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# An Overview of Secondary Aquifers in Nebraska

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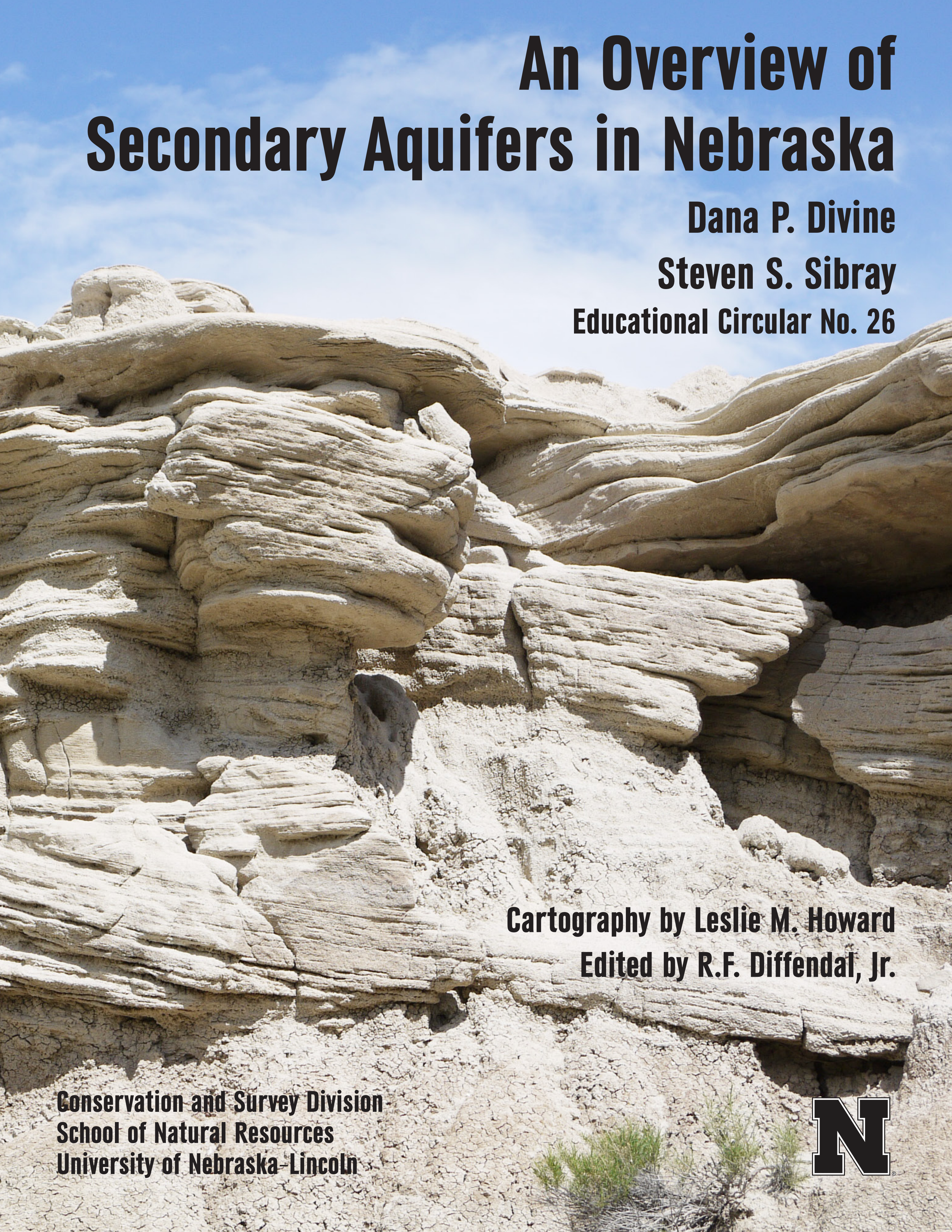
Educational Circular No. 26



Cartography by Leslie M. Howard

Edited by R.F. Diffendal, Jr.

Conservation and Survey Division
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Institute of Agriculture and Natural Resources
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*Cover photo: Brule Sandstone at Toadstool Geologic Park, Sioux County, Nebraska. All photos by the authors, unless otherwise noted.*

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# DEDICATION

This publication is dedicated to the well drillers of Nebraska, past and present, whose work has provided many geologic samples from the secondary aquifers, and whose sample descriptions provide the basis for this publication.

*Conservation and Survey Division drilling crew*
*Photo courtesy of Shawna Richter-Ryerson, University of Nebraska*

# INTRODUCTION

An aquifer is a body of geologic material that yields water in economically useful quantities. This definition is fairly simple, but describing the structure of aquifers and the ways in which they store and yield water is much more complicated. Thus, aquifers remain an abstract concept for many people, and all the more so because they are not directly visible. This publication describes seven secondary aquifers in Nebraska so that they will be better understood by the people who already depend on them, and by those who seek to use them in the future.

Many Nebraskans are familiar with the two largest, most extensively used aquifers in the state. These aquifers, called primary aquifers, are the High Plains aquifer (sometimes called the Ogallala aquifer) and the shallow, unconsolidated (loose) sand and gravel that is common across the state. The High Plains aquifer underlies much of the state, and although it typically yields large volumes of water, there are places where it does not, especially along its margins (Fig. 1). The "sand and gravel aquifer" is not a single, continuous sheet of sediment. Instead, the term refers broadly to the sand and gravel that is present in a variety of settings including: river and stream valleys; paleovalleys (buried ancient valleys); sand dunes; and glacial drainages. The sand and gravel aquifer overlies the High Plains aquifer across much of central Nebraska, and the presence of two primary

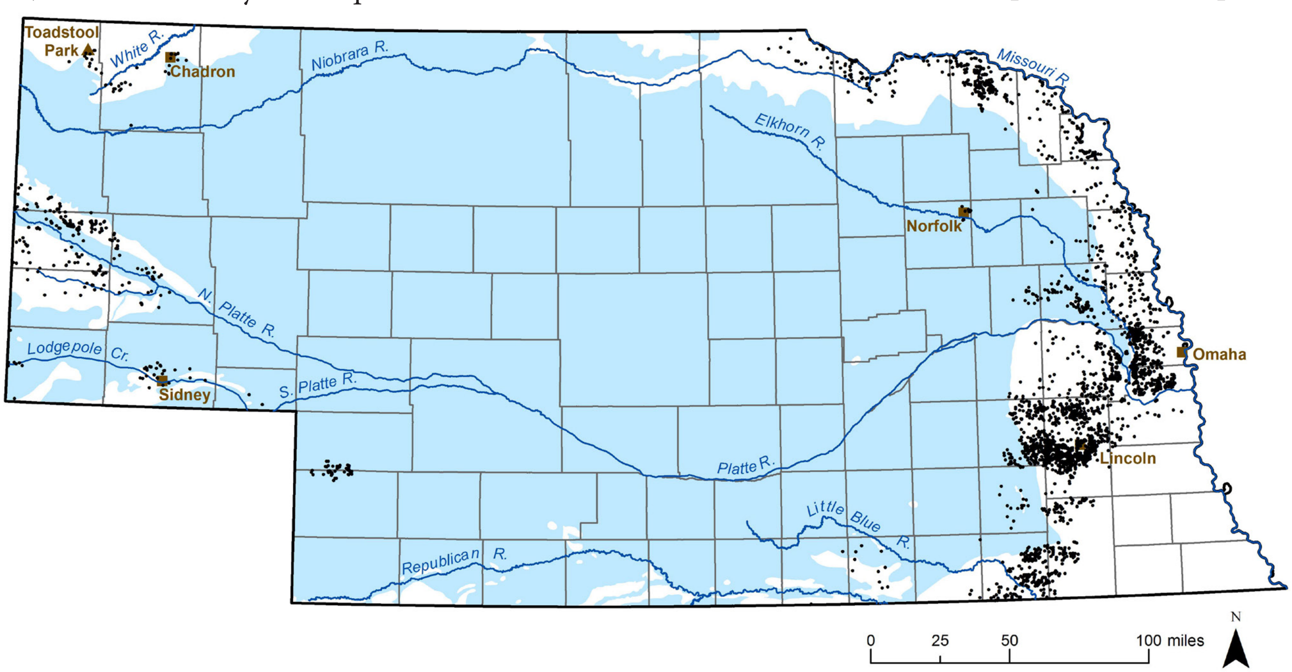
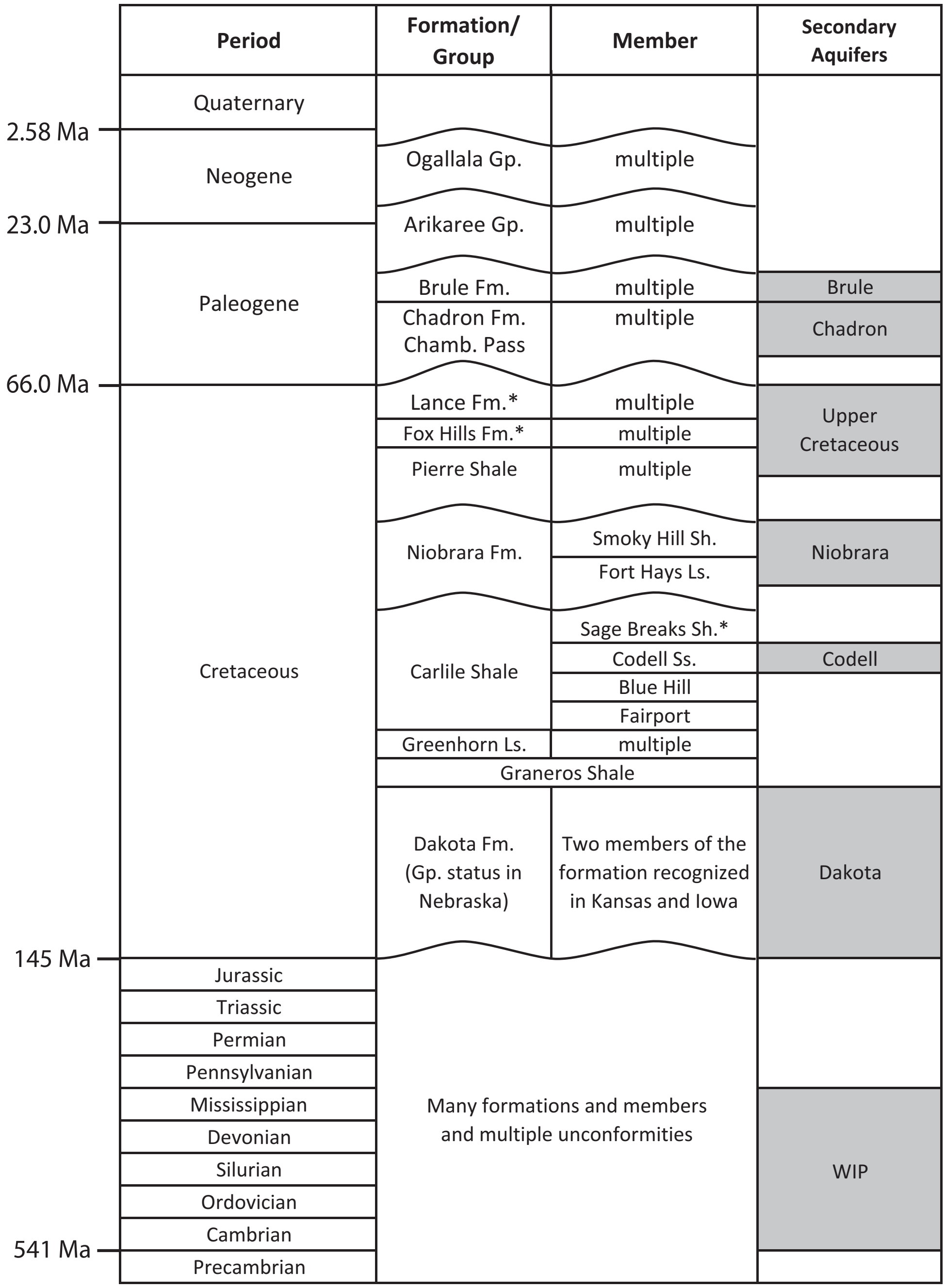



*Figure 1. Locations of wells in secondary aquifers (black dots) relative to the High Plains aquifer (shown in blue).*

aquifers results in copious amounts of groundwater. These primary aquifers are thin or absent in much of eastern Nebraska and in much of the Panhandle. Secondary aquifers, which generally have lower yield and poorer water quality than primary aquifers, are consequently important to a large segment of the population in these two areas.

The primary aquifers are hosted by weakly consolidated materials (i.e., very soft sedimentary rocks) or unconsolidated (loose) sediments. The secondary aquifers in this publication are all hosted by bedrock units (Fig. 2) that are generally more consolidated and harder to drill through than the strata associated with the primary aquifers. The




Modified from Korus and Joeckel, 2011.

* applies in the vicinity of the Denver-Julesburg Basin
Ls = Limestone
Sh = Shale
Ss = Sandstone
Gp = Group
Fm = Formation
Ma = Millions of years ago
WIP = Western Interior Plains

*Figure 2. Stratigraphic chart showing the chronologic order of geologic units in Nebraska. Wavy lines represent unconformities (gaps in the rock record).*

primary and secondary aquifers also differ in that the primary aquifers are more likely than secondary aquifers to be unconfined, while the secondary aquifers are more likely to be confined.

The water in an unconfined aquifer is in direct connection with the atmosphere, which means it is typically shallow and has little or no fine-grained material deposited between it and the land surface. The elevation of water in an unconfined aquifer is colloquially called the water table (the technical definition of the water table is more complicated). The water table is at or below the top of the aquifer. When a well in an unconfined aquifer is pumped, the pore space between sand grains is drained and the elevation of the water table is lowered. Conversely, a confined aquifer is not in direct contact with the atmosphere. The water in this type of aquifer is generally under pressure. When a well is installed in a confined aquifer, the pressure pushes the water up the well above the top of the aquifer. The elevation of water in a confined well is called the pressure head and the imaginary surface that would be created by connecting the pressure heads from multiple wells across an area is called the potentiometric surface. Simply put, the potentiometric surface is to confined aquifers what the water table is to unconfined aquifers. When wells in confined aquifers are pumped, the pressure head falls rapidly, but the pore spaces in the aquifer do not drain until the pressure is completely dissipated. Flowing wells occur when the pressure head is sufficient to push the water in the well higher than the land surface.

The secondary aquifers of Nebraska are herein discussed from geologically oldest to youngest. All of the strata hosting secondary aquifers in eastern Nebraska are older than those that host secondary aquifers in the Panhandle, which makes it convenient to divide our forthcoming discussion into two parts, the eastern and western parts of Nebraska. We have identified registered wells that produce exclusively from each of the secondary aquifers, thereby providing a very specific geographic characterization of secondary aquifers relative to current and historic use. When more than one secondary aquifer underlies an area, the aquifers occur at different depths and are separated by low-permeability strata that limit hydraulic connection between aquifers.

The discussion of each secondary aquifer addresses each the following questions:

- Where is the aquifer located?
- How extensively is it used in Nebraska?
- What are the average well depth, depth to water, and yield in Nebraska?
- Where are the recharge and discharge areas?
- What is the water quality of the aquifer?
- What are potential problems associated with using the aquifer?
- What do cuttings from strata hosting the aquifer look like?

Although Nebraska's secondary aquifers are inadequately studied, we hope that this publication will both increase public awareness and stimulate scientific attention.

*Photo courtesy of Conservation and Survey Division*

*Dana Divine and Sue Lackey, Conservation and Survey Division*

# SECONDARY AQUIFERS IN EASTERN NEBRASKA

There are four secondary aquifers in eastern Nebraska. These aquifers, from oldest (stratigraphically lowest) to youngest (stratigraphically highest) (Fig. 2) are the: Western Interior Plains (WIP) aquifer system, Dakota aquifer, Codell aquifer, and Niobrara aquifer. The extent to which these aquifers are used varies from only one active registered pumping well in the Western Interior Plains aquifer system to more than 3,000 active registered wells in the Dakota aquifer (Fig. 3a-e). The bedrock map (Fig. 3a) identifies the bedrock units that directly underlie the unconsolidated sediments and soils that cover most of Nebraska. Each of the points in Figure 3b-e represents an active registered well in a specific aquifer. Most of the wells in an aquifer correspond to the area where the rock strata hosting the aquifer is the first (shallowest) rock unit encountered after drilling downward through unconsolidated materials. However, in some areas wells were drilled through younger bedrock units to access an underlying secondary aquifer. Wells in these areas plot atop the shallowest bedrock unit shown in figure 3a even though the water is sourced from a deeper bedrock aquifer.

## Western Interior Plains aquifer system

### Where is the Western Interior Plains aquifer system located?

The Western Interior Plains aquifer system as defined by the U. S. Geological Survey underlies Kansas, much of Nebraska, and a portion of western Missouri (Figure 4-page 6, Table 1-pages 8-9) (Miller and Appel, 1997). It consists mostly of dolostone (altered limestone), limestone, and sandstone strata that are stratigraphically equivalent and hydrologically connected to geologic units in the Ozark Plateaus aquifer system of southern Missouri and northern Arkansas (Miller and Appel, 1997; Miller and Vandike, 1997). The main distinction between the two regional aquifer systems is that the water quality in the Western Interior Plains aquifer system is generally much poorer than that in the Ozark Plateaus aquifer system (Miller and Appel, 1997).

The Western Interior Plains and Ozark Plateaus aquifer systems are hosted by Cambrian through Mississippian strata. Younger Pennsylvanian and Permian (323 Ma to 252 Ma) strata overlie the Western Interior Plains aquifer system in eastern Nebraska, but they are not high-yielding enough on a regional scale to be included in large aquifer systems (Table 1). Locally, the Pennsylvanian and Permian units provide water to low-yielding wells (Engberg and Druliner, 1987; Miller and Vandike, 1997). Specific aquifers are defined in these units in Kansas (Macfarlane, 2000), but no such aquifers are recognized in Nebraska. Nevertheless, the constituent bedrock strata provide limited amounts of groundwater to a small number of wells in ten counties in the state (Engberg and Druliner, 1987).

The U.S. Geological Survey term “Western Interior Plains aquifer system” is useful for grouping water bearing geologic units on a regional scale, but it also has limitations. First, the term is not applied in Iowa, even though the hydrostratigraphic units are generally continuous across eastern Nebraska and western Iowa (Carlson et al., 1986). Second, the term lacks specificity in describing aquifers at the scale of an individual state or some part thereof. Most states subdivide aquifer systems into specific aquifers, the stratigraphic components of which vary somewhat from state to state.

