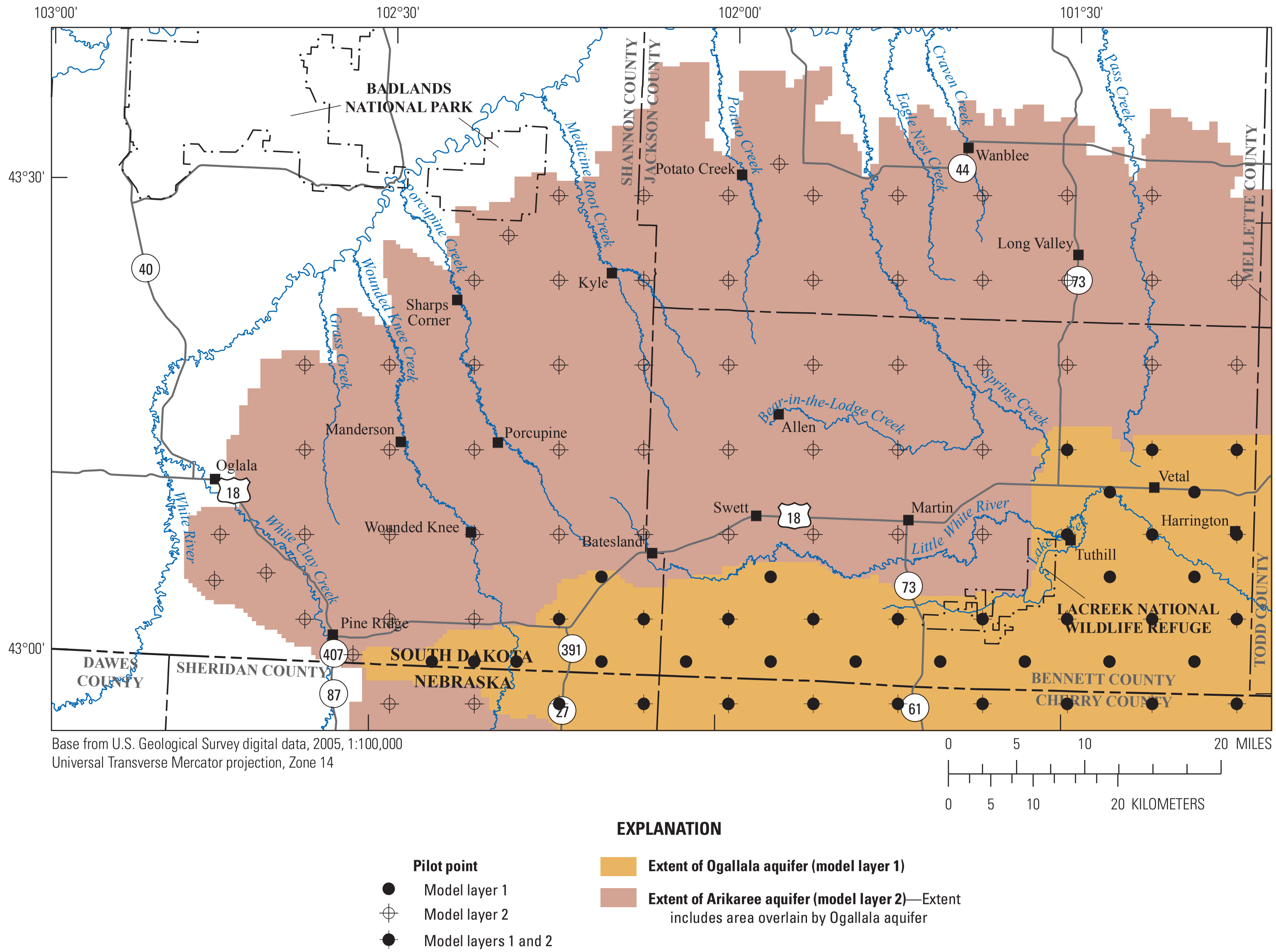


Figure 15. Location of pilot points used for interpolation of horizontal hydraulic conductivity to the model domain in the study area.

of model layer 2. The additional pilot points were used to improve the model to measurement fit in those areas. Kriging factors used in parameter estimation were created based on user-supplied variograms generated with the PEST groundwater utility programs PPK2FAC and FAC2REAL (Doherty, 2008). Each of the 40 pilot points in model layer 1 and the 82 pilot points in model layer 2 were represented as a parameter in the parameter estimation process.

Vertical hydraulic conductivity for model layers 1 and 2 was represented with parameters VKA1_1 and VKA2_1, respectively. Vertical hydraulic conductivity parameters represent the ratio of the vertical to horizontal hydraulic conductivity in each layer. Specific yield for the Ogallala aquifer was represented with parameter SY1_1. Specific yield for the Arikaree aquifer was represented by two zone parameters SY2_1 and SY2_2 (fig. 16). Parameter SY2_1 was used to represent the western and northern parts of the aquifer where the aquifer generally was unconfined. Parameter SY2_2 was used to represent the southeastern part of the Arikaree aquifer where withdrawals for irrigation were greatest. Specific storage for the Arikaree aquifer was represented with parameter SS2_2. Vertical hydraulic conductivity and storage parameters were optimized in model calibration.

Recharge

The MODFLOW Recharge package (Harbaugh, 2005) was used to simulate recharge to the Ogallala and Arikaree aquifers. Recharge rates, estimated based on the percentage of precipitation as described in the “Conceptual Model” section of this report, were represented in the model by three parameters that were optimized during model calibration. These parameters, RCH1_1 for recharge zone 1, RCH2_1 for recharge zone 2, and RCH2_2 for zone 3 (fig. 12), were multipliers applied to the estimated recharge rates for each zone listed in table 4. MODFLOW–NWT applied recharge to the uppermost active model cell during the simulation process. Recharge was applied to the cell even if it went dry during the iterative numerical solution of the groundwater-flow equations.

Discharge

Evapotranspiration, well withdrawals, and discharge to streams were simulated using various MODFLOW–2005 packages. Simulation of these discharge components are described in the following sections.

Evapotranspiration

The MODFLOW–2005 Evapotranspiration package (Harbaugh, 2005) was used to simulate evapotranspiration from the Ogallala aquifer and the unconfined part of the Arikaree aquifer. When the simulated water level was at land surface, the evapotranspiration rate was equal to the maximum potential evapotranspiration rate (table 5). An evapotranspiration multiplier parameter, EVT1_1, was adjusted during the model calibration process to refine application of the estimated maximum potential evapotranspiration rates in the model.

The evapotranspiration rate decreased linearly in relation to depth of the simulated hydraulic head below the mean land-surface altitude for the model cell to an extinction depth. The extinction depth was set to 10 to 20 ft in lowlying areas near streams and to 7 ft elsewhere. This extinction depth was assumed to be the mean depth of the root zone (Long and Putnam, 2010). The land-surface altitude was determined by taking the mean altitude from the NED (U.S. Geological Survey, 2006) within each model cell. For cells that included deeply incised stream channels, the mean altitude was compared to the minimum NED altitude within the cell, and the land-surface altitude was set as 2 ft above the minimum altitude. This adjustment was made to better approximate the evapotranspiration from riparian areas along deeply incised stream channels.

Discharge to Streams

Discharge to streams was simulated using the MODFLOW–2005 River and Drain packages (Harbaugh, 2005). Perennial streams were represented with the River package, and intermittent streams were represented with the Drain package. The River package simulates the connection between surface water and groundwater. The hydraulic conductance between the streambed and aquifer (streambed conductance) is defined as hydraulic conductivity of the riverbed material times the cross-sectional area of the stream reach divided by the streambed thickness (McDonald and Harbaugh, 1988). River cells can remove water from or add water to the aquifer depending on the direction of the gradient between river stage and aquifer hydraulic head. The Drain package is similar to the River package; however, only discharge from the aquifer to the drain is simulated. Drain cells can only remove water from the aquifer when water levels are at or above the elevation of the drain bottom.

Model cells that represented streams were grouped in 17 reaches (fig. 17). Of the 17 stream reaches, 11 perennial streams were simulated using the River package and 6 ephemeral streams were simulated using the Drain package (fig. 17, table 11). Streambed conductance for the 11 perennial streams was represented as a parameter that was optimized during model calibration. Streambed conductance for the six ephemeral streams was determined by trial and error to produce the best initial model to measurement fit. Most groundwater discharge to the six ephemeral streams was taken up by evapotranspiration; unfortunately, no streamgaging records were available for comparison during the calibration period. A streambed conductance of 10 ft^2/s was used to simulate sporadic groundwater discharge to the six ephemeral streams represented by drain cells. The streambed conductance was set relatively low to produce a reasonable mean groundwater discharge by WY; however, the actual streambed conductance probably is greater than 10 ft^2/s. The stream reaches represented in the model as drains were identified based on the

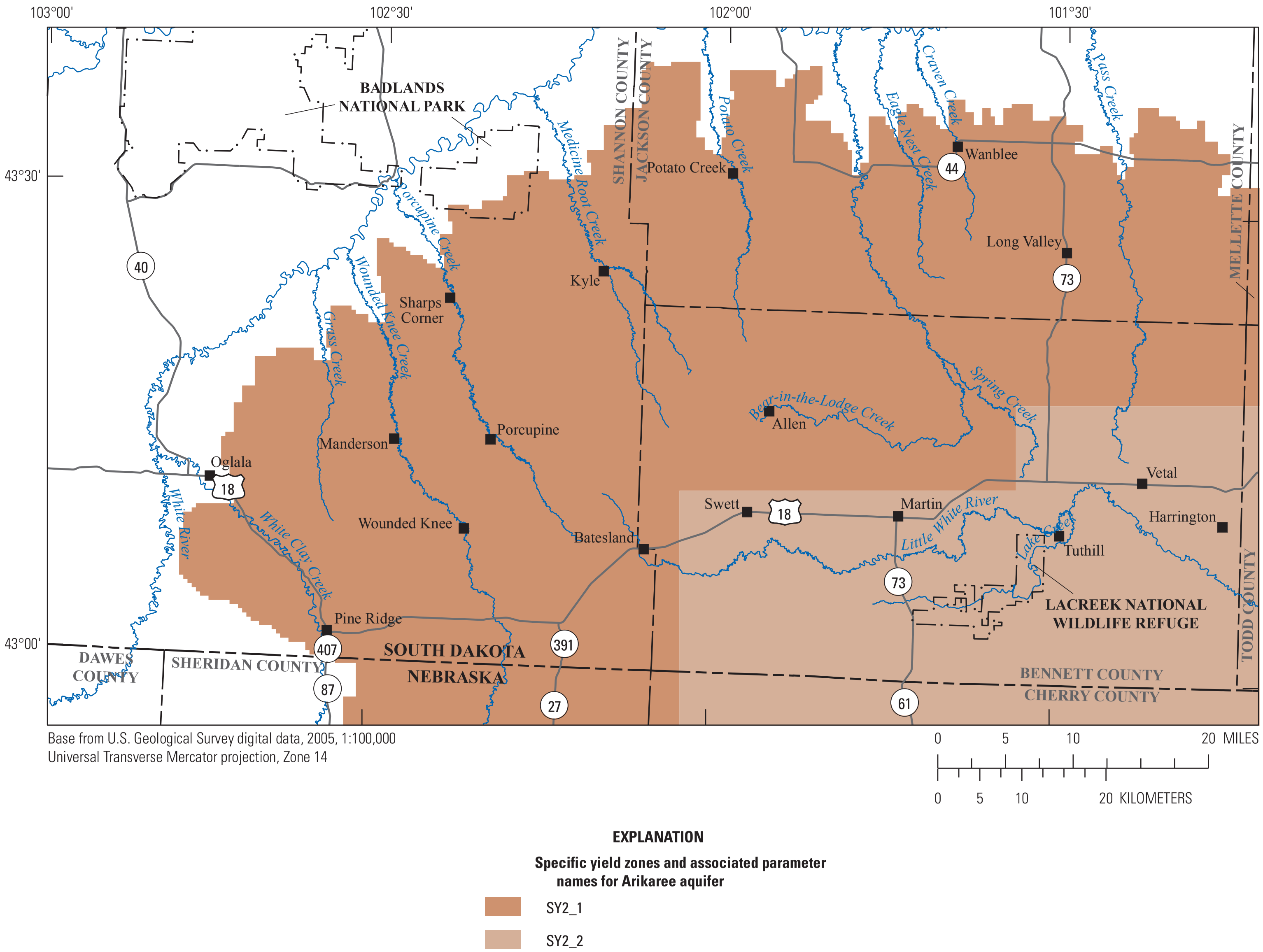


Figure 16. Specific yield zones and associated model parameters for model layer 2 representing the Arikaree aquifer in the study area.

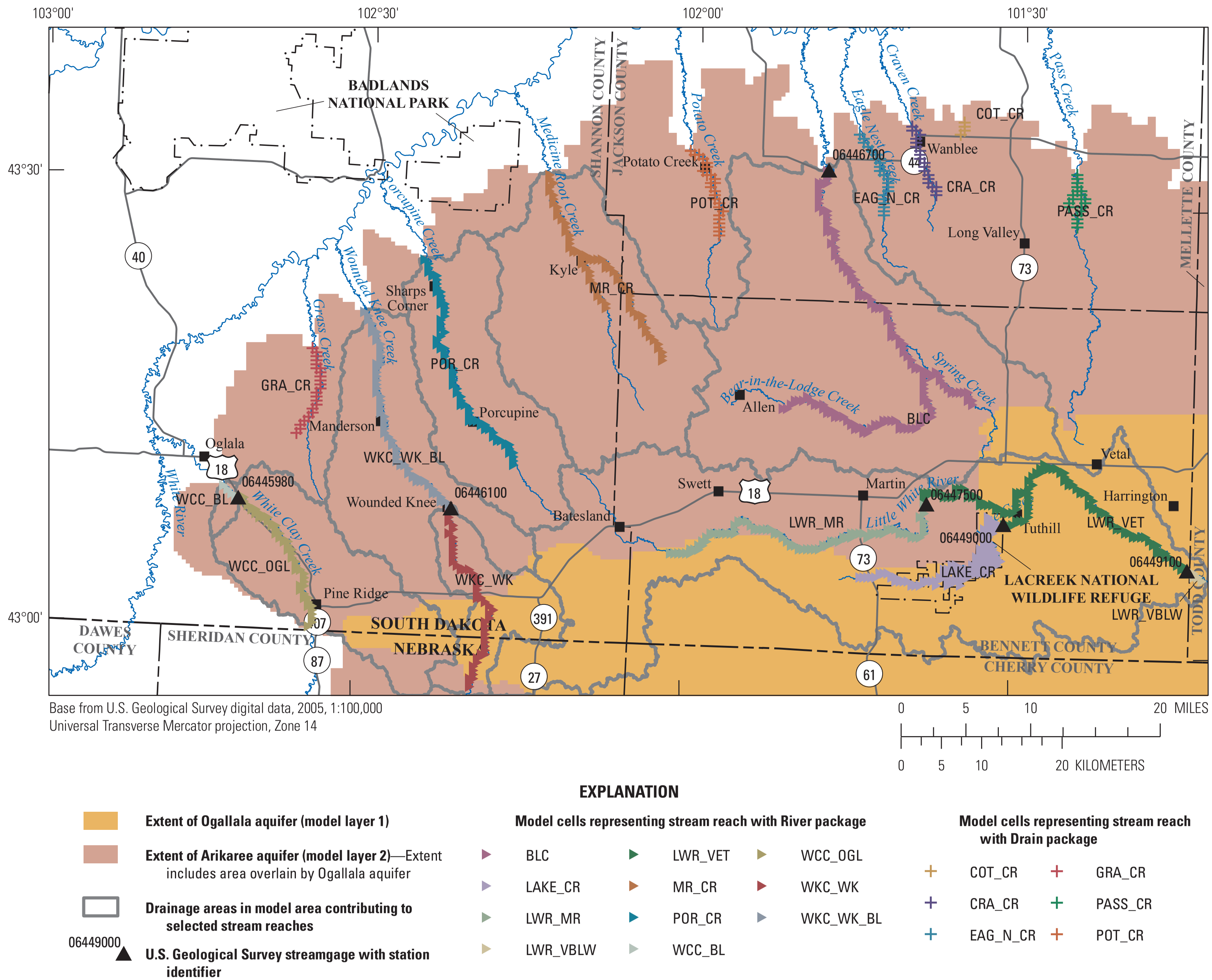


Figure 17. Stream reaches represented with MODFLOW–2005 River and Drain packages, streambed conductance parameters, selected contributing drainage areas, and streamgages for modeled streams in the study area.

Table 11. Stream reach identifier, conductance parameter, and observation weights for modeled streams in the study area.

