Prepared in cooperation with the
Rosebud Sioux Tribe

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

Water-Resources Investigations Report 03-4043

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

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Rapid City, South Dakota: 2003

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CONVERSION FACTORS, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

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

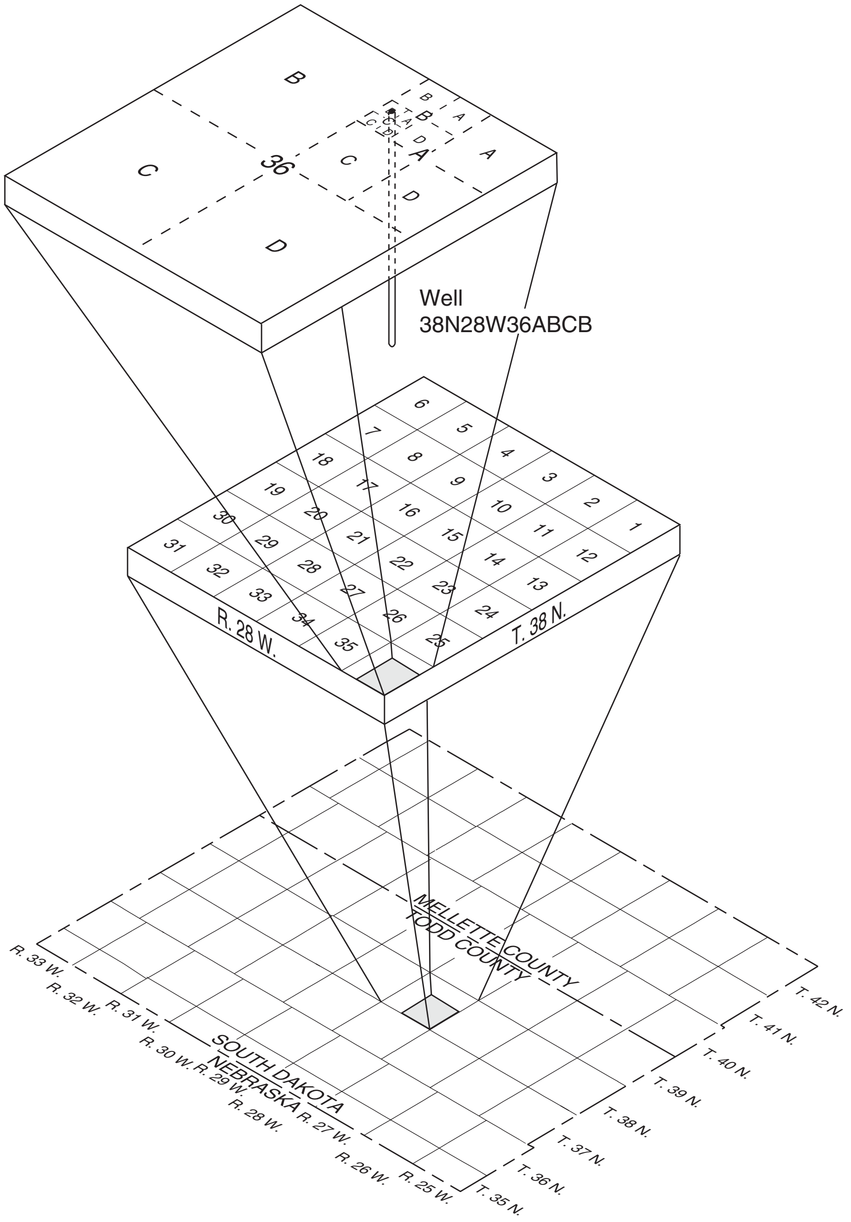
Temperature in degrees Fahrenheit (° F) may be converted to degrees Celsius (° C) as follows:

$$°C = (°F - 32) / 1.8$$

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

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

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



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ABSTRACT

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

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

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

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

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

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

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

INTRODUCTION

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

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

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

Purpose and Scope

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

Acknowledgments

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

DESCRIPTION OF STUDY AREA

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

Physiography, Land Use, and Climate

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

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

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

Drainage Features and Streamflow

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

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

Geology

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

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

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

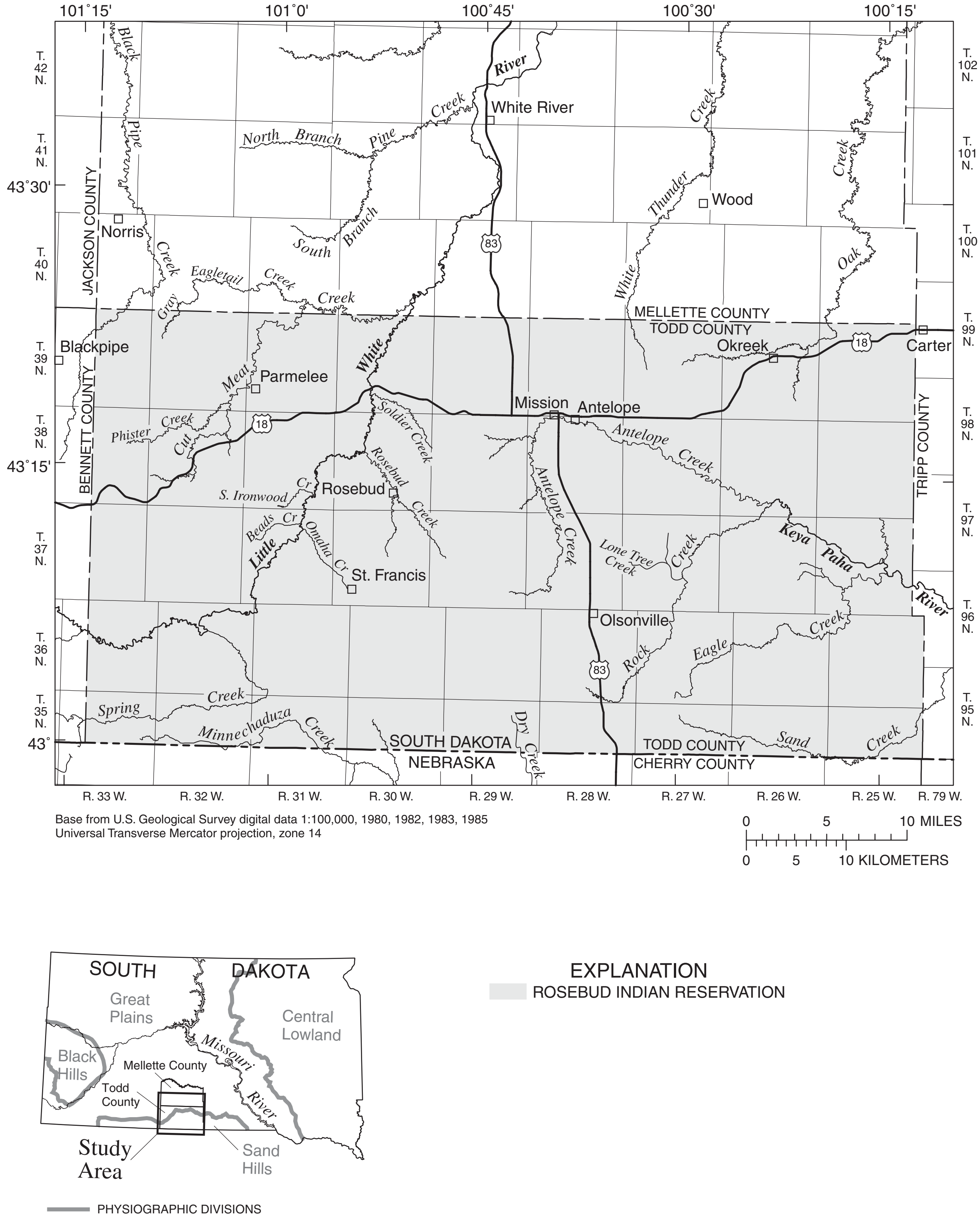


Figure 1. Study area and locations of main physiographic divisions (physiographic divisions modified from Fenneman, 1946; Flint, 1955).