Table 1 shows the hydrostratigaphic correlation of Paleozoic aquifers in Nebraska, Iowa, Kansas, and Missouri and the various names applied to them. The water-bearing bedrock units in the Western Interior Plains aquifer system have neither been studied in detail nor given specific

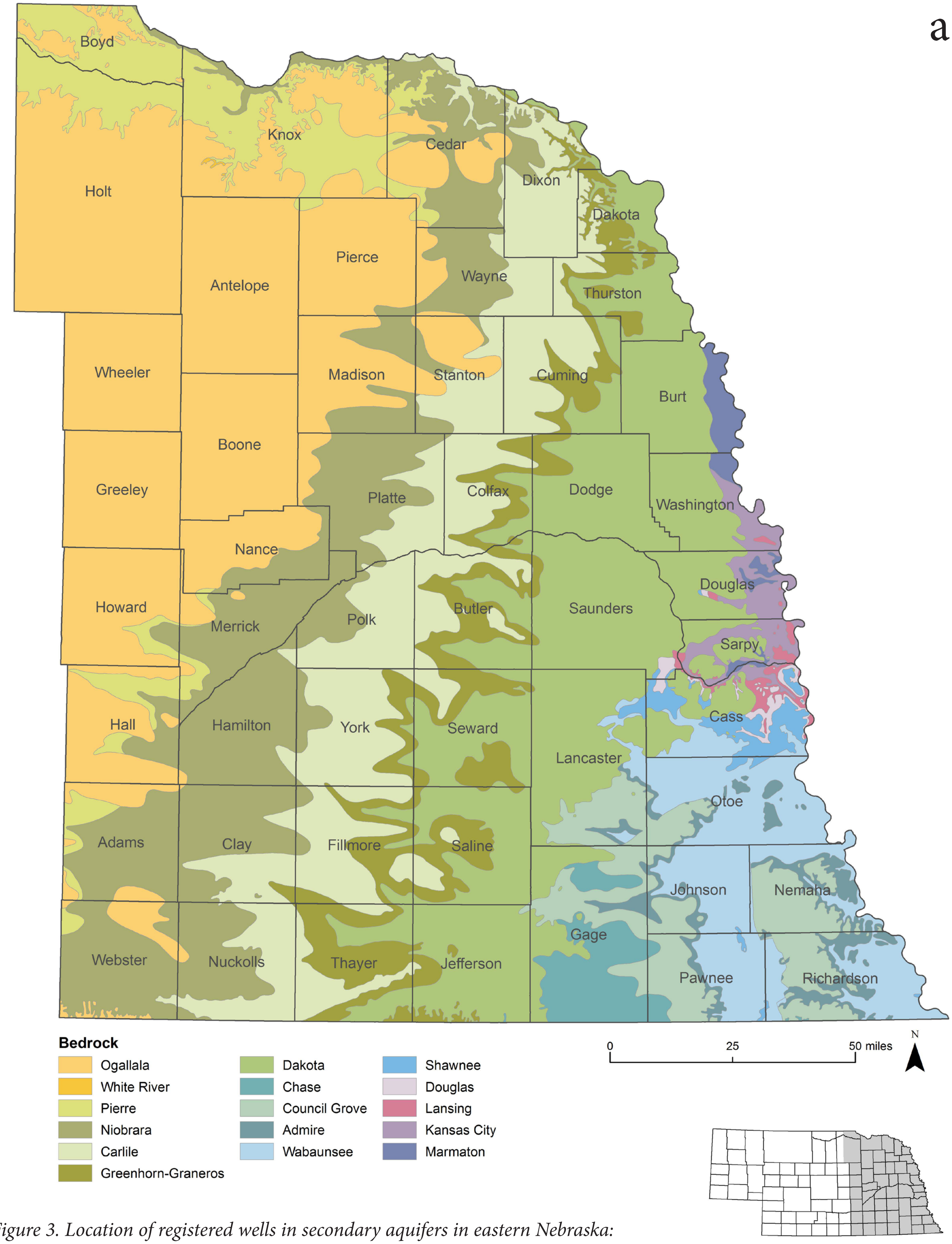



*Figure 3. Location of registered wells in secondary aquifers in eastern Nebraska: (a) upper-most bedrock units (from Burchett, 1986); (b) Western Interior Plains aquifer system well location; (c) Dakota aquifer well locations; (d) Codell aquifer well locations; (e) Niobrara aquifer well locations.*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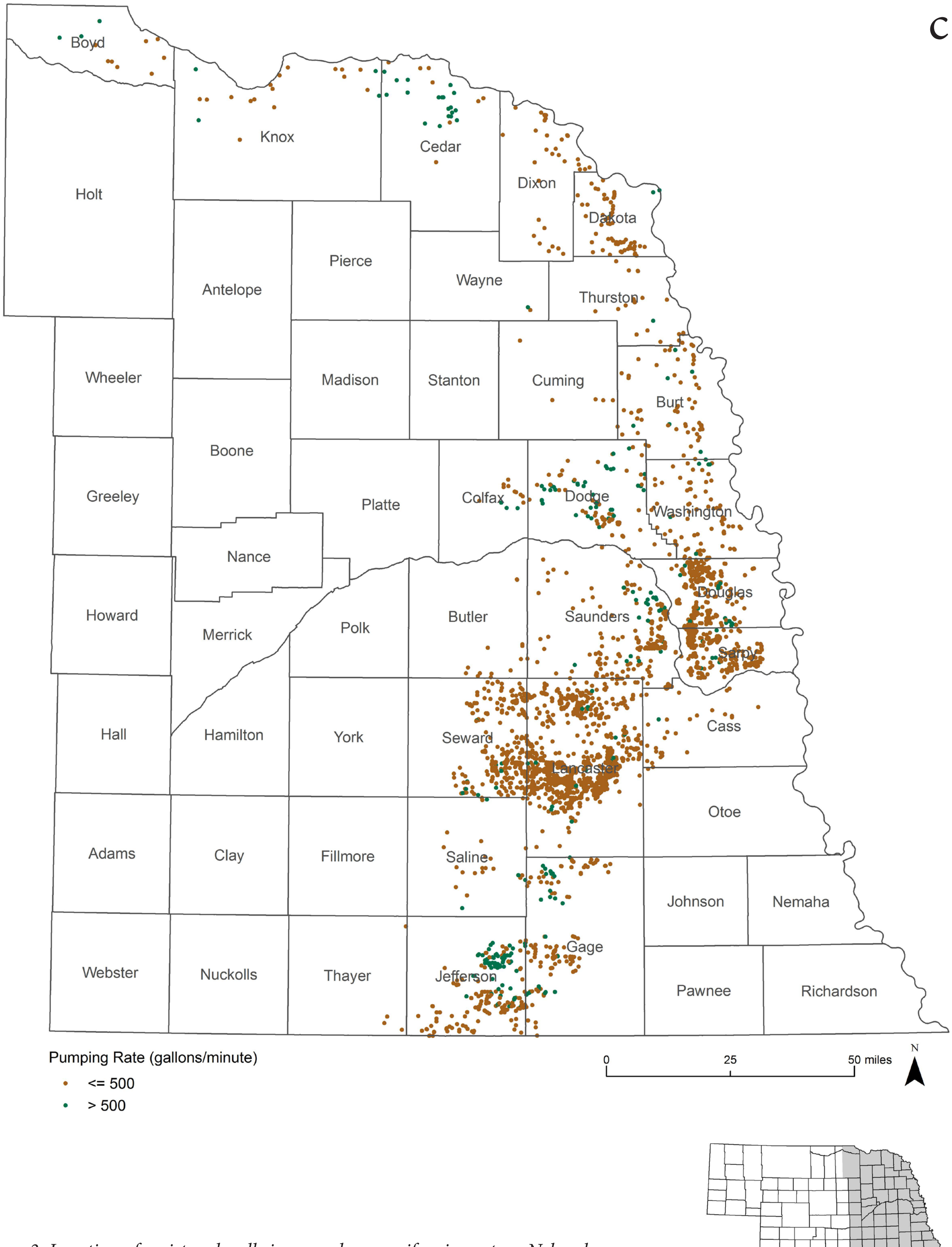


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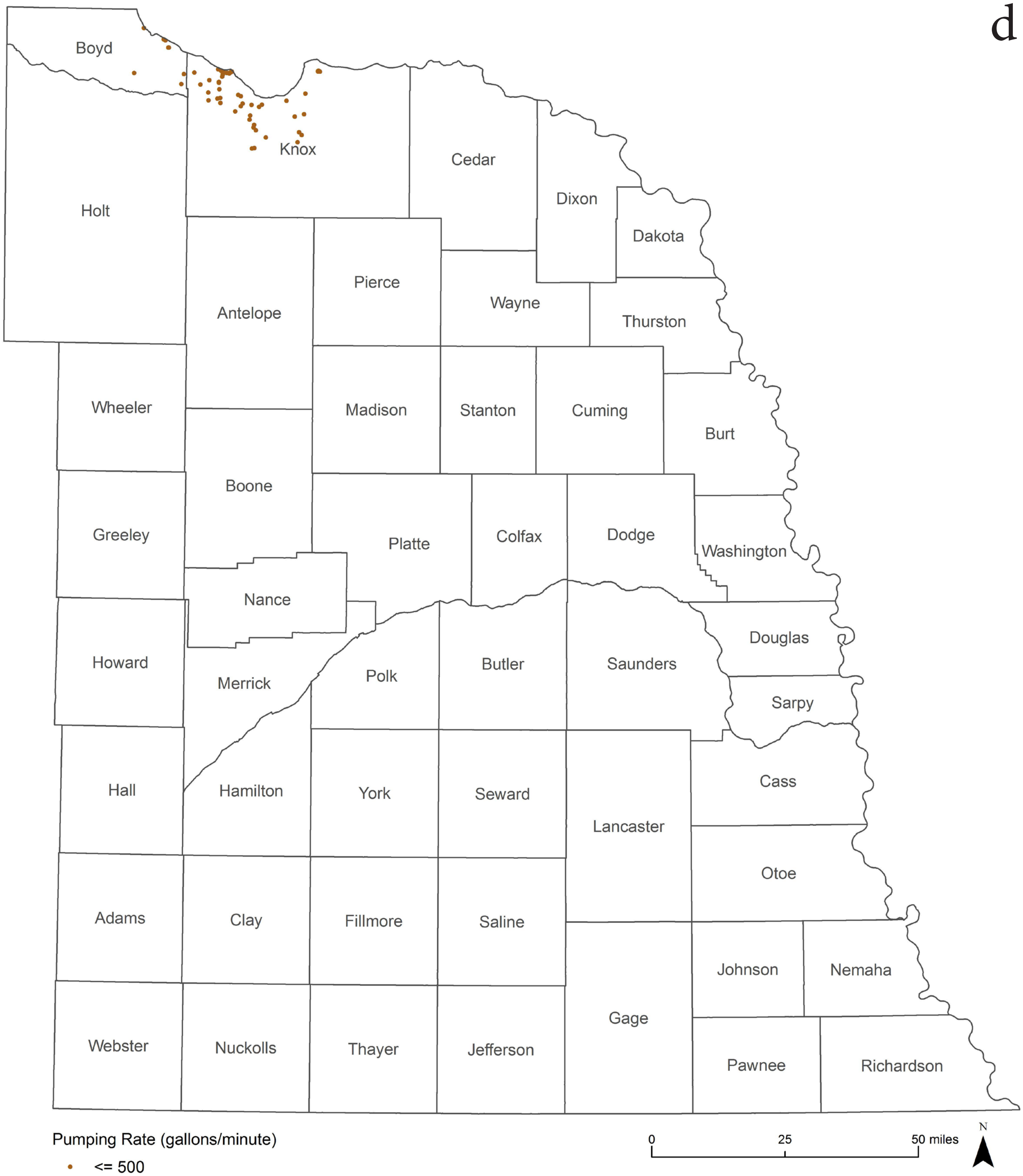
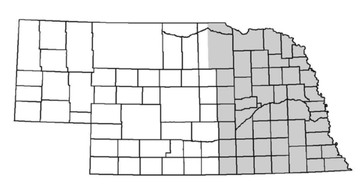
d



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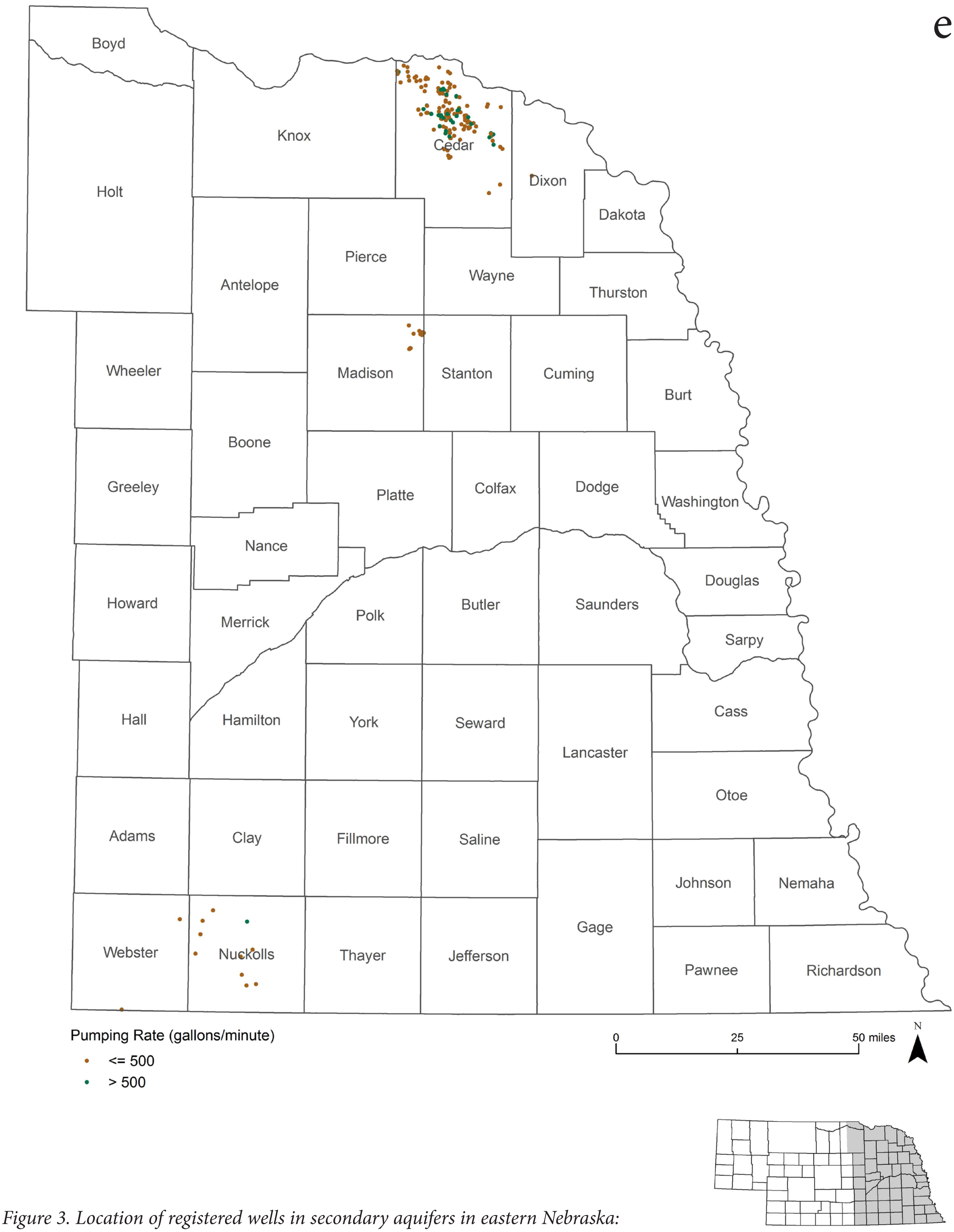


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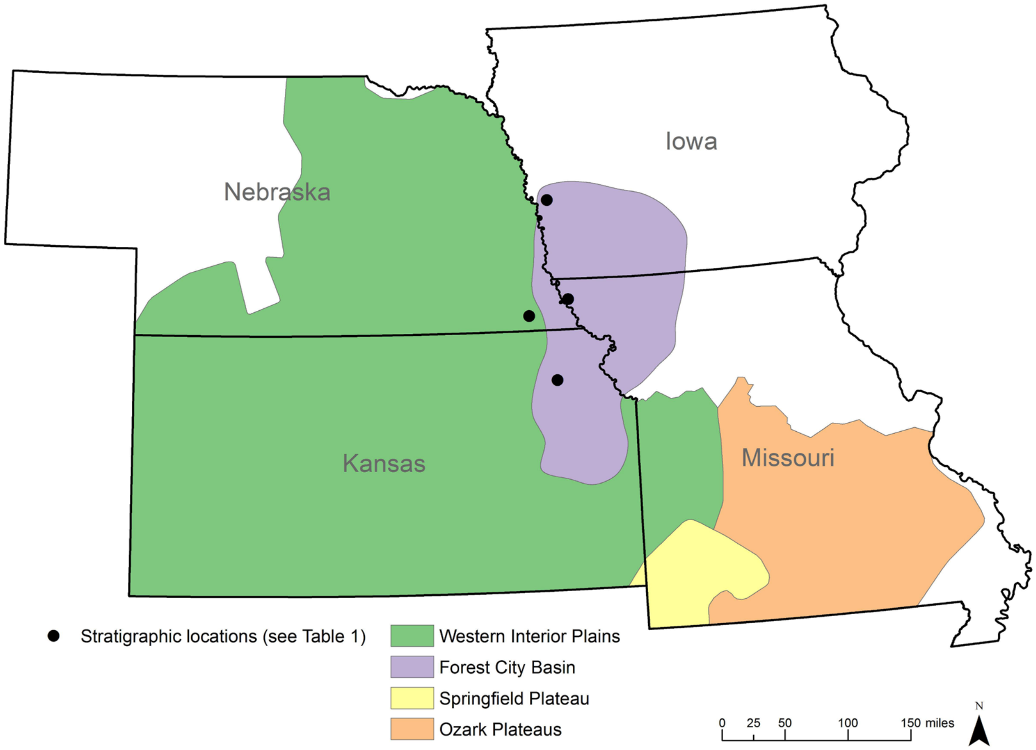



*Figure 4. Location of regional Paleozoic aquifer systems in relation to the Forest City basin.*

names in Nebraska. Nevertheless, water-bearing stratigraphic intervals appear to correlate with defined aquifers in adjacent states (Table 1). In Nebraska, these bedrock units are used as water sources only in the extreme eastern portions of the state; in central Nebraska and Kansas, the water in the aquifer system is saline to brine, with estimated total dissolved solids (TDS) concentrations ranging from 11,000 to 200,000 milligrams per liter (mg/l) (Korus et al., 2013; Macfarlane, 2000; Miller and Appel, 1997; Carlson and Sibray, 1992). The TDS concentration is a common measure for characterizing general water quality, and ranges of TDS are assigned the terms fresh, brackish, saline, and brine in order from lowest to highest TDS (Helgesen et al., 1993).

