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Simulated Ground-Water Flow in the Ogallala and Arikaree Aquifers, Rosebud Indian Reservation Area, South Dakota

Water-Resources Investigations Report 03-4043

U.S. Department of the Interior
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CONVERSION FACTORS, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/s)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
inch	2.54	centimeter
inch	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer

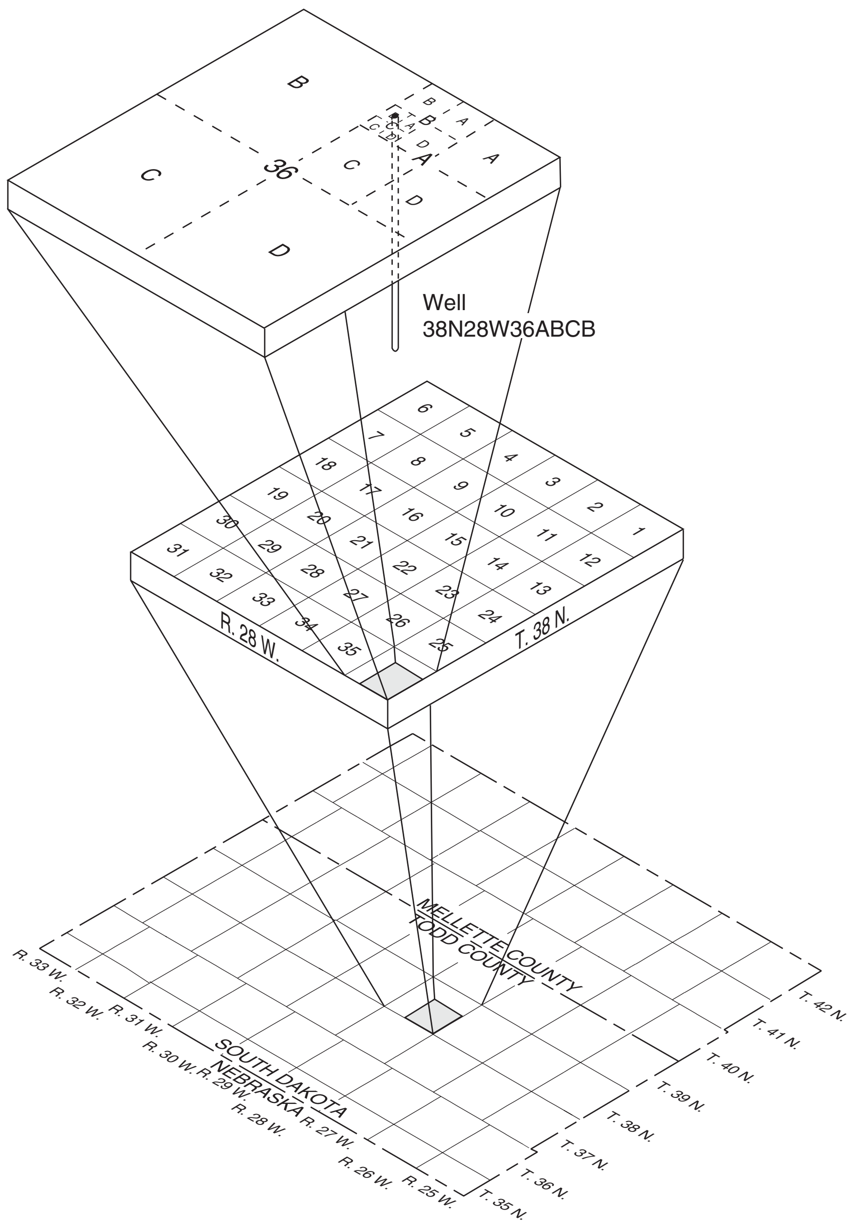
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Altitude: In this report, vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Water year (WY): Water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends. Thus, the water year ending September 30, 1998, is called "WY98."

Well-numbering system. The well number consists of the township number, followed by "N," the range number followed by "W," and the section number followed by a maximum of four uppercase letters that indicate, respectively, the 160-, 40-, 10-, and 2 1/2-acre tract in which the well is located. These letters are assigned in a counterclockwise direction beginning with "A" in the northeast quarter. A serial number following the last letter is used to distinguish between wells in the same 2 1/2-acre tract.



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ABSTRACT

The Ogallala and Arikaree aquifers are important water resources in the Rosebud Indian Reservation area and are used extensively for irrigation, municipal, and domestic water supplies. Continued or increased withdrawals from the Ogallala and Arikaree aquifers in the Rosebud Indian Reservation area have the potential to affect water levels in these aquifers. This report describes a conceptual model of ground-water flow in these aquifers and documents the development and calibration of a numerical model to simulate ground-water flow. Data for a twenty-year period (water years 1979 through 1998) were analyzed for the conceptual model and included in steady-state and transient numerical simulations of ground-water flow for the same 20-year period.

A three-dimensional ground-water flow model, with two layers, was used to simulate ground-water flow in the Ogallala and Arikaree aquifers. The upper layer represented the Ogallala aquifer, and the lower layer represented the Arikaree aquifer. The study area was divided into grid blocks 1,640 feet (500 meters) on a side, with 153 rows and 180 columns.

Areal recharge to the Ogallala and Arikaree aquifers occurs from precipitation on the outcrop areas. The recharge rate for the steady-state simulation was 3.3 inches per year for the Ogallala aquifer and 1.7 inches per year for the Arikaree aquifer for a total recharge rate of 266 cubic feet per second.

Discharge from the Ogallala and Arikaree aquifers occurs through evapotranspiration, discharge to streams, and well withdrawals. Discharge rates in cubic feet per second for the steady-state simulation were 184 for evapotranspiration, 46.8 and 19.7 for base flow to the Little White and Keya Paha Rivers, respectively, and 11.6 for well withdrawals from irrigation use. Estimated horizontal hydraulic conductivity used for the numerical model ranged from 0.2 to 120 feet per day in the Ogallala aquifer and 0.1 to 5.4 feet per day in the Arikaree aquifer. A uniform vertical hydraulic conductivity value of 6.6×10^{-4} feet per day was applied to the Ogallala aquifer. Vertical hydraulic conductivity was estimated for five zones in the Arikaree aquifer and ranged from 8.6×10^{-6} to 7.2×10^{-1} feet per day. Average rates of recharge, maximum evapotranspiration, and well withdrawals were included in the steady-state simulation, whereas the time-varying rates were included in the transient simulation.

Model calibration was accomplished by varying parameters within plausible ranges to produce the best fit between simulated and observed hydraulic heads and base-flow discharges from the Ogallala and Arikaree aquifers. For the steady-state simulation, the root mean square error for simulated hydraulic heads for all wells was 26.8 feet. Simulated hydraulic heads were within ±50 feet of observed values for 95 percent of the wells. For the transient simulation, the difference between the simulated and observed means for hydrographs was within

±40 feet for all observation wells. The potentiometric surfaces of the two aquifers calculated by the steady-state simulation established initial conditions for the transient simulation.

A sensitivity analysis was used to examine the response of the calibrated steady-state model to changes in model parameters including horizontal and vertical hydraulic conductivity, evapotranspiration, recharge, and riverbed conductance. The model was most sensitive to recharge and horizontal hydraulic conductivity.

INTRODUCTION

The Ogallala and Arikaree aquifers are included in the High Plains aquifer system that underlies parts of eight States and extends from southern South Dakota to Texas. About 20 percent of the irrigated land in the United States is in the region underlain by the High Plains aquifer, and nearly 30 percent of the ground water used for irrigation in the United States is pumped from the High Plains aquifer (Weeks and others, 1988).

The High Plains aquifer underlies about 4,750 square miles in south-central South Dakota (Gutentag and others, 1984) including most of the Rosebud Indian Reservation. In this area, the Ogallala and Arikaree aquifers are important water resources and are used extensively for irrigation, municipal, and domestic water supplies. Water levels in the High Plains aquifer in South Dakota generally did not change significantly from 1980 to 1999 (McGuire, 2001). However, water-level declines greater than 60 feet were measured from 1980 to 1999 in the aquifer in other areas, including Kansas, New Mexico, and Texas (McGuire, 2001). Prior to 1980, water levels in the High Plains aquifer had declined more than 100 feet in some areas (Luckey and others, 1981). Thus, continued or increased withdrawals from the Ogallala and Arikaree aquifers in the Rosebud Indian Reservation area have the potential to affect water levels in these aquifers and base-flow discharge to area streams.

The Rosebud Sioux Tribe has identified a need for water-resource tools to evaluate management issues associated with the Ogallala and Arikaree aquifers, such as planning for source-water protection, describing potential impacts of contamination, and estimating sustainable aquifer withdrawals. A primary tool conceived by the Tribe was a numerical ground-water flow model of these aquifers for the Rosebud Indian Reservation. Therefore, the Tribe has worked in cooperation with the U.S. Geological Survey (USGS) to develop the model described in this report. Further development of this numerical model would allow the Tribe to simulate the effects of various hydrologic stresses such as increased ground-water withdrawals or drought conditions.

Purpose and Scope

The purpose of this report is to describe a numerical model developed to simulate ground-water flow in the Ogallala and Arikaree aquifers in the Rosebud Indian Reservation area. This report also describes a conceptual model used in developing the numerical ground-water flow model of the aquifers. Steady-state and transient simulations performed for the 20-year period of water years (WY) 1979-98 (October 1, 1978, through September 30, 1998) are described in this report.

Acknowledgments

The authors would like to recognize important contributions by the Rosebud Sioux Tribe to the development of the ground-water flow model described in this report. Development of a calibrated numerical model has resulted from the Tribe's long-term commitment to obtaining hydrologic information, which has been obtained through a series of water-resource investigations that the Tribe has participated in and by data-collection networks operated or supported by the Tribe. Characterization of the Ogallala and Arikaree aquifers was enabled by a substantial program of test-hole drilling and installation of observation wells that was a major component of a water-resource investigation (Carter, 1998) involving the Tribe, USGS, and Geological Survey Program of the South Dakota Department of Environment and Natural Resources. Water-level data from the resulting network of observation wells and from other State and Tribal observation wells have been instrumental for calibration of the numerical model. Tribal support and involvement in collection of streamflow data has been critical for estimation of ground-water discharge rates. The Tribe also was actively involved in study design, conceptualization of the ground-water flow system, technical evaluation of model performance, and review of this completion report.

DESCRIPTION OF STUDY AREA

The study area includes areas within and immediately surrounding the Rosebud Indian Reservation where the Ogallala and Arikaree aquifers are present (fig. 1). The original boundaries of the Rosebud Indian Reservation included all or nearly all of Mellette, Todd, Tripp, and Gregory (east of Tripp) Counties, and a small portion of Lyman County (east of northern Tripp County). Various revisions to the Rosebud Indian Reservation boundary have occurred; the boundary was revised to include only Todd County in 1975 (fig. 1).

Physiography, Land Use, and Climate

Much of the study area has rolling topography, and numerous deep valleys drain into the White River to the north. The northern portion of the study area is in the Great Plains physiographic province, and the southern portion is in the Sand Hills physiographic province (fig. 1).

Agriculture is the primary land use within the study area. Cattle ranching is the primary agricultural activity, with most land used for grazing or hay production. Less than 15 percent of the land is used for crops, which include wheat, sorghum, oats, corn, and alfalfa (Springer, 1974). Most of the crop land is located in south-central Todd County, where extensive irrigation from the Ogallala aquifer occurs.

The climate is subhumid, and the average annual precipitation (1961-1990) is about 19 inches (U.S. Department of Commerce, 1998). About 8 percent of the average annual precipitation becomes streamflow; however, this quantity varies due to climatic conditions (Carter, 1998).

Drainage Features and Streamflow

The major streams that drain the study area (fig. 2) are the Little White River, which flows into the White River in northern Mellette County, and the Keya Paha River, which flows into the Niobrara River in Nebraska. Some of the smaller streams include Black Pipe, White Thunder, Oak, and Minnechaduza Creeks.

Ground-water discharge from the Ogallala and Arikaree aquifers provides base flow to the Little White River, Keya Paha River, and Minnechaduza Creek. These streams generally receive more than one-half of their flow from ground-water discharge, especially during the winter months (Carter, 1998). Direct runoff is the largest component of streamflow for streams with minimal discharge from the Ogallala and Arikaree aquifers. In addition, numerous ephemeral springs occur along the Little White River.

Geology

The exposed rocks and sediments in the study area range from sedimentary rocks of Cretaceous age to unconsolidated deposits of Quaternary age. Deeper rocks include rocks of Precambrian age, the Ordovician-age Winnipeg and Red River Formations, the Mississippian-age Madison Limestone, and the Pennsylvanian- and Permian-age Minnelusa Formation. Cretaceous-age rocks include the Inyan Kara Group, Skull Creek Shale, Dakota Formation, Graneros Shale, Greenhorn Formation, Carlile Shale, Niobrara Formation, and Pierre Shale. Tertiary-age rocks include the White River Group, Arikaree Formation, and Ogallala Formation. Unconsolidated deposits include windblown, terrace, and alluvial deposits (table 1). The following descriptions of the Arikaree and Ogallala Formations are from Ellis and others (1971).

The Arikaree Formation consists of silicified claystone, silty clays, siltstone, and poorly consolidated sandstone, all of which are a light pinkish-tan. The basal 50 to 150 feet usually is composed of silty and sandy beds that commonly are separated from the upper clayey part by 5 to 10 feet of thin-bedded limestone. Thickness of the Arikaree Formation ranges from 0 to 620 feet. The Arikaree Formation forms gently rolling grass-covered hills similar to those formed by the Ogallala Formation, but the banks formed by the Arikaree Formation along streams usually are steeper.

The Ogallala Formation consists of an upper unit composed of well-cemented, fine-grained sandstone and a lower unit composed of poorly consolidated clay, silt, and sand. The contact between the units commonly is marked by a bed of silty volcanic ash in the base of the upper unit. This marker bed ranges in thickness from 1 to 4 feet. Locally, however, silty limestone or gravel beds may be found at the base of the upper unit. The composition of the beds in the lower unit ranges from silty clay to coarse sand and varies both vertically and horizontally. A 5- to 20-foot-thick bed of coarse sand and gravel commonly

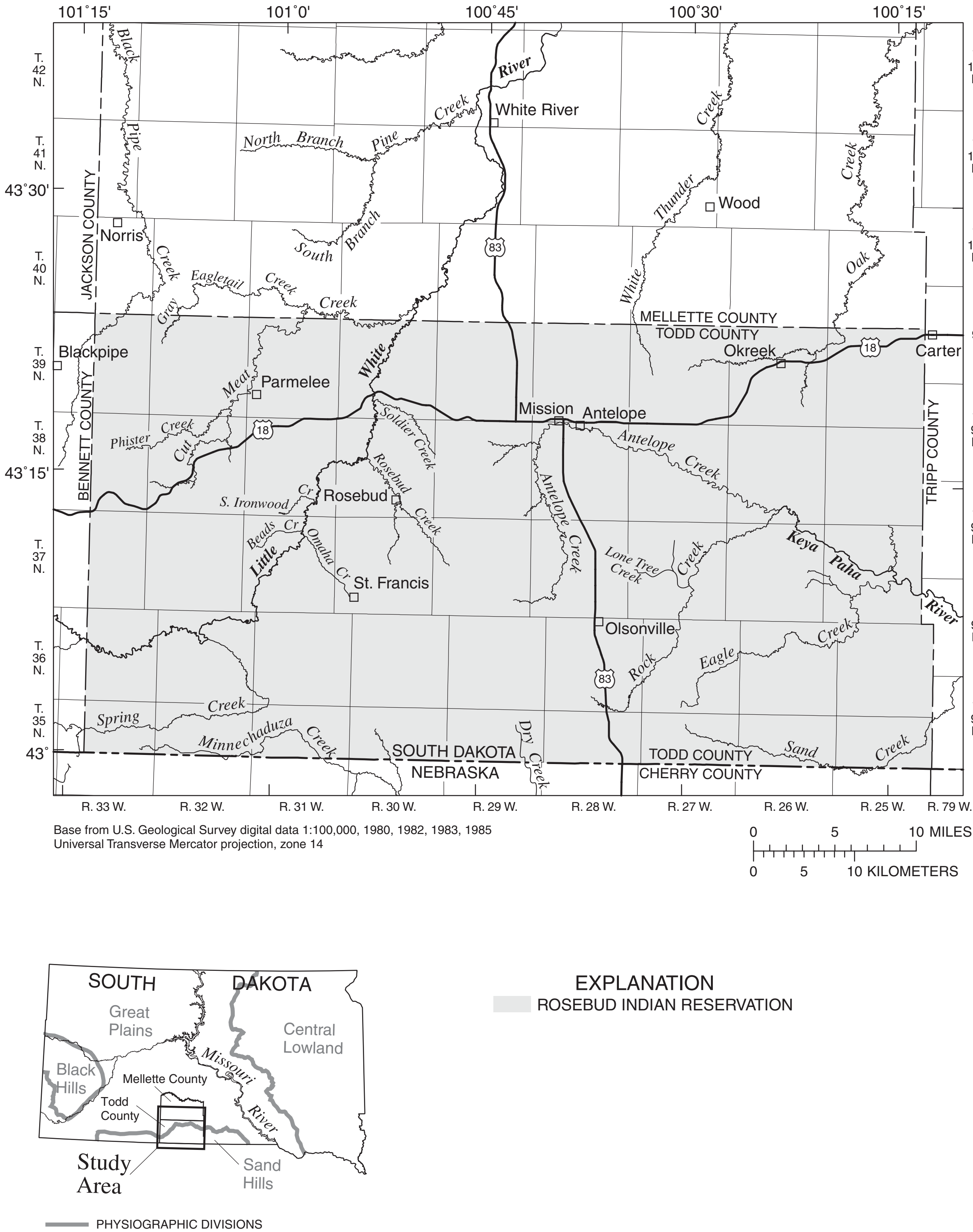


Figure 1. Study area and locations of main physiographic divisions (physiographic divisions modified from Fenneman, 1946; Flint, 1955).

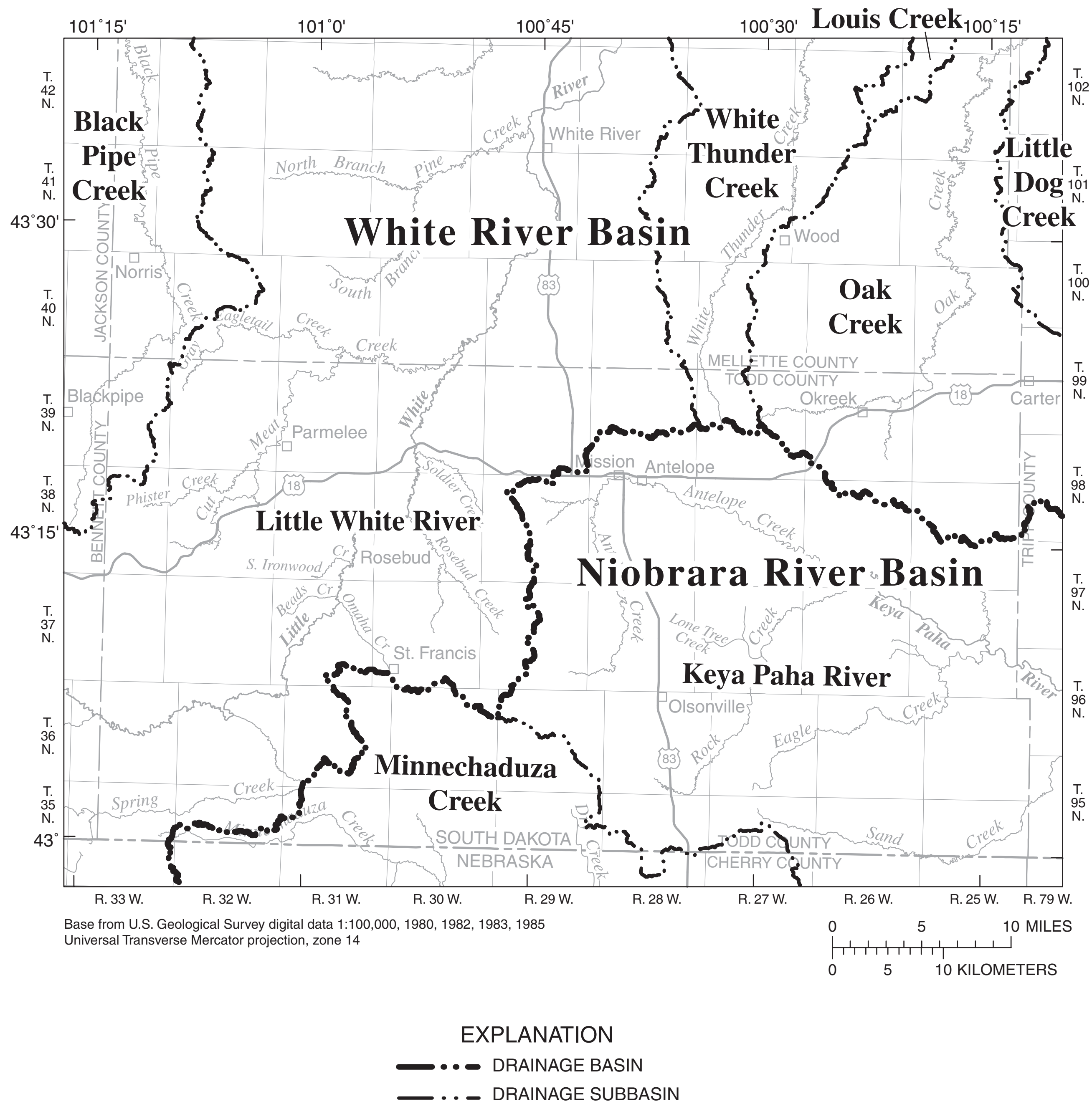


Figure 2. Drainage basins in study area.

Table 1. Generalized stratigraphic column showing geologic units and hydrologic characteristics

[From Carter, 1998]

Era	System	Formation or deposit	Thickness (feet)	Description and origin	Hydrologic characteristics
Cenozoic	Quaternary	Alluvium	0-35	Brown, varies between clay, silts, fine to coarse sand, and gravel. Generally sandy along the Little White River and other streams that flow over deposits of Tertiary age. Generally clayey with some thin sand beds along intermittent streams that flow over the Pierre Shale. Fluvial.	Locally, deposits are moderately permeable along the Little White River and relatively impermeable along streams that flow over the Pierre Shale. Yields generally are adequate to supply domestic and stock wells except along streams that flow over the Pierre Shale. Water is fresh, low in concentrations of dissolved solids, and soft to moderately hard except in deposits underlain by the Pierre Shale.
		Windblown sand deposits	0-150	Brown, unconsolidated, very fine to medium grained, uniform, quartz sand; characterized by dune topography and blowouts. Eolian.	Generally very permeable and water bearing; yields are adequate to supply stock and domestic wells except where deposits are small.
		Terrace deposits	0-105	Brown, silty clay, sand, and gravel. Commonly, the silty and sandy layers are partly cemented, and the gravel and sand beds commonly are interbedded with laminated silty clay. Fluvial.	Generally water bearing in the basal portion of the deposits. Yields are usually adequate to supply stock and domestic wells. Water is fresh, low in concentrations of dissolved solids, and soft to moderately hard except in areas where the water-bearing deposits are underlain by the Pierre Shale.
	Tertiary	Ogallala Formation	0-240	Tan to olive, fine- to medium-grained sandstone with some silty clay. Upper unit of Ogallala Formation also is known as the Ash Hollow Formation and the lower unit as the Valentine Formation. Fluvial.	The upper part of the formation generally has low permeability, but small seeps occur near its base. The lower part of the formation can be very permeable and generally is water-bearing; yields are adequate to supply stock and domestic wells and can supply irrigation wells in some areas. Water is fresh, low in concentrations of dissolved solids, and soft to moderately hard.
		Arikaree Formation	0-620	Pinkish tan to red; consists of poorly consolidated, tuffaceous sandstone, siltstone, shale, and silty clay. The Rosebud Formation sometimes is differentiated as a unit within the Arikaree Formation. Basal unit is composed mostly of silts and sands. Fluvial.	The upper part of the formation generally has low permeability, but can yield small amounts of water from fractures, joints, and silty layers. The basal part is moderately permeable and can supply water for domestic and stock wells. Water is fresh, low in concentrations of dissolved solids, and soft to moderately hard.
		White River Group (undifferentiated)	0-470	Yellow to brown, poorly consolidated siltstone and claystone with some beds of fine sand. Units of the White River Group sometimes are differentiated into the Brule and Chadron Formations. Fluvial.	Permeability varies from low to moderate, depending on the clay content. Yields are usually adequate to supply water to stock and domestic wells. Water is slightly saline, moderate in concentrations of dissolved solids, and hard depending on the proximity of the aquifer to the Pierre Shale.

Mesozoic	Cretaceous	Pierre Shale	600-1,395	Bluish-black shale with some layers of bentonite. Marine.	Most of the formation is relatively impermeable. Can yield small amounts of water if fractures or sandy zones are present. Typically not considered an aquifer. Water is saline, high in concentrations of dissolved solids, and very hard.
		Niobrara Formation	125-175	Tan to gray, highly calcareous shale. Commonly described by drillers as "chalk." Marine.	Water-bearing traits are largely unknown. May yield sufficient water for some purposes.
		Carlile Shale	300-400	Light grayish blue to black, noncalcareous shale. Marine.	Very low permeability. Water-bearing traits are largely unknown.
		Greenhorn Formation	100-120	Tan, bluish, white, or gray calcareous shale. Marine.	Water-bearing traits are largely unknown.
		Graneros Shale	130-200	Dark-gray non-calcareous shale. Marine.	Very low permeability. Water-bearing traits are largely unknown.
		Dakota Formation (Dakota Sandstone)	270-340	Interbedded tan to white sandstone and dark-colored shale. Sandstone is composed of loose to well-cemented, very fine to coarse quartz sand; cement most commonly is calcium carbonate. Marine.	Permeable sandstone beds yield moderate quantities of water under artesian pressure for stock and domestic wells. The water is highly mineralized and cannot be used for irrigation purposes.
		Skull Creek Shale	95-150	Dark bluish-gray shale. Marine.	Very low permeability. Water-bearing traits are largely unknown.
		Inyan Kara Group (undifferentiated)	100-275	White to light-gray or tan sandstone and siltstone; contains beds of gray to black and reddish to buff shale. The Inyan Kara Group sometimes is divided into the Fall River and Lakota Formations. Continental to marginal marine.	Permeable sandstone beds yield moderate quantities of water under artesian pressure for stock and domestic wells. The water is highly mineralized and cannot be used for irrigation purposes.
Paleozoic	Permian and Pennsylvanian	Minnelusa Formation	300-530	Consists of interbedded sandstone, siltstone, dolomite, limestone, anhydrite, and shale. Marine.	Permeable zones can yield adequate water for stock and domestic wells under artesian pressure. Water is lower in dissolved solids than the Dakota Sandstone and Inyan Kara aquifers. Can be used for irrigation on crops that are tolerant of salt with proper salinity management.
	Mississippian	Madison Formation	90-240	Light gray to buff, varies from pure limestone to pure dolomite with various combinations of the two. Marine.	Permeable zones can yield adequate water for stock and domestic wells under artesian pressure. Water is lower in dissolved solids than the Dakota Sandstone and Inyan Kara aquifers. Can be used for irrigation on crops that are tolerant of salt with proper salinity management.
	Ordovician	Red River and Winnipeg Formations (undifferentiated)	0-170	The Red River Formation mostly consists of dolomite, and the Winnipeg Formation mostly consists of sandstones. Marine.	Water-bearing traits largely unknown. Not used as an aquifer in vicinity of study area.
Precambrian				Granite.	Water-bearing traits largely unknown. Not used as an aquifer in vicinity of study area.

occurs in the basal part of the lower unit. Thickness of the upper unit ranges from 0 to 40 feet and the lower unit ranges from 0 to 200 feet. The upper unit forms the caprock on the isolated buttes and ridges in the southeastern and northwestern parts of Todd County. The lower unit forms the gently rolling grasslands in south-central Todd County. The upper unit of the Ogallala Formation also is known as the Ash Hollow Formation, and the lower unit also is known as the Valentine Formation.

Hydrogeologic Setting

The shallow aquifers in the study area are the alluvial, Ogallala, Arikaree, and White River aquifers. These shallow aquifers consist primarily of unconsolidated sand and gravel or poorly consolidated sandstones and siltstones. The deeper, bedrock aquifers are the Pierre, Dakota Sandstone, Inyan Kara, Minnelusa, and Madison aquifers. In the southern part of the study area, ground water generally can be obtained from shallow wells (less than 300 feet) completed either in Quaternary-age alluvial deposits or in Tertiary-age deposits (Ogallala Formation, Arikaree Formation, or White River Group). Ground water is more difficult to obtain in the northern part of the study area where the Tertiary deposits have been eroded resulting in surface exposure of the Pierre Shale (fig. 3).

The Ogallala aquifer comprises the saturated sandstones and silt of the Ogallala Formation. The upper unit of the Ogallala Formation has relatively low permeability, but small seeps occur near its base (Ellis and others, 1971). The lower unit of the Ogallala Formation generally is water bearing; however, the permeability of that unit varies with lithology (Ellis and others, 1971).