[--, not applicable]

Stream reach identifier and conductance parameter (fig. 17)	Description of stream reach	Observation weight for parameter estimation
	Stream reach represented with MODFLOW–NWT River package	
BLC	Bear-in-the-Lodge Creek and Spring Creek tributary. Streamgage 06446700 is located at model boundary	10
LAKE_CR	Lake Creek upstream from streamgage 06447500	10
LWR_MR	Little White River upstream from streamgage 06447500	10
LWR_VBLW	Little White River downstream from streamgage 06449100 to model boundary	--
LWR_VET	Little White River between streamgage 06447500 and streamgage 06449100, which includes the part of Lake Creek from streamgage 06449000 to mouth at Little White River	10
MR_CR	Medicine Root Creek	4
POR_CR	Porcupine Creek	4
WCC_BL	White Clay Creek downstream from streamgage 06445980	--
WCC_OGL	White Clay Creek upstream from streamgage 06445980	10
WKC_WK	Wounded Knee Creek upstream from streamgage 06446100 to model boundary	10
WKC_WK_BL	Wounded Knee Creek downstream from streamgage 06446100 to model boundary	4
	Stream reach represented with MODFLOW–NWT Drain package	
COT_CR	Cotton Creek	--
CRA_CR	Craven Creek	--
EAG_N_CR	Eagle Nest Creek	--
GRA_CR	Grass Creek	--
PASS_CR	Pass Creek	--
POT_CR	Potato Creek	--

generalized potentiometric surface for the Arikaree aquifer (fig. 9), by selecting reaches where the groundwater gradient was towards the stream.

Water Use

Well withdrawals were represented using the MODFLOW–NWT Well package (Niswonger and others, 2011). Well withdrawals were assigned to the model cells at locations shown in figure 13.

Model Calibration

Model calibration was completed by linking parameter estimation software PEST (Doherty, 2010) with MODFLOW–NWT (Niswonger and others, 2011). The PEST software uses statistical parameter estimation techniques to optimize model parameters, such as aquifer storage properties, spring and river conductance, and hydraulic conductivity. The PEST software is a model-independent calibration tool that applies nonlinear parameter estimation techniques. The PEST software systematically adjusts model parameters based on comparisons between model simulated values and observed values of hydraulic head and base flow. The PEST software attempts to minimize the sum of square weighted differences (residuals) between model simulated and observed values (Doherty, 2010); this sum is referred to as the objective function.

The PEST software uses regularized inversion (Doherty, 2003, 2010) and can use pilot points for estimation of spatial hydraulic properties. This approach allowed for a relatively large number of parameters to be optimized and estimated simultaneously. Classical methods for estimating hydraulic conductivity values and distributions within a model include subdividing a model area into zones of piecewise consistency where the hydraulic properties are assumed to be spatially uniform. However, recent studies have shown that interpolating values for a model area based on a set of estimable points (pilot points) distributed throughout the model area can achieve a minimum error variance solution to the inverse problem and allow maximum extraction of information contained in the observation dataset (Doherty, 2003; Moore and Doherty, 2005).

Parameter estimation by use of PEST involves repeatedly comparing model-computed input variables to observed measurements, such as hydraulic head, until the best modeled fit to the observed data is mathematically determined. Guidelines by Doherty and Hunt (2010) for using PEST to calibrate groundwater models were used for the parameter estimation approach in this study. Hydraulic properties estimated by PEST included hydraulic conductivity, vertical hydraulic conductivity anisotropy, aquifer storage, and riverbed conductance. Groundwater recharge and evapotranspiration also were estimated by PEST.

During the calibration process, hydraulic conductivity was estimated at 122 pilot-point locations distributed throughout the model domain. Pilot points were used as the method of spatial parameterization for the model inputs of hydraulic conductivity and represent the heterogeneity of the aquifer at a scale that was manageable for calibration. Hydraulic conductivity was optimized using PEST and assigned to 122 pilot points (40 in model layer 1 and 82 in model layer 2) distributed throughout the model domain rather than directly to the grid elements of the model (Doherty, 2003, 2010). The result of this method is a smooth variation of calibrated hydraulic conductivity over the model domain. Other parameters optimized during the calibration process included vertical hydraulic conductivity anisotropy (VKA1_1 and VKA2_1), aquifer storage (SS2_2, SY1_1, SY2_1, and SY2_2), recharge and evapotranspiration multipliers (RCH1_1, RCH2_1, RCH2_2, and EVT1_1), and riverbed conductance (BLC, LAKE_CR, LWR_MR, LWR_VBLW, LWR_VET, MR_CR, POR_CR, WCC_BL, WCC_OGL, WKC_WK, and WKC_WK_BL). The location and distribution of model input parameters are described in the “Hydrogeologic Representation” section of this report.

Automated parameter estimation approaches, such as PEST, relate observed measurements, such as hydraulic head and stream base flow, to model input parameters that represent physical properties of the simulated groundwater system. The best modeled fit to the observed data is then iteratively evaluated by varying the input parameters and assessing the resulting model to measurement fit. Guidelines by Doherty and Hunt (2010) for using PEST for groundwater-model calibration were used for the parameter estimation approach in this study.

Calibration Targets

In this report, model calibration targets refer to observed or estimated values of hydraulic head and base flow that correspond to specific model output, which are used to assess the ability of the model to accurately simulate the groundwater system. A residual is the difference between the model simulated value and a calibration target (simulated minus observed). Calibration targets included 50 long-term observation wells that had time-series measurements of hydraulic head, 633 wells that had single hydraulic-head measurements (U.S. Geological Survey, 2010), and 9 stream reaches with estimated groundwater discharge (base flow) by water year. Relative weights were assigned to the observations to approximately equalize the contribution of different types of observations during the calibration process and to reflect the confidence in the observed values. Observations with a higher confidence were reflected in the calibration process with a higher weight.

Hydraulic heads for 12 long-term observation wells in the Ogallala aquifer were assigned a weight of 0.5 for 2 representative hydraulic heads per water year (60 total hydraulic head measurements per well); thus, the combined weight for each of these wells (number of measurements per well times the measurement weight for the 1980-2009 calibration period) would be about 30. Single hydraulic-head measurements for four wells completed in the Ogallala aquifer, which were site visited, were assigned a weight of 1.0. Single hydraulic-head measurements for 44 wells completed in the Ogallala aquifer, which were not site visited, were assigned a weight of 0.5.

Hydraulic heads for 38 long-term observation wells in the Arikaree aquifer with multiple measurements were assigned a weight of 0.5 for 2 representative hydraulic heads per water year. Single hydraulic-head measurements for 335 wells completed in the Arikaree aquifer, which were site visited, were assigned a weight of 1.0. Single hydraulic-head measurements for 248 wells completed in the Arikaree aquifer, which were not site visited, were assigned a weight of 0.5.

Groundwater discharge (base-flow) calibration targets (table 12) were estimated for nine of the stream reaches based on calculated base flow at gaged streams (table 7). A weight of 10 was assigned to discharge calibration targets that were determined directly from base-flow calculations, and a weight of 4 was assigned to calibration targets for the three stream reaches estimated from correlations with discharge determined for a nearby gaged stream (table 11), as described in the following paragraphs.

Bear-in-the-Lodge Creek and Spring Creek were represented with a single stream reach and riverbed conductance parameter (BLC; fig. 17, table 11). Streamgage 06446700 on Bear-in-the-Lodge Creek (fig. 17) is located at the northern edge of the model boundary for model layer 2, downstream from the confluence with Spring Creek, and has a contributing drainage area entirely within the study area; therefore, calibration targets for groundwater discharge by WY were the calculated base flow for streamgage 06446700 (table 7), with a mean discharge for WYs 1980–2009 of 11.7 ft^3/s (table 12).

White Clay Creek was represented with stream reaches and riverbed conductance parameters WCC_OGL and WCC_BL (fig. 17, table 11). Parameter WCC_OGL represented the White Clay Creek stream reach in the model area upstream from streamgage 06445980 (fig. 17). The drainage area upstream from the streamgage was 146 mi^2, or 39 percent of the total upstream contributing drainage area of 376 mi^2 (table 6). Calibration targets for this stream reach were assigned (table 12) as 39 percent of the base flow calculated for the streamgage (table 7) with a mean discharge for WYs 1980–2009 of 3.1 ft^3/s (table 12). Parameter WCC_BL represented the small stream reach downstream from the streamgage. This stream reach was assumed to have the same streambed conductance as the upstream stream reach represented by parameter WCC_OGL. Parameter WCC_BL was tied to WCC_OGL in model calibration.

Table 12. Calibration targets for groundwater discharge (base flow) for selected stream reaches.

Water year	Stream reach identifier (table 11; fig. 17) and estimated discharge to stream reach (cubic feet per second)								
	BLC	WCC_OGL[a]	WKC_WK	WKC_WK_BL	POR_CR	MR_CR	LWR_MR	LAKE_CR	LWR_VET
1980	7.2	2.0	2.1	4.2	2.7	4.2	10.0	13.7	16.8
1981	7.7	2.1	2.3	4.5	2.9	4.5	10.7	6.5	8.6
1982	10.7	2.9	3.2	6.2	4.1	6.3	14.9	17.3	14.5
1983	12.3	3.3	3.7	7.2	4.7	7.3	17.1	9.3	17.6
1984	11.5	3.1	3.4	6.7	4.4	6.8	16.0	16.9	19.1
1985	7.8	2.1	2.3	4.5	3.0	4.6	10.9	6.1	12.2
1986	11.1	3.0	3.3	6.4	4.2	6.5	15.4	18.6	13.1
1987	12.5	3.4	3.7	7.2	4.8	7.4	17.3	21.6	9.4
1988	10.9	2.9	3.3	6.3	4.1	6.4	15.2	19.6	13.2
1989	7.8	2.1	2.3	4.5	3.0	4.6	10.8	8.6	13.0
1990	8.9	2.4	2.6	5.2	3.4	5.3	12.3	11.4	17.6
1991	10.5	2.8	3.1	6.1	4.0	6.2	14.6	22.8	21.9
1992	8.6	2.3	2.6	5.0	3.3	5.1	12.0	13.8	18.7
1993	12.4	3.3	3.7	7.2	4.7	7.3	17.2	22.2	16.4
1994	15.3	4.1	4.6	8.9	5.8	9.0	21.3	30.2	15.4
1995	17.4	4.7	5.2	10.1	6.6	10.3	24.1	26.7	19.1
1996	14.4	3.9	4.3	8.4	5.5	8.5	20.0	30.5	19.8
1997	19.4	5.2	5.8	11.3	7.4	11.4	27.0	37.2	21.0
1998	15.9	4.3	4.7	9.2	6.0	9.4	22.1	31.7	28.8
1999	17.4	4.7	5.2	10.1	6.6	10.3	24.1	29.2	28.3
2000	15.9	4.3	4.7	9.2	6.0	9.4	22.1	16.2	18.1
2001	15.3	4.1	4.6	8.9	5.8	9.0	21.2	28.2	15.9
2002	10.0	2.7	3.0	5.8	3.8	5.9	13.9	21.6	12.2
2003	9.7	2.6	2.9	5.6	3.7	5.7	13.5	18.0	15.4
2004	7.8	2.1	2.3	4.5	3.0	4.6	10.8	14.8	14.3
2005	11.1	3.0	3.3	6.4	4.2	6.5	15.4	22.2	26.8
2006	10.1	2.7	3.0	5.8	3.8	6.0	14.0	10.7	12.7
2007	7.3	2.0	2.2	4.2	2.8	4.3	10.1	11.5	18.7
2008	9.5	2.5	2.8	5.5	3.6	5.6	13.2	21.6	13.5
2009	13.5	3.6	4.0	7.8	5.1	8.0	18.7	19.9	10.6
Mean	11.7	3.1	3.5	6.8	4.4	6.9	16.2	19.3	16.8

[a]Value calculated as 39 percent of base flow at streamgage on the basis of percentage of drainage area that was in study area.

Wounded Knee Creek was represented with stream reaches and riverbed conductance parameters WKC_WK and WKC_WK_BL (fig. 17, table 11). Parameter WKC_WK represented the Wounded Knee Creek stream reach upstream from streamgage 06446100 (fig. 17). The drainage area upstream from the streamgage was about 72 mi^2, and the total upstream contributing drainage area was 73.5 mi^2 (table 6); therefore, the calibration targets (table 12) for this stream reach were assigned as the base flow calculated for the streamgage (table 7), with a mean discharge for WYs 1980–2009 of 3.5 ft^3/s (table 12). Parameter WKC_WK_BL represented the stream reach downstream from streamgage 06446100. The calibration targets for this stream reach were assigned by correlation with stream reach BLC based on contributing drainage area. The contributing drainage area for stream reach WKC_WK_BL was 244 mi^2 compared to 423 mi^2 for stream reach BLC (table 6); therefore, the calibration targets for stream reach WKC_WK_BL were assigned as 58 percent of calibration target for stream reach BLC with a mean discharge for WYs 1980–2009 of 6.8 ft^3/s (table 12).

Porcupine Creek was represented with stream reach identifier and riverbed conductance parameter POR_CR (fig. 17, table 11). The calibration targets for this stream reach were assigned by correlation with stream reach BLC based on contributing drainage area. The contributing drainage area for stream reach POR_CR was 159 mi^2 compared to 423 mi^2 for stream reach BLC (table 6); therefore, the calibration targets for stream reach POR_CR were assigned as 38 percent of calibration target for stream reach BLC with a mean discharge for WYs 1980–2009 of 4.4 ft^3/s (table 12).

Medicine Root Creek was represented with stream reach and riverbed conductance parameter MR_CR (fig. 17, table 11). The calibration targets for this stream reach were assigned by correlation with stream reach BLC based on contributing drainage area. The contributing drainage area for stream reach MR_CR was 250 mi^2 compared to 423 mi^2 for stream reach BLC (table 6); therefore, the calibration targets for stream reach MR_CR were assigned as 59 percent of calibration target for stream reach BLC with a mean discharge for WYs 1980–2009 of 6.9 ft^3/s (table 12).

Little White River and Lake Creek were represented with stream reaches and riverbed conductance parameters LWR_MR, LAKE_CR, LWR_VET, and LWR_VBLW (fig. 17, table 11). Calibration targets for stream reach LWR_MR (table 12) were assigned the calculated base flow for streamgage 06447500 (fig. 17; table 7) because the contributing drainage area is entirely within the study area. Mean discharge for stream reach LWR_MR for WYs 1980–2009 was 16.2 ft^3/s (table 12). Calibration targets for stream reach LAKE_CR (table 11) were assigned the calculated base flow for streamgage 06449000 (fig. 17; table 7) because the contributing drainage area is entirely within the study area. Mean discharge for stream reach LAKE_CR for WYs 1980–2009 was 19.3 ft^3/s (table 12). Calibration targets for stream reach LWR_VET were assigned the calculated base flow for streamgage 06449100 (fig. 17; table 7) minus the calibration targets for stream reaches LWR_MR and LAKE_CR. Mean discharge for stream reach LWR_VET for WYs 1980–2009 was 16.8 ft^3/s (table 12). Parameter LWR_VBLW was assumed to have the same conductance as parameter LWR_VET.

Calibrated Parameters

Parameter values were estimated for recharge multipliers, maximum potential evapotranspiration multiplier, streambed conductance, and horizontal and vertical hydraulic conductivity. Specific yield was estimated for model layers 1 and 2, and specific storage was determined for the part of model layer 2 (the Arikaree aquifer) overlain by model layer 1 (the Ogallala aquifer).

The final calibrated recharge multipliers were 1.00 for recharge zone 1, 0.74 for recharge zone 2, and 0.70 for recharge zone 3. The equivalent calibrated recharge rates for the transient simulation (table 13) for WYs 1980–2009 averaged 3.3 in/yr for the Ogallala aquifer (zone 1) and 1.1 in/yr for the Arikaree aquifer (zones 2 and 3). Recharge by WY ranged from 0.9 to 11.8 in/yr for the Ogallala aquifer and from 0.3 to 2.5 in/yr for the Arikaree aquifer. The calibrated mean maximum potential evapotranspiration multiplier was 1.01. The equivalent maximum evapotranspiration rate averaged 35.4 in/yr for WYs 1980–2009 and ranged from 28.8 to 39.9 in/yr by WY.

The final calibrated streambed conductance (table 14) for perennial stream reaches represented with the River package ranged from 101 to 1,360 ft^2/d and averaged 530 ft^2/d. A uniform value of 10 ft^2/d was specified for intermittent streams represented with the Drain package; these conductance values were not estimated during the calibration process.

The final calibrated horizontal hydraulic conductivity for the Ogallala aquifer ranged from 4 to 70 ft/d (fig. 18) and averaged 27 ft/d. The largest hydraulic conductivity values in model layer 1 (the Ogallala aquifer) were located in the south-central part of the study area. The final calibrated horizontal hydraulic conductivity for model layer 2 (the Arikaree aquifer) ranged from 0.2 to 8 ft/d (fig. 19) and averaged 1.0 ft/d. The hydraulic conductivity for 98 percent of model layer 2 was less than 3 ft/d.