The mapped extent of the Western Interior Plains aquifer system includes the Forest City basin, a somewhat poorly defined structural depression in which certain stratigraphic units are present at greater depth than in surrounding areas (Prior et al., 2003). Where these stratigraphic units are deeply buried, groundwater quality is significantly poorer relative to areas outside the basin where the same strata lie at shallower depths (Olcott, 1992). This difference in water quality develops because shallow aquifers are generally recharged with relatively fresh water that passes through the hydrologic cycle quickly relative to deep water that may spend thousands of years in the aquifer, during which time it dissolves minerals from the host rocks. The Western Interior Plains aquifer system is suitable for high-yield, non-potable wells only on the western edge of the Forest City Basin where no other high-yield aquifers exist. Within the basin potential aquifer units may be petroleum reservoirs.

| Total Dissolved Solids (mg/l) | Salinity Category |
|---|---|
| 500 | recom. drinking water limit |
| 0-1,000 | fresh |
| 1,000-10,000 | brackish |
| 10,000-35,000 | saline |
| ~ 35000 | sea water |
| > 35,000 | brine |

## How extensively is the Western Interior Plains aquifer system used in Nebraska?

Wells in the Western Interior Plains aquifer system are limited to the Omaha area. Pipes (1987) listed the users of Western Interior Plains aquifer system wells as follows: Henry Doorly Zoo for maintenance of an artificial waterfall and fish pond;

Omaha Cold Storage for cooling water; Missouri River Waste Water Treatment Plant for general non-potable water needs and sewage dilution; Lonergran Lake for lake-level maintenance; and one domestic supply well in Washington County. Many of the wells in the aquifer were historically flowing, but hydraulic heads have declined substantially in the Omaha Metro area (Pipes, 1987), with the water level at Henry Doorly Zoo measured at about 42 feet (13 m) below ground surface in 2015 (Nebraska Department of Natural Resources, undated). In 1905, N.H. Darton listed 13 wells producing "water of excellent quality, having sufficient head to afford surface flows over a wide area" in strata we would now assign to the Western Interior Plains aquifer system. One well seven miles west of Omaha reportedly flowed at a rate of over a million gallons per day (Darton, 1905). A review of the Nebraska Department of Natural Resources registered well database in 2016 identified three pumping wells in the Western Interior Plains aquifer system, only one of which was listed as active (Fig. 3b).

The Western Interior Plains aquifer system is not widely used because of its comparatively great depth and inferior water quality, at least according to modern standards. In contrast, hydrostratigraphically equivalent aquifers in Iowa and farther east are heavily used, as is the Ozark Plateaus aquifer system in southern Missouri and Arkansas (Prior et al., 2003; Miller and Appel, 1997; Miller and Vandike, 1997). This contrast in use is the result of Paleozoic aquifers being shallower and receiving more recharge in those more eastern and southeastern locales.

### What are the average well depth, depth to water, and yield of Western Interior Plains aquifer system wells in Nebraska?

The single active pumping well in Nebraska is a commercial well in Cass County registered to Omaha Public Power District (Fig. 3b). The total depth of this well is 1,215 feet (370 m) with a static water level of 198 feet (60 m) and a pumping rate of 200 gpm (760 lpm). A well installed at the Henry Doorly Zoo in 2015 is 2,008 feet (612 m) deep and the static water level is 42 feet (13 m) below ground surface, but this well is listed as inactive and no pumping rate has been recorded for it (Nebraska Department of Natural Resources, undated). The specific aquifers from which these wells produce cannot be determined from the well logs. Well depth, depth to water, and yield vary considerably given the wide variety of individual aquifers that exist within the system (Olcott, 1992; Pipes, 1987).

Paleozoic bedrock units consist mostly of alternating limestone, dolostone, and shale. Dolostone is limestone that has been chemically altered after burial due to the introduction of magnesium by groundwater. Magnesium atoms replace calcium atoms, gradually converting calcite (the chief mineral in limestones) to dolomite, and thus a limestone is converted to a dolostone.

A dolostone can have significantly more pore space than its precursor limestone because the crystal structure of dolomite is smaller than calcite (Murray, 1960). In this case, the resulting porosity is called "secondary porosity" because it was not originally present when the rock formed, but instead developed over time due to alteration of the rock. Other types of secondary porosity include dissolution fractures and vugs (visible cavities larger than an intergranular pore space). Development of secondary porosity results in potentially higher well yield.

### Where are the recharge and discharge areas of the Western Interior Plains aquifer?

Recharge areas for the Western Interior Plains aquifer system in Nebraska have not been identified, but speculatively, recharge is more likely where the strata are closest to the surface in the vicinity of the Missouri River in northeastern Nebraska and the Nemaha Uplift in southeastern Nebraska (Carlson and Sibray, 1992). Regional groundwater movement is southeastward to eastward (Miller and Appel, 1997; Olcott, 1992) and much of the groundwater discharges to springs and streams in the transition zone between the Western Interior Plains and the Ozark Plateaus aquifer systems (Miller and Appel, 1997).

| Era | System | ROCK STRATIGRAPHIC UNITS | | | | |
|---|---|---|---|---|---|---|
| | | Pawnee County, NE | Jackson County, KS | Atchison County, MO | Forest City Basin, NE | Harrison/Pott., IA |
| Paleozoic | Permian | | Council Grove Gp. | | | |
| | Pennsylvanian | | Admire Gp. | Indian Cave Ss. | | |
| | | Wabaunsee Gp. | Wabaunsee Gp. | Wabaunsee Gp. | Wabaunsee Gp. | |
| | | Shawnee Gp. | Shawnee Gp. | Shawnee Gp. | Shawnee Gp. | Shawnee Gp. |
| | | Douglas Gp. | Douglas Gp. | Douglas Gp. | Douglas Gp. | Douglas Gp. |
| | | Lansing Gp. | Lansing Gp. | Lansing Gp. | Lansing Gp. | Lansing Gp. |
| | | Kansas City Gp. | Kansas City Gp. | Kansas City Gp. | Kansas City Gp. | Kansas City Gp. |
| | | | Pleasanton Gp. | Pleasanton Gp. | Pleasanton Gp. | Pleasanton Gp. |
| | | | Marmaton Gp. | Marmaton Gp. | Marmaton Gp. | Marmaton Gp. |
| | | | Cherokee Gp. | Cherokee Gp. | Cherokee Gp. | Cherokee Gp. |
| | | | Penn. basal congl. | Riverton Sh. | Penn. basal congl. | |
| | Mississippian | | | Ste. Genevieve Fm. | | |
| | | | | St. Louis Ls. | St. Louis Fm. | St. Louis Fm. |
| | | | | Salem Fm. | | |
| | | | | Warsaw Fm. | Warsaw Fm. | Warsaw Fm. |
| | | | Osagean | Keokuk Ls. | Keokuk Ls. | Keokuk Ls. |
| | | | | Burlington Ls. | Burlington Ls. | Burlington Ls. |
| | | | Gilmore City Ls. | Gilmore City Ls. | Gilmore City Ls. | Gilmore City Ls. |
| | | | Sedalia Dol. | | | |
| | | | Chouteau Ls. | Chouteau Gp. | Chouteau Gp. | Maynes Creek Fm. |
| | | | | | | North Hill Gp. |
| | Devonian | | Boice Sh. | Boice Sh. | Boice Sh. | Femmennian strata undiff. |
| | | | Chattanooga Sh. | Chattanooga Sh. | Chattanooga Sh. | |
| | | | | Lime Creek Fm. | Lime Creek Fm. | Lime Creek Fm. |
| | | | | | | |
| | | | | Cedar Valley Gp. | Cedar Valley Gp. | Cedar Valley Gp. |
| | | | mid-Devonian undiff. | Wapsipinicon Gp. | Wapsipinicon Gp. | |
| | Silurian | | | | | |
| | | | Silurian undiff. | Silurian undiff. | Silurian undiff. | Silurian undiff. |
| | Ordovician | | Maquoketa Sh. | Maquoketa Sh. | Maquoketa Sh. | Maquoketa Sh. |
| | | | Viola Ls. | | | |
| | | | Galena Gp. | Galena Gp. | Galena Gp. | Galena Gp. |
| | | | Platteville Fm. | Plattin Fm. | Platteville Fm. | Platteville Fm. |
| | | | | | | Glenwood Sh. |
| | | | St Peter Ss. | St. Peter Ss. | St. Peter Ss. | St. Peter Ss. |
| | | | | | | |
| | | | Arbuckle Gp. | Jefferson City Dol. | Prairie Du Chien Gp. | |
| | | | | Roubidoux Fm. | | Oneota Fm. |
| | | | | Gasconade Dol. | | |
| | | | | Eminence Dol. | Jordan Ss. | Jordan Ss. |
| | Cambrian | | | Potosi Dol. | | St. Lawrence Fm. |
| | | | | Derby-Doerun Dol. | | |
| | | | | Davis Fm. | | Davis Fm. |
| | | | | Bonneterre Fm. | Bonneterre Dol. | Bonneterre Fm. |
| | | | Lamotte Ss. | Lamotte Ss. | Lamotte Ss. | Mount Simon Ss. |

*Table 1. Hydrostratigraphic correlations of Paleozoic aquifers in Nebraska, Iowa, Kansas, and Missouri.*

| AQUIFERS | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Nebraska** | **Iowa** | **Kansas** | **Missouri** | **USGS** | | | |
| | | Flint Hills | | | | | |
| | | | | | | | |
| | | Osage Cuestas | | | | | |
| | | | | | | | |
| | | | | WIP (upper) | Mississippian aquifer | Ozark Plateaus aquifer system | Springfield Plateau aquifer |
| water bearing | Miss. (upper) | Springfield Plateau aquifer | Springfield Plateau aquifer | | | | |
| | | | | | | | |
| | Miss. (lower) | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| water bearing | Lime Creek | | | Western Interior Plains aquifer system (lower) | Silurian-Devonian aquifer | | Ozark aquifer |
| | | | | | | | |
| | Cedar Valley | | | | | | |
| | | | | | | | |
| water bearing | Silurian | | | | | | |
| | Galena-Maquoketa | | | | | | |
| water bearing | | | Ozark aquifer (upper) | | | | |
| | | | | | | | |
| water bearing | Cambro-Ordovician (Jordan) | | | | St. Peter-Prairie du Chien-Jordan | | |
| | | | Ozark aquifer (lower) | | | | |
| | | Ozark aquifer | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | St. Francois | | | | St. Francois |
| water bearing | Mt. Simon | | | | Mt. Simon | | |

*Table 1 (continued). Hydrostratigraphic correlations of Paleozoic aquifers in Nebraska, Iowa, Kansas, and Missouri.*

## What is the water quality in the Western Interior Plains aquifer?

The water quality of the Western Interior Plains aquifer system in Nebraska is marginal to very poor (brackish to brine). Carlson and Sibray (1992) and Pipes (1987) summarized the results of measured total dissolved solids (TDS) concentrations in water samples and estimated concentrations from down-hole geophysical logs. The U.S. Environmental Protection Agency's secondary drinking water standard for TDS is 500 mg/l. Essentially all of the groundwater samples analyzed from the Western Interior Plains aquifer system attain or well exceed this concentration, frequently by an order of magnitude or more.

The oldest unit for which there is water quality data in Nebraska is the Cambrian-Ordovician zone associated with the St. Peter Sandstone, Prairie Du Chien Group, and the Jordan Sandstone (Table 1). Reported data indicate an approximate range in TDS from 720 mg/l to 3,800 mg/l in this aquifer across much of eastern Nebraska, although one sample in Richardson County is reported at 33,785 mg/l (Carlson and Sibray, 1992). Across much of Iowa, this aquifer has generally good water quality and is widely used for high-yield wells, although in some locations it is treated to reduce radium concentrations (Prior et al., 2003; Carlson and Sibray, 1992).

The stratigraphically next-highest aquifer lies in the Galena Group (Fig. 2) and it has measured TDS concentrations from approximately 500 mg/l to about 2,000 mg/l across much of eastern Nebraska, except in Richardson County where measured concentrations range from 7,580 mg/l to 9,500 mg/l (Carlson and Sibray, 1992). Pipes (1987) estimated a TDS concentration of 640 mg/l in the Omaha area for the aquifer hosted by the Galena Group, which he concluded was the highest-quality water that could be expected for the entire Paleozoic succession in the area.

Previous studies group the Silurian aquifer shown in Table 1 with the overlying Devonian aquifer (Carlson and Sibray, 1992; Olcott, 1992; Pipes, 1987), although the intervening Wapsipinicon Group may be an aquitard (Prior et al., 2003; Witzke, undated). Pipes (1987) estimated that the Silurian-Devonian aquifers have a TDS of 2,500 mg/l, which falls within the 1,000 mg/l to 6,000 mg/l range reported by Carlson and Sibray (1992).

The Mississippian aquifer, although it is shallower than other aquifers in the Western Interior Plains aquifer system, is also likely to be of comparatively low quality. Pipes (1987) deemed this zone unacceptable for most uses in the Omaha area. The one measured sample reported by Carlson and Sibray (1992) was 6,560 mg/l in Otoe County. TDS concentrations estimated from bore hole electrical logs for this aquifer in eastern Nebraska range from 14,000 mg/l to 25,000 mg/l (Carlson and Sibray, 1992).

The most abundant dissolved ions overall in the Western Interior Plains aquifer system are sodium (Na), chloride (Cl), and sulfate ($SO_4$) (Olcott, 1992; Pipes, 1987). Pipes (1987) found that sodium-sulfate type groundwater was most common in the aquifer system, except in the aquifer hosted by the Galena Group, which was of sodium-bicarbonate type.

## What are the potential problems associated with using the Western Interior Plains aquifer system?

Use of the Western Interior Plains aquifer system in Nebraska is fundamentally limited by its comparatively great depth and its marginal to very poor (brackish to brine) water quality. The lack of scientific information about this aquifer system in Nebraska also impairs assessment and, ultimately, development. The aquifer system is shallower, the water quality is better, and the individual aquifers are well-defined east of Nebraska, but water-level declines coincide with this much greater usage. The regional Cambrian-Ordovician aquifer that corresponds to the St. Peter Sandstone, Prairie Du Chien Group, and Jordan Sandstone geologic units is under stress from extensive groundwater withdrawals in southeastern Wisconsin, Iowa, and the Chicago area (Olcott, 1992), with a potentiometric surface decline of 50 to 150 feet (15 to 45 m) in Iowa (Prior et al., 2003).

### What do cuttings from strata hosting the Western Interior Plains aquifer look like?

The Cambrian-Ordovician aquifer associated with the St. Peter Sandstone, the Prairie Du Chien Group, and the Jordan Sandstone consists of sandy limestone and dolostone with interbedded fine to coarse sandstone (Carlson and Sibray, 1992). The St. Peter Sandstone is characteristically composed of well-sorted, frosted, rounded sand, consisting almost entirely of quartz, and pure white where unweathered (Miller and Vandike, 1997). In eastern Nebraska, the St. Peter Sandstone averages only 30 feet (9 m) in thickness (Pipes, 1987).

The Ordovician aquifer associated with the Galena Group consists of interbedded dolostones and diagnostic cherty dolostones, many of which have well-developed vugs. Chert is a hard, siliceous sedimentary rock, similar to the material known as flint, and can be challenging to drill through if abundant. Where the characteristic cherty dolostone is absent, it may be difficult to distinguish the Galena Group from the overlying Maquoketa Formation, which consists of argillaceous (clayey) dolostones or calcareous shale (Korus, 2013; Pipes, 1987; Condra and Reed, 1959).

The Devonian aquifer generally consists of interbedded cherty, sandy, and shaly dolostones, with some shale (Korus, 2013; Carlson and Sibray, 1992; Pipes, 1987). The Silurian System in the region has nearly uniform characteristics and it has never been formally differentiated in Nebraska (Condra and Reed, 1959). It consists of cherty dolostones with significant vuggy porosity within some beds (Korus, 2013; Pipes, 1987).

The Mississippian aquifer in Nebraska consists of interbedded limestone and dolostone. The limestone may be oolitic (consisting of small, spheroidal grains with concentric layers) and the dolostone may contain chert and glauconite (greenish colored clay) (Korus, 2013; Pipes, 1987). Chert and glauconite are both secondary minerals that develop after deposition of the host rock, and typically reduce its original permeability (Knauth, 1979; Diaz et al., 2003). Ooids generally form on the sea floor in shallow tropical seas. Unconsolidated ooids have high porosity, but compaction and cementation into rock reduces the porosity and permeability of oolitic limestones to various extents depending on the geochemical environment (Cussey and Friedman, 1977).

*Photo courtesy of Dr. R.M. Joeckel, University of Nebraska*

*The St. Peter Sandstone overlain by the darker Glenwood Shale along U.S. Highway 151 in southwestern Wisconsin.*

## Dakota Aquifer (Maha Aquifer of the Great Plains Aquifer System)

### Where is the Dakota aquifer located?

The Dakota Group is present under approximately 94% of Nebraska, absent only in the southeastern corner of the state. It crops out at the land surface in several places in eastern Nebraska, where it is a secondary aquifer, but may be as much as 3,500 feet (1,067 m) below the land surface in western Nebraska, where it is a petroleum reservoir with TDS concentrations ranging from about 10,000 to more than 100,000 mg/l (Miller and Appel, 1997; Carlson and Sibray, 1992; Ellis, 1984).

The Dakota Group and its equivalents are present from Minnesota to Kansas and, although they are roughly the same age, these units vary considerably in type of source material, grain size, elevation, and hydraulic connection to adjacent geologic units. This variability led geologists to subdivide and name (and often rename) the units so that many different geologic strata were called the "Dakota aquifer." This usage of the term "Dakota aquifer" created confusion, and in 1993, the U.S. Geological Survey proposed that the term Great Plains Aquifer System, subdivided into lower Apishapa and upper Maha aquifers, be used in place of geologic stratigraphic names such as Dakota (Helgesen et al., 1993). This formal aquifer nomenclature is now used in the scientific literature, but in eastern Nebraska the aquifer is still referred to colloquially as the Dakota aquifer with little confusion because it consists solely of the undivided Dakota Group (Condra and Reed, 1959).

### How extensively is the Dakota aquifer used in Nebraska?

The Dakota aquifer was first developed in South Dakota east of the Missouri River, where in 1905 there were more than 1,000 flowing Dakota wells (Darton, 1905). By 1928 there were some 15,000 wells in the Dakota aquifer in North Dakota and South Dakota combined (Helgesen et al., 1984). Moderate withdrawals occurred from the aquifer in Nebraska and Kansas during the 1940s and the 1950s, but use became significant for the first time in the 1960s and then doubled in the 1970s when the region experienced drought (Miller and Appel, 1997; Helgesen et al., 1984).

Nebraska has about 3,400 registered active wells screened entirely in the Dakota aquifer as of 2015. Most of these wells (74%) are private domestic wells. Irrigation wells account for 11% of the total number, livestock wells for 4%, monitoring wells for 4%, public supply (with and without spacing protection) for 3%, commercial wells for 1%, and unspecified other uses for 3% (Figure 5). The average yield for irrigation and commercial wells is about 550 gpm (2,082 lpm). Domestic supply

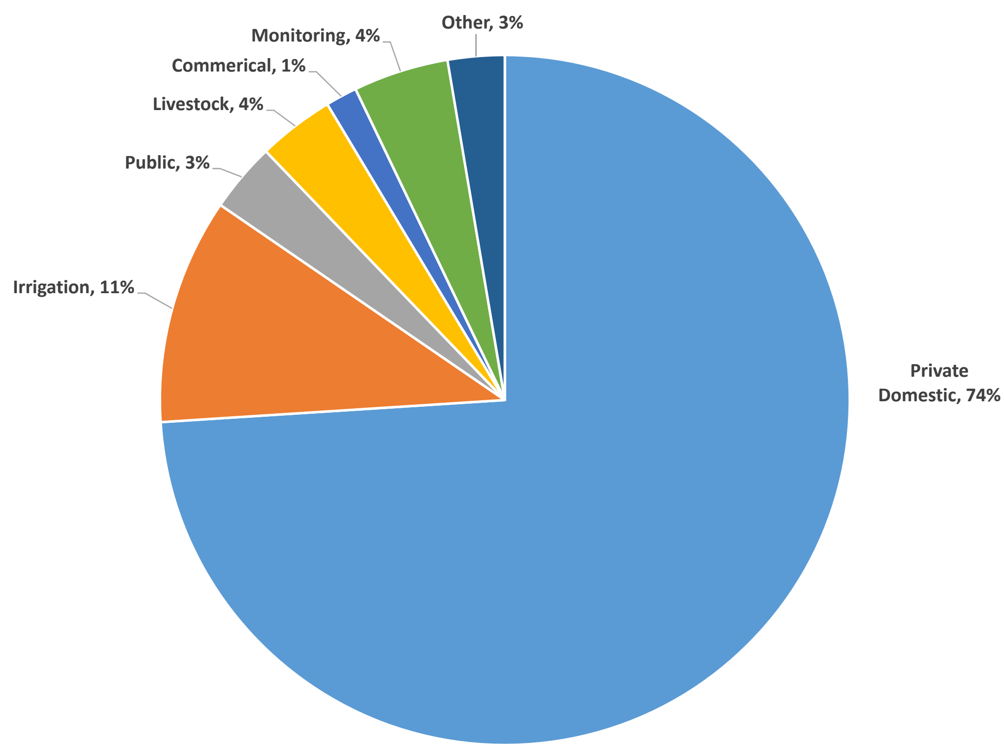



*Figure 5. Distribution of well use type for the Dakota aquifer. The well use for wells in the "Other" category is not specified in the Nebraska Department of Natural Resources Registered Groundwater Wells database.*

also accounts for the majority of Dakota wells in Kansas, with some irrigation use also occurring (Whittemore, et al., 2014). In Iowa, public water supply is estimated to account for more than half of the volume pumped from the aquifer (Gannon and Vogelgesang, undated).

