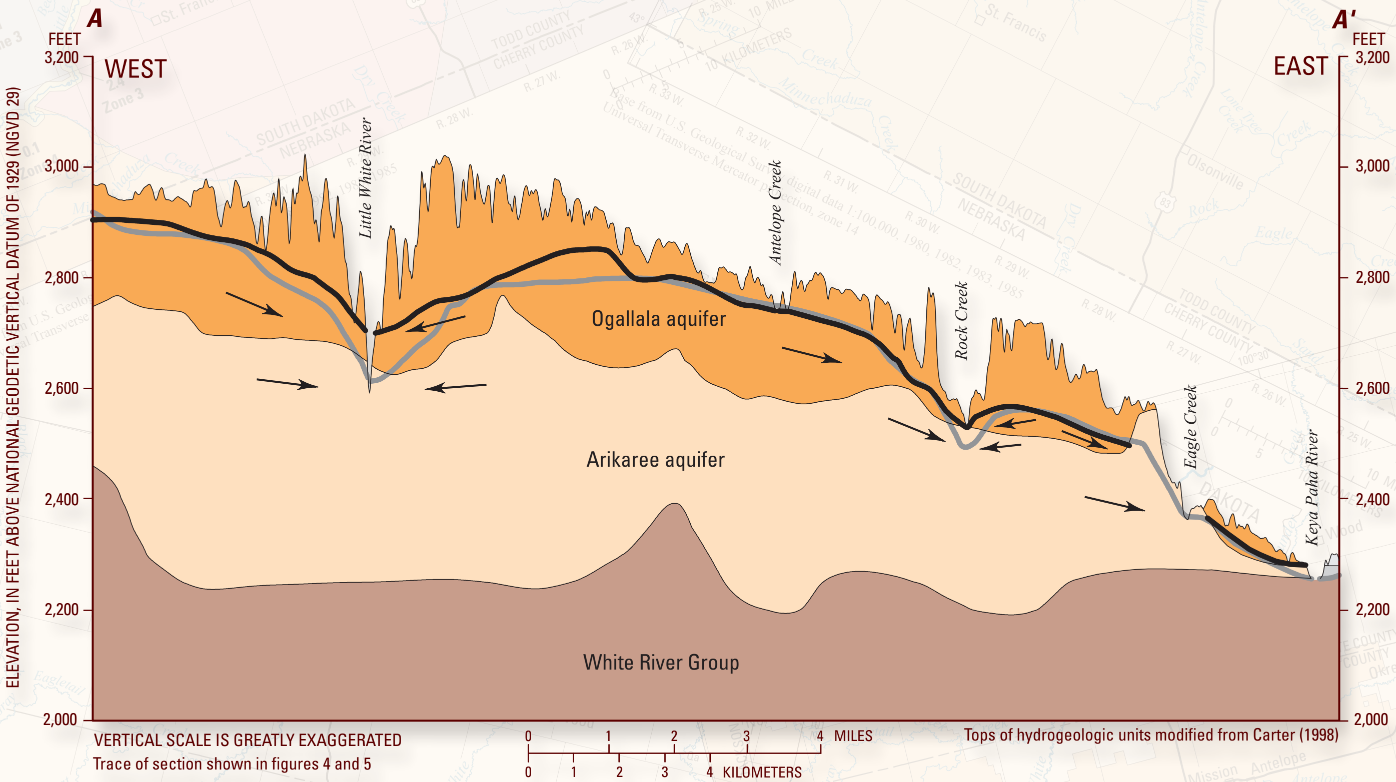
Prepared in cooperation with the Rosebud Sioux Tribe

Simulated Groundwater Flow in the Ogallala and Arikaree Aquifers, Rosebud Indian Reservation Area, South Dakota—Revisions with Data Through Water Year 2008 and Simulations of Potential Future Scenarios



Scientific Investigations Report 2010–5105

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

EXPLANATION FOR THE COVER ILLUSTRATION
(figure 6 from this report)

- Average hydraulic head in Arikaree aquifer, water years 1979–98
- Average hydraulic head in Ogallala aquifer, water years 1979–98
- General direction of groundwater flow

Simulated Groundwater Flow in the Ogallala and Arikaree Aquifers, Rosebud Indian Reservation Area, South Dakota—Revisions with Data Through Water Year 2008 and Simulations of Potential Future Scenarios

By Andrew J. Long and Larry D. Putnam

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

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Conversion Factors, Abbreviations, and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

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

$$°F=(1.8×°C)+32$$

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

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

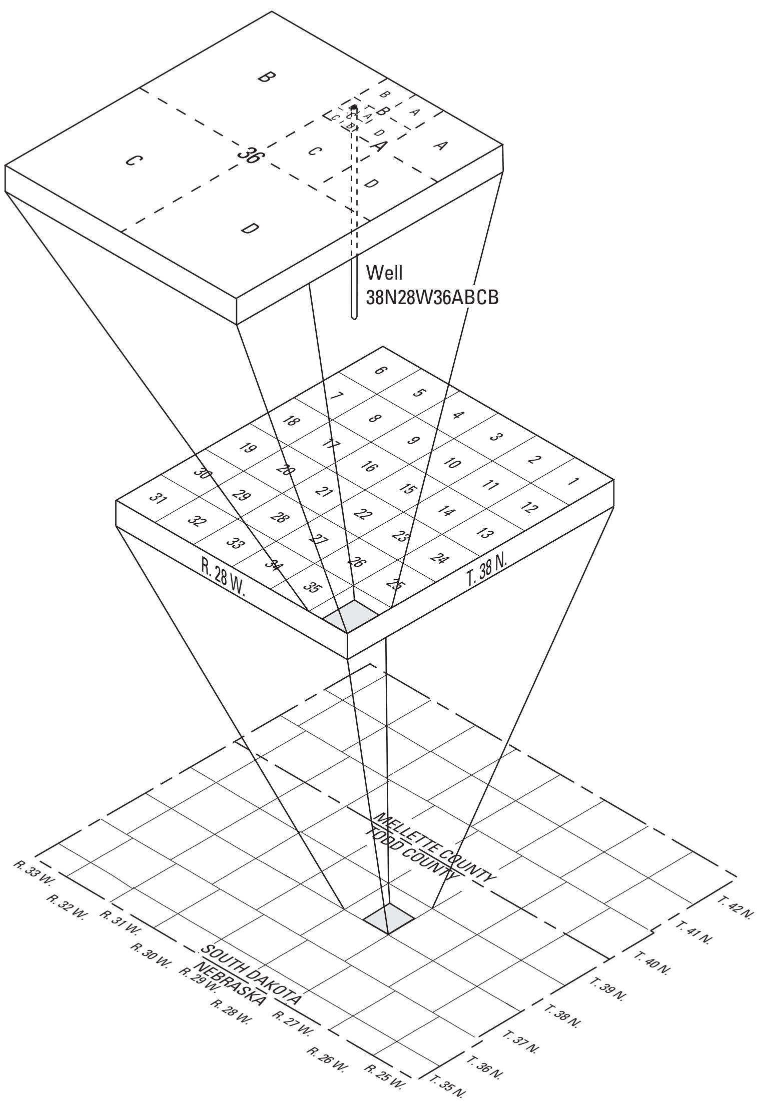
Water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends.

Abbreviations and Acronyms

K	hydraulic conductivity
R^2	coefficient of determination
RMSE	root mean square error
SWUDS	U.S. Geological Survey's Site-Specific Water-Use Data System
USGS	U.S. Geological Survey

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.



Simulated Groundwater Flow in the Ogallala and Arikaree Aquifers, Rosebud Indian Reservation Area, South Dakota—Revisions with Data through Water Year 2008 and Simulations of Potential Future Scenarios

By Andrew J. Long and Larry D. Putnam

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. Drought 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 documents revisions and recalibration of a previously published three-dimensional, numerical groundwater-flow model for this area. Data for a 30-year period (water years 1979 through 2008) were used in steady-state and transient numerical simulations of groundwater flow. In the revised model, revisions include (1) extension of the transient calibration period by 10 years, (2) the use of inverse modeling for steady-state calibration, (3) model calibration to base flow for an additional four surface-water drainage basins, (4) improved estimation of transient aquifer recharge, (5) improved delineation of vegetation types, and (6) reduced cell size near large capacity water-supply wells. In addition, potential future scenarios were simulated to assess the potential effects of drought and increased groundwater withdrawals.

The model comprised two layers: the upper layer represented the Ogallala aquifer and the lower layer represented the Arikaree aquifer. The model's grid had 168 rows and 202 columns, most of which were 1,640 feet (500 meters) wide, with narrower rows and columns near large water-supply wells. Recharge to the Ogallala and Arikaree aquifers occurs from precipitation on the outcrop areas. The average recharge rates used for the steady-state simulation were 2.91 and 1.45 inches per year for the Ogallala aquifer and Arikaree aquifer, respectively, for a total rate of 255.4 cubic feet per second (ft^3/s). Discharge from the aquifers occurs through evapotranspiration, discharge to streams as base flow and spring flow, and well withdrawals. Discharge rates for the steady-state simulation were 171.3 ft^3/s for evapotranspiration, 74.4 ft^3/s for net outflow to streams and springs, and 11.6 ft^3/s for well withdrawals. Estimated horizontal hydraulic conductivity used for the numerical model ranged from 0.2 to 84.4 feet per day (ft/d) in the Ogallala aquifer and from 0.1 to 4.3 ft/d in the Arikaree aquifer. A uniform vertical hydraulic conductivity value of 4.2×10^{-4} ft/d was estimated for the Ogallala aquifer. Vertical hydraulic conductivity was estimated for five zones in the Arikaree aquifer and ranged from 8.8×10^{-5} to 3.7 ft/d. 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.

Inverse modeling techniques were used for steady-state model calibration. These methods were designed to estimate parameter values that are, statistically, the most likely set of values to result in the smallest differences between simulated and observed hydraulic heads and base-flow discharges. For the steady-state simulation, the root mean square error for simulated hydraulic heads for all 383 wells was 27.3 feet. Simulated hydraulic heads were within ±50 feet of observed values for 93 percent of the wells. The potentiometric surfaces of the two aquifers calculated by the steady-state simulation established initial conditions for the transient simulation. For the transient simulation, the difference between the simulated and observed means for hydrographs was within ±40 feet for 98 percent of 44 observation wells.

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 maximum evapotranspiration and least sensitive to riverbed and spring conductances.

To simulate a potential future drought scenario, a synthetic recharge record was created, the mean of which was equal to 64 percent of the average estimated recharge rate for the 30-year calibration period. This synthetic recharge record was used to simulate the last 20 years of the calibration period under drought conditions. Compared with results of the calibrated model, decreases in hydraulic-head values for the drought scenario at the end of the simulation period

were as much as 39 feet for the Ogallala aquifer. To simulate the effects of potential increases in pumping, well withdrawal rates were increased by 50 percent from those estimated for the 30-year calibration period for the last 20 years of the calibration period. Compared with results of the calibrated model, decreases in hydraulic-head values for the scenario of increased pumping at the end of the simulation period were as much as 13 feet for the Ogallala aquifer.

This numerical model is suitable as a tool to help understand the flow system, to help confirm that previous estimates of aquifer properties were reasonable, and to estimate aquifer properties in areas without data. The model also is useful to help assess the effects of drought and increases in pumping by simulations of these scenarios, the results of which are not precise but may be considered when making water management decisions.

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. In 2000, the High Plains aquifer supplied 23 percent of all groundwater used for irrigation, public supply, and industry, and 30 percent of groundwater used for irrigation in the United States (Maupin and Barber, 2005).

The High Plains aquifer underlies about 4,750 square miles (mi^2) 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. From about 1950, when little water use for irrigation occurred, to 2007, groundwater storage declines in the High Plains aquifer nationwide ranged from 0.6 million acre-feet (acre-ft) in South Dakota to 140 million acre-ft in Texas (McGuire, 2009). 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 effects of contamination, and evaluating effects of drought cycles. A primary tool conceived by the Tribe was a numerical groundwater-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 an initial model (Long and others, 2003) and more recently to revise the model with data through September 30, 2008.

Model revisions include (1) extension of the transient calibration period by 10 years to include data measured through 2008, (2) the use of inverse modeling for steady-state calibration that minimized the squares of the differences between measured and simulated flow metrics, (3) model calibration to base flow for an additional four surface-water drainage basins, (4) improved estimation of transient aquifer recharge using a method that considers antecedent rainfall effects, (5) improved estimation of vegetation types based on satellite imagery for evapotranspiration processes, and (6) reduced cell size near municipal water-supply wells. In addition, potential future scenarios were simulated to assess the effects of potential future hydrologic stresses such as drought conditions and increased groundwater withdrawals.

Purpose and Scope

The purpose of this report is to describe a conceptual and numerical model developed to simulate groundwater flow in the Ogallala and Arikaree aquifers in the Rosebud Indian Reservation area. The numerical model is a revision of that described in Long and others (2003). Steady-state simulation of average conditions (based on measured data for water years 1979–1998) was used for model calibration. Transient simulations were executed for a 30-year period of measured data consisting of water years 1979–2008 (October 1, 1978, through September 30, 2008). For convenience of the reader, much of the background material and description of the conceptual model covered in the report by Long and others (2003) is included in this report.

Acknowledgments

The authors would like to recognize important contributions by the Rosebud Sioux Tribe to the development of the groundwater-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 USGS, Rosebud Sioux Tribe, 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 groundwater discharge rates. The Tribe also was actively involved in study design, conceptualization of the groundwater-flow system, technical evaluation of model performance, and review of this report.

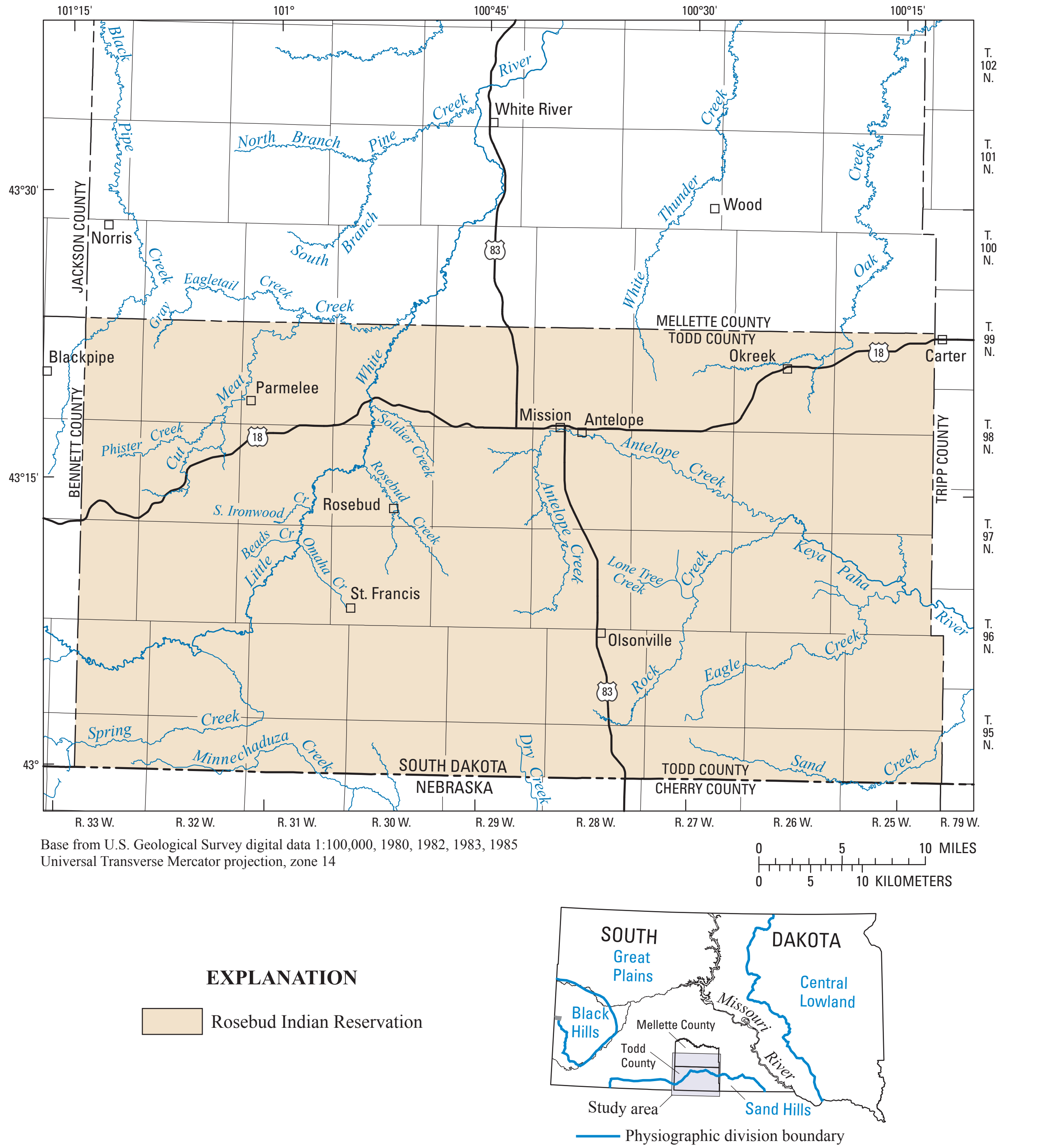


Figure 1. Study area (from Long and others, 2003; physiographic divisions modified from Fenneman, 1946; Flint, 1955).

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 (Carter, 1998); the boundary was revised to include only Todd County in 1975 (fig. 1).

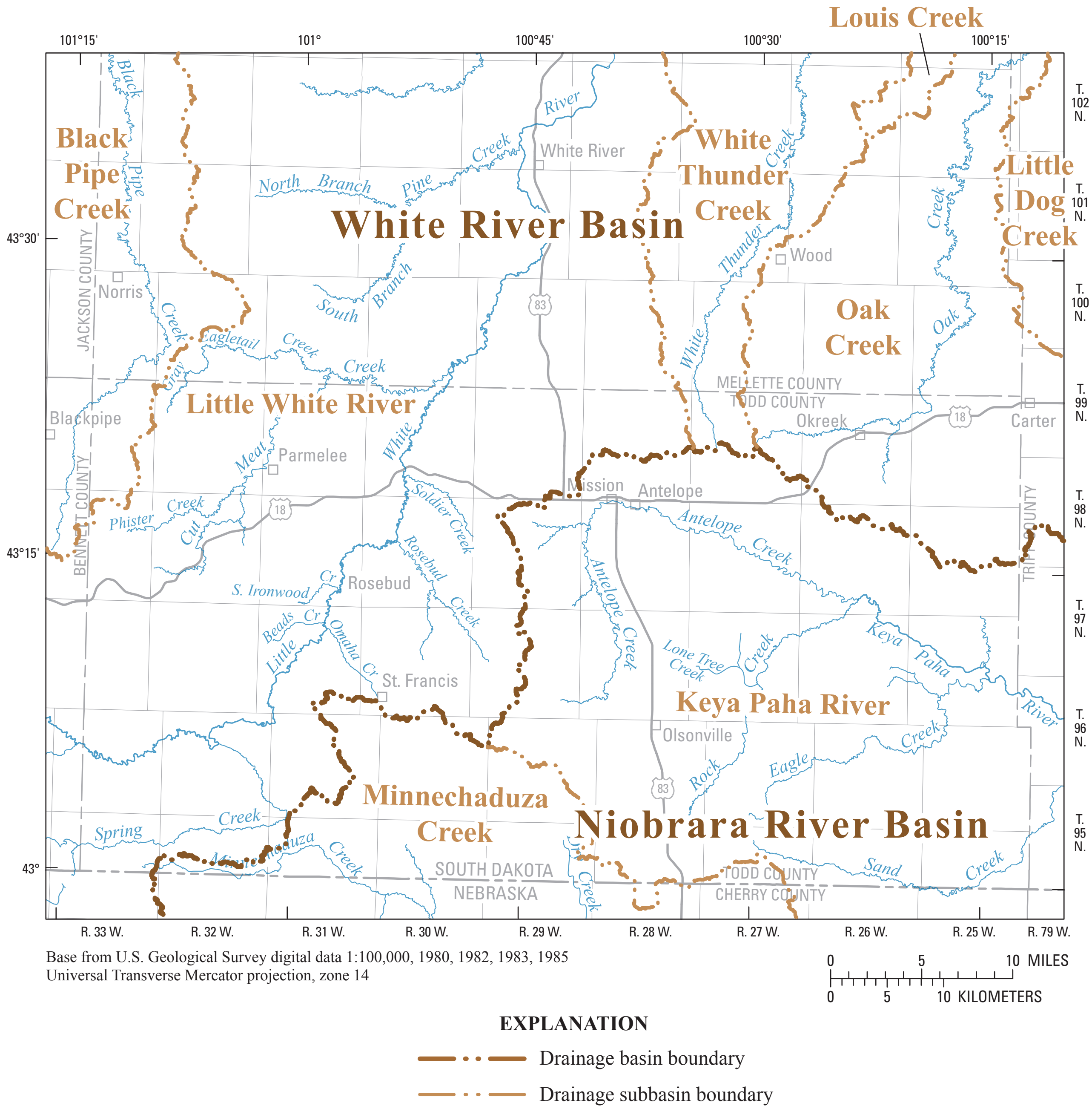


Figure 2. Drainage basins in the study area (from Long and others, 2003).

Physiography and Land Use

The northern part of the study area is in the Great Plains physiographic province, and the southern part is in the Sand Hills physiographic province (fig. 1). Much of the study area has rolling topography, and numerous deep valleys drain into the White River to the north. 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 with an annual precipitation of about 20 inches (National Climatic Data Center, 2010; Mission station 395620 in Todd County). About 8 percent of the average annual precipitation becomes streamflow; however, this quantity varies because of 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. Groundwater discharge from the Ogallala and Arikaree aquifers provides base flow to the Little White River, Keya Paha River, and several smaller creeks. These streams generally receive more than one-half of their flow from groundwater 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 Red River and Winnipeg Formations, the Mississippian-age Madison Limestone, and the Permian- and Pennsylvanian-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 terrace, windblown, 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 (ft) generally is composed of silty and sandy beds that commonly are separated from the upper clayey part by 5 to 10 ft of thin-bedded limestone. Thickness of the Arikaree Formation ranges from 0 to 620 ft. 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 commonly are steeper.

The Ogallala Formation consists of an upper unit composed of well-cemented, fine- to medium-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 ft. 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 vertically and horizontally. A 5- to 20-ft thick bed of coarse sand and gravel commonly occurs in the basal part of the lower unit. Thickness of the upper unit ranges from 0 to 40 ft and the lower unit ranges from 0 to 200 ft. 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.

Hydrologic 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, groundwater generally can be obtained from shallow wells (less than 300 ft) completed in Quaternary-age alluvial deposits or in Tertiary-age deposits (Ogallala Formation, Arikaree Formation, or White River Group). Groundwater 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 sandstone 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 mi^2 in Todd County with an estimated 17 million acre-ft 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 ft (Carter, 1998), and the aquifer is fully saturated in some areas. In the study area, the aquifer generally is thickest in the central part of Todd County where withdrawals from the aquifer for irrigation are highest. The Ogallala aquifer is overlain by unconsolidated deposits consisting of alluvium near streams and windblown sand deposits composed of fine- to medium-grained sand, similar to that of the Ogallala Formation, 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 layers 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 ft 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 (gal/min; Carter, 1998). Long and others (2003) estimated hydraulic conductivity to be in the range of 0.2–120 feet per day (ft/d).

The Arikaree aquifer generally comprises the saturated sandstones and siltstones of the Arikaree Formation. The

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

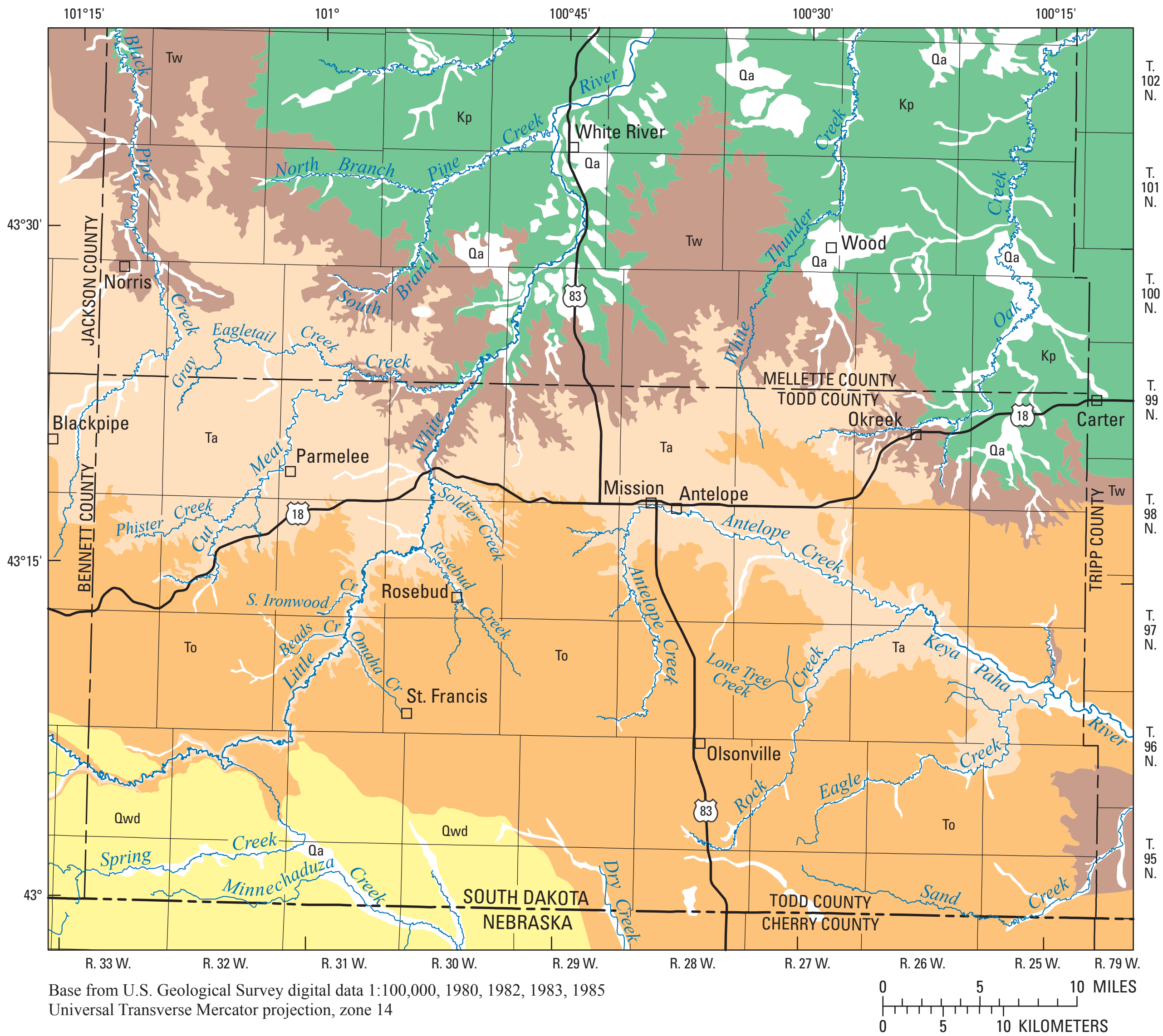
[From Carter, 1998]

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.

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

[From Carter, 1998]

Era	System	Formation or deposit	Thickness (feet)	Description and origin	Hydrologic characteristics
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.



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 surficial geology of study area (modified from Ellis and others, 1971).

Ogallala aquifer, where present, overlies the Arikaree aquifer 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). Long and others (2003) estimated hydraulic conductivity to be in the range of 0.1–5.4 ft/d.

The Arikaree aquifer underlies 1,360 mi^2 in Todd and Mellette Counties with an estimated 50 million acre-ft of water in storage (Carter, 1998). The thickness of the Arikaree aquifer ranges from 0 to 618 ft, with an average of 290 ft (Carter, 1998). In the study area, the Arikaree aquifer is thickest in southern Todd County. Hydraulic heads in the Arikaree aquifer range from 0 to greater than 150 ft below land surface (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 gal/min 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).

Conceptual Model

The windblown sand deposits overlying the Ogallala aquifer in the southwestern part of the study area have similar hydrogeological properties and are in direct connection with the Ogallala aquifer, and therefore, these units are conceptualized as a single water-bearing unit. The Ogallala and Arikaree aquifers were assumed to be hydraulically connected with the limiting factor of the low permeability of the Arikaree aquifer, which is enhanced by fractures. The White River Group contains an aquifer but was considered an underlying confining unit because of numerous clay lenses that impede vertical groundwater movement.

Recharge to the Ogallala and Arikaree aquifers occurs from precipitation on the outcrop areas, and regional flow enters the study area from the west. Groundwater originating from precipitation 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, public supply, domestic, and stock wells.