The vertical hydraulic conductivity for the Ogallala aquifer (parameter VKA1_1) averaged 1.4 ft/d (0.05 times the horizontal hydraulic conductivity). The vertical hydraulic conductivity for the Arikaree aquifer (parameter VKA2_1) averaged 0.004 ft/d (0.004 times the horizontal hydraulic conductivity).

Specific yield for the Ogallala aquifer was 0.15 (parameter SY1_1). Specific yield for the Arikaree aquifer was 0.027 for zone 1 (parameter SY2_1) and 0.018 for zone 2 (parameter SY2_2; fig. 16) and averaged 0.02. Specific storage for the Arikaree aquifer (parameter SS2_2) was 1.7×10^{-6} per foot.

Table 13. Calibrated transient recharge rates by recharge zone.

Water year	Calibrated recharge rate by zone (fig. 12) (inches per year)		
	Zone 1	Zone 2	Zone 3
1980	1.1	0.3	0.4
1981	3.0	0.8	0.5
1982	4.4	1.7	1.3
1983	4.3	1.5	1.0
1984	2.2	0.7	0.7
1985	1.3	0.4	0.4
1986	5.6	2.1	1.4
1987	1.9	0.9	0.7
1988	1.8	1.1	0.7
1989	0.9	0.4	0.4
1990	2.8	1.0	0.7
1991	4.4	1.0	1.0
1992	2.3	0.8	1.3
1993	3.2	1.8	1.9
1994	2.7	0.7	0.9
1995	5.3	1.9	1.5
1996	3.7	1.9	1.3
1997	5.9	1.7	2.1
1998	4.5	1.4	0.8
1999	11.8	1.8	2.5
2000	2.1	0.8	1.0
2001	2.5	1.0	1.2
2002	1.1	0.5	0.7
2003	1.5	0.6	0.5
2004	2.5	0.7	0.7
2005	4.4	1.9	1.3
2006	1.6	0.8	1.1
2007	2.1	1.0	0.8
2008	2.7	1.6	1.3
2009	4.1	2.4	1.3
Mean	3.3	1.2	1.0

Table 14. Calibrated streambed conductance for stream reaches represented in model.

Stream reach identifier (table 11; fig. 17)	Streambed conductance (feet squared per second)
Stream reach represented with MODFLOW–NWT river package	
BLC	1,360
LAKE_CR	337
LWR_MR	1,233
LWR_VET	209
LWR_VET	209
MR_CR	1,035
POR_CR	290
WCC_BL	426
WCC_OGL	426
WKC_WK	204
WKC_WK_BL	101
Stream reach represented with MODFLOW–NWT drain package	
COT_CR	10
CRA_CR	10
EAG_N_CR	10
GRA_CR	10
PASS_CR	10
POT_CR	10

Sensitivity Analysis

The model's ability to estimate a parameter value during calibration is related to the sensitivity of the changes in the model output relative to changes in the parameter value. The relative composite sensitivity of a model parameter is a measure of the composite changes in model outputs that are incurred by a small change in the value of the parameter (Doherty, 2010). The model is most sensitive to parameters associated with a high relative composite sensitivity and least sensitive to parameters associated with a low relative composite sensitivity. PEST calculated the relative composite sensitivity for each adjustable model parameter (fig. 20). Parameter HK1 was used to represent the mean relative composite sensitivity for all pilot points associated with model layer 1, and parameter HK2 was used to represent the mean relative composite sensitivity for all pilot points associated with model layer 2. Model outputs were most sensitive to changes in the multiplier parameter EVT1_1, which was associated with the evapotranspiration applied to the model. Model outputs also were highly sensitive to changes in the multiplier parameter RCH1_1, which was associated with the recharge to the Ogallala aquifer in the model area. The model was least sensitive to the vertical hydraulic conductivity anisotropy parameters VKA1_1 and VKA2_1.

Comparison of Simulated and Observed Values

Comparison of the steady-state potentiometric surface simulated by the calibrated model to the generalized potentiometric surface for the Ogallala aquifer (fig. 21) indicates similar groundwater-flow directions and gradients. The largest differences between the potentiometric surfaces were in the south-central part of the model area where the simulated potentiometric surface was lower and smoother than the generalized potentiometric surface. The mean difference between simulated and observed hydraulic heads (residuals) for

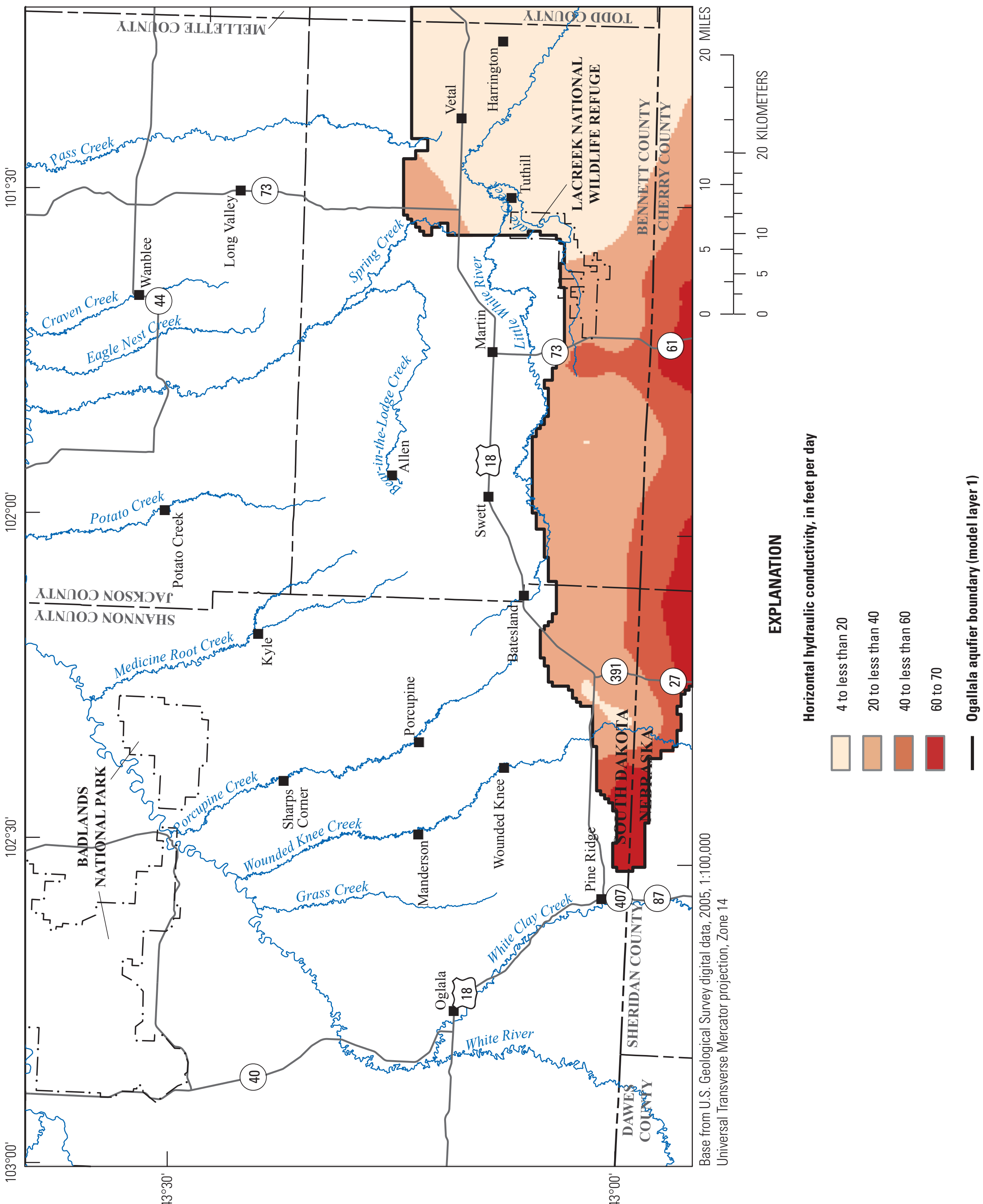


Figure 18. Calibrated horizontal hydraulic conductivity for model layer 1 representing the Ogallala aquifer in the study area.

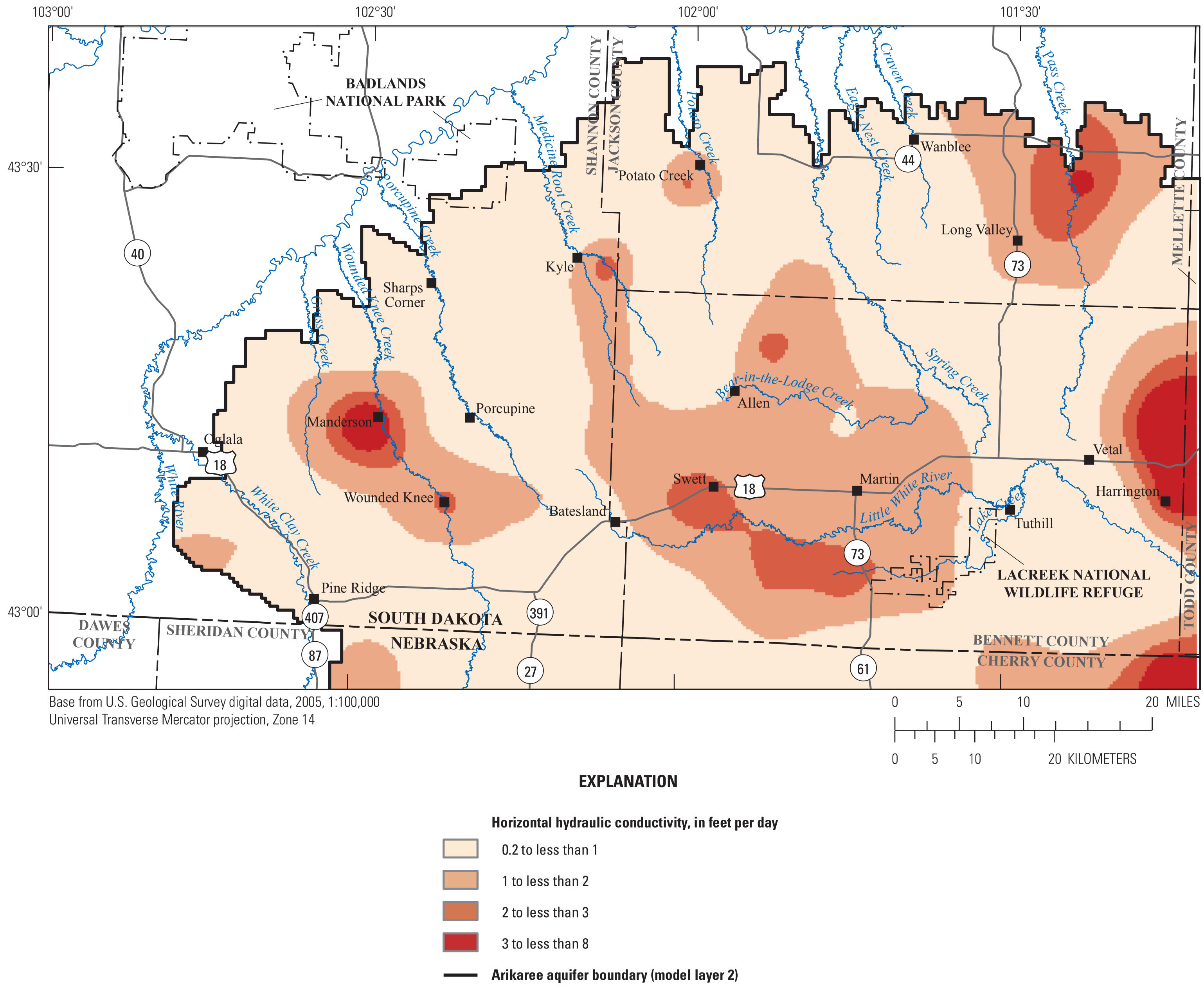


Figure 19. Calibrated horizontal hydraulic conductivity for model layer 2 representing the Arikaree aquifer in the study area.

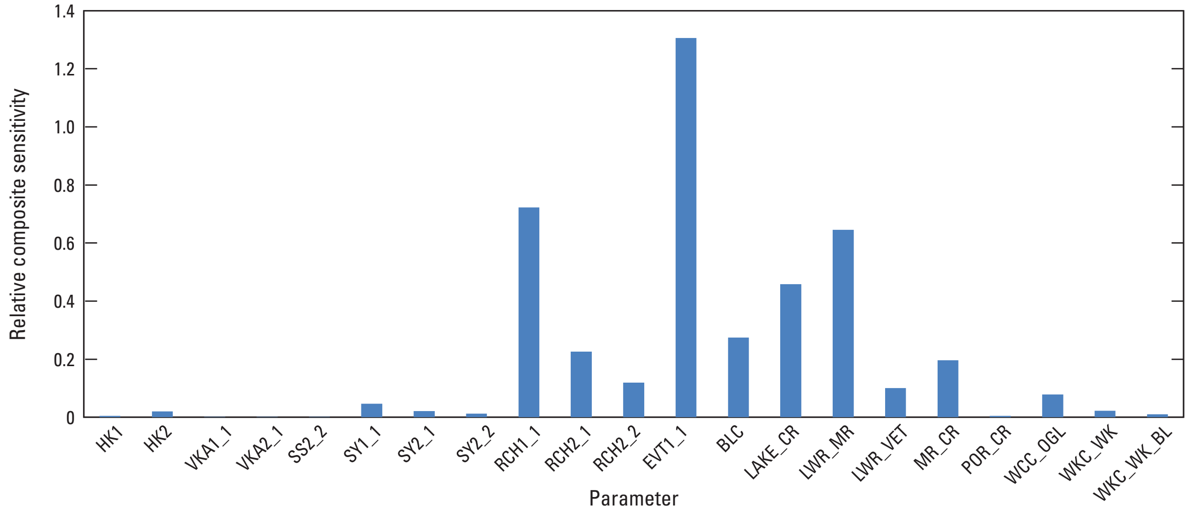


Figure 20. Relative composite parameter sensitivities, as defined by Doherty (2010), for the numerical model.

long-term observation wells completed in the Ogallala aquifer for the transient simulation for WYs 1980–2009 ranged from -30.0 to 24.9 ft (table 15; fig. 22). The mean arithmetic difference for all measurements at observation wells completed in the Ogallala aquifer was 2.7 ft. Individual water-level measurements from 60 wells were used to create the generalized potentiometric surface, although measurements for only 48 wells occurred within the simulation period (WYs 1980–2009); therefore, only these 48 water-level measurements made during WYs 1980–2009 were used during model calibration (table 1–1; fig. 23). The difference between simulated and observed hydraulic heads for wells with single measurements for WYs 1980–2009 ranged from -84.8 to 29.9 ft with the largest negative differences in the south-central and southeast parts of the study area (fig. 23). The mean arithmetic difference between the 731 simulated and observed hydraulic heads in the Ogallala aquifer (683 from observation wells and 48 from single water-level measurements) was 1.4 ft, and the mean absolute difference was 12.6 ft.

Hydrographs for four representative wells labeled with letters A through D shown in figure 22 were selected for comparison between the simulated and observed hydraulic heads for the transient simulation (fig. 24*A*–*D*). The simulated and observed hydrographs for well A (fig. 24*A*) indicate similar hydraulic-head trends with some observed values that probably reflect intermittent pumping withdrawals. The hydrographs for well B (fig. 24*B*) indicate a downward trend in simulated hydraulic head at the beginning of the transient simulation that is not present in the observed values. The hydrographs for well C (fig. 24*C*) indicate similar trends with very small residuals between simulated and observed hydraulic heads. The hydrographs for well D (fig. 24*D*) indicate similar trends between simulated and observed hydraulic heads; however, the simulated values are about 15 ft lower than observed values.

Comparison of the simulated steady-state potentiometric surface for the Arikaree aquifer (fig. 25) to the generalized potentiometric surface indicates generally similar groundwater-flow directions; however, the simulated potentiometric surface indicates flatter hydraulic gradients in several areas where the generalized potentiometric surface indicates relatively steep hydraulic gradients. This difference in hydraulic gradients can generally be observed throughout Shannon County and in the western part of Jackson County (fig. 25). The mean difference between simulated and observed transient hydraulic heads (residuals) for individual long-term observation wells completed in the Arikaree aquifer for WYs 1980–2009 ranged from -29.6 to 70.4 ft (table 16; fig. 26). The mean arithmetic difference for the observation wells was 9.5 ft. The difference between simulated and observed hydraulic heads for wells with single measurements for the transient simulation for WYs 1980–2009 ranged from -164.9 to 155.4 (fig. 27). Eighty-two percent of the simulated single-measurement values were within plus or minus 50 ft of the observed values. The mean arithmetic difference between the 2,754 simulated and observed hydraulic heads in the Arikaree aquifer (2,171 from observation wells and 583 from single water-level measurements) was 9.8 ft, and the mean absolute difference was 17.2 ft.