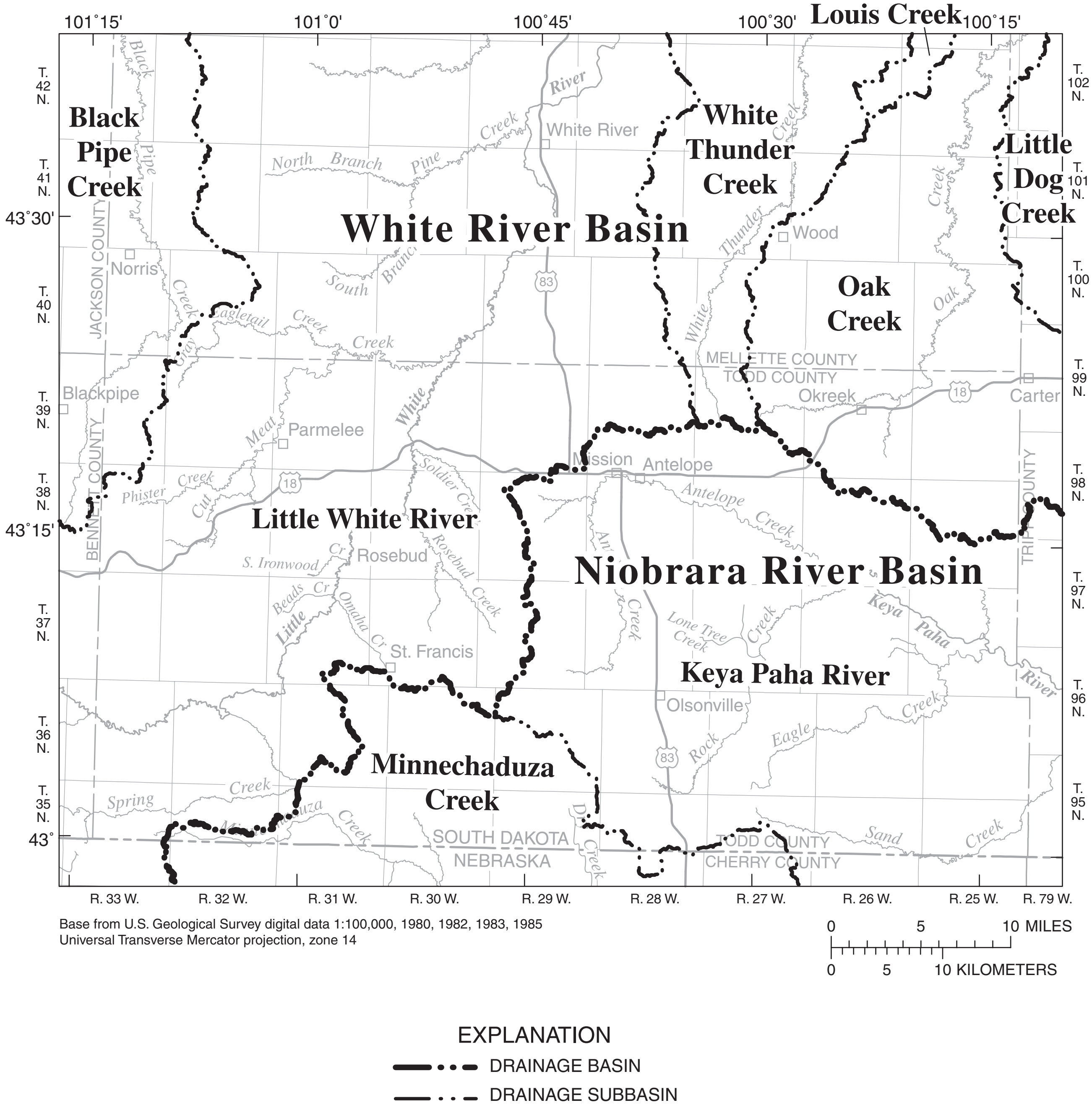


Figure 2. Drainage basins in study area.

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

[From Carter, 1998]

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

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

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

Hydrogeologic Setting

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

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

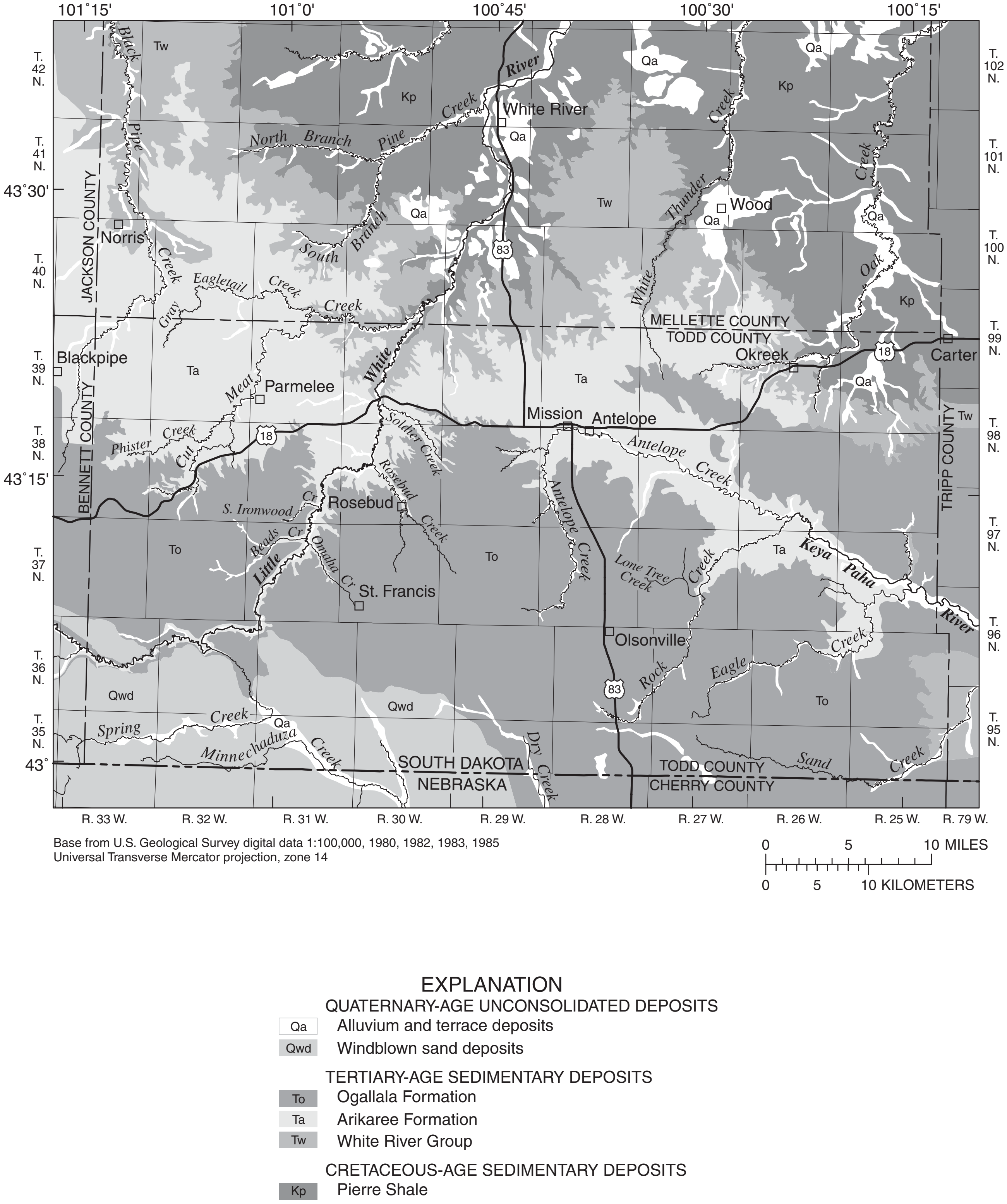
The Ogallala aquifer is present throughout most of the southern part of the study area, where it underlies 950 square miles in Todd County with an estimated 17 million acre-feet of water in storage (Carter, 1998). The Ogallala aquifer is not present in the northern part of the study area. The saturated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