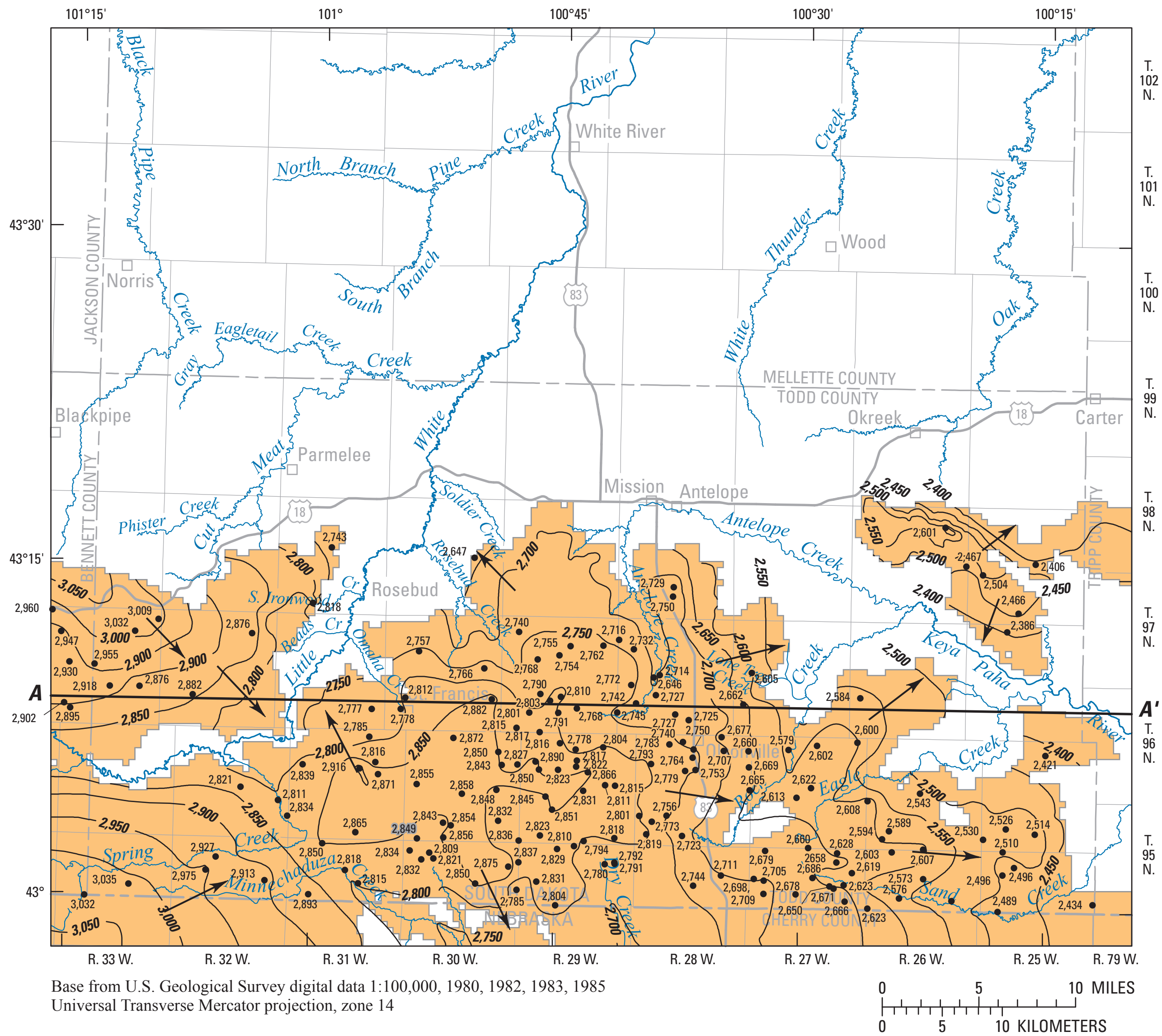
For analysis of groundwater flow, data for a 30-year period (water years 1979–2008) were analyzed. Each water year was subdivided into three periods (hereinafter referred to as stress periods) for a total of 90 stress periods for analysis based on the hydrologic characteristics of each period: (1) a 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 90 stress periods are numbered 1 through 90 starting with the fall and winter period of water year 1979. 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.

Groundwater Flow

Carter (1998) constructed average potentiometric surfaces for the Ogallala and Arikaree aquifers for water years 1979–98 and evaluated hydraulic gradients, flow directions, and aquifer boundaries. Long and others (2003) revised these potentiometric surfaces (figs. 4 and 5). Water levels measured during 1996 for more than 350 wells, primarily domestic, open to the Ogallala and Arikaree aquifers were documented by Carter (1998). Water levels also are available for 44 Tribal and State observation wells open to the Ogallala and Arikaree aquifers for 1979–2008. Of these, 21 are maintained by the Rosebud Sioux Tribe (Rosebud Sioux Tribe, written commun., 2009), and 23 are maintained by the South Dakota Department of the Environment and Natural Resources (Ken Buhler, South Dakota Department of the Environment and Natural Resources, written commun., 2009). During water years 1979–2008, some of these water levels increased, some decreased, and some had little change. Water levels changed as much as 6 and 12 ft for Ogallala and Arikaree aquifers, respectively. There was little, if any, change in general water-level trends from 1999 to 2008 in comparison to the previous 20 years. This is consistent with estimated water-level changes for the High Plains aquifer in South Dakota, where the area-weighted water-level change from 1950 to 2007 was 0 ft, the change from 2005–06 was 0.2 ft, and the change from 2006–07 was -0.2 ft (McGuire, 2009). Additional information regarding water-level trends in the study area is in the “Transient Simulation” section of this report.

Water levels generally fluctuated between 1 and 4 ft seasonally. Hydraulic head in the Ogallala aquifer ranged from about 3,000 ft on the western boundary of the study area to about 2,400 ft on the eastern boundary (fig. 4). Hydraulic head in the Arikaree aquifer ranged from about 3,000 ft in the southwestern corner of the study area to about 2,400 ft in parts of the northern and eastern boundaries of the aquifer (fig. 5). Information on wells used to estimate potentiometric surfaces is in Appendix 1.

Groundwater flow in the Ogallala and Arikaree aquifers in the study area generally is to the east or northeast. Locally, groundwater flow is topographically controlled and is towards the Little White and Keya Paha Rivers or smaller streams (figs. 4 and 5). Domestic water use is small in comparison to



EXPLANATION

Active model cells for Ogallala aquifer

A A' **Trace of geologic section** (fig. 6)

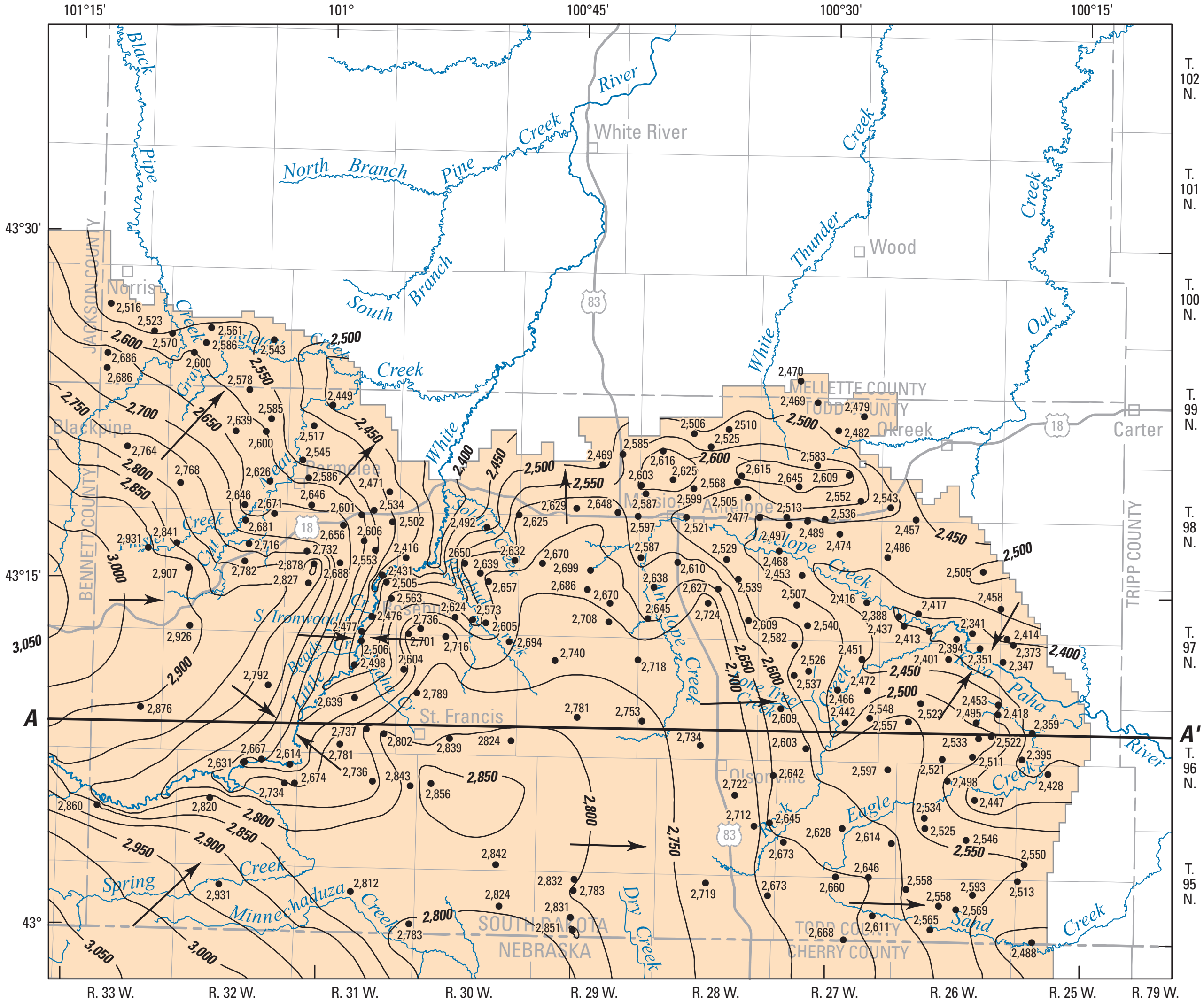
— 2,400 — **Aquifer potentiometric contour**—Shows average altitude at which water level would have stood in tightly cased wells, water years 1979–98. Contour interval is 50 feet. Datum is NGVD of 1929

General direction of groundwater 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 (from Long and others, 2003).

irrigation, and municipal water-supply wells have little local effect on groundwater flow. Groundwater 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 direction of groundwater 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 groundwater 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 between the surface-drainage basins (fig. 2) and the potentiometric surfaces (figs. 4 and 5) shows that groundwater divides are related to the surface-drainage basins.



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

Active model cells for Arikaree aquifer

A A' Trace of geologic section (fig. 6)

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

General direction of groundwater flow

2,804 **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 (from Long and others, 2003).

On the basis of previous estimates and model calibration, Long and others (2003) estimated hydraulic conductivity (*K*) values. For the Ogallala aquifer, horizontal *K* estimates ranged from 0.2 to 120 ft/d, and the vertical *K* estimate was 6.6×10^{-4} ft/d. For the Arikaree aquifer, horizontal *K* estimates ranged from 0.1 to 5.4 ft/d, and vertical *K* estimates ranged from 8.6×10^{-6} to 7.2×10^{-1} ft/d.

Recharge

Recharge to the Ogallala aquifer occurs from infiltration of precipitation on the outcrop of the Ogallala Formation and the overlying windblown sand deposits in the southeastern part of the study area. Recharge to the Arikaree aquifer occurs from infiltration of precipitation on the outcrop of the Arikaree Formation.

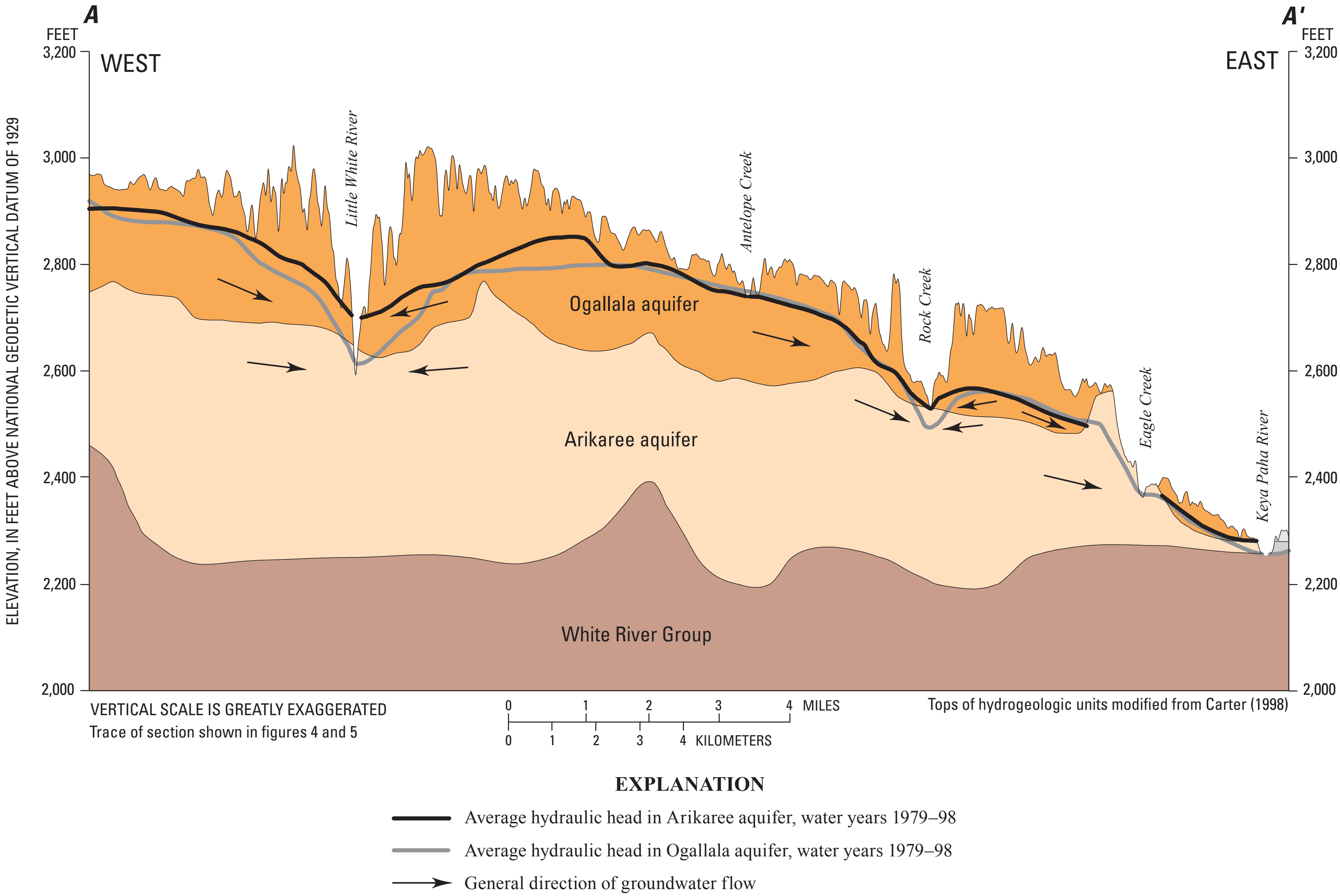


Figure 6. Relation between hydraulic head, hydrogeologic units, and topographic features.

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 (in/yr) for the study area (Langbein, 1949), 2.6 in/yr in the upper Niobrara River Basin (Bradley, 1956), 3.07 in/yr for the Sand Hills of Nebraska (Rahn and Paul, 1975), and 8 percent of precipitation or 1.3 to 1.8 in/yr for South Dakota (Kolm and Case, 1983). These estimates primarily pertain to precipitation recharge to the overlying Ogallala aquifer. The lower permeability of the Arikaree aquifer, particularly in the upper part, may prevent that aquifer from accepting as much precipitation recharge as the Ogallala aquifer.

Recharge to the aquifers from infiltrating irrigation water, or irrigation return flow, was considered negligible because total irrigation for the study area was less than 5 percent of estimated recharge in the study area, and irrigation return flow was assumed to be a small fraction of total irrigation. Additional details on irrigation and recharge estimates are in the “Well Withdrawals” and “Model Calibration” sections.

Evapotranspiration

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. The water-table altitude influences the evapotranspiration rate. When the water table is at the land surface, evapotranspiration is larger than when the water table is below the land surface. Evapotranspiration is smallest when the water table is below the root zone. Generally, the depth of this root zone is assumed to be about 5 to 10 ft in the study area with deeper root penetration associated with pine and deciduous forests, which are common as much as one-half mile (mi) from the Little White River and its tributaries between Spring Creek and Soldier Creek. Forests also are common near streams along the northern extent of the outcrop of the Arikaree Formation. Other parts of the study area generally are grasslands or agricultural. Land-cover information was obtained from the Multi-Resolution Land Characteristics Consortium (2009) to differentiate forests from grasslands and agricultural areas. To simplify the vegetation zones, small areas less than about 0.7 mi^2 were removed and included in the surrounding vegetation zones (see “Numerical Model” section).

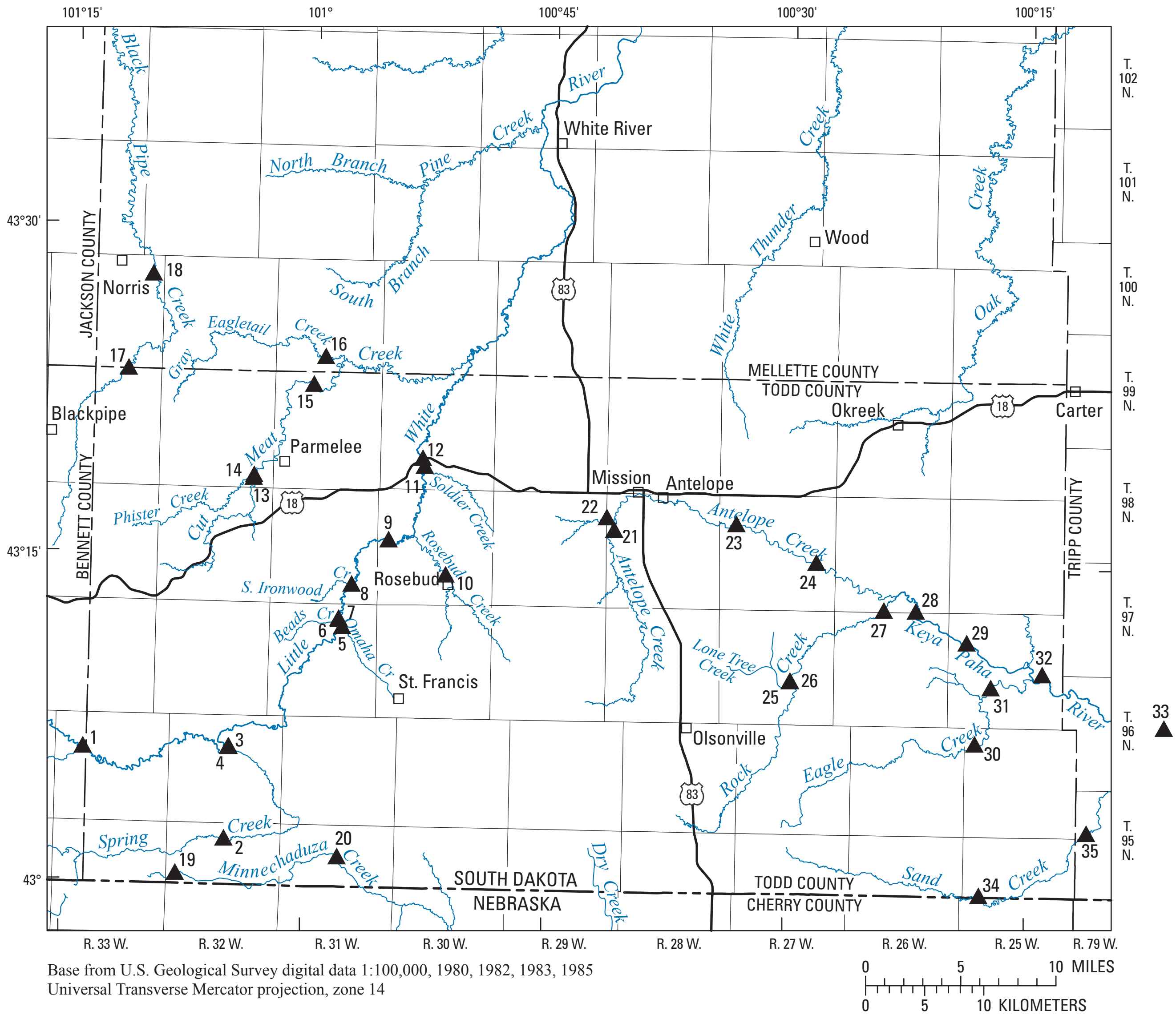
Maximum evapotranspiration during summer stress periods was estimated as 70 percent of pan evaporation on the basis of the relation between pan evaporation and evapotranspiration described by Farnsworth and others (1982). Pan evaporation rates in the study area were assumed to be similar to those at a National Weather Service climatological data station at Cottonwood (National Climatic Data Center, 2010; station 391972), which is located about 75 mi northwest of the study area. Pan evaporation records were available for the months of June through September for the 30 water years included in the analysis. The estimated maximum evapotranspiration for the 30 summer stress periods (table 2) ranged from 20.4 to 30.7 inches (in.), with a median value of 26.5 in. On the basis of sparse pan evaporation data for spring and late fall, a value for all spring stress periods was estimated as 9 in., and a value for all fall/winter stress periods was estimated as 3 in. On the basis of these estimates and the assumption that maximum evapotranspiration was 70 percent of pan evaporation, the maximum evapotranspiration was calculated as 6.3 and 2.1 in., respectively, for the spring and fall/winter stress periods.

Discharge to Streams and Springs

Springs and seeps discharge groundwater to streams in the study area. Long and others (2003) estimated the average groundwater discharge, or base flow, to the Little White and Keya Paha Rivers in the study area for water years 1979–98 as 49 and 23 ft^3/s, respectively. These estimates were made

Table 2. Estimated maximum evapotranspiration rate during summer stress periods, water years 1979–2008.

Water year	Stress period	Pan evaporation (inches)	Estimated maximum June–September evapotranspiration (inches)
1979	3	35.4	24.8
1980	6	41.6	29.1
1981	9	35.5	24.9
1982	12	31.4	22.0
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
1999	63	32.0	22.4
2000	66	38.9	27.2
2001	69	35.4	24.7
2002	72	40.5	28.3
2003	75	40.5	28.3
2004	78	36.5	25.5
2005	81	38.9	27.3
2006	84	40.2	28.1
2007	87	40.6	28.4
2008	90	34.5	24.1



EXPLANATION

10▲ **Measurement site**—Number is map index number in table 3

Figure 7. Streamflow measurement sites for seepage runs during 1999 and 2006.

by applying hydrograph separation methods to continuous streamflow measurements. Additional manual streamflow measurements were used to verify these estimates and to estimate base flow for four other drainage basins—Cut Meat Creek, Black Pipe Creek, Minnechaduza Creek, and Sand Creek (table 3). Four sets of synoptic measurements of streamflow at low-flow conditions during late summer and fall were collected to assess base flow. Streamflow was measured by wading streams with vertical-axis bucket-wheel current meters as described by Rantz and others (1982). Streamflow was measured at 35 sites (fig. 7) twice during 1999 and twice during 2006, with the exception of a few sites that were not measured on all four dates because of limited access (table 3). These measurements were made during periods when direct runoff was not observed to occur and thus represent approximate base-flow conditions.

Base flow for the Little White River in the study area is approximated by the subtraction of base flow at the furthest upstream site (site 1) from base flow at the furthest downstream site (site 12), and base flow for the Keya Paha River is approximated by base flow at site 33 (fig. 7, table 3). The average of these base-flow approximations for the four measurements was 54 and 18 ft^3/s for the Little White and Keya Paha Rivers, respectively (table 3). These values are similar to estimates of 49 and 23 ft^3/s made by using hydrograph separation techniques on continuous streamflow data

Table 3. Measured streamflow at selected sites during seepage runs during 1999 and 2006. Estimates of base flow for each drainage basin are shown.

[Shading indicates data used in estimating drainage basin base flow; --, not measured; NA, not applicable]

Map label (fig. 7)	Site identficiation number	Station name	Streamflow, in cubic feet per second					
			July 27–29, 1999[a]	Aug. 30–Sept. 1, 1999[a]	Aug. 7–9, 2006	Oct. 16–17, 2006	Average	Drainage basin base-flow estimate
		Little White River drainage basin						
1	06449100	Little White River near Vetal, SD	72.0	44.9	20.4	33.4	NA	NA
2	430158101045400	Spring Creek near Cody, NE	2.1	--	--	--	NA	NA
3	430610101044300	Spring Creek near Spring Creek, near St. Francis, SD	9.1	4.3	3.5	3.7	NA	NA
4	430611101044600	Little White River below Spring Creek, near St. Francis, SD	117	66.1	39.9	57.9	NA	NA
5	431146100574900	Omaha Creek near Rosebud, SD	.9	.8	.6	1.0	NA	NA
6	431205100580200	Beads Creek near Rosebud, SD	1.5	1.0	.4	1.6	NA	NA
7	431208100580300	Little White River below Beads Creek	117	75.6	50.1	71.8	NA	NA
8	431343100571700	South Fork Ironwood Creek, near Rosebud, SD	1.8	1.6	1.3	1.8	NA	NA
9	06449300	Little White River above Rosebud, SD	119	84.9	57.0	81.4	NA	NA
10	06449400	Rosebud Creek at Rosebud, SD	8.0	7.8	4.6	8.0	NA	NA
11	431911100525200	Soldier Creek near Rosebud, SD	1.7	1.9	0	1.3	NA	NA
12	06449500	Little White River near Rosebud, SD	140	99.3	60.7	85.3	NA	NA
		Site 12 minus site 1	68.0	54.4	40.3	51.9	53.7	49[a,b]
		Cut Meat Creek drainage basin						
13	431830101033400	Phister Creek near Parmelee, SD	.7	.6	.1	.4	NA	NA
14	431837101033200	Cut Meat Creek below Phister Creek, near Parmelee, SD	1.1	.7	.1	.5	NA	NA
15	432249100595500	Cut Meat Creek near Parmelee, SD	2.4	0	0	0	0.6	NA
16	432405100591300	Gray Eagletail Creek near Parmelee, SD	2.1	2.3	0	0	1.1	1.7
		Black Pipe Creek drainage basin						
17	432323101113300	Black Pipe Creek near Black Pipe, SD	3.9	2.8	.2	2.4	NA	NA
18	432743101100900	Black Pipe Creek near Norris, SD	3.6	--	0	.7	1.4	1.2
		Minnechaduza Creek drainage basin						
19	430021101075300	Minnechaduza Creek near Cody, NE	.1	--	--	--	NA	NA
20	430114100574900	Minnechaduza Creek near Kilgore, NE	2.7	--	.2	--	1.5	3.0
		Keya Paha River drainage basin						
21	06463900	Antelope Creek near Mission, SD	2.0	3.2	0	2.0	NA	NA
22	431700100412500	Antelope Creek tributary above Mission, SD	.5	.6	0	.2	NA	NA
23	431648100331800	Antelope Creek below Antelope Lake near Mission, SD	4.3	1.3	.1	.2	NA	NA

Table 3. Measured streamflow at selected sites during seepage runs during 1999 and 2006. Estimates of base flow for each drainage basin are shown.—Continued

[Shading indicates data used in estimating drainage basin base flow; --, not measured; NA, not applicable]

Map label (fig. 7)	Site identficiation number	Station name	Streamflow, in cubic feet per second					
			July 27–29, 1999[a]	Aug. 30–Sept. 1, 1999[a]	Aug. 7–9, 2006	Oct. 16–17, 2006	Average	Drain-age basin base-flow estimate
		Keya Paha River drainage basin—Continued						
24	431506100281600	Antelope Creek above Keya Paha River near Mission, SD	6.1	1.7	.2	.6	NA	NA
25	430940100294800	Lone Tree Creek near Olsonville, SD	.7	.6	.4	.4	NA	NA
26	430940100294600	Rock Creek below Lone Tree Creek, near Olsonville, SD	5.2	4.4	2.9	3.3	NA	NA
27	431258100240000	Rock Creek near Mission, SD	9.4	8.6	4.1	5.9	NA	NA
28	431257100220000	Keya Paha River below Rock Creek near Mission, SD	19.3	14.1	4.7	8.6	NA	NA
29	431132100184700	Keya Paha River above Eagle Creek near Mission, SD	19.8	15.4	5.2	8.2	NA	NA
30	430645100185200	Eagle Creek near Olsonville, SD	.2	.4	0	--	NA	NA
31	430930100171500	Eagle Creek near Keyapaha, SD	1.6	2.2	1.0	1.3	NA	NA
32	431008100140300	Keya Paha River below Eagle Creek, SD	22.0	15.6	7.0	9.4	NA	NA
33	06464100	Keya Paha River near Keyapaha, SD	26.5	22.4	9.6	11.5	17.5	23.0[a]
		Sand Creek drainage basin						
34	425959100174900	Sand Creek near Valentine, NE	--	--	--	--	NA	NA
35	430254100111000	Sand Creek near Keya Paha, SD	4.4	4.5	2.6	4.0	3.9	3.9

[a]From Long and others (2003).

[b]Estimated for drainage area within the study area only.

by Long and others (2003), which indicates that the additional manual measurements could be used to approximate base flow for the four smaller drainage basins in the study area. Therefore, the average streamflow measurements for sites 15, 16, 18, 20, and 35 were used to estimate base flow for the Cut Meat, Black Pipe, Minnechaduza, and Sand Creek drainage basins (fig. 7, table 3). The Black Pipe Creek drainage basin is partly outside of the study area, and the base-flow estimate was reduced accordingly from 1.4 to 1.2 ft^3/s based on the proportion of the area outside of the study area. Site 20 on Minnechaduza Creek is about midway between the stream's headwaters and the model boundary, and to account for unmeasured flow downstream from site 20, the average flow of 1.5 ft^3/s at site 20 was doubled (3.0 ft^3/s) and used as the base-flow estimate for the drainage basin. The base-flow estimate of 1.7 ft^3/s for the Cut Meat drainage basin is the sum of the average flows for sites 15 and 16. The base-flow estimate of 3.9 ft^3/s for the Sand Creek drainage basin is the average flow at site 35. The four smaller drainage basins were estimated to have a total average base flow of 9.8 ft^3/s. These estimates are inclusive of spring flow along streambanks. For the Little White and Keya Paha Rivers, the original base-flow estimates of 49 and 23 ft^3/s from Long and others (2003) based on continuous streamflow data were used (table 3). Estimated base flow for these two rivers is about 88 percent of the total estimated base flow.

Springs are located along the northern contact of the Arikaree Formation with the underlying 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 groundwater to emerge as springflow.

Well Withdrawals

Well withdrawals in the study area occur primarily for irrigation but also for public supply, domestic use, and stock use. Irrigation withdrawals from the Ogallala aquifer are especially important in Todd County and mainly occur east of St. Francis (fig. 8), where the saturated thickness of the Ogallala aquifer is greatest. The acres of irrigated land in Todd County from 1985 to 2005 ranged from 10,000 to 11,000 acres (U.S. Geological Survey, 2009). Irrigation withdrawals are variable because they are affected by numerous factors, such as climatic conditions, commodity prices, and energy costs. Most of the wells used for irrigation in the study area were constructed in the 1970s.

Water-use data for irrigation and public supply 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 (U.S. Geological Survey, 2009). Data on groundwater 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 (1981–2005). The SWUDS database includes 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 (table 4).

Groundwater withdrawals for 1979 and 1980 were estimated as the average withdrawals for the period 1981–85 and proportioned to each well according to the estimated withdrawals for 1981. Groundwater withdrawals for 2006–08 were estimated as being equal to withdrawals for 2005. The

Table 4. Estimated groundwater withdrawals for irrigation and public supply in the study area, 1979–2008.