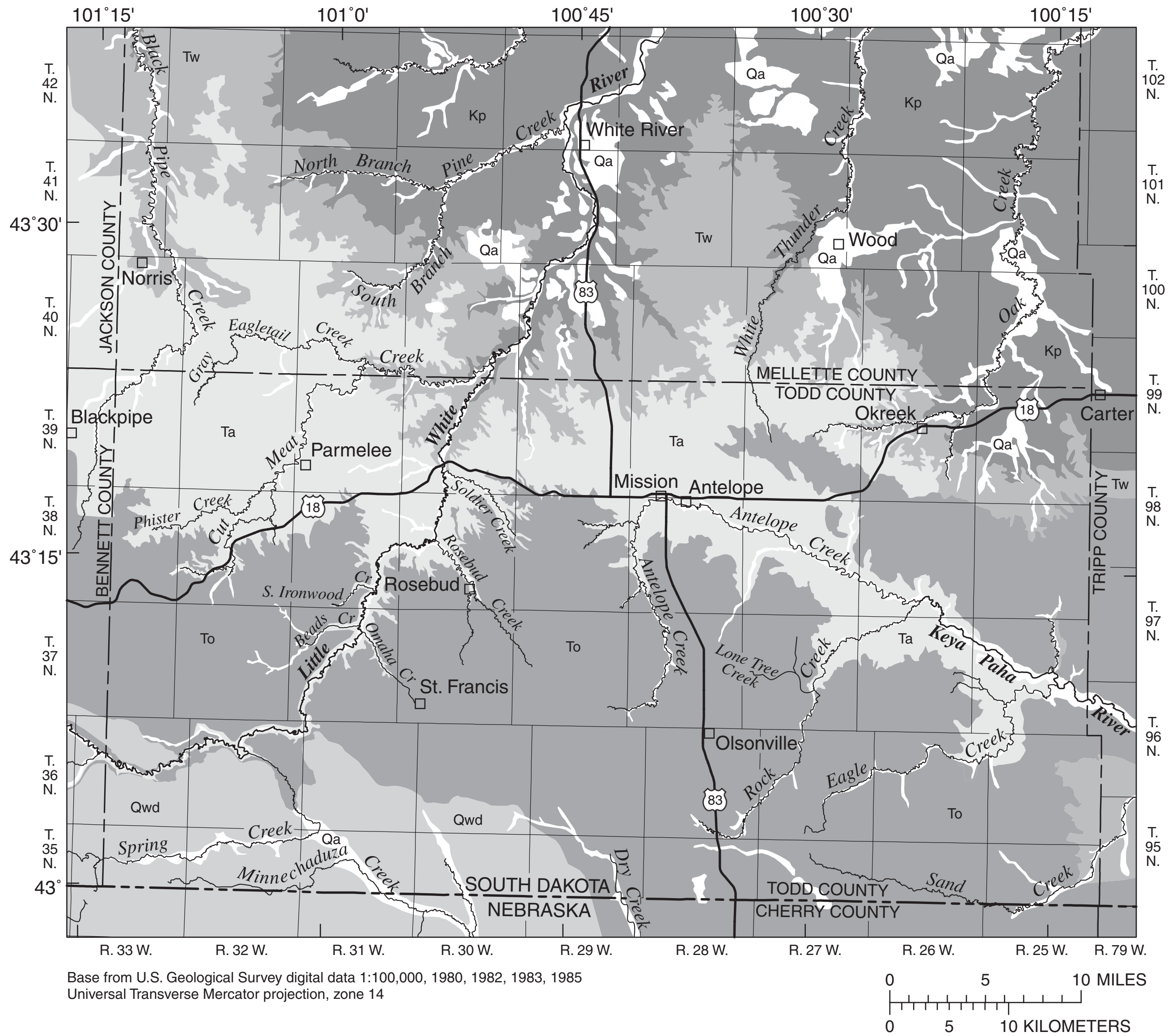
The Ogallala aquifer is present throughout most of the southern part of the study area, where it underlies 950 square miles in Todd County with an estimated 17 million acre-feet of water in storage (Carter, 1998). The Ogallala aquifer is not present in the northern part of the study area. The saturated thickness of the Ogallala aquifer in the study area averages 137 feet (Carter, 1998), and the aquifer is fully saturated in some areas. In the study area, the aquifer generally is thickest in the central portion of Todd County, where withdrawals from the aquifer for irrigation are highest. The Ogallala aquifer is overlain by unconsolidated deposits consisting of alluvium and windblown sand in the southwestern part of the study area (fig. 3).

The Ogallala aquifer is unconfined except in the southwestern part of the study area where the aquifer is confined by well-cemented or concretion beds in the upper part of the formation (Carter, 1998). Where unconfined, the depth to water ranges from 0 to greater than 150 feet below land surface (Carter, 1998). In some areas, the water table in the Ogallala aquifer can be considerably above the altitude of stream bottoms, and numerous seeps occur along hillsides and cliffs in these areas. The Ogallala aquifer has the highest yield potential of all aquifers in the study area with wells yielding from 1 to 1,250 gallons per minute (Carter, 1998).

The Arikaree aquifer generally comprises the saturated sandstones and siltstones of the Arikaree Formation. The Arikaree Formation underlies the Ogallala aquifer, where present, everywhere in the study area except in the extreme eastern part of Todd County where the Arikaree Formation does not exist. Beds in the upper clayey part of the Arikaree Formation are composed of relatively low-permeability material, but generally yield water from fractures, joints, and thin silty zones (Ellis and others, 1971). The basal sandy and silty part of the formation is moderately permeable (Ellis and others, 1971).

The Arikaree aquifer underlies 1,360 square miles in Todd and Mellette Counties with an estimated 50 million acre-feet of water in storage (Carter, 1998). The thickness of the Arikaree aquifer ranges from 0 to 618 feet, with an average of 290 feet (Carter, 1998). In the study area, the Arikaree aquifer is thickest in southern Todd County.

The Arikaree aquifer generally is confined where overlain by less permeable materials in the lower part of the Ogallala Formation, and the lower part of the Arikaree aquifer can be confined where low-permeability material occurs in the upper part of the aquifer. Hydraulic heads in the aquifer generally are within 60 feet below land surface under confined conditions, and range from 0 to greater than 150 feet under unconfined conditions (Carter, 1998). Like the Ogallala aquifer, the water table in the Arikaree aquifer can be considerably higher in some areas than the altitude of stream bottoms, and numerous seeps occur along hillsides and cliffs in these areas. Well yields range from 1 to 1,005 gallons per minute depending on clay content in the aquifer, consolidation of the materials, and well construction; yields generally are less than those from the Ogallala aquifer but are substantially greater than yields from the underlying White River aquifer (Carter, 1998).



EXPLANATION

QUATERNARY-AGE UNCONSOLIDATED DEPOSITS

- Qa — Alluvium and terrace deposits
- Qwd — Windblown sand deposits

TERTIARY-AGE SEDIMENTARY DEPOSITS

- To — Ogallala Formation
- Ta — Arikaree Formation
- Tw — White River Group

CRETACEOUS-AGE SEDIMENTARY DEPOSITS

- Kp — Pierre Shale

Figure 3. Generalized geologic map showing surficial geology of study area (modified from Ellis and others, 1971).

SIMULATED GROUND-WATER FLOW

A conceptual model of the Ogallala and Arikaree aquifers was used to analyze ground-water flow and to develop a numerical model to simulate ground-water flow in the aquifers. Steady-state and transient simulations were done with the numerical model. For transient simulations, a 20-year period (1979-98) was subdivided into 60 stress periods.

Conceptual Model

The conceptual model includes the potentiometric surface, hydraulic properties, and recharge and discharge components. The conceptual model and simplifying assumptions are discussed in this section.

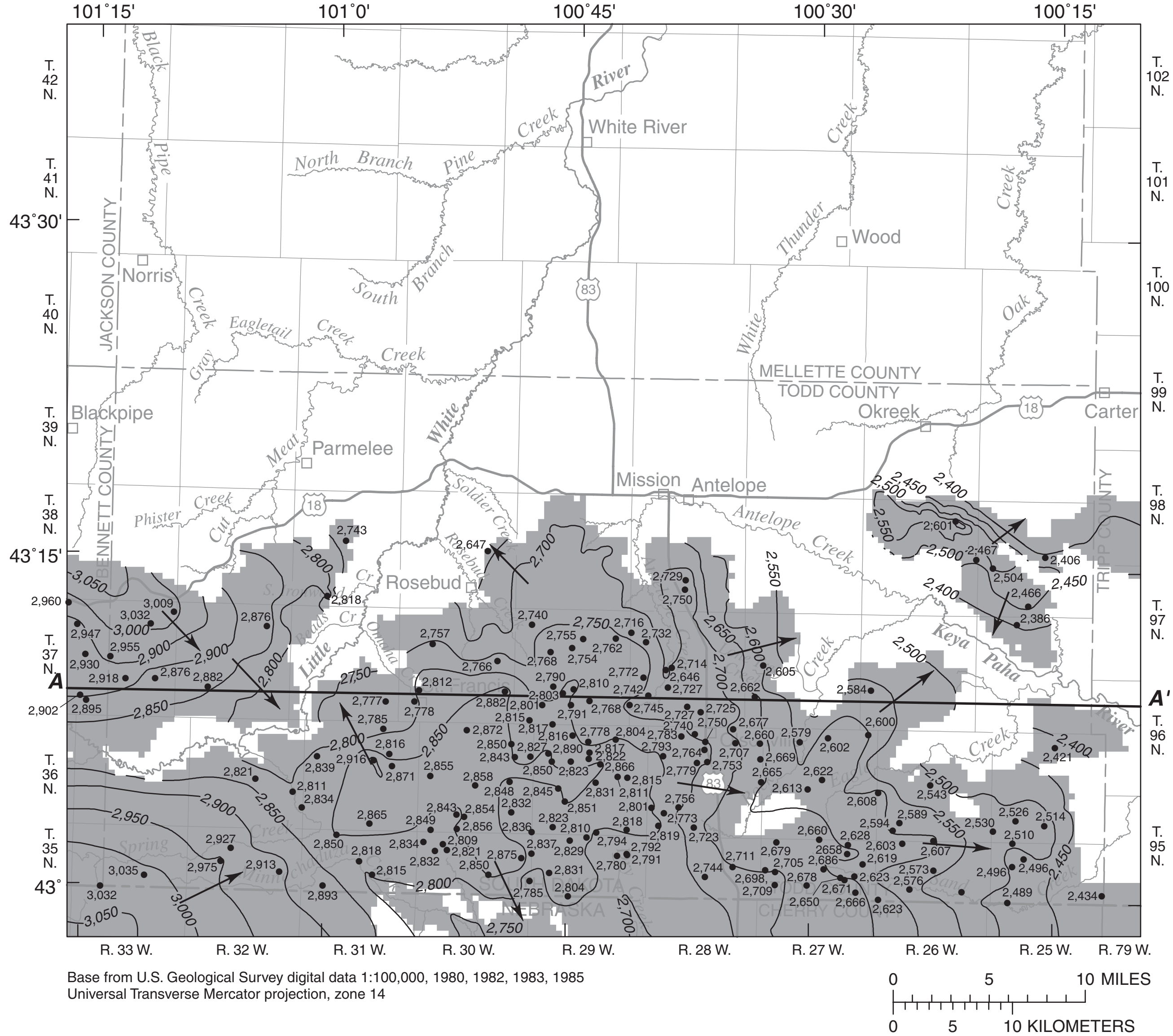
The windblown deposits overlying the Ogallala aquifer in the southwest part of the study area are composed of fine- to medium-grained sand, similar to that of the Ogallala Formation, and were included with the Ogallala aquifer as a single layer for ground-water flow analysis. The Ogallala and Arikaree aquifers were assumed to be hydraulically connected. The White River Group contains an aquifer but was considered an underlying confining unit because of numerous clay lenses that impede vertical ground-water movement.

Areal recharge to the Ogallala and Arikaree aquifers occurs from precipitation on the outcrop areas, and regional flow enters the study area from the west. Ground water from areal recharge moves from areas of higher altitude toward streams that gain flow from the Ogallala and Arikaree aquifers. Discharge by evapotranspiration from the aquifers occurs in areas where the water table is near the land surface, which generally occurs in topographically low areas. Many of the springs that discharge along the banks of the Little White and Keya Paha Rivers probably flow from the Ogallala aquifer because the Arikaree aquifer generally has lower permeability than the Ogallala aquifer. The Arikaree aquifer discharges to springs and seeps on the northern boundary of the aquifer where the surface drainage is towards the north. In addition, discharge from the aquifers occurs through withdrawals from irrigation, domestic, and stock wells.

For analysis of ground-water flow, data for a twenty-year period (WY 1979-98) were analyzed. Each water year was subdivided into three periods (hereinafter referred to as stress periods) for a total of 60 stress periods for analysis based on the hydrologic characteristics of each period: (1) a fall and winter period, which included the months of October through February; (2) a spring period, which included the months of March through May; and (3) a summer period which included the months of June through September. The 60 stress periods are numbered 1 through 60 starting with the fall and winter period of WY 1979. For example, fall and winter of WY 1979 is stress period 1, spring of WY 1979 is stress period 2, and summer of WY 1979 is stress period 3. During most of the fall and winter period, evapotranspiration is very small because the ground is frozen, plant growth is limited, and precipitation is less than in the spring or summer periods. During the spring period, precipitation is greater than during the fall and winter period, and the evapotranspiration rate is less than during the summer period. During the summer period, evapotranspiration is greatest and irrigation withdrawals are largest.

Potentiometric Surface

Average potentiometric surfaces were estimated for the analysis period (WY 1979-98) for the Ogallala and Arikaree aquifers (figs. 4 and 5, respectively) for calibration of the steady-state model. Boundaries of the aquifers were modified from Carter (1998) to represent areas with sufficient saturation for inclusion in the numerical model. The parts of the aquifers not included were areas where saturation was intermittent or that generally had less than 10 feet of saturation. Water levels during 1996 were documented by Carter (1998) for wells completed in the Ogallala and Arikaree aquifers. Long-term water-level records are available for 17 observation wells completed in the Ogallala aquifer and 6 observations wells completed in the Arikaree aquifer that are maintained by the South Dakota Department of Environment and Natural Resources (State observation wells). During the 20-year period, some of the water levels for wells with long-term records increased, some decreased, and some changed very little. Water levels changed as much as about 6 feet for the Ogallala aquifer and 12 feet for the Arikaree aquifer. These water levels generally fluctuate between 1 and 4 feet seasonally.



EXPLANATION

AREA OF THE OGALLALA AQUIFER CONSIDERED

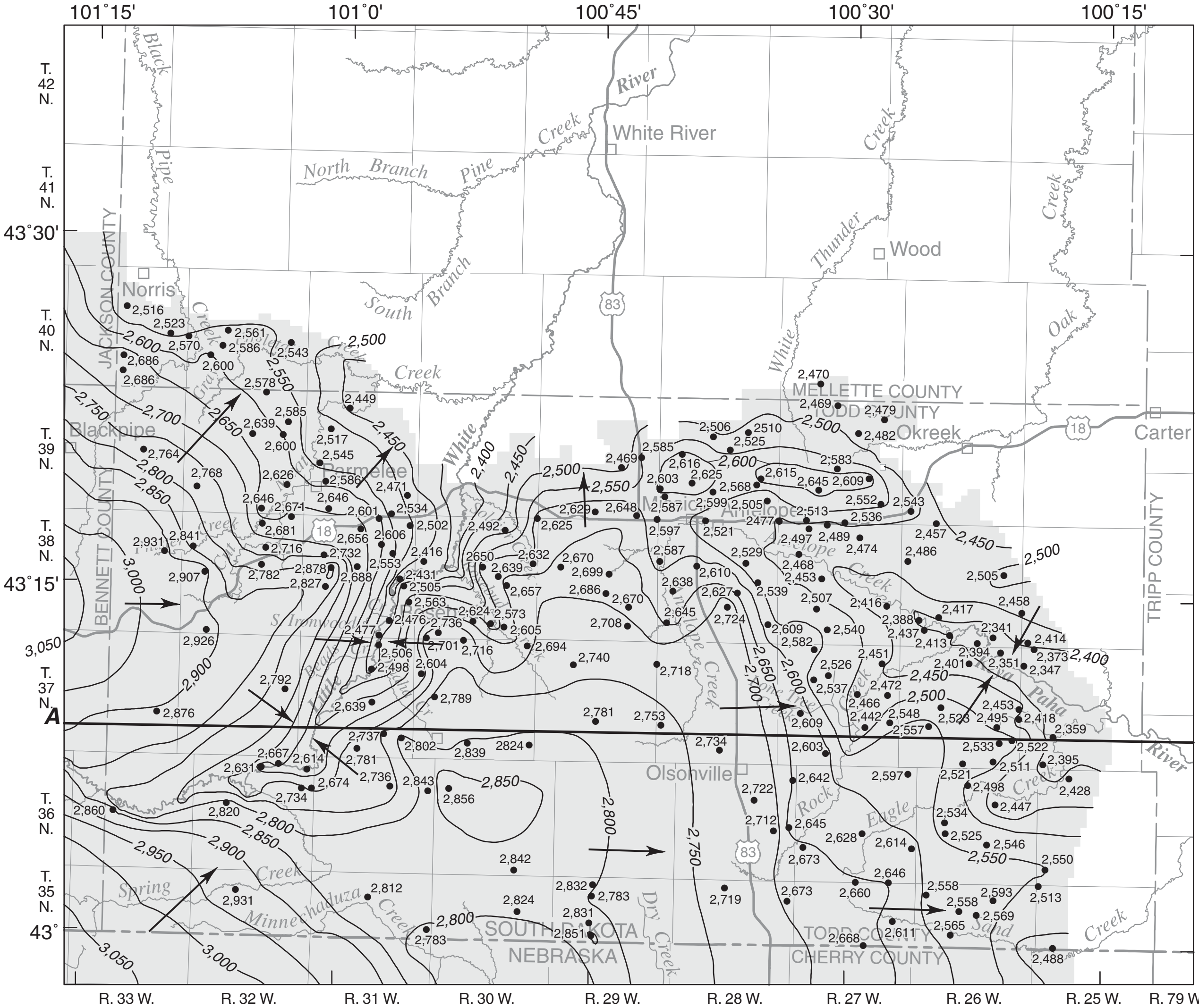
A — A' LINE OF GEOLOGIC SECTION (figure 6)

—*2,400*— POTENTIOMETRIC CONTOUR—Shows average altitude at which water level would have stood in tightly cased wells, 1979-98. Contour interval is 50 feet. Datum is NGVD of 1929.

⟶ GENERAL DIRECTION OF GROUND-WATER FLOW

• 2,804 WATER WELL—Number is estimated average hydraulic head for water years 1979-98, in feet above NGVD of 1929

Figure 4. Estimated average potentiometric surface of the Ogallala aquifer (modified from Carter, 1998).



Base from U.S. Geological Survey digital data 1:100,000, 1980, 1982, 1983, 1985
Universal Transverse Mercator projection, zone 14

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

AREA OF THE ARIKAREE AQUIFER CONSIDERED

A'——A' LINE OF GEOLOGIC SECTION (figure 6)

—2,800— POTENTIOMETRIC CONTOUR—Shows average altitude at which water level would have stood in tightly cased wells, 1979-98. Contour interval is 50 feet. Datum is NGVD of 1929.

——→ GENERAL DIRECTION OF GROUND-WATER FLOW

• 2,824 WATER WELL—Number is estimated average hydraulic head for water years 1979-98, in feet above NGVD of 1929

Figure 5. Estimated average potentiometric surface of the Arikaree aquifer (modified from Carter, 1998).

For the wells with long-term records, average water levels for the 20-year period were calculated, and the difference between the 20-year average water level and the 1996 water level was calculated for each well. The calculated differences for the Ogallala aquifer ranged from -1.9 to 4.1 feet with a mean difference for the 17 wells of -1.0 foot. The difference was positive at only four of the 16 wells located in the southeastern, south-central, and northwestern parts of the study area. The calculated differences for the Arikaree aquifer ranged from -5.7 to 4.9 feet with a mean difference for the six wells of -1.8 ft. The difference was positive at only one of the seven wells located in the south-central part of the study area. A continuous surface was interpolated from these differences using an inverse-distance-weighting method. Single water-level measurements made during 1996 at 398 water wells were adjusted to an average for the 20-year period by adding the value of the interpolated difference surface at each well's location to obtain an estimated water-level altitude.

These estimated and calculated average water-level altitudes for 398 wells were used as control points to construct the estimated average potentiometric surfaces. Because the estimated average water levels are generally based on only one measurement and the long-term records of nearby observation wells, the estimates do not necessarily represent accurate average values; however, because water-level fluctuations at observation wells were relatively small, potential errors in these estimates also are small. In addition, the accuracy of the estimated average potentiometric surface decreases with distance from control points. Average hydraulic heads for the wells used as control points are listed in tables 15 and 16, in the "Supplemental Information" section at the end of this report. Surface-water altitudes for perennial stream reaches also were used as control points.

Ground-water flow in both the Ogallala and Arikaree aquifers in the study area generally is to the east or northeast. Locally, ground-water flow is topographically controlled and is towards the Little White River, Keya Paha River, and associated tributaries (figs. 4 and 5). Ground water flows from recharge areas towards streams and topographically low areas where discharge occurs as base flow to streams or evapotranspiration. The relation between hydraulic heads and topographic features (fig. 6) shows the local influence of streams on the general northeasterly direction of ground-water flow. In particular, the Little White River, which is deeply incised into the Ogallala aquifer and to a lesser extent into the Arikaree aquifer, strongly influences ground-water flow. The Keya Paha River is hydraulically connected to the Arikaree aquifer (fig. 3), and tributary streams gain water from the Ogallala aquifer. A comparison of the surface-drainage basins (fig. 2) and the potentiometric surfaces (figs. 4 and 5) shows that ground-water divides are related to the surface-drainage basins.

Hydraulic head in the Ogallala aquifer ranges from about 3,000 feet on the western boundary of the study area to about 2,400 feet on the eastern boundary (fig. 4). To the east of the Little White River, ground-water flow is northwesterly toward the river from topographically higher areas. In the south-central portion of the study area, ground-water flow is southerly toward streams flowing into Nebraska. In the northeastern portion of the study area, ground-water flow is towards the Keya Paha River. In a small area in the northeastern part of the study area, ground water flows northerly from the topographic ridge.

Hydraulic head in the Arikaree aquifer ranges from about 3,000 feet on the western and southwestern boundary of the study area to about 2,400 feet on the northeastern boundary of the aquifer (fig. 5). Ground-water flow in the Arikaree aquifer is similar to flow in the Ogallala aquifer in areas where the Arikaree aquifer is overlain by the Ogallala aquifer. Ground-water flow in the northern portion of the study area, where the Arikaree Formation is exposed, is northerly following the topography.

Hydraulic Properties

Hydraulic properties of the Ogallala and Arikaree aquifers in and near the study area have been estimated by previous investigators (table 2). For the High Plains aquifer, hydraulic conductivities in south-central South Dakota, estimated from 205 well logs, ranged from 3.6 to 160 feet per day, with an average of 30 feet per day (Kolm and Case, 1983).

For the Ogallala aquifer, hydraulic conductivities determined from aquifer tests in south-central Todd County ranged from 7.9 to 21.6 feet per day, and specific yields ranged from 0.02 to 0.03 (Kremlin-Smith, 1984). Hydraulic conductivities estimated from specific capacity data for 21 wells ranged from 1.2 to 25.2 feet per day (Kremlin-Smith, 1984).

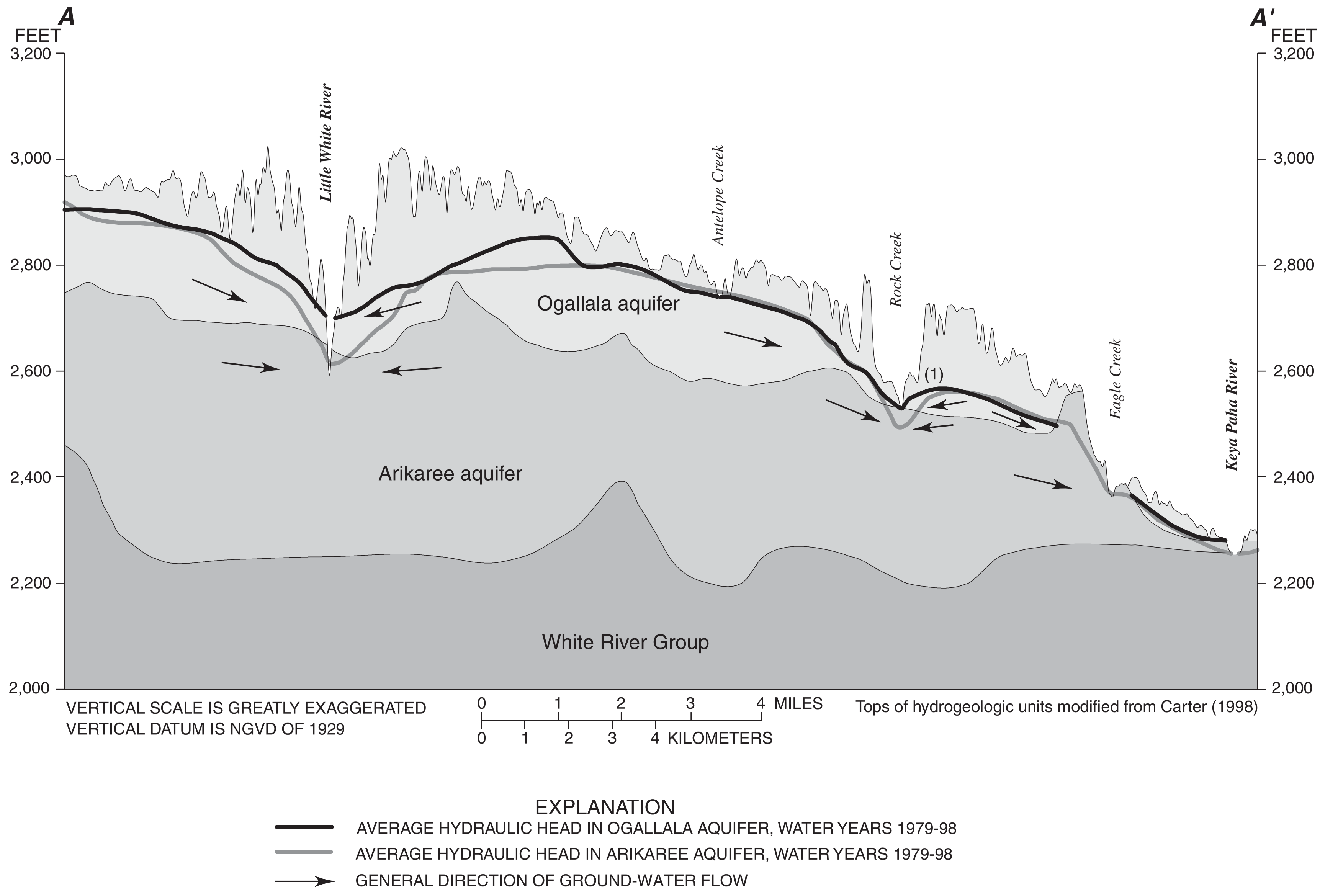


Figure 6. Relation between average hydraulic head, hydrogeologic units, and topographic features. Location of section is shown in figures 4 and 5. This section shows an area (1) of intermittent saturation, which is not included in the area of the Ogallala aquifer considered in figure 4.

Table 2. Previously published hydraulic properties within or near the study area

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

Method	In study area	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Storage coefficient (dimensionless)	Specific yield (dimensionless)	Location	Source
Ogallala Aquifer							
Time drawdown aquifer test	Yes	7,005	[1]70	$2.6x10^{-3}$	0.057	36N32W22	Rahn and Paul, 1975
Distance drawdown aquifer test	Yes	3,234	[1]32	$5.5x10^{-2}$	--	36N32W22	Rahn and Paul, 1975
Aquifer test	Yes	2,995	21.6	--	0.02	37N29W31CCA	Kremlin-Smith, 1984
Aquifer test	Yes	1,644	7.9	--	0.03	36N29W14CAC	Kremlin-Smith, 1984
Aquifer test	Yes	3,088	17.5	--	0.02	37N29W 8ABB	Kremlin-Smith, 1984
Specific capacity	Yes	180-3,476	1.2-25.2	--	--	Todd County	Kremlin-Smith, 1984
Specific capacity	Yes	2-2,400 Average 600	--	--	--	Todd County	Carter, 1998
Unknown	No	800-9,200 Average 2,800	--	--	--	16 wells to the south and east of Todd County within 100 miles of Todd County	Newport, 1959
Arikaree Aquifer							
Specific capacity	Yes	2-2,000 Average 90	--	--	--	Todd County	Carter, 1998
Aquifer test	No	1,250	13	$7.0x10^{-3}$	0.03	Shannon County 35N44W17	Greene and others, 1991
Aquifer test	No	300	1	$3.0x10^{-4}$	--	Shannon County 35N44W17	Greene and others, 1991
Aquifer test	No	310	1.0	$3.9x10^{-4}$	--	Shannon County 35N44W	Sipe, 1989
Time drawdown (single well)	No	298	1.0	$3.9x10^{-4}$	--	Shannon County 35N44W	Sipe, 1989
Time recovery (single well)	No	326	1.0	--	--	Shannon County 35N44W	Sipe, 1989
Core sample	No	--	2	--	--	Sioux County, Nebraska 28N55W6	Bradley, 1956
High Plains Aquifer[2]							
Grain size descriptions	Yes	--	3.6-160 Average 30	--	0-0.25	Todd County	Kolm and Case, 1983

[1]Calculated from transmissivity based on saturated thickness of 100 feet.
[2]Includes Ogallala aquifer and upper Arikaree aquifer.

Based on aquifers tests of the Arikaree aquifer near Pine Ridge, South Dakota (located about 70 miles west of the study area), Sipe (1989) estimated hydraulic conductivity to be 1.0 foot per day and storage coefficient to be $3.9x10^{-4}$. Greene and others (1991) reported aquifer tests in two of the sandier units of the Arikaree aquifer near Pine Ridge. Hydraulic properties determined for an upper unconfined unit composed of fine to medium sand include hydraulic conductivity of 13 feet per day, storage coefficient of $7x10^{-3}$, and specific yield of 0.03. Hydraulic properties determined for a lower confined unit composed of fine to very fine sand include hydraulic conductivity of 1 foot per day and storage coefficient of $3x10^{-4}$. The hydraulic conductivity of a core sample from the Arikaree Formation in Nebraska was about 2 feet per day (Bradley, 1956).