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

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

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

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



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

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

SIMULATED GROUND-WATER FLOW

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

Conceptual Model

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

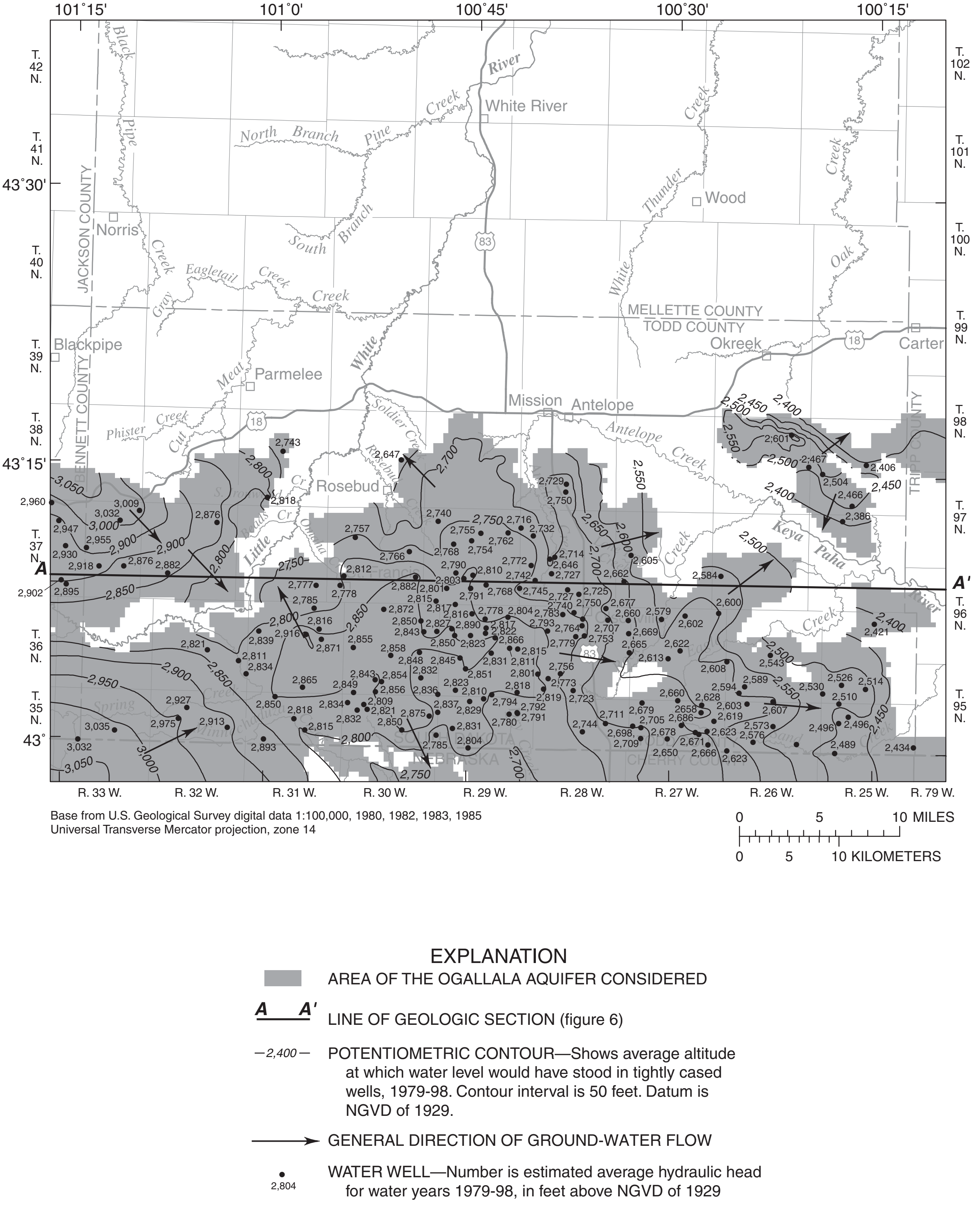
The windblown deposits overlying the Ogallala aquifer in the southwest part of the study area are composed of fine- to medium-grained sand, similar to that of the Ogallala Formation, and were included with the Ogallala aquifer as a single layer for ground-water flow analysis. The Ogallala and Arikaree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