Hydrographs for six representative wells labeled with letters E through J in figure 26 were selected for comparison of the simulated and observed trends in hydraulic heads (fig. 28*A*–*F*). The hydrographs for well E (fig. 28*A*) indicate a simulated flat hydraulic head with less fluctuation than the observed values. Well E is located close to a river cell, which limited the fluctuation in the simulated hydraulic heads. The hydrographs for well F (fig. 28*B*) indicate similar trends in hydraulic head with small residuals between simulated and observed values. The hydrographs for well G (fig. 28*C*) indicate similar upward trends but with more fluctuation in the simulated values than observed values. The hydrographs for well H (fig. 28*D*) indicate similar trends between simulated and observed hydraulic heads; however, the simulated values

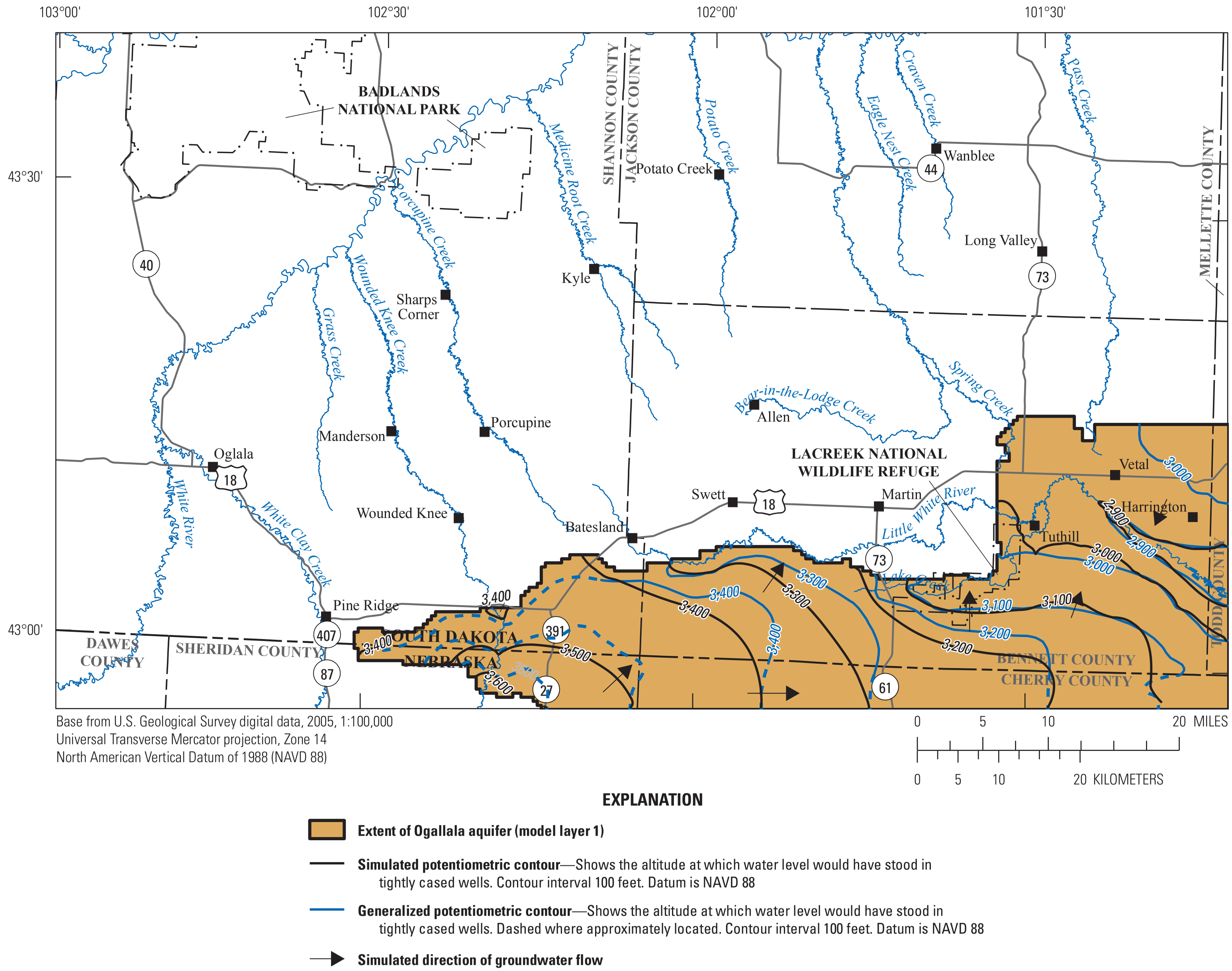


Figure 21. Comparison of simulated potentiometric surface to the generalized potentiometric surface for the Ogallala aquifer for the steady-state simulation in the study area.

Table 15. Difference between simulated and observed hydraulic heads for long-term observation wells completed in the Ogallala aquifer for the transient simulation, water years 1980–2009.

[USGS, U.S. Geological Survey; --, not applicable]

USGS station identifiction number	Local number	Number of observations	Arithmetic mean of differences between simiulated and observed values	Mean of absolute difference between simiulated and observed values
431531101282701	38N35W16CCCC	60	5.3	5.3
431255101212001	38N34W32DDDD	59	-3.1	5.2
431250101163701	37N34W 1AAAA2	48	24.9	24.9
431136101200901	37N34W 9AAAA	60	-4.2	6.9
431018101152001	37N33W17CCCC	60	21.5	21.5
430949101292701	37N35W20CBBA	60	1.8	1.8
430840101213602	37N34W28CCCC2	52	19.6	19.6
430825101151801	37N33W32BBBB2	57	8.6	8.6
430521101223401	36N34W18CCCC2	59	5.6	5.6
430256101160001	36N34W36DBCB	56	-1.7	1.8
430255101291801	36N35W31CDBD	53	-30.0	30.0
425956101424101	35N37W19AADD	59	-15.5	15.5
Mean	--	--	2.7	12.0

are about 30 ft higher than observed values. The hydrographs for well I (fig. 28*E*) also indicate simulated values about 30 ft higher than observed values. The hydrographs for well J (fig. 28*F*) indicate similar trends between the simulated and observed hydraulic heads; however, the simulated values are about 30 ft lower than the observed values.

Simulated mean groundwater discharge to streams in the transient simulation, which was represented by 17 stream reaches, was 107.8 ft^3/s (table 17). The difference between the mean simulated and observed discharges for the transient simulation ranged from -3.3 to 3.2 ft^3/s. For stream reaches with estimated (observed) groundwater base flow, the simulated total discharge was 92.1 ft^3/s compared to estimated (observed) total discharge of 88.7 ft^3/s.

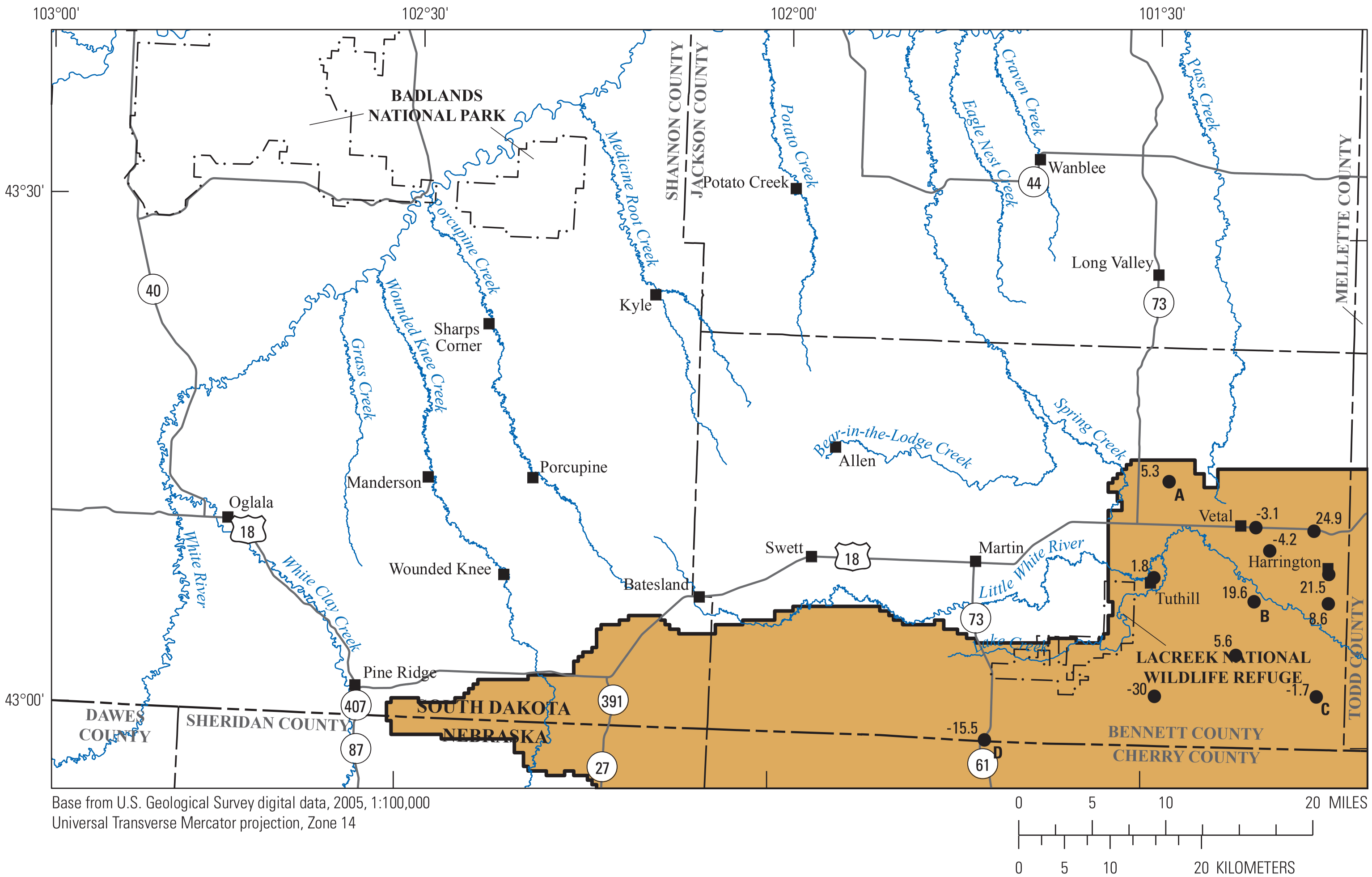
Hydrographs comparing observed and simulated discharge for the six stream reaches with groundwater discharge estimated based on gaged streamflow (table 7) in general are similar (fig. 29). For stream reach WCC_OGL, simulated and observed discharge values were similar. For stream reach WKC_WK, simulated and observed values also were similar but the simulated values were higher than observed values at the end of the wet period in the late 1990s. For stream reach BLC, simulated and observed values were similar but there was less fluctuation in the simulated values. For stream reaches LWR_MR and LAKE_CR, simulated and observed discharge values were similar but the simulated values were lower than observed values during the wet period in the late 1990s. For stream reach LWR_VET, trends in simulated and observed values were similar; however, the magnitude of change in the simulated values was greater in WY 1987 and less in WY 2006 compared to observed values.

Simulated Water Budgets

The simulated steady-state model water budget balanced; inflows and outflows averaged 459 ft^3/s (table 18). The percentages of inflows were 17 percent from constant-head boundaries, 9 percent from streams, and 74 percent from recharge. The percentages of outflows were 8 percent to constant-head boundaries, 1 percent to wells, 31 percent to streams, and 59 percent to evapotranspiration.

Simulated transient water budgets for selected years (table 18) indicate the difference in water budgets for a dry period (WYs 1987–1989) and a wet period (WYs 1997–1999). Precipitation (table 1) for WYs 1987–1989 averaged about 4 in. less than the 30-year mean, and precipitation for WYs 1987–1999 averaged about 7 in. greater than the 30-year mean. Compared to the steady-state budget, the recharge rate decreased 228 ft^3/s in WY 1989 and resulted in a decrease in water going into storage of 182 ft^3/s and a decrease in evapotranspiration of 27 ft^3/s. Compared to the steady-state budget, the recharge rate increased 699 ft^3/s in WY 1999 and resulted in an increase in water going into storage of 514 ft^3/s and an increase in evapotranspiration of 98 ft^3/s.

Water budgets for transient simulation by model layer (table 19) for dry WY 1989 and wet WY 1999 indicate that net flow from the Ogallala aquifer (model layer 1) to the Arikaree aquifer (model layer 2) ranged from about 22 ft^3/s in dry years (such as 1989) to about 36 ft^3/s in wet years (such as 1999). In WY 1989, 55 percent of the total recharge was applied to the Arikaree aquifer and 45 percent was applied to the Ogallala aquifer. In WY 1999, 33 percent of the total recharge was applied to the Arikaree aquifer and 67 percent was applied to the Ogallala aquifer.



EXPLANATION

Extent of Ogallala aquifer (model layer 1)

-1.7 C **Observation well completed in Ogallala aquifer**—Number is mean difference between simulated and observed hydraulic head, in feet. Letter is well identifier for representative well hydrograph (fig. 24)

Figure 22. Mean difference between simulated and observed hydraulic heads for long-term observation wells completed in the Ogallala aquifer in the study area for the transient simulation, water years 1980–2009.

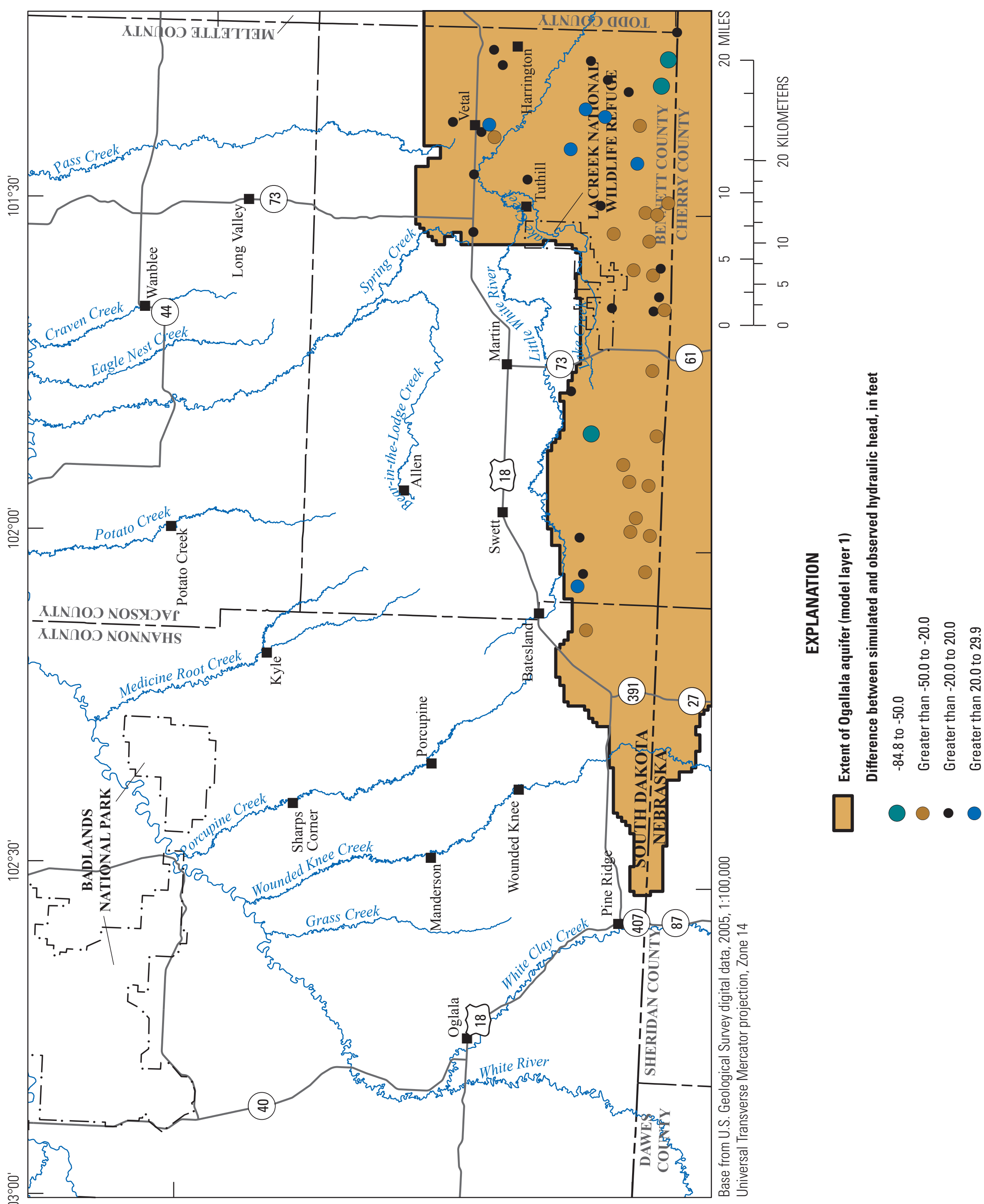


Figure 23. Difference between simulated and observed hydraulic heads for wells completed in the Ogallala aquifer in the study area with a single measurement for the transient simulation, water years 1980–2009.