Year	Acre-feet	Cubic feet per second[a]		
	Total	Ogallala aquifer	Arikaree aquifer	Total
1979	6,796	28.1	0	28.1
1980	6,796	28.1	0	28.1
1981	6,852	28.3	0	28.3
1982	7,054	29.2	0	29.2
1983	5,504	22.7	0	22.7
1984	7,751	32.0	0.05	32.0
1985	6,818	28.2	0	28.2
1986	7,481	30.7	.23	30.9
1987	5,437	22.2	.23	22.5
1988	7,054	29.2	0	29.2
1989	14,524	59.5	.56	60.0
1990	10,020	41.1	.28	41.4
1991	6,234	25.8	0	25.8
1992	5,178	21.4	0	21.4
1993	5,886	24.0	.28	24.3
1994	8,256	33.8	.28	34.1
1995	7,088	29.2	.09	29.3
1996	11,862	49.0	.00	49.0
1997	10,053	41.4	.14	41.5
1998	6,459	26.5	.19	26.7
1999	6,470	26.6	.19	26.7
2000	7,593	31.1	.28	31.4
2001	9,267	38.2	.14	38.3
2002	13,255	54.4	.37	54.8
2003	12,761	52.5	.23	52.7
2004	12,783	52.5	.37	52.8
2005	10,772	44.2	.28	44.5
2006	10,772	44.2	.28	44.5
2007	10,772	44.2	.28	44.5
2008	10,772	44.2	.28	44.5
Average	8,611	35.4	.17	35.6

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

estimated groundwater withdrawal for the study area by year ranged from about 5,200 to 14,500 acre-ft and averaged 8,611 acre-ft (table 4), or 35.6 ft^3/s over a 4-month period. The largest estimated irrigation use during the analysis period was in 1989 when precipitation was about 4 in. below normal.

Numerical Model

The numerical flow model of the Ogallala and Arikaree aquifers described in this report is a revision of that described by Long and others (2003), which was an analysis that included water years 1979–98. The revised model includes water years 1979–2008 for transient simulation and was discretized into 90 seasonal stress periods, or three stress periods per year. Future scenarios of potential drought and increased pumping were simulated for a 20-year period with the calibrated model. Other revisions are listed in table 5 and described in more detail in subsequent sections.

Model Design

MODFLOW-2000 (Harbaugh and others, 2000), which is a numerical, three-dimensional, finite-difference groundwater model, was used to simulate flow in the aquifers. Details of the MODFLOW-2000 packages that were included in the model were described by 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, and time-varying rates were included in the transient simulation. Model parameters estimated by calibration were horizontal and vertical hydraulic conductivity (*K*), recharge and evapotranspiration rates, and the vertical hydraulic conductances of riverbeds and springs.

Grid and Boundary Conditions

The model had two layers: the upper layer represented the Ogallala aquifer and surficial Quaternary-age deposits, and the lower layer represented the Arikaree aquifer. The model's grid had 168 rows oriented east-west and 202 columns oriented north-south. Most of the rows and columns were 1,640 ft (500 meters (m)) wide, except that smaller rows and columns were used in areas where large water-supply wells are located because of potentially steep hydraulic gradient in these areas. These rows and columns were 984 ft (300 m) wide (fig. 9). The height of each cell is equal to the estimated formation thickness, which was determined on the basis of structure-contour maps of the Arikaree Formation and White River Group (Carter, 1998) and land-surface elevation data at a 30-m grid resolution (National Elevation Dataset, 2006). These elevation data were used to represent the top of layer 1, where the Ogallala Formation and overlying windblown deposits are exposed to the land surface, and the top of layer 2, where the Arikaree Formation is exposed. The altitude of the top of the Arikaree Formation, where buried, 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 simulated so that cells were convertible between confined and unconfined conditions. Although the top of layer 1 is the land surface, there is no option in MODFLOW to simulate a layer as strictly unconfined. If hydraulic head in a convertible cell exceeds the top of layer 1, the cell will convert to confined (McDonald and Harbaugh, 1988). This occurs where discharge to simulated streams and spring occurs, which prevents pressure from building in these cells and allows outflow to occur. 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 (figs. 9 and 10). Other boundaries were designated as no-flow boundaries, which included the edges of the aquifers or where study area boundaries were approximately parallel to the estimated groundwater-flow direction.

Table 5. Revisions to the model described by Long and others (2003).

Category	2003 model[a]	Revision in 2010 model
Simulated period, in water years	1979–1998	1979–2008.
Calibration method	Trial-and-error	Inverse modeling.
Base-flow calibration	Two drainage basins	Six drainage basins.
Recharge estimate	Percentage of precipitation as a constant	Percentage of recharge is variable.
Delineation of vegetation types	Topographic maps	Satellite imagery.
Model cell discretization	Uniform cell size (1,640 feet each side)	Variable cell size with smallest cells near municipal production wells (984 to 1,640 feet each side).

[a]Long and others (2003).

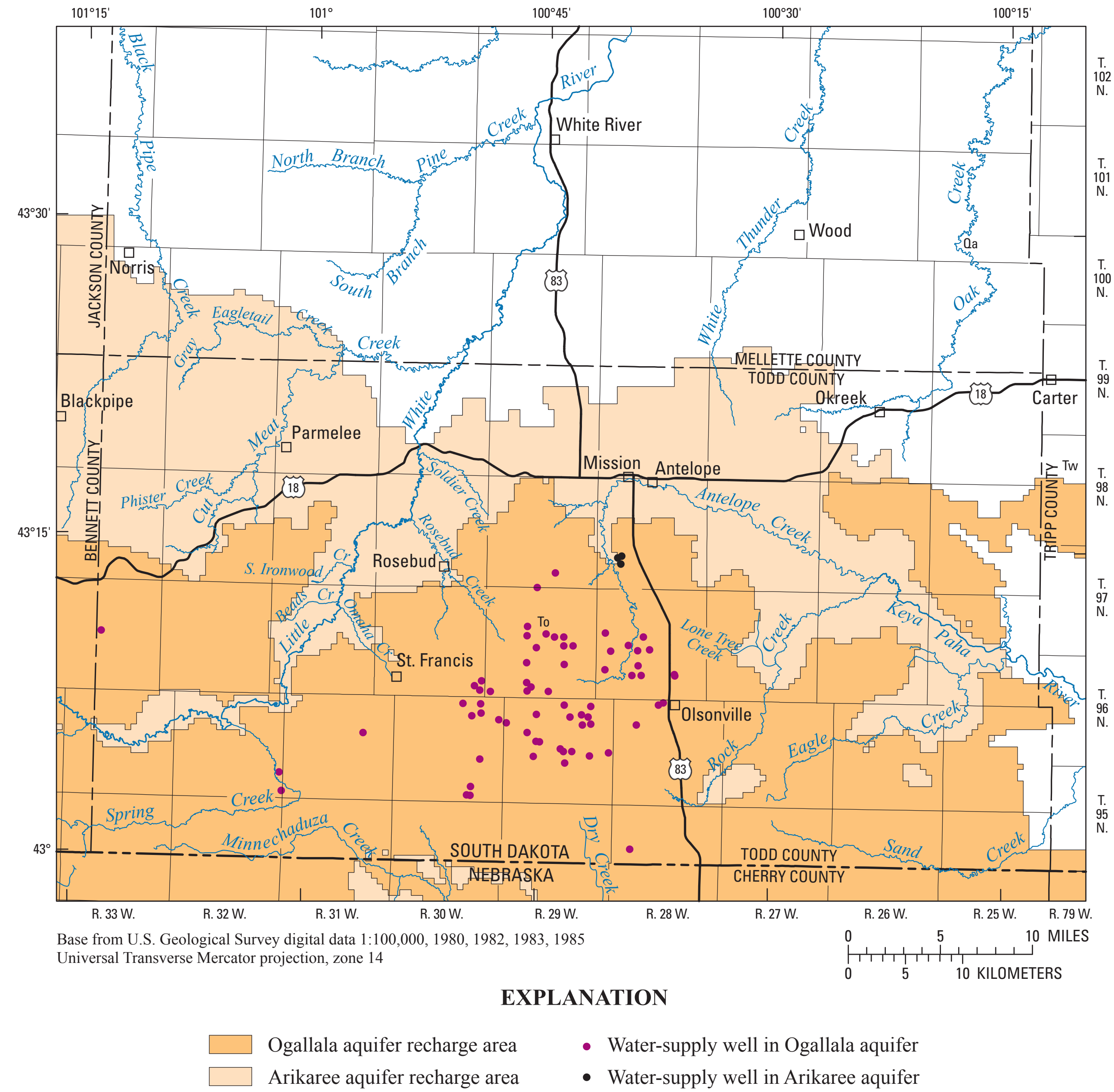


Figure 8. Recharge areas and locations of water-supply wells.

Hydraulic Conductivity

Zones of constant *K* were delineated by considering potential structural features, and specific capacities of wells (figs. 11–13). Five major zones for horizontal and vertical *K* were separated along stream reaches because of the possibility of structural control of streams. Subareas within these zones in the Ogallala aquifer partly were delineated in accordance with spatial variations of specific capacity of wells (fig. 11), especially high specific capacities in the central part of the model area between the Little White and Keya Paha Rivers (Long and others, 2003). Subareas were further delineated as needed for model calibration purposes as described in the "Model Calibration" section. Parameter estimation for these zones by inverse modeling resulted in horizontal *K* values ranging from about 0.2 to 84.4 ft/d for the Ogallala aquifer and about 0.1 to 4.3 ft/d for the Arikaree aquifer (figs. 11 and 12). Zones of large horizontal *K* were assigned along the Little White and Keya Paha Rivers in layer 2 (fig. 12) to allow for a substantial groundwater discharge that occurs to these streams. Higher horizontal *K* may be the result of near-surface weathering, which probably extends below the water table in these topographically low areas. In addition, if the locations of these streams are affected by fractures or faults, higher *K* values could result. The process of delineating hydraulic conductivity zones is further described in the "Model Calibration" section.

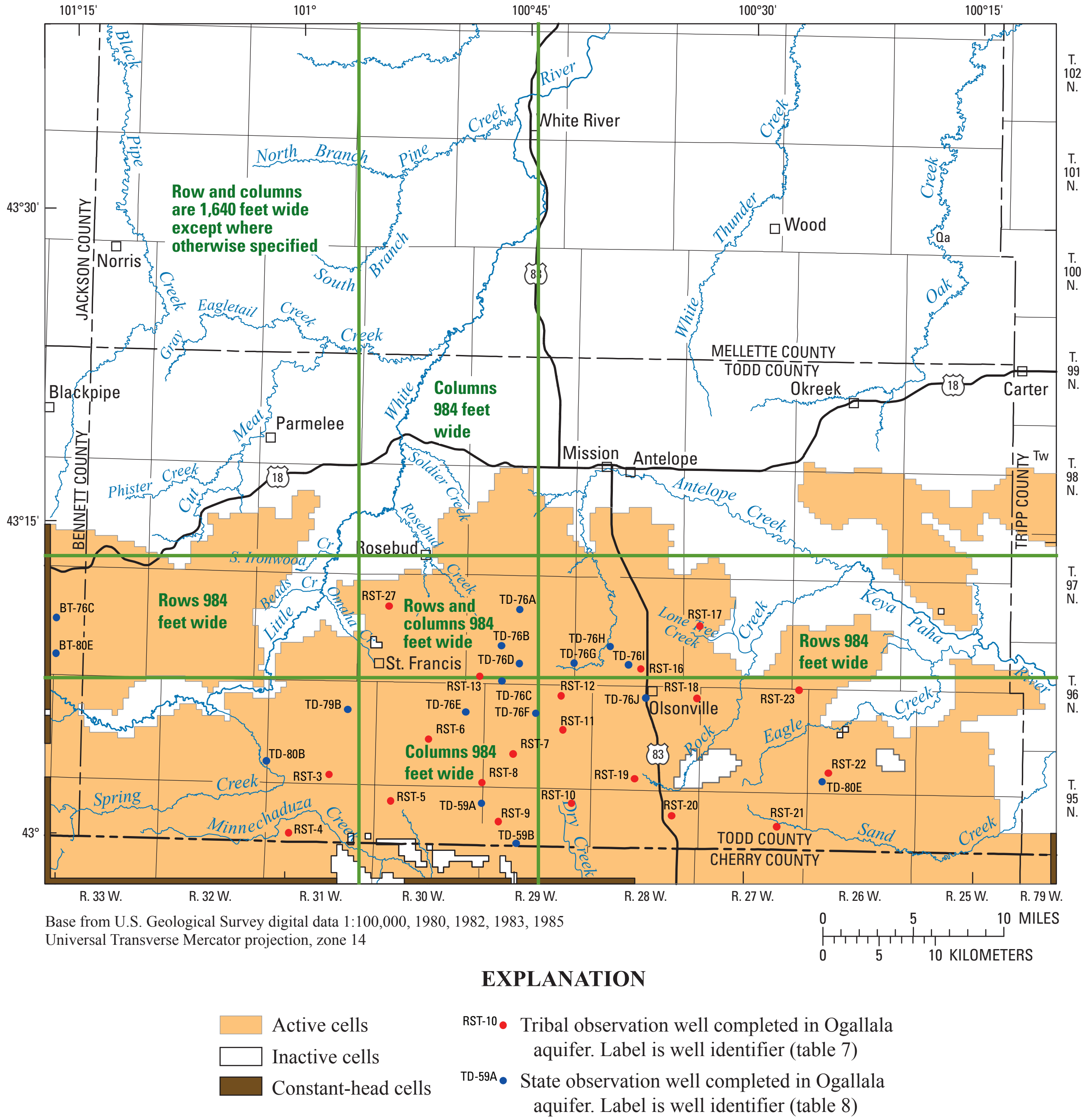


Figure 9. Cell types in the Ogallala aquifer (layer 1), observation wells completed in the Ogallala aquifer, and row and column widths for the Ogallala and Arikaree aquifers.

MODFLOW-2000 calculates vertical *K* between adjacent layers as the harmonic mean of vertical *K* for the two layers. The Arikaree aquifer was delineated into five vertical *K* zones, but because of the harmonic mean calculation, it was not necessary to delineate the Ogallala aquifer into zones to produce unique vertical *K* values between the two layers. A constant value of 4.2×10^{-4} ft/d was estimated for the Ogallala aquifer and ranged from 8.8×10^{-5} to 3.7 ft/d for the Arikaree aquifer (fig. 13).

Recharge

Recharge accounted for by the Recharge Package in MODFLOW-2000 (McDonald and Harbaugh, 1988) is the amount of infiltrating precipitation that surpasses the root zone and reaches the water table. Recharge rates for the steady-state simulation were estimated from model calibration (see “Model Calibration” section) and were consistent with previously published values. Recharge was 2.91 in/yr for the Ogallala aquifer (about 15 percent of average precipitation for

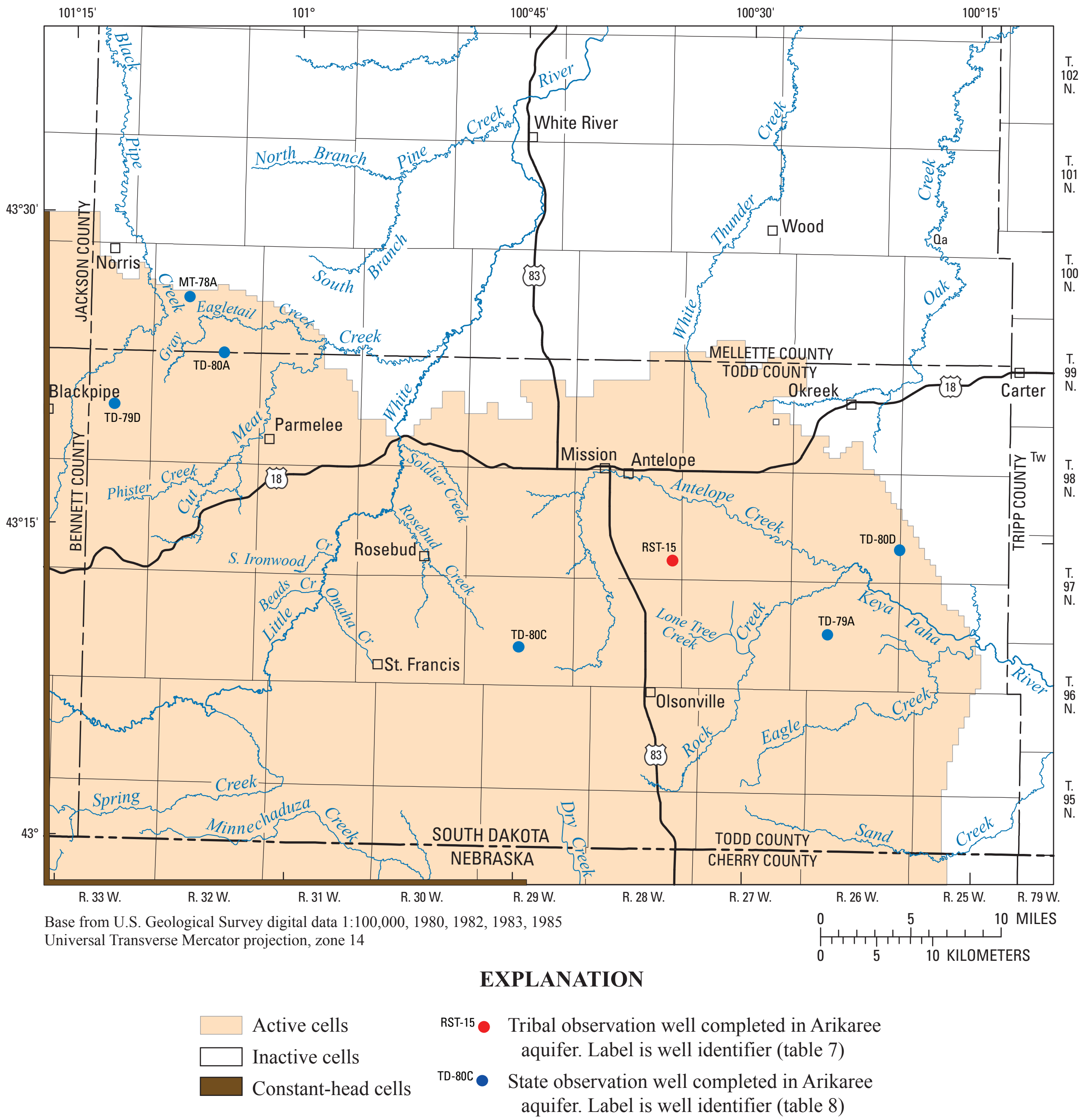


Figure 10. Cell types in the Arikaree aquifer (layer 2) and observation wells completed in the Arikaree aquifer.

1978–2008) and 1.45 in/yr for the Arikaree aquifer (about 7.5 percent of average precipitation for 1978–2008), for a total rate of 255.4 ft^3/s. Although recharge probably is spatially variable, a uniform distribution was assumed for each of the two recharge areas (fig. 8) because of insufficient data. A lower rate of recharge for the Arikaree aquifer than the Ogallala aquifer is consistent with the lower permeability of the Arikaree aquifer. Precipitation records were available for a National Weather Service Climatological Data station in the town of Mission (National Climatic Data Center, 2010; station 395620), which is located near the center of the study area.

For the transient simulation, the antecedent rainfall conditions were considered in estimating recharge. During a rainstorm, the preexisting soil moisture content heavily influences the effectiveness of precipitation in recharging groundwater. The amount of rain that has fallen prior to a rainfall event—the antecedent rainfall condition—largely determines soil moisture content. Heavy rains prior to an event can saturate the root zone and decrease evapotranspiration rates in the unsaturated zone. The amount of precipitation that is not removed by evapotranspiration commonly is referred to as effective precipitation in rainfall-runoff modeling. Neglecting

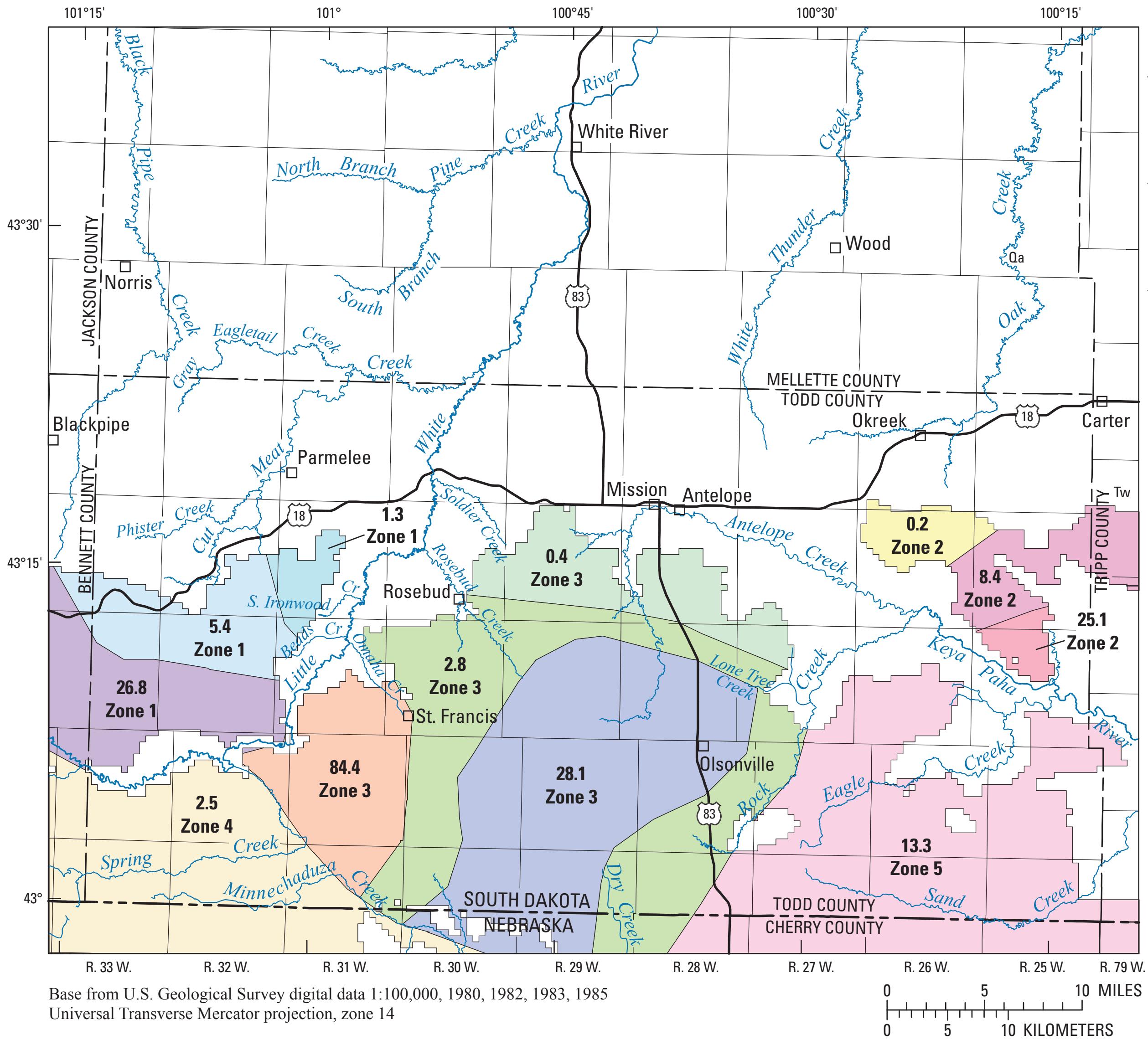


Figure 11. Estimated horizontal hydraulic conductivity of the Ogallala aquifer, in feet per day. Hydraulic conductivity of subareas within five major parameter zones are shown in each shaded area.

direct runoff, effective precipitation is synonymous with groundwater recharge. Direct runoff was assumed negligible on the outcrop of the Ogallala Formation and overlying surficial deposits because of the high permeability of these sandy media. Because of the low permeability of the Arikaree aquifer, some direct runoff was assumed to occur. The method of Jakeman and Hornberger (1993) can be used to calculate an antecedent rainfall index s_i, which weights the daily rainfall by previous rainfall. The weighting s_i is distributed exponentially backward in time by

$$s_i = cr_i + (1-a^{-1})s_{i-1}$$
$$= c[r_i + (1-a^{-1})s_{i-1} + (1-a^{-1})^2 s_{i-2} + ...] \quad i = 0, 1, \ldots N, \quad 0 > s_i > 1, \tag{1}$$

where c is a normalizing parameter to limit s_i to values between 0 and 1 [1/inches], a adjusts the influence of antecedent conditions [dimensionless], r_i is total daily rainfall [inches], and i is the time step in days. Effective daily precipitation, or recharge, u_i [inches] is then calculated by

$$u_i = r_i s_i \tag{2}$$

A value of $a = 24$ was estimated by inverse modeling for a rainfall-runoff simulation in western South Dakota (Long, 2009) and was used to estimate recharge for the Ogallala aquifer. Values of r_i were from the Weather Service Climatological Data station at Mission (National Climatic Data Center, 2010; station 395620). A value of $c = 0.059$ for the Ogallala aquifer was used because this resulted in an average recharge rate equal to 15 percent of precipitation for the 30-year period, which was consistent with the recharge rate estimated by the steady-state calibration. Recharge rates for the Ogallala

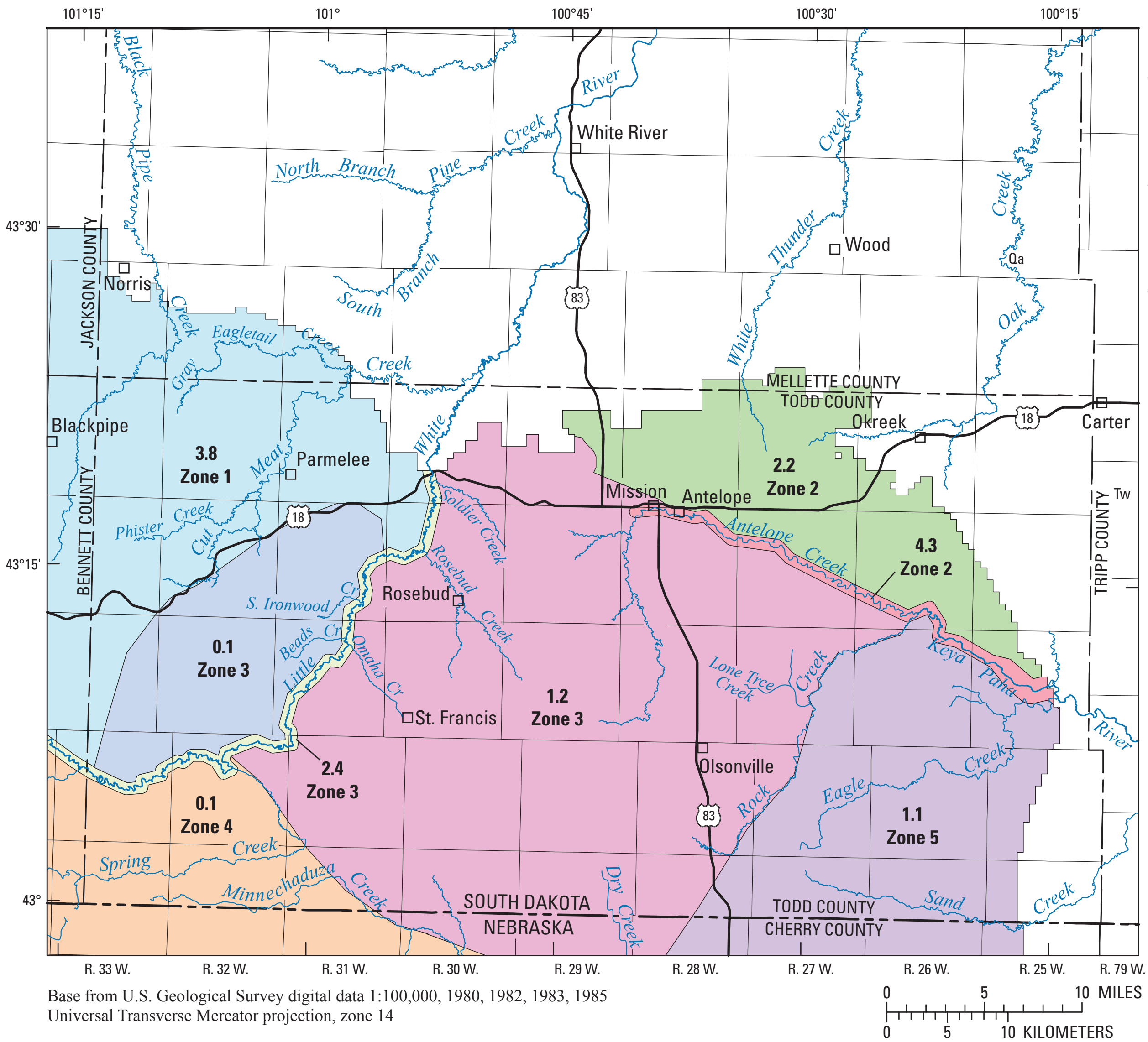


Figure 12. Estimated horizontal hydraulic conductivity of the Arikaree aquifer, in feet per day. Hydraulic conductivity of subareas within five major parameter zones are shown in each shaded area.

aquifer in total inches for each stress period were calculated as the sum of the effective daily precipitation (u_i) for each stress period (table 6). As averages of daily values, recharge rates for each stress period ranged from 1.9 to 33.7 percent of precipitation for the Ogallala aquifer. Recharge by stress period for the Arikaree aquifer was estimated as one-half that of the Ogallala aquifer to be consistent with the steady-state simulation and to account for direct runoff.

Discharge

Various MODFLOW-2000 packages were used to simulate the discharge components of evapotranspiration, discharge to streams, and well withdrawals. The Evapotranspiration Package (McDonald and Harbaugh, 1988) 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, referred to as the extinction depth. This extinction depth was set to 10 ft in areas with woody vegetation (U.S. Geological Survey, 1955) and to 7 ft elsewhere (fig. 14). The evapotranspiration 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 for each cell was set to the average land-surface altitude for the area covered by the cell based on a 30-m digital elevation model.

The Evapotranspiration Package accounts for only part of total evapotranspiration because it affects groundwater at or below the water table only. Evapotranspiration of infiltrating or suspended groundwater in the unsaturated zone is not

Table 6. Estimated recharge to the Ogallala aquifer, water years 1979–2008.