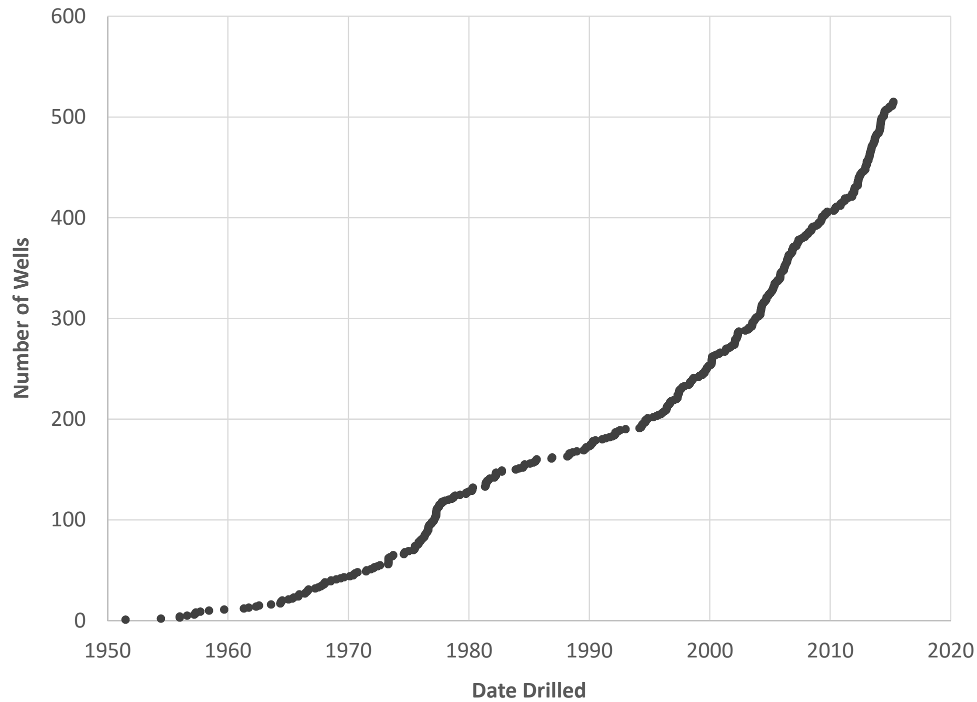



*Figure 6. Cumulative number of registered Dakota aquifer wells in Nebraska. Only irrigation, commercial, and public supply wells are included in the count.*

Figure 6 shows the cumulative number of commercial, irrigation and public supply wells by completion date that were active in Nebraska as of 2015. Domestic and other low capacity wells are excluded because registration of those wells was not required until 1993, and their inclusion with the high-yield wells creates an artificial increase starting in 1993. Figure 6 shows that the number of high-yield wells increases exponentially from 1950 onward, with an especially high rate in the late 1970s, which corresponds to a drought. The first registered domestic well that remains active was installed in Douglas County in 1960. Since 1993, the number of registered domestic wells in the Dakota aquifer in eastern Nebraska has increased at a rate of about 130 wells per year.

## What are the average well depth, depth to water, and yield of Dakota wells in Nebraska?

Most of the porosity in the Dakota aquifer is intergranular, although joints, fractures, and bedding planes exist and transmit water locally in the sandstones. Much of the aquifer is confined, but there are significant areas were the aquifer is unconfined and localized recharge and discharge occur.

Dakota wells in Nebraska are primarily located along a northeast-southwest belt where the Dakota Group is the uppermost bedrock unit, although about 10% of Dakota wells are located west of this belt where younger Cretaceous confining units overlie the Dakota Group, particularly in Dixon, Cedar, Knox and Boyd counties (Fig. 3a,c). Large pressure heads exist in this area (Table 2) and some wells flow. Table 2 shows that the average total depth of Dakota wells varies considerably in Nebraska. The greatest average total depth (about 1,020 feet [311 m]) is in Boyd County, with the shallowest wells on average occurring in Cass County (about 130 feet [40 m]). The average depth to water is much less variable, ranging from about 200 feet (61 m) in Knox County to about 65 feet (20 m) in Cass and Thayer counties. Large pressure heads in the deep wells reduce the depth to water in these wells and the overall difference in depth to water in the aquifer across the state.

Groundwater in the Dakota aquifer flows predominantly to the east in eastern Nebraska. The potentiometric surface elevation varies from about 1,300 feet (396 m) in wells on the western side of the aquifer to about 1,100 feet (335 m) in wells on the eastern edge. Knox County appears to be an exception to this rule: there, the potentiometric surface elevation may be as high as 1,500 feet (457 m) and groundwater flows to the north (Korus et al., 2013). The flow direction is not necessarily similar in surrounding states due to localized recharge and discharge areas (Burkhart, 1984; McGovern, 1984; Munter et al., 1983). Compared with the earliest survey conducted in 1908, head

| County | Average Static Water Level, ft | Average Total Depth, ft | Average yield, gpm |
|---|---|---|---|
| **Boyd** | 175 | 1,021 | 352 |
| **Burt** | 98 | 218 | 127 |
| **Butler** | 168 | 392 | 39 |
| **Cass** | 65 | 127 | 87 |
| **Cedar** | 102 | 660 | 746 |
| **Colfax** | 121 | 321 | 153 |
| **Cumming** | 133 | 304 | 16 |
| **Dakota** | 105 | 236 | 65 |
| **Dixon** | 167 | 365 | 43 |
| **Dodge** | 74 | 271 | 353 |
| **Douglas** | 124 | 236 | 96 |
| **Gage** | 88 | 162 | 200 |
| **Jefferson** | 91 | 201 | 309 |
| **Knox** | 199 | 810 | 414 |
| **Lancaster** | 90 | 182 | 44 |
| **Saline** | 74 | 188 | 160 |
| **Sarpy** | 108 | 196 | 55 |
| **Saunders** | 67 | 173 | 127 |
| **Seward** | 143 | 300 | 55 |
| **Thayer** | 65 | 168 | 11 |
| **Thurston** | 104 | 267 | 113 |
| **Washington** | 141 | 250 | 96 |

*Table 2. Average depth to static water and average total depth of Dakota aquifer wells by county.*

declines averaging about 130 feet (40 m) were noted as early as the 1950s in areas of South Dakota where artesian pressure existed (Barkley, 1953). More recent estimates put the greatest regional head declines on the order of tens of feet (Helgesen et al., 1993).

The potential yield of the Dakota aquifer ranges widely due to variability in the texture, thickness, and degree of cementation of sandstone bodies within it (McGovern, 1984). Likewise, the actual pumping rate varies due to regional needs. In Nebraska, Lancaster County has the largest number of Dakota wells (about 1,420 wells), 85% of which are domestic with average well yields of 20 gpm (76 lpm), although commercial and irrigation wells in the county suggest that the aquifer is capable of supplying 800 gpm (3,028 lpm), in places.

## Where are the recharge and discharge areas of the Dakota aquifer?

The Dakota Group is associated with a wide range of geomorphic settings and, therefore, there are several mechanisms for recharge of and discharge from the aquifer. In its outcrop and subcrop belt (where it is present at and near the land surface), the vertical infiltration (downward movement) of precipitation and surface water may contribute to recharge. However, depending on topography, the aquifer may instead discharge to surface water (Divine, 2015; Divine, 2014; Gosselin et al., 2001; Miller and Appel, 1997; Schoon, 1984; McGovern, 1984; Burkart, 1984; Munter et al., 1983). West of the subcrop belt, the Dakota aquifer is overlain by younger, Cretaceous marine shales. Shales are generally considered to be aquitards, but some studies suggest that if they are of sufficiently large areal extent, they can transmit substantial quantities of water downward, despite their low values of hydraulic conductivity (Helgesen et al., 1993). Indeed, this may be the case relative to the shales overlying the Dakota aquifer in Nebraska.

A second mechanism for recharge to the Dakota aquifer is vertical recharge from below. Various Paleozoic strata underlie the Dakota aquifer. In Nebraska, the most common of these units are Pennsylvanian and Permian limestones, shales, and evaporites that probably supply the high sodium chloride water that occurs in and around Lancaster County (Fig. 7) (Gosselin et al., 2001). In northeastern Nebraska (Boyd, Knox, Cedar, and Dixon counties), groundwater in the Dakota aquifer is high in dissolved sulfate. In this area and the adjacent parts of South Dakota, dissolved sulfate is believed to be sourced from underlying Mississippian-aged limestones (Stotler et al., 2010).

Lateral flow accounts for at least some of the recharge to the Dakota aquifer. The Dakota aquifer in Iowa receives lateral inflow from Minnesota (Munter et al., 1983) and South Dakota receives inflow from North Dakota (Case, 1984). Regional potentiometric heads suggest possible lateral flow from the Front Range in Colorado to western Nebraska, but water chemistry indicates that the water does not pass through the Denver Basin and, therefore, the water in the Dakota aquifer in eastern Nebraska originated in Nebraska (Gosselin et al., 2001).

## What is the water quality in the Dakota aquifer?

Water quality in the Dakota aquifer varies considerably in Nebraska and the surrounding region. Fresh water (total dissolved solids less than 1,000 mg/l) occurs mostly along the eastern and southern margins of the aquifer in portions of Nebraska, Kansas, and Iowa, where vertical recharge from precipitation is important (Whittemore et al., 2014; Gosselin et al., 2001; Carlson and Sibray, 1992; Munter et al., 1983). In the highest quality parts of the aquifer in Nebraska, the dominant water types are calcium-bicarbonate, calcium-magnesium bicarbonate, or calcium-sodium bicarbonate (Fig. 7) (Gosselin et al., 2001) and the majority use type is domestic (Fig. 5).

High sulfate concentrations in northeastern Nebraska push the total dissolved solids (TDS) concentration to 1,000 mg/l or greater in many wells (Gosselin et al., 2001). Nevertheless, the Dakota aquifer is still used in that area, but primarily for livestock and irrigation wells. Similarly elevated sulfate concentrations have been reported in adjacent parts of South Dakota and Iowa (Burkhart, 1984; Schoon, 1984; Munter et al., 1983).

Dakota aquifer wells with localized high sodium chloride are fairly common in Lancaster County and may have TDS concentrations that are brackish to brine. These wells are used mostly for domestic purposes in association with reverse osmosis treatment systems. The source of the high sodium chloride is probably dissolution of evaporate layers in underlying Paleozoic rocks; the saline water in the Paleozoic rocks moves into the Dakota aquifer where the pressure head pushes groundwater upward through gaps in confining units (Kelly, 2011; Harvey et al., 2007). The Dakota aquifer is

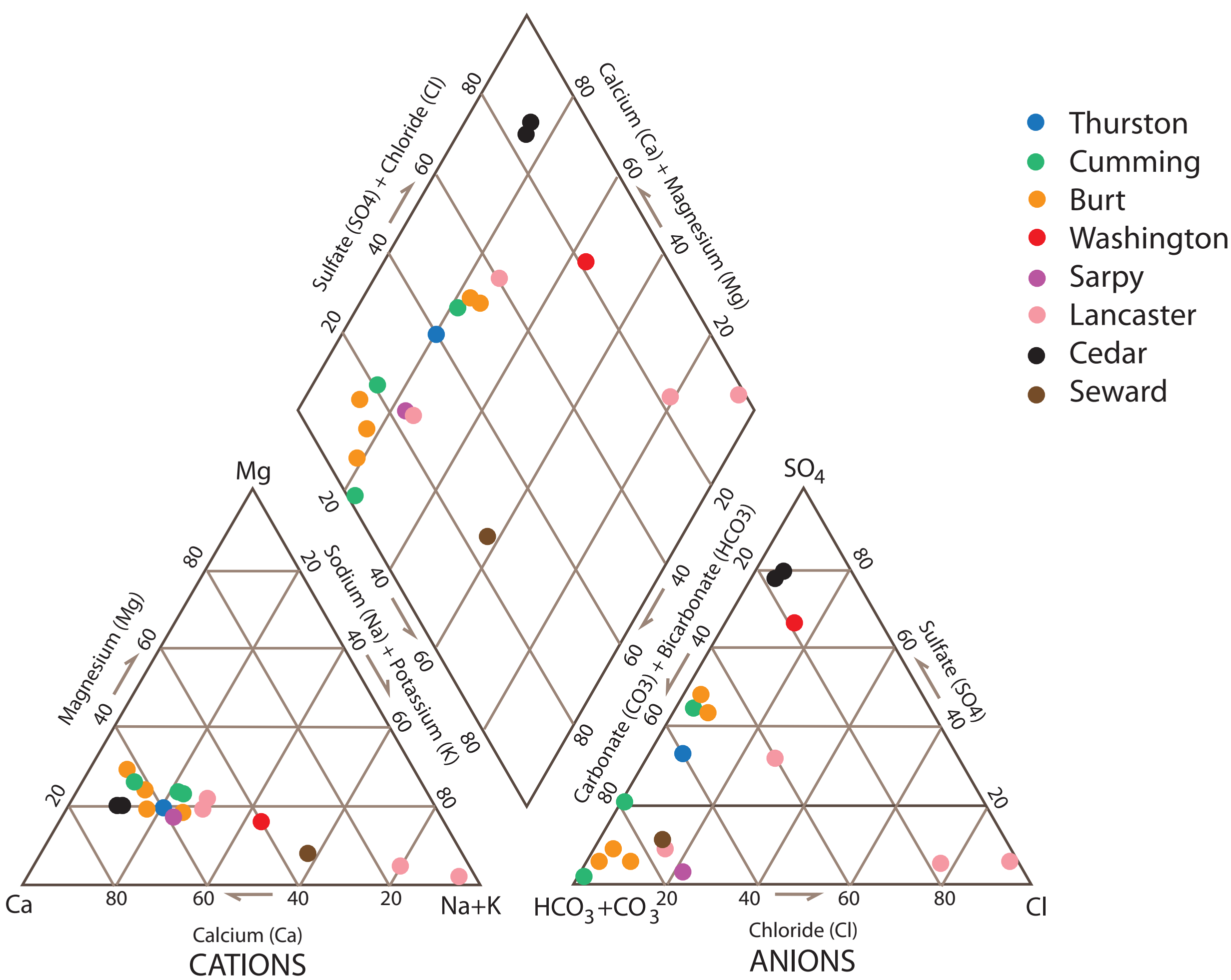



*Figure 7. Piper diagram depicting water chemistry for the Dakota aquifer, eastern Nebraska. Proportions of positively charged (cations) and negatively charged (anions) ions are plotted separately on the triangles, with the overall major ion chemistry shown in the central diamond. Data are from Gosselin et al. (2001) and U.S. Geological Survey (undated).*

also used for irrigation in Lancaster County, but these wells are susceptible to increasing sodium chloride concentrations in response to pumping (Gosselin et al., 2001).

## What are potential problems associated with using the Dakota aquifer in Nebraska?

The greatest potential for problems associated with the Dakota aquifer is where the aquifer is confined and recharge is primarily from below. The generally older groundwater expected in such settings will tend to have elevated total dissolved solids, typically in the form of sodium chloride or sodium sulfate, depending on the location. Confined aquifers also experience more drawdown in response to pumping than do unconfined aquifers. Although the pressure head in confined aquifers also tends to rebound quickly once pumping stops, intensive seasonal pumping can pull low-quality water upward and over time reduce the water quality, eventually making it unsuitable for irrigation.

## What do cuttings from strata hosting the Dakota aquifer look like?

The Dakota Group includes shales, mudstones, siltstones, sands, sandstones, gravels and conglomerates. Where sandstone and conglomerate units crop out or subcrop, oxidation produces characteristic yellowish-red to brown colors. Where deeply buried, the same geologic materials are typically light gray to light brown in color. Sands and sandstones of the Dakota Group are typically quartz-rich and they lack pinkish potassium feldspar or granite grains (which are common in the primary sand and gravel aquifer units in Nebraska). The gravels in the Dakota consist mostly of quartz, chert, and other hard minerals. Individual grains may vary widely in color. Gravels occur chiefly in the lowest (oldest) parts of the unit. Thin beds of lignite (brown to black, soft coal) are common in some parts of the Dakota Group.

The mudstone and shale units of the Dakota may be red, light gray, gray, and brownish yellow. Where two or more of these colors are present, the unit is described as mottled or variegated and identification of the unit as the Dakota Group is fairly easy. Light gray or gray mudstones without mottles can be confused with older, stratigraphically lower, Pennsylvanian and Permian mudrocks, or with overlying Quaternary sediments, such as glacial till. Divine et al., (2015) provides photographs of Dakota outcrops and cuttings.

*The Dakota aquifer exposed along Antelope Creek in Lincoln, Nebraska.*

## Codell Aquifer

### Where is the Codell aquifer located?

The Codell aquifer underlies an approximately 460 mi$^2$ area of Boyd and Knox counties (Fig. 3d). It is hosted by the Codell Sandstone member of the Carlile Shale (Divine et al., 2016). The Codell aquifer is shallow in eastern Nebraska, South Dakota, and Kansas in comparison to western Nebraska, Colorado, and Wyoming where the Codell Sandstone is a petroleum reservoir. Indeed, the depth to the Codell aquifer increases from about 250 feet (76 m) in eastern Nebraska to more than 3,000 feet (915 m) in western Nebraska (Divine et al., 2016; Busch, 1976).

The Codell aquifer is more widely recognized in South Dakota and Kansas than it is in eastern Nebraska because in both of those states it is used over a larger area and it crops out in many places at the land surface. Recognizing the Codell Sandstone in boreholes in eastern Nebraska may be difficult because the unit is relatively thin (between 8 and 80 feet [2.4 to 24 m] in thickness) and because it may consist of as many as three separate sandstone units separated by thin shales (Divine et al., 2016). The location of the Codell Sandstone member within the Carlile Shale can be anywhere within the top 50 feet of that latter formation (Divine et al., 2016).