Recharge

Recharge to the Ogallala aquifer occurs from infiltration of precipitation on the outcrop of the Ogallala Formation and the windblown sands in the southeast portion of the study area. Recharge to the Arikaree aquifer occurs from infiltration of precipitation on the outcrop of the Arikaree Formation.

Previous investigators have estimated recharge for the High Plains aquifer, which includes the Ogallala and Arikaree aquifers. These estimates include 15 percent of precipitation or 2.5 to 3.0 inches per year (Langbein, 1949), 2.6 inches per year in the upper Niobrara River Basin (Bradley, 1956), 1.0 to 2.5 inches per year (McGuinness, 1963), 3.07 inches per year for the Sand Hills of Nebraska (Rahn and Paul, 1975), and 8 percent of precipitation or 1.3 to 1.8 inches per year for South Dakota (Kolm and Case, 1983). The lower permeability of the Arikaree aquifer, particularly in the upper part, may prevent that aquifer from accepting as much recharge as the Ogallala aquifer. The range of estimated values given by all of these investigators is 1.0 to 3.07 inches per year, which is equal to 111 to 341 cubic feet per second when applied over the outcrop areas of the Ogallala and Arikaree aquifers in the study area (1,509 square miles).

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. Discharge to streams occurs as springs and seeps. For the purpose of this analysis, all spring discharge is assumed to reach a stream and contribute to base flow. Well withdrawals are from irrigation, domestic, and stock wells.

Evapotranspiration

Evapotranspiration is an important mechanism of ground-water discharge from the Ogallala and Arikaree aquifers. Evapotranspiration occurs when the water table is at or near the land surface and thus generally occurs in topographically low areas such as river valley bottoms. Maximum evapotranspiration occurs when the water table is at the land surface; however, evapotranspiration is limited by the depth of the root zone. Generally, the depth of this root zone is assumed to be 5 to 10 feet in the study area, with deeper root penetration associated with trees. Areas of trees are common up to one-half mile from the Little White River and its tributaries between Spring Creek and Soldier Creek. Trees also are common near streams along the northern extent of the outcrop of the Arikaree Formation (fig. 3). Other parts of the study area are generally grasslands or agricultural.

Maximum evapotranspiration during summer stress periods was estimated as about 70 percent of pan evaporation based on the relation between pan evaporation and evapotranspiration described by Farnsworth and others (1982). Pan evaporation rates in the study area were assumed to be similar to those at a National Weather Service climatological data station at Cottonwood (U.S. Department of Commerce, 1978-98), which is located about 75 miles northwest of the study area. Pan evaporation records were available for the months of June through September for the 20 water years included in the analysis. The estimated maximum evapotranspiration for the 20 summer stress periods (table 3) ranged from 20.4 to 30.7 inches, with an average of 25.6 inches. Based on limited pan evaporation data for spring and late fall, a value for the spring stress periods was estimated as 9 inches, and a value for the winter stress periods was extrapolated as 3 inches. Based on these estimates, the maximum evapotranspiration was calculated as 6.3 and 2.1 inches, respectively, for the spring and winter stress periods. The estimated 20-year average maximum evapotranspiration rate was 34 inches per year. The actual evapotranspiration rate for the study area was not estimated because it is a complex process and dependent on multiple factors.

Table 3. Maximum evapotranspiration during summer stress periods, water years 1979-98

[--, not applicable]

Water year	Stress period	Pan evaporation (inches)	Maximum June-September evapotranspiration (inches)
1979	3	35.4	24.8
1980	6	41.5	29.1
1981	9	35.5	24.8
1982	12	31.3	21.9
1983	15	40.4	28.3
1984	18	38.0	26.6
1985	21	39.7	27.8
1986	24	29.9	20.9
1987	27	39.5	27.6
1988	30	43.8	30.7
1989	33	42.1	29.5
1990	36	40.5	28.3
1991	39	37.8	26.5
1992	42	30.8	21.6
1993	45	29.2	20.4
1994	48	37.4	26.2
1995	51	36.2	25.3
1996	54	39.5	27.7
1997	57	32.1	22.5
1998	60	31.3	21.9
Average	--	36.6	25.6

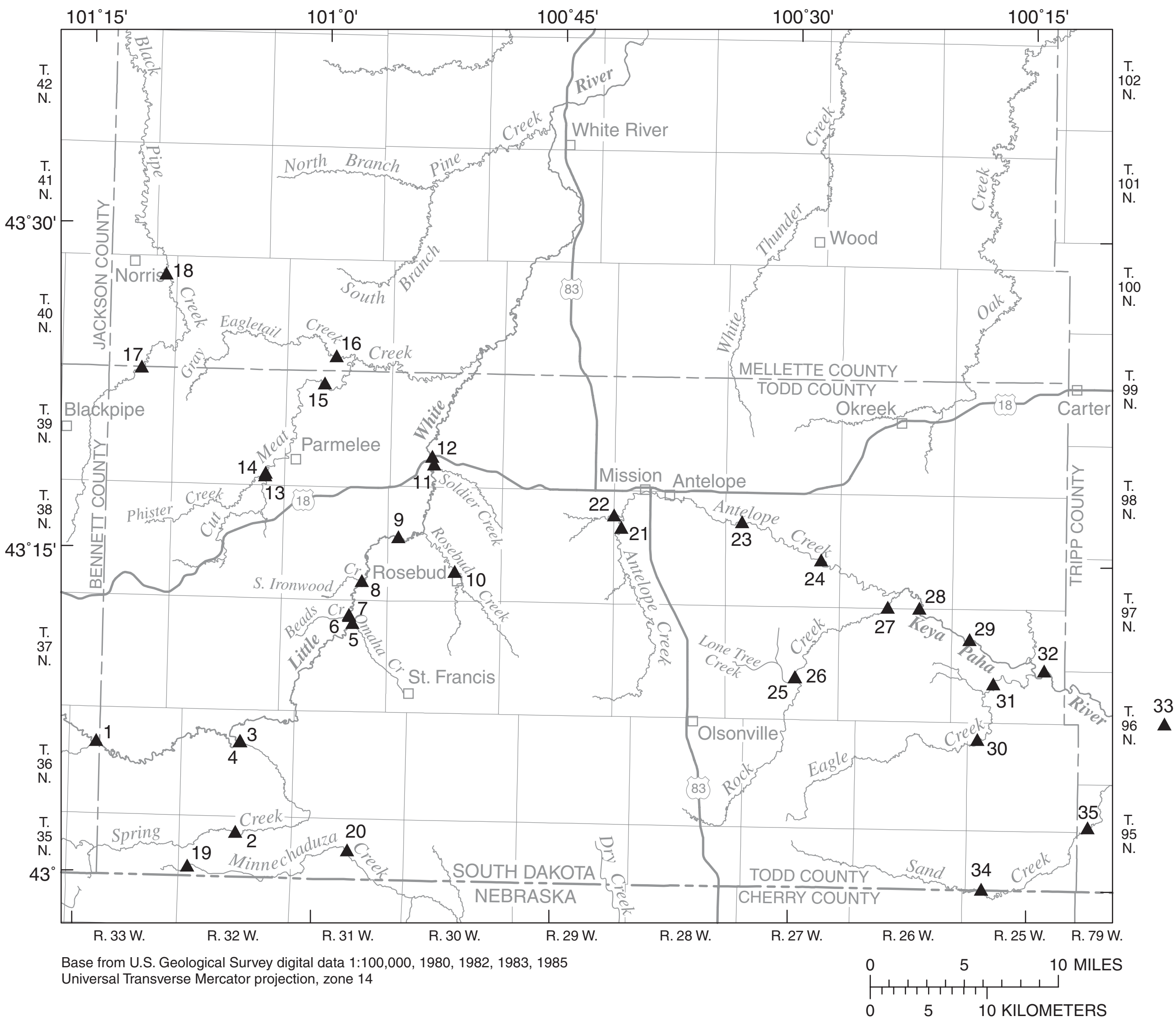
Discharge to Streams

Springs and seeps discharge ground water to streams in the study area. Seepage runs, which consisted of synoptic measurements of streamflow under near base-flow conditions, were conducted in the study area to obtain information describing streamflow gains in the study area. Streamflow was measured at 35 sites (fig. 7, table 4). These measurements were taken during periods when direct runoff was not observed to occur and thus represent near base-flow conditions. Although the seepage runs occurred during WY 1999, which was after the period considered in the model (WY 1979-98), the measurements provide insights regarding the relative magnitude of ground-water discharge that contributes to base flow in various streams.

Base flow in the Little White and Keya Paha Rivers in the study area was estimated for the 60 stress periods during WY 1979-98 using the hydrograph separation program, HYSEP (Sloto and Crouse, 1996). Streamflow at gaging stations 06449100 (Little White River near Vetal; site 1), 06449500 (Little White River near Rosebud; site 12), and 06464100 (Keya Paha River near Keyapaha; site 33) was used to estimate average base flow for each month in these two streams for the study area. Base flow for the Little White River Basin in the study area was determined by subtracting the base flow at site 1 from the base flow at site 12. All base flow estimated for site 33 was assumed to originate in the study area because the headwaters for the Keya Paha River are contained in the study area. Records for WY 1979-81 were unavailable for site 33; streamflow for this period was estimated from correlation with streamflow at downstream station 06464500 (Keya Paha River at Wewela).

Base flow calculated by HYSEP for the spring stress periods (March-May) generally increased dramatically from the fall-winter stress periods (October-February); however, actual base flow probably does not fluctuate to this magnitude. The large increases during the spring periods probably include a component of shallow interflow that occurs after periods of precipitation and possibly some direct runoff. The fall-winter periods are probably a better estimate of base flow, because these periods are influenced very little by recent precipitation. However, springtime base flow is assumed to increase somewhat in response to rising ground-water levels followed by a gradual decline during summer. Therefore, calculated base flow for spring periods was adjusted by reducing the increase from the fall-winter periods by 75 percent. The summer period was then estimated as the average of the two previous periods (table 5). Although this method is considered an improvement over the HYSEP estimate, it is only a very general estimate, and its accuracy has not been verified. The estimated 20-year average base flow was 49 cubic feet per second for the Little White River and 23 cubic feet per second for the Keya Paha River.

Other springs are located along the northern contact of the Arikaree Formation with the White River Group and discharge from the Arikaree aquifer into streams flowing to the north. Spring discharge probably takes place near this contact because of the very low permeability of the White River Group, which causes northerly flowing ground water to emerge as springflow.



EXPLANATION

10▲ MEASUREMENT SITE—Number is map label number in table 4

Figure 7. Streamflow measurement sites for seepage runs during water year 1999.

Table 4. Measured streamflow at selected sites during seepage runs in water year 1999

[e, estimated; --, not measured]

Map label (fig. 7)	Site identification number	Latitude	Longitude	Station Name	Streamflow (cubic feet per second)	
					July 27-29, 1999	Aug. 30-Sept. 1, 1999
				Little White River Drainage Basin		
1	06449100	430603	1011349	Little White River near Vetal, SD	72	44.9
2	430158101045400	430158	1010454	Spring Creek near Cody, NE	2.08	--
3	430610101044300	430610	1010443	Spring Creek near Spring Creek, SD	9.18	4.29
4	430611101044500	430611	1010445	Little White River below Spring Creek	117.4	66.1
5	431146100574900	431146	1005749	Omaha Creek near Rosebud, SD	0.91	0.79
6	431205100580200	431205	1005802	Beads Creek near Rosebud, SD	1.5	1.0
7	431208100580300	431208	1005803	Little White River below Beads Creek	117	75.6
8	431343100571700	431343	1005717	South Fork Ironwood Creek	1.77	1.60
9	06449300	431547	1005502	Little White River above Rosebud, SD	119	84.9
10	06449400	431414	1005126	Rosebud Creek at Rosebud, SD	8.0	7.84
11	431911100525200	431911	1005252	Soldier Creek near Rosebud, SD	1.73	1.88
12	06449500	431932	1005300	Little White River near Rosebud, SD	140	99.3
				Cut Meat Creek Drainage Basin		
13	431830101033400	431830	1010334	Phister Creek near Parmelee, SD	0.74	0.56
14	431837101033200	431837	1010332	Cut Meat Creek below Phister Creek	1.1	0.67
15	432249100595500	432249	1005955	Cut Meat Creek near Parmelee, SD	2.38	0.01
16	432405100591300	432405	1005913	Gray Eagletail Creek near Parmelee, SD	2.09	2.25
				Black Pipe Creek Drainage Basin		
17	432323101113300	432323	1011133	Black Pipe Creek near Black Pipe, SD	3.9	2.79
18	432743101100900	432743	1011009	Black Pipe Creek near Norris, SD	3.6	--
				Minnechaduza Creek Drainage Basin		
19	430021101075300	430021	1010753	Minnechaduza Creek near Cody, NE	e0.1	--
20	430114100574900	430114	1005749	Minnechaduza Creek near Kilgore, NE	2.72	[1]16.3
				Keya Paha River Drainage Basin		
21	06463900	431626	1004056	Antelope Creek near Mission, SD	2.0	3.17
22	431700100412500	431700	1004125	Antelope Creek tributary above Mission, SD	0.5	0.58
23	431648100331800	431648	1003318	Antelope Creek below Antelope Lake near Mission, SD	4.33	1.29
24	431506100281600	431506	1002816	Antelope Creek above Keya Paha River near Mission, SD	6.1	1.74
25	430940100294800	430940	1002948	Lone Tree Creek near Olsonville, SD	0.72	0.56
26	430940100294600	430940	1002946	Rock Creek below Lone Tree Creek	5.24	4.44
27	431258100240000	431258	1002400	Rock Creek near Mission, SD	9.39	8.56
28	431257100220000	431257	1002200	Keya Paha River below Rock Creek near Mission, SD	19.3	14.1
29	431132100184700	431132	1001847	Keya Paha River above Eagle Creek near Mission, SD	19.8	15.4
30	430645100185200	430645	1001852	Eagle Creek near Olsonville, SD	0.21	0.36

Table 4. Measured streamflow at selected sites during seepage runs in water year 1999–Continued

[e, estimated; --, not measured]

Map label (fig. 7)	Site identification number	Latitude	Longitude	Station Name	Streamflow (cubic feet per second)	
					July 27-29, 1999	Aug. 30-Sept. 1, 1999
				Keya Paha River Drainage Basin—Continued		
31	430930100171500	430930	1001715	Eagle Creek near Keyapaha, SD	1.56	2.21
32	431008100140300	431008	1001403	Keya Paha River below Eagle Creek, SD	22.0	15.6
33	06464100	430745	1000624	Keya Paha River near Keyapaha, SD	26.5	22.4
34	425959100174900	425959	1001749	Sand Creek near Valentine, NE	0	0
35	430254100111000	430254	1001110	Sand Creek near Keya Paha, SD	4.43	4.45

[1]Streamflow influenced by rain storm.

Well Withdrawals

Well withdrawals in the study area occur from irrigation, domestic, and stock wells. Withdrawals for irrigation use are much larger than for domestic and stock uses; thus, withdrawals for domestic and stock uses were assumed to be negligible. Municipal withdrawals also were considered negligible because of the small and disperse population.

Irrigation withdrawals from the Ogallala aquifer are especially important in Todd County. Pivot irrigation units were identified using aerial photographs. Most irrigation wells in the study area are located east of St. Francis (fig. 8), where the saturated thickness of the Ogallala aquifer is greatest. Of the 97 pivot irrigation units identified from aerial photographs in the study area, 94 were assumed to be completed in the Ogallala aquifer based on well data in the USGS Ground-Water Site Inventory (GWSI) database. Most of the wells used for irrigation in the study area were constructed in the 1970's, and well construction records are incomplete.

Water-use data are compiled every 5 years as part of the USGS National Water-Use Information Program in cooperation with local, State, and Federal agencies and is aggregated by counties for each State. The acres of irrigated land in Todd County that were compiled for 1985, 1990, and 1995 remained steady at slightly more than 10,000 acres (U.S. Geological Survey, 1996, 2001). The estimated area of traces for pivots shown in figure 8 is about 11,000 acres, which is close to the reported irrigated acreage. Irrigation withdrawals are variable because they are affected by numerous factors, such as climatic conditions, commodity prices, and energy costs.

Data on irrigation withdrawals from the Ogallala and Arikaree aquifers in the study area were compiled from the USGS Site-Specific Water-Use Data System (SWUDS) for the period of available record (1981-98). The SWUDS database includes irrigation water use reported by operators under specific water-use permits. The reported use for a permit can include more than one well or center-pivot irrigation system. In the study area, water-use records were identified for 41 of the center pivots (fig. 8) by examining well data in the GWSI database, which usually includes a water-rights permit number. When the water use reported under a specific permit included more than one center pivot, the reported values were allocated equally among the associated irrigation wells. Irrigation withdrawals for the remaining center pivots were estimated based on the average withdrawals for the 41 identified wells. Irrigation withdrawals for 1979 and 1980 were estimated based on the reported withdrawals in the early 1980's. The estimated irrigation withdrawal for the study area by year ranged from about 3,000 to 21,000 acre-feet, and averaged 8,415 acre-feet (table 6), or 34.8 cubic feet per second over a 4-month period at an average application rate of 8.7 inches per year. The average withdrawal rate is 11.6 cubic feet per second if a 12-month period is assumed. The largest estimated irrigation use during the analysis period was in 1989 when precipitation was about 4 inches below normal.

Table 5. Estimates of base flow in the Little White and Keya Paha Rivers, water years 1979-98

[--, not applicable]

Stress period	Time period	Base flow (cubic feet per second)		Stress period	Time period	Base flow (cubic feet per second)	
		Little White River	Keya Paha River			Little White River	Keya Paha River
1	Oct. 1978 - Feb. 1979	30	6	32	Mar. - May 1989	41	17
2	Mar. - May 1979	41	13	33	June - Sept. 1989	38	15
3	June - Sept. 1979	35	9	34	Oct. 1989 - Feb. 1990	40	14
4	Oct. 1979 - Feb. 1980	26	14	35	Mar. - May 1990	45	17
5	Mar. - May 1980	32	16	36	June - Sept. 1990	43	15
6	June - Sept. 1980	29	15	37	Oct. 1990 - Feb. 1991	51	12
7	Oct. 1980 - Feb. 1981	49	7	38	Mar. - May 1991	56	18
8	Mar. - May 1981	50	8	39	June - Sept. 1991	53	15
9	June - Sept. 1981	49	8	40	Oct. 1991 - Feb. 1992	49	16
10	Oct. 1981 - Feb. 1982	40	9	41	Mar. - May 1992	53	18
11	Mar. - May 1982	42	17	42	June - Sept. 1992	51	17
12	June - Sept. 1982	41	13	43	Oct. 1992 - Feb. 1993	51	13
13	Oct. 1982 - Feb. 1983	50	30	44	Mar. - May 1993	61	23
14	Mar. - May 1983	62	34	45	June - Sept. 1993	56	18
15	June - Sept. 1983	56	32	46	Oct. 1993 - Feb. 1994	44	18
16	Oct. 1983 - Feb. 1984	50	29	47	Mar. - May 1994	55	21
17	Mar. - May 1984	54	40	48	June - Sept. 1994	50	20
18	June -Sept. 1984	52	34	49	Oct. 1994 - Feb. 1995	38	19
19	Oct. 1984 - Feb. 1985	43	17	50	Mar. - May 1995	52	34
20	Mar. - May 1985	45	21	51	June - Sept. 1995	45	27
21	June - Sept. 1985	44	19	52	Oct. 1995 - Feb. 1996	46	43
22	Oct. 1985 - Feb. 1986	39	13	53	Mar. - May 1996	55	48
23	Mar. - May 1986	46	26	54	June - Sept. 1996	51	45
24	June - Sept. 1986	43	19	55	Oct. 1996 - Feb. 1997	85	48
25	Oct. 1986 - Feb. 1987	59	26	56	Mar. - May 1997	85	58
26	Mar. - May 1987	66	38	57	June - Sept. 1997	85	53
27	June -Sept. 1987	63	32	58	Oct. 1997 - Feb. 1998	48	34
28	Oct. 1987-Feb. 1988	48	14	59	Mar. - May 1998	58	39
29	Mar. - May 1988	52	22	60	June - Sept. 1998	53	36
30	June - Sept. 1988	50	18	Average	--	49	23
31	Oct. 1988 - Feb. 1989	36	13				

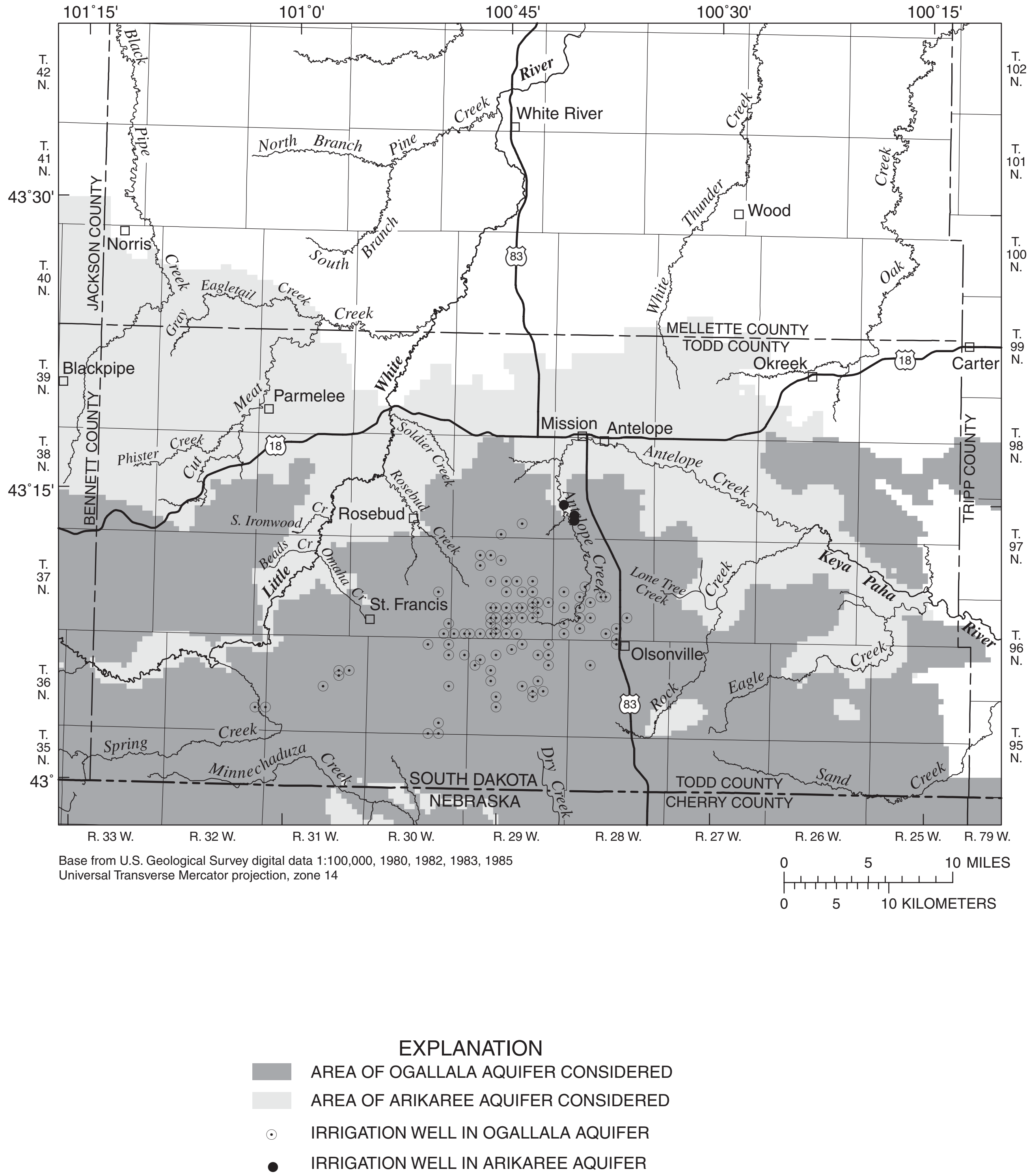


Figure 8. Locations of irrigation wells completed in the Ogallala and Arikaree aquifers.

Table 6. Estimated ground-water withdrawals for irrigation use in the study area, 1979-98

Year	Irrigation withdrawals			
	Acre-feet	Cubic feet per second[1]		
	Total	Total	Ogallala aquifer	Arikaree aquifer
1979	4,617	19.1	18.7	0.4
1980	4,617	19.1	18.7	.4
1981	4,697	19.4	18.7	.7
1982	3,291	13.6	13.5	.1
1983	5,861	24.2	24.0	.2
1984	4,385	18.1	17.9	.2
1985	7,763	32.1	31.9	.2
1986	7,344	30.4	30.4	0
1987	5,878	24.3	24.3	0
1988	11,561	47.8	47.7	.1
1989	20,843	86.1	85.9	.2
1990	11,314	46.8	46.8	0
1991	10,121	41.8	41.6	.2
1992	5,037	20.8	20.7	.1
1993	7,793	32.2	32.1	.1
1994	9,548	39.5	39.2	.3
1995	8,962	37.0	37.0	0
1996	15,284	63.2	63.0	.2
1997	12,198	50.4	50.3	.1
1998	7,192	29.7	29.5	.2
Average	8,415	34.8	34.6	.2

[1]Withdrawal rate based on a 4-month irrigation season (June-September).

Numerical Model

A numerical model of the Ogallala and Arikaree aquifers in the study area was used for steady-state and transient simulations of ground-water flow. A 20-year analysis period (WY 1979-98), which was temporally discretized into 60 seasonal stress periods as previously described, was used in the transient simulation. Design and calibration of the numerical model are described in the following sections.

Model Design

MODFLOW-2000 (Harbaugh and others, 2000), which is a numerical, three-dimensional, finite-difference ground-water model, was used to simulate flow in the aquifers. Detailed descriptions of MODFLOW-2000 packages that were incorporated in the model are presented in McDonald and Harbaugh (1988) and Harbaugh and others (2000). These packages included Layer-Property Flow, River, Recharge, Well, Drain, and Evapotranspiration. Average rates of recharge, maximum evapotranspiration, and well withdrawals were included in the steady-state simulation, whereas the time-varying rates that the averages were computed from were included in the transient simulation.

Grid and Boundary Conditions

The model grid consisted of two layers, each with 153 rows and 180 columns. All grid cells were 1,640 feet (500 meters) on a side. The upper layer (layer 1) represented the Ogallala aquifer, and the lower layer (layer 2) represented the Arikaree aquifer. The height of each cell was equal to the estimated formation thickness, which was determined based on structure-contour maps of the Arikaree Formation and White River Group (Carter, 1998) and a 30-meter digital elevation model (DEM) of the land surface. The DEM was used to represent the top of layer 1 and the top of layer 2 where the Arikaree Formation is exposed to the land surface. The altitude of the top of the Arikaree Formation represented the bottom of layer 1 and top of layer 2; the altitude of the top of the White River Group represented the bottom of layer 2.

Both layers were modeled so that cells were convertible between confined and unconfined conditions. Cells of constant hydraulic head were used on the western model boundary and the western part of the southern boundary for both layers and also in the southeastern corner for layer 1 (Ogallala aquifer) (figs. 9 and 10). All other boundaries were designated as "no-flow boundaries," which includes the edges of the aquifers or where model boundaries were approximately parallel to the estimated ground-water flow direction.

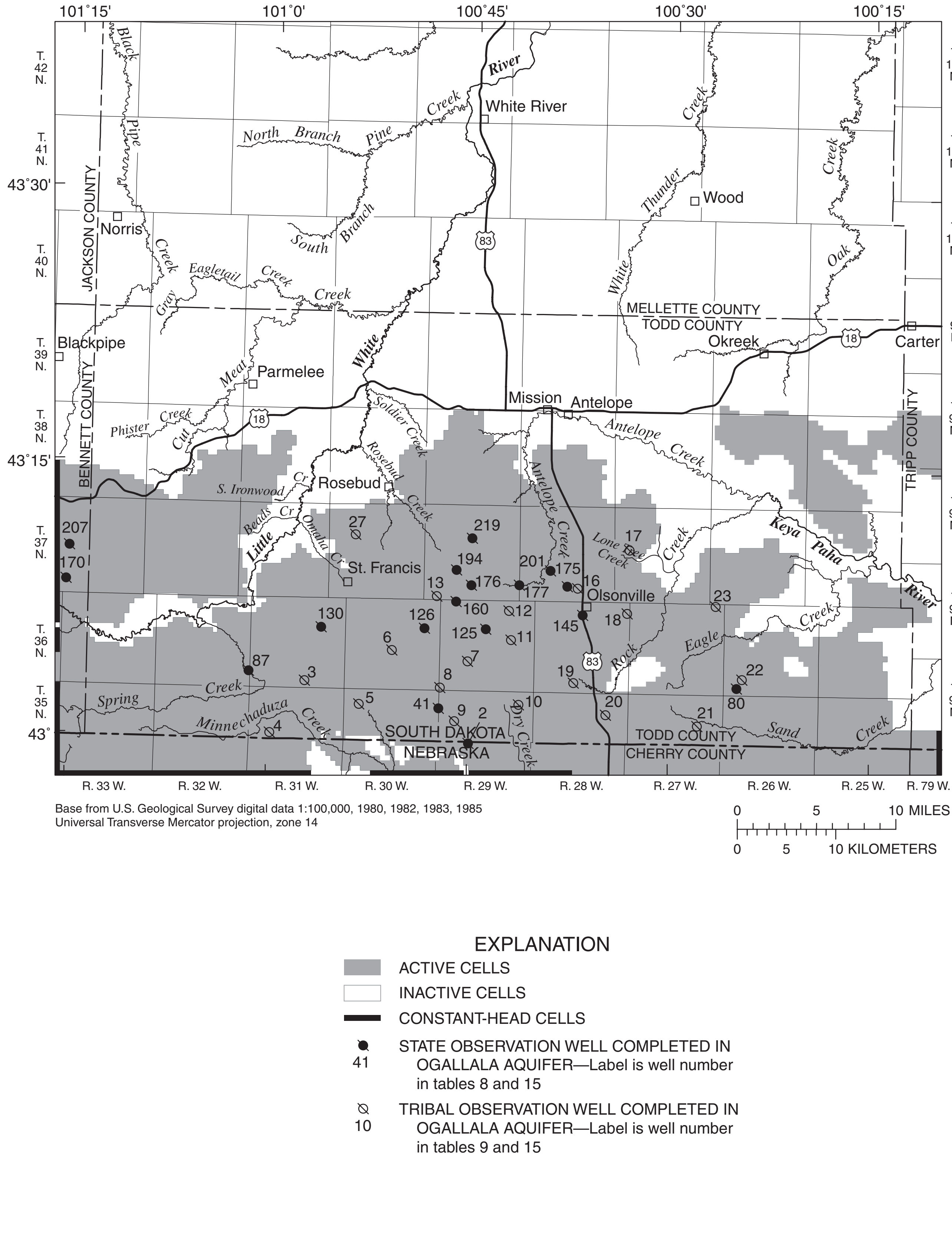


Figure 9. Cell types in the Ogallala aquifer (layer 1). Locations of observation wells completed in Ogallala aquifer also are shown.