Stress period	Water year	Months	Precipitation (inches)	Recharge to Ogallala aquifer (inches)	Recharge as a percentage of precipitation[a]
1	1979	Oct.–Feb.	1.48	0.03	1.9
2	1979	Mar.–May	4.67	.36	7.6
3	1979	June–Sept.	11.50	2.33	20.3
4	1980	Oct.–Feb.	3.20	.25	7.9
5	1980	Mar.–May	3.34	.19	5.6
6	1980	June–Sept.	7.16	.86	12.0
7	1981	Oct.–Feb.	3.17	.21	6.6
8	1981	Mar.–May	5.92	.66	11.1
9	1981	June–Sept.	10.05	1.78	17.7
10	1982	Oct.–Feb.	4.67	.45	9.7
11	1982	Mar.–May	9.84	1.85	18.8
12	1982	June–Sept.	13.46	3.45	25.7
13	1983	Oct.–Feb.	5.35	.78	14.6
14	1983	Mar.–May	8.47	1.28	15.1
15	1983	June–Sept.	9.70	1.53	15.8
16	1984	Oct.–Feb.	3.80	.25	6.7
17	1984	Mar.–May	6.67	.65	9.8
18	1984	June–Sept.	7.65	1.00	13.1
19	1985	Oct.–Feb.	2.76	.14	5.2
20	1985	Mar.–May	3.11	.17	5.5
21	1985	June–Sept.	7.67	.82	10.6
22	1986	Oct.–Feb.	4.04	.28	7.0
23	1986	Mar.–May	8.34	1.06	12.7
24	1986	June–Sept.	12.83	2.07	16.1
25	1987	Oct.–Feb.	3.72	.33	8.8
26	1987	Mar.–May	8.40	1.12	13.4
27	1987	June–Sept.	6.63	.96	14.5
28	1988	Oct.–Feb.	3.06	.13	4.3
29	1988	Mar.–May	6.57	.82	12.5
30	1988	June–Sept.	7.85	1.23	15.7
31	1989	Oct.–Feb.	1.23	.03	2.4
32	1989	Mar.–May	2.96	.13	4.3
33	1989	June–Sept.	9.75	1.46	14.9
34	1990	Oct.–Feb.	2.55	.19	7.4
35	1990	Mar.–May	6.70	.67	10.1
36	1990	June–Sept.	10.69	2.44	22.8
37	1991	Oct.–Feb.	2.37	.10	4.1
38	1991	Mar.–May	10.70	2.22	20.8
39	1991	June–Sept.	8.16	2.75	33.7
40	1992	Oct.–Feb.	4.16	.23	5.6
41	1992	Mar.–May	1.99	.09	4.6
42	1992	June–Sept.	13.20	2.51	19.0
43	1993	Oct.–Feb.	2.37	.09	3.7
44	1993	Mar.–May	5.40	.57	10.6
45	1993	June–Sept.	9.77	1.31	13.4
46	1994	Oct.–Feb.	4.01	.25	6.2

Table 6. Estimated recharge to the Ogallala aquifer, water years 1979–2008.—Continued

Stress period	Water year	Months	Precipitation (inches)	Recharge to Ogallala aquifer (inches)	Recharge as a percentage of precipitation[a]
47	1994	Mar.–May	3.75	0.36	9.7
48	1994	June–Sept.	12.45	2.14	17.2
49	1995	Oct.–Feb.	2.98	.18	6.2
50	1995	Mar.–May	10.35	1.69	16.3
51	1995	June–Sept.	8.07	1.52	18.9
52	1996	Oct.–Feb.	6.33	1.05	16.7
53	1996	Mar.–May	7.03	.91	13.0
54	1996	June–Sept.	7.68	1.04	13.6
55	1997	Oct.–Feb.	4.58	.42	9.3
56	1997	Mar.–May	6.47	.77	12.0
57	1997	June–Sept.	11.07	2.00	18.1
58	1998	Oct.–Feb.	3.11	.22	7.0
59	1998	Mar.–May	5.66	.50	8.8
60	1998	June–Sept.	13.78	3.05	22.1
61	1999	Oct.–Feb.	6.87	.94	13.7
62	1999	Mar.–May	8.87	1.48	16.7
63	1999	June–Sept.	14.15	2.91	20.6
64	2000	Oct.–Feb.	2.10	.09	4.5
65	2000	Mar.–May	9.61	1.98	20.6
66	2000	June–Sept.	8.90	1.97	22.1
67	2001	Oct.–Feb.	6.21	.52	8.3
68	2001	Mar.–May	8.32	1.20	14.5
69	2001	June–Sept.	9.38	1.53	16.3
70	2002	Oct.–Feb.	3.98	.42	10.4
71	2002	Mar.–May	4.36	.35	8.0
72	2002	June–Sept.	5.11	.51	9.9
73	2003	Oct.–Feb.	2.65	.13	4.9
74	2003	Mar.–May	5.30	.49	9.3
75	2003	June–Sept.	6.00	.71	11.9
76	2004	Oct.–Feb.	2.13	.08	4.0
77	2004	Mar.–May	7.29	.79	10.8
78	2004	June–Sept.	10.27	1.59	15.5
79	2005	Oct.–Feb.	4.99	1.06	21.2
80	2005	Mar.–May	10.23	1.93	18.9
81	2005	June–Sept.	10.56	2.18	20.7
82	2006	Oct.–Feb.	2.49	.11	4.3
83	2006	Mar.–May	5.59	.61	10.8
84	2006	June–Sept.	10.35	1.36	13.2
85	2007	Oct.–Feb.	2.72	.14	5.2
86	2007	Mar.–May	7.76	.94	12.1
87	2007	June–Sept.	8.15	1.24	15.2
88	2008	Oct.–Feb.	5.58	.79	14.1
89	2008	Mar.–May	6.32	.66	10.5
90	2008	June–Sept.	13.62	3.21	23.6

[a]Average of daily values for each stress period.

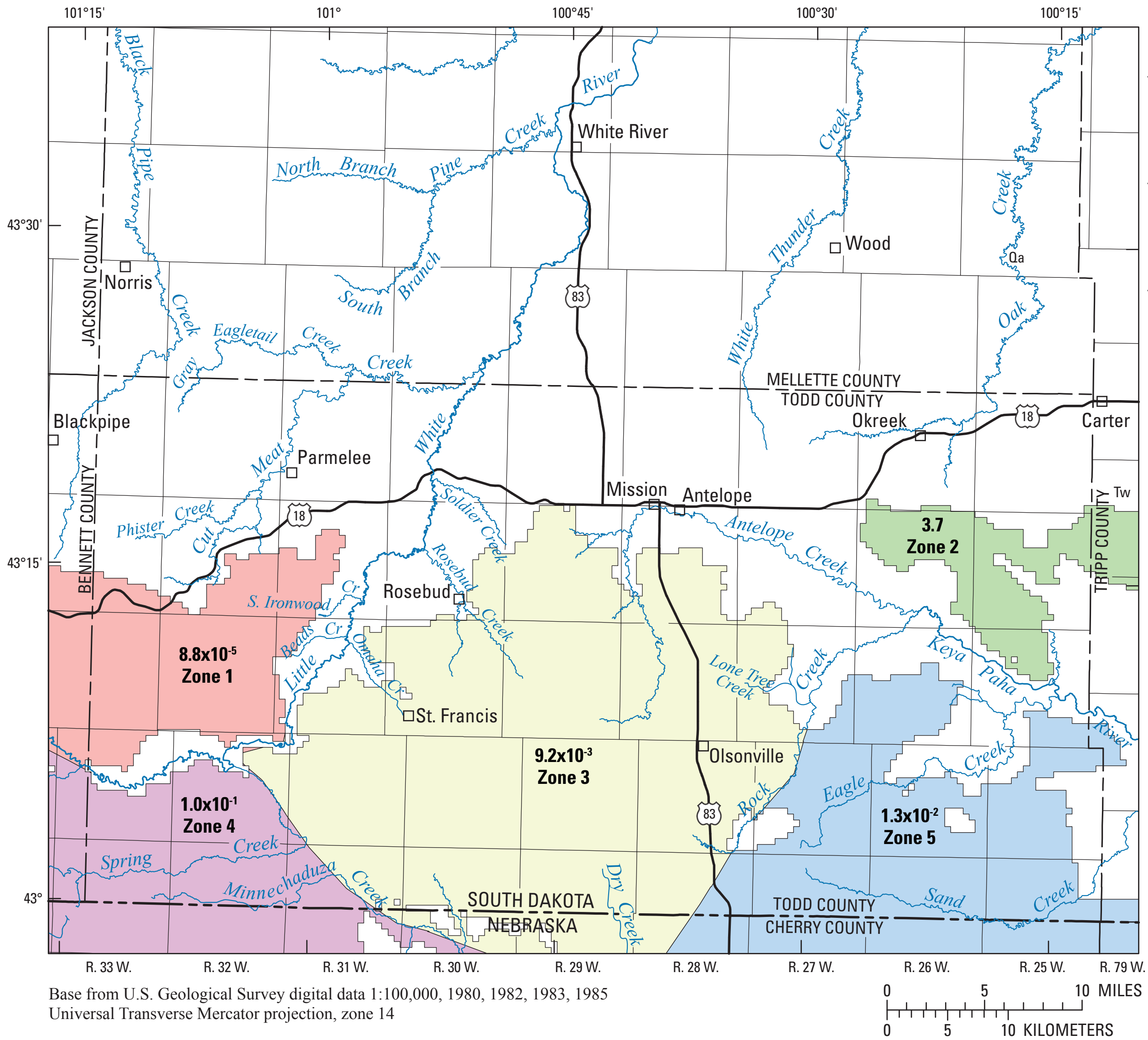


Figure 13. Estimated vertical hydraulic conductivity (*K*), in feet per day, for the Arikaree aquifer in five parameter zones where overlain by the Ogallala aquifer.

accounted for. Estimation of the recharge rate as some percentage of total precipitation, as previously described, accounts for this remaining part of the evapotranspiration process.

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 groundwater and surface water by allowing streams to gain or lose water on the basis of the difference between the surrounding hydraulic head and stream stage through riverbed material. The hydraulic conductance of this material is defined by McDonald and Harbaugh (1988) as hydraulic conductivity of the material times the cross-sectional area of the stream reach divided by the streambed thickness. Estimated riverbed conductance was based on model calibration. Model cells were designated as river leakage cells along major streams and tributaries for six streams groups (fig. 14), which are (1) the Little White River and tributaries upstream from site 12 (fig. 7); (2) the Keya Paha River and tributaries; (3) Black Pipe Creek; (4) Gray Eagle and Cut Meat Creeks; (5) Sand Creek; and (6) Minnechaduza and Dry Creeks. River leakage cells were placed in stream reaches that are at or below the estimated potentiometric surface for the recharge area of the aquifer upon which the reach is located (figs. 4 and 5). Above these altitudes, streams are dry except during intense storms. Digital elevation data were used to determine stream locations, and thus river leakage cells do not always coincide exactly with streams shown on figure 14.

The Drain Package simulated springs discharging from the Ogallala aquifer along the banks of the Little White River and along the northern edge of the Arikaree aquifer (fig. 14). The Drain Package is similar to the River Package except that drain cells can only take water out of the aquifer, whereas river

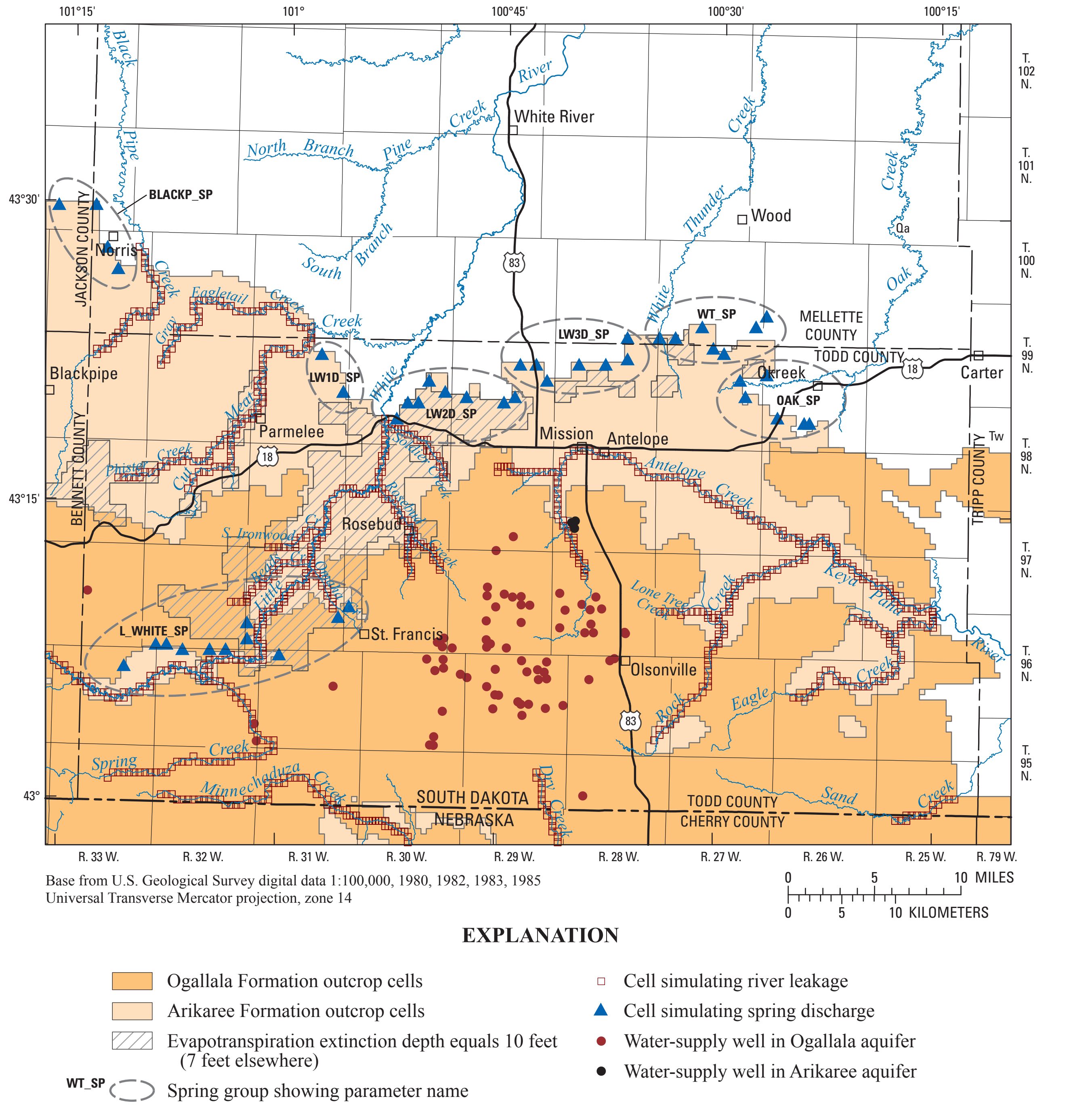


Figure 14. River cells, evapotranspiration zones, spring cells, and water-supply wells in the Ogallala and Arikaree aquifers.

cells can also recharge the aquifer (McDonald and Harbaugh, 1988). Model cells were designated as drain cells for seven spring groups (fig. 14), and drain (spring) conductance was estimated by model calibration for each spring group.

Well withdrawals were simulated with the Well Package (McDonald and Harbaugh, 1988) to withdraw water from each well at a specified rate. Well withdrawals used in the transient simulation are listed in table 4, and locations are shown in figures 8 and 14. Because water use was negligible from October through May, total annual withdrawals were assigned to the summer stress periods only (June–September). For the steady-state calibration, the average withdrawal rate was calculated as 11.6 ft^3/s.

Model Calibration

The steady-state simulation was calibrated to the estimated average water levels shown in figures 4 and 5 and to the estimated base flows listed in table 3. The transient model was

Table 7. Selected data for Tribal observation wells in the study area.

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929]

Well name (figs. 9 and 10)	Site identification numer	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average measured hydraulic head (feet above NGVD of 1929)	Steady-state simulated hydraulic head (feet above NGVD of 1929)	Residual[a]
RST-3	430309100570901	36N31W34DBBC	Ogallala	2,920	91	2,865	2,833	-32
RST-4	430017100595101	35N31W17CCDA	Ogallala	2,896	62	2,893	2,888	-5
RST-5	430159100531001	35N30W 6DDDD	Ogallala	2,853	84	2,832	2,850	18
RST-6	430501100504901	36N30W22CBBB	Ogallala	2,888	137	2,858	2,860	2
RST-7	430415100451401	36N29W29ACAA	Ogallala	2,870	134	2,851	2,830	-21
RST-8	430258100471401	36N30W36DDDA	Ogallala	2,885	123	2,836	2,846	10
RST-9	430100100460501	35N29W18AAAA	Ogallala	2,870	84	2,831	2,844	13
RST-10	430154100411801	35N29W 2DDDD	Ogallala	2,800	44	2,792	2,790	-2
RST-11	430530100422501	36N29W14CDAB	Ogallala	2,893	200	2,811	2,801	-10
RST-12	430712100421301	36N29W 2CDCC	Ogallala	2,850	200	2,804	2,791	-13
RST-13	430755100582301	37N29W31DACC	Ogallala	2,921	275	2,815	2,824	9
RST-15	431342100344101	38N28W36ABCB	Arikaree	2,620	73	2,609	2,577	-32
RST-16	430820100371401	37N28W34ABDA	Ogallala	2,783	171	2,725	2,733	8
RST-17	431027100333001	37N27W18DDAB	Ogallala	2,609	53	2,605	2,613	8
RST-18	430702100330501	36N28W12AABA	Ogallala	2,806	215	2,660	2,678	18
RST-19	430243100371701	36N28W33BDDD	Ogallala	2,753	75	2,723	2,732	9
RST-20	430122100344501	35N28W11DBBB	Ogallala	2,728	94	2,711	2,711	0
RST-21	430057100275401	35N27W14BAAB	Ogallala	2,690	84	2,671	2,636	-35
RST-22	430335100241401	36N26W32BBAA	Ogallala	2,619	78	2,589	2,594	5
RST-23	430728100135801	36N27W 1BDDD	Ogallala	2,627	58	2,600	2,607	7
RST-27	431127100532801	37N30W 8DACC	Ogallala	2,880	150	2,759	2,805	46

[a]Residual is the difference between simulated hydraulic head and average measured hydraulic head.

calibrated to water levels measured frequently in Tribal and State observation wells during water years 1979–2008.

Steady-State Simulation

Steady-state conditions were numerically approximated by simulating a 100-year stress period in transient mode with constant recharge and discharge rates. This method was more numerically stable and used fewer iterations than the equivalent simulation in steady-state mode. The potentiometric surface from the steady-state simulation established initial conditions for the transient simulation.

Calibration of the steady-state model primarily was accomplished by applying what is commonly known as inverse modeling. This method is an efficient way to determine an optimum set of parameter values that minimize the residuals between measured and simulated flow metrics, such as hydraulic head, base flow, and spring flow. Parameters estimated by inverse modeling were those describing hydraulic conductivity (K), recharge, maximum evapotranspiration, riverbed conductance, and spring conductance.

Optimization of parameter values by inverse modeling was accomplished by linking the parameter estimation software PEST (Doherty, 2004) with MODFLOW-2000. PEST is an iterative parameter estimation process that applies nonlinear estimation techniques described by Levenberg (1944), Marquardt (1963), and Doherty (2004). This allows a nonlinear problem to be linearized in relation to the best parameter set for the current iteration. A new set of parameters is then estimated in an attempt to improve model calibration, and the process is repeated until the residuals are minimized. Parameter sensitivities and confidence intervals are determined by calculating the derivatives of all observations with respect to all parameters. This calibration approach was considered an improvement over the trial-and-error methods because it was more efficient and objective and provided a statistical assessment of model uncertainty, including confidence intervals on estimated parameter values and a matrix of parameter correlation coefficients.

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

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929]

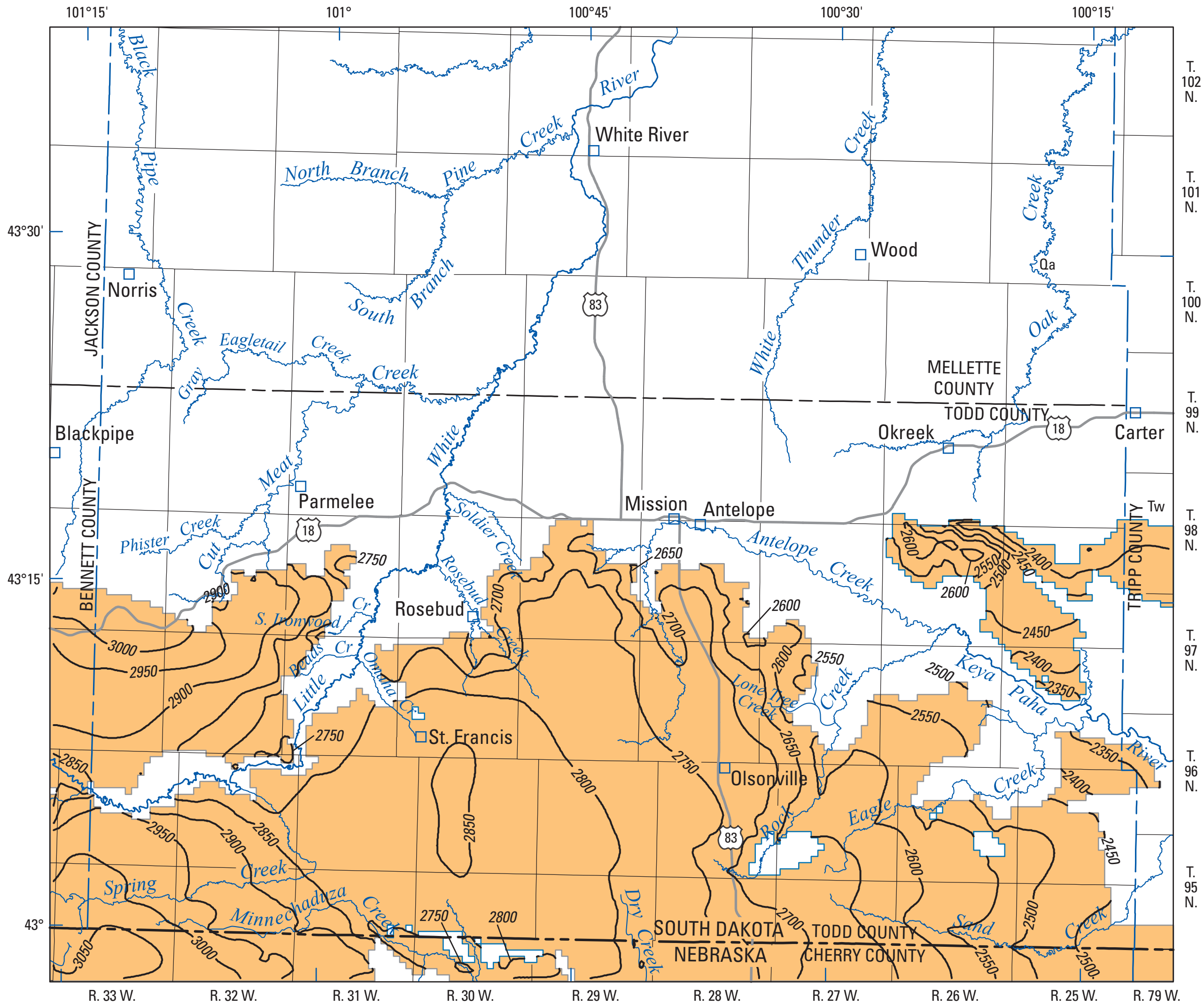
Well name (figs. 9 and 10)	Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Other name	Average measured hydraulic head (feet above NGVD of 1929)	Steady-state simulated hydraulic head (feet above NGVD of 1929)	Residual[a]
BT-76C	431018101152001	37N33W17CCCC	Ogallala	2,998	181	S207	2,930	2,929	-1
BT-80E	430825101151801	37N33W32BBBB2	Ogallala	2,960	143	S170	2,902	2,901	-1
MT-78A	432554101065601	40N32W21BBBB	Arikaree	2,576	163	S384	2,561	2,567	6
TD-59A	430148100471001	35N29W 7BBBB	Ogallala	2,903	83	S41	2,837	2,849	12
TD-59B	425957100445601	35N29W20AADD	Ogallala	2,890	128	S2	2,804	2,833	29
TD-76A	431109100445901	37N29W16AAAA	Ogallala	2,852	184	S219	2,754	2,786	32
TD-76B	430924100460601	37N29W29AAAA	Ogallala	2,868	204	S194	2,790	2,802	12
TD-76C	430748100455601	37N29W33CCCC	Ogallala	2,909	203	S160	2,817	2,814	-3
TD-76D	430840100445601	37N29W28DDDD	Ogallala	2,858	195	S176	2,791	2,793	2
TD-76E	430610100481701	36N30W13BBBB	Ogallala	2,916	225	S126	2,843	2,844	1
TD-76F	430609100434201	36N29W16AAAA	Ogallala	2,863	222	S125	2,822	2,809	-13
TD-76G	430842100411301	37N28W30CCCB	Ogallala	2,770	184	S177	2,745	2,764	19
TD-76H	430932100390001	37N28W21CCCC	Ogallala	2,772	163	S201	2,727	2,731	4
TD-76I	430839100373801	37N28W27CCCC	Ogallala	2,805	182	S175	2,727	2,739	12
TD-76J	430701100363001	36N28W10BBBB	Ogallala	2,823	183	S145	2,750	2,745	-5
TD-79A	431020100243501	37N26W16CCBB	Arikaree	2,530	137	S210	2,523	2,521	-2
TD-79B	430613101561701	36N31W14BAAA	Ogallala	2,955	160	S130	2,816	2,830	14
TD-79D	432044101115201	39N33W15DDDD	Arikaree	2,800	360	S361	2,764	2,781	17
TD-80A	432310101045501	39N32W 3AAAA	Arikaree	2,610	125	S374	2,578	2,585	7
TD-80B	430340101012301	36N32W25DDDD	Ogallala	2,841	125	S87	2,834	2,829	-5
TD-80C	430959100444001	37N29W22CCCC	Arikaree	2,882	265	S205	2,781	2,787	6
TD-80D	431430100195901	38N25W30BCBB	Arikaree	2,483	144	S274	2,458	2,451	-7
TD-80E	430310100245501	36N26W31ADDD	Ogallala	2,620	125	S80	2,594	2,605	11

[a]Residual is the difference between simulated hydraulic head and average measured hydraulic head.

The criterion for estimating optimum parameter values was to achieve a minimum value for the sum of the squared and weighted residuals, or differences, between simulated and observed hydraulic heads and base flows in streams. This is referred to as the objective function. Water-level measurements for 383 wells that were used for estimation of potentiometric surfaces of the Ogallala and Arikaree aquifers (figs. 4 and 5) were used in calibration of the steady-state model. These wells included 44 observation wells with long-term water-level records that also were used for calibration of the transient model. The rest were wells mainly used for water supply. The observation wells included 21 Tribal wells, of which 20 were completed in the Ogallala aquifer and 1 was completed in the Arikaree aquifer, and 23 State wells, of which 17 were completed in the Ogallala aquifer and 6 were completed in the Arikaree aquifer (figs. 9 and 10). Selected data for the Tribal and State observation wells are shown in table 7 and table 8, respectively. The model also was calibrated to estimated base flow in streams. As described in the "Conceptual Model" section, estimated base-flow values for the Little White River, Keya Paha River, Cut Meat Creek, Black Pipe Creek, Minnechaduza Creek, and Sand Creek were 49, 23, 1.7, 1.2, 3.0, and 3.9 ft^3/s, respectively.

The primary calibration objective was to minimize the objective function. A second calibration objective for the steady-state simulation was to have the simulated potentiometric surfaces and hydraulic gradients generally resemble those of the estimated average potentiometric surfaces (water years 1979–98). The simulated steady-state potentiometric surfaces (figs. 15 and 16) are similar to the estimated average potentiometric surfaces (figs. 4 and 5) in comparisons of both hydraulic heads and gradients.

Simulated hydraulic heads matched observed values to within ±50 ft for 93 percent of the 383 wells used in the steady-state calibration. Fifty feet is about 7 percent of the total hydraulic head relief for the estimated average



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

EXPLANATION

Ogallala aquifer active cells

—2750— **Simulated potentiometric contour**—Shows average altitude at which water level would have stood in tightly cased wells, water years 1979–98. Contour interval is 50 feet. Datum is NGVD of 1929

Figure 15. Potentiometric surface of the Ogallala aquifer for steady-state simulation.

potentiometric surfaces in the model area, which is about 780 ft for the Ogallala aquifer and 720 ft for the Arikaree aquifer. A histogram shows the distribution of the hydraulic-head residuals for the 383 wells (fig. 17). Results for the 44 observation wells was better than for all 383 wells. Simulated hydraulic heads for observation wells were within ±40 ft of the observed hydraulic heads for 98 percent of these wells. The root mean square error (RMSE) for all 383 wells was 27.3 ft. The mean error was 4.3 ft, which indicates a slight model bias toward overestimating hydraulic head values. For the observation wells only, the RMSE was 15.8 ft, and the mean error was 3.4 ft. A linear regression analysis of simulated and observed water levels for all 383 wells (fig. 18) yielded an R^2 value (coefficient of determination) of 0.97. The total simulated base flow was 73.3 ft^3/s, which is about 10 percent less than the total estimated base flow of 81.8 ft^3/s (table 9).