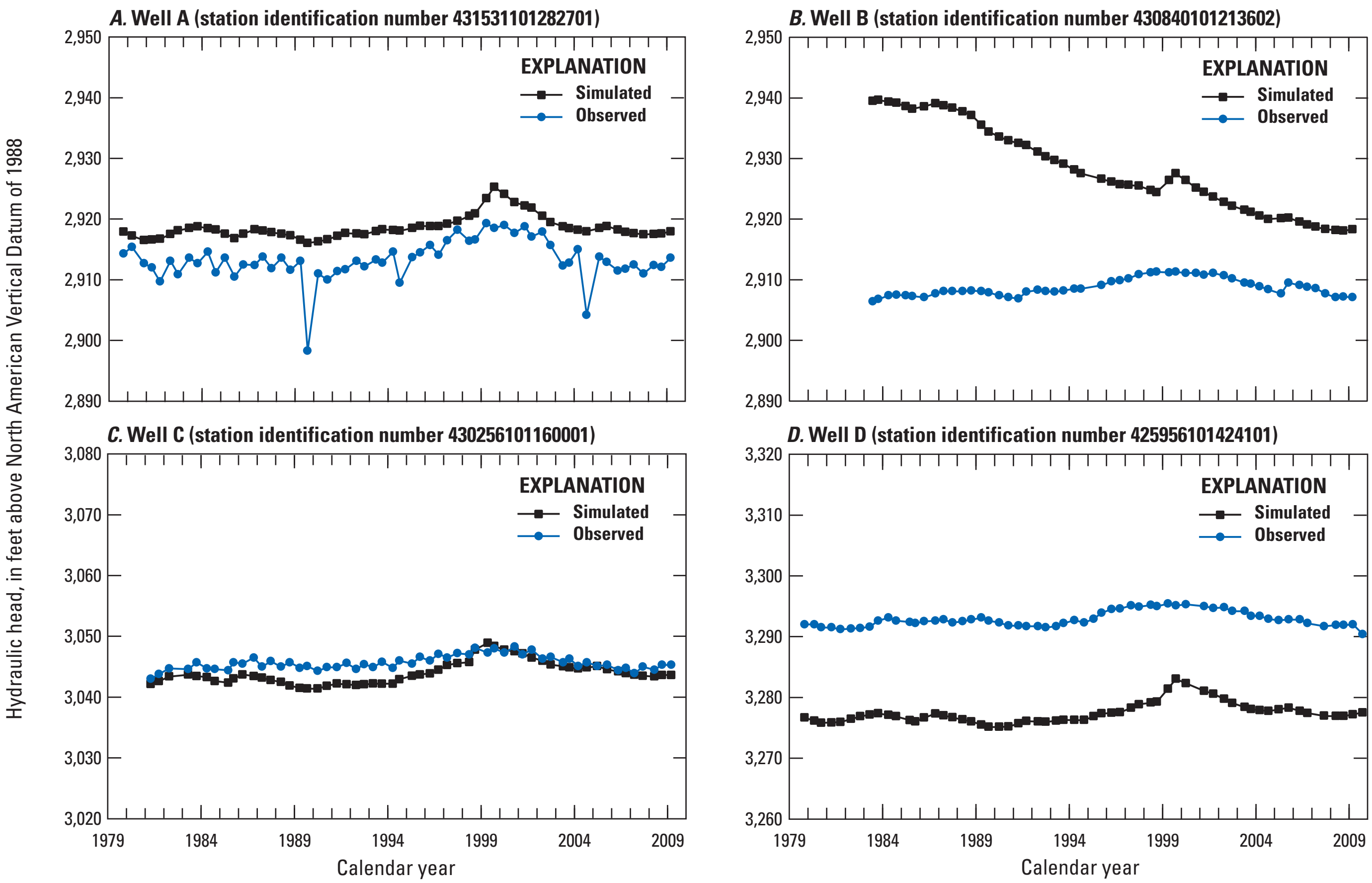


Figure 24. Simulated and observed hydraulic heads for the transient simulation for selected observation wells completed in the Ogallala aquifer in the study area. *A*, well A; *B*, well B; *C*, well C, and *D*, well D.

Hypothetical Simulations

Simulations of hypothetical increased well withdrawals and extended drought were completed using the calibrated model. The Arikaree aquifer is present in most of the Pine Ridge Indian Reservation area, and therefore the results of hypothetical increased withdrawal and extended drought simulations were compared to the results of the calibrated simulation for the Arikaree aquifer. The comparisons were made to provide a general characterization of the groundwater response to additional stresses.

A hypothetical increased well withdrawal scenario was simulated with additional withdrawals of 0.2 ft^3/s from 50 hypothetical wells completed in the Arikaree aquifer (fig. 30). The simulation represents a total increase in well withdrawals of 10 ft^3/s from the Arikaree aquifer. The difference in hydraulic head between the end of the 30-year calibrated simulation and the end of the 30-year hypothetical increased pumping simulation ranged from 0 to 66 ft (fig. 30). A new equilibrium in hydraulic head was approached near the end of the 30-year simulation. As the effects of pumping on hydraulic head propogated outward, a larger fraction of pumping was offset by decreases in evapotranspiration and discharge to streams. The greatest drawdowns in hydraulic head were in upland areas and less in stream valleys where the hydraulic head was within 7 ft of the evapotranspiration extinction depth. Where the Arikaree aquifer was confined, the decrease in hydraulic head was small compared to the unconfined part of the aquifer because of induced inflow to the Arikaree aquifer from the overlying Ogallala aquifer.

Simulation results for the hypothetical increased well withdrawals were compared to the calibrated 30-year simulation to describe how various water budget components for the Arikaree aquifer were affected over time (fig. 31). Increased well withdrawal resulted in an increase in inflow from the overlying Ogallala aquifer and decreases in aquifer storage, discharge to streams, and evapotranspiration. In the first year, decreased aquifer storage accounted for about 69 percent (6.9 ft^3/s) of the overall increased well withdrawal rate. Decreases in discharge to streams accounted for about 6 percent (0.6 ft^3/s), decreased evapotranspiration accounted for about 7 percent (0.7 ft^3/s), and increased inflow from the Ogallala aquifer accounted for about 18 percent (1.8 ft^3/s) of increased well withdrawal. Increased inflow at constant-head boundaries as a result of increased pumping was less than 1 percent. After 10 years of pumping, decreased discharge to

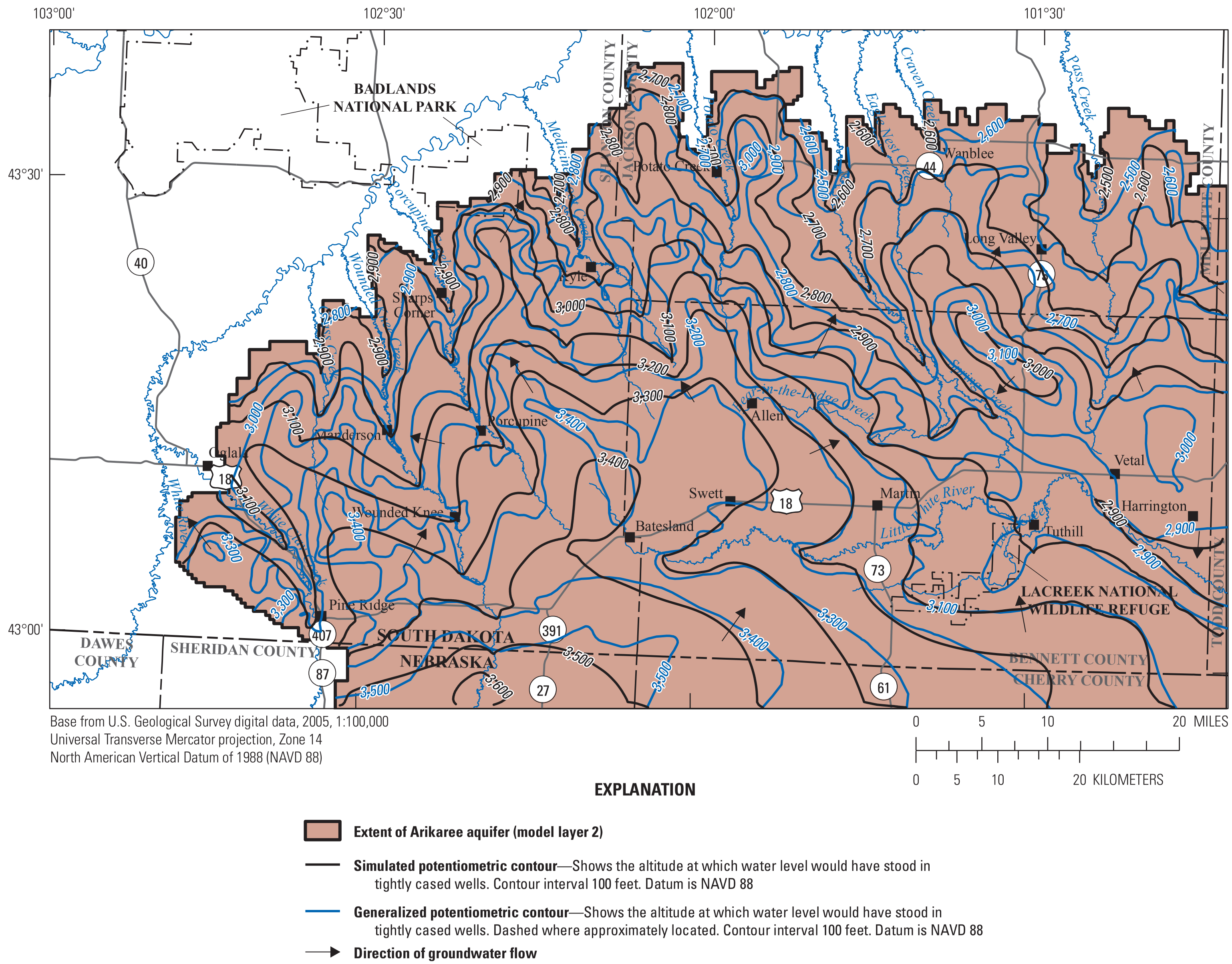


Figure 25. Comparison of the simulated potentiometric surface to the generalized potentiometric surface for the Arikaree aquifer for the steady-state simulation in the study area.

Table 16. Difference between simulated and observed hydraulic heads for long-term observation wells completed in the Arikaree aquifer in the study area for the transient simulation, water years 1980–2009.

[USGS, U.S. Geological Survey; --, not applicable]

USGS station identifiction number	Local number	Number of observations	Arithmetic mean of differences between simiulated and observed values	Mean of absolute difference between simiulated and observed values
430027102311801	35N44W17DBCA	43	32.0	32.0
433100102002101	41N39W19ACAA	60	28.8	28.8
433020101394201	41N37W24DDDD	53	-3.9	3.9
432740101223501	40N34W 6DDDA	58	7.8	7.8
430055101440002	40N37W30DDDD2	58	36.5	36.5
432410101294002	40N35W31AAAA2	54	70.4	70.4
432120101120001	39N41W17CBBB	58	23.9	23.9
431958101582101	39N39W19DDBC (2)	56	-9.2	9.2
432038101223501	39N34W19AAAA (2)	56	29.2	29.2
431530101264101	38N35W23BABB	61	1.5	1.5
431458101483001	38N38W22CBDC	57	5.0	5.0
431022101570101	37N39W17DDDD	60	3.3	3.3
431022101555001	37N39W16DDDD	56	-7.7	7.7
431045101293701	37N35W18DABA	59	6.1	6.1
430928101532401	37N39W26AAAA	60	-0.8	0.8
431018101212001	37N34W17DDDD	59	-17.7	17.7
430923101484301	37N38W28AAAA	61	-1.1	1.1
430835101554601	37N39W34BBB	60	-2.4	2.4
430925101272001	37N35W28AAAA	60	9.4	9.4
430748102154801	36N42W 4ABA	58	4.7	4.7
430832101364701	37N36W31AAA	60	-0.1	0.1
430744101593201	36N40W 2ABA	60	5.6	5.6
430835101295001	37N35W31AAAA (2)	60	0.9	0.9
430840101213601	37N34W28CCCC	60	27.2	27.2
430715101444701	36N38W 1DCDD (2)	60	7.0	7.0
430706101391001	36N37W11BBBB	62	-4.1	4.1
430757101223801	36N35W 1AAAA	53	19.6	19.6
430642101455801	36N38W10ADDD	61	6.6	6.6
430757101264701	36N35W 9BAAA	53	-29.6	29.6
430653101383401	36N35W11BDAD	54	25.9	25.9
430620101234501	36N35W12CCCC	53	14.8	14.8
430524101481601	36N38W16CCCC	57	17.8	17.8
430520101260401	36N35W15CCCC	57	16.8	16.8
430429101320401	36N36W22DDDD (2)	60	5.1	5.1
430253101420701	36N37W32DBCB	52	-0.7	0.7
430200102130001	35N42W 1CDCB	57	-6.8	6.8
430027102311806	35N44W17DBCA6	45	32.1	32.1
432251103221001	39N43W 2BAAA	60	23.1	23.1
Mean	--	--	9.5	14.3

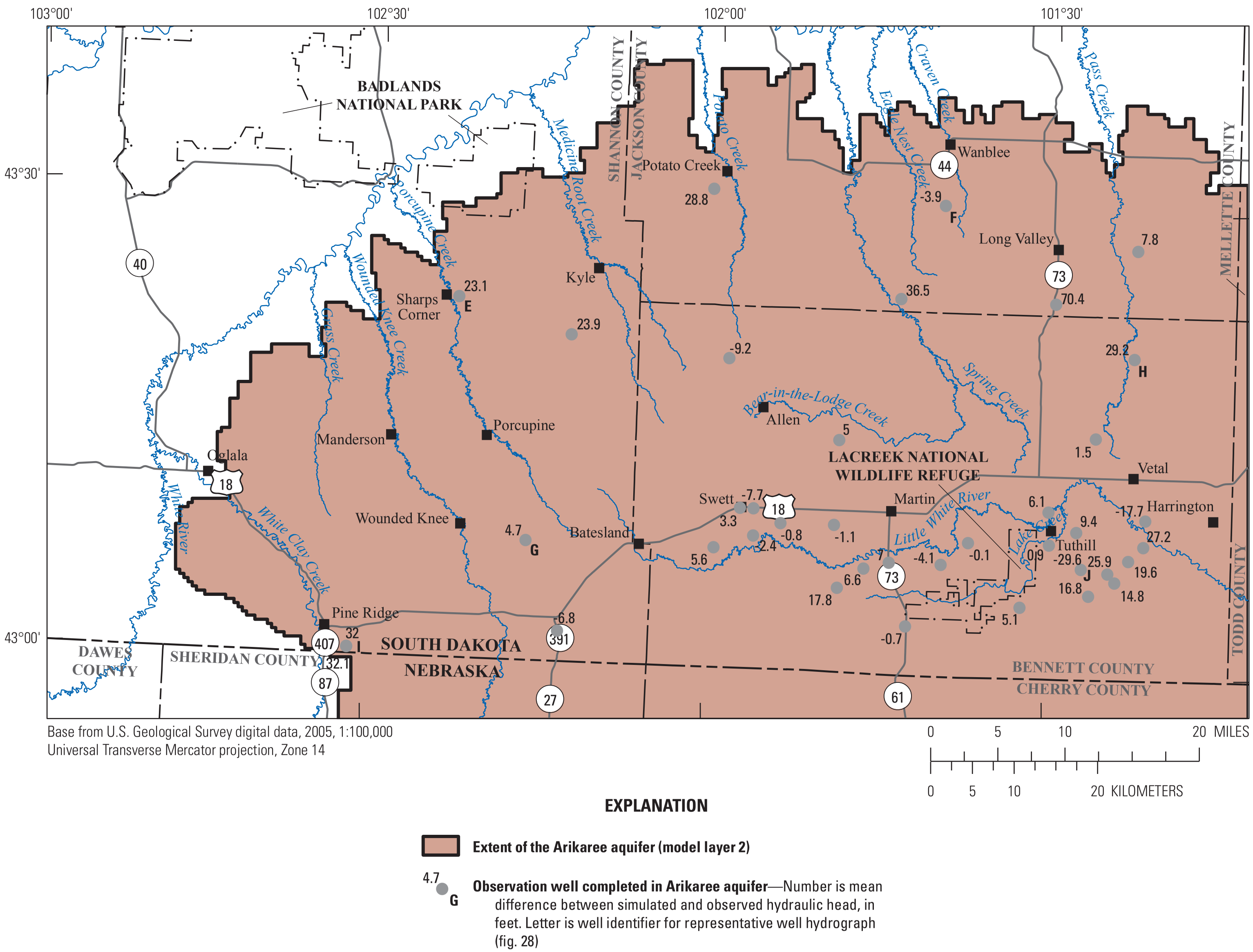


Figure 26. Mean difference between simulated and observed hydraulic heads for long-term observation wells completed in the Arikaree aquifer in the study area for the transient simulation, water years 1980–2009.