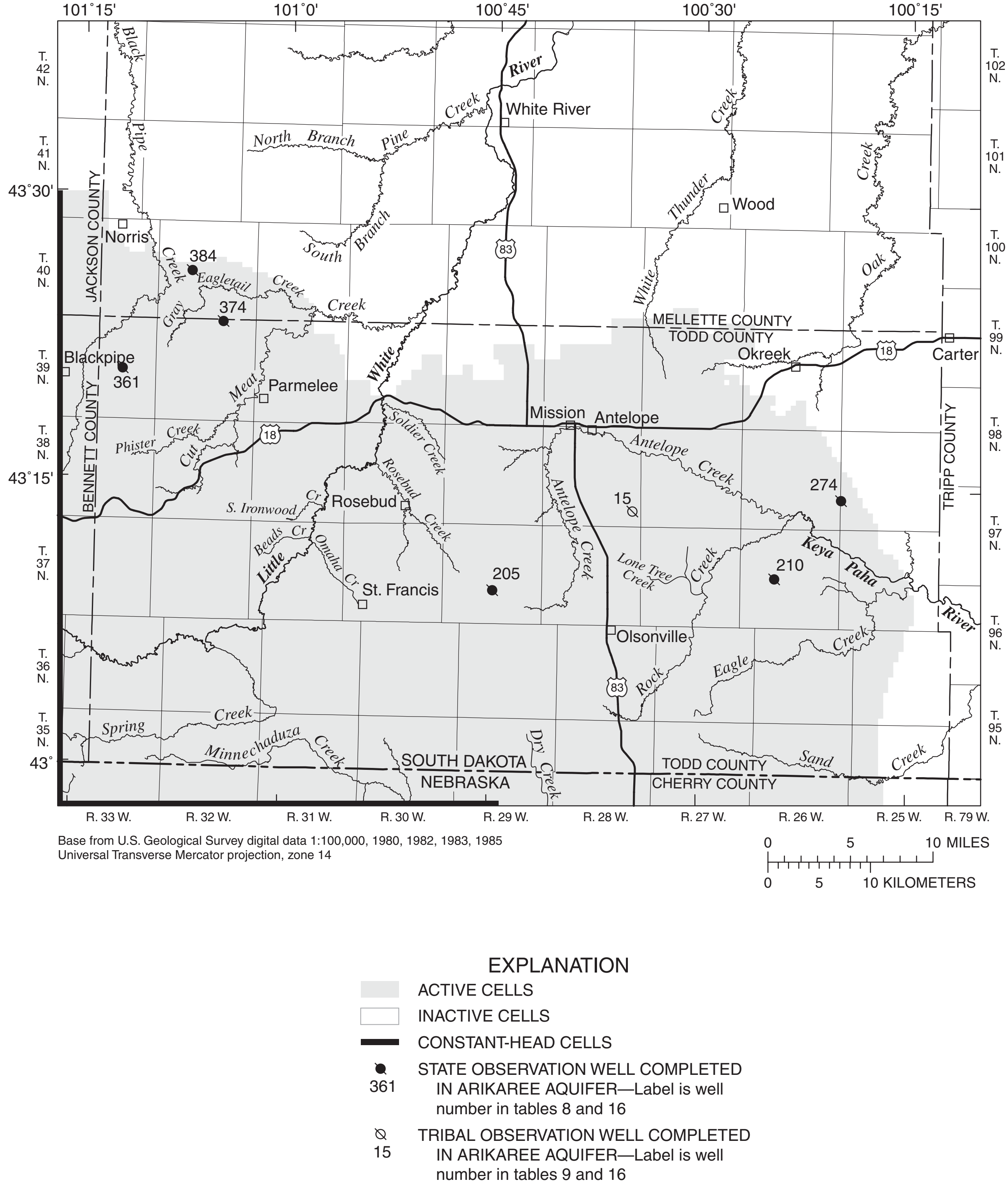


Figure 10. Cell types in the Arikaree aquifer (layer 2). Locations of observation wells completed in Arikaree aquifer also are shown.

Representation of Hydraulic Properties

Estimated horizontal hydraulic conductivity for the Ogallala aquifer ranged from 0.2 to 120 feet per day (fig. 11). Estimated values were based on previously published values (table 2), the spatial distribution of specific capacities in the study area (fig. 12), and model calibration. Specific capacity computed for 64 wells completed in the Ogallala aquifer ranges from 0.01 to 58.0 gallons per minute per foot, with an average of 3.8 gallons per minute per foot. Figure 12 shows the generalized distribution of specific capacity in the Ogallala aquifer based on these 64 wells. These specific capacity ranges do not represent actual values because the data were smoothed and compared relatively within the study area. The greater specific capacity in the central part of the model area between the Little White and Keya Paha Rivers coincides with a concentration of irrigation pivots, and the overall specific capacity distribution is generally consistent with the distribution of hydraulic conductivity shown in figure 11. Kolm and Case (1983) analyzed grain-size distributions to estimate horizontal hydraulic conductivity for the High Plains aquifer (fig. 13), which includes the Ogallala and Arikaree aquifers. The spatial distribution of horizontal hydraulic conductivity estimated by Kolm and Case (1983) is in general agreement with that shown in figure 11.

Estimated horizontal hydraulic conductivity for the Arikaree aquifer ranged from 0.05 to 6.0 feet per day (fig. 14). Estimated values were based on previously published values (table 2) and model calibration. Specific capacity computed for 14 wells completed in the Arikaree aquifer ranges from 0.01 to 10.0 gallons per minute per foot, with an average of 0.4 gallons per minute per foot. Although specific capacity data were insufficient to estimate the spatial distribution of horizontal hydraulic conductivity in the Arikaree aquifer, these data and the horizontal hydraulic conductivity values shown in table 2 indicate that horizontal hydraulic conductivity values in the Arikaree aquifer are lower and have less variability than in the Ogallala aquifer. Zones of large horizontal hydraulic conductivity were assigned along the Little White and Keya Paha Rivers (fig. 14) in order to calibrate to the substantial ground-water discharge that occurs to these streams. In these areas, the alluvium was combined with model layer 2 and thus required a higher hydraulic conductivity. Other possible reasons for higher hydraulic conductivity are near-surface weathering, which probably extends below the water table in these topographically low areas. In addition, if the locations of these streams are influenced by fractures or faults, higher hydraulic conductivity could result.

Previously published values and specific-capacity data were used as general indicators for hydraulic conductivity values and distributions; however, model calibration carried the most weight in determining the final values and distributions. Hydraulic conductivity values and the spatial distribution of zones were varied by trial and error to obtain an optimum fit to observed hydraulic heads and base flows. Greater discretization of zones could have improved that fit by adjusting hydraulic conductivities near individual wells or very small groups of wells; however, the data did not support this degree of heterogeneity. Therefore, the calibration accuracy obtained using the larger zones shown in figures 11 and 14 was considered sufficient to fulfill the objectives of this study.

A uniform vertical hydraulic conductivity value was applied to the Ogallala aquifer, whereas vertical hydraulic conductivity was estimated for five zones in the Arikaree aquifer (fig. 15). Zone delineation for hydraulic properties was determined by considering potential structural features and by trial-and-error methods to achieve an optimum fit to observed data. Because stream locations may have structural control, zone boundaries were initially placed along streams to create five major zones for horizontal and vertical hydraulic conductivity. Although the use of potential structural features for these boundaries is arbitrary, data were not sufficient to determine different boundaries. These five zones were used as a starting point for the delineation of subzones when necessary. Subzone delineation and estimated values were determined by trial-and-error model calibration.

MODFLOW-2000 calculates vertical hydraulic conductivity between adjacent layers as the harmonic mean of the two layers, which resulted in unique values of the harmonic mean for each of the five conductivity zones in the Arikaree aquifer. Estimated vertical hydraulic conductivity was 6.6×10^{-4} feet per day for the Ogallala aquifer and ranged from 8.6×10^{-6} to 7.2×10^{-1} feet per day for the Arikaree aquifer (fig. 15).

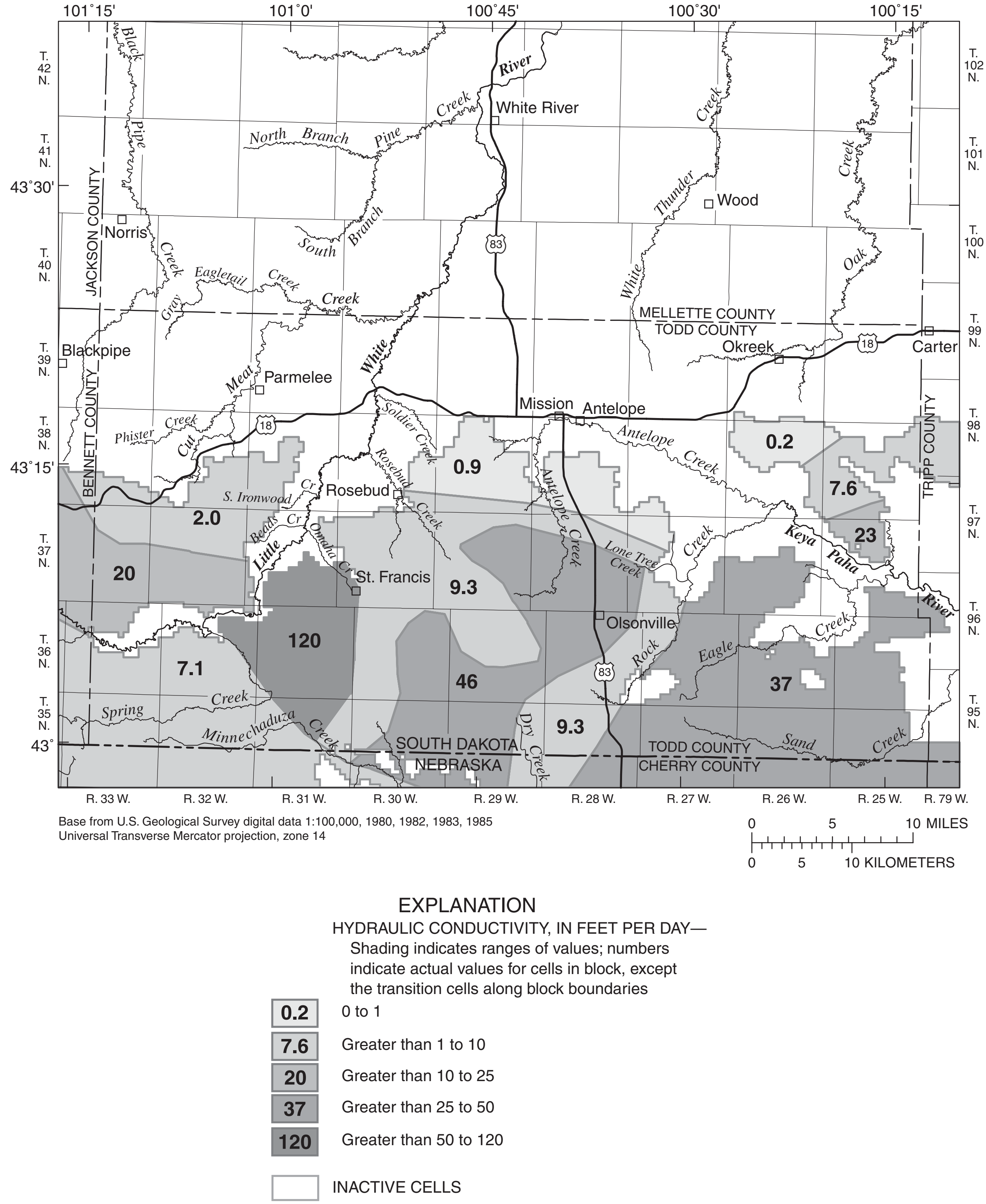
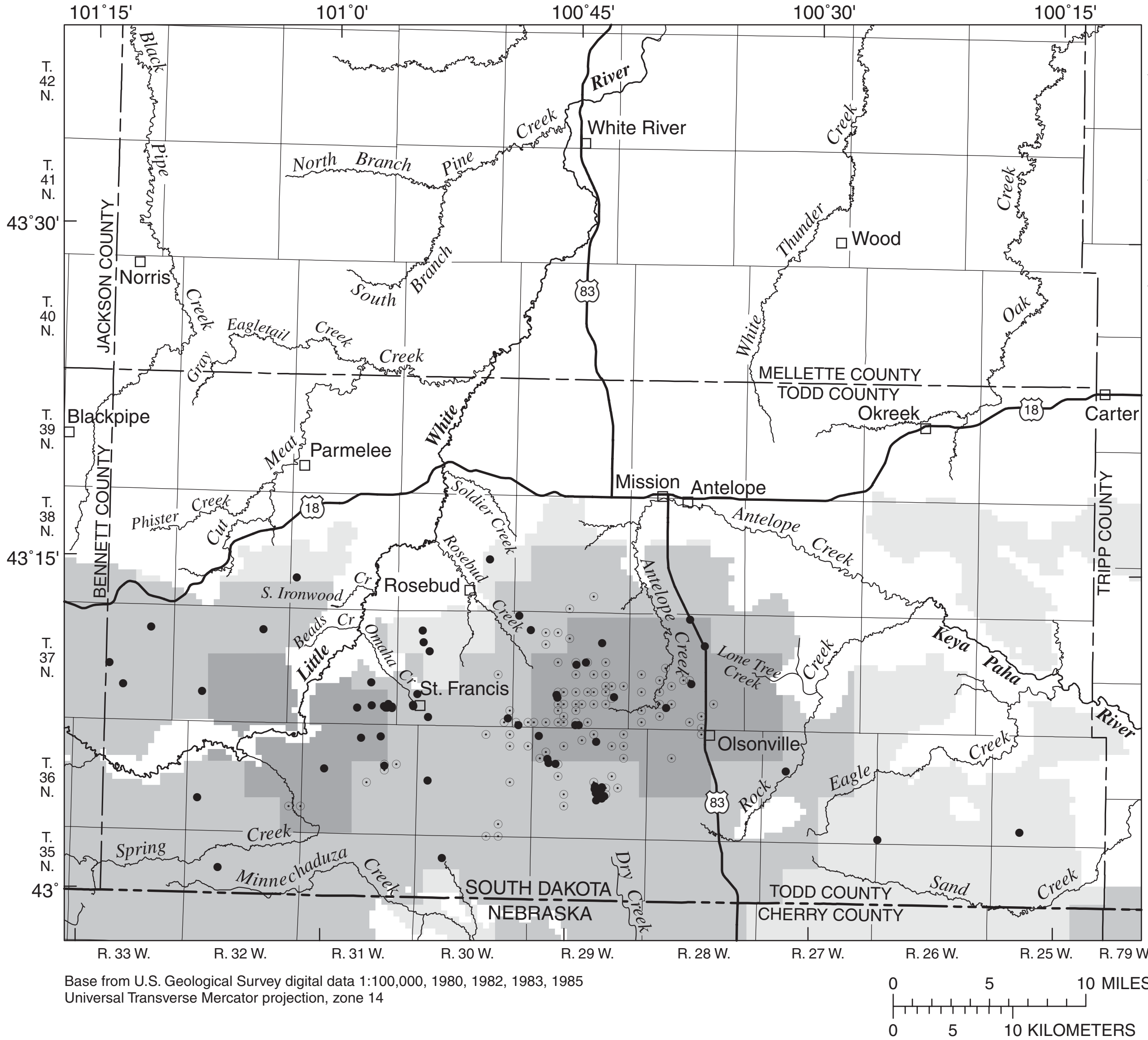


Figure 11. Estimated horizontal hydraulic conductivity of the Ogallala aquifer.



EXPLANATION

ESTIMATED SPECIFIC CAPACITY RANGE

Low

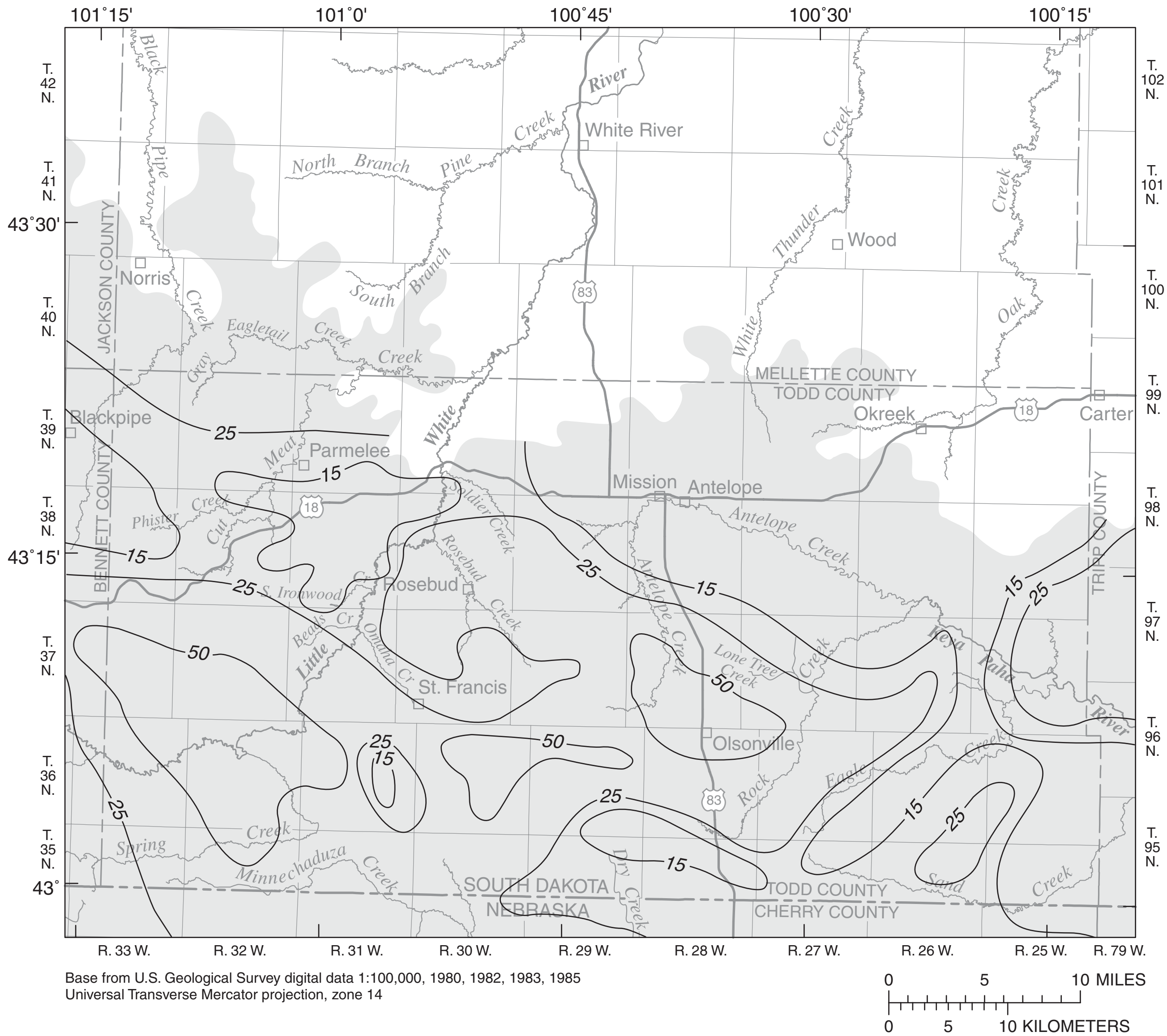
Medium

High

IRRIGATION WELL IN THE OGALLALA AQUIFER

WELL WITH COMPUTED SPECIFIC CAPACITY

Figure 12. Generalized specific capacity ranges in the Ogallala aquifer.

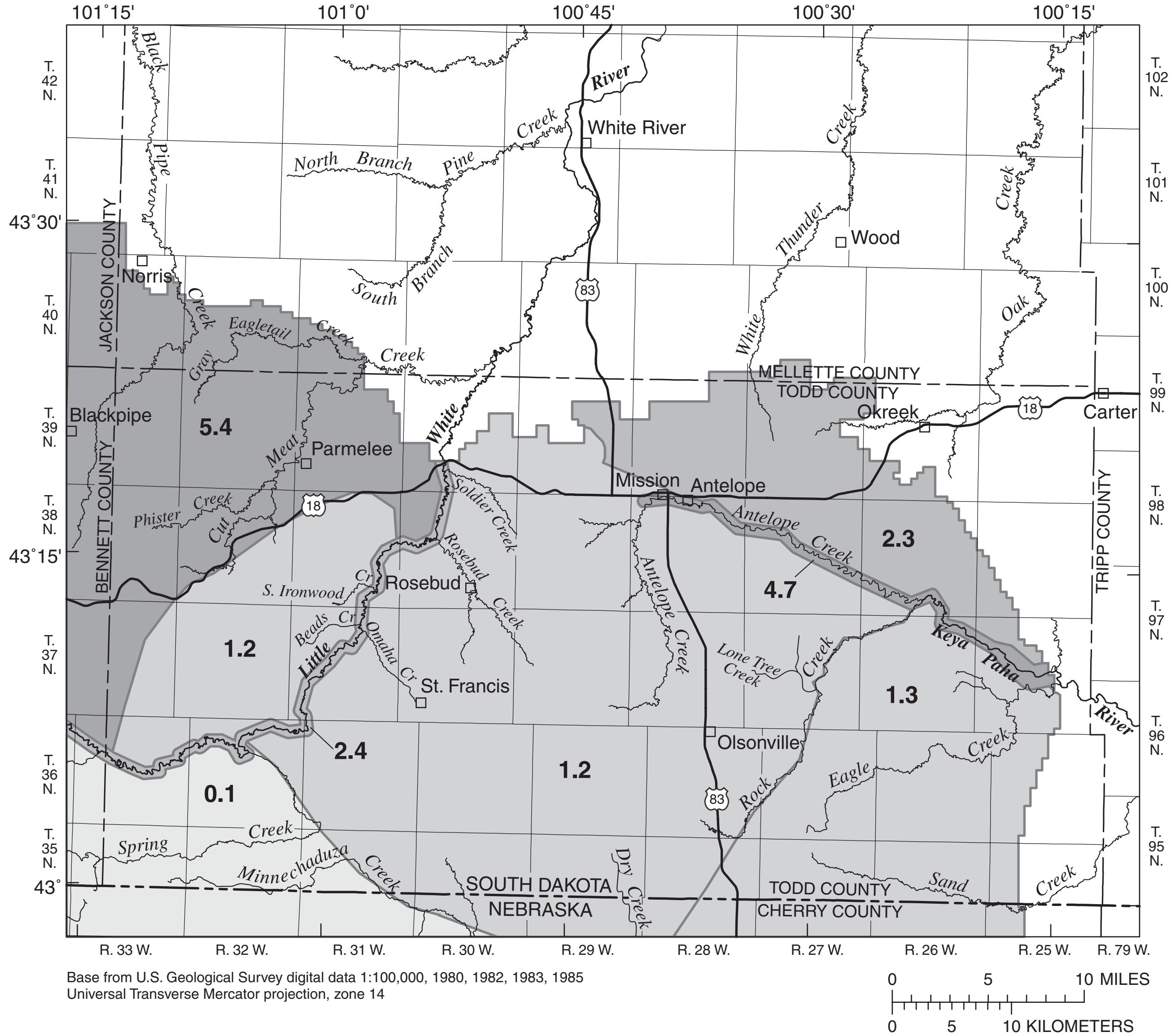


EXPLANATION

HIGH PLAINS AQUIFER

25 — LINE OF EQUAL HYDRAULIC CONDUCTIVITY, IN FEET PER DAY. Interval is variable (modified from Kolm and Case, 1983)

Figure 13. Hydraulic conductivity estimated from grain-size descriptions in the High Plains aquifer.



EXPLANATION

HYDRAULIC CONDUCTIVITY, IN FEET PER DAY—
Shading indicates ranges of values; numbers indicate actual values for cells in block, except the transition cells along block boundaries

- **0.1** 0.05 to 0.1
- **1.2** Greater than 0.1 to 2.0
- **2.3** Greater than 2.0 to 4.0
- **5.4** Greater than 4.0 to 6.0

Figure 14. Estimated horizontal hydraulic conductivity of the Arikaree aquifer.

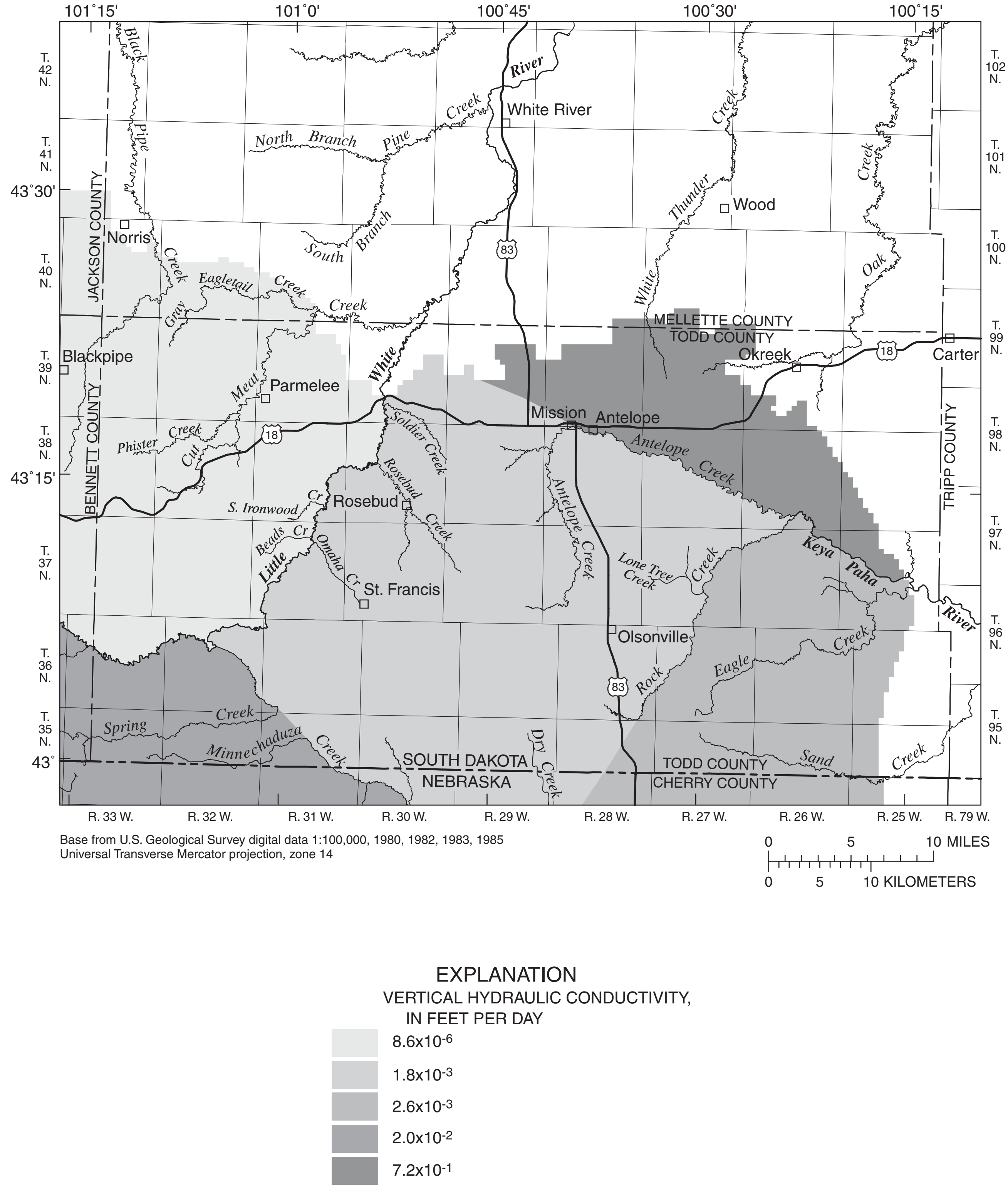


Figure 15. Estimated vertical hydraulic conductivity of the Arikaree aquifer.

Representation of Recharge and Discharge

Recharge rates for the steady-state simulation were estimated from previously published values and model calibration. Recharge was 3.3 inches per year for the Ogallala aquifer (17 percent of average precipitation) and 1.7 inches per year for the Arikaree aquifer (8.5 percent of average precipitation). Although recharge probably is spatially variable, a uniform distribution was assumed for each of the two outcrop areas because of insufficient data. A lower rate of recharge for the Arikaree aquifer than the Ogallala aquifer allowed a better fit to observed heads. These percentages were applied to the precipitation rates for each stress period to obtain recharge rates for the transient simulation (table 7). Precipitation records (table 7) were available for a National Weather Service Climatological Data station at Mission (U.S. Department of Commerce, 1978-98), which is located near the center of the study area.