Because a large number of estimated parameters can result in high parameter correlations and large parameter confidence intervals, the horizontal *K* areas were grouped into five major parameter zones for each model layer (figs. 11 and

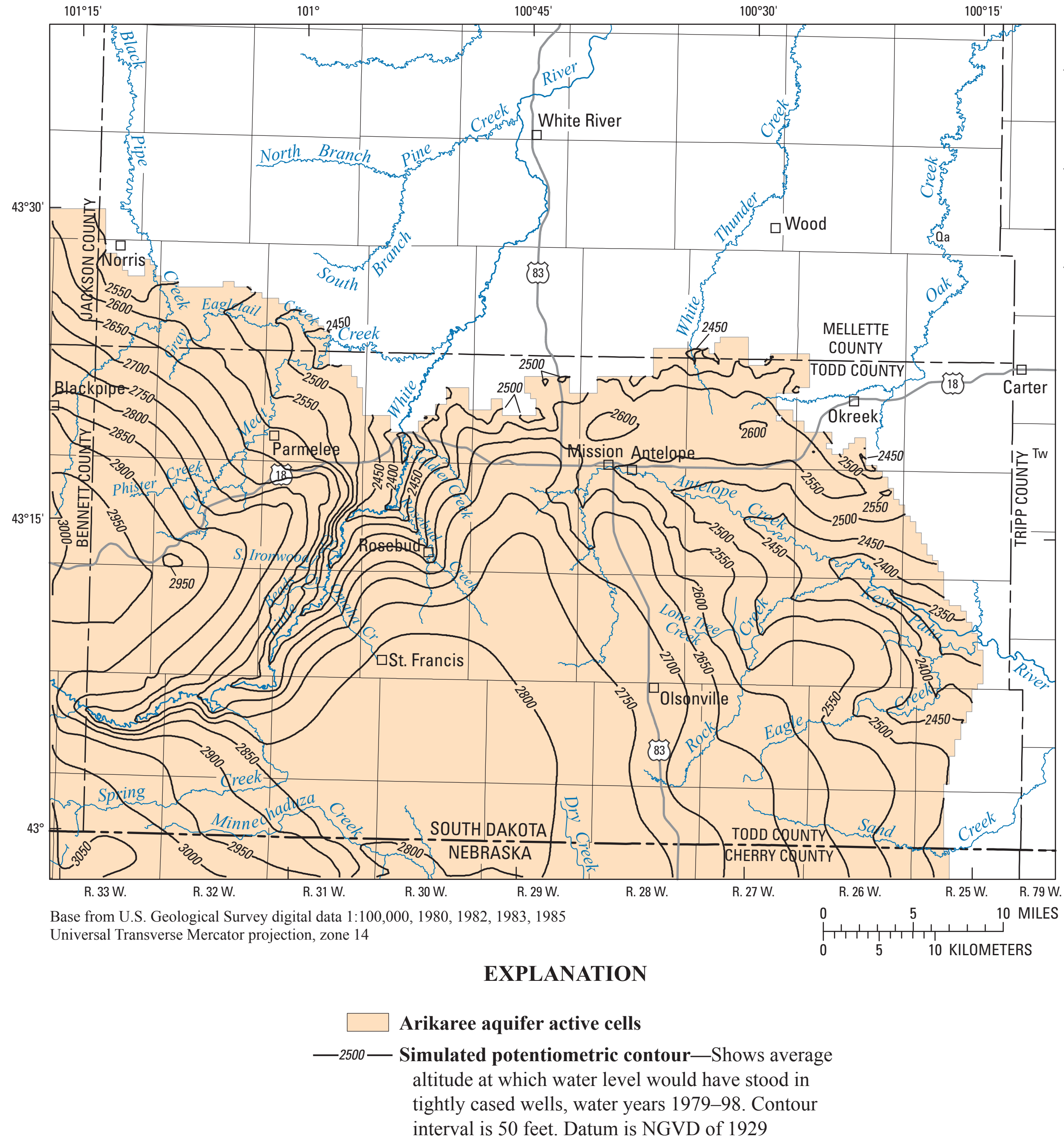


Figure 16. Potentiometric surface of the Arikaree aquifer for steady-state simulation.

12). One parameter value was estimated by inverse modeling for each of these 10 zones. Prior to executing the inverse modeling process, these parameter values were multiplied by values assigned to subareas within the parameter zones to allow variation within parameter zones. Subarea values were assigned on the basis of specific capacities of wells (Long and others, 2003) and the assumption that horizontal *K* for the Arikaree aquifer is highest near streams (figs. 11 and 12). Trial-and-error was used to further refine subarea values in an iterative process with inverse modeling in order to minimize the objective function. As a result of this calibration process, an additional subarea, which was not part of the previously published model, was delineated in the northeastern part of zone 1 (horizontal *K* of 1.3 ft/d, fig. 11).

The shaded subareas in figures 11 and 12 show the results of this multiplication, which are the final horizontal *K* values used in the steady-state simulation. Vertical *K* was assumed to be homogeneous within each of the five parameter zones for the Arikaree aquifer (fig. 13), and a uniform vertical *K* value was applied to the Ogallala aquifer because parameter

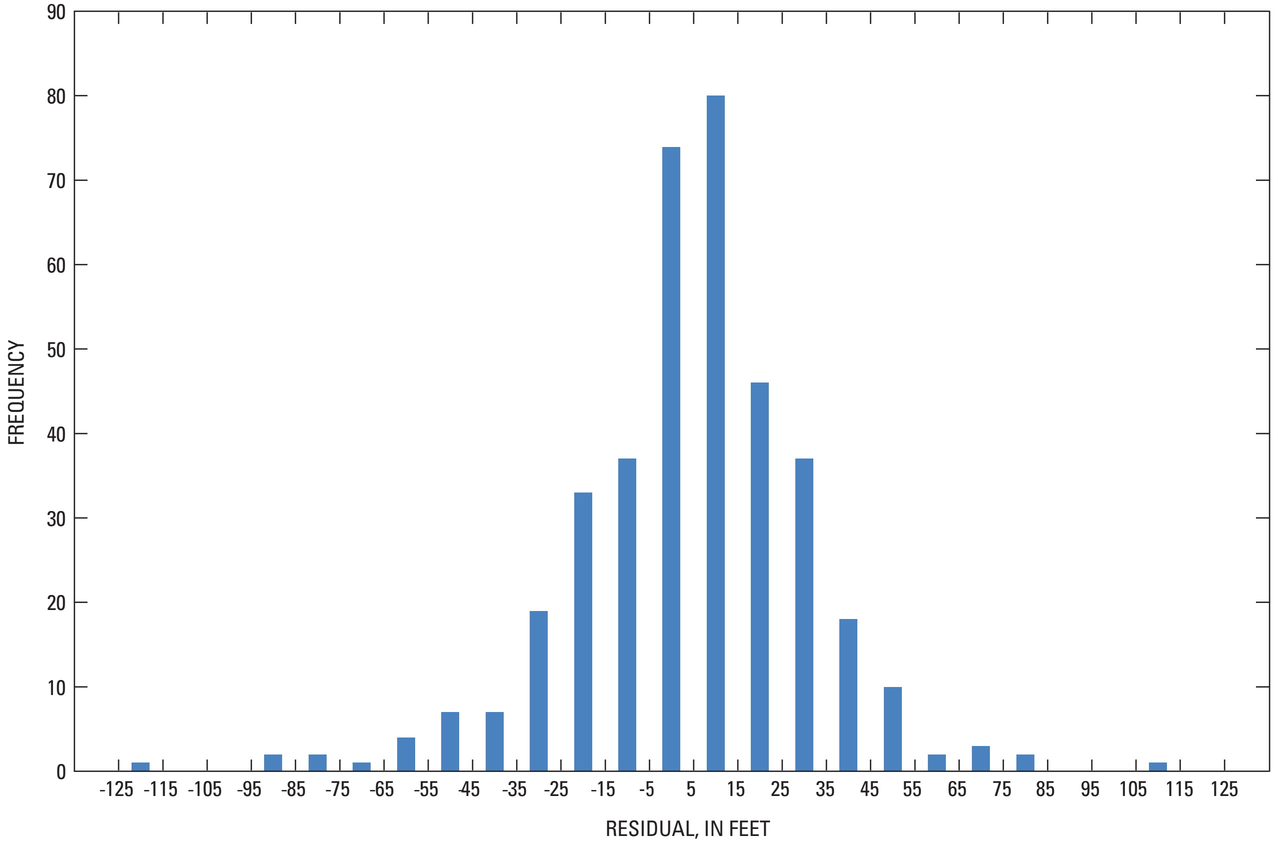


Figure 17. Histogram of residuals of average observed and steady-state simulated hydraulic head for 383 wells, water years 1979–98.

estimates for only one of the two intervening layers need to be adjusted for calibration. This resulted in a total of six parameter values for vertical *K*. Greater discretization of horizontal or vertical *K* might have further minimized the objective function by adjusting *K* near individual wells or small groups of wells, but the available data did not support this degree of detail. Therefore, the calibration accuracy obtained using these parameter zones and subareas was considered sufficient to fulfill the objectives of this study.

Table 9. Comparison of steady-state simulated and estimated base flows for six surface-water drainage basins.

[ft^3/s, cubic feet per second]

Stream	Base flow (ft^3/s)	
	Estimated	Steady-state simulated[a]
Little White River	49.0	36.7
Keya Paha River	23.0	20.0
Cut Meat Creek	1.7	8.4
Black Pipe Creek	1.2	1.3
Minnechaduza Creek	3.0	3.2
Sand Creek	3.9	3.8
Total	81.8	73.3

[a]Net outflow. Includes spring flow along river banks.

The remaining parameter categories were recharge, maximum evapotranspiration, riverbed conductance, and spring conductance. Two recharge rates were estimated by inverse modeling: one rate for the Ogallala aquifer recharge area and a second rate for the Arikaree aquifer recharge area (fig. 8). A single value applied to the entire model for the maximum evapotranspiration rate was estimated by inverse modeling. A value for each of the six riverbed conductance cell groups and seven spring conductance cell groups was estimated by inverse modeling (fig. 14). With these additional parameter values, there were a total of 32 values to be estimated by inverse modeling for the steady-state simulation (table 10).

These 32 parameter values were estimated during an initial execution of the inverse modeling process. However, diagnostics, such as large parameter confidence intervals, insensitivity of several parameters, and many highly correlated parameters, indicated the need to group some parameters together and thereby reduce the total number of parameters to be estimated directly by inverse modeling. This was accomplished by tying parameters together, a method in which a

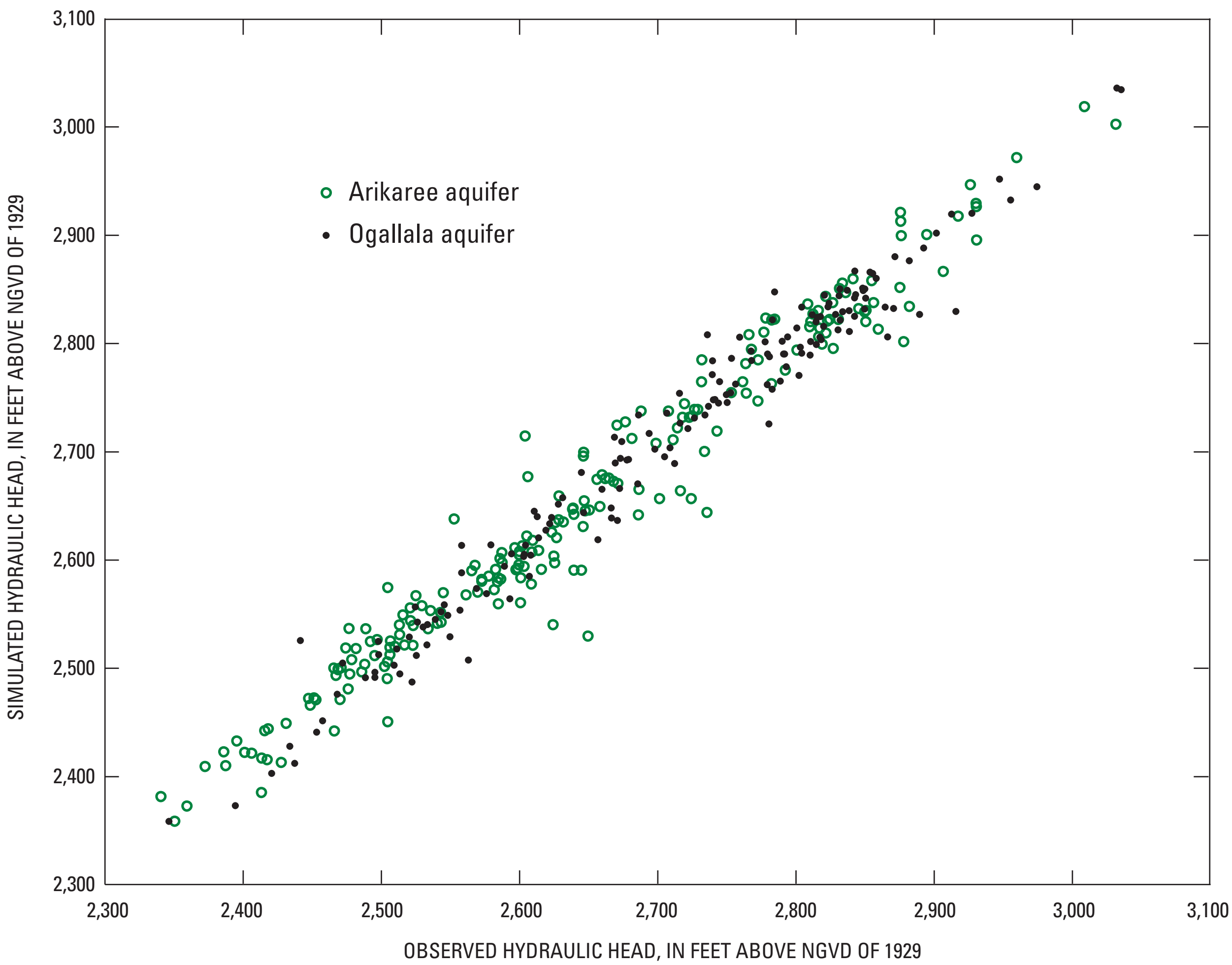


Figure 18. Linear regression of average observed and simulated steady-state hydraulic heads for 383 wells, water years 1979–98.

parameter is tied to an independent parameter, which can be adjusted during the inverse modeling process. The two parameters maintain a constant ratio based on their starting values, but only the independent parameter takes an active role in the inverse modeling process. Parameter confidence intervals are calculated for independent parameters but not for tied parameters (table 10). The least sensitive parameters were tied to more sensitive parameters of the same type. The 32 parameter values estimated during the initial execution were used as starting values for the independent and tied parameters.

Recharge to the Arikaree aquifer was tied to recharge to the Ogallala aquifer. All of the vertical *K* parameters for the Arikaree aquifer were tied to the single vertical *K* parameter for the Ogallala aquifer. Riverbed conductance parameters for small drainage basins were tied to the Little White and Keya Paha River conductance parameters, and most of the spring conductance parameters were tied to one spring. This resulted in 15 independent parameters estimated directly by inverse modeling and 17 parameters estimated indirectly by being tied to 7 of the independent parameters (table 10). The range of values within which each parameter could be estimated was limited to what was considered physically reasonable. This prevented PEST from estimating unreasonable parameter values simply because they reduced the value of the objective function.

PEST calculated 95-percent confidence intervals on parameters, which indicates 95 percent confidence that a parameter value within this range results in the smallest possible objective function (table 10). In the final execution, the largest confidence intervals were associated with parameters WT_SP, VKA1_1, KEYA_PAHA, and L_WHITE_SP. It is noted that these confidence intervals rely on an assumption of linearity, which might not be valid at wide confidence limits. Other parameters, for example RECH1, had small confidence intervals indicating a high degree of confidence in these estimates relative to some other parameters. The estimated recharge rates for the Ogallala and Arikaree aquifers of 2.91 and 1.45 in/yr, respectively, are about 15 and 7.5 percent of average precipitation for the simulated period.

The water budget for the steady-state simulation balanced (inflows minus outflows) with a discrepancy of 0.2 percent (table 11). Total inflow from model constant-head boundaries

Table 10. Parameter values estimated by inverse modeling for the steady-state simulation.

[ft/d, feet per day; ft^2/d, feet squared per day; in/yr, inches per year; --, not applicable]

Parameter name	Estimated value	95-percent confidence intervals		Units	Tied to	Value applied to transient model	Description
		Lower limit	Upper limit				
HK1_1	48.81	21.98	108.40	ft/d	--	Yes	Horizontal hydraulic conductivity layer 1, zone 1.
HK1_2	15.25	1.47	158.41	ft/d	--	Yes	Horizontal hydraulic conductivity layer 1, zone 2.
HK1_3	25.61	12.30	53.32	ft/d	--	Yes	Horizontal hydraulic conductivity layer 1, zone 3.
HK1_4	4.54	--	--	ft/d	HK1_5	Yes	Horizontal hydraulic conductivity layer 1, zone 4.
HK1_5	40.33	10.45	155.58	ft/d	--	Yes	Horizontal hydraulic conductivity layer 1, zone 5.
HK2_1	2.52	.42	15.07	ft/d	--	Yes	Horizontal hydraulic conductivity layer 2, zone 1.
HK2_2	1.44	.58	3.58	ft/d	--	Yes	Horizontal hydraulic conductivity layer 2, zone 2.
HK2_3	.81	.69	.95	ft/d	--	Yes	Horizontal hydraulic conductivity layer 2, zone 3.
HK2_4	.06	--	--	ft/d	HK2_5	Yes	Horizontal hydraulic conductivity layer 2, zone 4.
HK2_5	.73	.10	5.12	ft/d	--	Yes	Horizontal hydraulic conductivity layer 2, zone 5.
VKA1_1	$4.18x10^{-4}$	$3.45x10^{-7}$	.507	ft/d	--	Yes	Vertical hydraulic conductivity layer 1.
VKA2_1	$8.77x10^{-5}$	--	--	ft/d	VKA1_1	Yes	Vertical hydraulic conductivity layer 2, zone 1.
VKA2_2	3.66	--	--	ft/d	VKA1_1	Yes	Vertical hydraulic conductivity layer 2, zone 2.
VKA2_3	$9.18x10^{-3}$	--	--	ft/d	VKA1_1	Yes	Vertical hydraulic conductivity layer 2, zone 3.
VKA2_4	.101	--	--	ft/d	VKA1_1	Yes	Vertical hydraulic conductivity layer 2, zone 4.
VKA2_5	$1.32x10^{-2}$	--	--	ft/d	VKA1_1	Yes	Vertical hydraulic conductivity layer 2, zone 5.
RECH1	2.91	2.80	3.03	in/yr	--	No	Recharge layer 1.
RECH2	1.45	--	--	in/yr	RECH1	No	Recharge layer 2.
EVTR1	53.02	48.71	57.70	in/yr	--	No	Maximum evapotranspiration rate.
L_WHITE	$8.64x10^{3}$	$1.79x10^{3}$	$4.16x10^{4}$	ft^2/d	--	Yes	Riverbed conductance.
KEYA_PAHA	$4.72x10^{3}$	22.0	$1.01x10^{6}$	ft^2/d	--	Yes	Riverbed conductance.
CUTMEAT	$5.56x10^{2}$	--	--	ft^2/d	L_WHITE	Yes	Riverbed conductance.
MDUZA	$4.01x10^{3}$	--	--	ft^2/d	L_WHITE	Yes	Riverbed conductance.
BLACKPIPE	$1.44x10^{2}$	--	--	ft^2/d	L_WHITE	Yes	Riverbed conductance.
SAND	$4.72x10^{3}$	--	--	ft^2/d	KEYA_PAHA	Yes	Riverbed conductance.
L_WHITE_SP	$1.00x10^{4}$	$2.17x10^{2}$	$4.61x10^{5}$	ft^2/d	--	Yes	Spring conductance.
BLACKP_SP	$9.80x10^{2}$	--	--	ft^2/d	WT_SP	Yes	Spring conductance.
LW1D_SP	$9.75x10^{2}$	--	--	ft^2/d	WT_SP	Yes	Spring conductance.
LW2D_SP	$1.00x10^{3}$	--	--	ft^2/d	WT_SP	Yes	Spring conductance.
LW3D_SP	$1.00x10^{3}$	--	--	ft^2/d	WT_SP	Yes	Spring conductance.
WT_SP	$1.28x10^{3}$	1.14	$1.45x10^{6}$	ft^2/d	--	Yes	Spring conductance.
OAK_SP	$9.80x10^{2}$	--	--	ft^2/d	WT_SP	Yes	Spring conductance.

Table 11. Water budget for steady-state simulation compared with the water budget from Long and others (2003).

[ft^3/s, cubic feet per second; %, percent]

	Flow rate (ft^3/s)	
	2003 model[a]	Revised model (this report)
Inflows		
Storage	0.5	0.2
Constant-head boundary	17.9	12.5
River leakage	2.1	8.1
Recharge	266.2	255.4
Total inflows	286.7	276.1
Outflows		
Storage	0.7	0.2
Constant-head boundary	13.2	9.9
Well withdrawals	11.6	11.6
Springs along northern boundary	.5	1.1
River leakage[b]	78.0	81.4
Evapotranspiration	183.9	171.3
Total outflows	287.9	275.5
Summary		
Inflows minus outflows	-1.2	0.6
Budget descrepancy	-.4%	.2%

[a]Long and others (2003).

[b]Includes spring flow along river banks.

for the steady-state simulation was 12.5 ft^3/s. Discharge rates for the steady-state simulation were 171.3 ft^3/s for evapotranspiration, 74.4 ft^3/s for net outflow (outflow minus inflow) to streams and springs, 11.6 ft^3/s for well withdrawals, and 9.9 ft^3/s as outflow from model constant-head boundaries.

A sensitivity analysis was used to examine the response of the steady-state model to changes in parameter values. During each simulation when a parameter was being tested, the other parameters remained at the steady-state calibrated value. The fractional changes in the objective function values for a 5-percent change in parameter values are shown in figure 19. The model was most sensitive to HK2_3, RECH1, and RECH2 followed by HK1_3, VKA1_1, and EVTR1. In terms of parameter classes, the model was most sensitive to recharge and maximum evapotranspiration rate and least sensitive to riverbed and spring conductances (fig. 20).

This sensitivity analysis was useful for quantifying the sensitivity of each parameter with respect to all other parameters. The information gained from this analysis is limited, however, because it does not take into account parameter sensitivities as they covary with other parameters. Confidence intervals on parameter estimates calculated by PEST take into account these sensitivities as parameters covary (Doherty, 2004) and thus provide an assessment of confidence in the values estimated. Also, high correlation between two parameters indicates parameter sets that when varied in a complementary manner have little effect on the objective function value (Doherty, 2004), and thus highly correlated parameters are not desirable. A matrix of parameter correlation coefficients for the independent parameters shows no highly correlated parameter pairs (correlation coefficient greater than 0.95) with the highest correlation coefficient of 0.64 occurring between RECH1 and VKA1_1 (table 12).

A comparison of estimated K values shows differences between calibration of the model described by Long and others (2003) and the revised model described in this report (table 13). The percent deviation from Long and others (2003) ranged from 0 for several values to more than 900 for one of the vertical K values (table 13). Estimated values with the largest percent change were associated with the small parameter sensitivities (fig. 19), and thus, changes in these parameter values resulted in only minor changes to model outcome. These and other revisions to the model resulted in minor changes to the steady-state water budget (table 11).

Transient Simulation

All parameter estimates from the steady-state calibration except for the time-varying parameters recharge and maximum evapotranspiration rate were applied to the transient model (table 10). Estimated recharge and maximum evapotranspiration rates for the transient model are shown in tables 6 and 2, respectively. Estimated recharge for the Arikaree aquifer was one-half that of the Ogallala aquifer (table 6). Additional adjustments to model parameters were not necessary to achieve acceptable calibration. Calibration criteria for the transient simulation consisted of approximately reproducing the general temporal trends of the hydrographs for the 44 observation wells. No attempt was made to calibrate the transient simulation to match hydraulic heads in the observation wells closer than that required for the steady-state simulation (±50 ft). Therefore, a difference of as much as 50 ft between the observed and simulated well hydrographs was acceptable if the general trends matched reasonably well.

In most cases, the simulated water levels were within 40 ft of observed values, and the general trends in simulated and observed hydraulic heads matched reasonably well with some exceptions (figs. 21 and 22). In some cases, the simulated hydrograph had an upward trend when the observed hydrograph had a downward trend, or the opposite. In other cases, the trends were consistent. Although the simulated hydrograph trends were not always consistent with those observed, the overall variability of simulated hydrographs generally was consistent with the variability of the observed hydrographs, and it is this variability that is of most concern for purposes of simulating the effects of drought or increased pumping. Measured water levels for well RST-19 (fig. 22) declined by about 30 ft in less than 1 year. Because this is unusual for the Ogallala aquifer and is the only well where such a large decline occurred, the data may be in error.

Table 12. Parameter correlation matrix showing correlation coefficients for all parameter pair combinations. (Parameter names defined in table 10).

[--, not included because of redundancy]

Parameter name	L_WHITE_SP	WT_SP	HK1_1	HK1_2	HK1_3	HK1_5	HK2_1	HK2_2	HK2_3	HK2_5	VKA1_1	RECH1	EVTR1	L_WHITE	KEYA_PAHA
L_WHITE_SP	1.00	--	--	--	--	--	--	--	--	--	--	--	--	--	--
WT_SP	-.52	1.00	--	--	--	--	--	--	--	--	--	--	--	--	--
HK1_1	-.07	.02	1.00	--	--	--	--	--	--	--	--	--	--	--	--
HK1_2	-.04	.03	0	1.00	--	--	--	--	--	--	--	--	--	--	--
HK1_3	-.08	.02	.10	.18	1.00	--	--	--	--	--	--	--	--	--	--
HK1_5	-.02	-.01	.04	.20	.32	1.00	--	--	--	--	--	--	--	--	--
HK2_1	.04	-.09	-.10	-.01	.13	.06	1.00	--	--	--	--	--	--	--	--
HK2_2	-.01	.02	.04	.02	.23	.18	.07	1.00	--	--	--	--	--	--	--
HK2_3	-.35	.26	.04	0	-.07	.01	-.01	.01	1.00	--	--	--	--	--	--
HK2_5	.01	.11	.04	.01	.10	-.14	.06	.05	.01	1.00	--	--	--	--	--
VKA1_1	-.07	.12	-.19	.14	-.29	-.03	-.28	-.12	-.07	-.19	1.00	--	--	--	--
RECH1	-.10	.10	-.07	.38	.26	.40	-.11	.18	-.03	-.06	.64	1.00	--	--	--
EVTR1	-.02	.01	0	.06	.06	.08	0	.07	0	.01	.02	.14	1.00	--	--
L_WHITE	.14	.18	.03	-.02	.01	-.01	-.13	.01	.01	.01	-.10	-.07	-.01	1.00	--
KEYA_PAHA	.01	-.77	.02	-.02	.02	.03	.02	-.03	.01	-.15	-.08	-.06	0	.01	1.00

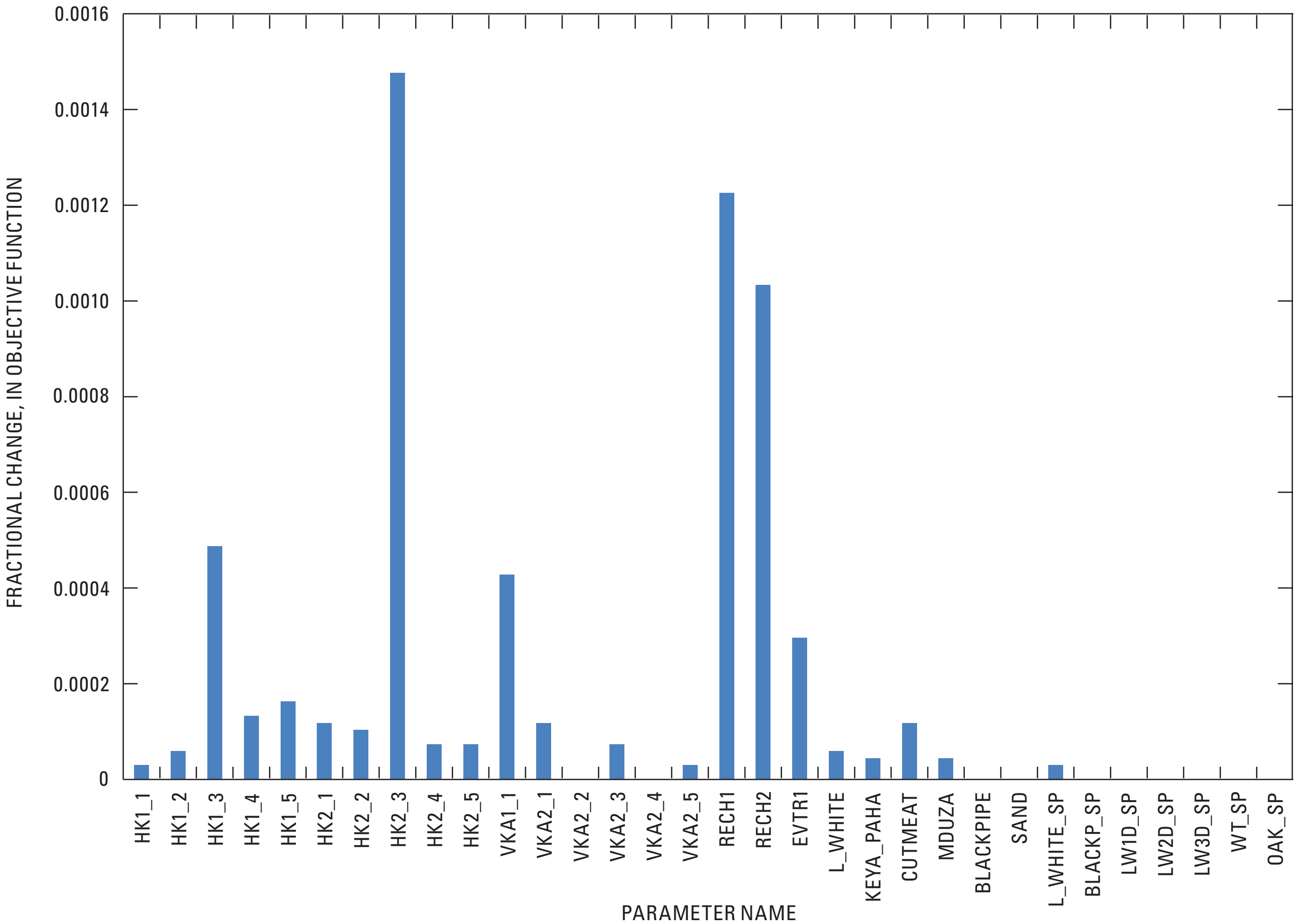


Figure 19. Relative parameter sensitivities as a fractional change in the objective function (sum of the squared weighted residuals) resulting from a 5-percent change in parameter values. (Parameter names defined in table 10).

Simulation of Potential Future Scenarios

Model simulations were conducted to assess ground-water responses to potential future drought and increases in well withdrawals. A synthetic drought simulation recharge record was created that has similar variability to that of the original estimated record (table 6), except that on average, the synthetic drought record was approximately equal to the 30th-percentile recharge rates for each model season of the original record. Random variability was added to this 30th-percentile recharge rate for each season with a maximum possible variability that was similar to that of the original estimated record for each respective season. This resulted in a mean drought recharge rate for the overall record of 1.87 in/yr for the Ogallala aquifer, or 64 percent of the original average recharge rate of 3.91 in/yr. The simulation was executed as a 30-year transient simulation with the first 10 years having the same recharge as in the original record. The synthetic drought record was used for last 20 years of the simulation. Hydro-graphs of the simulated observation wells plotted with results of the non-drought simulation show the effects of this drought scenario for selected sites (fig. 23). The simulated maximum decline in water levels for the 44 observation wells as a result of the drought simulation ranged from about 1 to 16 ft, and about 50 percent of the wells had declines of 8 to 16 ft.

The differences in hydraulic-head values between results of the calibrated model and the drought scenario at the end of the 30-year simulation ranged from 0 to 39 ft for the Ogallala aquifer. The largest differences were in the northwestern part of the model area followed by the center of the model area where many irrigation wells are located. The shift in position of potentiometric contours from those of the calibrated model to those of the drought scenario indicates the differences (fig. 24).