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

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

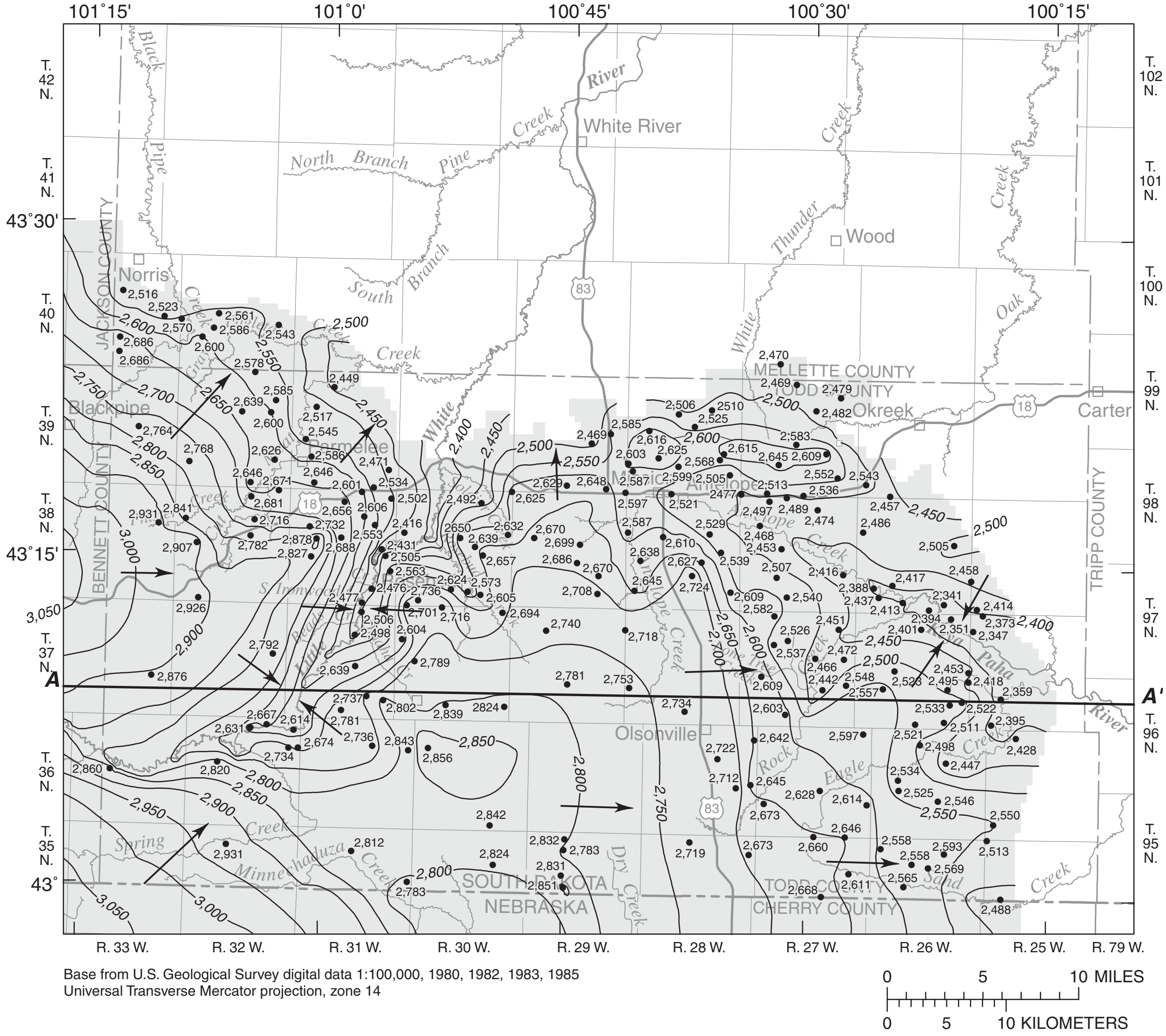
Potentiometric Surface

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



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

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



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

EXPLANATION

▨ AREA OF THE ARIKAREE AQUIFER CONSIDERED

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

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

——→ GENERAL DIRECTION OF GROUND-WATER FLOW

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

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

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

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

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

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

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

Hydraulic Properties

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

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

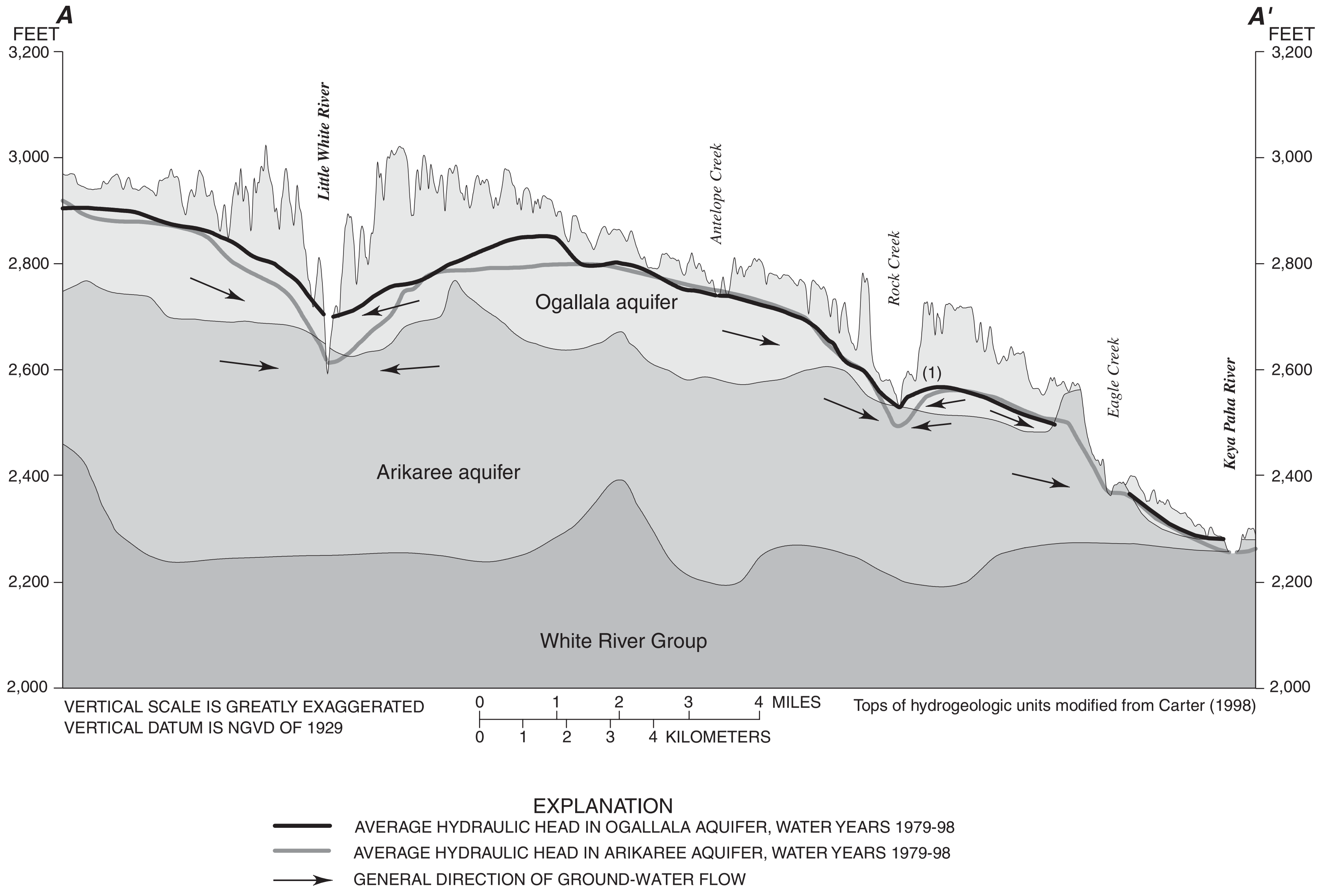


Figure 6. Relation between average hydraulic head, hydrogeologic units, and topographic features. Location of section is shown in figures 4 and 5. This section shows an area (1) of intermittent saturation, which is not included in the area of the Ogallala aquifer considered in figure 4.

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

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

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

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

[2] Includes Ogallala aquifer and upper Arikaree aquifer.

Based on aquifers tests of the Arikaree aquifer near Pine Ridge, South Dakota (located about 70 miles west of the study area), Sipe (1989) estimated hydraulic conductivity to be 1.0 foot per day and storage coefficient to be 3.9×10^{-4}. Greene and others (1991) reported aquifer tests in two of the sandier units of the Arikaree aquifer near Pine Ridge. Hydraulic properties determined for an upper unconfined unit composed of fine to medium sand include hydraulic conductivity of 13 feet per day, storage coefficient of 7×10^{-3}, and specific yield of 0.03. Hydraulic properties determined for a lower confined unit composed of fine to very fine sand include hydraulic conductivity of 1 foot per day and storage coefficient of 3×10^{-4}. The hydraulic conductivity of a core sample from the Arikaree Formation in Nebraska was about 2 feet per day (Bradley, 1956).

Recharge

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

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

Discharge

Discharge from the Ogallala and Arikaree aquifers occurs through evapotranspiration, discharge to streams, and well withdrawals. Discharge by evapotranspiration generally occurs in topographically low areas. Discharge to streams occurs as springs and seeps. For the purpose of this analysis, all spring discharge is assumed to reach a stream and contribute to base flow. Well withdrawals are from irrigation, domestic, and stock wells.

Evapotranspiration

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

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

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

[--, not applicable]

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

Discharge to Streams

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

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

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

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

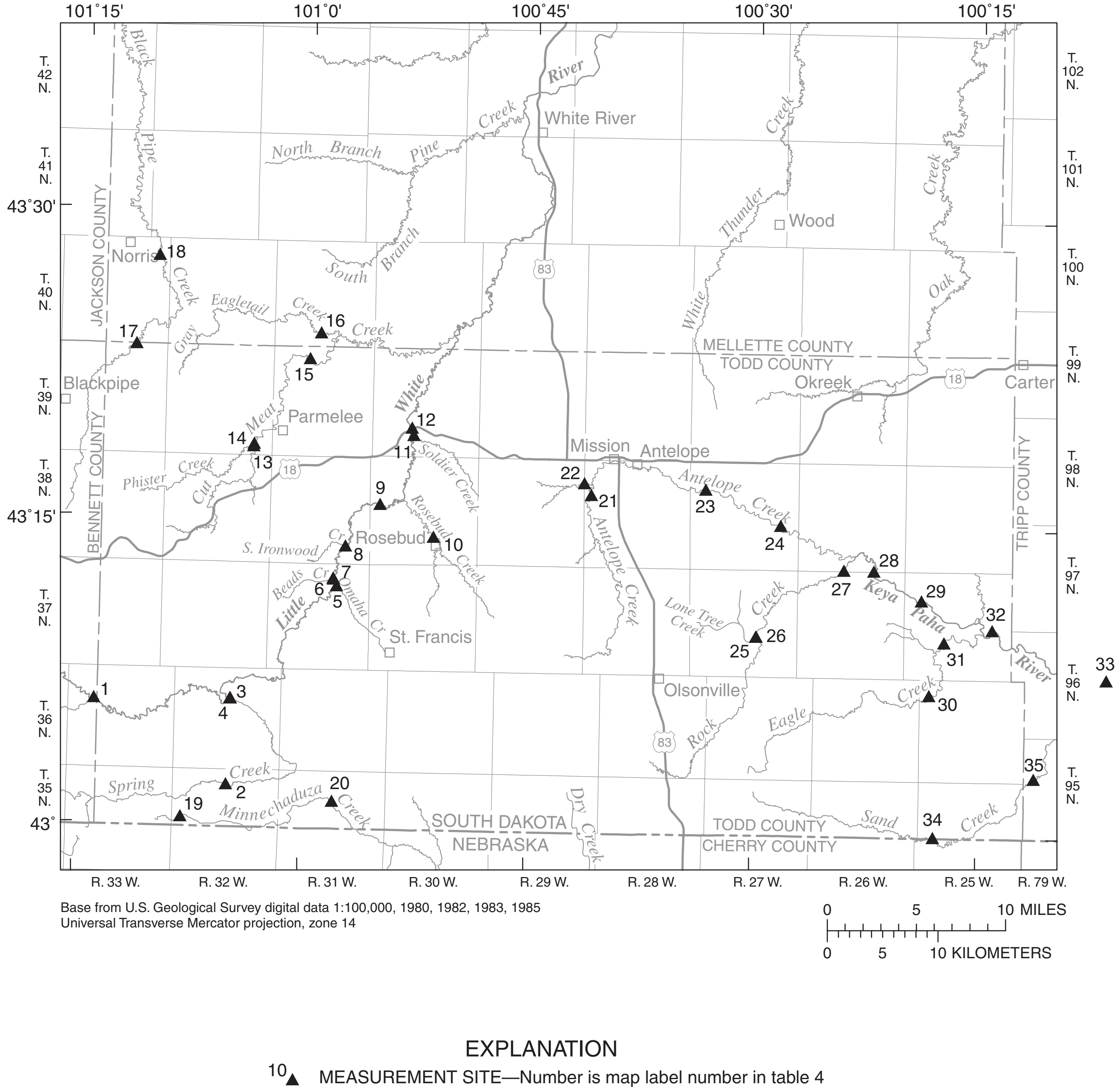


Figure 7. Streamflow measurement sites for seepage runs during water year 1999.

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

[e, estimated; --, not measured]

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

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

[e, estimated; --, not measured]

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

[1] Streamflow influenced by rain storm.