Various MODFLOW-2000 packages were used to simulate the discharge components of evapotranspiration, discharge to streams, and well withdrawals. The "Evapotranspiration" package was designed to simulate evapotranspiration from the uppermost aquifer in any given cell where the water table is within a specified depth below the land surface (McDonald and Harbaugh, 1988). This so-named extinction depth was set to 10 feet in areas with woody vegetation (U.S. Geological Survey, 1955) and to 5 feet elsewhere, which reflects estimated rooting depths for woody vegetation, grasslands, and crops (fig. 16). The evapotranspiration (ET) rate is zero at the extinction depth and increases linearly to a maximum rate when the water level is at or above the land surface. The land-surface altitude was set to the average altitude for each cell based on a 30-meter DEM.

Discharge to streams, which includes springs and seeps, was represented using two packages. The "River" package in MODFLOW-2000 was used to simulate the hydraulic connection between ground water and surface water by allowing streams to gain or lose water based on the difference between the surrounding hydraulic head and stream stage through riverbed material of a specified hydraulic conductance (McDonald and Harbaugh, 1988). Estimated riverbed conductance was based on model calibration. Model cells were designated as river cells along major streams and tributaries where the potentiometric surface intersected the land surface (fig. 16). The "Drain" package simulated springs discharging from the Ogallala aquifer along the banks of the Little White River and springs along the northern edge of the Arikaree aquifer (fig. 16). Drains were added in stream channels where springs were likely to occur and where drains improved model calibration. Drain conductance was estimated by model calibration. The "Drain" package is similar to the "River" package except that drain cells can only take water out of the aquifer, whereas river cells also can recharge the aquifer (McDonald and Harbaugh, 1988).

Irrigation well withdrawals were simulated with the "Well" package (McDonald and Harbaugh, 1988) to withdraw water from each well at a specified rate. Irrigation withdrawals are listed in table 6, and locations are shown in figures 8 and 16.

Model Calibration

Model calibration was accomplished by varying the model-input parameters within plausible ranges to produce the best fit between simulated and observed hydraulic heads in the Ogallala and Arikaree aquifers and base flows in streams. Steady-state and transient simulations were analyzed to determine the best combination of model-input parameters.

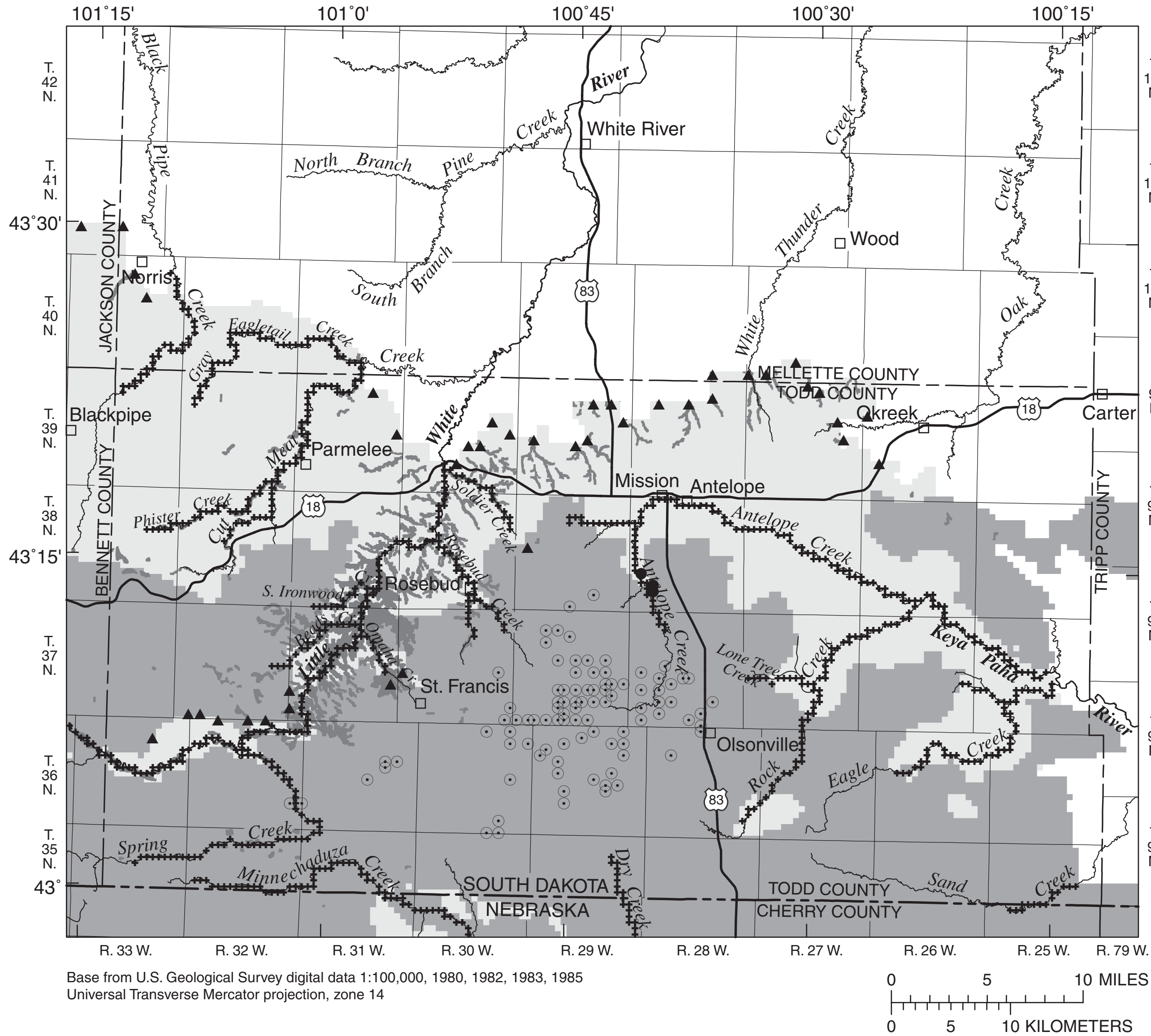
Water-level measurements for 398 wells that were used for estimation of potentiometric surfaces of the Ogallala and Arikaree aquifers (figs. 4 and 5) were considered for calibration of the steady-state model. These wells include 44 observation wells with long-term water-level records that were used for calibration of the transient model and 354 public and private wells. The observation wells include 23 State wells (of which 17 are completed in the Ogallala aquifer and 6 are completed in the Arikaree aquifer) and 21 Tribal wells (of which 20 are completed in the Ogallala aquifer and 1 is completed in the Arikaree aquifer) (figs. 9 and 10). Selected data for the State and Tribal observation wells are presented in tables 8 and 9, respectively.

The majority of the State and Tribal observation wells are concentrated in the central part of the study area (fig. 9) where irrigation is prevalent (fig. 8). The Ogallala aquifer in the central part of the study area is of primary concern to the Rosebud Sioux Tribe and is the main focus of the numerical model.

Table 7. Estimated recharge to the Ogallala and Arikaree aquifers, water years 1979-98

[--, not applicable]

Water year	Stress period	Precipitation (inches)	Recharge to Ogallala aquifer (inches)	Recharge to Arikaree aquifer (inches)	Water year	Stress period	Precipitation (inches)	Recharge to Ogallala aquifer (inches)	Recharge to Arikaree aquifer (inches)
1979	1	1.5	0.3	0.1	1989	31	1.2	.2	.1
	2	4.7	.8	.4		32	3.0	.5	.3
	3	11.5	2.0	1.0		33	9.8	1.7	.8
1980	4	3.2	.5	.3	1990	34	2.6	.4	.2
	5	3.3	.6	.3		35	6.7	1.1	.6
	6	7.2	1.2	.6		36	10.7	1.8	.9
1981	7	3.2	.5	.3	1991	37	2.4	0.4	0.2
	8	5.9	1.0	.5		38	10.7	1.8	.9
	9	10.1	1.7	.9		39	8.2	1.4	.7
1982	10	4.7	.8	.4	1992	40	2.3	.4	.2
	11	9.8	1.7	.8		41	2.0	.3	.2
	12	13.5	2.3	1.1		42	13.2	2.2	1.1
1983	13	5.4	.9	.5	1993	43	2.4	.4	.2
	14	8.5	1.4	.7		44	5.4	.9	.5
	15	9.7	1.7	.8		45	9.8	1.7	.8
1984	16	3.8	.7	.3	1994	46	4.0	.7	.3
	17	5.4	.9	.5		47	3.8	.6	.3
	18	7.7	1.3	.7		48	12.5	2.1	1.1
1985	19	2.8	.5	.2	1995	49	2.9	.5	.2
	20	3.1	.5	.3		50	10.4	1.8	.9
	21	7.7	1.3	.7		51	8.1	1.4	.7
1986	22	4.0	.7	.3	1996	52	6.3	1.1	.5
	23	8.3	1.4	.7		53	7.0	1.2	.6
	24	12.8	2.2	1.1		54	7.7	1.3	.7
1987	25	3.5	.6	.3	1997	55	4.6	.8	.4
	26	8.4	1.4	.7		56	6.5	1.1	.6
	27	6.6	1.1	.6		57	11.1	1.9	.9
1988	28	3.1	.5	.3	1998	58	3.1	.5	.3
	29	6.6	1.1	.6		59	5.7	1.0	.5
	30	7.9	1.3	.7		60	13.8	2.3	1.2
					Average annual	--	19.6	3.3	1.7



EXPLANATION

- ACTIVE CELLS IN OGALLALA FORMATION OUTCROP
- ACTIVE CELLS IN ARIKAREE FORMATION OUTCROP
- EVAPOTRANSPIRATION EXTINCTION DEPTH EQUALS 10 FEET (5 FEET ELSEWHERE)
- + RIVER CELL SIMULATING RIVER LEAKAGE
- ▲ DRAIN CELL SIMULATING SPRING DISCHARGE
- ⊙ IRRIGATION WELL IN OGALLALA AQUIFER
- ● IRRIGATION WELL IN ARIKAREE AQUIFER

Figure 16. Evapotranspiration, river cells, drain cells, and irrigation wells in the Ogallala and Arikaree aquifers.

Table 8. Selected data for State observation wells in the study area

Well number (figs. 9 and 10)	Site identification number	Local number	Aquifer	Land-surface altitude (feet above NGVD of 1929)	Well number (figs. 9 and 10)	Site Identification number	Local number	Aquifer	Land-surface altitude (feet above NGVD of 1929)
2	425957100445601	35N29W20AADD	Ogallala	2,890	177	430842100411301	37N28W30CCCB	Ogallala	2,770
41	430148100471001	35N29W 7BBBB	Ogallala	2,903	194	430924100460601	37N29W29AAAA	Ogallala	2,868
80	430310100245501	36N26W31ADDD	Ogallala	2,620	201	430932100390001	37N28W21CCCC	Ogallala	2,772
87	430340101012301	36N32W25DDDD	Ogallala	2,841	207	431018101152001	37N33W17CCCC	Ogallala	2,998
125	430609100434201	36N29W16AAAA	Ogallala	2,863	219	431109100445901	37N29W16AAAA	Ogallala	2,852
126	430610100481701	36N30W13BBBB	Ogallala	2,916	205	430959100444001	37N29W22CCCC	Arikaree	2,882
130	430613101561701	36N31W14BAAA	Ogallala	2,955	210	431020100243501	37N26W16CCBB	Arikaree	2,530
145	430701100363001	36N28W10BBBB	Ogallala	2,823	274	431430100195901	38N25W30BCBB	Arikaree	2,483
160	430748100455601	37N29W33CCCC	Ogallala	2,909	361	432044101115201	39N33W15DDDD	Arikaree	2,800
170	430825101151801	37N33W32BBBB2	Ogallala	2,960	374	432310101045501	39N32W 3AAAA	Arikaree	2,610
175	430839100373801	37N28W27CCCC	Ogallala	2,805	384	432554101065601	40N32W21BBBB	Arikaree	2,576
176	430840100445601	37N29W28DDDD	Ogallala	2,858					

Table 9. Selected data for Tribal observation wells in the study area

Well number (figs. 9 and 10)	Site identification number	Local number	Aquifer	Land-surface altitude (feet above NGVD of 1929)	Well number (figs. 9 and 10)	Site Identification number	Local number	Aquifer	Land-surface altitude (feet above NGVD of 1929)
3	430309100570901	36N31W34DBBC	Ogallala	2,920	16	430820100371401	37N28W34ABDA	Ogallala	2,783
4	430017100595101	35N31W17CCDA	Ogallala	2,896	17	431027100333001	37N27W18DDAB	Ogallala	2,609
5	430159100531001	35N30W 6DDDD	Ogallala	2,853	18	430702100330501	36N28W12AABA	Ogallala	2,806
6	430501100504901	36N30W21DAAA	Ogallala	2,888	19	430243100371701	36N28W33BDDD	Ogallala	2,753
7	430415100451401	36N29W29ACAA	Ogallala	2,870	20	430122100344501	35N28W11DBBB	Ogallala	2,728
8	430258100471401	36N30W36DDDA	Ogallala	2,885	21	430057100275401	35N27W14BAAB	Ogallala	2,690
9	430100100460501	35N29W18AAAA	Ogallala	2,870	22	430335100241401	36N26W32BBAA	Ogallala	2,619
10	430154100411801	35N29W 2DDDD	Ogallala	2,800	23	430728100135801	36N27W 1BDDD	Ogallala	2,627
11	430530100422501	36N29W14CDAB	Ogallala	2,893	27	431127100532801	37N30W 8DACC	Ogallala	2,880
12	430712100421301	36N29W 2CDCC	Ogallala	2,850	15	431342100344101	38N28W36ABCB	Arikaree	2,620
13	430755100582301	37N29W31DACC	Ogallala	2,921					

Steady-State Simulation

The numerical model was used to simulate average (steady-state) flow conditions for the 20-year period (WY 1979-98) previously described. Steady-state conditions were numerically approximated for the steady-state simulation by using a transient simulation with one 100-year stress period using constant input flow rates. The model was more stable and closed in fewer iterations with the 100-year transient stress period than with a steady-state stress period. The potentiometric surface from the steady-state simulation established initial conditions for the transient simulation.

The first calibration criterion for the steady-state simulation was that the simulated potentiometric surfaces and hydraulic gradients generally match those of the estimated average potentiometric surfaces. The simulated steady-state potentiometric surfaces (figs. 17 and 18) generally are similar to the estimated average potentiometric surfaces (figs. 4 and 5) in comparison to both hydraulic heads and gradients, indicating satisfaction of this criterion.

A second calibration criterion included matching 95 percent of all wells to within ±50 feet of the observed hydraulic heads. This second criterion was considered adequate because 50 feet is about 7 percent of the difference between the maximum and minimum hydraulic heads of the estimated average potentiometric surfaces in the model area (total hydraulic head relief); hydraulic head relief is about 780 feet in the Ogallala aquifer and 720 feet in the Arikaree aquifer.

Simulated hydraulic heads matched observed values to within ±50 feet for 95 percent of the wells. A histogram shows the distribution of the difference between the observed and simulated hydraulic heads (residuals) (fig. 19). The fit was considerably better for the 44 State observation wells (fig. 19B) than for all wells (fig. 19A). Observation well data were weighted more heavily in calibration because of a higher degree of confidence in that data. Simulated hydraulic heads at all of the State observation wells were within ±22 feet of the observed hydraulic heads, which is about 3 percent of the total hydraulic head relief in the Ogallala and Arikaree aquifers. The residuals for 20 of these State observation wells were within ±12 feet (fig. 19B). Simulated hydraulic heads at all of the Tribal observation wells were within ±45 feet of the observed hydraulic heads, which is about 6 percent of the total hydraulic head relief in the Ogallala and Arikaree aquifers. The residuals for 15 of these Tribal observations wells were within ±20 feet (fig. 19C). The root mean square error (RMSE) for all wells was 26.8 feet. The mean error was -3.7 feet, which indicates a model bias toward overestimating head values. For the State and Tribal observation wells only, the RMSE was 21.4 feet, and the mean error was -1.6 feet. A linear regression analysis of simulated hydraulic heads and observed hydraulic heads for all wells (fig. 20) yielded an R^2 value (coefficient of determination) of 0.97.

Base flow is another important component of calibration. Base flow is sensitive to many model components besides riverbed conductance. Results of the steady-state calibration to estimated base flow are shown in table 10.

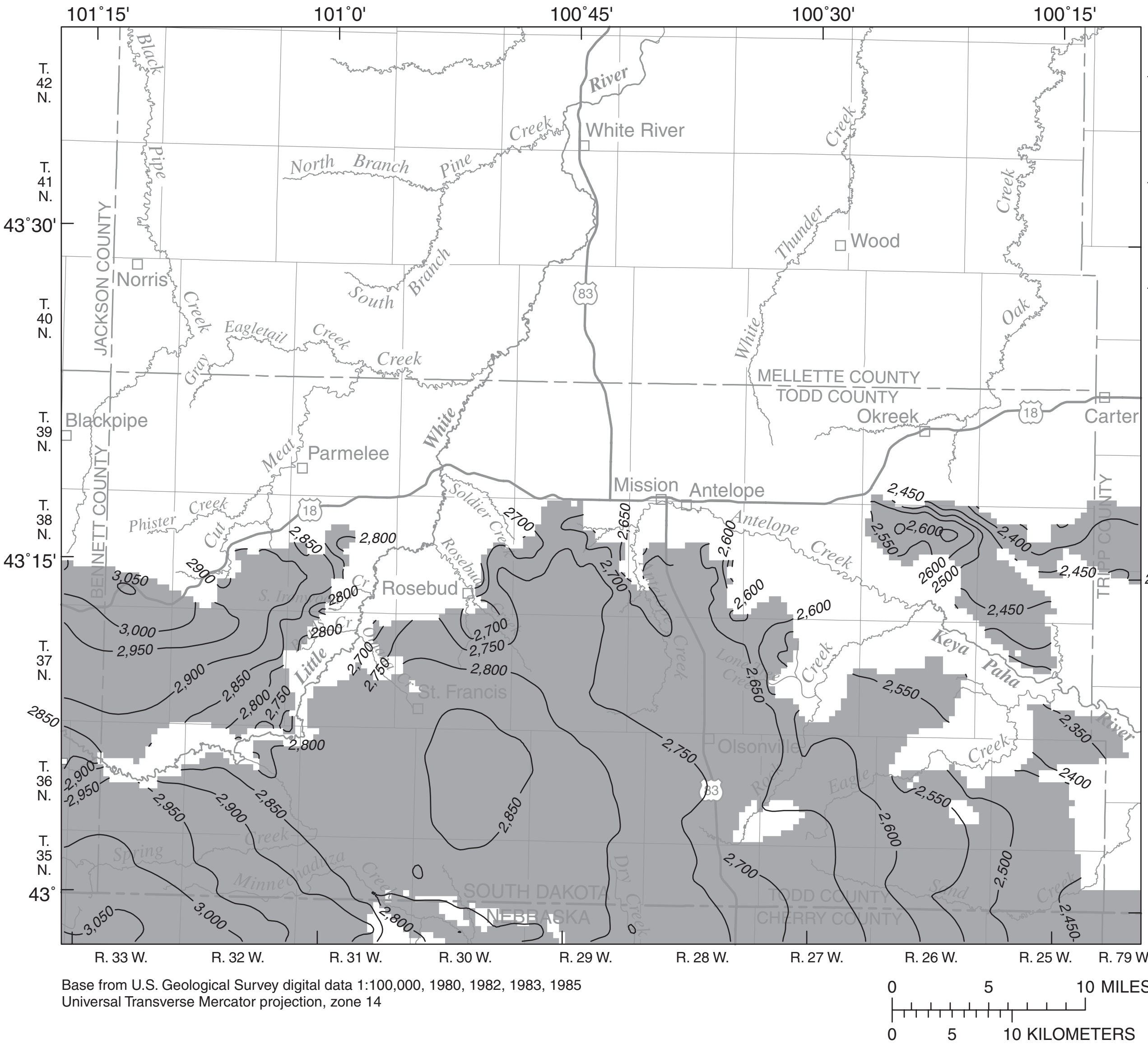
A sensitivity analysis was used to examine the response of the numerical model calibrated to the steady-state condition to changes in model parameters including horizontal and vertical hydraulic conductivity, evapotranspiration, recharge, and riverbed conductance. During each simulation when a parameter was being tested, the other parameters were set to the steady-state calibrated value. Each parameter was changed uniformly over the entire model area. The percent changes in the sum of squared weighted residuals between the simulated and observed hydraulic heads for selected changes in parameter values are shown in figure 21. The model was most sensitive to recharge and horizontal hydraulic conductivity.

The water budget for the steady-state simulation balances (inflows minus outflows) with a percent discrepancy of -0.41 (table 11). The recharge rate used for the numerical model was within the range of values listed in the conceptual model. The exact amount of irrigation well withdrawals that were estimated (table 6) was used in the numerical model. The river leakage from the aquifers into the Little White and Keya Paha Rivers calculated by the numerical model was within 3.3 cubic feet per second of the estimated base flow for each of the two rivers.

Table 10. Comparison of simulated and estimated base flow for the Little White and Keya Paha Rivers for the steady-state simulation

Stream	Base flow (cubic feet per second)		Percent error of simulated compared to estimated base flow
	Estimated[1]	Model simulated	
Little White River	49	46.79	4.5
Keya Paha River	23	19.70	14

[1]From table 5.



EXPLANATION

ACTIVE CELLS IN THE OGALLALA AQUIFER

—2,400— SIMULATED POTENTIOMETRIC CONTOUR—Shows average altitude at which water level would have stood in tightly cased wells, 1979-98. Contour interval is 50 feet. Datum is NGVD of 1929.

Figure 17. Potentiometric surface of the Ogallala aquifer for the steady-state simulation.

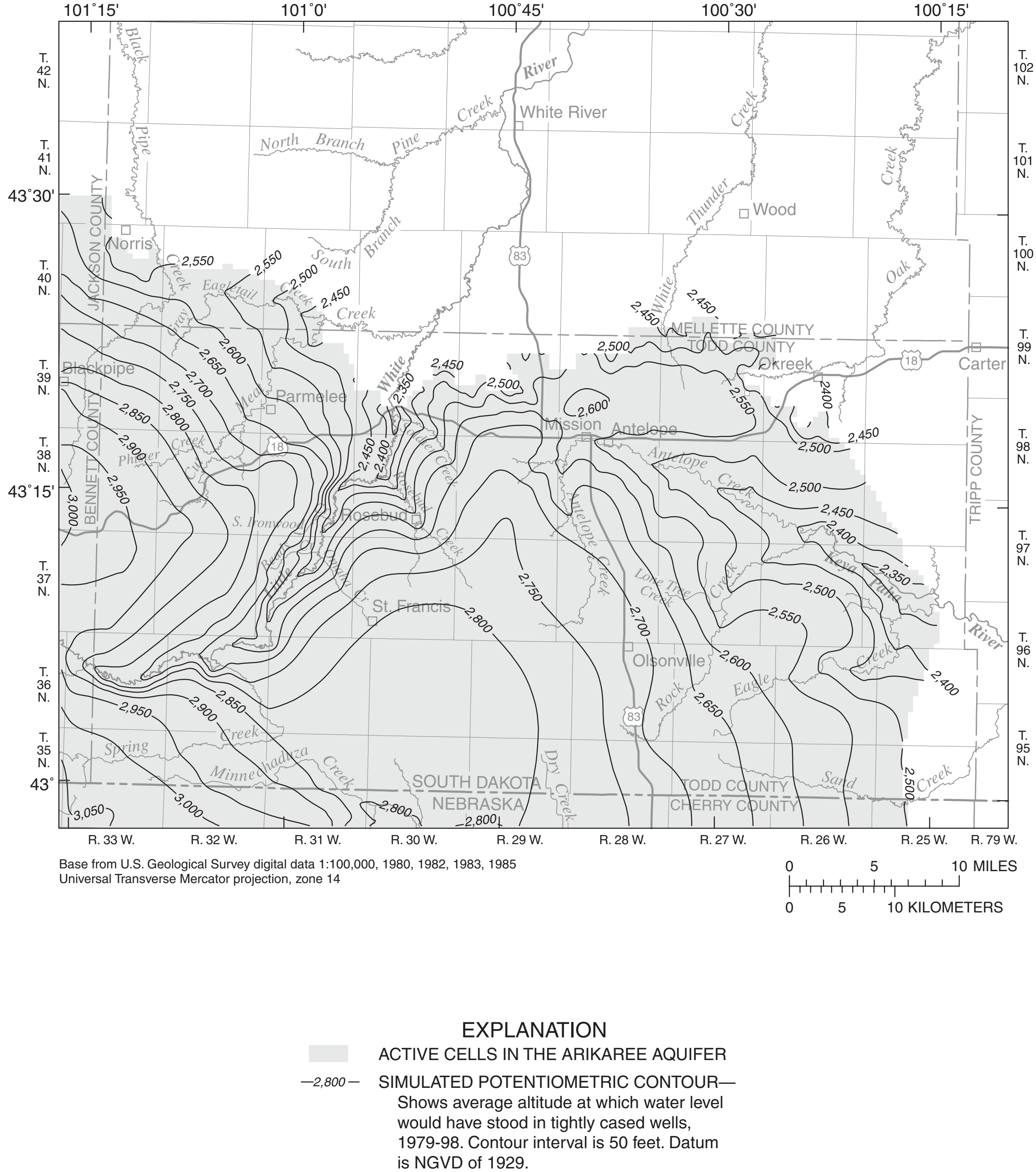


Figure 18. Potentiometric surface of the Arikaree aquifer for the steady-state simulation.

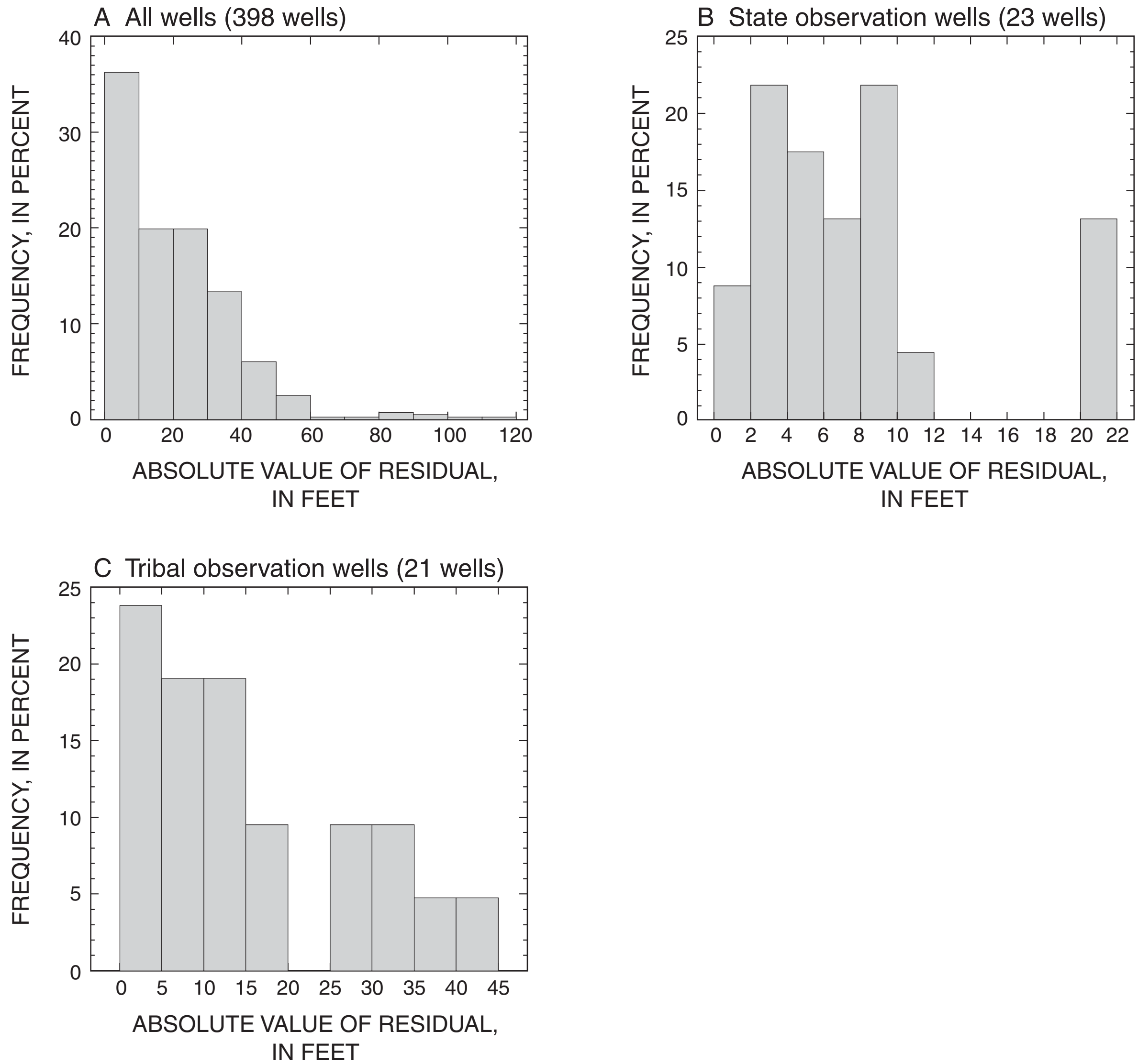


Figure 19. Histograms of residuals of estimated average observed and steady-state simulated hydraulic head in A) all wells, B) State observation wells, and C) Tribal observation wells for the Ogallala and Arikaree aquifers, water years 1979-98.