### How extensively is the Codell aquifer used in Nebraska?

There were approximately 70 active registered wells screened entirely within the Codell aquifer as of 2015. Almost all of the wells serve domestic or livestock purposes. The Codell aquifer is used in six counties in Kansas, and some 73 wells were identified there in 1990. The thickness of the Codell aquifer in Kansas is similar to that in Nebraska, ranging from 0 to 90 feet (0 to 27 m) (Weigand, 1991). In South Dakota, the Codell aquifer underlies parts of at least 12 counties and is approximately 30 to 50 feet (9 to 15 m) thick (Barkley, 1953). The number of Codell wells in South Dakota is not documented, but in the 1970s water quality samples were collected from the Codell aquifer in ten counties (Koch and McGarvie, 1988; Hamilton, 1984; 1989; Hansen, 1983; 1986; Kume, 1977; Jorgensen, 1971).

### What are the average well depth, depth to water, and yield of Codell wells in Nebraska?

Most of the porosity in the Codell aquifer is intergranular, meaning groundwater exists in pore spaces between grains. Much of the aquifer is confined, so the water is under pressure and rises up inside wells above the top of the aquifer. Unconfined conditions may exist under the Missouri River where the river alluvium is in direct contact with the Codell Sandstone.

The average depth of wells in the Codell aquifer is about 285 feet (87 m), the average depth to water is approximately 120 feet (37 m), and the average yield is 14 gpm (53 lpm). The direction of groundwater flow is northeasterly toward the Missouri River, with the potentiometric surface elevation ranging from a high of about 1,320 feet (402 m) above mean sea level at the southern edge of the aquifer to about 1,210 feet (369 m) at the Missouri River (Divine et al., 2016). In South Dakota the gradient is also toward the Missouri River (Kume, 1977; Jorgensen, 1971). These observations suggest that the river is a natural discharge location and hydrologic boundary that groundwater in the Codell aquifer does not cross.

### Where are the recharge and discharge areas of the Codell aquifer?

Alluvial sediments below the Missouri River are likely to be the location of natural discharge from the Codell aquifer. Pumping from wells can be considered an artificial discharge. Other discharges may exist, but have not been identified. More research is needed to identify the recharge area(s) for the Codell aquifer. It is possible that at least part of the water in the Codell aquifer was recharged by glacial melt water at outcrops in South Dakota before the Missouri River trench formed a hydrologic boundary (Divine et al., 2016). Other non-glacial recharge sources are likely, but have not yet been identified. The Codell Sandstone has been completely eroded in places between western Kansas and eastern Nebraska, so no connection between those two aquifer locations currently exists.

### What is the water quality in the Codell aquifer?

Groundwater in the Codell aquifer tends to be elevated in total dissolved solids, sodium, chloride, and sometimes sulfate (Fig. 8). It typically yields "soft water" with low calcium and magnesium concentrations (Divine et al., 2016; Kume, 1977; Jorgensen, 1971). The sodium chloride concentration is sufficiently high to preclude use of the Codell aquifer for irrigation, and chloride concentrations appear to coincide with well depth (Divine et al., 2016). The elevated sulfate concentrations in the aquifer may result from pyrite or marcasite weathering in the overlying Pierre or Carlile shales, which may be most pronounced in wells that are located along drainages where the Niobrara Formation subcrops and the Niobrara-Carlile contact is probably subjected to the greatest amount of weathering (Joeckel et al., 2011).

### What are potential problems associated with using the Codell aquifer in Nebraska?

The restricted geographic distribution and confined nature of the Codell aquifer in eastern Nebraska increase the susceptibility of wells within it to water-level declines. Historically, water-level monitoring has not been systematic, so the response of the Codell aquifer to present levels of pumping is unknown. The unknown location of potential recharge area(s) also makes it impossible to predict the rate or quality of recharge at this time.

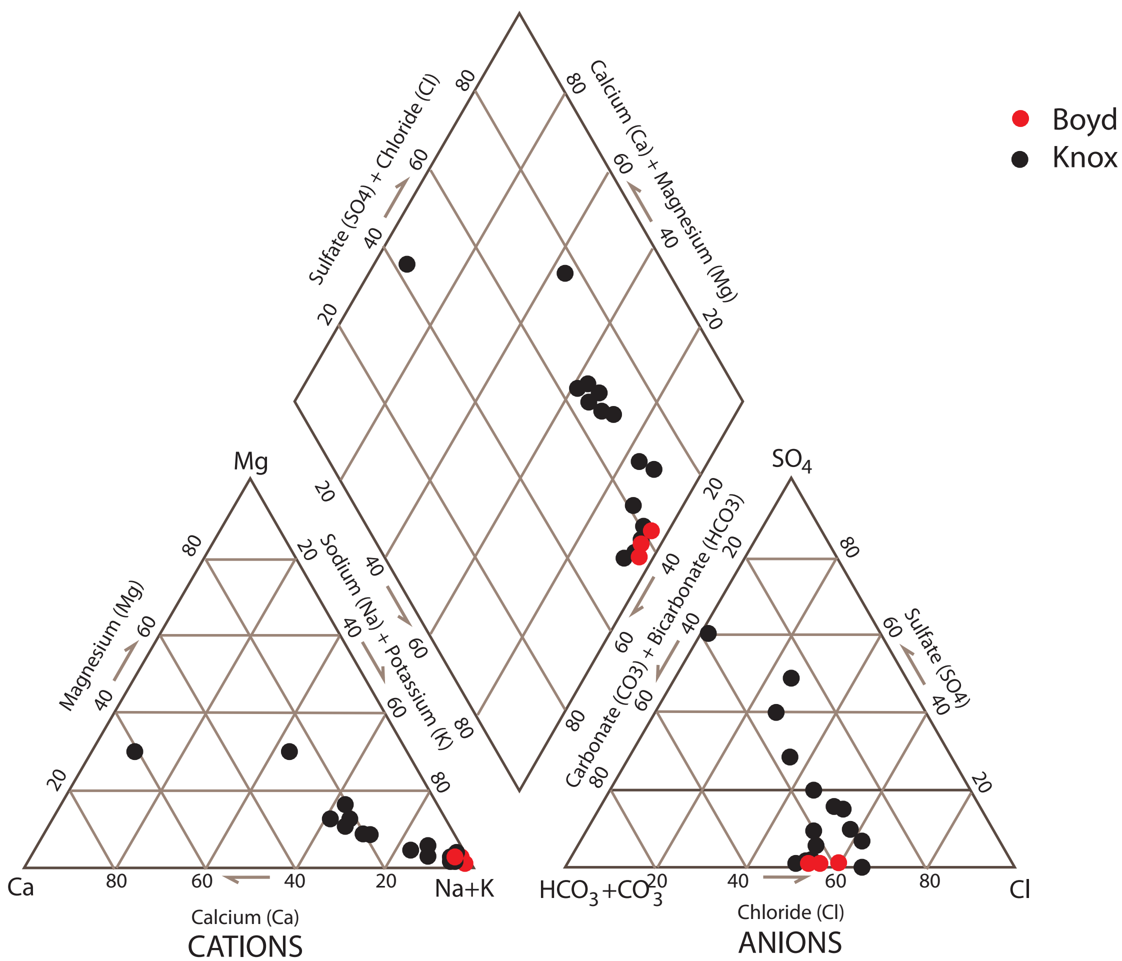



*Figure 8. Piper diagram depicting water chemistry for the Codell aquifer, eastern Nebraska. Proportions of positively charged (cations) and negatively charged (anions) ions are plotted separately on the triangles, with the overall major ion chemistry shown in the central diamond. Data are from Divine et al. (2016).*

### What do cuttings from strata hosting the Codell aquifer look like?

In eastern Nebraska, the Codell Sandstone is fine- to medium-grained sand and sandstone which is gray in color (Condra and Reed, 1959), but in South Dakota it includes siltstone, sand, sandstone and conglomerate of colors varying from gray, brown, reddish-brown, or black (Kume, 1977; Hedges, 1975; Christensen, 1974;). In Kansas the Codell may be yellowish-gray, dark yellowish-orange, dark gray or brown (Weigand, 1991).

Photo courtesy of Dr. R.M. Joeckel, University of Nebraska

*The Codell Sandstone Member of the Carlile Shale at its contact with the more resistant Fort Hays Limestone Member of the Niobrara Formation in Ellis County, Kansas.*

## Niobrara Aquifer

### Where is the Niobrara aquifer located in Nebraska?

Niobrara aquifer wells are located in Cedar and Dixon counties, northeastern-most Madison County, and in or near Nuckolls County (Fig. 3e). Cedar County hosts the greatest number of wells and it is the only area in which high-capacity irrigation wells screened entirely in the Niobrara aquifer are common. The aquifer is relatively shallow in eastern Nebraska, South Dakota, and Kansas in comparison to western Nebraska, Colorado, and Wyoming where the Niobrara Formation is a petroleum reservoir.

### How extensively is the Niobrara aquifer used in Nebraska?

There are three distinct groups of wells located mostly in Cedar, Madison, and Nuckolls counties. Cedar County has more than 150 registered active Niobrara wells, about half of which are irrigation wells that yield about 430 gpm (1,625 lpm) on average. The Madison County cluster of wells includes about 15 wells, none of which are irrigation wells. There is one commercial well producing 225 gpm (852 lpm). The domestic wells yield about 20 gpm (76 lpm) on average. The Nuckolls County well cluster, which overlies a high on the bedrock surface between the Little Blue and

Republican rivers, also includes approximately 15 wells screened entirely in the Niobrara aquifer. Almost all of these wells are livestock or domestic wells and they have average yields of about 10 gpm (38 lpm). The distribution of well types for all of the registered Niobrara wells is summarized in Figure 9.

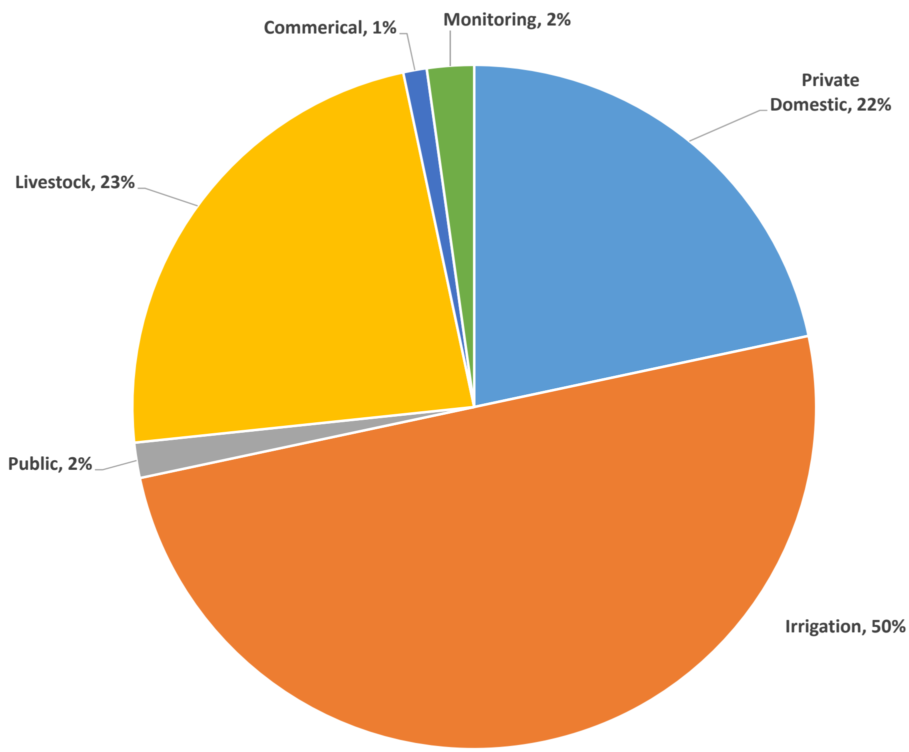



*Figure 9. Distribution of well use type for the Niobrara aquifer.*

## What are the average well depth, depth to water, and yield of Niobrara wells in Nebraska?

Wells have been drilled into the Niobrara Formation where it lies at shallow depths; in all but seven of the wells, the top of the Niobrara Formation is 90 feet (27 m) or less below land surface, and the greatest well depth is only 170 feet (52 m). The average depth of Niobrara wells in Nebraska is about 107 feet (33 m), the average depth to water is 37 feet (11 m), and the yield varies widely. Historic test-hole drilling in South Dakota also found that the highest yielding areas of the aquifer occur where the top of the Niobrara Formation is less than 100 feet (30 m) below ground surface (Jorgensen, 1971).

## Where are the recharge and discharge areas of the Niobrara aquifer?

There are very few data from the Niobrara aquifer, and recharge and discharge areas have not been identified. Recharge probably occurs wherever the formation lies at shallow depths and can readily receive precipitation and/or surface water from a losing stream. Natural discharge from the formation occurs as seeps along the bluffs of the Missouri River, and probably also to gaining streams.

## What is the water quality in the Niobrara aquifer?

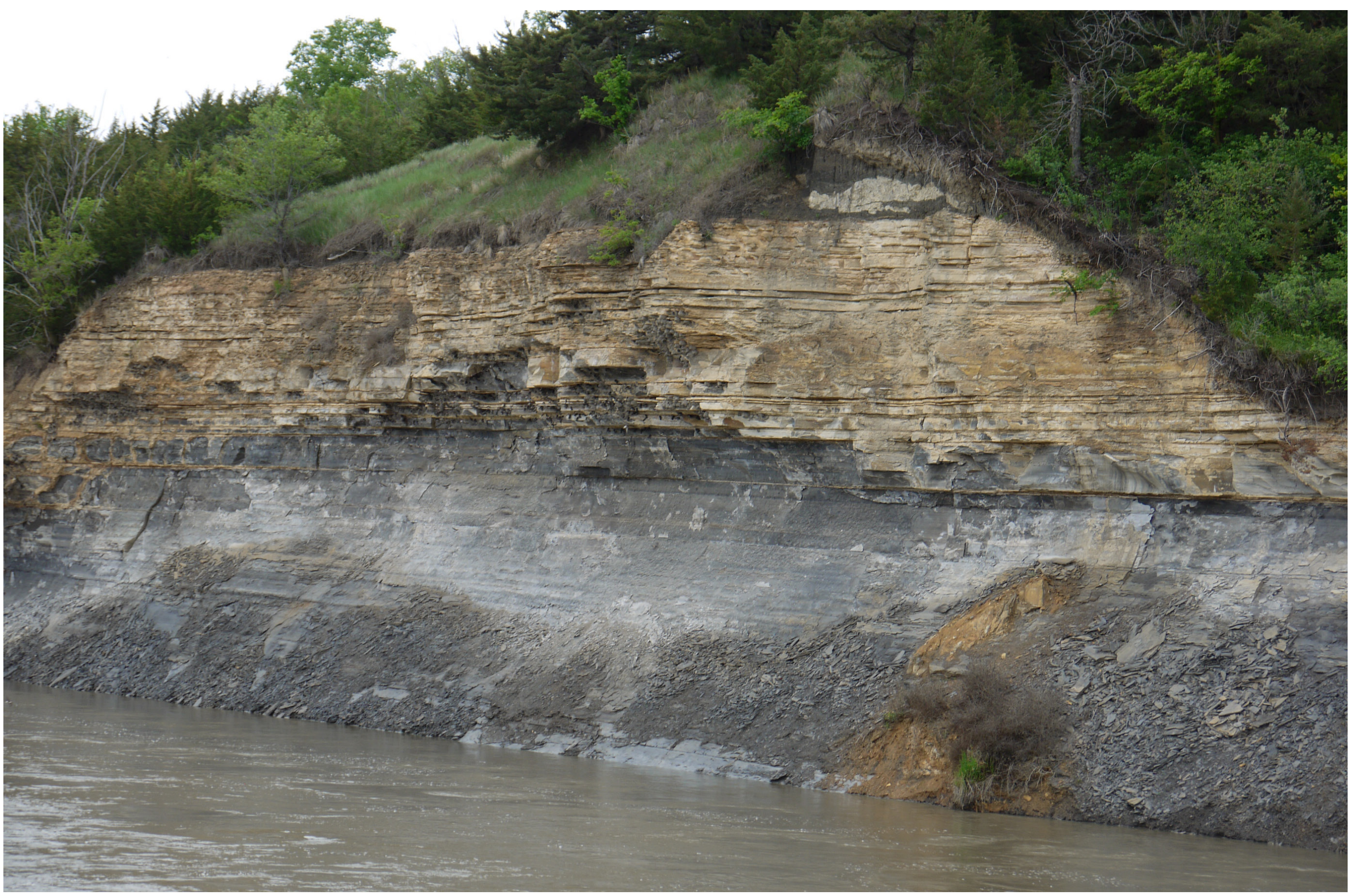
Historic data suggest that water from the Niobrara has relatively high concentrations of calcium and sulfate (Engberg and Druliner, 1987), but there is a lack of current water quality data for the Niobrara aquifer in Nebraska. Carbonate aquifers typically have high concentrations of calcium, magnesium, sulfate, and iron (Drever, 1997; Freeze and Cherry, 1979). Weathered pyrite and secondary gypsum deposits in the Pierre or Carlile shales may be a potential source of iron and sulfate (Joeckel et al., 2011) to the Niobrara aquifer in Nebraska.

### What are the potential problems associated with using the Niobrara aquifer?

The porosity, permeability, and distribution and orientation of joints and bedding planes (planar, weak zones in rock along which dissolution and weathering may occur) in the Niobrara aquifer are not well understood, and siting wells to achieve desired yields is a challenge. Although many people think of high-yield limestone wells as intercepting vertical fractures, it is much more likely that a well will intercept and source water from horizontal bedding planes (Walker, 1956). In general, wells that intercept a limited number of openings (or narrow or short openings) are vulnerable to seasonal water level declines because fracture porosity is generally a few percent or less (Freeze and Cherry, 1979) and very little water is actually stored in the vicinity of the well. Where water quantity is sufficient, the quality may be hard (high calcium and/or magnesium) relative to sand and sandstone aquifers.

### What do cuttings from strata hosting the Niobrara aquifer look like?

The Niobrara Formation consists of interbedded chalk, limestone, shale, and bentonite (weathered volcanic ash). In northeastern Nebraska, the chalky limestone and shale may include some siltstone and sandstone (Witzke et al., 1983). The color of the Niobrara varies from dark gray to white, depending on the lithology, organic content, and extent of weathering (Maher, 2014; Diffendal and Voorhies, 1994). The formation generally drills easily and cuttings will effervesce in dilute acid (Divine et al., 2015). The overlying Pierre and underlying Carlile shales are generally noncalcareous and, therefore, those cuttings generally will not react with dilute acid.



*The Niobrara Formation exposed along the banks of the Niobrara River at Niobrara State Park in Knox County, Nebraska.*

## SECONDARY AQUIFERS IN WESTERN NEBRASKA

Three secondary aquifers underlie parts of western Nebraska. These aquifers, from oldest (stratigraphically lowest) to youngest (stratigraphically highest) are the: Upper Cretaceous aquifer, Chadron aquifer, and Brule sand-sandstone aquifer (Fig. 10a-d). The Chadron and Brule sand-sandstone aquifers are ancient alluvial valley fills within the strata of the widespread White River Group, but the aquifers themselves are localized and restricted by ancient topography (Swinehart et al., 1985). The most productive unit of the Upper Cretaceous aquifer is present only in the extreme southwestern part of the Panhandle, the hosting strata having been removed elsewhere by erosion prior to deposition of the White River Group.