To assess the effects of potential increases in pumping, well withdrawal rates were increased by 50 percent from those listed in table 4 for the last 20 years of record. The first 10 years of record were unchanged from table 4 (fig. 25). The simulated maximum decline in water levels for the 44 observation wells as a result of simulated pumping increases ranged from less than 0.5 to 5 ft. The differences in hydraulic-head values between results of the calibrated model and the increased scenario of pumping at the end of the 30-year simulation ranged from 0 to 13 ft for the Ogallala

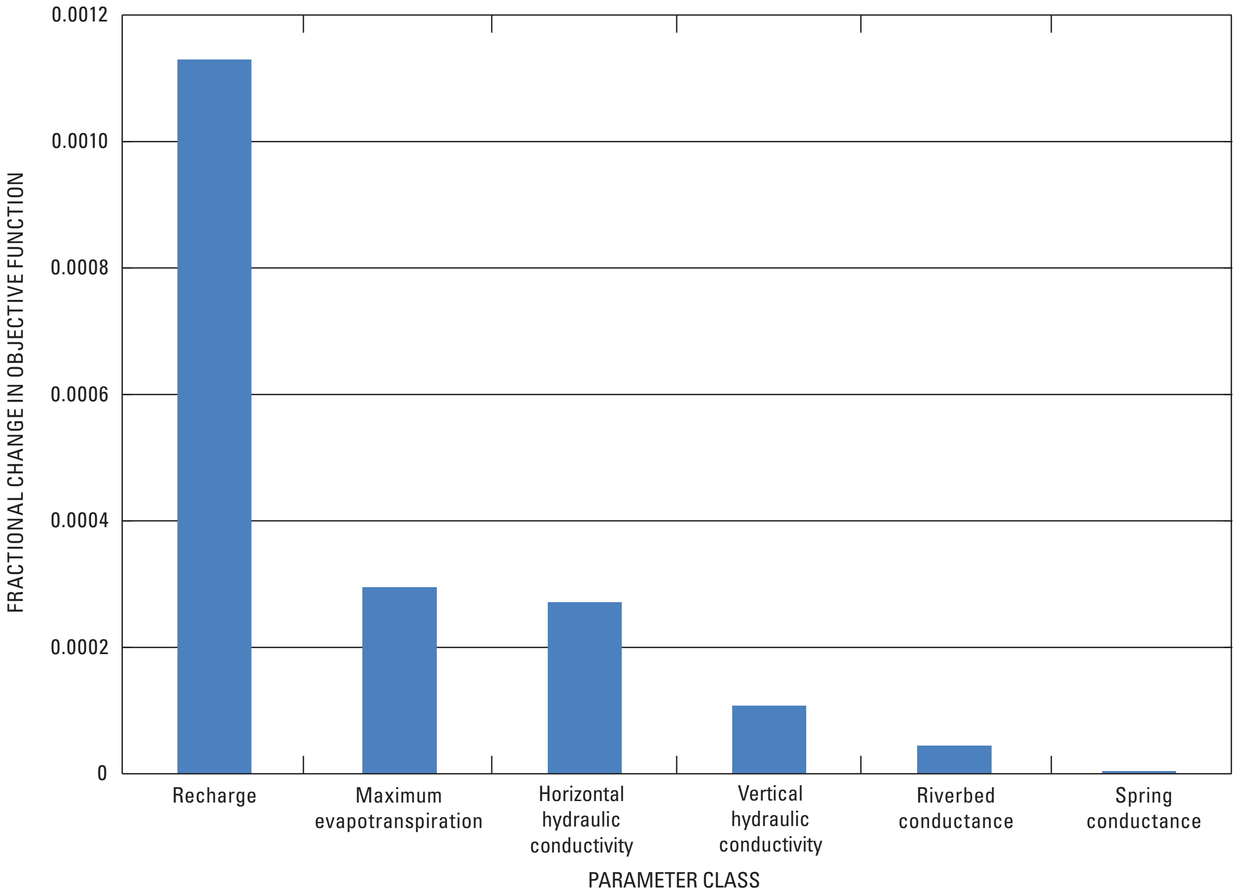


Figure 20. Relative sensitivities of parameter classes as a percent change in the objective function (sum of the squared weighted residuals) resulting from a 5-percent change in parameter values. Sensitivities were calculated as averages of those in figure 19.

aquifer, with the largest differences in the center of the model area where many irrigation wells are located. The shift in position of potentiometric contours from those of the calibrated model to those of the drought scenario are shown in figure 26; the shift generally is only evident in the center of the model area where the largest groundwater withdrawals occur.

Model Limitations

For purposes and objectives of this study, the numerical model adequately simulates flow in the Ogallala and Arikaree aquifers in the study area. However, water managers should be aware of the model's limitations. There are uncertainties in model input parameters, most importantly recharge, evapotranspiration, and horizontal and vertical hydraulic conductivity. Although these parameters had a large influence on model results, extensive field data with respect to these were not available. The objective function possibly could have been reduced more by breaking down further the spatial discretization of some parameters, such as hydraulic conductivity or recharge; however, without additional field data, finer discretization was not justifiable. Combinations of parameter values other than those used in this model also might give satisfactory results, and thus, parameter confidence intervals help to quantify the uncertainty in the final set of estimated parameter values. The use of inverse modeling methods resulted in more objective parameter estimates than did previous trial-and-error methods.

This numerical model is suitable as a tool to help understand the flow system, to help confirm that previous estimates of aquifer properties were reasonable, and to estimate aquifer properties in areas without data. The model also is useful to help assess the effects of drought and increases in pumping by simulations of these scenarios, the results of which are not precise but may be considered when making water management decisions. 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.

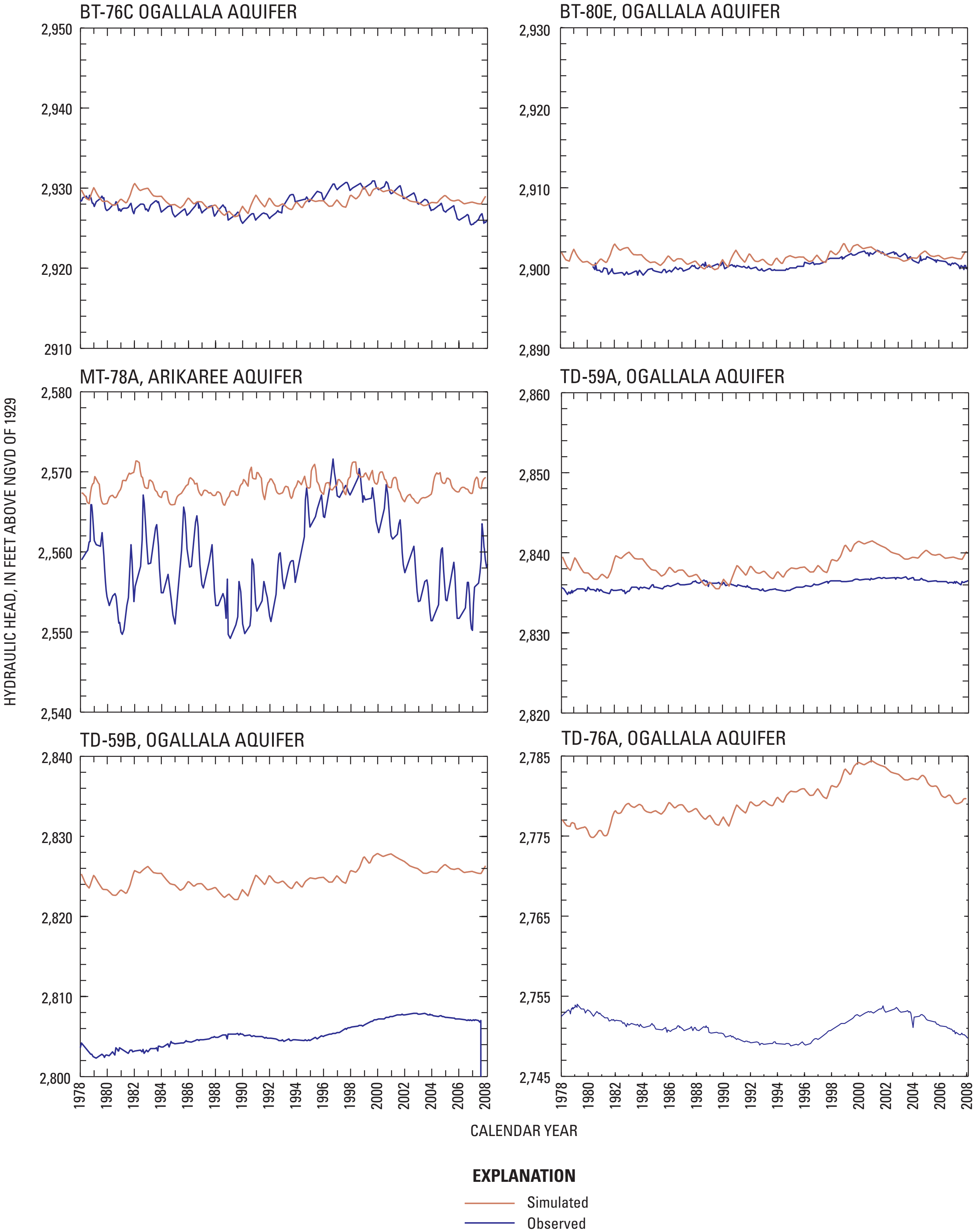


Figure 21. Hydrographs showing simulated and observed data for State observation wells for calibrated transient model.

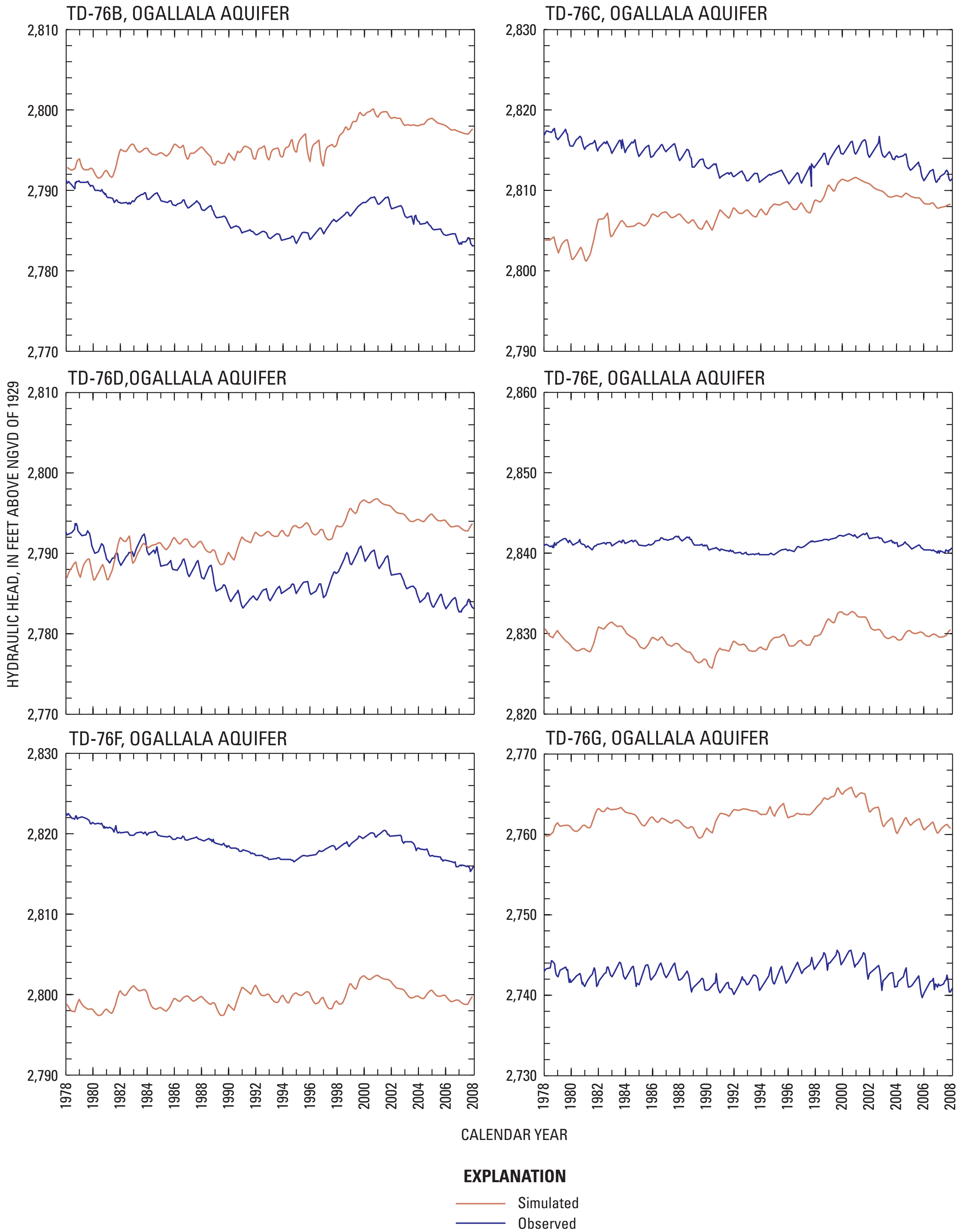


Figure 21. Hydrographs showing simulated and observed data for State observation wells for calibrated transient model.—Continued

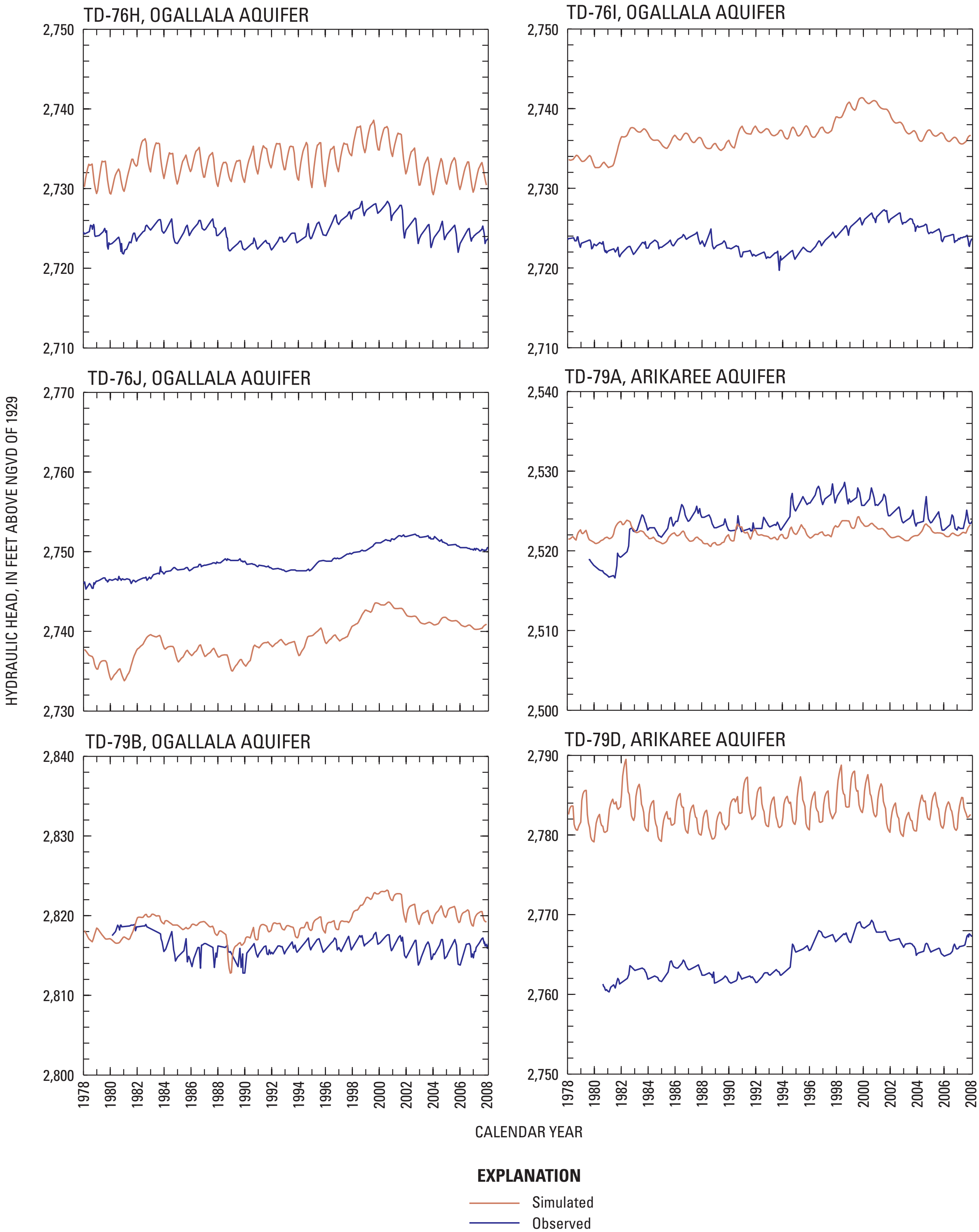


Figure 21. Hydrographs showing simulated and observed data for State observation wells for calibrated transient model.—Continued

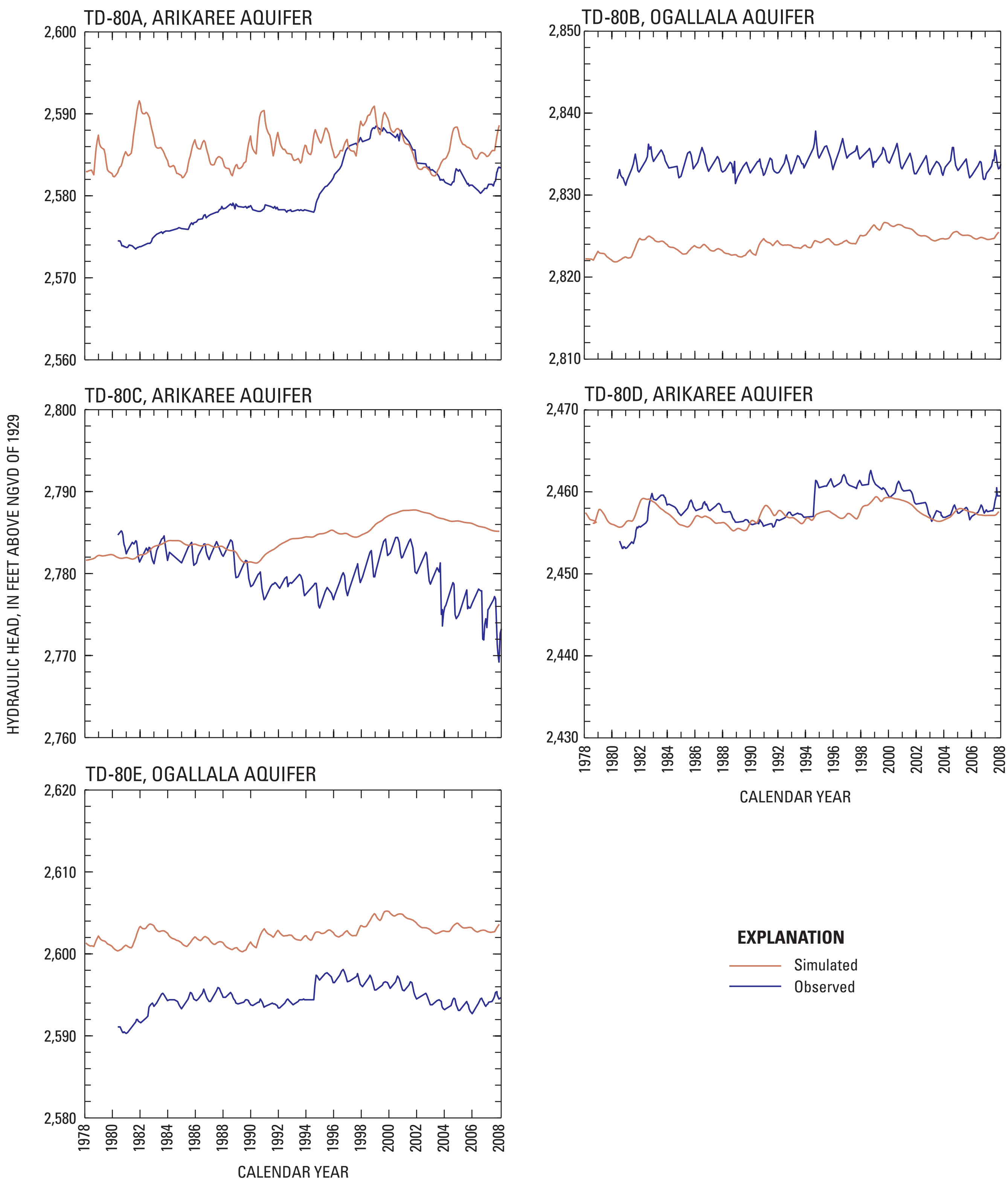


Figure 21. Hydrographs showing simulated and observed data for State observation wells for calibrated transient model.—Continued

Table 13. Comparison of estimated hydraulic conductivity values for the model described by Long and others (2003) and the revised model described in this report.

[--, not applicable]

Zone	2003 model[a]	Revised model described in this report	Deviation from 2003 model as a percentage
Horizontal hydraulic conductivity layer 1			
Zone 1	--	1.3	--
Zone 1	2	5.4	170
Zone 1	20	26.8	34
Zone 2	.2	.2	0
Zone 2	7.6	8.4	11
Zone 2	23	25.1	9
Zone 3	.9	.4	-56
Zone 3	9.3	2.8	-70
Zone 3	46	28.1	-39
Zone 3	120	84.4	-30
Zone 4	2.5	2.5	0
Zone 5	37	13.3	-64
Horizontal hydraulic conductivity layer 2			
Zone 1	5.4	3.8	-30
Zone 2	2.3	2.2	-4
Zone 2	4.7	4.3	-9
Zone 3	1.2	1.2	0
Zone 3	2.4	2.4	0
Zone 3	1.2	.1	-92
Zone 4	.1	.1	0
Zone 5	1.3	1.1	-15
Vertical hydraulic conductivity layer 1			
Zone 1	6.6×10^{-4}	4.2×10^{-4}	-37
Vertical hydraulic conductivity layer 2			
Zone 1	8.6×10^{-6}	8.8×10^{-5}	923
Zone 2	.72	3.7	414
Zone 3	1.8×10^{-3}	9.2×10^{-3}	411
Zone 4	2.0×10^{-2}	.10	400
Zone 5	2.6×10^{-3}	1.3×10^{-2}	400

[a]Long and others (2003).

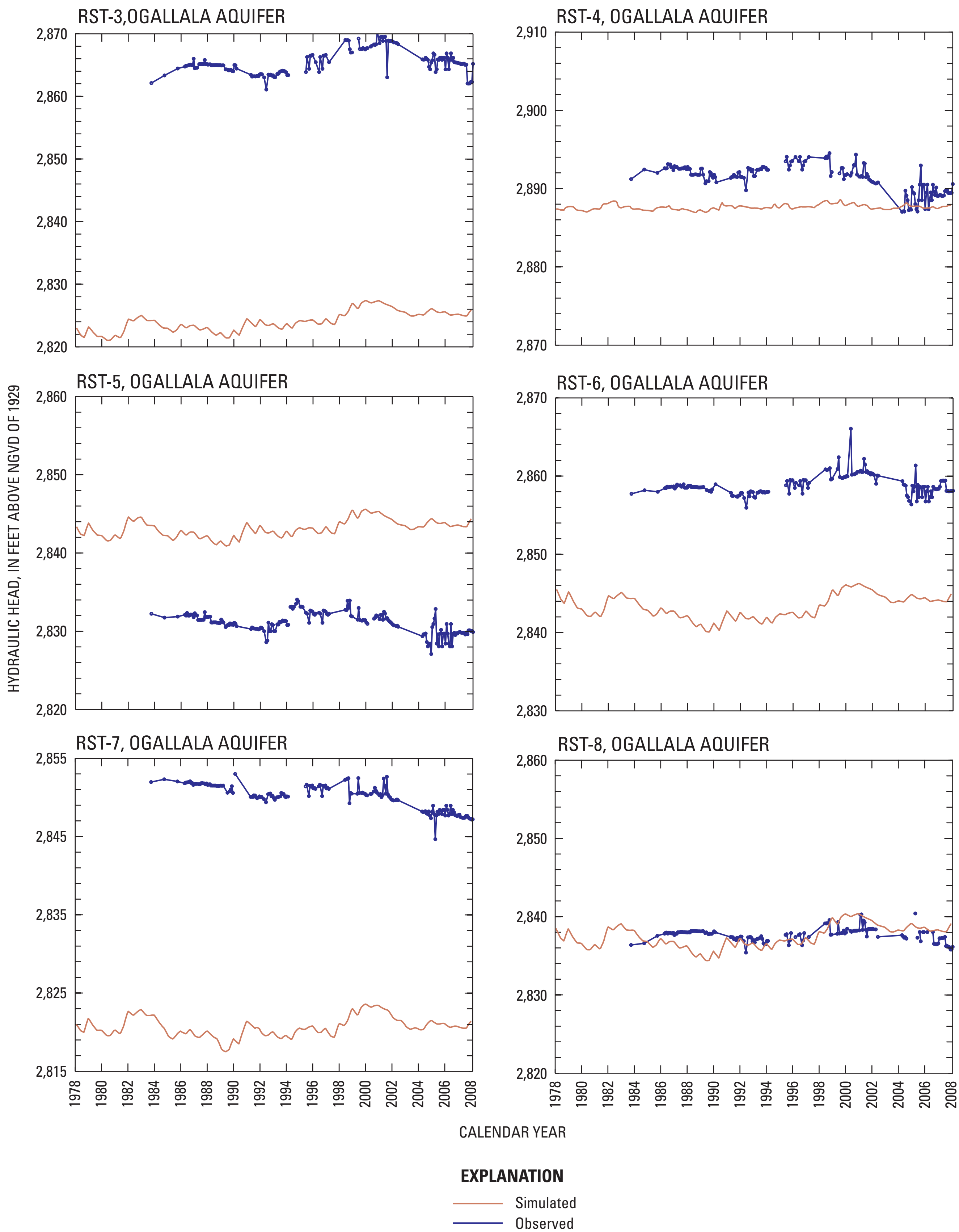


Figure 22. Hydrographs showing simulated and observed data for Tribal observation wells for calibrated transient model.