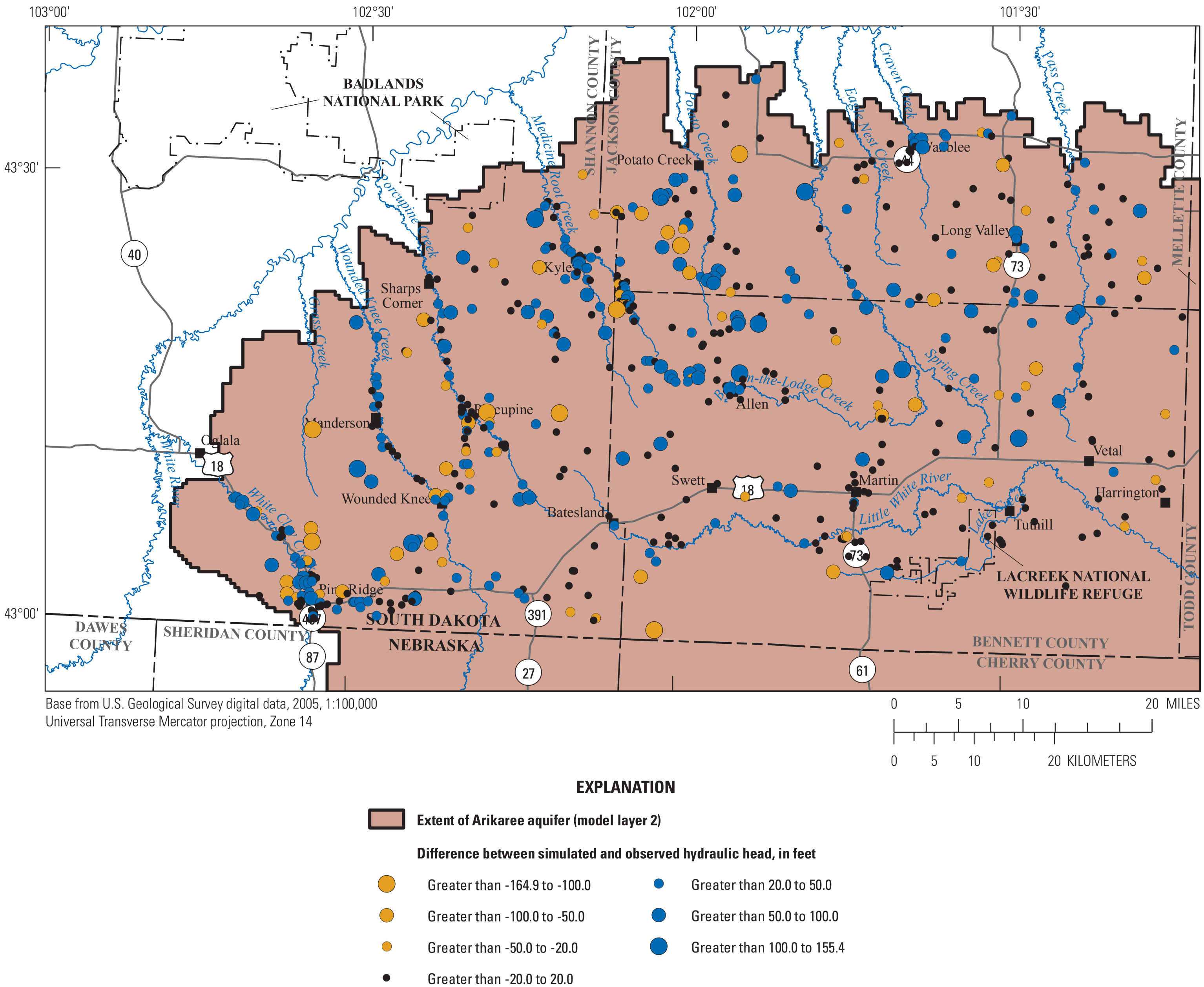


Figure 27. Difference between simulated and observed hydraulic head for wells completed in the Arikaree aquifer in the study area with a single measurement for the transient simulation, water years 1980–2009.

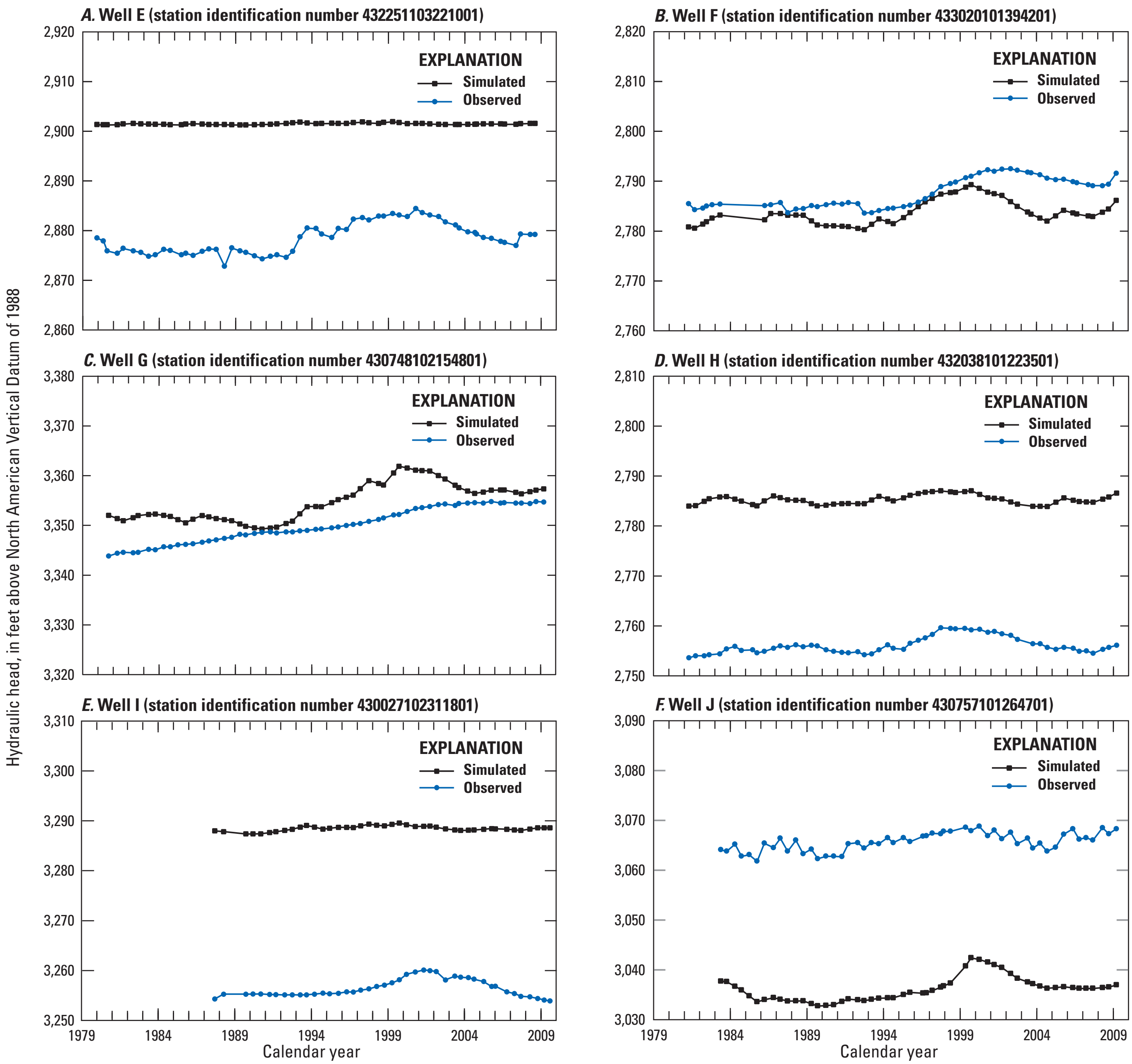


Figure 28. Simulated and observed hydraulic heads for the transient simulation for selected observation wells completed in the Arikaree aquifer in the study area. *A*, well E; *B,* well F; *C*, well G; *D*, well H; *E*, well I; and *F*, well J.

Table 17. Mean simulated groundwater discharge to stream reaches in the study area for transient simulation, water years 1980–2009.

[--, not applicable]

Stream reach identifier (table 11; fig. 17)	Description of stream reach	Mean groundwater discharge to stream reaches, water years 1980–2009 (cubic feet per second)		Difference between mean simulated and observed discharge (cubic feet per second)
		Simulated	Observed	
Stream reach with estimated groundwater discharge				
BLC[a]	Bear-in-the-Lodge Creek and Spring Creek tributary. Streamgage 06446700 is located at model boundary	12.1	11.7	0.4
LAKE_CR[a]	Lake Creek upstream from streamgage 06447500	16.6	19.3	-2.7
LWR_MR[a]	Little White River upstream from streamgage 06447500	12.9	16.2	-3.3
LWR_VET[a]	Little White River between streamgage 06447500 and streamgage 06449100, which includes the part of Lake Creek from streamgage 06449000 to mouth at Little White River	20.0	16.8	3.2
MR_CR[b]	Medicine Root Creek	7.9	6.9	1.0
POR_CR[b]	Porcupine Creek	5.0	4.4	0.6
WCC_OGL[a]	White Clay Creek upstream from streamgage 06445980	3.0	3.1	-0.1
WKC_WK_BL[b]	Wounded Knee Creek downstream from streamgage 06446100 to model boundary	9.8	6.8	3.0
WKC_WK[a]	Wounded Knee Creek upstream from stream-gage 06446100 to model boundary	4.8	3.5	1.3
Subtotal		92.1	88.7	3.4
Stream reach without estimated groundwater discharge				
COT_CR	Cotton Creek	0.6	--	--
CRA_CR	Craven Creek	1.7	--	--
EAG_N_CR	Eagle Nest Creek	1.9	--	--
GRA_CR	Grass Creek	2.9	--	--
LWR_VET_BLW	Little White River downstream from stream-gage 06449100 to model boundary	3.6	--	--
PASS_CR	Pass Creek	1.7	--	--
POT_CR	Potato Creek	3.0	--	--
WCC_BL	White Clay Creek downstream from stream-gage 06445980	0.3	--	--
Total groundwater discharge to streams		107.8	--	--

[a]Discharge calculated from streamflow-gaging records.

[b]Discharge calculated from correlation with discharge for nearby gaged stream reaches.

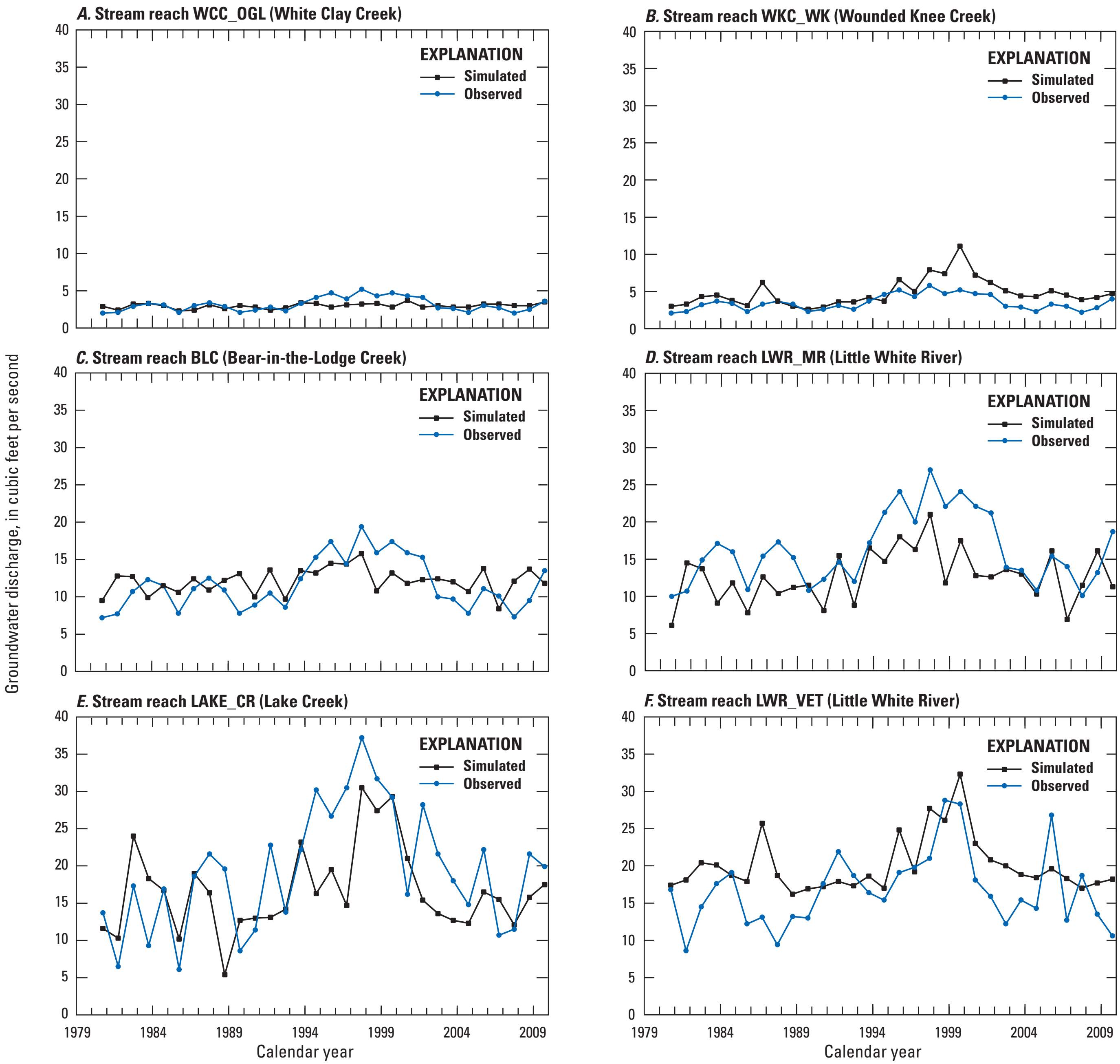


Figure 29. Simulated and estimated discharge for stream reaches with gaged streamflow in the study area.

Table 18. Water budget for steady-state and transient simulations for selected water years.

[Budget component rates in cubic feet per second; WY, water year]

	Budget component	Steady state	Dry period		Wet period	
			WY 1987	WY 1989	WY 1997	WY 1999
		Inflows				
	Constant head	80	81	87	70	59
	From streams	41	38	39	25	29
	Recharge	347	240	119	654	1,046
Total		468	359	245	749	1,134
		Outflows				
	Constant head	38	38	35	43	56
	Wells	6	10	19	12	11
	To streams	141	142	136	178	185
	Evapotranspiration	270	271	243	301	368
Total		455	461	427	534	620
Change in storage (inflows minus outflows)		0[a]	-102	-182	215	514

[a]For the steady state stress period, the change in storage is 0. Inflows minus outflows equals 13 cubic feet per second.

streams accounted for 19 percent (1.9 ft^3/s) of the increased well withdrawal and decreased evapotranspiration accounted for 23 percent (2.3 ft^3/s). After 20 years of pumping, decreased discharge to streams accounted for 23 percent (2.3 ft^3/s) of the increased well withdrawal and decreased evapotranspiration accounted for 51 percent (5.1 ft^3/s). At the end of the 30-year increased pumping simulation, decreased discharge to streams accounted for about 26 percent (2.6 ft^3/s) of increased well withdrawal, and decreased evapotranspiration accounted for 53 percent (5.3 ft^3/s). The change in aquifer storage represented only about 3 percent (0.3 ft^3/s) of increased well withdrawal, and inflow from the overlying Ogallala aquifer remained at 18 percent (1.8 ft^3/s) of increased well withdrawal. As time progressed, a greater percentage of the pumping was accounted for by decreases in discharge to streams and evapotranspiration. Most of the decreased discharge to streams was realized during the first 10 years of the increased pumping simulation, whereas evapotranspiration generally continued to decrease throughout the simulation.