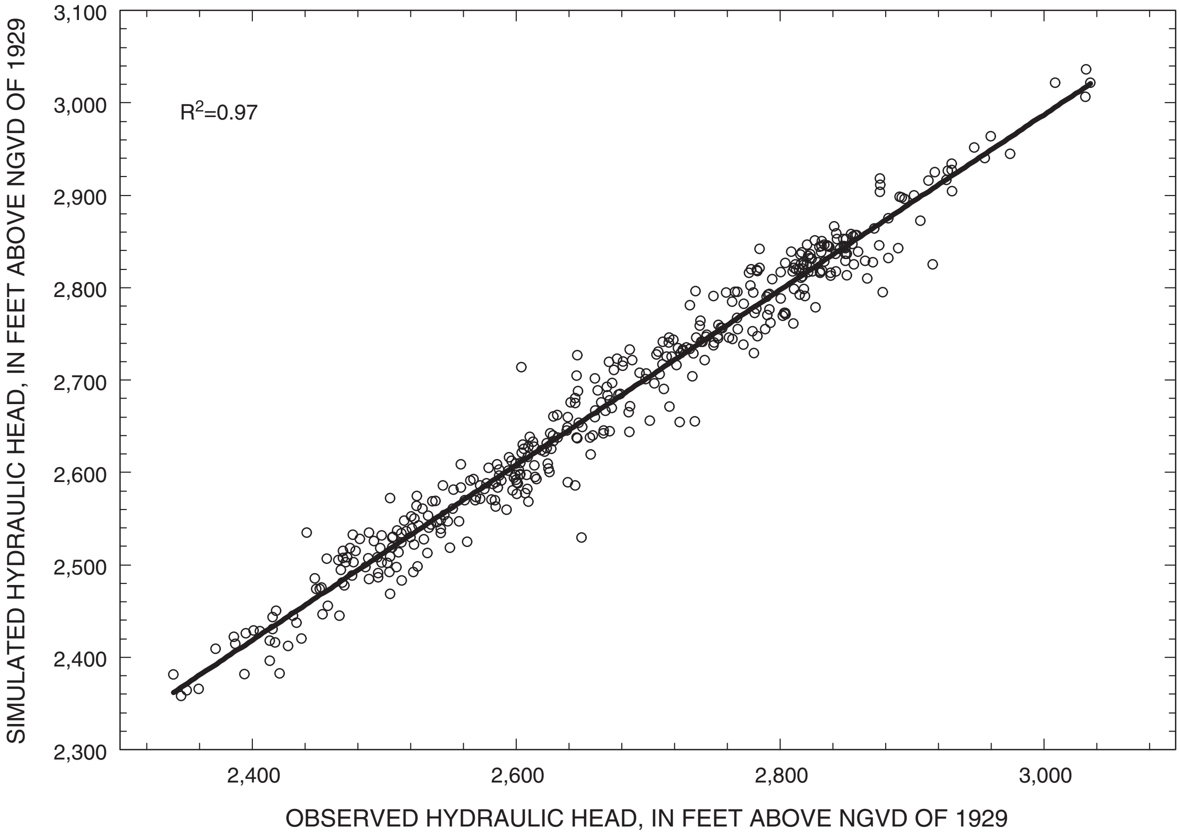


Figure 20. Linear regression of observed and simulated hydraulic heads for all wells.

Table 11. Steady-state water budget for numerical simulation compared with flow estimates for conceptual model

[--, not estimated or not applicable]

Flow component	Flow rate (cubic feet per second)	
	Numerical model	Conceptual model
Inflows		
Storage	0.52	--
Constant-head boundaries	17.90	--
River leakage	2.05	--
Recharge	266.20	111-341
Total inflows	286.67	--
Outflows		
Storage	0.74	--
Constant-head boundaries	13.16	--
Irrigation wells	11.60	11.6
Springs along northern boundary	0.50	--
Little White River	[1]46.79	[1]49
Keya Paha River	19.70	23
Other river leakage	11.50	--
Evapotranspiration	183.87	--
Total outflows	287.86	--
Inflows - outflows	-1.19	--
Percent discrepancy	-0.41	--

[1]Includes springflow contributing to base flow in river

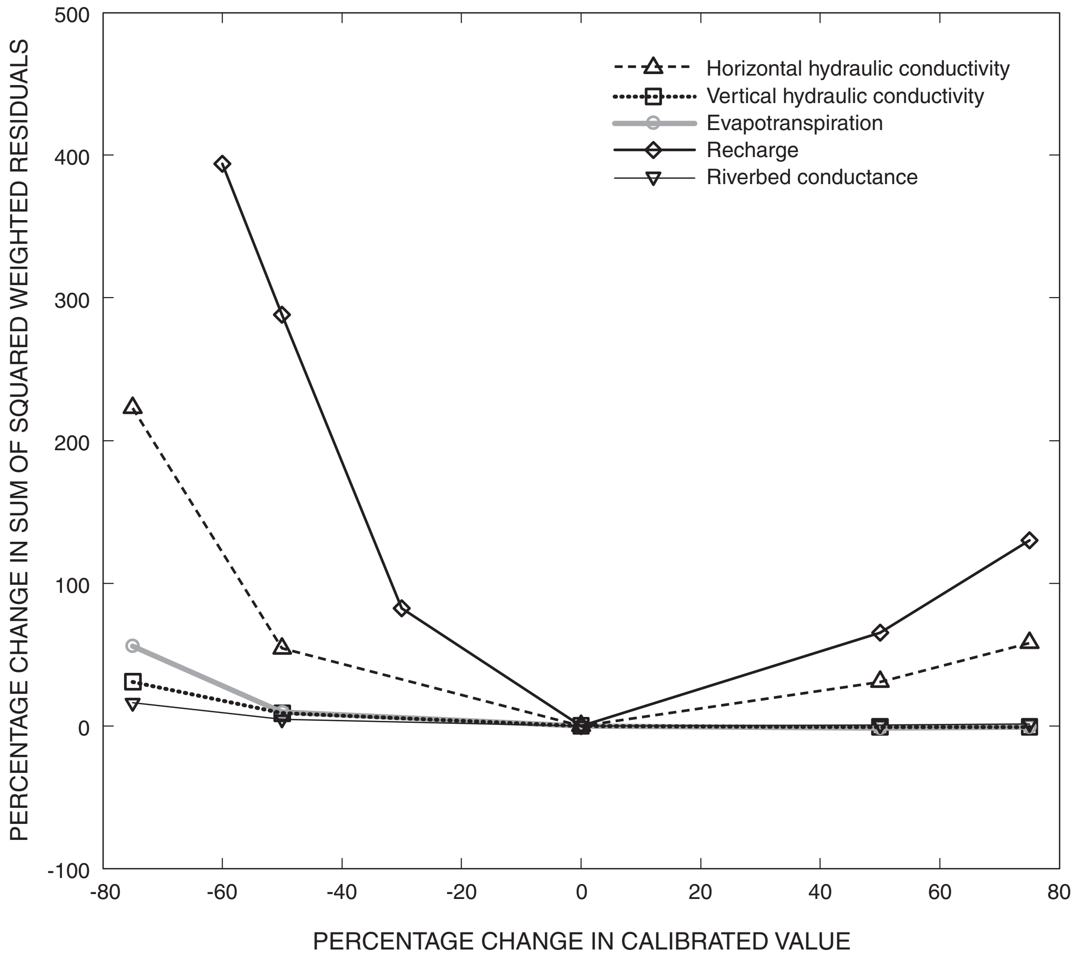


Figure 21. Results of sensitivity analysis.

Transient Simulation

Calibration criteria for the transient simulation consisted of approximately reproducing the general temporal trends of the hydrographs for the 23 State observation wells and 21 Tribal observation wells. There was no attempt to calibrate the transient simulation to match hydraulic heads in the observation wells closer than that required for the steady-state simulation (±50 feet). Therefore, a difference of up to 50 feet between the observed and simulated well hydrographs was acceptable if the general trends matched reasonably well.

Hydrographs for State and Tribal observation wells are shown in figures 22 and 23, which show that the general trends in simulated and observed hydraulic heads matched reasonably well. Basic statistics were calculated for comparison of observed and simulated hydraulic heads for observation wells (tables 12 and 13). The differences of the means of observed and simulated data were within 40 feet for all observation wells. Comparison of standard deviations, variances, and ranges for observed and simulated data are indications of how well the model simulated hydraulic head fluctuations for each well. The model overestimated hydraulic heads for 13 of the State wells and 8 of the Tribal wells. These wells have a negative number in the "Difference of observed and simulated means" column. The model underestimated hydraulic heads for 10 of the State wells and 13 of the Tribal wells. For all observation wells, the model overestimated hydraulic heads for 48 percent of the wells and underestimated hydraulic heads for 52 percent of the wells. However, the mean of the difference of observed and simulated means (tables 12 and 13) is -3.7 for State wells, -1.0 for Tribal wells, and -2.4 for all observation wells, which indicates a model bias toward overestimating hydraulic heads.

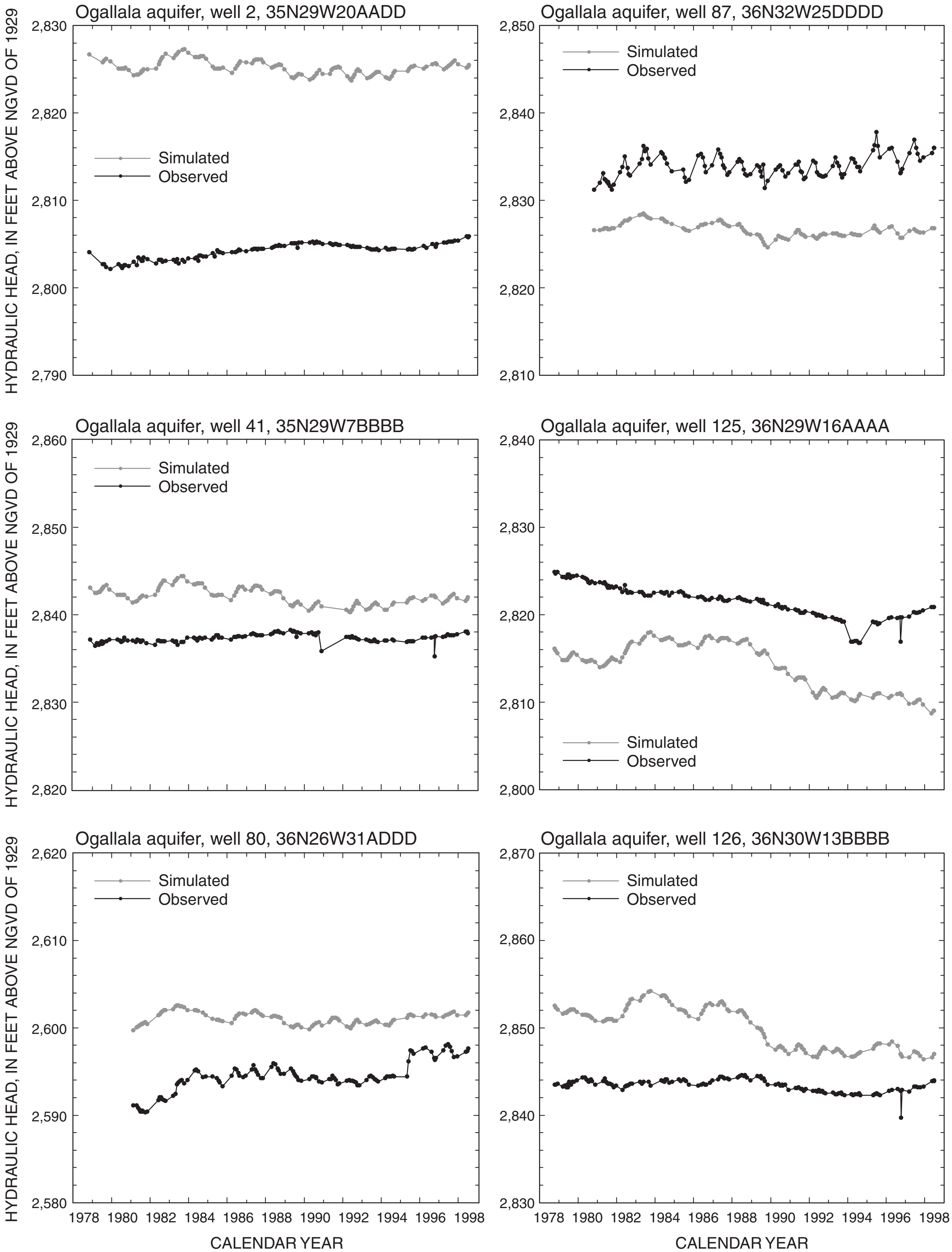


Figure 22. Hydrographs showing simulated and observed data for State observation wells.

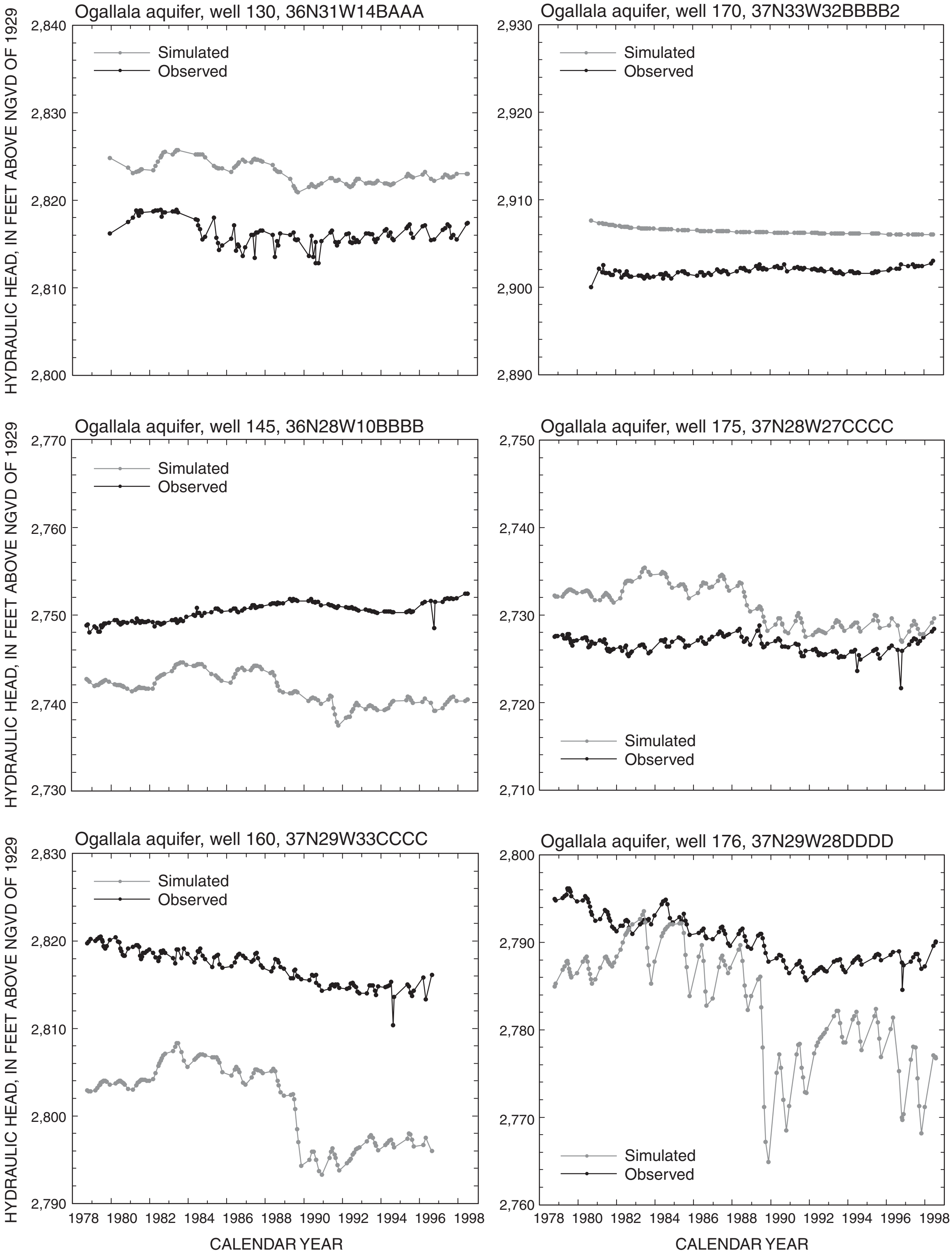


Figure 22. Hydrographs showing simulated and observed data for State observation wells.—Continued

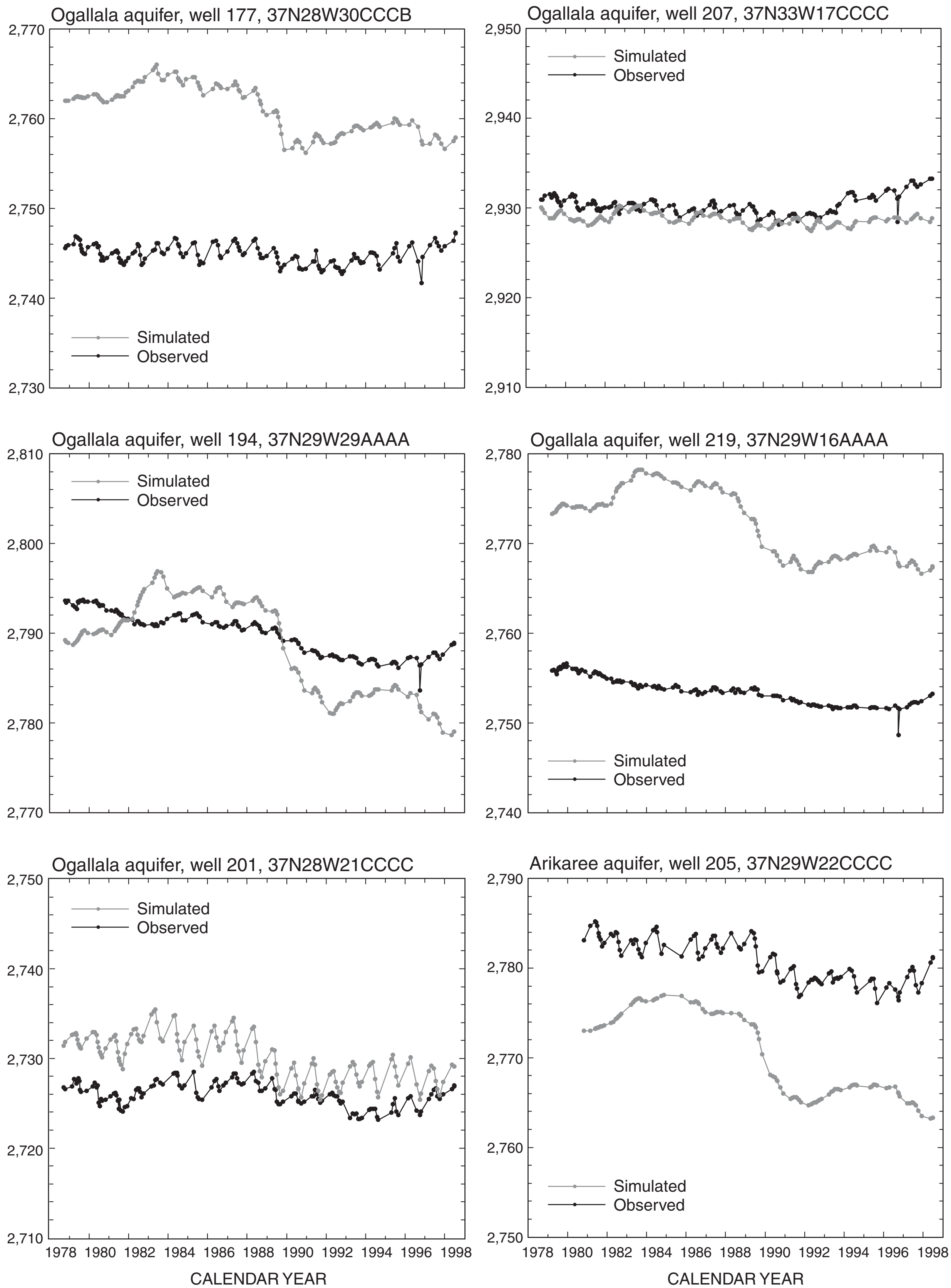


Figure 22. Hydrographs showing simulated and observed data for State observation wells.—Continued

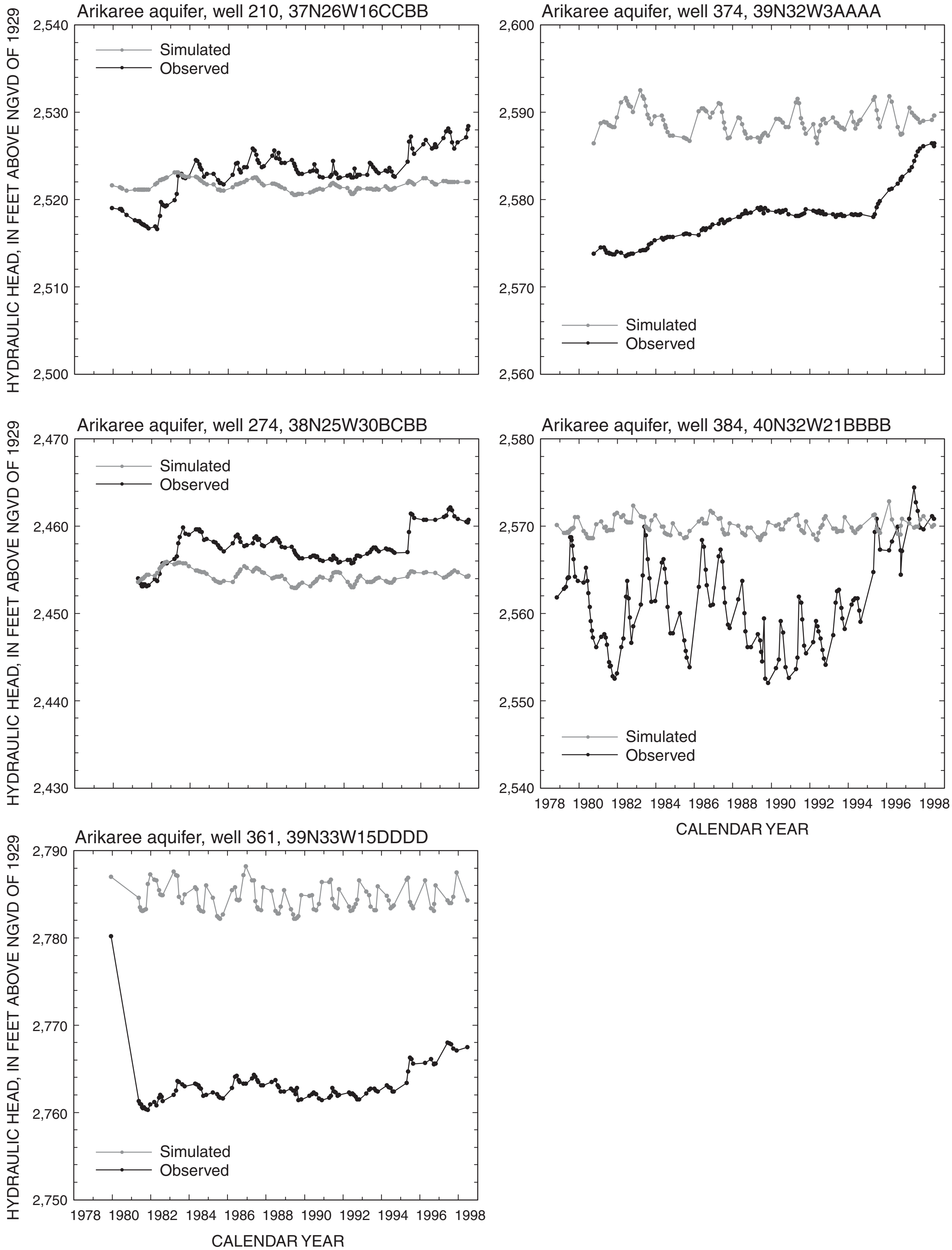


Figure 22. Hydrographs showing simulated and observed data for State observation wells.—Continued

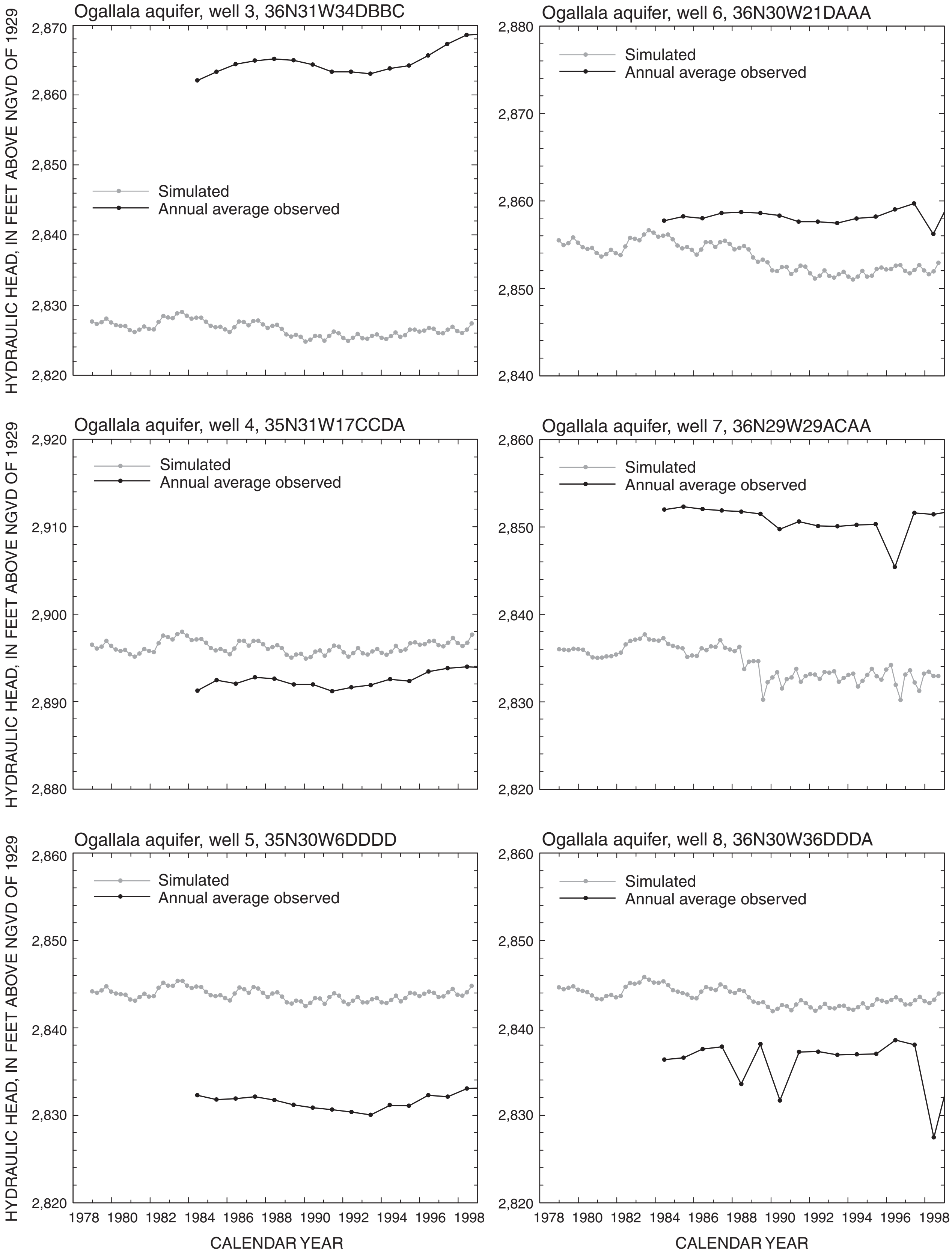


Figure 23. Hydrographs showing simulated and annual average observed data for Tribal observation wells.