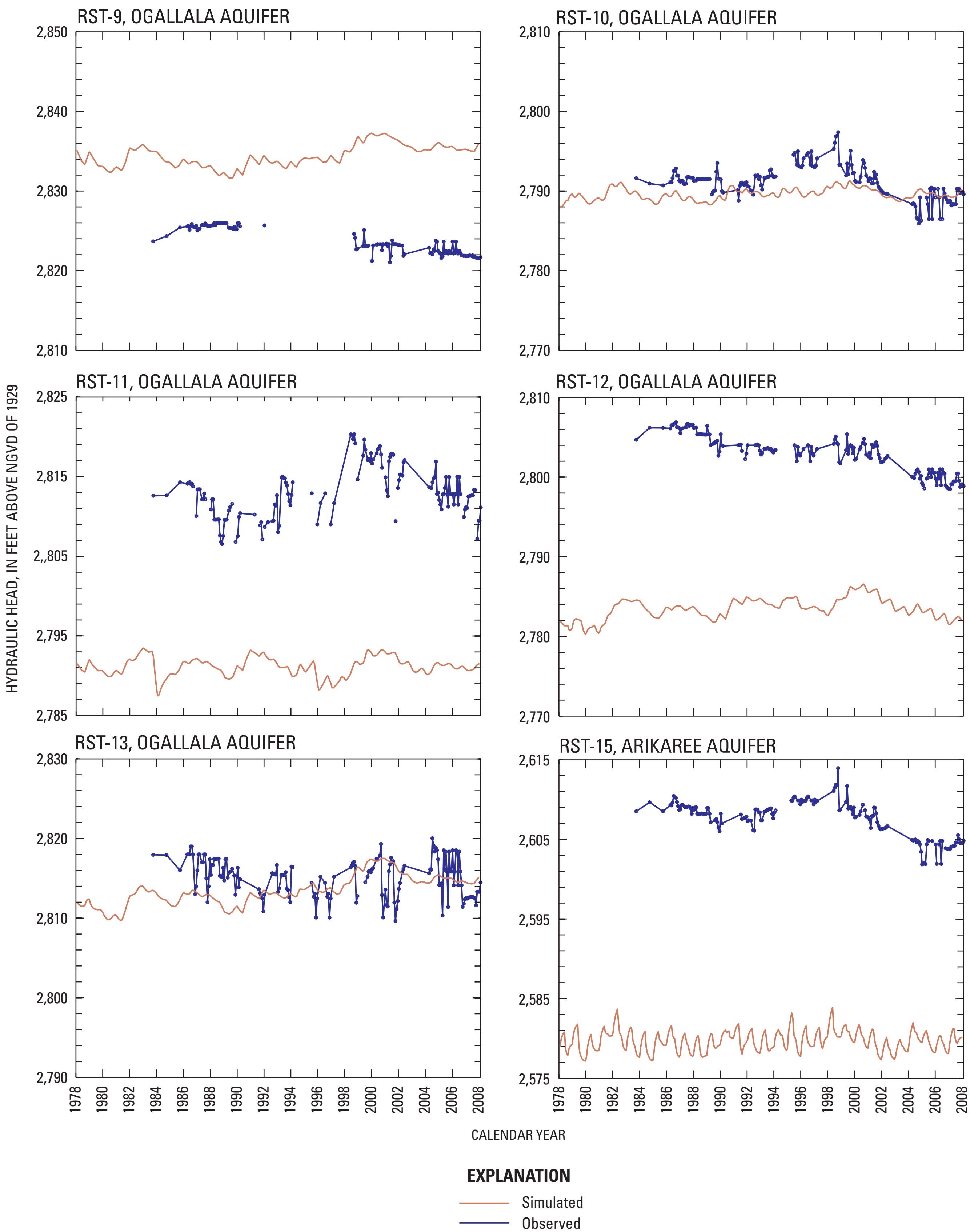


Figure 22. Hydrographs showing simulated and observed data for Tribal observation wells for calibrated transient model.—Continued

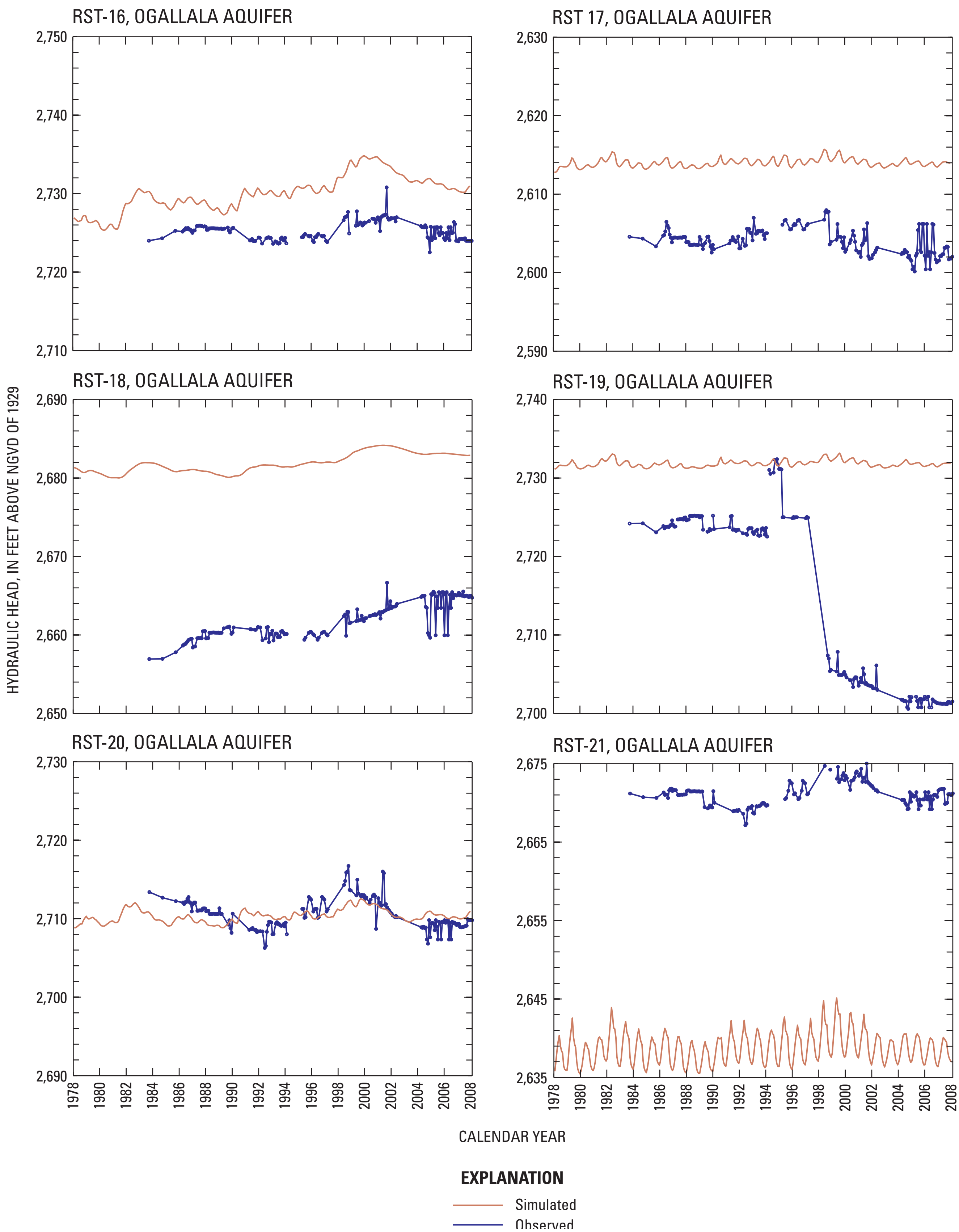


Figure 22. Hydrographs showing simulated and observed data for Tribal observation wells for calibrated transient model.—Continued

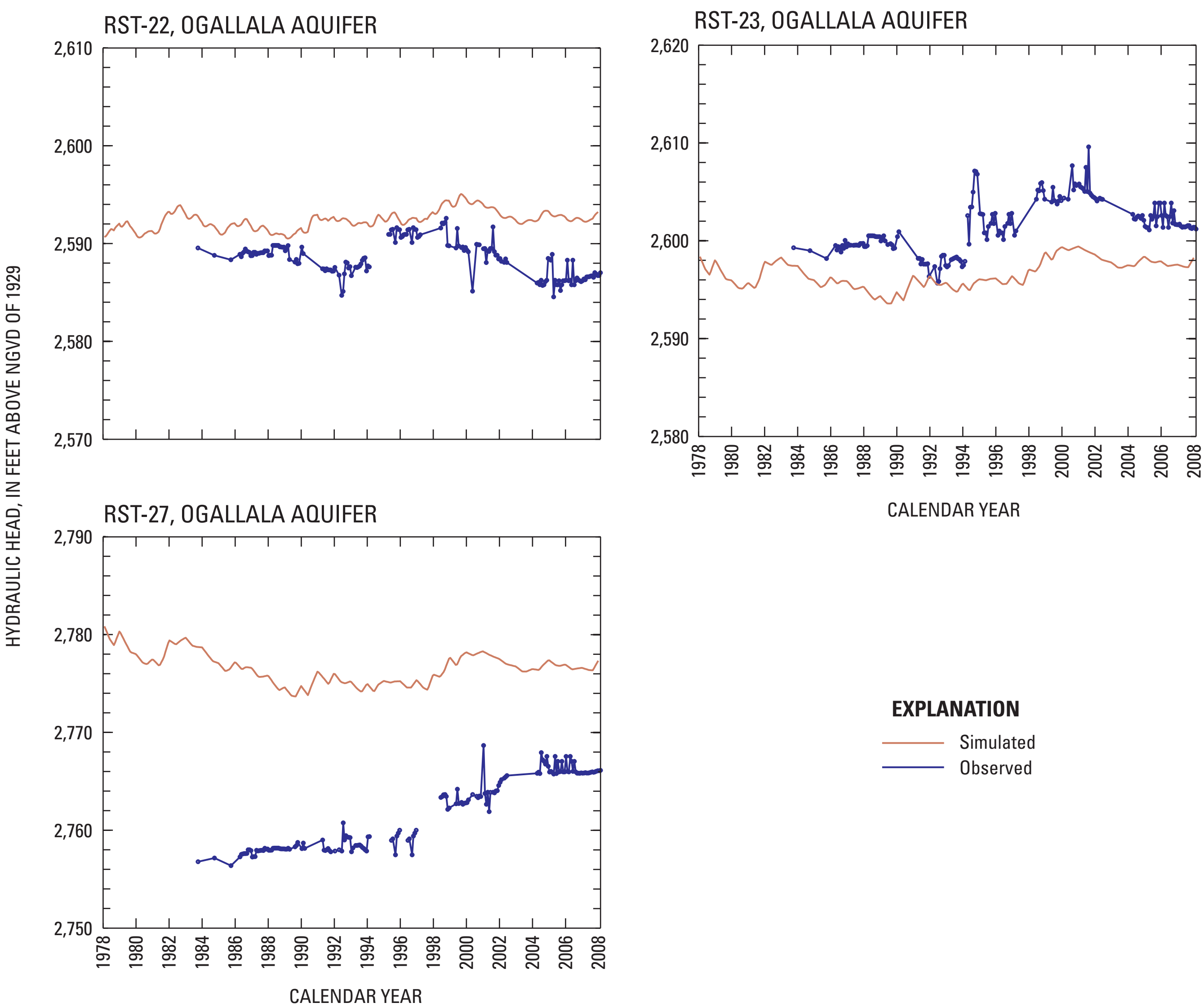


Figure 22. Hydrographs showing simulated and observed data for Tribal observation wells for calibrated transient model.—Continued

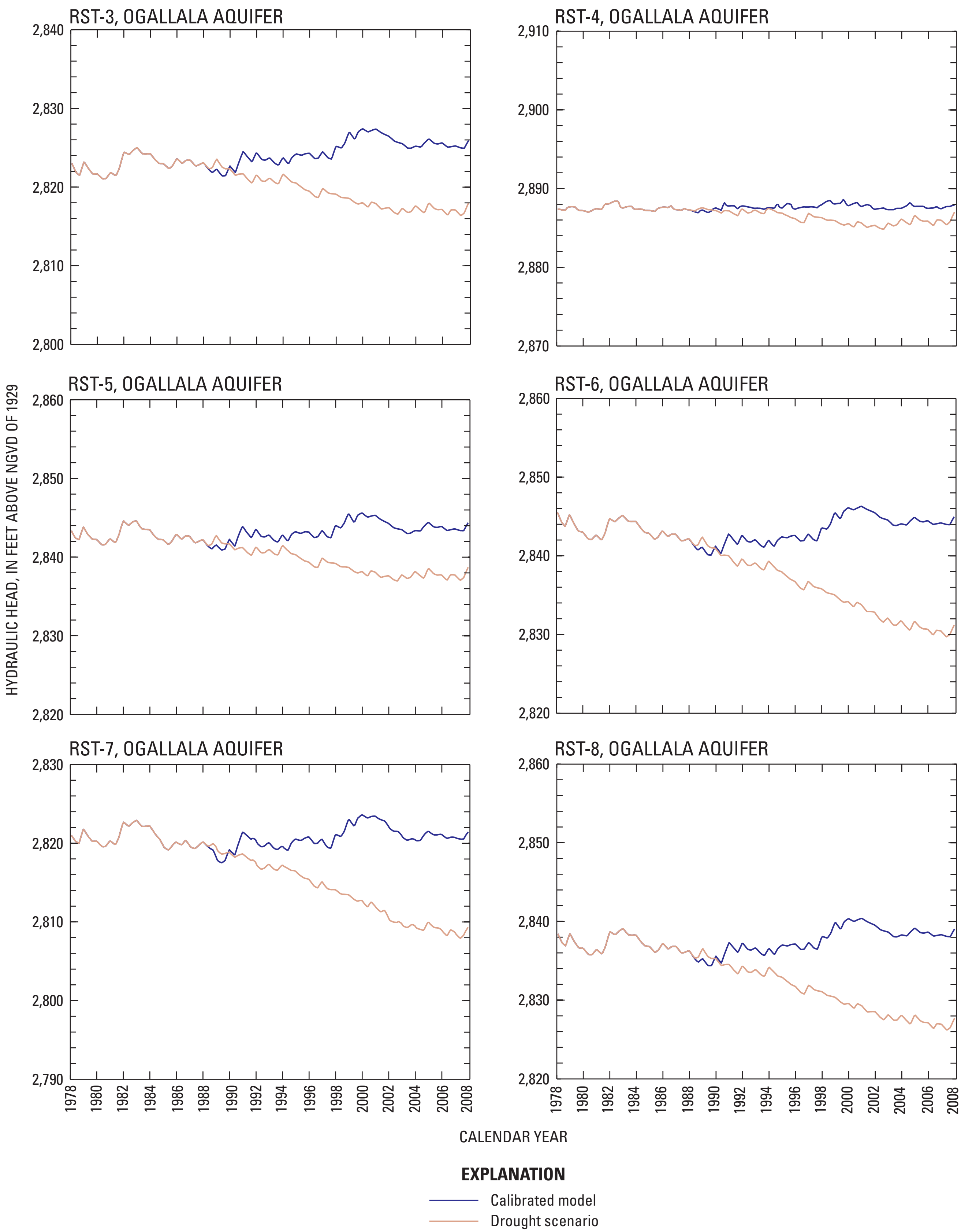


Figure 23. Hydrographs showing the differences of water levels in wells between results of the calibrated model and the assumed potential drought scenario for the 30-year simulation period for selected sites for the Ogallala aquifer.

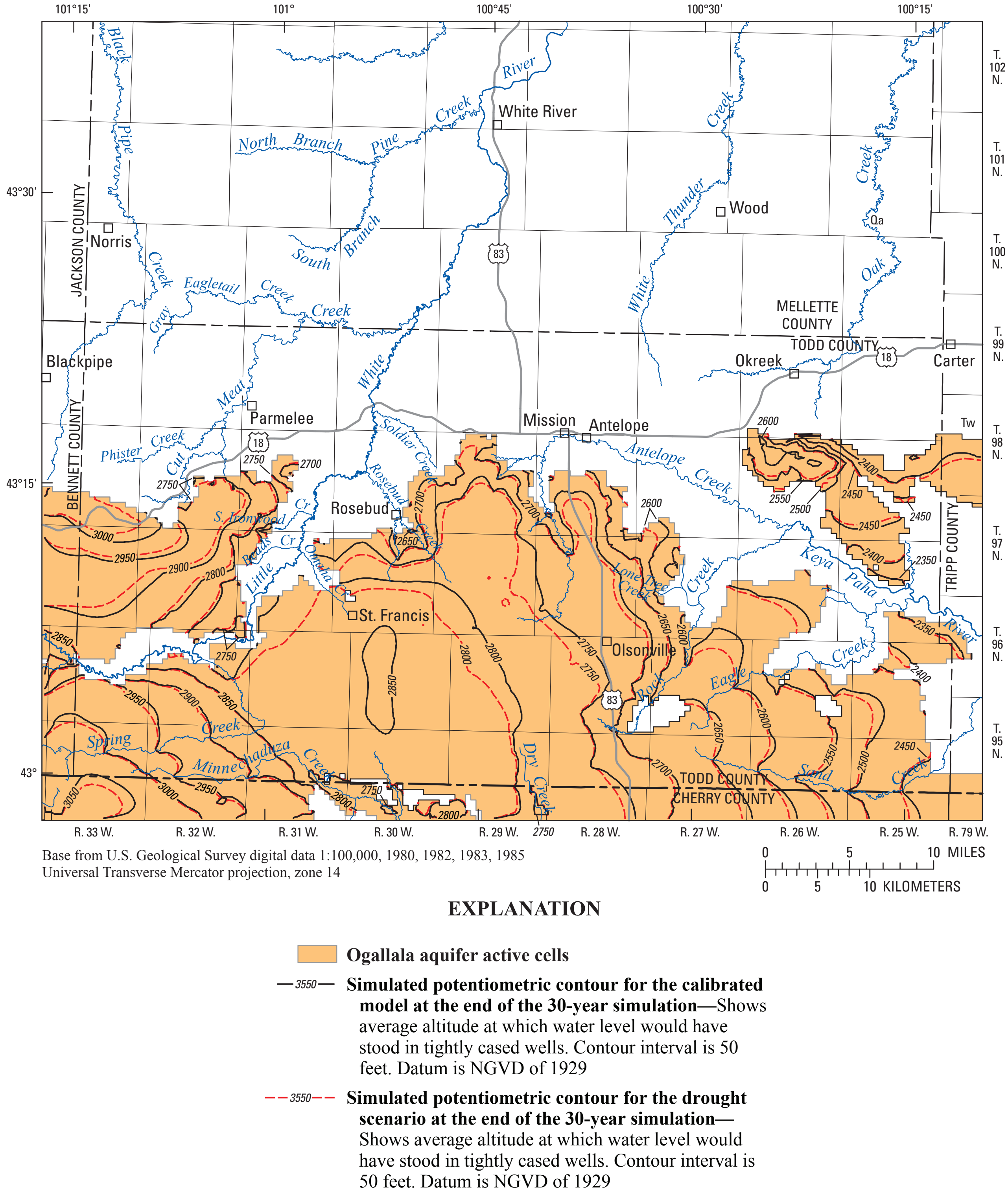


Figure 24. Simulated potentiometric surfaces for the calibrated model and the drought scenario at the end of a 30-year simulation period for the Ogallala aquifer.

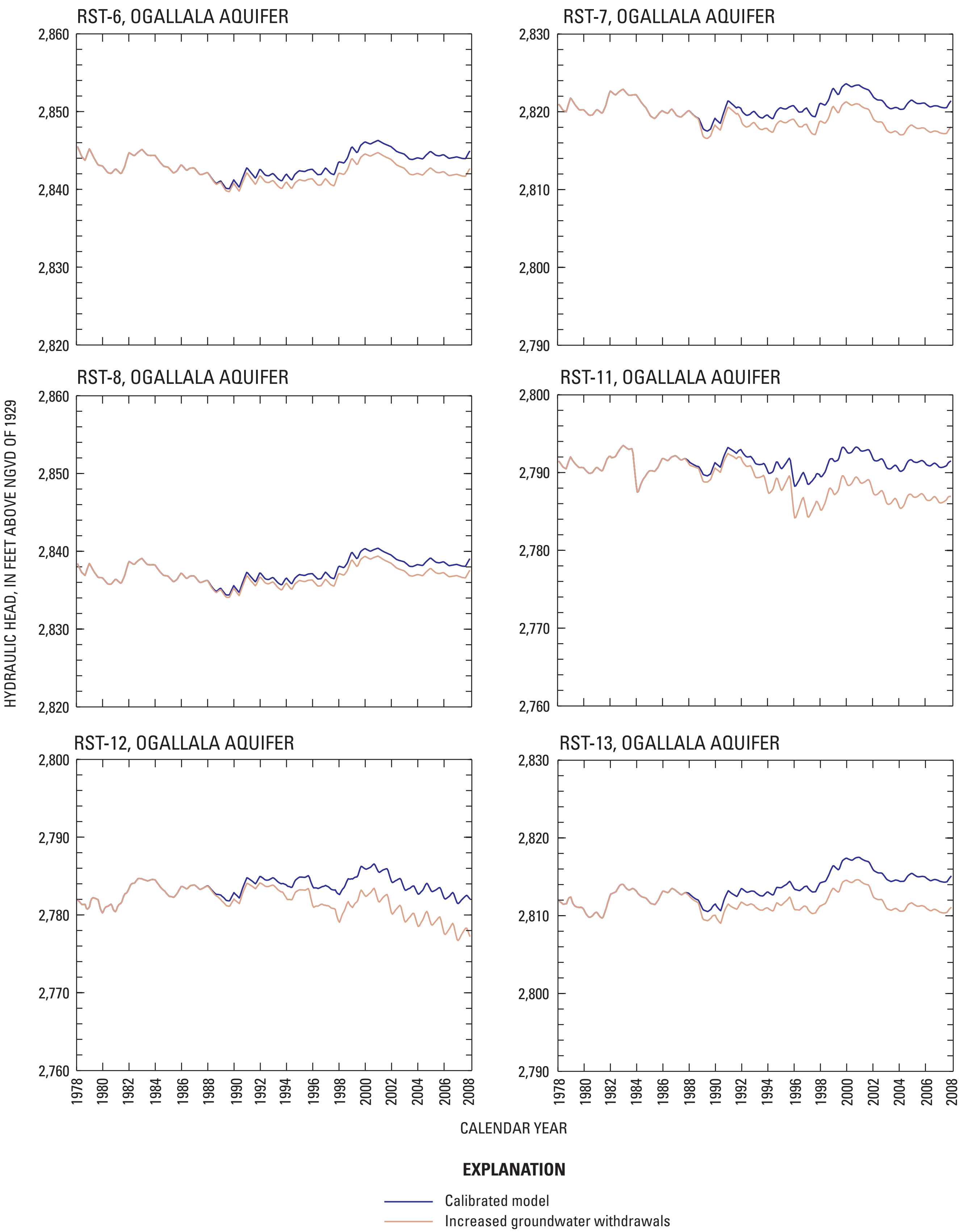
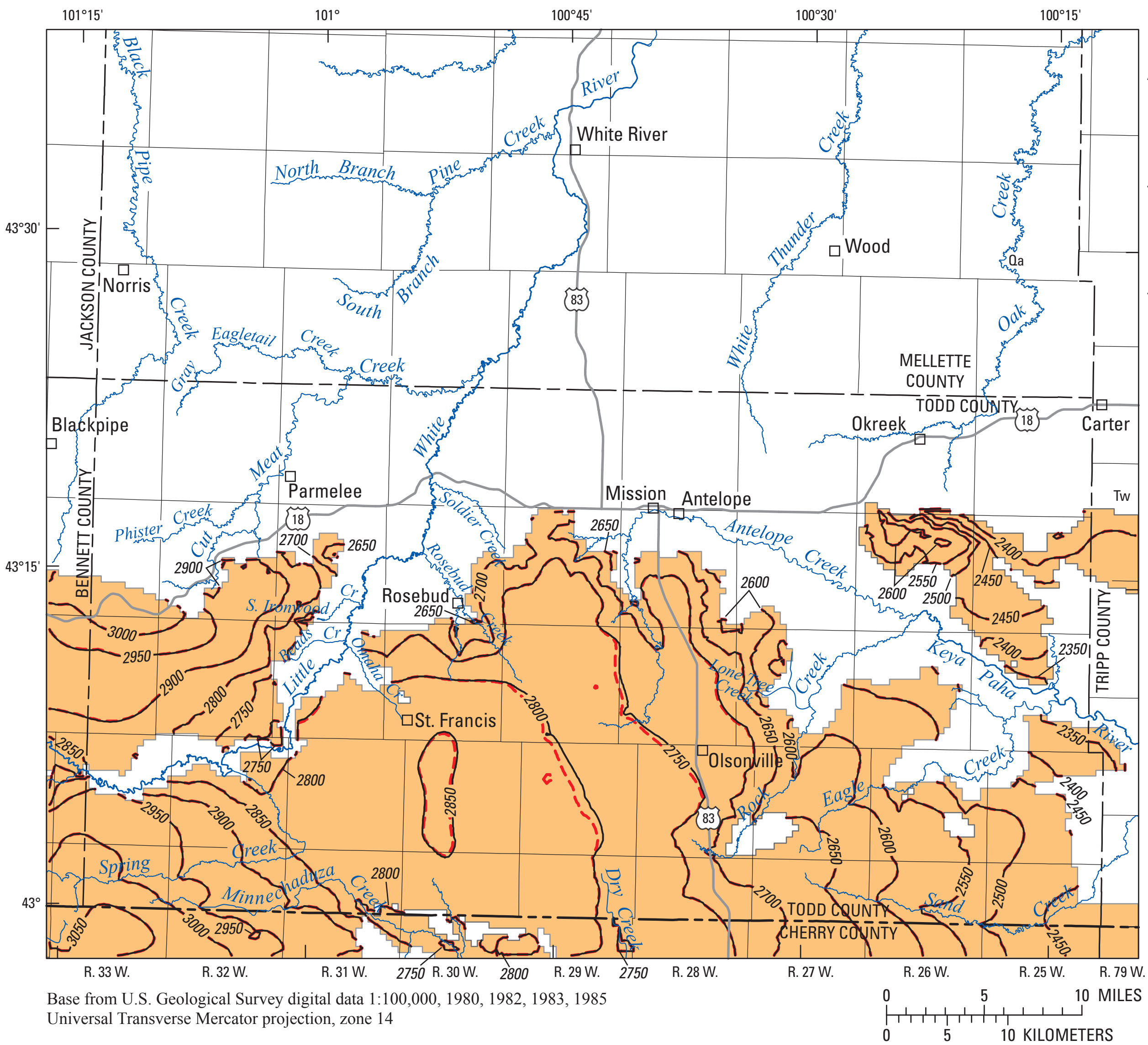


Figure 25. Hydrographs showing the differences in water levels in wells between results of the calibrated model and the scenario of pumping increased by 50 percent for the 30-year simulation period for selected sites for the Ogallala aquifer.



EXPLANATION

Ogallala aquifer active cells

—2800— **Simulated potentiometric contour for the calibrated model at the end of the 30-year simulation**—Shows average altitude at which water level would have stood in tightly cased wells. Contour interval is 50 feet. Datum is NGVD of 1929

– –2850– – **Simulated potentiometric contour for the increased pumping scenario at the end of the 30-year simulation**—Shows average altitude at which water level would have stood in tightly cased wells. Contour interval is 50 feet. Datum is NGVD of 1929

Figure 26. Simulated potentiometric surfaces for the calibrated model and the scenario of pumping increased by 50 percent at the end of a 30-year simulation period for the Ogallala aquifer.

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 assessing the effects of drought and potential increases in groundwater withdrawals. To address this need, the U.S. Geological Survey has worked in cooperation with the Rosebud Sioux Tribe to revise and recalibrate a previously published three-dimensional, numerical groundwater-flow model for this area by using data from October 1978 through September 2008.

The model had two layers to represent the Ogallala and Arikaree aquifers. The model grid had 168 rows and 202 columns, most of which were 1,640 feet (500 meters) wide, with narrower rows and columns near large water-supply wells. Data for a 30-year period (water years 1979 through 2008) were used in steady-state and transient numerical simulations of groundwater flow. Revisions to the model include (1) extension of the transient calibration period by 10 years, (2) the use of inverse modeling for steady-state calibration, (3) model calibration to base flow for an additional four surface-water drainage basins, (4) improved estimation of transient aquifer recharge, (5) improved delineation of vegetation types, and (6) reduced cell size near large capacity water-supply wells. In addition, potential future scenarios were simulated to assess the potential effects of drought and increased groundwater withdrawals.

Recharge to the Ogallala and Arikaree aquifers occurs from precipitation on the outcrop areas, and regional flow enters the study area from the west. Groundwater originating from precipitation 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 springs, and well withdrawals. Well withdrawals in the study area are for irrigation, municipal, domestic, and stock use, the largest of which is for irrigation. Evapotranspiration generally occurs in topographically low areas and along streams. Maximum evapotranspiration occurs only when the water level is at the land surface.

Multiple streamflow measurements were made in the study area to obtain information describing stream base flow. Average base flow was estimated for six surface-water drainage basins in the study area, including the Little White and Keya Paha Rivers, which were estimated to have average base flows of 49 and 23 cubic feet per second, respectively. The four smaller drainage basins (Cut Meat Creek, Black Pipe Creek, Minnechaduza Creek, and Sand Creek) were estimated to have a total average base flow of 9.8 cubic feet per second. These estimates are inclusive of spring flow along stream banks.

Average inflow and outflow rates for water years 1979–2008 were used in the steady-state simulation, whereas the time-varying rates were used in the transient simulation. The steady-state model was calibrated to average water levels in 383 wells and estimated average base-flow rates for 6 surface-water drainage basins. Inverse modeling techniques were used for steady-state model calibration. These methods were designed to estimate parameter values that are, statistically, the most likely set of values to result in the smallest overall differences between simulated and observed hydraulic heads and base-flow discharges. Parameters estimated by this method were hydraulic conductivity, recharge, maximum evapotranspiration, riverbed conductance, and spring conductance.

The average recharge rates used for the steady-state simulation were 2.91 and 1.45 inches per year applied to outcrops of the Ogallala and Arikaree aquifers, respectively, for a total rate of 255.4 cubic feet per second. Total inflow from model boundaries for the steady-state simulation was 12.5 cubic feet per second. Discharge rates in cubic feet per second for the steady-state simulation were 171.3 for evapotranspiration, 74.4 for net outflow to streams and springs, 11.6 for well withdrawals, and 9.9 as outflow from model boundaries. Estimated horizontal hydraulic conductivity used for the numerical model ranged from 0.2 to 84.4 feet per day for the Ogallala aquifer and 0.1 to 4.3 feet per day for the Arikaree aquifer. A uniform vertical hydraulic conductivity value of 4.2×10^{-4} feet per day was estimated for the Ogallala aquifer. Vertical hydraulic conductivity was estimated for five zones in the Arikaree aquifer and ranged from 8.8×10^{-5} to 3.7 feet per day.

For the steady-state simulation, the root mean square error for simulated hydraulic heads for all wells was 27.3 feet. Simulated hydraulic heads were within ±50 feet of observed values for 93 percent of the 383 wells. For the transient simulation, the difference between the simulated and observed means for hydrographs was within ±40 feet for 98 percent of 44 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 parameter values. The model was most sensitive to recharge and maximum evapotranspiration and least sensitive to riverbed and spring conductances.

To simulate a potential future drought scenario, a synthetic recharge record was created, the mean of which was equal to 64 percent of the average estimated recharge rate for the 30-year calibration period. This synthetic recharge record was used to simulate the last 20 years of the calibration period under drought conditions. Compared with results of the calibrated model, decreases in hydraulic-head values for the drought scenario at the end of the simulation period were as much as 39 feet for the Ogallala aquifer. To simulate the effects of potential increases in pumping, well withdrawal rates were increased by 50 percent from those estimated for the 30-year calibration period for the last 20 years of the calibration period. Compared with results of the calibrated model, decreases in hydraulic-head values for the scenario of increased pumping at the end of the simulation period were as much as 13 feet for the Ogallala aquifer.

This numerical model is suitable as a tool to help understand the flow system, to help confirm that previous estimates of aquifer properties were reasonable, and to estimate aquifer properties in areas without data. The model also is useful to help assess the effects of drought and increases in pumping by simulations of these scenarios, the results of which are not precise but may be considered when making water management decisions. Limitations of the model should be taken into account when applying the model to water management.