Well Withdrawals

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

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

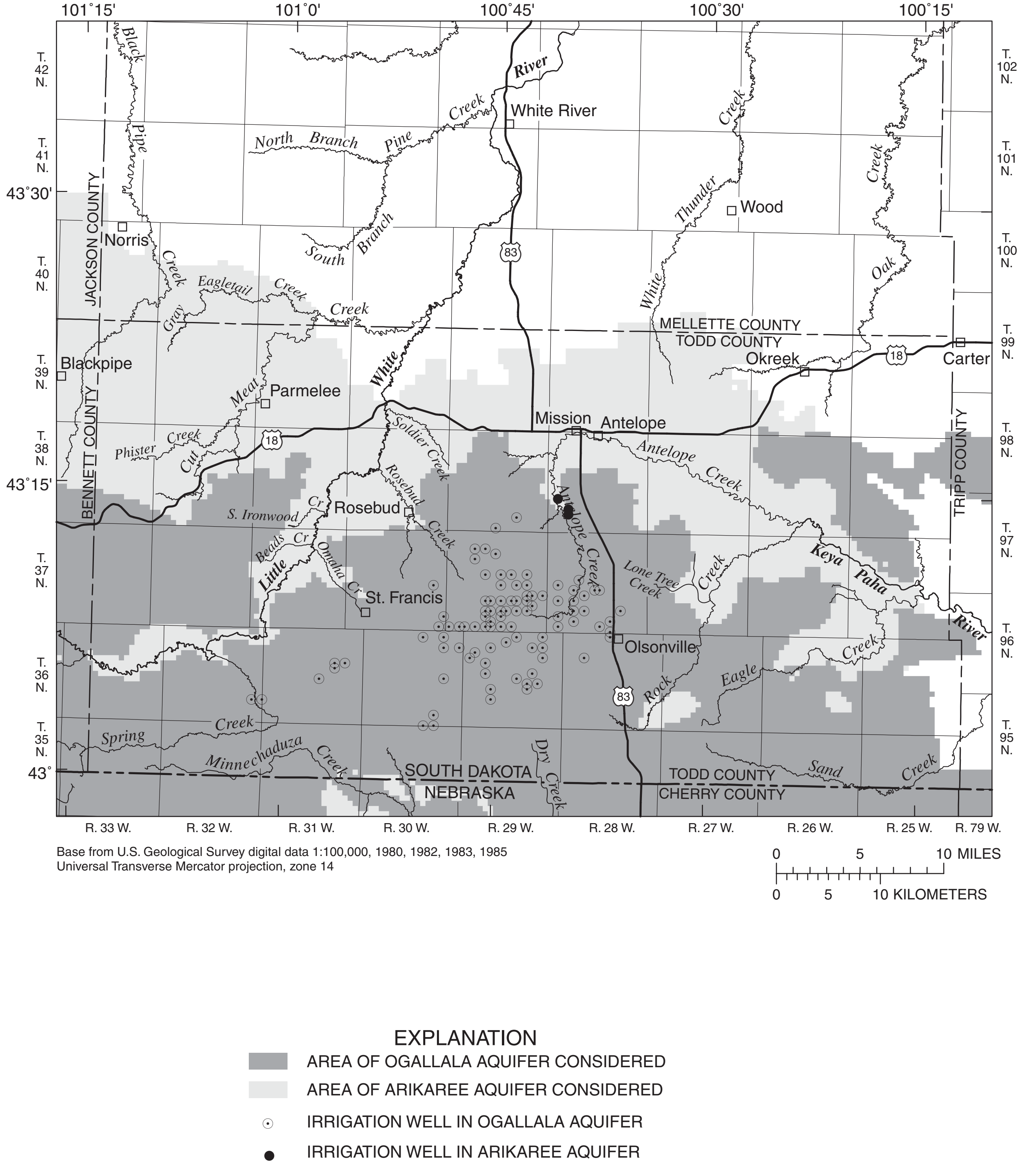
Water-use data are compiled every 5 years as part of the USGS National Water-Use Information Program in cooperation with local, State, and Federal agencies and is aggregated by counties for each State. The acres of irrigated land in Todd County that were compiled for 1985, 1990, and 1995 remained steady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

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

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

[--, not applicable]