### Upper Cretaceous Aquifer

#### Where is the Upper Cretaceous Aquifer Located?

The Upper Cretaceous aquifer is hosted by all or part of three formations: Lance, Fox Hills Sandstone, and the upper Pierre Shale. In Nebraska, these three formations are present only in the southwestern part of the Panhandle (Figs. 10b and 11) (Swinehart et al., 1985). The Lance Formation consists of interbedded clay and siltstone with thin beds of fine-grained sandstone and coal in localized channel bodies of coarse-grained sandstone. The Fox Hills Sandstone is a marine sandstone underlying the Lance Formation, and is the highest-yielding formation in the Upper Cretaceous aquifer. It is an important aquifer in the Denver Basin and is also used as an aquifer in North Dakota, South Dakota, Wyoming and Montana along the margins of the Williston and Powder River basins (Fig. 12) (Whitehead, 1996; Robson and Banta, 1995). The upper Pierre Shale, or "transition zone" of the Pierre, is a thick sequence of fine-grained marine sandstones and shales that grades into the Fox Hills Sandstone (DeGraw, 1969). The upper Pierre Shale interval fines into central Banner County and then grades eastward into the thick shale sequence that typifies the Pierre Shale across the remainder of the state.

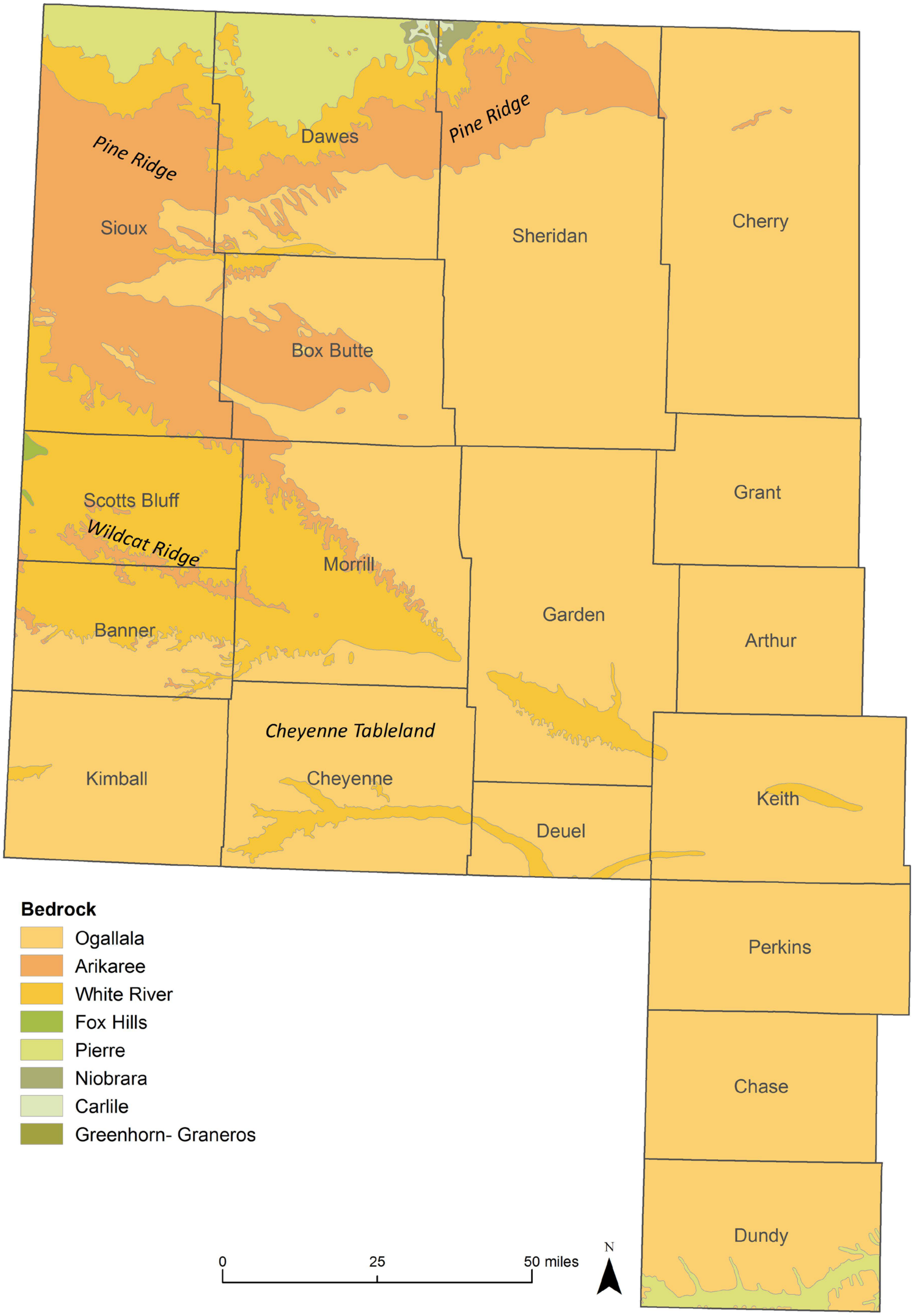
#### How extensively is the Upper Cretaceous aquifer used in Nebraska?

Eleven active wells and one inactive well have been identified in the Upper Cretaceous aquifer in Nebraska (Fig. 10b), all of which are used for livestock or domestic purposes. With the exception of one well in Banner County, all of these wells are located in the extreme western parts of Kimball and Scotts Bluff counties.

#### What are the average well depth, depth to water, and yield of Upper Cretaceous wells in Nebraska?

The average total depth of wells in the Upper Cretaceous aquifer is 503 feet (153 m), the average depth to water is 136 feet (41 m), and the average yield is 11 gpm (42 lpm). The Upper Cretaceous aquifer is confined by clays in the overlying Chadron Formation. Wenzel et al. (1946) reported wells flowing small amounts of water in the Lyman, Nebraska, area in 1946 (Scotts Bluff County), but none of the Upper Cretaceous wells in Nebraska currently flow.

a



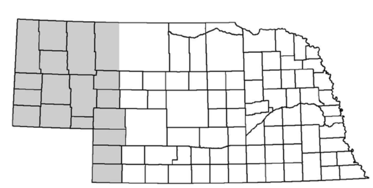



*Figure 10. Location of registered wells in secondary aquifers in western Nebraska: (a) upper-most bedrock units (from Burchett, 1986); (b) Upper Cretaceous aquifer well locations; (c) Chadron aquifer well locations; (d) Brule sand-sandstone aquifer well locations.*

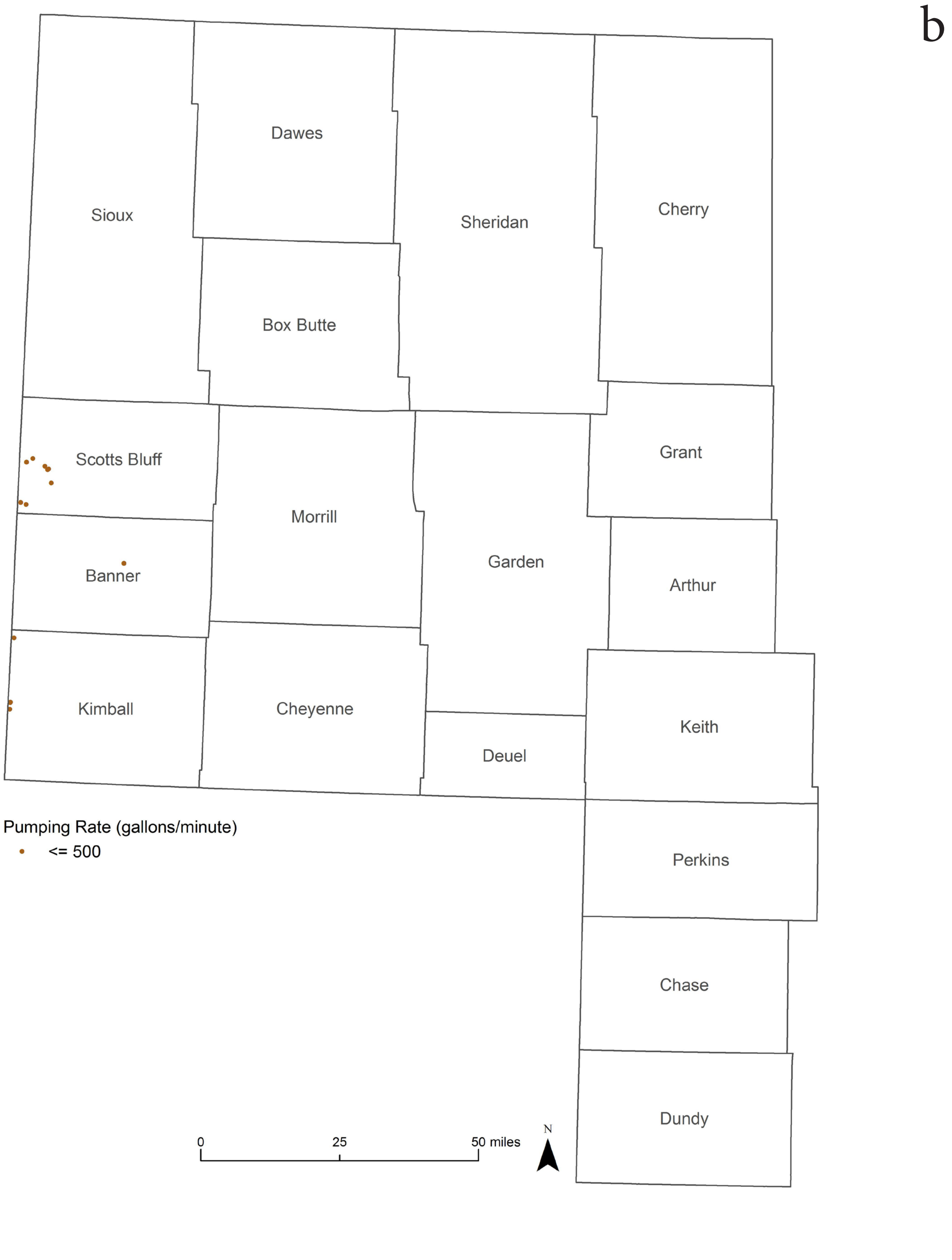
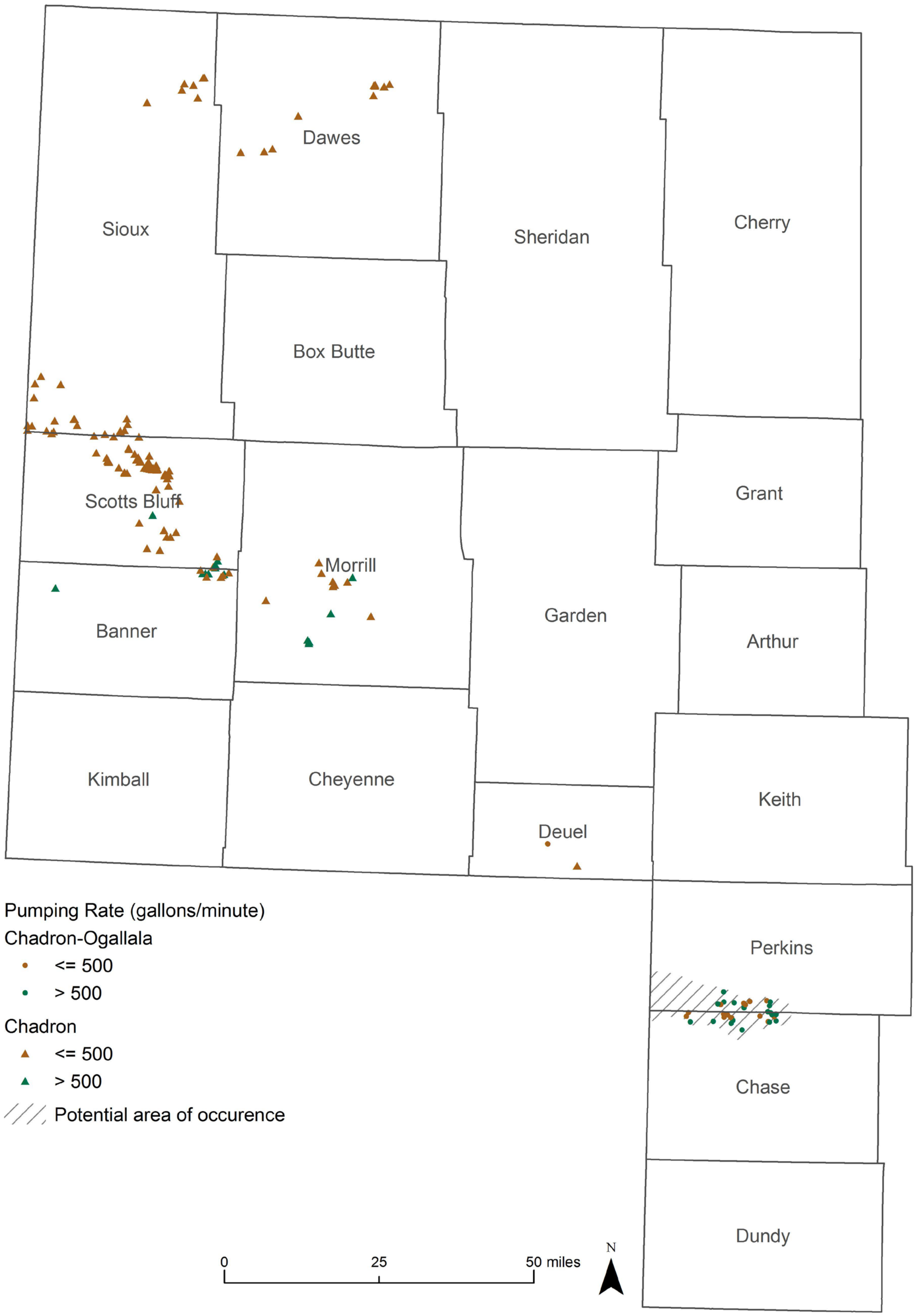



*Figure 10. Location of registered wells in secondary aquifers in western Nebraska: (a) upper-most bedrock units (from Burchett, 1986); (b) Upper Cretaceous aquifer well locations; (c) Chadron aquifer well locations; (d) Brule sand-sandstone aquifer well locations.*

c



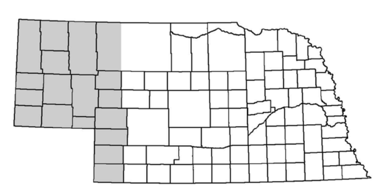
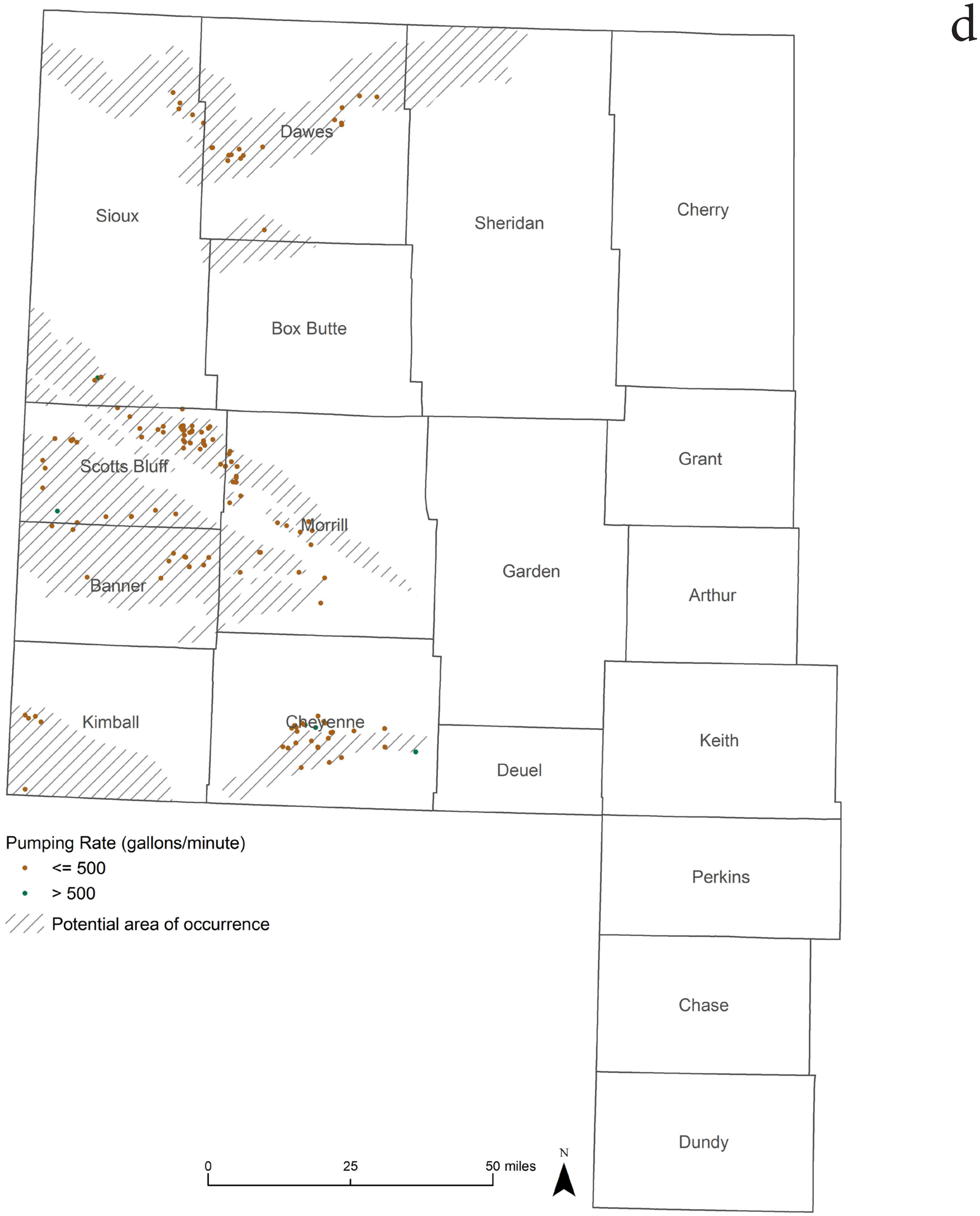



*Figure 10. Location of registered wells in secondary aquifers in western Nebraska: (a) upper-most bedrock units (from Burchett, 1986); (b) Upper Cretaceous aquifer well locations; (c) Chadron aquifer well locations; (d) Brule sand-sandstone aquifer well locations.*



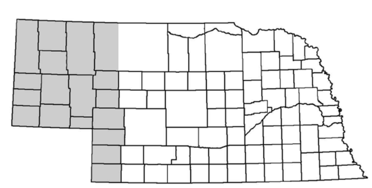



*Figure 10. Location of registered wells in secondary aquifers in western Nebraska: (a) upper-most bedrock units (from Burchett, 1986); (b) Upper Cretaceous aquifer well locations; (c) Chadron aquifer well locations; (d) Brule sand-sandstone aquifer well locations.*