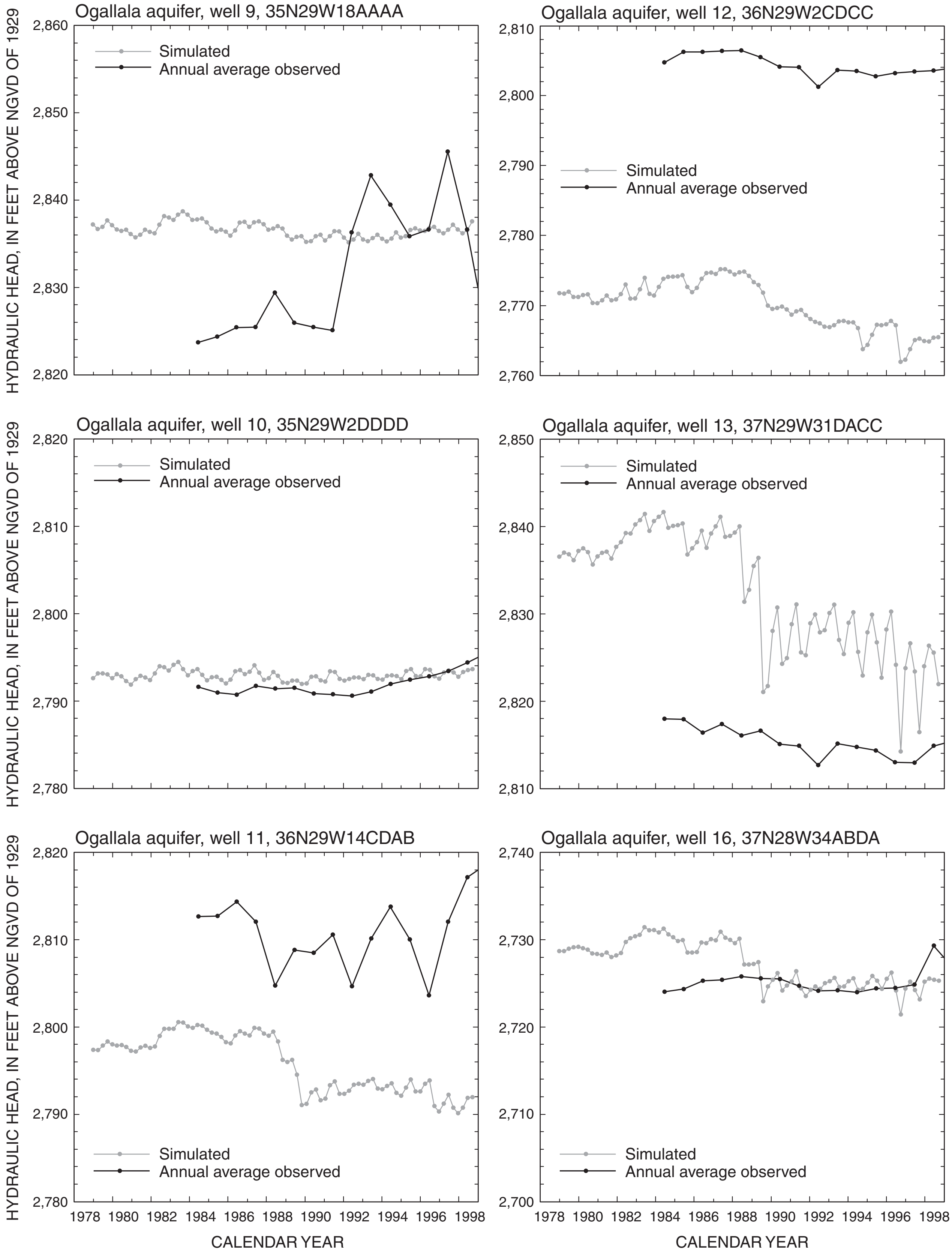


Figure 23. Hydrographs showing simulated and annual average observed data for Tribal observation wells.—Continued

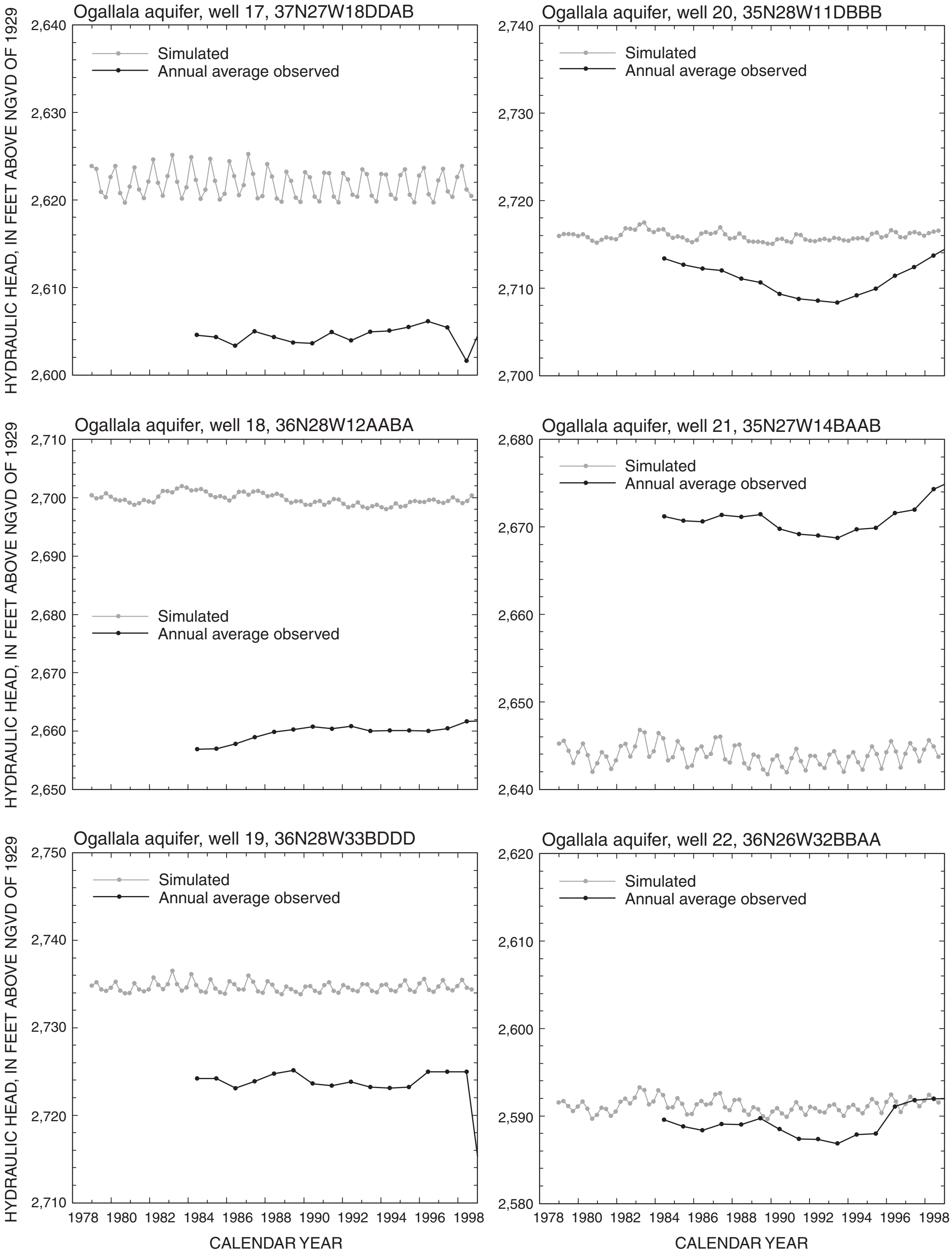


Figure 23. Hydrographs showing simulated and annual average observed data for Tribal observation wells.—Continued

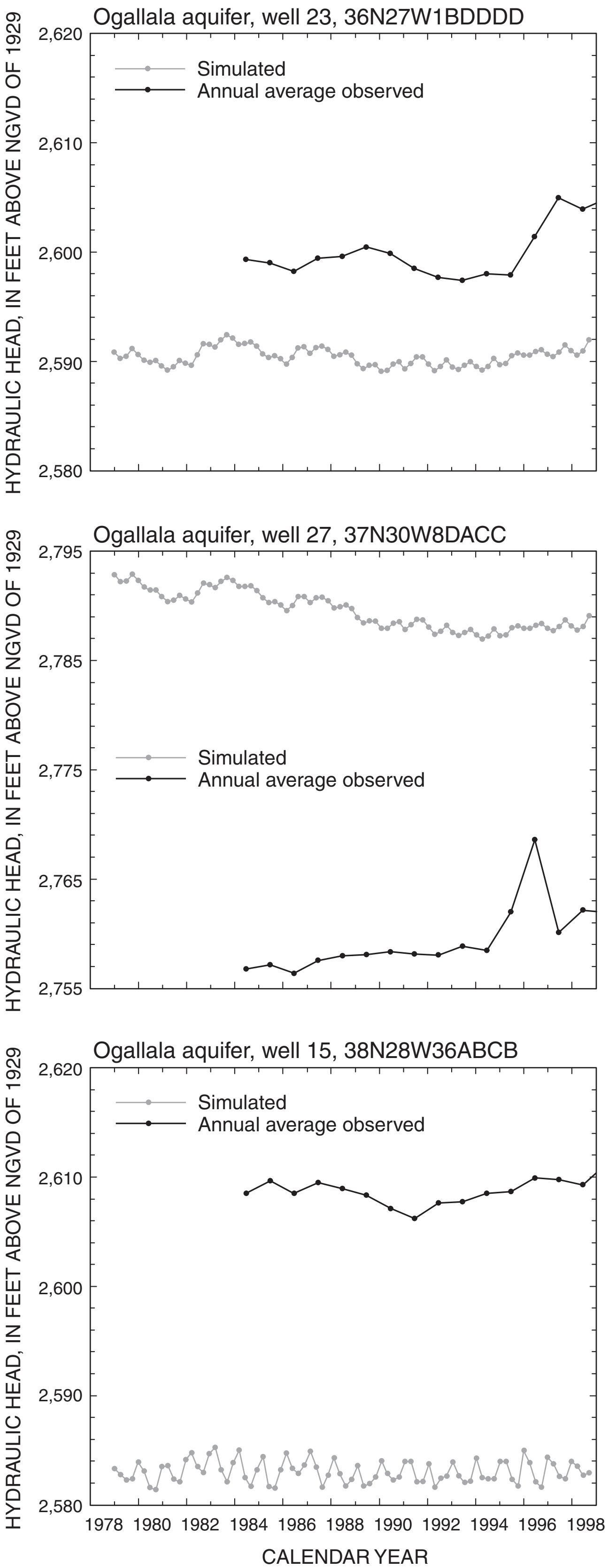


Figure 23. Hydrographs showing simulated and annual average observed data for Tribal observation wells.—Continued

Table 12. Comparison of observed and simulated hydraulic heads for State observation wells for the transient simulation

[Hydraulic heads in feet above NGVD of 1929. --, not applicable]

State well number	Data type	Mean	Standard deviation	Variance	Range	Minimum	Maximum	Difference of observed and simulated means	Average of absolute value of residuals[1]
2	Observed	2,804	0.90	0.80	4	2,802	2,806		
	Simulated	2,825	.81	.66	3	2,824	2,827	-21	20.9
41	Observed	2,837	.47	.22	3	2,835	2,838		
	Simulated	2,842	.96	.93	4	2,840	2,844	-5	4.9
80	Observed	2,594	1.81	3.26	8	2,590	2,598		
	Simulated	2,601	.69	0.47	3	2,600	2,603	-7	6.7
87	Observed	2,834	1.31	1.70	7	2,831	2,838		
	Simulated	2,827	.79	.62	4	2,825	2,829	7	7.3
125	Observed	2,822	1.90	3.60	8	2,817	2,825		
	Simulated	2,814	2.62	6.88	9	2,809	2,818	8	7.4
126	Observed	2,843	.69	.48	5	2,840	2,845		
	Simulated	2,850	2.40	5.75	8	2,846	2,854	-7	6.7
130	Observed	2,816	1.46	2.14	6	2,813	2,819		
	Simulated	2,823	1.25	1.57	5	2,821	2,826	-7	6.9
145	Observed	2,750	1.06	1.12	4	2,748	2,752		
	Simulated	2,742	1.75	3.05	8	2,737	2,745	8	8.7
160	Observed	2,817	2.04	4.17	11	2,810	2,821		
	Simulated	2,802	4.34	18.86	15	2,793	2,808	15	15.4
175	Observed	2,727	.95	.91	7	2,722	2,729		
	Simulated	2,735	2.03	4.12	8	2,731	2,739	-8	8.1
176	Observed	2,791	2.87	8.26	11	2,785	2,796		
	Simulated	2,783	6.63	43.99	29	2,765	2,794	8	7.5
177	Observed	2,745	1.09	1.20	5	2,742	2,747		
	Simulated	2,761	2.62	6.88	10	2,756	2,766	-16	16.2
194	Observed	2,790	2.38	5.68	10	2,784	2,794		
	Simulated	2,788	4.62	21.34	16	2,779	2,795	2	3.1
201	Observed	2,726	1.31	1.71	6	2,723	2,729		
	Simulated	2,733	2.43	5.89	11	2,728	2,739	-7	7.0

Table 12. Comparison of observed and simulated hydraulic heads for State observation wells for the transient simulation–Continued

[Hydraulic heads in feet above NGVD of 1929. --, not applicable]

State well number	Data type	Mean	Standard deviation	Variance	Range	Minimum	Maximum	Difference of observed and simulated means	Average of absolute value of residuals[1]
207	Observed	2,930	1.06	1.12	5	2,928	2,933		
	Simulated	2,929	.64	.41	3	2,927	2,930	1	1.6
219	Observed	2,754	1.55	2.40	8	2,749	2,757		
	Simulated	2,773	3.76	14.12	11	2,767	2,778	-19	18.9
170	Observed	2,902	.44	.20	3	2,900	2,903		
	Simulated	2,906	.36	.13	2	2,906	2,908	-4	4.6
205	Observed	2,781	2.39	5.70	9	2,776	2,785		
	Simulated	2,777	3.45	11.90	10	2,772	2,782	4	3.7
210	Observed	2,523	2.81	7.89	11	2,517	2,528		
	Simulated	2,522	.62	.38	3	2,520	2,523	1	2.7
274	Observed	2,458	2.08	4.31	9	2,453	2,462		
	Simulated	2,454	.73	.54	3	2,453	2,456	4	3.4
361	Observed	2,763	2.37	5.60	20	2,760	2,780		
	Simulated	2,784	1.48	2.20	6	2,782	2,788	-21	21.4
374	Observed	2,578	3.06	9.39	12	2,574	2,586		
	Simulated	2,589	1.38	1.92	7	2,586	2,593	-11	11.1
384	Observed	2,561	5.25	27.56	22	2,552	2,574		
	Simulated	2,570	.86	.74	5	2,568	2,573	-9	8.8
Mean	--	--	--	--	--	--	--	-3.7	8.8

[1]The residual is the difference of the observed and simulated value.

Table 13. Comparison of observed and simulated hydraulic heads for Tribal observation wells for the transient simulation

[Observed data based on annual averages. Hydraulic heads in feet above NGVD of 1929. --, not applicable]

Tribal well number	Data type	Mean	Standard deviation	Variance	Range	Minimum	Maximum	Difference of observed and simulated means
3	Observed	2,826	.89	.80	3	2,825	2,828	
	Simulated	2,865	1.67	2.79	7	2,862	2,869	-39
4	Observed	2,896	.64	.41	3	2,895	2,898	
	Simulated	2,892	.85	.71	3	2,891	2,894	4
5	Observed	2,844	.59	.34	3	2,842	2,845	
	Simulated	2,831	.82	.68	3	2,830	2,833	13
6	Observed	2,853	1.52	2.30	5	2,851	2,856	
	Simulated	2,858	.80	.64	4	2,856	2,860	-5
7	Observed	2,834	1.75	3.05	7	2,830	2,837	
	Simulated	2,851	1.69	2.87	7	2,845	2,852	-17
8	Observed	2,843	.90	.81	3	2,842	2,845	
	Simulated	2,836	2.98	8.90	12	2,827	2,839	7
9	Observed	2,836	.73	.54	3	2,835	2,838	
	Simulated	2,832	7.45	55.56	22	2,824	2,846	4
10	Observed	2,793	.51	.26	2	2,792	2,794	
	Simulated	2,792	1.11	1.23	3	2,791	2,794	1
11	Observed	2,795	3.29	10.83	10	2,790	2,800	
	Simulated	2,810	3.83	14.65	13	2,804	2,817	-15
12	Observed	2,770	3.83	14.70	13	2,762	2,775	
	Simulated	2,804	1.54	2.38	5	2,801	2,806	-34
13	Observed	2,831	6.93	47.99	28	2,814	2,842	
	Simulated	2,815	1.71	2.94	5	2,813	2,818	16
16	Observed	2,726	2.50	6.24	10	2,721	2,731	
	Simulated	2,725	1.32	1.75	5	2,724	2,729	1
17	Observed	2,622	1.58	2.49	5	2,620	2,625	
	Simulated	2,604	1.09	1.18	4	2,602	2,606	18
18	Observed	2,700	.90	.81	3	2,698	2,701	
	Simulated	2,660	1.40	1.97	5	2,657	2,662	40
19	Observed	2,735	.55	.30	2	2,734	2,736	
	Simulated	2,724	.77	.59	2	2,723	2,725	11
20	Observed	2,716	.45	.21	2	2,715	2,717	
	Simulated	2,711	1.81	3.28	6	2,708	2,714	5

Table 13. Comparison of observed and simulated hydraulic heads for Tribal observation wells for the transient simulation–Continued

[Observed data based on annual averages. Hydraulic heads in feet above NGVD of 1929. --, not applicable]

Tribal well number	Data type	Mean	Standard deviation	Variance	Range	Minimum	Maximum	Difference of observed and simulated means
21	Observed	2,644	1.15	1.31	4	2,642	2,646	
	Simulated	2,671	1.43	2.04	5	2,669	2,674	-27
22	Observed	2,591	.76	.58	3	2,590	2,593	
	Simulated	2,589	1.58	2.50	5	2,587	2,592	2
23	Observed	2,590	.75	.56	3	2,589	2,592	
	Simulated	2,600	2.21	4.89	8	2,597	2,605	-10
27	Observed	2,789	1.34	1.78	5	2,787	2,792	
	Simulated	2,759	3.08	9.50	13	2,756	2,769	30
15	Observed	2,583	0.98	0.96	3	2,582	2,585	
	Simulated	2,609	1.04	1.09	4	2,606	2,610	-26
Mean	--	--	--	--	--	--	--	-1.0

The simulated base flow from ground-water discharge for the Ogallala and Arikaree aquifers had less fluctuation between stress periods than did the estimated base flow (fig. 24), which corresponds with the data in table 5. This may represent limitations of either base-flow estimates or the model or both. The average simulated base flow was within 8 percent of the average of estimated values for the Little White River and within 13 percent for the Keya Paha River (table 14). The simulated base flow for the Little White River included springs within the Little White River Basin above Soldier Creek, which were assumed to contribute base flow to the river.

Table 14. Comparison of average simulated and estimated base flow for the Little White and Keya Paha Rivers for the transient-state simulation, water years 1979-98

Stream	Base flow (cubic feet per second)		Percent error of simulated to estimated base flow
	Estimated[1]	Model simulation	
Little White River	49	45	8
Keya Paha River	23	20	13

[1]From table 5.

Model Limitations

The numerical model adequately simulates flow in the Ogallala and Arikaree aquifers in the study area for the purposes and objectives of this study; however, water managers should be aware of the model's limitations. There are uncertainties in many model input parameters, most importantly recharge, evapotranspiration, and horizontal and vertical hydraulic conductivity. Although these parameters had a major influence on model results, extensive data were not available. The combination of parameter values used in this model were based on many considerations. The parameter values were chosen within the general ranges of previously published values, and therefore, the model's accuracy is dependent, in part, on the accuracy of those estimates. Calibration of the model possibly could be improved by breaking down further the spatial discretization of some parameters, such as hydraulic conductivity or recharge; however, without more field data, finer discretization was not justifiable. In this case, a simpler model adequately represented the system. The degree of discretization and the parameter values chosen for this model were a balance between that based on calibration and that based on available parameter data; however, combinations of parameter values other than that used in this model also may give satisfactory results.

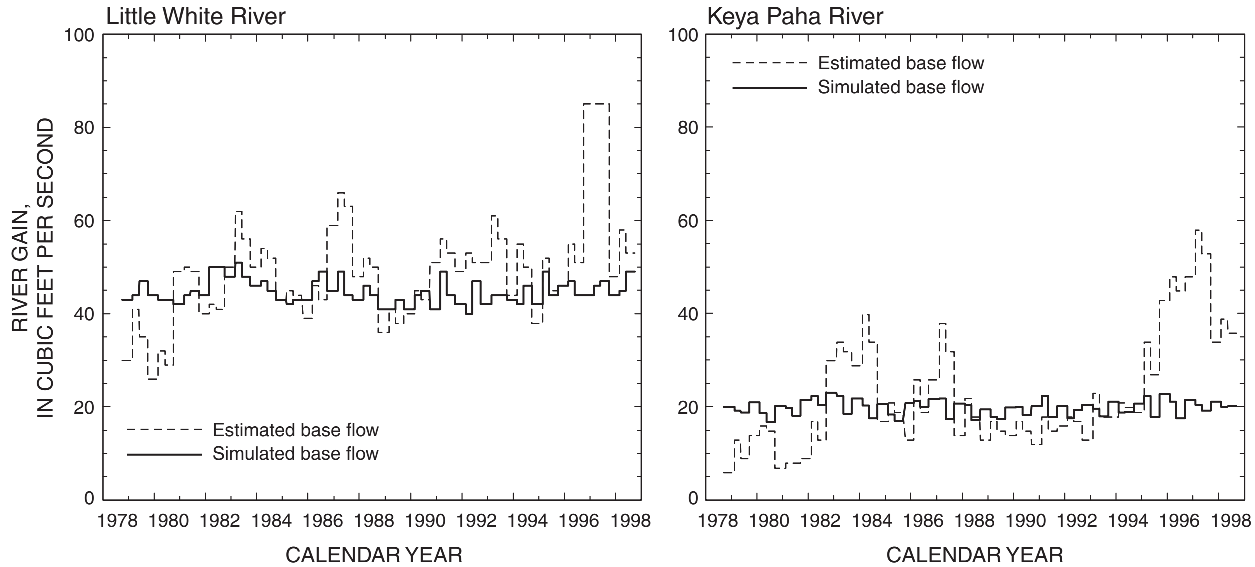


Figure 24. Comparison of estimated and simulated base flow for the Little White and Keya Paha Rivers.

This numerical model is suitable as a tool to help understand the flow system, to confirm that previous estimates of aquifer properties are reasonable, and to estimate aquifer properties in areas without data. Limitations of the model should be taken into account when applying the model to water management. With additional data, further refinement of the model would be possible, which could improve the accuracy of model prediction of the effects of additional stresses on the system, such as increased withdrawals or drought.

SUMMARY

The Ogallala and Arikaree aquifers are important water resources in the Rosebud Indian Reservation area and are used extensively for irrigation, municipal, and domestic water supplies. Continued or increased withdrawals from the Ogallala and Arikaree aquifers in the Rosebud Indian Reservation area have the potential to affect water levels in these aquifers. A water-resource tool was needed to evaluate management and environmental issues associated with the Ogallala and Arikaree aquifers, such as planning for source-water protection, describing potential impacts of contamination, and estimating sustainable aquifer withdrawals. To address this need, the U.S. Geological Survey (USGS) has worked in cooperation with the Rosebud Sioux Tribe to develop a numerical model to simulate ground-water flow in the Ogallala and Arikaree aquifers in the Rosebud Indian Reservation area. This report describes a conceptual model of ground-water flow in the aquifers and documents the development and calibration of a numerical model to simulate ground-water flow. Data for a twenty-year period (water years 1979 through 1998) were analyzed for the conceptual model. Steady-state and transient simulations were performed for the same 20-year period.

Areal recharge to the Ogallala and Arikaree aquifers occurs from precipitation on the outcrop areas, and regional flow enters the study area from the west. Ground water from areal recharge moves from areas of higher altitude toward streams that gain flow from the Ogallala and Arikaree aquifers. Discharge from the Ogallala and Arikaree aquifers occurs through evapotranspiration, discharge to streams, and well withdrawals. Evapotranspiration generally occurs in topographically low areas and along streams, and maximum evapotranspiration occurs when the water level is at the land surface.

Seepage runs were conducted in the study area to obtain information describing streamflow gains in the study area. Base flow was estimated at gaging stations using a hydrograph separation method. The 20-year average estimated base flow was 49 cubic feet per

second for the Little White River and 23 cubic feet per second for the Keya Paha River.

Well withdrawals in the study area occur from irrigation, domestic, and stock wells. Withdrawals for domestic and stock uses were assumed to be negligible compared with irrigation use. The 20-year average estimated irrigation withdrawal was 11.6 cubic feet per second.

The conceptual model of ground-water flow was simulated with a numerical model with two aquifer layers using MODFLOW-2000. The upper layer represented the Ogallala aquifer, and the lower layer represented the Arikaree aquifer. The study area was divided into grid blocks 1,640 feet (500 meters) on a side, with 153 rows and 180 columns. Combinations of constant-head and no-flow boundaries were used to best represent boundary conditions.

Estimated horizontal hydraulic conductivity used for the numerical model ranged from 0.2 to 120 feet per day in the Ogallala aquifer and 0.1 to 5.4 feet per day in the Arikaree aquifer. A uniform vertical hydraulic conductivity value of $6.6x10^{-4}$ feet per day was applied to the Ogallala aquifer. Vertical hydraulic conductivity was estimated for five zones in the Arikaree aquifer and ranged from $8.6x10^{-6}$ to $7.2x10^{-1}$ feet per day.

The recharge rate for the steady-state simulation was 3.3 and 1.7 inches per year for the Ogallala and Arikaree aquifers, respectively, for a total recharge rate of 266 cubic feet per second. Discharge rates in cubic feet per second for the steady-state simulation were 184 for evapotranspiration, 46.8 and 19.7 for base flow to the Little White and Keya Paha Rivers, respectively, and 11.6 for well withdrawals from irrigation.

Model calibration was accomplished by varying the model parameters within plausible ranges to produce the best fit between simulated and observed hydraulic heads in the Ogallala and Arikaree aquifers. Steady-state simulations representing average conditions over the 20-year analysis period were analyzed to determine the optimum combination of model parameters. The potentiometric surface calculated from the steady-state simulation established initial conditions for the transient simulation. Water-level measurements were available for 354 public and private wells, 23 State observation wells, and 21 Tribal observation wells.

Calibration criteria for the steady-state simulation included: (1) generally matching the simulated potentiometric surfaces and hydraulic gradients to those of the estimated potentiometric surfaces, and (2) matching hydraulic heads at 95 percent of the wells to within ±50 feet of the observed hydraulic heads. Calibration criteria for the transient simulation included matching the general trends of the 23 State observation well hydrographs and 21 Tribal observation well hydrographs. There was no attempt to calibrate the well hydrographs closer than that required by the steady-state model (±50 feet). Results of the steady-state and transient simulations were within the calibration criteria established to meet the objectives of the study.

A sensitivity analysis was used to examine the response of the numerical model calibrated to steady-state conditions to changes in model parameters including horizontal and vertical hydraulic conductivity, evapotranspiration, recharge, and riverbed conductance, which were increased and decreased for the sensitivity analysis. The model was most sensitive to recharge and horizontal hydraulic conductivity.

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SUPPLEMENTAL INFORMATION

Table 15. Wells used for estimating potentiometric surface of the Ogallala aquifer

[Well locations are shown in figure 4. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Average hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 9)
430239100174301	35N25W 5BBAA	430242	1001731	2,518	2,509.5	--
430200100164801	35N25W 5DDD	430200	1001648	2,501	2,495.5	--
430151100173901	35N25W 8BB	430139	1001730	2,513	2,495.5	--
430023100115602	35N25W13DADD2	430023	1001156	2,443	2,433.9	--
430002100174801	35N25W20BBBC	430002	1001748	2,493	2,488.6	--
430237100241201	35N26W 5BA	430237	1002419	2,635	2,603.1	--
430126100222001	35N26W10CBBA2	430126	1002220	2,618	2,572.8	--
430033100203001	35N26W14DB	430028	1002036	2,530	2,520.4	--
430040100233901	35N26W17DAB	430033	1002349	2,583	2,576.3	--
430006100254301	35N26W19BBAC	430004	1002545	2,660	2,623.4	--
430236100274201	35N27W 2ABCC	430232	1002740	2,700	2,628.3	--
430215100273301	35N27W 2DBCC	430207	1002742	2,695	2,658.3	--
430245100292801	35N27W 3BBBB	430245	1002928	2,671	2,660.2	--
430230100320301	35N27W 6AAC	430235	1003205	2,710	2,679.1	--
430121100323001	35N27W 7CACB	430119	1003245	2,724	2,698.1	--
430115100322101	35N27W 7DACC	430115	1003208	2,731	2,705.1	--
430119100291801	35N27W10CBBB	430124	1002909	2,717	2,685.6	--
430103100280601	35N27W11CCDC	430102	1002806	2,682	2,650.5	--
430106100271403	35N27W11DD	430106	1002714	2,637	2,623.4	--
430139100264401	35N27W12B	430139	1002644	2,636	2,619.3	--
430057100275401	35N27W14BAAB	430100	1002751	2,690	2,671.0	T21
430022100270901	35N27W14DAA	430022	1002709	2,676	2,666.4	--
430039100301001	35N27W16BD	430039	1003010	2,695	2,677.8	--
430039100320801	35N27W18A	430039	1003208	2,725	2,709	--
430122100344501	35N28W11DBBB	430126	1003446	2,728	2,711.2	T20
430055100362702	35N28W15BBBD2	430055	1003627	2,754	2,744.2	--
430154100411801	35N29W 2DDDD	430156	1004118	2,800	2,792.0	T10
430156100411901	35N29W 2DDDD2	430156	1004119	2,800	2,791.2	--
430238100434801	35N29W 4AA	430238	1004348	2,830	2,810	--
430226100445203	35N29W 4BCCB3	430225	1004450	2,845	2,828.9	--
430148100471001	35N29W 7BBBB	430151	1004711	2,903	2,837.3	S41
430151100415402	35N29W11ABBB2	430151	1004154	2,800	2,779.7	--
430100100460501	35N29W18AAAA	430100	1004604	2,870	2,831.4	T9
425957100445601	35N29W20AADD	425957	1004453	2,890	2,804.3	S2
430212100524001	35N30W 5CA	430212	1005240	2,828	2,808.7	--

Table 15. Wells used for estimating potentiometric surface of the Ogallala aquifer–Continued