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



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

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

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

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

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

Numerical Model

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

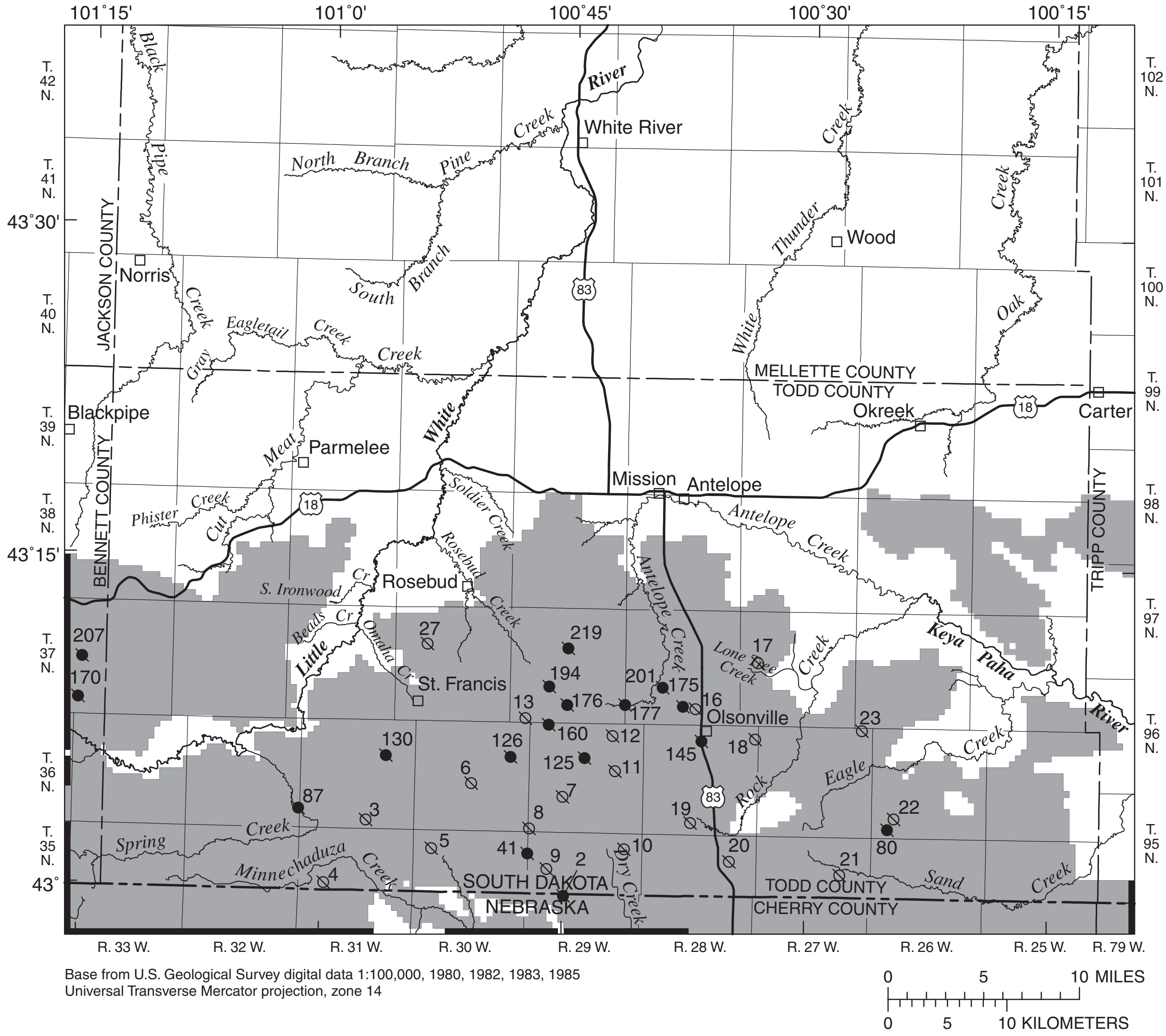
Model Design

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

Grid and Boundary Conditions

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

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

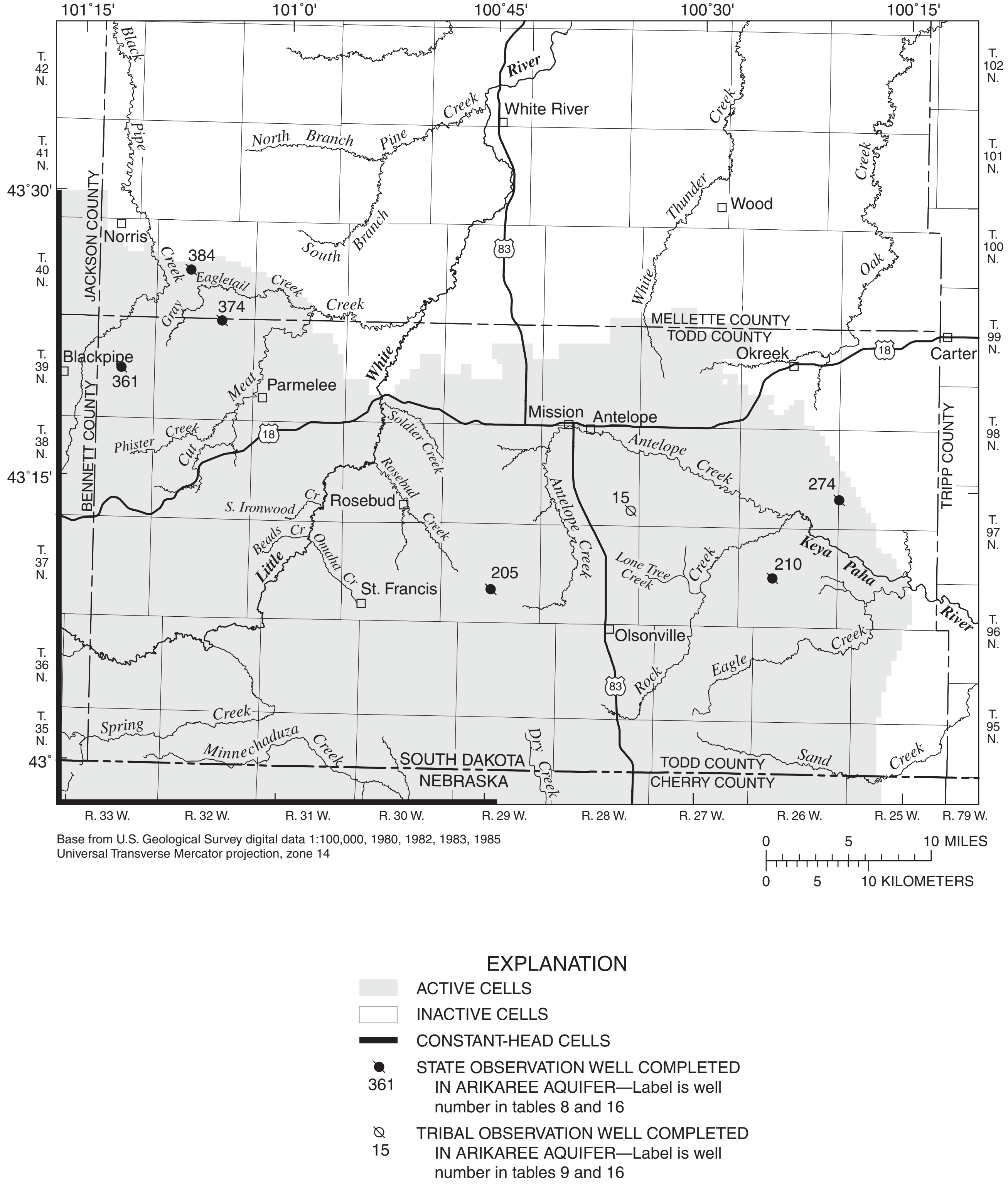


Base from U.S. Geological Survey digital data 1:100,000, 1980, 1982, 1983, 1985
Universal Transverse Mercator projection, zone 14

EXPLANATION

▨	ACTIVE CELLS
☐	INACTIVE CELLS
▬	CONSTANT-HEAD CELLS
● 41	STATE OBSERVATION WELL COMPLETED IN OGALLALA AQUIFER—Label is well number in tables 8 and 15
⌀ 10	TRIBAL OBSERVATION WELL COMPLETED IN OGALLALA AQUIFER—Label is well number in tables 9 and 15

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



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

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

Representation of Hydraulic Properties

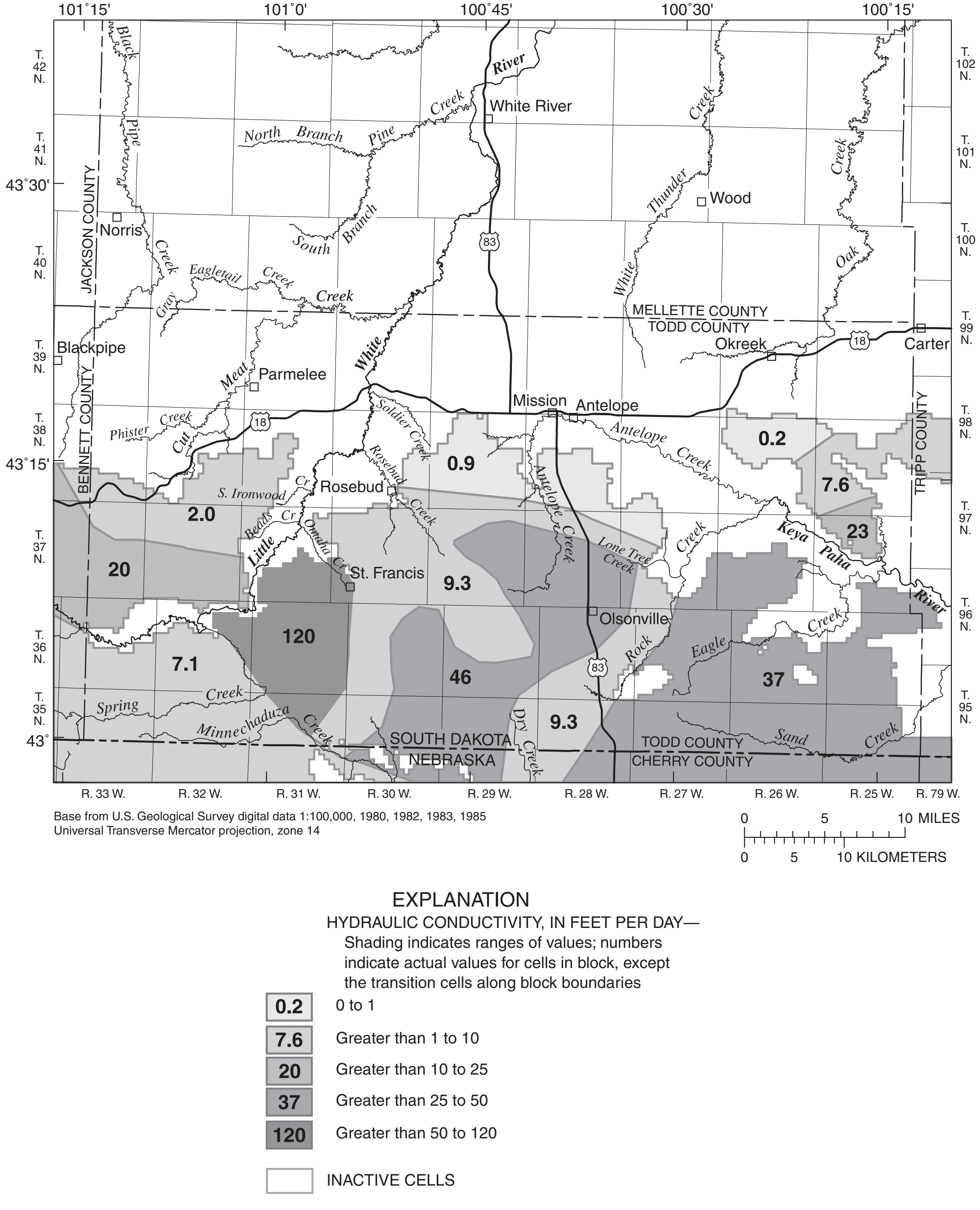
Estimated horizontal hydraulic conductivity for the Ogallala aquifer ranged from 0.2 to 120 feet per day (fig. 11). Estimated values were based on previously published values (table 2), the spatial distribution of specific capacities in the study area (fig. 12), and model calibration. Specific capacity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

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

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

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

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



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

EXPLANATION

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

0.2	0 to 1
7.6	Greater than 1 to 10
20	Greater than 10 to 25
37	Greater than 25 to 50
120	Greater than 50 to 120
☐	INACTIVE CELLS