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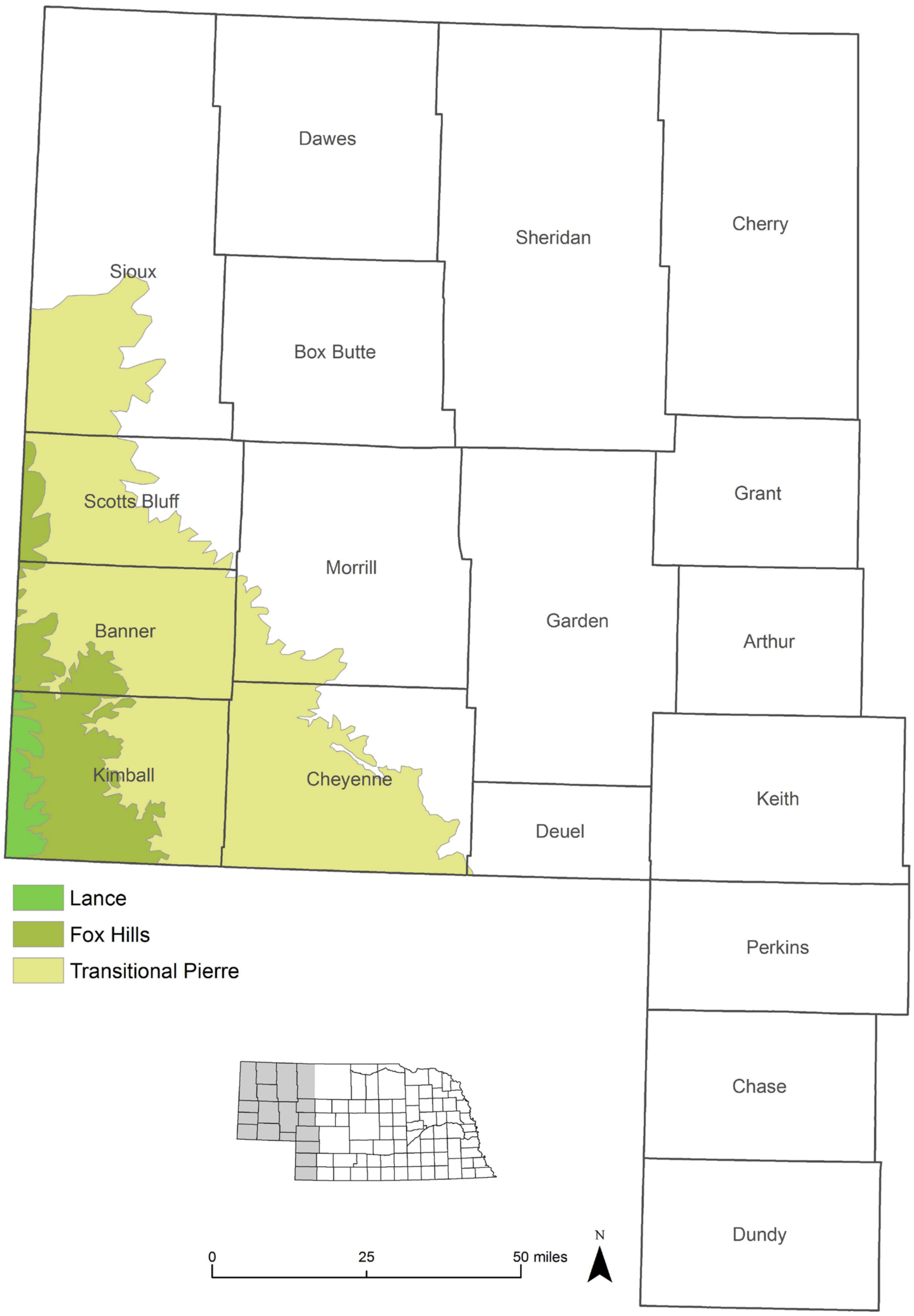



*Figure11. Upper Cretaceous bedrock units in the Nebraska panhandle (modified from DeGraw, 1969).*

and Wyoming where the Lance Formation, Fox Hills Sandstone, and the Pierre Shale are exposed at the surface (Robson and Banta, 1995). Localized discharge to streams occurs near the recharge area, but most of the discharge from the aquifer is probably through pumping (Robson and Banta, 1995). Natural discharge may occur at lower elevations in the North Platte valley where alluvium was deposited on top of these formations near the Wyoming-Nebraska state line.

## What is the water quality of the Upper Cretaceous aquifer?

The water quality of the Upper Cretaceous aquifer in Nebraska is poor. Chemical analyses for four wells in the aquifer in Nebraska have been completed (Verstraeten et al., 1995; Sibray, unpublished). Three of the wells associated with the Fox Hills Sandstone near the western edge of Scotts Bluff County are sodium bicarbonate type, and one well completed in the upper Pierre Shale "transition zone" in central Banner County is sodium bicarbonate plus chloride type (Fig. 13).

## Where are the recharge and discharge areas of the Upper Cretaceous aquifer?

The recharge and discharge areas for the Upper Cretaceous aquifer are not well defined. Some recharge occurs at relatively high elevations on the east flank of the Front Range in Colorado

The average total dissolved solids (TDS) concentration for water samples from the three Fox Hills Sandstone wells is about 700 mg/l, although the concentration in upper Pierre Shale "transition zone" well in central Banner County is considerably higher at 1,240 mg/l (Verstraeten et al., 1995). The sodium concentration averages 280 mg/l for the Fox Hills Sandstone wells and 510 mg/l for

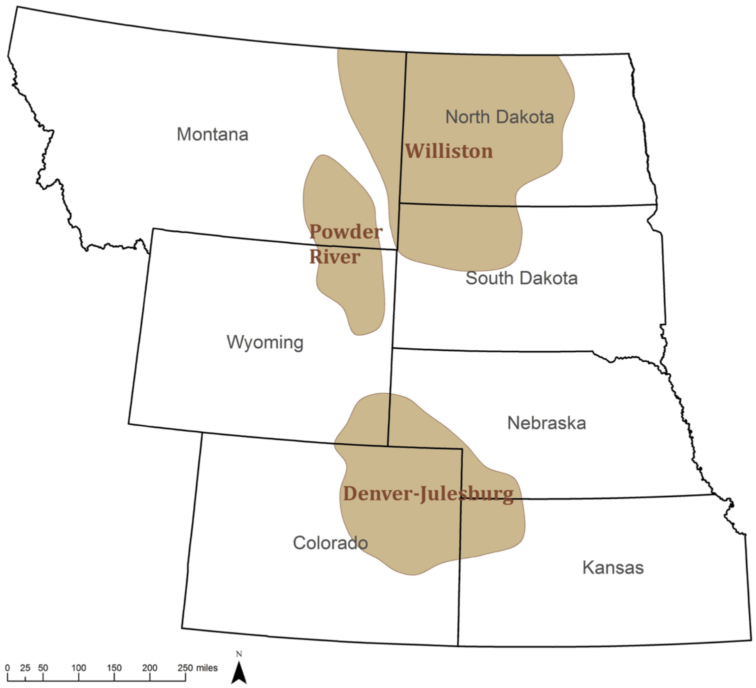



*Figure 12. Structural basins relevant to western Nebraska.*

the Pierre well; the recommended limit for sodium in drinking water is 30 to 60 mg/l (U.S. EPA, 2012). The chloride concentration for the upper Pierre Shale "transition zone" well is 250 mg/l, which is the recommended limit for drinking water (U.S. EPA, 2012). The water from this well is treated before it is used for human consumption.

## What are the problems associated with using the Upper Cretaceous aquifer in Nebraska?

Poor water quality, primarily high concentrations of sodium and possibly chloride, is the biggest limitation to development of the aquifer, although low transmissivity in the sandstone units comprising the aquifer also restrict the aquifer to livestock and domestic development.

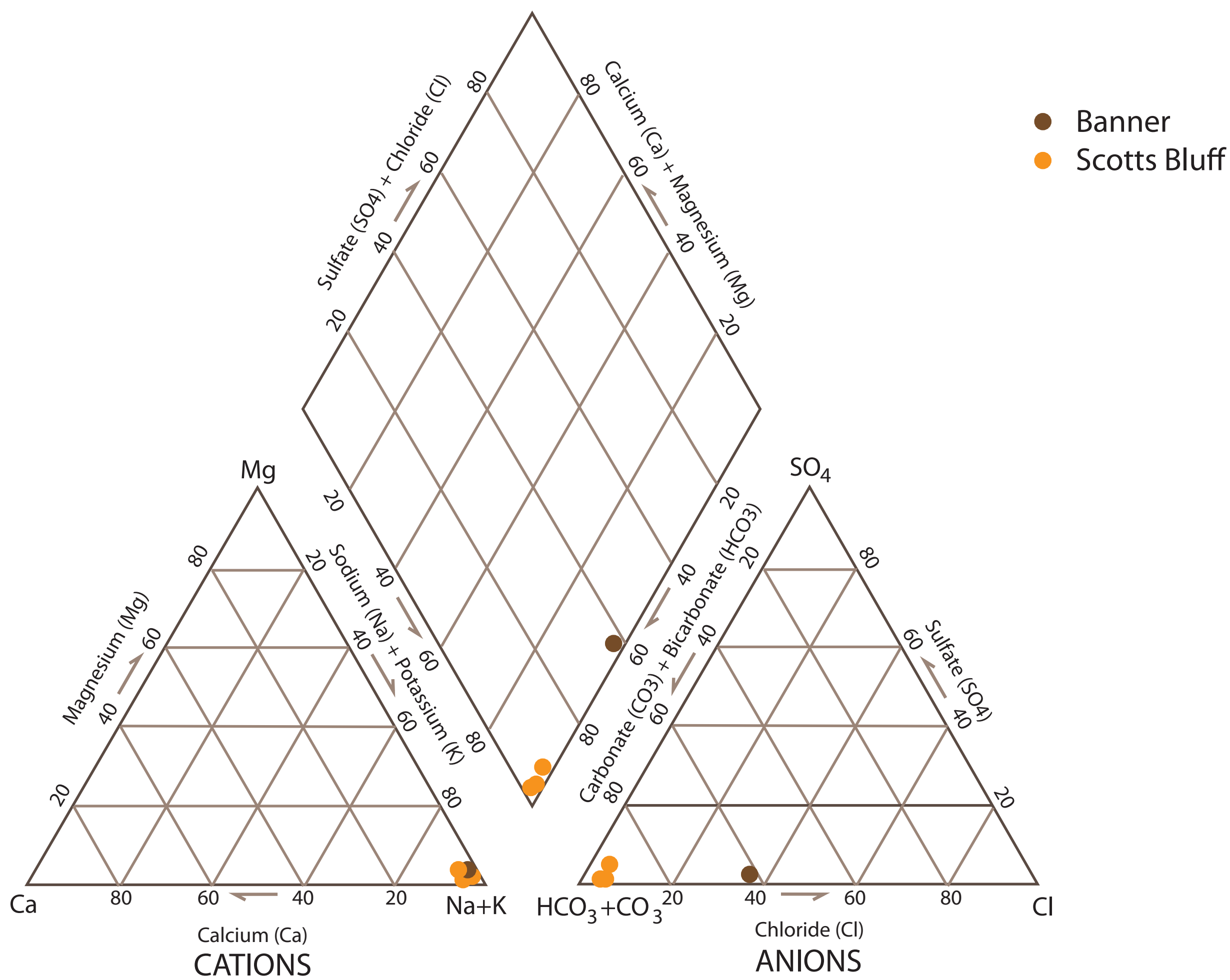



*Figure 13. Piper diagram depicting water chemistry for wells in the Upper Cretaceous aquifer, western Nebraska. Proportions of positively charged (cations) and negatively charged (anions) ions are plotted separately on the triangles, with the overall major ion chemistry shown in the central diamond. Data are from Verstraeten et al. (1995) and Sibray (unpublished).*

### What do the cuttings from strata hosting the Upper Cretaceous aquifer look like?

The Lance Formation consists of white to light gray claystones and siltstones interbedded with quartz sandstones and minor, thin coal beds. The Fox Hills Sandstone is a yellow to light gray to white, quartz sandstone. The white to light gray, pyrite-containing Fox Hills Sandstone was extensively altered to yellow-stained sandstones due to the presence of limonite, an iron mineral that forms when pyrite or marcasite is exposed to oxygen-rich groundwater or subaerial weathering in a process that may have started many millions of years ago. The process could be active today and the yellow-stained sandstone can be found many miles from the nearest outcrop. There are uranium deposits in the Fox Hills Sandstone that were mined in northeastern Colorado and uranium mineralization occurs in the Fox Hills Sandstone in extreme southwestern Kimball County.

The upper Pierre Shale "transition zone" consists of interbedded dark gray, fine-grained quartz sandstone and interbedded dark gray shale. The transition zone of the Pierre Shale is also stained yellow in western Scotts Bluff County, which complicates identification of the gradational contact with the Fox Hills Sandstone. Sandstones of the Upper Cretaceous aquifer can be tightly cemented and drilling can be slow with poor recovery of cuttings of fine-grained sand and interstratified shale.

*Photo courtesy of Dr. Brian Romans, Virginia Tech*

*The Fox Hills Sandstone cropping out (yellow unit) near Morrison, Colorado. The Fox Hills Sandstone is the most productive unit in the Upper Cretaceous aquifer, but does not crop out in Nebraska.*

## The Chadron Aquifer

### Where is the Chadron aquifer located?

The Chadron aquifer is developed primarily in the Nebraska Panhandle (Fig. 10c), and could also be a minor source of groundwater in parts of southwestern South Dakota, eastern Wyoming and northeastern Colorado. It is also used for irrigation in combination with the High Plains aquifer in Perkins and Chase counties. The Chadron aquifer is hosted by the Chadron Formation, which was first named in 1898 from exposures near the town of Chadron in Dawes County (Darton, 1899). A second, older, formation named the Chamberlain Pass Formation was described almost a century later based on outcrop studies in South Dakota (Terry and Evans, 1994), and could host some of the Chadron aquifer, but distinguishing between the Chadron Formation and the Chamberlain Pass Formation in the subsurface is difficult. The Crow Butte *in situ*-recovery uranium mine in the Crawford area is most likely in the Chamberlain Pass Formation, however, for the purposes of our discussion, we will refer to all the Lower White River water-bearing formations underlying the Chadron Formation confining layers as the Chadron aquifer (Fig. 14).

The Chadron aquifer is overlain by a regional confining unit that is also part of the Chadron Formation. This confining unit consists mostly of greenish bentonitic clay and some white, reddish, and yellowish clays. There are also thin beds of lacustrine (deposited in lakes) limestone in the upper Chadron confining clay unit. The confining unit can be identified as far east as Antelope County, Nebraska. The stratigraphy underneath the confining unit, however, is complex. In South Dakota, there are two basal sands of different ages, both of which fill valleys cut into the underlying Pierre Shale (Fig. 14) (Terry and Evans, 1994).

### How extensively is the Chadron aquifer used in Nebraska?

There are about 163 active registered wells screened entirely in the Chadron aquifer. Most of these wells are used for domestic (64%) and livestock (15%) purposes, although some (12%) are used for irrigation (Fig. 15). At least 51 additional registered irrigation wells were screened across both the High Plains aquifer and the Chadron aquifer as of 2015. Most of these two-aquifer wells are located near the boundary between Chase and Perkins counties. The Chadron aquifer, most likely the Chamberlain Pass Formation, is also developed for the recovery of uranium in the Crow Butte uranium mine area in Dawes County. Uranium exists as the mineral coffinite, which is dissolved by injecting water with oxygen into the formation. The water with dissolved uranium is then pumped through an ion exchange plant where the uranium is stripped out and recovered, and the water recycled and pumped back into the formation.

### What are the average well depth, depth to water and yield of Chadron wells in Nebraska?

The average depth of Chadron aquifer wells is 353 feet (108 m), the average depth to water is 144 feet (44 m) and the average yield of irrigation wells is about 870 gpm (3,293 lpm). The Chadron aquifer is confined, and near Crawford (Dawes County) and other low-lying areas, Chadron aquifer wells may flow at the land surface (Gjelsteen and Collings, 1988). The confined nature of the Chadron aquifer also results in significant seasonal drawdowns of the hydraulic head. Irrigation development of the Chadron aquifer in T. 20 N., R. 53 W. —known as the Horseshoe Bend area of Scotts Bluff and Banner counties—during the 1970's interfered with domestic wells. This development led to the first legal hearing regarding groundwater control areas in Nebraska (Nebraska Department of Water Resources, 1976). A groundwater control area was not established at that time because the impacted area was small.

### Where are the recharge and discharge areas of the Chadron aquifer?

Very little is known about the recharge and discharge areas of the Chadron aquifer. Recharge is most likely to occur near outcrops in eastern Wyoming. Discharge may occur to the east where

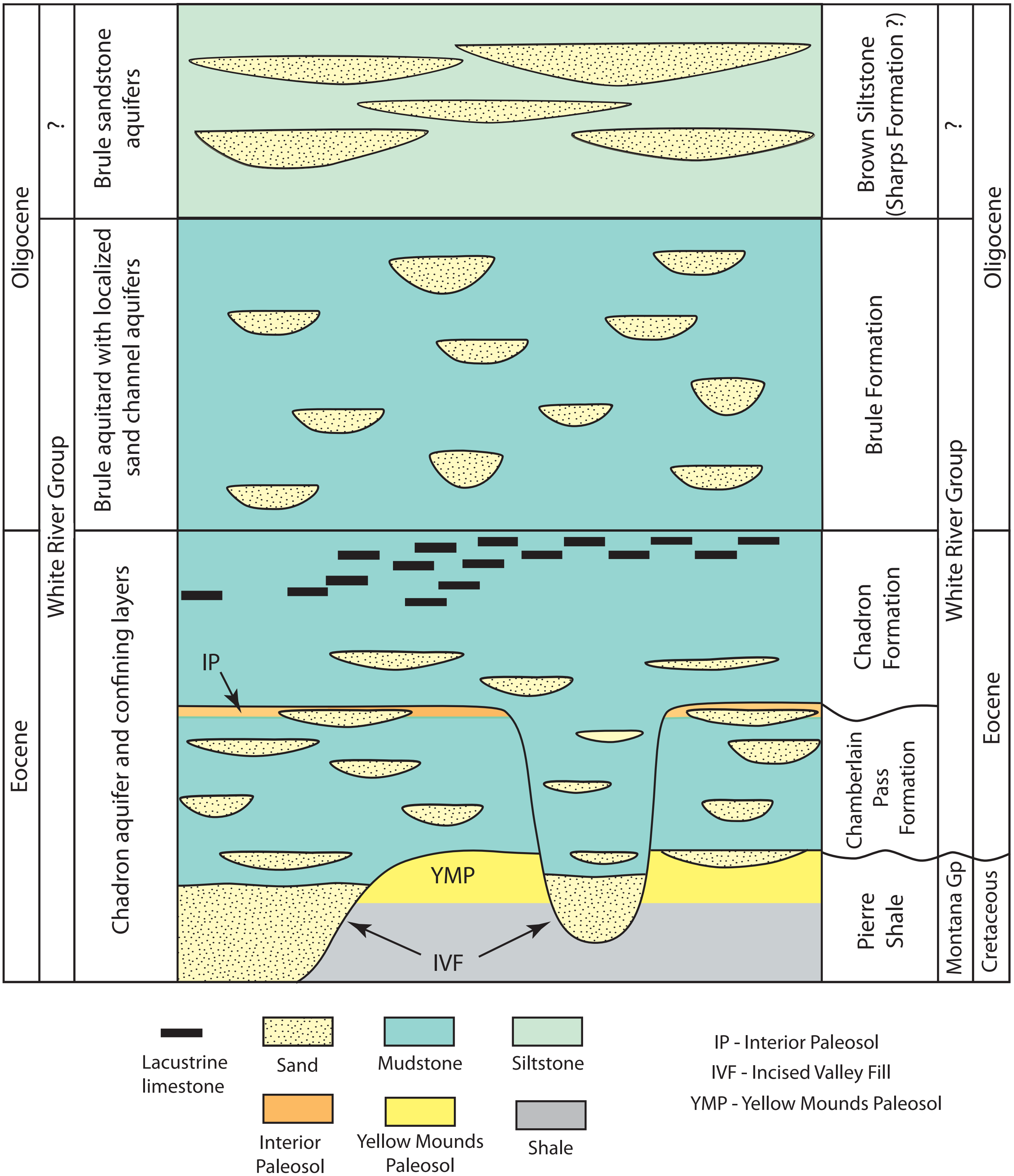



*Figure 14. Generalized stratigraphy diagram showing the relative positions of the Pierre Shale, Chadron, and Brule aquifers (modified from Sibray, 2011; Terry et al., 1995; and Swinehart et al., 1985).*

the Chadron Formation directly underlies the High Plains aquifer. Gjelsteen and Collings (1988) report that some discharge from this aquifer is to springs and to alluvium in the area north of Crawford (Dawes County) where erosion has exposed the Chadron sandstone.

