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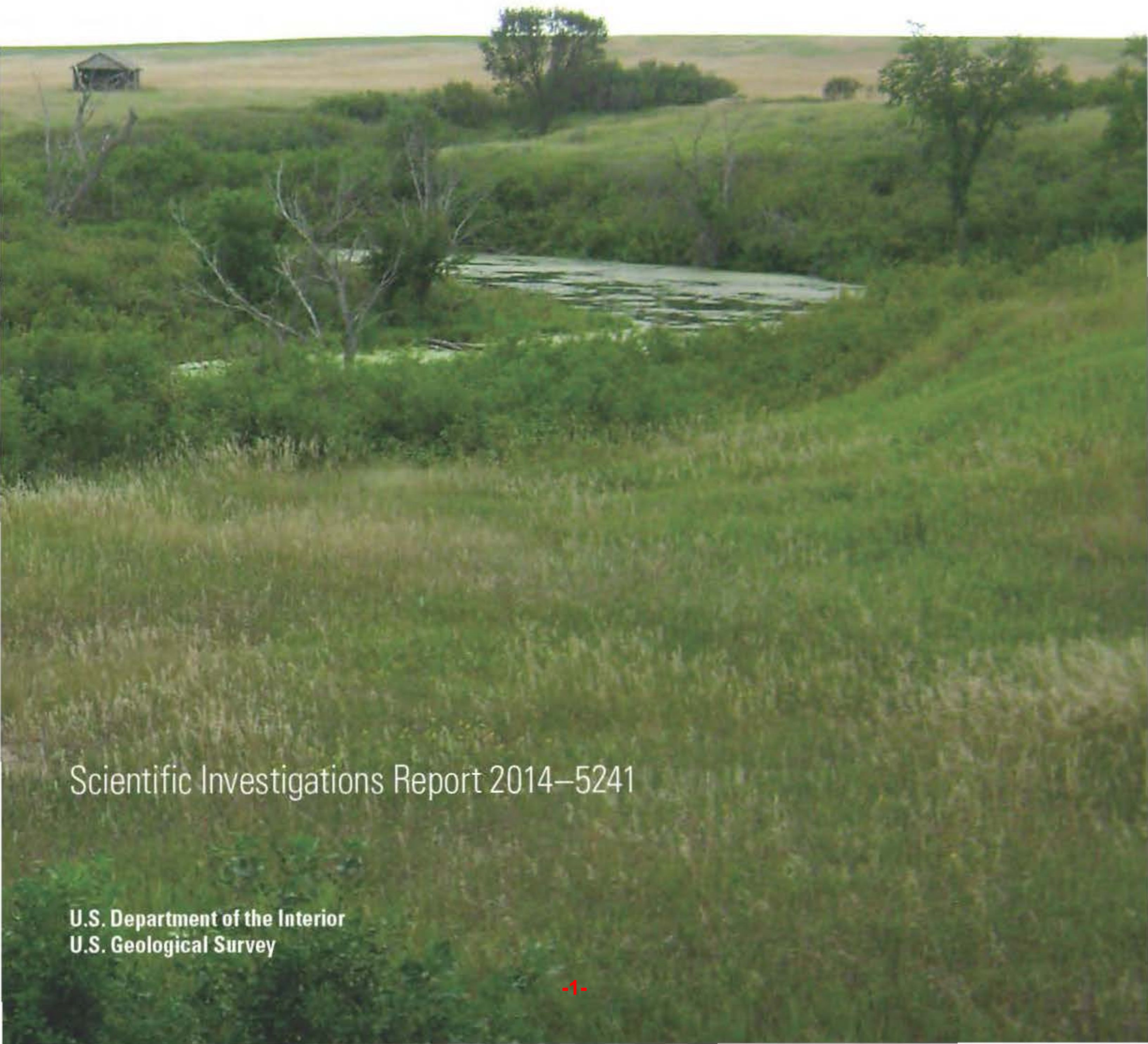
Conceptual and Numerical Models of Groundwater Flow in the Ogallala and Arikaree Aquifers, Pine Ridge Indian Reservation Area, South Dakota, Water Years 1980–2009



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

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

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

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

Introduction

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

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

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

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

Purpose and Scope

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

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

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

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

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

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

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

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

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

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

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

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

Hydrogeologic Setting

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

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

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

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

[a]From Harksen and Macdonald (1967).

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

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

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

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

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

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

Conceptual Model

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

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