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

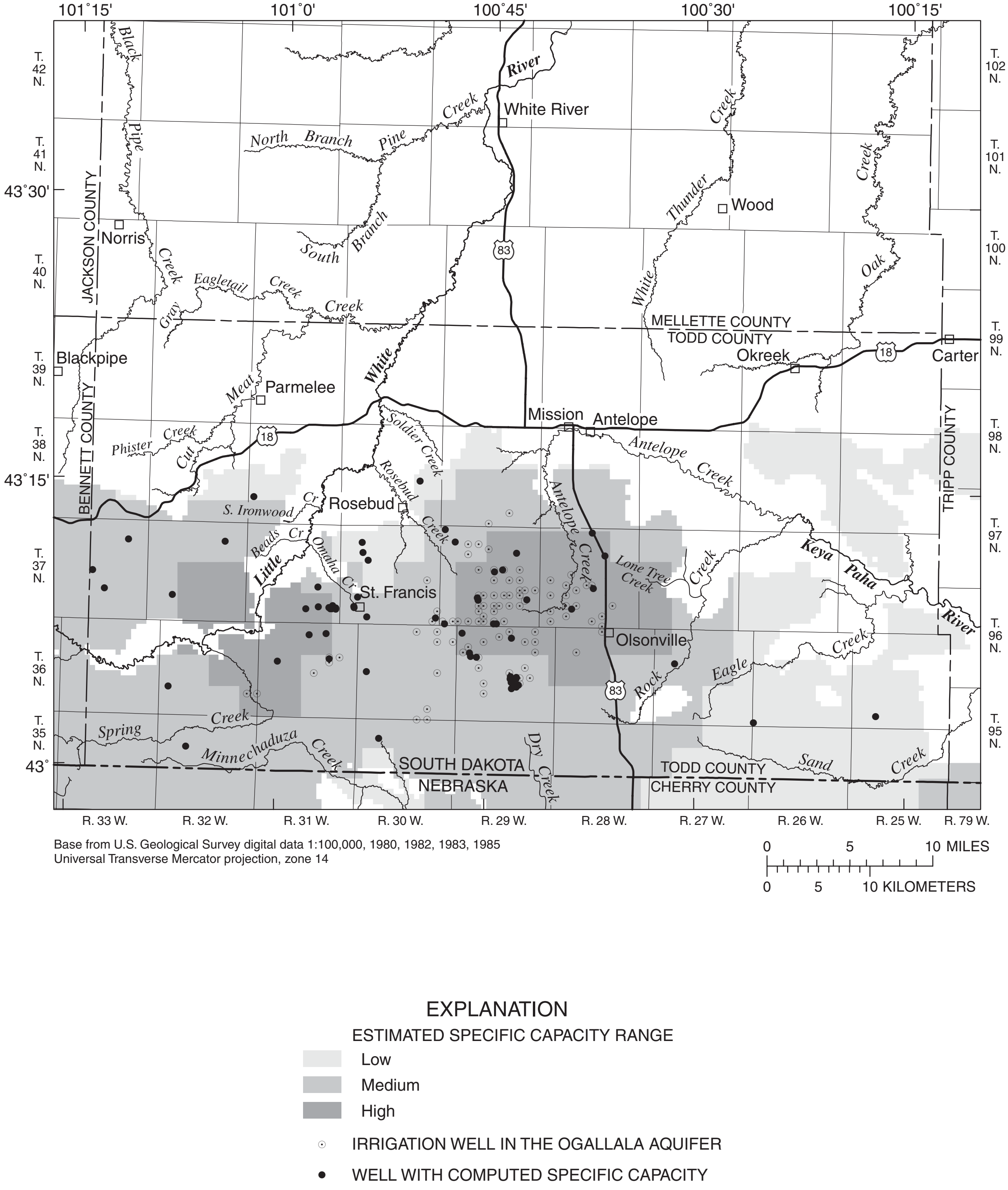
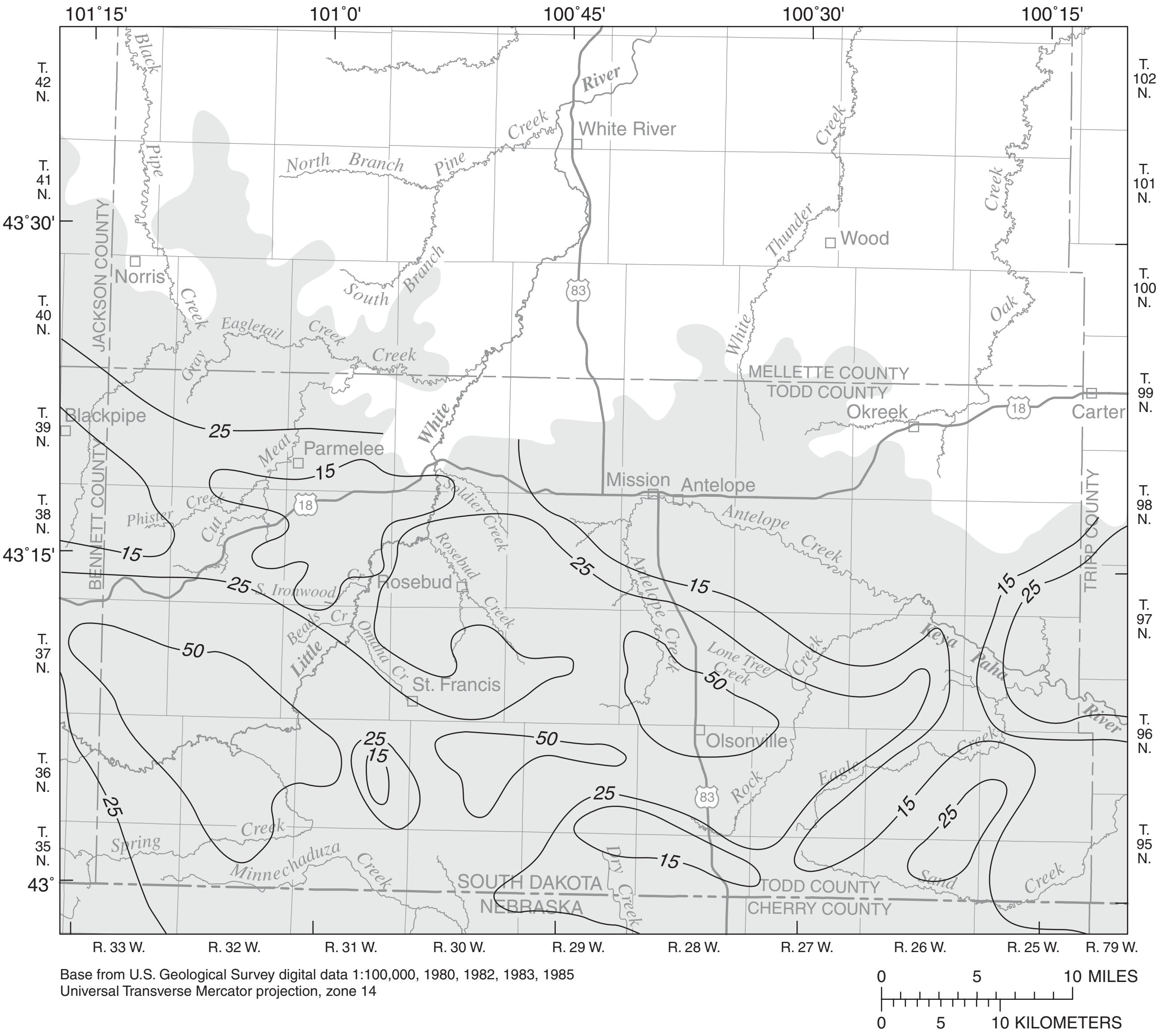


Figure 12. Generalized specific capacity ranges in the Ogallala aquifer.



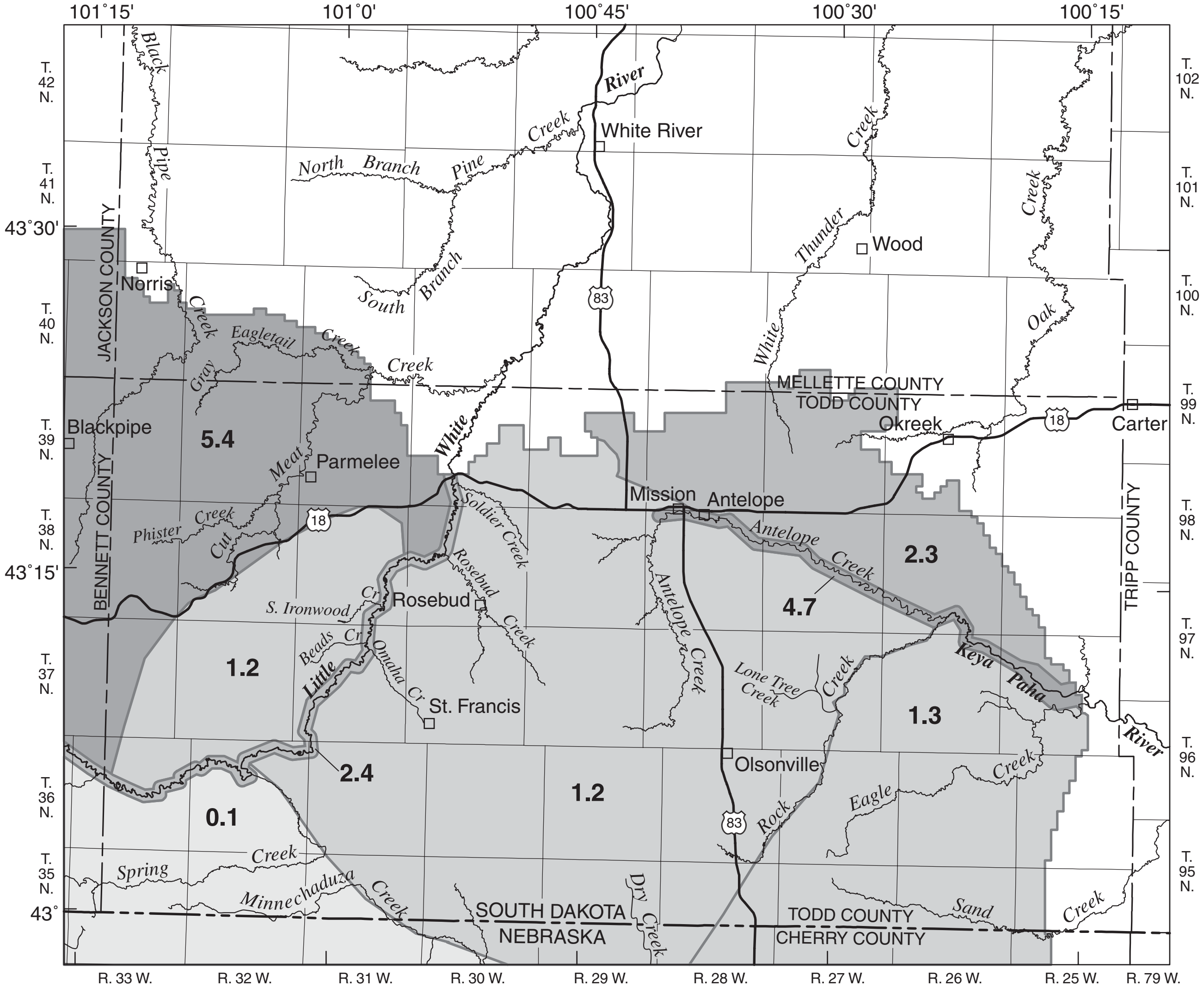
Base from U.S. Geological Survey digital data 1:100,000, 1980, 1982, 1983, 1985
Universal Transverse Mercator projection, zone 14