A hypothetical drought scenario was simulated using a decrease in recharge of 0.2 in. (24 ft^3/s) for each simulated water year. The difference in hydraulic head between the end of the 30-year calibrated simulation and the end of the hypothetical drought simulation ranged from 0 to 10.9 ft (fig. 32). The smallest declines in hydraulic head were in the stream valleys, and the greatest declines were in upland areas. Drawdown generally was smaller in the Arikaree aquifer in the southern part of the model area where the Arikaree aquifer is overlain by the Ogallala aquifer. Constant-head boundary conditions likely affect this simulation, and the actual decline in hydraulic head would likely be greater near the southern and eastern boundaries with an extended drought.

Decreased recharge to the Arikaree aquifer during the hypothetical drought was offset mainly by decreases in aquifer storage, discharge to streams, and evapotranspiration (fig. 33). In the first year, decreased aquifer storage accounted for about 79 percent (17.0 ft^3/s) of the overall decreased annual recharge, decreased discharge to streams accounted for about 5 percent (1.2 ft^3/s) of decreased recharge, and decreased evapotranspiration accounted for about 15 percent (3.6 ft^3/s) of decreased recharge. Inflow through constant-head cells accounted for only about 1 percent (0.2 ft^3/s) of decreased recharge, and increased inflow from the Ogallala aquifer accounted for less than 1 percent of decreased recharge. After 10 years hypothetical drought, decreased discharge to streams accounted for 17 percent (4.0 ft^3/s) of decreased recharge, and decreased evapotranspiration accounted for 40 percent (9.4 ft^3/s). After 20 years of hypothetical drought, decreased discharge to streams accounted for 21 percent (4.9 ft^3/s) of the increased well withdrawal, and decreased evapotranspiration accounted for 72 percent (17.2 ft^3/s). At the end of 30-year hypothetical drought simulation, about 23 percent (5.5 ft^3/s) of decreased recharge was accounted for from decreased discharge to streams, 72 percent (17.3 ft^3/s) was from decreased evapotranspiration, and aquifer storage change represented 0 percent of decreased recharge. Increased inflow from the overlying Ogallala aquifer accounted for about 2 percent (0.5 ft^3/s) of decreased recharge, and inflow through constant-head cells accounted for about 3 percent (0.7 ft^3/s) of decreased recharge. As time progressed, a greater percentage of the reduced recharge rate was accounted for by decreased discharge to streams and evapotranspiration. Most of the decreased discharge to streams was realized during the first 10 years of the hypothetical drought simulation, whereas evapotranspiration generally continued to decrease throughout the simulation.

Table 19. Water budget for transient simulation for dry (1989) and wet (1999) water years by model layer in the study area.

[Budget component rates in cubic feet per second; WY, water year]

	Budget component	WY 1989	WY 1999
	Model layer 1		
Inflows	Constant head	70	46
	From streams	35	25
	Recharge	54	706
	From model layer 2	51	54
Total		210	831
Outflows	Constant head	12	28
	Wells	9	4
	To streams	70	101
	Evapotranspiration	156	216
	To model layer 2	73	90
Total		320	439
Change in storage (inflows minus outflows)		-110	392
	Model layer 2		
Inflows	Constant head	18	13
	From streams	3	5
	Recharge	65	340
	From model layer 1	73	90
Total		159	448
Outflows	Constant head	23	28
	Wells	10	7
	To streams	66	85
	Evapotranspiration	86	152
	To model layer 1	51	54
Total		236	326
Change in storage (inflows minus outflows)		-77	122

Model Limitations

The numerical model adequately simulated flow in the Ogallala and Arikaree aquifers in the study area for transient and hypothetical future conditions; however, as with any conceptual or numerical model, certain limitations should be considered when using the model and its results. Model limitations arise from aspects of the conceptual model and from simplifications inherent in the construction and calibration of the numerical model. These limitations include uncertainties in many of the numerical model input parameters, most importantly recharge, evapotranspiration, and horizontal hydraulic conductivity. These parameters greatly affected model results, and extensive field measurements or estimates were not available; therefore, these parameters were estimated or calculated with the data that were available.

The numerical model is limited in its application by simplifying assumptions that were necessary to represent the aquifers mathematically. Aquifer properties were averaged for a set of rectangular cells that represented a finite volume of aquifer material that could vary substantially within that volume. The materials that make up these aquifers were deposited in many discontinuous layers that ranged from impermeable clays to very permeable sands and gravels. Local hydraulic properties could vary substantially from the generalized representation in the model. Hydraulic connection between depositional layers could be very discontinuous. As a result, the actual response of the aquifers to local stress could vary substantially from that represented by the model. Ranges of hydraulic conductivity used in the numerical model were based on general ranges of previously published values (table 10), but final values were determined through model calibration. Model accuracy is dependent, primarily, on the accuracy of the estimates of

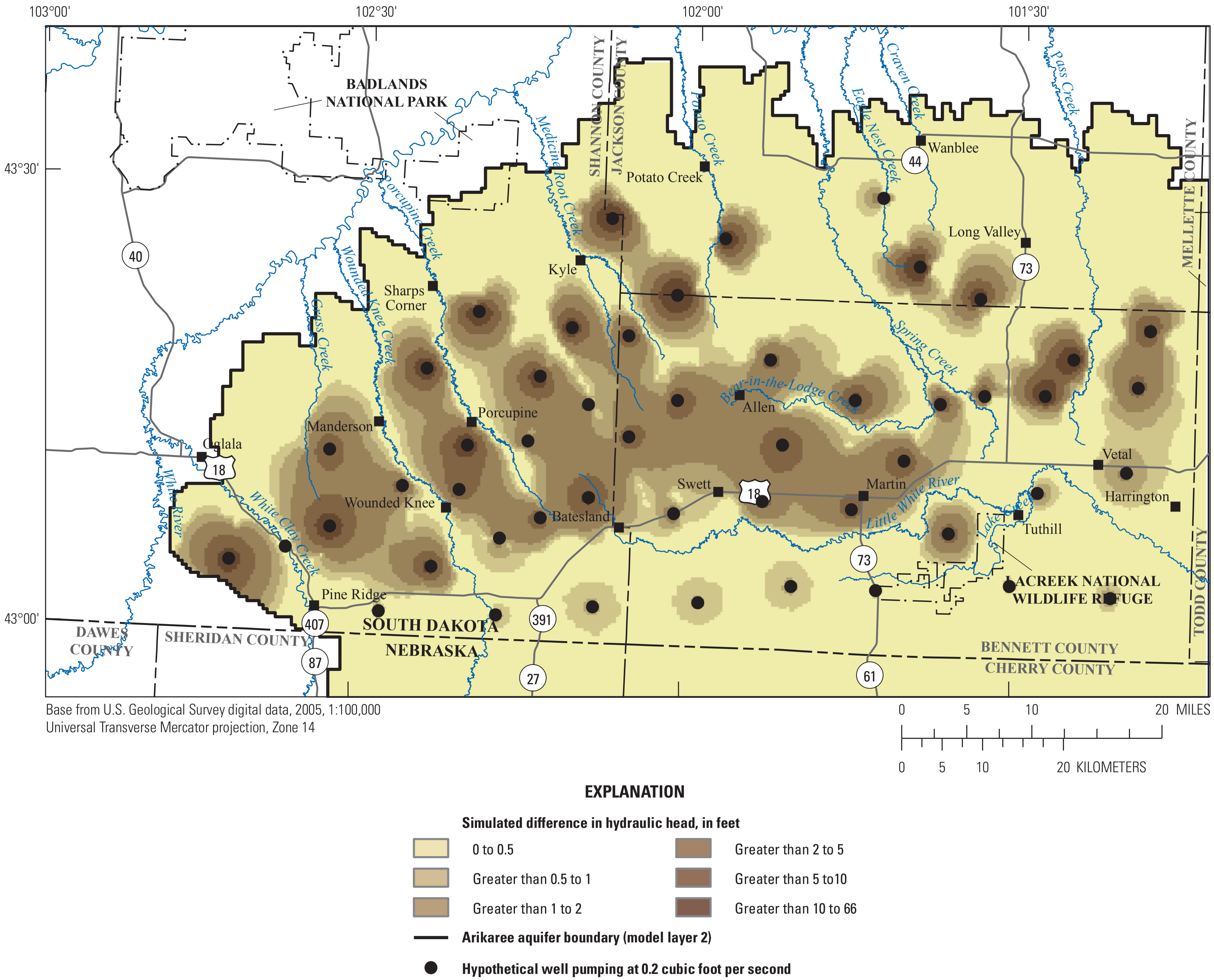


Figure 30. Simulated difference in hydraulic head in the Arikaree aquifer in the study area between the end of the calibrated simulation and the end of the 30-year simulation with 50 hypothetical wells completed in the Arikaree aquifer withdrawing 0.2 cubic foot per second.

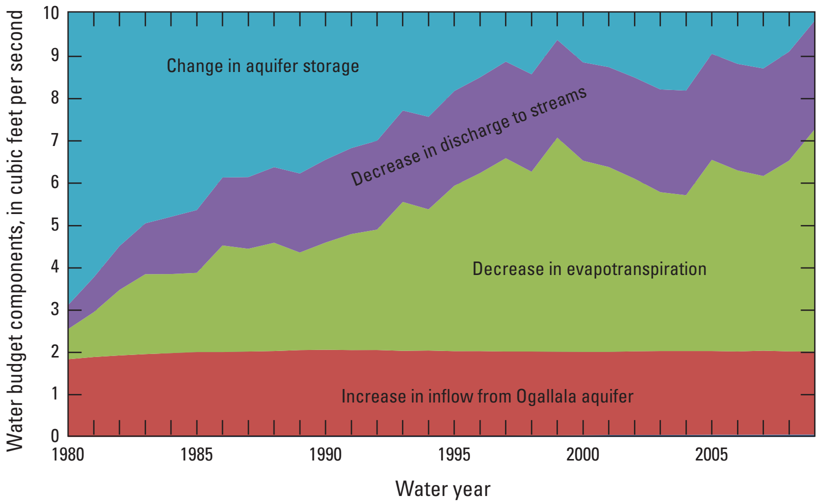


Figure 31. Change in simulated water budget components in the study area based on hypothetical additional withdrawals of 0.2 cubic foot per second at 50 hypothetical wells completed in the Arikaree aquifer compared to the calibrated simulation.

model input parameters. Nevertheless, calibration of the model yielded hydraulic conductivity distributions that were deemed acceptable, given the data available. It is reasonable to assume that similar hydraulic conductivity distributions could exist that also would yield satisfactory model results. Additionally, field-verified aquifer properties could help constrain the model calibration process, and, as a result, enhance the applicability of the model.

Limitations associated with representation of the surface-water network should be considered. Hydraulic interaction of the aquifers with streams likely is much more complex than the model can adequately represent. Little information was available regarding the streambed properties and how they change within the model area. The hydraulic properties of streambeds were integrated in the model over several stream miles when, in reality, the properties can change drastically at the foot scale. Streambed conductance can even be considered a transient property, subject to flooding events, which seasonally change the texture and thickness of the riverbed material in different stream reaches. In addition, these stream reaches could include a range of hydrologic conditions that include seeps, springs, and impermeable or very permeable layers. Variation in the incision and width of the streams into the underlying aquifer could be substantially different on a local scale.

Recharge, evapotranspiration, and pumping withdrawals also were averaged over time, which limited model calibration to these stresses. Calibration data were sparse in several areas, which also limited the effectiveness of model calibration. Special caution should be exercised when examining the effect of simulated stresses at local scales. Analysis of the effects of site-specific pumping stresses would require more site-specific investigation. The described model limitations should be considered when using the model to evaluate stresses on the aquifer and in making management decisions.

The calibration targets all contain error, which contributed to uncertainty in parameter estimation. It is difficult to quantify the error and uncertainty of individual targets. The two types of calibration targets, transient hydraulic-head measurements and discharge to streams as base flow, were used to the extent of available information. Weights were given to calibration targets in an attempt to impose a degree of certainty to the calibration process. In other words, calibration targets for measurements that had a higher certainty were given a higher weight; therefore, calibration targets for hydraulic-head measurements at observation wells with multiple measurements completed in the Ogallala and Arikaree aquifers were given much more weight when compared to wells with a single water-level measurement that had been site visited. Similarly, calibration targets for wells with a single water-level measurement that had not been site visited were given the lowest weight in the calibration process. For base-flow calibration targets, base flow determined along gaged stream reaches was given a higher weight when compared to base flow determined in ungaged reaches. Calibration targets for hydraulic head and base flow also were weighted proportionally in an attempt to prevent the model calibration process from becoming biased to one calibration target type; therefore, individual targets for base flow were given more weight in the calibration process compared to individual hydraulic-head targets.

Simulated hydraulic heads at observation wells (figs. 24 and 28) and simulated base flow (fig. 29) generally had less seasonal variability when compared with observed or estimated values. For some observation wells, multiple measurements were taken per year, which directly translated to multiple calibration targets for some model stress periods. It is possible that for locations with multiple calibration targets per stress period, some of the model to measurement misfit cannot be rectified during the calibration process. Nevertheless, all observations available were used during model calibration with the assumption that the calibration process would tend toward the mean of observations during any give stress period. Hydrographs for some observation wells also display a persistent bias. Some of the wells were close to model boundary conditions. For example, wells E and H (figs. 26 and 28) are close to river cells used to simulate groundwater exchange in

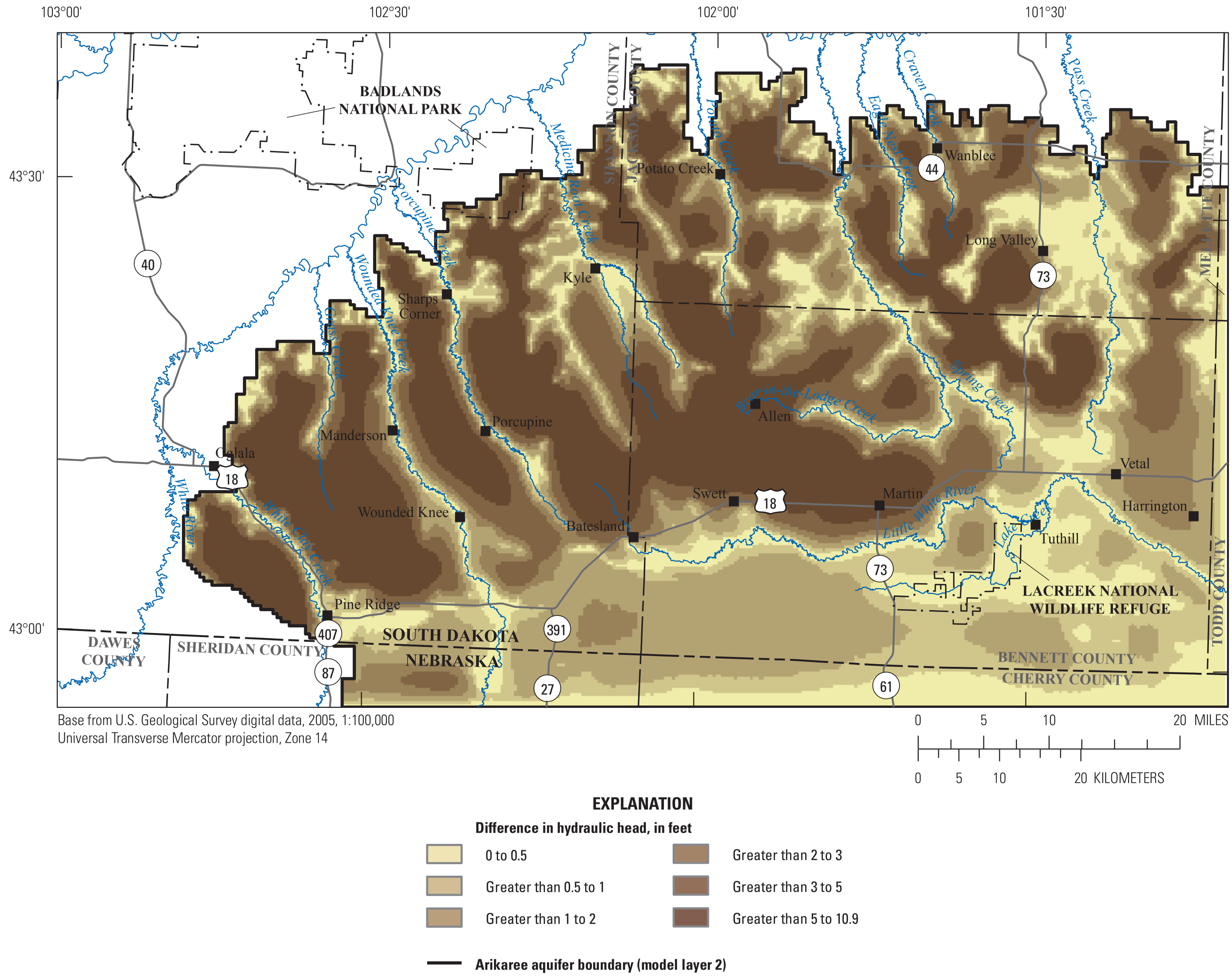


Figure 32. Difference in hydraulic head in the Arikaree aquifer in the study area between the end of calibrated simulation (nondrought simulation) and the end of the hypothetical 30-year drought simulation.