[Well locations are shown in figure 4. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Average hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 9)
430153100521303	35N30W 5DDCC3	430153	1005213	2,842	2,821.5	--
430217100535201	35N30W 6CABA	430217	1005352	2,873	2,833.7	--
430159100531001	35N30W 6DDDD	430153	1005309	2,853	2,831.6	T5
430139100474801	35N30W12ACBB	430139	1004748	2,935	2,875.3	--
430037100471601	35N30W13ADD	430037	1004716	2,895	2,784.8	--
430045100495701	35N30W15ACA	430045	1004957	2,880	2,850	--
430231100591501	35N31W 5AACC	430231	1005915	2,865	2,849.8	--
430120100574901	35N31W10CBBC	430120	1005749	2,823	2,817.9	--
430042100565801	35N31W15ACA	430042	1005658	2,822	2,814.7	--
430017100595101	35N31W17CCDA	430014	1005947	2,896	2,892.5	T4
430113101062401	35N32W 8D	430111	1010624	2,980	2,974.6	--
430152101054803	35N32W 9BABB3	430152	1010548	2,935	2,927.5	--
430047101025001	35N32W14A	430047	1010250	2,982	2,912.7	--
430028101111701	35N33W15DB	430028	1011117	3,060	3,035.4	--
425956101134503	35N33W20ABCC3	425956	1011345	3,050	3,032.4	--
430704100145901	36N25W10BABB	430704	1001459	2,442	2,420.8	--
430348100172001	36N25W29CDAC	430344	1001720	2,573	2,525.5	--
430315100184301	36N25W31BDCB	430315	1001843	2,552	2,530.4	--
430331100153301	36N25W33AA	430331	1001533	2,585	2,513.6	--
430454100255101	36N26W19BBC	430454	1002551	2,650	2,608.3	--
430515100225001	36N26W21AAB	430517	1002238	2,585	2,543.3	--
430310100245501	36N26W31ADDD	430312	1002455	2,620	2,594.4	S80
430335100241401	36N26W32BBAA	430337	1002431	2,619	2,589.2	T22
430246100222302	36N26W34CCC2	430246	1002223	2,634	2,607.2	--
430728100135801	36N27W 1BDDD	430735	1002632	2,627	2,600.0	T23
430721100290001	36N27W 3CA	430721	1002900	2,663	2,602.2	--
430705100304701	36N27W 5DDD	430709	1003045	2,600	2,579.4	--
430512100291801	36N27W15CC	430527	1002920	2,698	2,621.9	--
430458100300901	36N27W21BDDB	430500	1003013	2,664	2,613	--
430737100350602	36N28W 2BDAC2	430740	1003453	2,773	2,676.7	--
430719101380501	36N28W 5DACC	430718	1003804	2,818	2,782.9	--
430604100390801	36N28W 7DDB	430624	1003911	2,829	2,793.1	--
430649100364801	36N28W 9ADDA	430643	1003638	2,805	2,764.2	--
430701100363001	36N28W10BBBB	430705	1003635	2,823	2,750.3	S145
430700100344501	36N28W11ABB	430703	1003444	2,807	2,706.6	--

Table 15. Wells used for estimating potentiometric surface of the Ogallala aquifer–Continued

[Well locations are shown in figure 4. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Average hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 9)
430702100330501	36N28W12AABA	430706	1003313	2,806	2,659.8	T18
430618100330301	36N28W12DD	430620	1003310	2,675	2,668.8	--
430614100362503	36N28W15BABB3	430614	1003625	2,778	2,753	--
430601100364501	36N28W16ABCA	430607	1003705	2,805	2,779.4	--
430515100331201	36N28W24AAA	430518	1003306	2,685	2,664.8	--
430406100380701	36N28W29ACDC	430405	1003810	2,771	2,756.4	--
430403100395001	36N28W30BCDD	430403	1003950	2,820	2,800.8	--
430348100390401	36N28W30DDAB	430348	1003904	2,792	2,772.7	--
430314100392301	36N28W31ACDC	430314	1003923	2,839	2,819.1	--
430243100371701	36N28W33BDDD	430311	1003712	2,753	2,723.0	T19
430712100421301	36N29W 2CDCC	430706	1004208	2,850	2,804.3	T12
430714100445001	36N29W 4CCBC	430715	1004448	2,853	2,816.4	--
430624100461601	36N29W 7DDB	430624	1004616	2,925	2,889.7	--
430659100434901	36N29W 9AA	430659	1004349	2,845	2,777.8	--
430629100434401	36N29W 9DAD	430629	1004344	2,885	2,817.4	--
430530100422501	36N29W14CDAB	430528	1004158	2,893	2,810.8	T11
430522100411902	36N29W14DDDD2	430522	1004119	2,884	2,814.9	--
430558100430301	36N29W15ACBB	430558	1004303	2,884	2,866.4	--
430609100434201	36N29W16AAAA	430613	1004346	2,863	2,821.7	S125
430604100445201	36N29W17AADD1	430604	1004453	2,905	2,822.9	--
430603100460501	36N29W18AADD	430603	1004605	2,940	2,849.9	--
430450100453701	36N29W20CA	430450	1004537	2,868	2,845.4	--
430508100431901	36N29W22BBDD	430508	1004319	2,911	2,830.6	--
430415100451401	36N29W29ACAA	430415	1004512	2,870	2,850.8	T7
430305100455401	36N29W32CB	430305	1004554	2,835	2,823.3	--
430252100431301	36N29W34CD	430252	1004313	2,804	2,794.2	--
430302100412001	36N29W35DAD	430302	1004120	2,834	2,818.5	--
430723100512101	36N30W 4DBCB	430723	1005121	2,978	2,871.7	--
430652100484001	36N30W11ADBB	430652	1004840	2,949	2,850.5	--
430615100472701	36N30W12DDCD	430615	1004723	2,960	2,826.6	--
430610100481701	36N30W13BBBB	430613	1004820	2,916	2,843.4	S126
430518100533701	36N30W19ABB	430518	1005337	2,902	2,854.9	--
430501100504901	36N30W21DAAA	430453	1005045	2,888	2,858.3	T6
430507100483701	36N30W23ADBB	430507	1004837	2,934	2,848.4	--
430342100482901	36N30W26DDDB	430342	1004829	2,851	2,831.9	--

Table 15. Wells used for estimating potentiometric surface of the Ogallala aquifer–Continued

[Well locations are shown in figure 4. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Average hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 9)
430250100532701	36N30W31DCDA	430250	1005327	2,868	2,848.8	--
430327100512301	36N30W33BADD	430327	1005123	2,945	2,853.8	--
430334100515201	36N30W33BBB	430334	1005152	2,896	2,842.8	--
430254100515001	36N30W33CCBD	430254	1005150	2,879	2,855.7	--
430258100471401	36N30W36DDDA	430250	1004712	2,885	2,836.1	T8
430721100563001	36N31W 2CB	430721	1005630	2,934	2,784.8	--
430613101561701	36N31W14BAAA	430613	1005606	2,955	2,816.3	S130
430541100555501	36N31W14DB	430541	1005555	2,970	2,870.8	--
430555100570301	36N31W15ACAC	430555	1005703	3,005	2,915.8	--
430603101003401	36N31W18ABDD	430603	1010034	2,877	2,838.8	--
430309100570901	36N31W34DBBC	430306	1005714	2,920	2,864.8	T3
430458101042001	36N32W22CADA	430458	1010420	2,850	2,820.7	--
430426101020201	36N32W25BAA	430426	1010202	2,845	2,810.8	--
430340101012301	36N32W25DDDD	430340	1010123	2,841	2,833.9	S87
431236100172601	37N25W 4BCCA	431236	1001726	2,467	2,386.1	--
430932100262401	37N26W19DCC	430932	1002624	2,655	2,584.2	--
431027100333001	37N27W18DDAB	431035	1003306	2,609	2,604.5	T17
430909100333501	37N27W30BDDA	430909	1003335	2,722	2,662.1	--
431159100412103	37N28W 7BBBC3	431159	1004121	2,793	2,715.8	--
431021100384701	37N28W16CCDD	431024	1003845	2,744	2,714.4	--
430956100402901	37N28W19ACDD	430956	1004029	2,800	2,772.5	--
430932100390001	37N28W21CCCC	430930	1003858	2,772	2,726.6	S201
430839100373801	37N28W27CCCC	430839	1003745	2,805	2,726.6	S175
430907100401001	37N28W30ADDA	430907	1004010	2,757	2,741.5	--
430842100411301	37N28W30CCCB	430841	1004119	2,770	2,744.9	S177
430820100371401	37N28W34ABDA	430828	1003655	2,783	2,725.1	T16
430809100372401	37N28W34BDA	430725	1003715	2,800	2,740.4	--
431212100472901	37N29W 6DDBD	431212	1004727	2,868	2,739.8	--
431138100441601	37N29W10DBBB	431136	1004414	2,818	2,755.5	--
431141100422501	37N29W12BCDD	431141	1004215	2,825	2,761.5	--
431133100402201	37N29W13CBCD	431133	1004222	2,796	2,731.7	--
431109100445901	37N29W16AAAA	431112	1004457	2,852	2,753.6	S219
431100100461601	37N29W17AACD	431106	1004604	2,845	2,767.7	--
430920100444801	37N29W27BBCA	430920	1004448	2,877	2,810.4	--
430852100435001	37N29W27DACD	430850	1004348	2,825	2,768.1	--

Table 15. Wells used for estimating potentiometric surface of the Ogallala aquifer–Continued

[Well locations are shown in figure 4. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Average hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 9)
430909100452701	37N29W28ACBC	430905	1004527	2,880	2,803.4	--
430840100445601	37N29W28DDDD	430837	1004454	2,858	2,790.7	S176
430924100460601	37N29W29AAAA	430927	1004607	2,868	2,790.1	S194
430836100464301	37N29W29CDDD	430836	1004641	2,870	2,800.8	--
430755100582301	37N29W31DACC	430757	1004729	2,921	2,815.4	T13
430748100455601	37N29W33CCCC	430745	1004601	2,909	2,817.2	S160
431127100532801	37N30W 8DACC	431114	1005333	2,880	2,759.4	T27
431033100493201	37N30W13CBCD	431033	1004932	2,783	2,766.1	--
430910100490201	37N30W25ACBC	430911	1004902	2,899	2,882.2	--
430912100542301	37N30W29BCBB	430912	1005421	2,997	2,812.3	--
430848100544001	37N30W30DDBC	430842	1005437	2,980	2,778.2	--
430831100580301	37N31W25CCCB	430831	1005803	2,970	2,776.9	--
431200101034801	37N32W11ABA	431157	1010356	3,060	2,876.3	--
430907101073801	37N32W29ACB	430907	1010738	2,910	2,882.1	--
431222101093501	37N33W 1DAA	431222	1010954	3,104	3,008.8	--
431148101165001	37N33W 7ABD	431154	1011544	3,018	2,947.4	--
431156101105801	37N33W11AAB	431157	1011052	3,153	3031.6	--
431018101132301	37N33W16DCDC	431018	1011323	3,023	2,955.4	--
431018101152001	37N33W17CCCC	431018	1011520	2,998	2,930.3	S207
430929101104203	37N33W26AAAA3	430929	1011042	2,953	2,875.8	--
431432101123401	37N33W27BAA	430921	1011230	2,978	2,917.5	--
430836101152201	37N33W32BBBB	430836	1011522	2,960	2,894.8	--
430825101151801	37N33W32BBBB2	430834	1011518	2,960	2,901.8	S170
431250101163701	37N34W 1AAAA	431250	1011637	3,113	2,959.9	--
431540100154501	38N25W15DCCB	431540	1001545	2,467	2,406.2	--
431509100185901	38N25W19ADCC	431509	1001859	2,530	2,504.3	--
431327100164501	38N25W33ACD	431327	1001645	2,475	2,466.1	--
431716100212001	38N26W11AAB	431716	1002120	2,651	2,600.8	--
431532100200101	38N26W24AAAB	431532	1002001	2,503	2,467.3	--
431714100364101	38N28W20AAAD	431524	1003906	2,700	2,646.4	--
431427100375201	38N28W28ADAA	431427	1003754	2,781	2,729.1	--
431354100375201	38N28W28DDDD	431351	1003753	2,781	2,749.8	--
431435100414101	38N29W25AACB	431433	1004130	2,663	2,646.9	--
431318100532301	38N30W32DAAB	431318	1005321	2,838	2,818.3	--
431550100590501	38N31W16CABD	431550	1005905	2,747	2,743	--

Table 16. Wells used for estimating potentiometric surface of the Arikaree aquifer

[Well locations are shown in figure 5. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Adjusted hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 10)
430242100184801	35N25W 6BBA	430242	1001842	2,525	2,513.4	--
430003100174802	35N25W20BBBC3	430003	1001748	2,493	2,488.1	--
430204100212001	35N26W 3DDAB	430204	1002120	2,617	2,593.1	--
430216100252101	35N26W 6DBBA	430216	1002517	2,620	2,558.3	--
430127100230601	35N26W 9BDAD	430135	1002320	2,585	2,558.3	--
430126100221901	35N26W10CBBA3	430126	1002219	2,617	2,569.1	--
430033100234902	35N26W17DAB2	430033	1002349	2,583	2,565.4	--
430245100292701	35N27W 3BBBB4	430245	1002927	2,671	2,659.9	--
430106100271402	35N27W11DD2	430106	1002714	2,637	2,610.7	--
430000100285401	35N27W22ABBC	430003	1002855	2,679	2,668.1	--
430154100332601	35N28W 1DC	430154	1003326	2,683	2,673.1	--
430217100370801	35N28W 4ACCB	430224	1003707	2,753	2,719.4	--
430613100352901	35N28W14AAAA	430102	1003415	2,735	2,722	--
430226100445201	35N29W 4BCCB	430226	1004452	2,845	2,832.2	--
430225100445401	35N29W 5DDDA	430157	1004454	2,880	2,783.1	--
430048100450201	35N29W17AACD	430048	1004502	2,913	2,830.8	--
430014100445401	35N29W17DDDA	430014	1004454	2,878	2,850.6	--
430113100491601	35N30W11C	430113	1004916	2,910	2,824.1	--
430142100580301	35N31W 9AACD	430142	1005803	2,840	2,811.9	--
430021100543301	35N31W13D	430021	1005433	2,840	2,782.5	--
430153101054902	35N32W 9BABB5	430153	1010549	2,938	2,930.5	--
430727100170304	36N25W 5DBD	430721	1001700	2,440	2,427.6	--
430326100185001	36N25W31ABC	430326	1001819	2,597	2,549.9	--
430700100225701	36N26W 9AB	430700	1002257	2,505	2,498.3	--
430607100212101	36N26W15AAAB	430611	1002119	2,505	2,447.5	--
430528100242001	36N26W17CDD	430523	1002416	2,554	2,533.6	--
430455100241301	36N26W20CAD	430455	1002413	2,537	2,524.7	--
430424100214301	36N26W27ABBB	430427	1002147	2,588	2,545.7	--
430727100262801	36N27W 1	430727	1002628	2,650	2,597.4	--
430451100290001	36N27W22CDBA	430451	1002906	2,638	2,628.4	--
430410100261701	36N27W25ADBB	430415	1002611	2,658	2,614	--
430412100323001	36N27W30BDA	430413	1003233	2,693	2,672.6	--
430245100272401	36N27W35DCD	430246	1002730	2,673	2,646.5	--
430702100330501	36N28W12AAA	430706	1003313	2,806	2,641.6	--
430454100341801	36N28W23DAAC	430454	1003418	2,730	2,712.3	--

Table 16. Wells used for estimating potentiometric surface of the Arikaree aquifer–Continued

[Well locations are shown in figure 5. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Adjusted hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 10)
430448100332401	36N28W24ACA	430503	1003324	2,655	2,644.9	--
430627100532601	36N30W 7D	430627	1005326	2,960	2,856.3	--
430301100492101	36N30W35CBCC	430300	1004930	2,917	2,842.5	--
430630100565401	36N31W10DACD3	430630	1005654	2,958	2,736.1	--
430613100544901	36N31W12DCCD	430613	1005449	2,899	2,842.6	--
430650101021001	36N32W 1DCDC	430708	1010147	2,623	2,613.9	--
430721101032801	36N32W 2C	430721	1010328	2,660	2,666.6	--
430712101042801	36N32W 3CD	430712	1010428	2,686	2,631.4	--
430619101020501	36N32W12CD2	430619	1010205	2,895	2,733.9	--
430612101014401	36N32W12DD	430620	1010130	2,842	2,674.1	--
430537101062801	36N32W17DBD	430537	1010628	2,860	2,820.2	--
431500101133301	36N33W21BBC	430511	1011307	2,985	2,859.6	--
431254100191001	37N25W 6ABA	431254	1001910	2,410	2,372.6	--
431211100194502	37N25W 6CCC2	431211	1001945	2,369	2,346.5	--
430908100175801	37N25W29ACDD	430908	1001758	2,374	2,359.5	--
430757100183301	37N25W32CCAB	430757	1001833	2,423	2,395.5	--
431245100210801	37N26W 2ADAA	431245	1002108	2,383	2,350.5	--
431215100225801	37N26W 3CDA	431215	1002258	2,444	2,401.2	--
431020100243501	37N26W16CCBB	431020	1002435	2,530	2,522.9	S210
430931100251801	37N26W20CDD	430931	1002518	2,605	2,557	--
430932100211701	37N26W23DDCD	430932	1002117	2,538	2,495.2	--
431019100200001	37N26W24AAA	431019	1002000	2,471	2,453.3	--
430953100200001	37N26W24DAA	430953	1002000	2,451	2,418.3	--
430858100202301	37N26W25DBBD	430858	1002023	2,565	2,522.3	--
430851100210801	37N26W26DADD	430851	1002108	2,576	2,533.2	--
430756100231601	37N26W34CCAA	430756	1002316	2,540	2,521.2	--
430803100212801	37N26W35DBDA	430803	1002128	2,554	2,511.3	--
431212100280601	37N27W 1CC	431212	1002806	2,474	2,451.4	--
431245100320601	37N27W 5A	431245	1003206	2,593	2,581.7	--
431126100321001	37N27W 8D	431127	1003206	2,553	2,536.7	--
431139100311501	37N27W 9CAAA	431139	1003115	2,540	2,526.3	--
431050100274501	37N27W13BDD	431050	1002745	2,530	2,472.2	--
431051100293101	37N27W15ADD	431051	1002931	2,518	2,465.6	--
431000100325101	37N27W20BCD	431000	1003251	2,620	2,609.1	--
430938100273701	37N27W24DCB	430939	1002735	2,595	2,548.2	--

Table 16. Wells used for estimating potentiometric surface of the Arikaree aquifer–Continued

[Well locations are shown in figure 5. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Adjusted hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 10)
430926100290301	37N27W26BAB	430926	1002903	2,564	2,441.5	--
430817100312001	37N27W33BD	430817	1003120	2,620	2,603.5	--
431159100412102	37N28W 7BBBC2	431159	1004121	2,793	2,718	--
430922100410302	37N28W30BBAA2	430922	1004103	2,818	2,753.3	--
430821100373401	37N28W34BCAB	430821	1003734	2,808	2,734.4	--
431149100462301	37N29W 8AADC	431158	1004608	2,810	2,739.6	--
430959100444001	37N29W22CCCC	430929	1004453	2,882	2,780.9	S205
431238100490301	37N30W 1ACB	431240	1004858	2,740	2,693.9	--
431250100530101	37N30W 4BAA	431252	1005256	2,842	2,716.5	--
431122100551202	37N30W 7CDBA2	431124	1005506	2,770	2,604.2	--
431022100542301	37N30W17CCCB	431019	1005423	2,995	2,788.8	--
430824100522501	37N30W33ABD	430808	1005143	2,985	2,838.7	--
430800100491801	37N30W36A2	430812	1004845	2,935	2,824.5	--
431234100574401	37N31W 3ADAC	431234	1005744	2,512	2,506.3	--
431131100580701	37N31W10DBBB	431131	1005807	2,530	2,498.1	--
430920100581201	37N31W22ABCD2	431005	1005804	2,943	2,639.4	--
430838100561701	37N31W25CC	430836	1005611	3,015	2,802.3	--
430845100571903	37N31W26C3	430845	1005719	3,017	2,736.9	--
430807100591001	37N31W33DAA	430805	1005852	3,037	2,780.6	--
431030101031201	37N32W13CAD	431034	1010311	2,970	2,792.3	--
430929101104202	37N33W26AAAA2	430929	1011042	2,953	2,875.7	--
431430100195901	38N25W30BCBB	431428	1001955	2,483	2,457.6	S274
431311100193201	38N25W31CDBA	431311	1001932	2,426	2,413.6	--
431637100264101	38N26W 7CDB	431637	1002641	2,513	2,485.8	--
431554100203301	38N26W13BCCA	431604	1002101	2,608	2,504.6	--
431413100244901	38N26W29DAA	431413	1002449	2,440	2,417.5	--
431356100255401	38N26W30DAD	431405	1002558	2,420	2,387.5	--
431340100253901	38N26W32BBD	431340	1002539	2,452	2,437.4	--
431328100240901	38N26W33BDD	431328	1002409	2,424	2,413.4	--
431308100223101	38N26W34DDB	431308	1002231	2,417	2,394.5	--
431323100213501	38N26W35DBBA	431323	1002135	2,403	2,340.5	--
431736100293201	38N27W 3DAD	431736	1002932	2,526	2,474.3	--
431808100312801	38N27W 4BAB	431808	1003128	2,550	2,488.8	--
431757100323302	38N27W 5BDAB	431757	1003233	2,522	2,497	--
431650100330701	38N27W 7DAAB	431650	1003307	2,477	2,468.2	--

Table 16. Wells used for estimating potentiometric surface of the Arikaree aquifer–Continued

[Well locations are shown in figure 5. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Adjusted hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 10)
431548100314401	38N27W16CBCD	431548	1003144	2,484	2,452.7	--
431440100275301	38N27W25BABA	431440	1002753	2,448	2,415.8	--
431430100320101	38N27W28B	431430	1003201	2,518	2,506.7	--
431337100312101	38N27W33BDA	431337	1003121	2,570	2,540.5	--
431539100352401	38N28W13CCCC	431535	1003530	2,577	2,539.2	--
431625100361301	38N28W14BAAB	431625	1003613	2,589	2,529.4	--
431615100390701	38N28W17AADD	431615	1003907	2,664	2,609.6	--
431625100411801	38N28W18BBBA	431625	1004118	2,596	2,587.3	--
431512100402501	38N28W19ADCD	431509	1004029	2,673	2,638.5	--
431506100363601	38N28W23CBBB	431508	1003641	2,635	2,626.8	--
431430100371601	38N28W27ACB	431430	1003716	2,768	2,724.3	--
431347100404901	38N28W31ABBB	431347	1004049	2,666	2,645.1	--
431342100344101	38N28W36ABCB	431347	1003452	2,620	2,608.7	T15
431551100441601	38N29W15DBCD	431550	1004416	2,696	2,698.9	--
431536100472201	38N29W17BCDA	431605	1004705	2,687	2,669.5	--
431502100443801	38N29W22CAC	431500	1004426	2,730	2,686.3	--
431424100430601	38N29W26ACB	431425	1004305	2,750	2,670.5	--
431340100430401	38N29W35ACBB	431336	1004307	2,803	2,707.8	--
431809100483401	38N30W 1AAAA	431809	1004834	2,763	2,625.5	--
431740100502201	38N30W 2CAA	431737	1005027	2,640	2,492.2	--
431610100484701	38N30W13ADBB	431612	1004845	2,645	2,631.8	--
431537100504701	38N30W14CCCA	431537	1005047	2,723	2,639.4	--
431601100514301	38N30W15BDC	431601	1005143	2,650	2,649.7	--
431612100551201	38N30W18BADB	431612	1005512	2,550	2,415.7	--
431515100501701	38N30W23ACBC	431515	1005017	2,720	2,656.8	--
431255100545701	38N30W31DCCD	431254	1005439	2,872	2,701.4	--
431315100541301	38N30W32CBD	431309	1005415	2,887	2,735.7	--
431340100521405	38N30W33AA5	431408	1005206	2,840	2,624.3	--
431335100511101	38N30W34A	431335	1005111	2,600	2,572.8	--
431252100501801	38N30W35BDDB	431327	1005024	2,708	2,605.2	--
431744100561401	38N31W 1BACB2	431744	1005601	2,600	2,502.4	--
431744100583601	38N31W 3ABAB	431800	1005753	2,692	2,600.9	--
431733100585701	38N31W 4DABD2	431733	1005857	2,725	2,656	--
431623101010501	38N31W 8CCC	431623	1010105	2,787	2,732	--
431654100574302	38N31W10ADAC2	431654	1005743	2,698	2,606	--

Table 16. Wells used for estimating potentiometric surface of the Arikaree aquifer–Continued

[Well locations are shown in figure 5. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Adjusted hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 10)
431630100570201	38N31W11CDAA	431630	1005702	2,652	2,552.8	--
431520100593601	38N31W16DBAA	431555	1005907	2,710	2,688	--
431551101003901	38N31W17CAA	431551	1010039	2,880	2,878.1	--
431501101005701	38N31W20CBAA	431501	1010057	2,837	2,827.1	--
431526100563202	38N31W23AAAB2	431526	1005635	2,443	2,431.2	--
431508100562101	38N31W24BDAD	431508	1005620	2,605	2,504.8	--
431427100561201	38N31W25BBAC	431426	1005601	2,722	2,563.2	--
431259100574401	38N31W34DDAC	431259	1005744	2,502	2,477.2	--
431338100570901	38N31W35BA	431338	1005709	2,485	2,476.1	--
431738103035702	38N32W 1BAAC	431759	1010303	2,750	2,671.1	--
431740101044601	38N32W 3ADDD	431740	1010446	2,750	2,681.3	--
431637101084802	38N32W 7DCAB2	431637	1010848	2,890	2,841.3	--
431639101043102	38N32W11CBD2	431639	1010431	2,785	2,716.3	--
431554101044501	38N32W15DAAA	431554	1010445	2,805	2,782.3	--
431533101080501	38N32W17CCD	431533	1010805	3,059	2,906.7	--
431303101075401	38N32W32CDB	431303	1010754	3,032	2,926.3	--
431625101103001	38N33W12CCDC	431623	1011029	2,943	2,930.7	--
431843100263301	39N26W31BDA	431847	1002633	2,600	2,543	--
431830100250201	39N26W32DCDA	431816	1002502	2,533	2,456.9	--
432242100281201	39N27W 1CCB	432242	1002812	2,520	2,478.6	--
432316100305801	39N27W 3BBD	432316	1003058	2,500	2,468.9	--
432205100294301	39N27W10DABB	432205	1002943	2,513	2,481.7	--
432033100305601	39N27W21ADDA	432033	1003056	2,754	2,582.8	--
432009100290301	39N27W23CDBA	432009	1002903	2,651	2,609.5	--
431937100320101	39N27W29ADBD	431937	1003201	2,676	2,645	--
431815100341801	39N27W31CCC	431815	1003418	2,537	2,476.6	--
431818100324201	39N27W32CDCB2	431818	1003242	2,544	2,513.1	--
431814100302602	39N27W34CCDC2	431814	1003026	2,562	2,535.6	--
431903100282002	39N27W35AAAB2	431903	1002820	2,598	2,552.3	--
432150100381701	39N28W 9DCA	432150	1003817	2,518	2,506.3	--
432203100361301	39N28W11CAA	432203	1003613	2,535	2,509.9	--
432117100371601	39N28W15ACC	432117	1003716	2,585	2,525.1	--
432108100400001	39N28W17CBD	432103	1004006	2,683	2,615.8	--
432003100352501	39N28W24CC	432003	1003525	2,675	2,614.8	--
431907100350201	39N28W25CCD	431907	1003502	2,565	2,504.7	--

Table 16. Wells used for estimating potentiometric surface of the Arikaree aquifer–Continued

[Well locations are shown in figure 5. Hydraulic heads are estimated averages for water years 1979-98. NGVD of 1929, National Geodetic Vertical Datum of 1929. Agency code: S, State; T, Tribal. --, not applicable]

Site identification number	Local number	Latitude	Longitude	Land surface altitude (feet above NGVD of 1929)	Adjusted hydraulic head altitude (feet above NGVD of 1929)	Agency (S/T) and well number for observation wells (fig. 10)
431947100354001	39N28W26AADB	431947	1003540	2,628	2,567.9	--
431927100381501	39N28W28DBAA	431927	1003815	2,628	2,598.6	--
431949100392901	39N28W29ABAD	431949	1003929	2,634	2,624.9	--
431933100412101	39N28W30BCDB	431933	1004121	2,622	2,603.4	--
431912100410501	39N28W30CDBD	431912	1004105	2,601	2,587.4	--
431812100383901	39N28W33CDD	431812	1003839	2,563	2,520.9	--
432049100415301	39N29W13CC	432053	1004229	2,640	2,584.7	--
432025100434001	39N29W23BCD	432025	1004340	2,500	2,468.8	--
431830100450901	39N29W33DA	431830	1004509	2,657	2,628.6	--
431822100424301	39N29W35DDAB	431822	1004243	2,681	2,647.6	--
431813100413101	39N29W36DDDC	431813	1004131	2,645	2,596.7	--
432244100594502	39N31W 4CBDB2	432244	1005945	2,467	2,448.7	--
432149101005001	39N31W 8CACB	432149	1010050	2,653	2,516.8	--
432020101010901	39N31W19ACDA2	432020	1010127	2,625	2,544.9	--
431903100561701	39N31W25CCCA	431902	1005615	2,558	2,470.9	--
431933101010501	39N31W29BCB	431933	1010105	2,640	2,585.9	--
431823101005201	39N31W32CBDB	431823	1010052	2,685	2,646	--
431813100571001	39N31W35CDBD	431813	1005710	2,620	2,533.9	--
432310101045501	39N32W 3AAAA	432320	1010441	2,610	2,577.9	S374
432205101032201	39N32W11ACDA	432205	1010322	2,595	2,584.8	--
432131101034001	39N32W14AAA	432131	1010340	2,634	2,599.9	--
432131101053001	39N32W15BAB	432131	1010528	2,678	2,638.9	--
431922101032201	39N32W25CBAB	431922	1010322	2,705	2,626	--
431913101084001	39N32W30DBDC	431913	1010840	2,820	2,767.9	--
431820101045002	39N32W34DADC2	431820	1010450	2,781	2,646.2	--
432044101115201	39N33W15DDDD	432044	1011152	2,800	2,763.7	S361
432416100315601	40N27W32AAA	432412	1003200	2,478	2,470.1	--
432540101092202	40N32W19BCC2	432540	1010922	2,595	2,569.8	--
432515101071701	40N32W20DDBB	432518	1010737	2,597	2,586.4	--
432554101065601	40N32W21BBBB	432557	1010703	2,576	2,561.3	S384
432530101024801	40N32W24CBB	432530	1010319	2,568	2,543.3	--
432453101075601	40N32W29BCAB	432452	1010803	2,618	2,599.7	--
432654101130401	40N33W 9DDDA	432654	1011304	2,570	2,515.6	--
432545101102701	40N33W24BBDD	432545	1011027	2,548	2,523.1	--
432446101131104	40N33W28AD	432446	1011311	2,740	2,686.1	--
432407101131201	40N33W33AAB	432407	1011312	2,742	2,686.4	--