EXPLANATION

▨ HIGH PLAINS AQUIFER

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

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



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

EXPLANATION

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

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

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

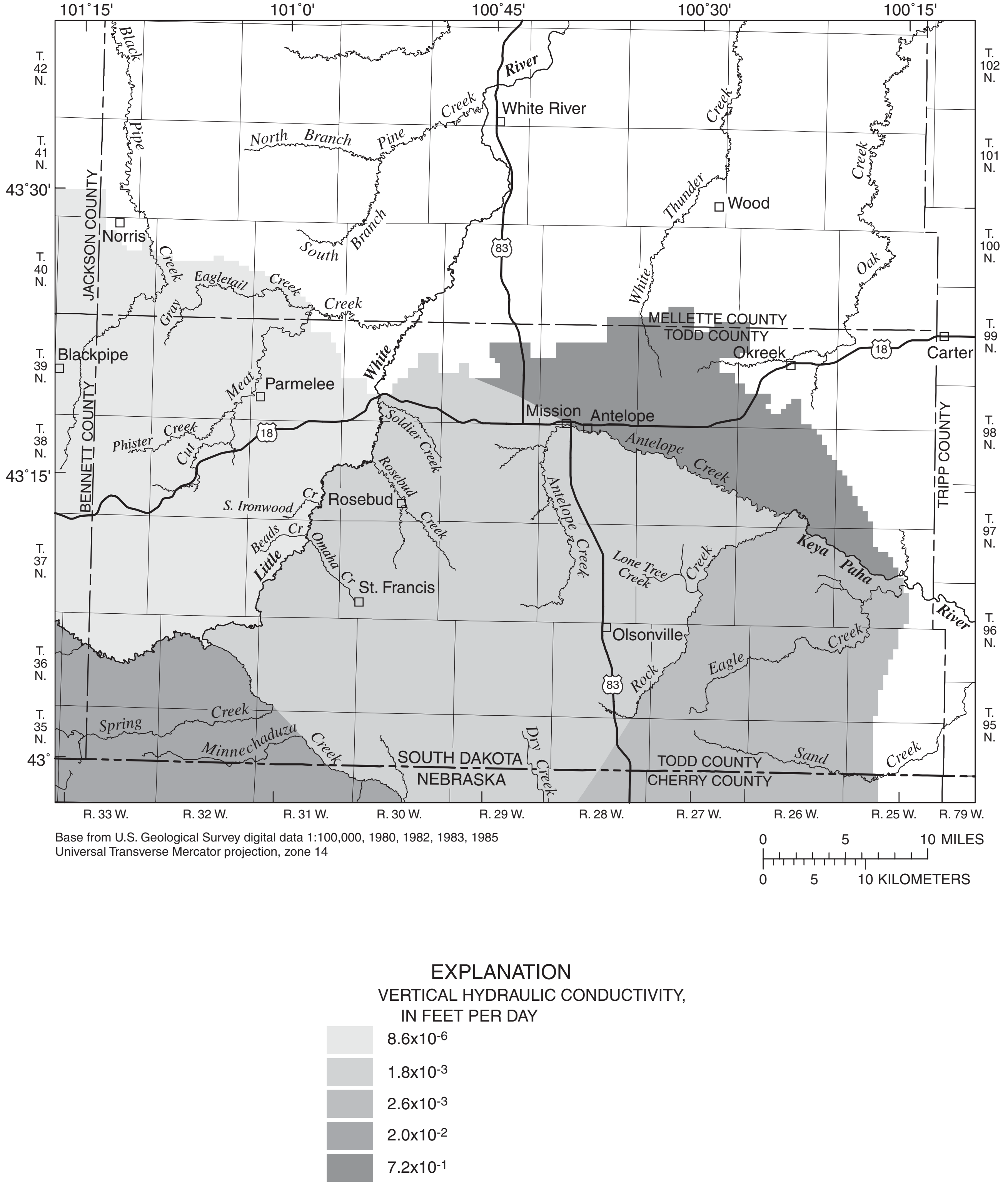


Figure 15. Estimated vertical hydraulic conductivity of the Arikaree aquifer.

Representation of Recharge and Discharge

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

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

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

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

Model Calibration

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

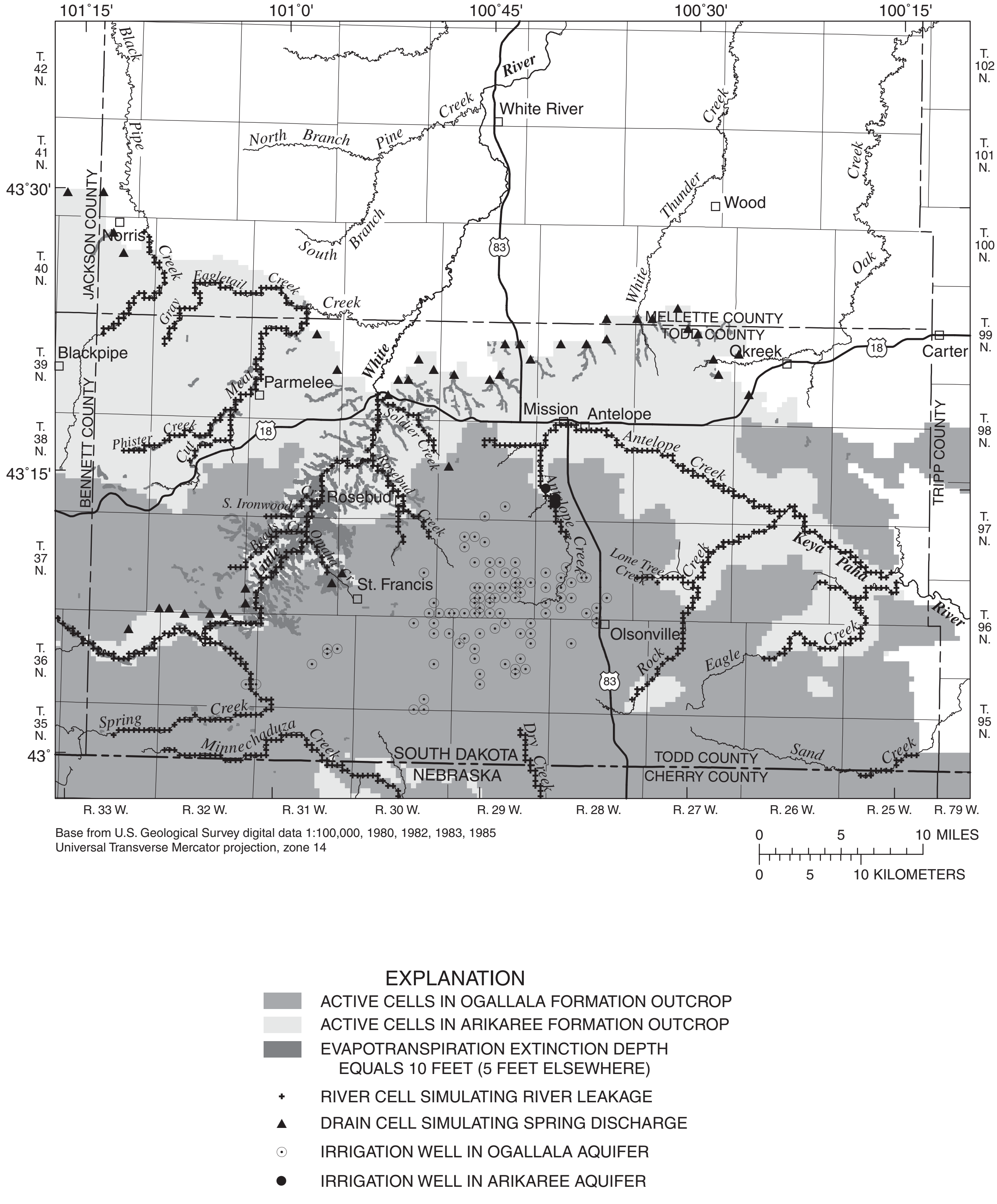
Water-level measurements for 398 wells that were used for estimation of potentiometric surfaces of the Ogallala and Arikaree aquifers (figs. 4 and 5) were considered for calibration of the steady-state model. These wells include 44 observation wells with long-term water-level records that were used for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

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

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

[--, not applicable]

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



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

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

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

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

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

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