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Appendix 1

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
430239100174301	35N25W 5BBAA	Ogallala	2,518	72	2,510	--
430200100164801	35N25W 5DDD	Ogallala	2,501	100	2,496	--
430242100184801	35N25W 6BBA	Arikaree	2,525	100	2,513	--
430151100173901	35N25W 8BB	Ogallala	2,513	90	2,496	--
430023100115602	35N25W13DADD2	Ogallala	2,443	160	2,434	--
430002100174801	35N25W20BBBC	Ogallala	2,493	47	2,489	--
430003100174802	35N25W20BBBC3	Arikaree	2,493	120	2,488	--
430204100212001	35N26W 3DDAB	Arikaree	2,617	120	2,593	--
430237100241201	35N26W 5BA	Ogallala	2,635	70	2,603	--
430216100252101	35N26W 6DBBA	Arikaree	2,620	132	2,558	--
430127100230601	35N26W 9BDAD	Arikaree	2,585	100	2,558	--
430126100222001	35N26W10CBBA2	Ogallala	2,618	82	2,573	--
430126100221901	35N26W10CBBA3	Arikaree	2,617	492	2,569	--
430033100203001	35N26W14DB	Ogallala	2,530	28	2,520	--
430040100233901	35N26W17DAB	Ogallala	2,583	60	2,576	--
430033100234902	35N26W17DAB2	Arikaree	2,583	103	2,565	--
430006100254301	35N26W19BBAC	Ogallala	2,660	100	2,623	--
430236100274201	35N27W 2ABCC	Ogallala	2,700	90	2,628	--
430215100273301	35N27W 2DBCC	Ogallala	2,695	--	2,658	--
430245100292801	35N27W 3BBBB	Ogallala	2,671	47	2,660	--
430245100292701	35N27W 3BBBB4	Arikaree	2,671	202	2,660	--
430230100320301	35N27W 6AAC	Ogallala	2,710	--	2,679	--
430121100323001	35N27W 7CACB	Ogallala	2,724	120	2,698	--
430115100322101	35N27W 7DACC	Ogallala	2,731	120	2,705	--
430119100291801	35N27W10CBBB	Ogallala	2,717	100	2,686	--
430103100280601	35N27W11CCDC	Ogallala	2,682	120	2,651	--
430106100271403	35N27W11DD	Ogallala	2,637	80	2,623	--
430106100271402	35N27W11DD2	Arikaree	2,637	120	2,611	--
430139100264401	35N27W12B	Ogallala	2,636	85	2,619	--
430057100275401	35N27W14BAAB	Ogallala	2,690	84	2,671	RST-21
430022100270901	35N27W14DAA	Ogallala	2,676	50	2,666	--
430039100301001	35N27W16BD	Ogallala	2,695	55	2,678	--
430039100320801	35N27W18A	Ogallala	2,725	55	2,709	--
430000100285401	35N27W22ABBC	Arikaree	2,679	75	2,668	--
430154100332601	35N28W 1DC	Arikaree	2,683	100	2,673	--
430217100370801	35N28W 4ACCB	Arikaree	2,753	140	2,719	--
430122100344501	35N28W11DBBB	Ogallala	2,728	94	2,711	RST-20
430613100352901	35N28W14AAAA	Arikaree	2,735	120	2,722	--
430055100362702	35N28W15BBBD2	Ogallala	2,754	76	2,744	--
430154100411801	35N29W 2DDDD	Ogallala	2,800	44	2,792	RST-10
430156100411901	35N29W 2DDDD2	Ogallala	2,800	37	2,791	--
430238100434801	35N29W 4AA	Ogallala	2,830	50	2,810	--
430226100445201	35N29W 4BCCB	Arikaree	2,845	113	2,832	--

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.—Continued

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
430226100445203	35N29W 4BCCB3	Ogallala	2,845	27	2,829	--
430225100445401	35N29W 5DDDA	Arikaree	2,880	135	2,783	--
430148100471001	35N29W 7BBBB	Ogallala	2,903	83	2,837	TD-59A
430151100415402	35N29W11ABBB2	Ogallala	2,800	110	2,780	--
430048100450201	35N29W17AACD	Arikaree	2,913	190	2,831	--
430014100445401	35N29W17DDDA	Arikaree	2,878	140	2,851	--
430100100460501	35N29W18AAAA	Ogallala	2,870	84	2,831	RST-9
425957100445601	35N29W20AADD	Ogallala	2,890	128	2,804	TD-59B
430212100524001	35N30W 5CA	Ogallala	2,828	105	2,809	--
430153100521303	35N30W 5DDCC3	Ogallala	2,842	108	2,822	--
430217100535201	35N30W 6CABA	Ogallala	2,873	105	2,834	--
430159100531001	35N30W 6DDDD	Ogallala	2,853	84	2,832	RST-5
430113100491601	35N30W11C	Arikaree	2,910	260	2,824	--
430139100474801	35N30W12ACBB	Ogallala	2,935	160	2,875	--
430037100471601	35N30W13ADD	Ogallala	2,895	140	2,785	--
430045100495701	35N30W15ACA	Ogallala	2,880	125	2,850	--
430231100591501	35N31W 5AACC	Ogallala	2,865	70	2,850	--
430142100580301	35N31W 9AACD	Arikaree	2,840	120	2,812	--
430120100574901	35N31W10CBBC	Ogallala	2,823	57	2,818	--
430021100543301	35N31W13D	Arikaree	2,840	125	2,783	--
430042100565801	35N31W15ACA	Ogallala	2,822	75	2,815	--
430017100595101	35N31W17CCDA	Ogallala	2,896	62	2,893	RST-4
430113101062401	35N32W 8D	Ogallala	2,980	80	2,975	--
430152101054803	35N32W 9BABB3	Ogallala	2,935	67	2,928	--
430153101054902	35N32W 9BABB5	Arikaree	2,938	452	2,931	--
430047101025001	35N32W14A	Ogallala	2,982	105	2,913	--
430028101111701	35N33W15DB	Ogallala	3,060	90	3,035	--
425956101134503	35N33W20ABCC3	Ogallala	3,050	165	3,032	--
430727100170304	36N25W 5DBD	Arikaree	2,440	45	2,428	--
430704100145901	36N25W10BABB	Ogallala	2,442	30	2,421	--
430348100172001	36N25W29CDAC	Ogallala	2,573	120	2,526	--
430326100185001	36N25W31ABC	Arikaree	2,597	100	2,550	--
430315100184301	36N25W31BDCB	Ogallala	2,552	70	2,530	--
430331100153301	36N25W33AA	Ogallala	2,585	70	2,514	--
430700100225701	36N26W 9AB	Arikaree	2,505	120	2,498	--
430607100212101	36N26W15AAAB	Arikaree	2,505	100	2,448	--
430528100242001	36N26W17CDD	Arikaree	2,554	50	2,534	--
430454100255101	36N26W19BBC	Ogallala	2,650	120	2,608	--
430455100241301	36N26W20CAD	Arikaree	2,537	140	2,525	--
430515100225001	36N26W21AAB	Ogallala	2,585	120	2,543	--
430424100214301	36N26W27ABBB	Arikaree	2,588	130	2,546	--
430310100245501	36N26W31ADDD	Ogallala	2,620	125	2,594	TD-80E
430335100241401	36N26W32BBAA	Ogallala	2,619	78	2,589	RST-22

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.—Continued

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
430246100222302	36N26W34CCC2	Ogallala	2,634	110	2,607	--
430727100262801	36N27W 1	Arikaree	2,650	128	2,597	--
430728100135801	36N27W 1BDDD	Ogallala	2,627	58	2,600	RST-23
430721100290001	36N27W 3CA	Ogallala	2,663	150	2,602	--
430705100304701	36N27W 5DDD	Ogallala	2,600	120	2,579	--
430512100291801	36N27W15CC	Ogallala	2,698	150	2,622	--
430458100300901	36N27W21BDDB	Ogallala	2,664	90	2,613	--
430451100290001	36N27W22CDBA	Arikaree	2,638	75	2,628	--
430410100261701	36N27W25ADBB	Arikaree	2,658	205	2,614	--
430412100323001	36N27W30BDA	Arikaree	2,693	140	2,673	--
430245100272401	36N27W35DCD	Arikaree	2,673	144	2,647	--
430737100350602	36N28W 2BDAC2	Ogallala	2,773	167	2,677	--
430719101380501	36N28W 5DACC	Ogallala	2,818	140	2,783	--
430604100390801	36N28W 7DDB	Ogallala	2,829	214	2,793	--
430649100364801	36N28W 9ADDA	Ogallala	2,805	70	2,764	--
430701100363001	36N28W10BBBB	Ogallala	2,823	183	2,750	TD-76J
430700100344501	36N28W11ABB	Ogallala	2,807	140	2,707	--
430702100330501	36N28W12AABA	Ogallala	2,806	215	2,660	RST-18
430618100330301	36N28W12DD	Ogallala	2,675	20	2,669	--
430614100362503	36N28W15BABB3	Ogallala	2,778	75	2,753	--
430601100364501	36N28W16ABCA	Ogallala	2,805	40	2,779	--
430454100341801	36N28W23DAAC	Arikaree	2,730	120	2,712	--
430515100331201	36N28W24AAA	Ogallala	2,685	140	2,665	--
430448100332401	36N28W24ACA	Arikaree	2,655	40	2,645	--
430406100380701	36N28W29ACDC	Ogallala	2,771	40	2,756	--
430403100395001	36N28W30BCDD	Ogallala	2,820	100	2,801	--
430348100390401	36N28W30DDAB	Ogallala	2,792	100	2,773	--
430314100392301	36N28W31ACDC	Ogallala	2,839	95	2,819	--
430243100371701	36N28W33BDDD	Ogallala	2,753	75	2,723	RST-19
430712100421301	36N29W 2CDCC	Ogallala	2,850	200	2,804	RST-12
430714100445001	36N29W 4CCBC	Ogallala	2,853	150	2,816	--
430624100461601	36N29W 7DDB	Ogallala	2,925	190	2,890	--
430659100434901	36N29W 9AA	Ogallala	2,845	200	2,778	--
430629100434401	36N29W 9DAD	Ogallala	2,885	209	2,817	--
430530100422501	36N29W14CDAB	Ogallala	2,893	200	2,811	RST-11
430522100411902	36N29W14DDDD2	Ogallala	2,884	225	2,815	--
430558100430301	36N29W15ACBB	Ogallala	2,884	160	2,866	--
430609100434201	36N29W16AAAA	Ogallala	2,863	222	2,822	TD-76F
430604100445201	36N29W17AADD R	Ogallala	2,905	243	2,823	--
430603100460501	36N29W18AADD	Ogallala	2,940	123	2,850	--
430450100453701	36N29W20CA	Ogallala	2,868	140	2,845	--
430508100431901	36N29W22BBDD	Ogallala	2,911	230	2,831	--
430415100451401	36N29W29ACAA	Ogallala	2,870	134	2,851	RST-7

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.—Continued

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
430305100455401	36N29W32CB	Ogallala	2,835	60	2,823	--
430252100431301	36N29W34CD	Ogallala	2,804	100	2,794	--
430302100412001	36N29W35DAD	Ogallala	2,834	45	2,819	--
430723100512101	36N30W 4DBCB	Ogallala	2,978	235	2,872	--
430627100532601	36N30W 7D	Arikaree	2,960	187	2,856	--
430652100484001	36N30W11ADBB	Ogallala	2,949	300	2,851	--
430615100472701	36N30W12DDCD	Ogallala	2,960	285	2,827	--
430610100481701	36N30W13BBBB	Ogallala	2,916	225	2,843	TD-76E
430518100533701	36N30W19ABB	Ogallala	2,902	145	2,855	--
430501100504901	36N30W22CBBB	Ogallala	2,888	137	2,858	RST-6
430507100483701	36N30W23ADBB	Ogallala	2,934	217	2,848	--
430342100482901	36N30W26DDDB	Ogallala	2,851	50	2,832	--
430250100532701	36N30W31DCDA	Ogallala	2,868	50	2,849	--
430327100512301	36N30W33BADD	Ogallala	2,945	180	2,854	--
430334100515201	36N30W33BBB	Ogallala	2,896	110	2,843	--
430254100515001	36N30W33CCBD	Ogallala	2,879	50	2,856	--
430301100492101	36N30W35CBCC	Arikaree	2,917	179	2,843	--
430258100471401	36N30W36DDDA	Ogallala	2,885	123	2,836	RST-8
430721100563001	36N31W 2CBCD	Ogallala	2,934	200	2,785	--
430630100565401	36N31W10DACD3	Arikaree	2,958	305	2,736	--
430613100544901	36N31W12DCCD	Arikaree	2,899	194	2,843	--
430613101561701	36N31W14BAAA	Ogallala	2,955	160	2,816	TD-79B
430541100555501	36N31W14DB	Ogallala	2,970	140	2,871	--
430555100570301	36N31W15ACAC	Ogallala	3,005	310	2,916	--
430603101003401	36N31W18ABDD	Ogallala	2,877	98	2,839	--
430309100570901	36N31W34DBBC	Ogallala	2,920	91	2,865	RST-3
430650101021001	36N32W 1DCDC	Arikaree	2,623	60	2,614	--
430721101032801	36N32W 2C	Arikaree	2,660	180	2,667	--
430712101042801	36N32W 3CD	Arikaree	2,686	118	2,631	--
430619101020501	36N32W12CD2	Arikaree	2,895	335	2,734	--
430612101014401	36N32W12DD	Arikaree	2,842	340	2,674	--
430537101062801	36N32W17DBD	Arikaree	2,860	205	2,820	--
430458101042001	36N32W22CADA	Ogallala	2,850	40	2,821	--
430426101020201	36N32W25BAA	Ogallala	2,845	55	2,811	--
430340101012301	36N32W25DDDD	Ogallala	2,841	125	2,834	TD-80B
431500101133301	36N33W21BBC	Arikaree	2,985	160	2,860	--
431236100172601	37N25W 4BCCA	Ogallala	2,467	100	2,386	--
431254100191001	37N25W 6ABA	Arikaree	2,410	120	2,373	--
431211100194502	37N25W 6CCC2	Arikaree	2,369	80	2,347	--
430908100175801	37N25W29ACDD	Arikaree	2,374	60	2,360	--
430757100183301	37N25W32CCAB	Arikaree	2,423	124	2,396	--
431245100210801	37N26W 2ADAA	Arikaree	2,383	109	2,351	--
431215100225801	37N26W 3CDA	Arikaree	2,444	95	2,401	--

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.—Continued

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
431020100243501	37N26W16CCBB	Arikaree	2,530	--	2,523	TD-79A
430932100262401	37N26W19DCC	Ogallala	2,655	160	2,584	--
430931100251801	37N26W20CDD	Arikaree	2,605	140	2,557	--
430932100211701	37N26W23DDCD	Arikaree	2,538	140	2,495	--
431019100200001	37N26W24AAA	Arikaree	2,471	110	2,453	--
430953100200001	37N26W24DAA	Arikaree	2,451	90	2,418	--
430858100202301	37N26W25DBBD	Arikaree	2,565	140	2,522	--
430851100210801	37N26W26DADD	Arikaree	2,576	140	2,533	--
430756100231601	37N26W34CCAA	Arikaree	2,540	140	2,521	--
430803100212801	37N26W35DBDA	Arikaree	2,554	140	2,511	--
431212100280601	37N27W 1CC	Arikaree	2,474	120	2,451	--
431245100320601	37N27W 5A	Arikaree	2,593	60	2,582	--
431126100321001	37N27W 8D	Arikaree	2,553	100	2,537	--
431139100311501	37N27W 9CAAA	Arikaree	2,540	120	2,526	--
431050100274501	37N27W13BDD	Arikaree	2,530	140	2,472	--
431051100293101	37N27W15ADD	Arikaree	2,518	150	2,466	--
431027100333001	37N27W18DDAB	Ogallala	2,609	53	2,605	RST-17
431000100325101	37N27W20BCD	Arikaree	2,620	80	2,609	--
430938100273701	37N27W24DCB	Arikaree	2,595	165	2,548	--
430926100290301	37N27W26BAB	Arikaree	2,564	250	2,442	--
430909100333501	37N27W30BDDA	Ogallala	2,722	150	2,662	--
430817100312001	37N27W33BD	Arikaree	2,620	120	2,604	--
431159100412102	37N28W 7BBBC2	Arikaree	2,793	243	2,718	--
431159100412103	37N28W 7BBBC3	Ogallala	2,793	98	2,716	--
431021100384701	37N28W16CCDD	Ogallala	2,744	80	2,714	--
430956100402901	37N28W19ACDD	Ogallala	2,800	120	2,773	--
430932100390001	37N28W21CCCC	Ogallala	2,772	163	2,727	TD-76H
430839100373801	37N28W27CCCC	Ogallala	2,805	182	2,727	TD-76I
430907100401001	37N28W30ADDA	Ogallala	2,757	80	2,742	--
430922100410302	37N28W30BBAA2	Arikaree	2,818	321	2,753	--
430842100411301	37N28W30CCCB	Ogallala	2,770	184	2,745	TD-76G
430820100371401	37N28W34ABDA	Ogallala	2,783	171	2,725	RST-16
430821100373401	37N28W34BCAB	Arikaree	2,808	200	2,734	--
430809100372401	37N28W34BDA (2)	Ogallala	2,800	171	2,740	--
431212100472901	37N29W 6DDBD	Ogallala	2,868	237	2,740	--
431149100462301	37N29W 8AADC	Arikaree	2,810	--	2,740	--
431138100441601	37N29W10DBBB	Ogallala	2,818	150	2,756	--
431141100422501	37N29W12BCDD	Ogallala	2,825	150	2,762	--
431211100194502	37N25W 6CCC2	Arikaree	2,369	80	2,347	--
430908100175801	37N25W29ACDD	Arikaree	2,374	60	2,360	--
430757100183301	37N25W32CCAB	Arikaree	2,423	124	2,396	--
431245100210801	37N26W 2ADAA	Arikaree	2,383	109	2,351	--
431133100402201	37N29W13CBCD	Ogallala	2,796	150	2,732	--

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.—Continued

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
431109100445901	37N29W16AAAA	Ogallala	2,852	184	2,754	TD-76A
431100100461601	37N29W17AACD	Ogallala	2,845	180	2,768	--
430959100444001	37N29W22CCCC	Arikaree	2,882	265	2,781	TD-80C
430920100444801	37N29W27BBCA	Ogallala	2,877	190	2,810	--
430852100435001	37N29W27DACD	Ogallala	2,825	180	2,768	--
430909100452701	37N29W28ACBC	Ogallala	2,880	150	2,803	--
430840100445601	37N29W28DDDD	Ogallala	2,858	195	2,791	TD-76D
430924100460601	37N29W29AAAA	Ogallala	2,868	204	2,790	TD-76B
430836100464301	37N29W29CDDD	Ogallala	2,870	88	2,801	--
430755100582301	37N29W31DACC	Ogallala	2,921	275	2,815	RST-13
430748100455601	37N29W33CCCC	Ogallala	2,909	203	2,817	TD-76C
431238100490301	37N30W 1ACB	Arikaree	2,740	220	2,694	--
431250100530101	37N30W 4BAA	Arikaree	2,842	265	2,717	--
431122100551202	37N30W 7CDBA2	Arikaree	2,770	187	2,604	--
431127100532801	37N30W 8DACC	Ogallala	2,880	150	2,759	RST-27
431033100493201	37N30W13CBCD	Ogallala	2,783	60	2,766	--
431022100542301	37N30W17CCCB	Arikaree	2,995	386	2,789	--
430910100490201	37N30W25ACBC	Ogallala	2,899	165	2,882	--
430912100542301	37N30W29BCBB	Ogallala	2,997	216	2,812	--
430848100544001	37N30W30DDBC	Ogallala	2,980	272	2,778	--
430824100522501	37N30W33ABD	Arikaree	2,985	265	2,839	--
430800100491801	37N30W36ADCA	Arikaree	2,935	320	2,825	--
431234100574401	37N31W 3ADAC	Arikaree	2,512	42	2,506	--
431131100580701	37N31W10DBBB	Arikaree	2,530	55	2,498	--
430920100581201	37N31W22ABCD2	Arikaree	2,943	430	2,639	--
430838100561701	37N31W25CC	Arikaree	3,015	370	2,802	--
430845100571903	37N31W26C3	Arikaree	3,017	350	2,737	--
430807100591001	37N31W33DAA	Arikaree	3,037	445	2,781	--
430831100580301	37N31W34ABAC	Ogallala	2,970	295	2,777	--
431200101034801	37N32W11ABA	Ogallala	3,060	245	2,876	--
431030101031201	37N32W13CAD	Arikaree	2,970	325	2,792	--
430907101073801	37N32W29ACB	Ogallala	2,910	165	2,882	--
431222101093501	37N33W 1DAA	Ogallala	3,104	285	3,009	--
431148101165001	37N33W 7ABD	Ogallala	3,018	260	2,947	--
431156101105801	37N33W11AAB	Ogallala	3,153	305	3,032	--
431018101132301	37N33W16DCDC	Ogallala	3,023	270	2,955	--
431018101152001	37N33W17CCCC	Ogallala	2,998	181	2,930	BT-76C
430929101104202	37N33W26AAAA2	Arikaree	2,953	395	2,876	--
430929101104203	37N33W26AAAA3	Ogallala	2,953	236	2,876	--
431432101123401	37N33W27BAA	Ogallala	2,978	120	2,918	--
430836101152201	37N33W32BBBB	Ogallala	2,960	185	2,895	--
430825101151801	37N33W32BBBB2	Ogallala	2,960	143	2,902	BT-80E
431250101163701	37N34W 1AAAA	Ogallala	3,113	245	2,960	--

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.—Continued

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
431540100154501	38N25W15DCCB	Ogallala	2,467	110	2,406	--
431509100185901	38N25W19ADCC	Ogallala	2,530	80	2,504	--
431430100195901	38N25W30BCBB	Arikaree	2,483	144	2,458	TD-80D
431311100193201	38N25W31CDBA	Arikaree	2,426	56	2,414	--
431327100164501	38N25W33ACD	Ogallala	2,475	24	2,466	--
431637100264101	38N26W 7CDB	Arikaree	2,513	90	2,486	--
431716100212001	38N26W11AAB	Ogallala	2,651	160	2,601	--
431554100203301	38N26W13BCCA	Arikaree	2,608	230	2,505	--
431532100200101	38N26W24AAAB	Ogallala	2,503	85	2,467	--
431413100244901	38N26W29DAA	Arikaree	2,440	90	2,418	--
431356100255401	38N26W30DAD	Arikaree	2,420	90	2,388	--
431340100253901	38N26W32BBD	Arikaree	2,452	85	2,437	--
431328100240901	38N26W33BDD	Arikaree	2,424	70	2,413	--
431308100223101	38N26W34DDB	Arikaree	2,417	100	2,395	--
431323100213501	38N26W35DBBA	Arikaree	2,403	100	2,341	--
431736100293201	38N27W 3DAD	Arikaree	2,526	100	2,474	--
431808100312801	38N27W 4BAB	Arikaree	2,550	100	2,489	--
431757100323302	38N27W 5BDAB	Arikaree	2,522	100	2,497	--
431650100330701	38N27W 7DAAB	Arikaree	2,477	--	2,468	--
431548100314401	38N27W16CBCD	Arikaree	2,484	90	2,453	--
431440100275301	38N27W25BABA	Arikaree	2,448	100	2,416	--
431430100320101	38N27W28B	Arikaree	2,518	110	2,507	--
431337100312101	38N27W33BDA	Arikaree	2,570	130	2,541	--
431539100352401	38N28W13CCCC	Arikaree	2,577	--	2,539	--
431625100361301	38N28W14BAAB	Arikaree	2,589	115	2,529	--
431615100390701	38N28W17AADD	Arikaree	2,664	--	2,610	--
431625100411801	38N28W18BBBA	Arikaree	2,596	--	2,587	--
431512100402501	38N28W19ADCD	Arikaree	2,673	--	2,639	--
431714100364101	38N28W20AAAD	Ogallala	2,700	--	2,646	--
431506100363601	38N28W23CBBB	Arikaree	2,635	--	2,627	--
431430100371601	38N28W27ACB	Arikaree	2,768	220	2,724	--
431427100375201	38N28W28ADAA	Ogallala	2,781	--	2,729	--
431354100375201	38N28W28DDDD	Ogallala	2,781	--	2,750	--
431347100404901	38N28W31ABBB	Arikaree	2,666	120	2,645	--
431342100344101	38N28W36ABCB	Arikaree	2,620	73	2,609	RST-15
431551100441601	38N29W15DBCD	Arikaree	2,696	--	2,699	--
431536100472201	38N29W17BCDA	Arikaree	2,687	100	2,670	--
431502100443801	38N29W22CAC	Arikaree	2,730	160	2,686	--
431435100414101	38N29W25AACB	Ogallala	2,663	--	2,647	--
431424100430601	38N29W26ACB	Arikaree	2,750	220	2,671	--
431340100430401	38N29W35ACBB	Arikaree	2,803	370	2,708	--
431809100483401	38N30W 1AAAA	Arikaree	2,763	180	2,626	--
431740100502201	38N30W 2CAA	Arikaree	2,640	265	2,492	--

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.—Continued

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
431610100484701	38N30W13ADBB	Arikaree	2,645	119	2,632	--
431537100504701	38N30W14CCCA	Arikaree	2,723	280	2,639	--
431601100514301	38N30W15BDC	Arikaree	2,650	158	2,650	--
431612100551201	38N30W18BADB	Arikaree	2,550	245	2,416	--
431515100501701	38N30W23ACBC	Arikaree	2,720	258	2,657	--
431255100545701	38N30W31DCCD	Arikaree	2,872	250	2,701	--
431315100541301	38N30W32CBD	Arikaree	2,887	265	2,736	--
431318100532301	38N30W32DAAB	Ogallala	2,838	47	2,818	--
431340100521405	38N30W33AA5	Arikaree	2,840	238	2,624	--
431335100511101	38N30W34A	Arikaree	2,600	--	2,573	--
431252100501801	38N30W35BDDB	Arikaree	2,708	219	2,605	--
431744100561401	38N31W 1BACB2	Arikaree	2,600	160	2,502	--
431744100583601	38N31W 3ABAB	Arikaree	2,692	200	2,601	--
431733100585701	38N31W 4DABD2	Arikaree	2,725	226	2,656	--
431623101010501	38N31W 8CCC	Arikaree	2,787	93	2,732	--
431654100574302	38N31W10ADAC2	Arikaree	2,698	210	2,606	--
431630100570201	38N31W11CDAA	Arikaree	2,652	240	2,553	--
431550100590501	38N31W16CABD (2)	Ogallala	2,747	20	2,743	--
431520100593601	38N31W16DBAA	Arikaree	2,710	128	2,688	--
431551101003901	38N31W17CAA	Arikaree	2,880	180	2,878	--
431501101005701	38N31W20CBAA	Arikaree	2,837	140	2,827	--
431526100563202	38N31W23AAAB2 R	Arikaree	2,443	60	2,431	--
431508100562101	38N31W24BDAD R	Arikaree	2,605	262	2,505	--
431427100561201	38N31W25BBAC	Arikaree	2,722	360	2,563	--
431259100574401	38N31W34DDAC	Arikaree	2,502	85	2,477	--
431338100570901	38N31W35BA	Arikaree	2,485	60	2,476	--
431738103035702	38N32W 1BAAC	Arikaree	2,750	262	2,671	--
431740101044601	38N32W 3ADDD	Arikaree	2,750	205	2,681	--
431637101084802	38N32W 7DCAB2	Arikaree	2,890	152	2,841	--
431639101043102	38N32W11CBD2	Arikaree	2,785	225	2,716	--
431554101044501	38N32W15DAAA	Arikaree	2,805	90	2,782	--
431533101080501	38N32W17CCD	Arikaree	3,059	154	2,907	--
431303101075401	38N32W32CDB	Arikaree	3,032	285	2,926	--
431625101103001	38N33W12CCDC	Arikaree	2,943	150	2,931	--
431843100263301	39N26W31BDA	Arikaree	2,600	140	2,543	--
431830100250201	39N26W32DCDA	Arikaree	2,533	153	2,457	--
432242100281201	39N27W 1CCB	Arikaree	2,520	80	2,479	--
432316100305801	39N27W 3BBD	Arikaree	2,500	65	2,469	--
432205100294301	39N27W10DABB	Arikaree	2,513	75	2,482	--
432033100305601	39N27W21ADDA	Arikaree	2,754	220	2,583	--
432009100290301	39N27W23CDBA	Arikaree	2,651	130	2,610	--
431937100320101	39N27W29ADBD	Arikaree	2,676	130	2,645	--
431815100341801	39N27W31CCC	Arikaree	2,537	160	2,477	--
431818100324201	39N27W32CDCB2	Arikaree	2,544	90	2,513	--

Appendix 1. Wells used for estimating potentiometric surfaces of the Ogallala and Arikaree aquifers.—Continued

[Hydraulic heads are estimated averages for water years 1979–98. NGVD of 1929, National Geodetic Vertical Datum of 1929. --, not applicable or unknown]

Site identification number	Legal location	Aquifer	Land surface altitude (feet above NGVD of 1929)	Well depth (feet)	Average hydraulic head (feet above NGVD of 1929)	Observation well name
431814100302602	39N27W34CCDC2	Arikaree	2,562	80	2,536	--
431903100282002	39N27W35AAAB2	Arikaree	2,598	91	2,552	--
432150100381701	39N28W 9DCA	Arikaree	2,518	68	2,506	--
432203100361301	39N28W11CAA	Arikaree	2,535	160	2,510	--
432117100371601	39N28W15ACC	Arikaree	2,585	160	2,525	--
432108100400001	39N28W17CBD	Arikaree	2,683	210	2,616	--
432003100352501	39N28W24CC	Arikaree	2,675	150	2,615	--
431907100350201	39N28W25CCD	Arikaree	2,565	150	2,505	--
431947100354001	39N28W26AADB	Arikaree	2,628	150	2,568	--
431927100381501	39N28W28DBAA	Arikaree	2,628	140	2,599	--
431949100392901	39N28W29ABAD	Arikaree	2,634	150	2,625	--
431933100412101	39N28W30BCDB	Arikaree	2,622	150	2,603	--
431912100410501	39N28W30CDBD	Arikaree	2,601	150	2,587	--
431812100383901	39N28W33CDD	Arikaree	2,563	140	2,521	--
432049100415301	39N29W13CC	Arikaree	2,640	200	2,585	--
432025100434001	39N29W23BCD	Arikaree	2,500	112	2,469	--
431830100450901	39N29W33DA	Arikaree	2,657	140	2,629	--
431822100424301	39N29W35DDAB	Arikaree	2,681	--	2,648	--
431813100413101	39N29W36DDDC	Arikaree	2,645	220	2,597	--
432244100594502	39N31W 4CBDB2	Arikaree	2,467	60	2,449	--
432149101005001	39N31W 8CACB	Arikaree	2,653	274	2,517	--
432020101010901	39N31W19ACDA2	Arikaree	2,625	300	2,545	--
431903100561701	39N31W25CCCA	Arikaree	2,558	170	2,471	--
431933101010501	39N31W29BCB	Arikaree	2,640	240	2,586	--
431823101005201	39N31W32CBDB	Arikaree	2,685	198	2,646	--
431813100571001	39N31W35CDBD	Arikaree	2,620	200	2,534	--
432310101045501	39N32W 3AAAA	Arikaree	2,610	125	2,578	TD-80A
432205101032201	39N32W11ACDA	Arikaree	2,595	125	2,585	--
432131101034001	39N32W14AAA	Arikaree	2,634	125	2,600	--
432131101053001	39N32W15BAB	Arikaree	2,678	200	2,639	--
431922101032201	39N32W25CBAB	Arikaree	2,705	180	2,626	--
431913101084001	39N32W30DBDC	Arikaree	2,820	138	2,768	--
431820101045002	39N32W34DADC2	Arikaree	2,781	300	2,646	--
432044101115201	39N33W15DDDD	Arikaree	2,800	360	2,764	TD-79D
432416100315601	40N27W32AAA	Arikaree	2,478	16	2,470	--
432540101092202	40N32W19BCC2	Arikaree	2,595	100	2,570	--
432515101071701	40N32W20DDBB	Arikaree	2,597	220	2,586	--
432554101065601	40N32W21BBBB	Arikaree	2,576	163	2,561	MT-78A
432530101024801	40N32W24CBB	Arikaree	2,568	152	2,543	--
432453101075601	40N32W29BCAB	Arikaree	2,618	240	2,600	--
432654101130401	40N33W 9DDDA	Arikaree	2,570	120	2,516	--
432545101102701	40N33W24BBDD	Arikaree	2,548	108	2,523	--
432446101131104	40N33W28AD	Arikaree	2,740	110	2,686	--
432407101131201	40N33W33AAB	Arikaree	2,742	225	2,686	--

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