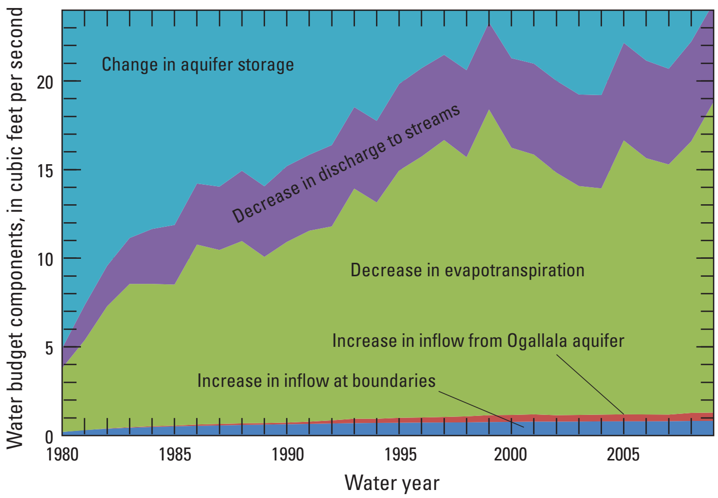


Figure 33. Change in simulated water budget components for the Arikaree aquifer in the study area based on the hypothetical drought simulation when compared to the calibrated simulation.

Porcupine Creek and Pass Creek, respectively (fig. 14). The proximity of a calibration target to a boundary condition could negatively affect the calibration process because the hydraulic head observed in the well may be directly affected by the hydraulic head in the boundary condition cell.

The simulated potentiometric surfaces were smoothed compared to the generalized potentiometric surfaces based on measured values. Simulated groundwater-flow directions generally were consistent with the conceptual model; however, at a local scale, groundwater-flow gradients could vary substantially compared to those calculated by the model. This probably resulted from simulating each aquifer as a single layer. The fluvial sediments that make up the aquifers include considerable layering of high and low permeability sediments that could result in large gradients between wells completed at different intervals within the aquifer.

Head-dependent boundary conditions, such as river and constant-head cells, for the two hypothetical future stress scenarios were assumed to be equivalent to the calibrated scenario. For this reason, it is possible that declines in hydraulic head near head-dependent boundary conditions may not represent potential declines during these stress scenarios. In fact, declines in hydraulic head would likely be greater than the model simulated values near head-dependent boundaries during extended time periods of increased aquifer stress.

The two-layer model grid with 1,640-ft grid spacing was determined to be sufficient spatial discretization, and one stress period per year was determined to be sufficient temporal discretization, to produce reasonable model results. The chosen discretization of spatially varied aquifer parameters and temporally varied aquifer stresses likely resulted in a smoothing of simulated changes in hydraulic head and base flow for the study area.

Summary

The Ogallala and Arikaree aquifers are the largest source of groundwater on the Pine Ridge Indian Reservation and are used extensively for irrigation and public and domestic water supplies. To assess the potential for decreased water levels and discharge to streams in the Pine Ridge Indian Reservation, conceptual and numerical models of groundwater flow in the Ogallala and Arikaree aquifers in southwestern South Dakota were developed by the U.S. Geological Survey in cooperation with the Oglala Sioux Tribe. The study area includes most of the Pine Ridge Reservation in Jackson and Shannon Counties and Indian trust lands in Bennett County in southwestern South Dakota.

The High Plains aquifer, which includes the Ogallala and Arikaree aquifers, generally is less developed in South Dakota compared with other areas underlain by this aquifer; thus, water levels in the High Plains aquifer in South Dakota generally changed less than 5 feet from 1980 to 1999. Despite minimal water-level changes in the High Plains aquifer in South Dakota, extensive withdrawals of groundwater for irrigation have caused water-level declines in many parts of the aquifer and increased concerns about the long-term sustainability; thus, continued or increased withdrawals from the aquifer or prolonged drought have the potential to affect water levels within the aquifer and discharge to important streams in the area.

Altitude of the land surface ranges from about 4,025 feet in the southwestern part of the study area to 2,100 feet in the northeastern part of the study area. The Ogallala and Arikaree aquifers generally consist of poorly consolidated claystones, siltstones, sandstones, and shale deposited in fluvial and lacustrine environments. Saturated thickness ranged from 10 to 314 feet for the Ogallala aquifer and from 10 to 862 feet for the Arikaree aquifer. Previous hydraulic conductivity estimates ranged from less than 1 to 180 feet per day (ft/d) for the Ogallala aquifer and less than 1 to 13 ft/d for the Arikaree aquifer.

Recharge to the Ogallala and Arikaree aquifers occurs from precipitation on the outcrop areas. Discharge from the Ogallala and Arikaree aquifers occurs through evapotranspiration, discharge to streams, and well withdrawals. Evapotranspiration generally occurs in topographically low areas along streams, and maximum evapotranspiration occurs when the water level is at the land surface.

The generalized groundwater-flow direction in the Ogallala and Arikaree aquifers is to the northeast with local flow towards streams. Precipitation for water years 1980–2009 ranged from about 11 to 39 inches per year (in/yr) and averaged about 19.1 in/yr. Estimated mean recharge for water years 1980–2009 was about 17.3 percent of precipitation for the Ogallala aquifer and 7.9 percent of precipitation for the Arikaree aquifer. The estimated mean maximum evapotranspiration rate for WYs 1980–2009 was about 35 in/yr. The estimated mean base flow for gaged streams in the study area was about 0.06 cubic foot per second (ft^3/s) per square mile of drainage area. Estimated mean total water use for water years 1980–2009 was 5.4 ft^3/s from the Ogallala aquifer and 7.1 ft^3/s from the Arikaree aquifer.

A two-layer numerical groundwater-flow model was constructed using MODFLOW–NWT with a uniformly spaced grid consisting of 166 rows and 288 columns with cells 1,640 feet on a side. The numerical model of the Ogallala and Arikaree aquifers was used to simulate steady-state and transient conditions for water years 1980–2009. Model calibration was accomplished using the Parameter ESTimation (PEST) program that adjusted individual model input parameters and assessed the difference between estimated and model-simulated values of hydraulic head and base flow. This program was designed to estimate parameter values that are statistically the most likely set of values to result in the smallest differences between simulated and observed values, within a given set of constraints.

For the numerical model, aquifer boundaries were no-flow on the northern and western sides of the model area and constant-head on the southern and eastern sides of the model area. The mean arithmetic difference between 731 simulated and observed hydraulic heads in the Ogallala aquifer (683 time-series measurements from observation wells and 48 from wells with a single water-level measurement) was 1.4 feet. The mean arithmetic difference between the 2,754 simulated and observed hydraulic heads in the Arikaree aquifer (2,171 time-series measurements from observation wells and 583 from wells with a single water-level measurement) was 9.8 feet. For stream reaches with estimated groundwater base flow, the simulated total discharge was 92.1 ft^3/s compared to estimated total discharge of 88.7 ft^3/s.

Calibrated recharge for the transient simulation averaged 3.3 in/yr for the Ogallala aquifer and 1.1 in/yr for the Arikaree aquifer. The calibrated mean maximum potential evapotranspiration rate was 35.4 in/yr. Streambed conductance for perennial stream reaches represented with the River package ranged from 101 to 1,360 square feet per day and averaged 530 square feet per day. Horizontal hydraulic conductivity for the Ogallala aquifer ranged from 4 to 70 ft/d and averaged 27 ft/d. Horizontal hydraulic conductivity for the Arikaree aquifer ranged from 0.2 to 8 ft/d and averaged 1.0 ft/d. The vertical hydraulic conductivity averaged 1.4 ft/d for the Ogallala aquifer and 0.004 ft/d for the Arikaree aquifer. Specific yield for the Ogallala aquifer was 0.15 and averaged 0.027 for the Arikaree aquifer. Specific storage for the Arikaree aquifer was 1.7×10^{-6} per foot.

Inflow and outflow for the calibrated steady-state model was 459 ft^3/s. The percentages of inflows were 17 percent from constant-head boundaries, 9 percent from streams, and 74 percent from recharge. The percentages of outflow were 8 percent to constant-head boundaries, 1 percent to wells, 31 percent to streams, and 59 percent to evapotranspiration. Simulated net inflow from the Ogallala aquifer to the Arikaree aquifer ranged from about 22 ft^3/s in dry years to about 37 ft^3/s in wet years.

Two hypothetical future stress scenarios were simulated using the calibrated numerical model. The simulations were completed using input from the 30-year simulation of water years 1980–2009. The first hypothetical scenario represented an increase in groundwater withdrawals from 50 hypothetical production wells completed in the Arikaree aquifer. Additional withdrawals of 0.2 ft^3/s were simulated at each of the 50 hypothetical wells. At the end of the 30-year hypothetical increased pumping simulation, water levels declined as much as 66 ft in the Arikaree aquifer, decreased discharge to streams accounted for about 26 percent (2.6 ft^3/s) of increased withdrawals, and decreased evapotranspiration accounted for about 53 percent (5.3 ft^3/s) of increased withdrawals.

The second hypothetical scenario represented a 30-year period of decreased recharge (drought) by decreasing recharge by 0.2 in (24 ft^3/s) for each water year. At the end of the hypothetical drought simulation, water levels declined as much as 10.9 ft in the Arikaree aquifer, decreased discharge to streams accounted for about 23 percent (5.5 ft^3/s) of decreased recharge, and decreased evapotranspiration accounted for about 72 percent (17.3 ft^3/s) of decreased recharge.

The numerical model is a tool that could be used to better understand the flow system of the Ogallala and Arikaree aquifers located in the Pine Ridge Reservation area in Bennett, Jackson, and Shannon Counties. Simplifying assumptions were necessary to represent the aquifers mathematically; although, field-verified aquifer properties could help constrain the model calibration process, and, as a result, enhance the applicability of the model. The long-term hydraulic-head measurements were simulated reasonably well using the numerical model. Discharge from the Ogallala and Arikaree aquifers to rivers, springs, and seeps was simulated using the numerical model with reasonable accuracy where data were available.

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Appendix 1. Water-Level Data Used to Estimate Generalized Potentiometric Surface of Ogallala Aquifer

Selected data for all wells used to estimate the generalized potentiometric surface of the Ogallala aquifer are presented in table 1–1.

Table 1–1. Selected data from wells used for generalized potentiometric surface of Ogallala aquifer in the study area.

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988]

Site identifier (fig. 8)	USGS station identification number	Local number	Land surface altitude (feet above NAVD 88)	Water-level period of record or date for single measurement	Hydraulic head (feet above NAVD 88)
1	431531101282701	38N35W16CCCC	2,941	1980–2009	2,912[a]
2	431255101212001	38N34W32DDDD	3,031	1980–2009	2,962[a]
3	431250101163702	37N34W 1AAAA2	3,114	1980–2003	2,960[a]
4	431136101200901	37N34W 9AAAA	2,979	1980–2009	2,955[a]
5	430949101292701	37N35W20CBBA	2,996	1980–2009	2,975[a]
6	431018101152001	37N33W17CCCC	2,999	1980–2009	2,931[a]
7	430840101213602	37N34W28CCCC2	2,991	1983–2009	2,909[a]
8	430825101151801	37N33W32BBBB2	2,961	1981–2009	2,903[a]
9	430521101223401	36N34W18CCCC (2)	3,072	1980–2009	3,059[a]
10	430255101291801	36N35W31CDBD	3,201	1983–2009	3,192[a]
11	430256101160001	36N34W36DBCB	3,051	1981–2009	3,046[a]
12	425956101424101	35N37W19AADD	3,298	1980–2009	3,293[a]
13	431555101161201	38N33W18BD	3,117	06/20/1979	3,037
14	431428101221901	38N34W29BB	2,979	02/28/1990	2,945
15	431318101264001	38N35W34CDBC	2,951	10/27/2005	2,938
16	431255101320701	38W36W35DDDD1	3,026	06/05/2007	2,976
17	431235101230801	37N33W 6BD	3,008	08/17/1989	2,942
18	431213101151301	37N33W 5C	3,128	10/17/1977	3,008
19	431201101221701	37N34W 5CCC	3,001	11/30/1980	2,926
20	431148101165001	37N33W 7ABD	3,019	04/30/1981	2,967
21	431144101233401	37N34W 7BC	2,971	10/11/1996	2,957
22	431118101170601	37N33W12DC	3,035	10/28/1996	2,953
23	431022101213601	37N34W17DDDD (2)	2,951	11/02/1978	2,921
24	430928101271601	37N35W21DDDD	2,989	09/29/2009	2,965
25	430807101233001	37N34W31B	3,001	07/25/1977	2,951
26	430716101214801	36N34W 6DBDC	3,021	02/06/1979	2,956
27	430625101303501	36N36W12ACAA	3,016	04/14/1977	3,006
28	430643101242701	36N35W11BDAA	3,055	09/29/2009	3,020
29	430611101460501	36N38W15AA	3,231	10/10/1992	3,201
30	430602101270201	36N35W16BAC	3,051	06/04/1905	3,023
31	430548101205201	36N34W17	3,046	05/21/1996	3,016
32	430532101163301	36N33W13BCC	3,035	05/30/2007	2,965

Table 1–1. Selected data from wells used for generalized potentiometric surface of Ogallala aquifer in the study area.—Continued

[USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988]

Site identifier (fig. 8)	USGS station identification number	Local number	Land surface altitude (feet above NAVD 88)	Water-level period of record or date for single measurement	Hydraulic head (feet above NAVD 88)
33	430519102033101	36N40W20ABBC	3,321	08/03/2004	3,314
34	430518101591001	36N40W23AA	3,397	05/08/1985	3,312
35	430505102022001	36N40W21BCCD	3,355	08/03/2004	3,346
36	430447101495101	36N38W19D	3,341	05/20/1985	3,328
37	430440102072501	36N41W22DD	3,499	12/30/1999	3,439
38	430437101292601	36N35W19C2	3,076	12/12/1990	3,066
39	430431101212901	36N34W19DDD	3,106	05/11/1994	3,048
40	430423101181101	36N34W27A	3,076	09/28/1989	3,034
41	430344101315402	36N36W26CC2	3,201	05/01/1992	3,136
42	430341101383601	36N40W25DD	3,144	04/20/2003	3,104
43	430337101283401	36N35W30DDDD	3,147	08/19/1965	3,140
44	430331101141201	36N33W32BB	3,000	04/01/1972	2,988
45	430247101420501	36N37W32B	3,281	08/01/1974	3,239
46	430306101454101	36N38W35C	3,361	08/01/1974	3,329
47	430300101191301	36N34W33DA	3,159	06/23/2006	3,089
48	430237101523401	35N39W 2BA	3,422	09/19/2007	3,397
49	430234101432601	35N37W 6B	3,251	08/01/1974	3,223
50	430221101350801	35N36W 5BDB	3,225	12/14/2006	3,202
51	430219101253401	35N35W 3	3,161	10/30/1987	3,133
52	430213101221101	35N34W 6BA	3,171	03/21/1990	3,161
53	430211101540301	35N39W 4DA	3,419	06/30/2008	3,414
54	430200101583001	35N40W 1CD	3,458	02/25/1983	3,451
55	430141101295801	35N36W12AAC	3,216	08/16/1991	3,208
56	430104101570501	35N39W 7BDA	3,452	02/23/1983	3,442
57	430123101323101	35N36W10DB	3,251	11/22/1988	3,225
58	430104101353101	35N36W 8CCC	3,251	12/02/1988	3,228
59	430057101384401	35N37W14BA	3,231	05/31/1988	3,216
60	430056102020301	35N40W16BAD	3,504	02/25/1983	3,494
61	430055101300701	35N26W13AB	3,231	06/23/1989	3,223
62	430055101440401	35N38W13AB	3,320	06/16/2004	3,319
63	430055101542101	35N39W16AA	3,458	09/07/2004	3,420
64	430053101183701	35N34W15AB	3,330	08/04/1999	3,172
65	430043101584801	35N40W13BCD	3,461	06/08/2004	3,453
66	430037101372801	35N37W13BD	3,261	05/30/1988	3,238
67	430034101345401	35N36W17DBB	3,241	10/31/1994	3,219
68	430030101495401	35N38W18DB	3,383	09/08/2004	3,377
69	430028101161501	35N34W13AC	3,146	06/17/1991	3,139
70	430015101383601	35N37W14CD	3,271	07/11/2002	3,263
71	430013101290201	35N35W18DC	3,231	07/29/1982	3,229
72	425956101134502	35N33W20ABCC2	3,051	09/14/1993	3,043

[a]Value represents mean hydraulic head for period of record.

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