## What is the water quality in the Chadron aquifer?

Water in the Chadron aquifer is generally of poor quality. Total dissolved solids (TDS) and sodium concentrations are uniformly high, but other aspects of water chemistry vary from place to

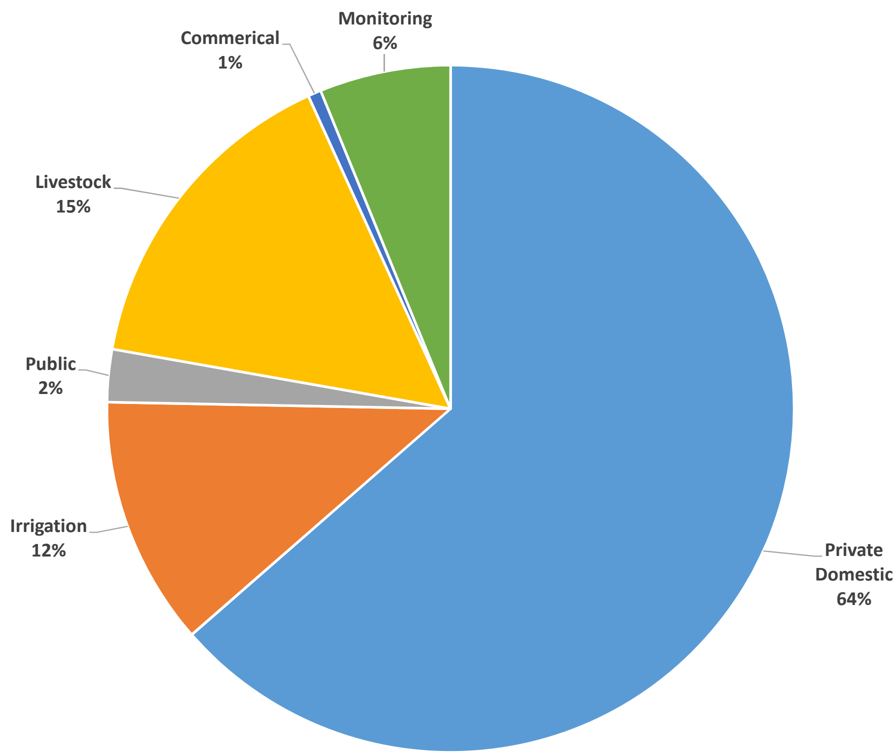



*Figure 15. Distribution of well use type for the Chadron aquifer.*

place (Fig. 16). In Scotts Bluff and southern Sioux counties, TDS averages 750 mg/l and the average sodium concentration is 368 mg/l (Verstraten et al., 1995). Two wells sampled had no detectable sulfate, and one of these wells had a gas bubbling out of solution (Verstraten et al., 1995). Anecdotal reports of methane gas from the Chadron aquifer in this area are consistent with the absence of sulfate in the water analysis, because in low-oxygen environments, microbes may use sulfate to convert organic matter to methane (Drever, 1997). Carbon-14 age dating from a well in the same area found no detectable radiological carbon, indicating the water was recharged at least 45,000 years ago (Harvey and Sibray 2001).

In western Dawes County, TDS in the Chadron aquifer averages about 1,320 mg/l, sodium values average approximately 400 mg/l, and the water type is described as sodium-sulfate with chloride ($Na$-$SO_4$ + Cl) (Spalding et al., 1984). Uranium concentrations ranged from 0.01 to 2,037 micrograms per liter (µg/l) with the highest values found in proximity to the Crow Butte uranium mine (Spalding et al., 1984). The maximum contaminant level (MCL) for uranium, classified as a heavy metal, is 30 µg/l and the main impact on human health from prolonged exposure is kidney damage.

Arsenic concentrations in the Chadron aquifer may also exceed the MCL of 10 µg/l. Three of five Chadron wells sampled by Verstraten et al. (1995) had arsenic concentrations exceeding the MCL of 10 µg/l. One of those wells was a flowing livestock well in Morrill County, which had an arsenic concentration of 59 µg/l, or nearly six times the MCL. This well yielded sodium sulfate plus chloride ($Na$-$SO_4$ + Cl) water similar to the Crawford area.

## What are the potential problems associated with using the Chadron aquifer?

Declining hydraulic head and reduced flow rates may occur where the Chadron aquifer is developed for irrigation because it is confined. However, the multiple problems associated with water quality are of potentially greater concern. High sodium levels will eventually impact sodium-sensitive crops, such as dry edible beans. Boron concentrations are also high in the Chadron aquifer, which can intensify problems associated with the high sodium concentration.

Use of the Chadron aquifer for human consumption should be monitored because of elevated uranium and arsenic concentrations. Although there is potential for uranium mineralization in the Chadron aquifer across a wide area (Sibray, 2011), uranium deposits are typically localized and high uranium concentrations have only been documented in the Crow Butte mine area. Uranium is not very soluble in low-oxygen environments, which is the case in the Chadron aquifer (Verstraeten et al., 1995).

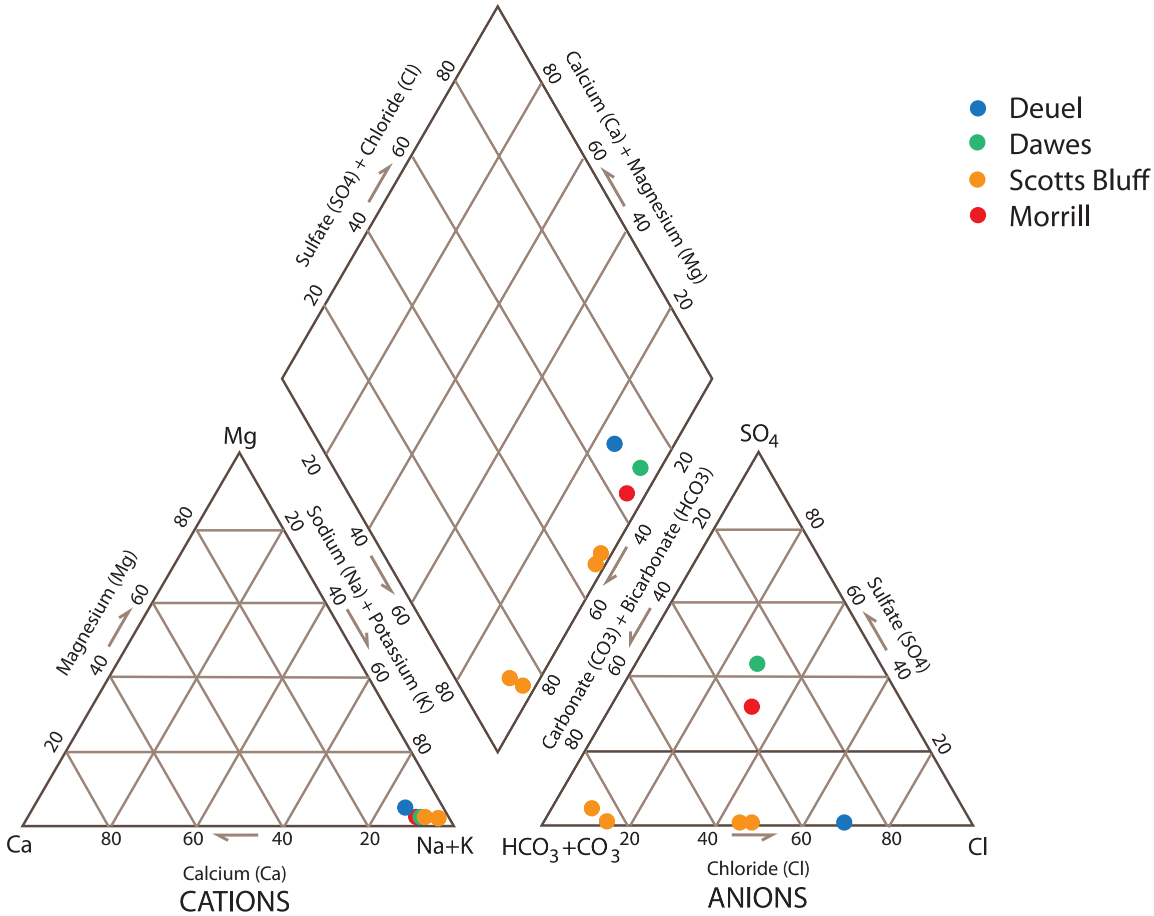


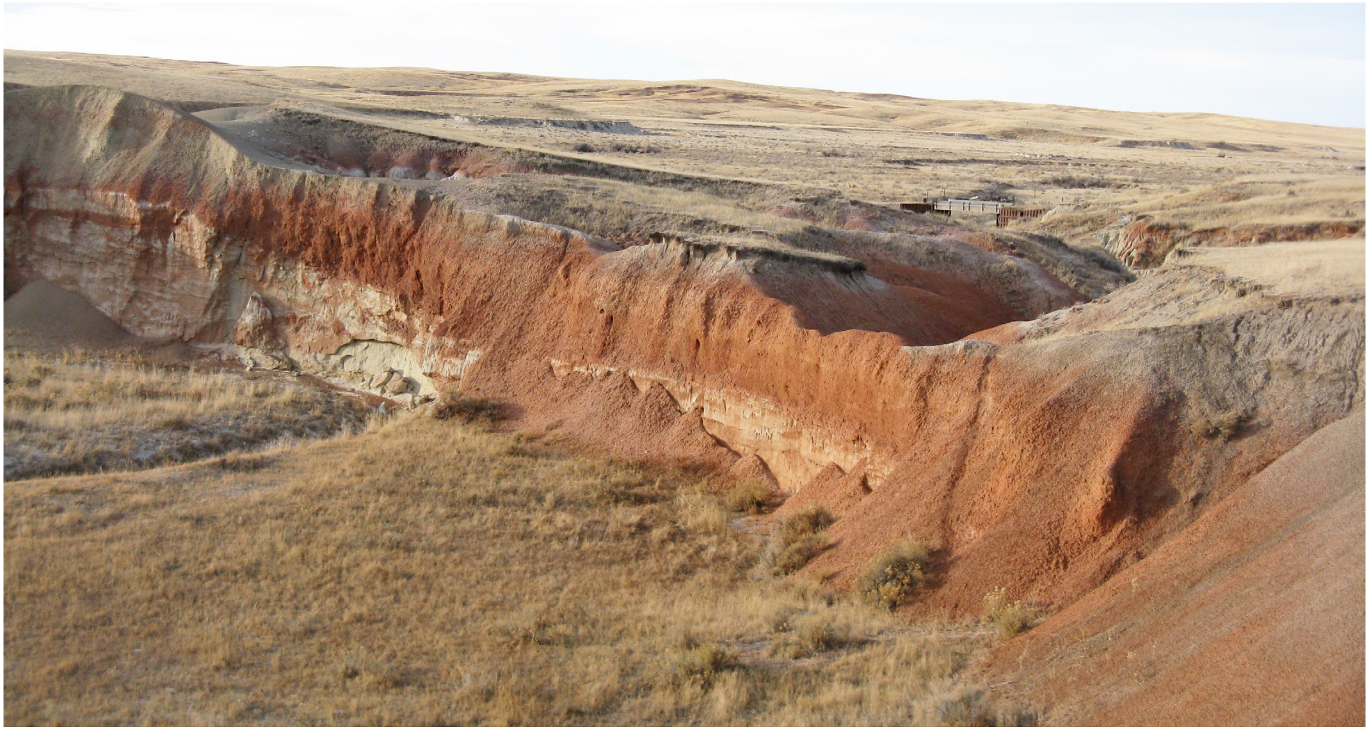

*Figure 16. Piper diagram depicting water chemistry for wells in the Chadron aquifer, western Nebraska. Proportions of positively charged (cations) and negatively charged (anions) ions are plotted separately on the triangles, with the overall major ion chemistry shown in the central diamond. Data are from Verstraeten et al. (1995) and Sibray (unpublished).*

Arsenic, unlike uranium, tends to be mobile in low-oxygen environments. At high concentrations, arsenic is a poison and even at low concentrations, it can cause health problems and increase the risk of cancer. In groundwater, arsenic is present as arsenate ($As^{+5}$) or arsenite ($As^{+3}$). Arsenite is potentially more damaging to health and is more powerful than arsenate in breaking down chromosomes, which may cause cancer (Gosselin et al., 2004). The owners of domestic wells developed in the Chadron aquifer should consider testing for arsenic. Private wells are not regulated by the U.S. Environmental Protection Agency or by the State of Nebraska, rendering water testing voluntary. If arsenic concentrations are found to be above the MCL of 10 µg/l, private well owners should consult U.S. Environmental Protection Agency guidelines on how to reduce arsenic concentrations. Arsenic concentrations can be reduced through techniques such as reverse osmosis, distillation, adsorption, and (anion) ion exchange (Dvorak et al., 2014).

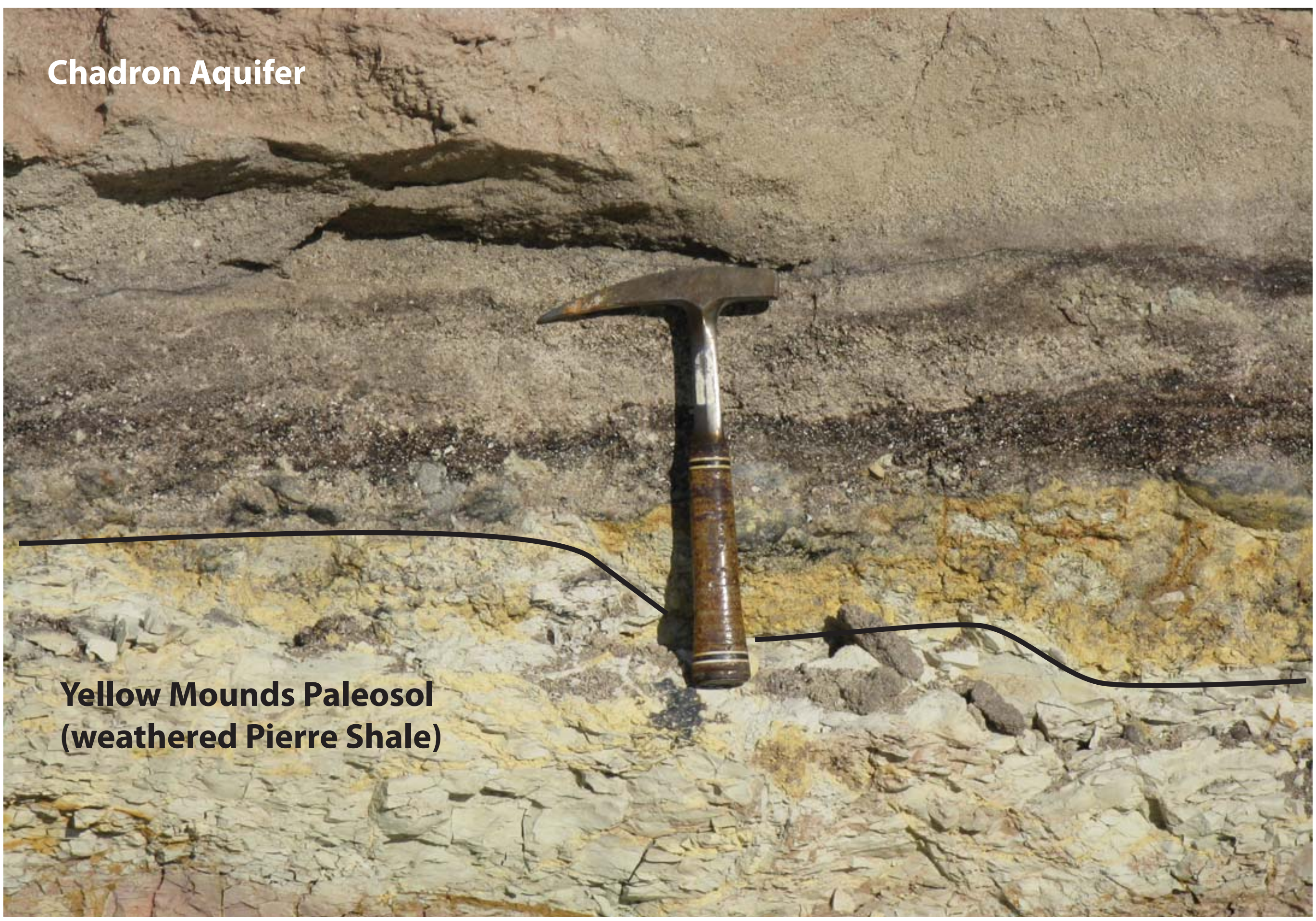
Methane—a colorless, odorless flammable gas—is a potential hazard in some Chadron aquifer wells. Methanogenic bacteria break down organic material, such as plant debris, and release methane as a byproduct. Methane in well water can be mitigated with passive venting or more active mitigation techniques such as air stripping.

## What do cuttings from strata hosting the Chadron aquifer look like?

The upper confining unit in the Chadron Formation is typically green claystone but white, yellow and red claystones are also present. Chadron Formation claystones are very sticky and they swell when wetted and drilled. Suitable drilling mud mixtures will help alleviate swelling during drilling and well installation. Sand and gravels in the aquifer part of the unit are typically white or greenish in color in fresh cutting returns.



*The Chadron aquifer, cropping out in Sioux County, Nebraska.*




*The Chadron aquifer and Yellow Mounds Paleosol contact (black line), Sioux County, Nebraska. The black material near the base of the Chadron aquifer is mostly organic material. Bacteria has generated methane from similar carbon-rich layers elsewhere in the Chadron aquifer. The Pierre Shale was weathered during development of the Yellow Mounds Paleosol, prior to deposition of the Chadron aquifer.*

# Brule Sand-Sandstone Aquifer

## Where is the Brule sand-sandstone aquifer located?

The Brule Formation consists of interbedded brown siltstone, mudstone, minor sandstones, and rare channels of arkosic (more than 25% feldspar) sand and gravel (Fig. 14). The Brule Formation is the youngest formation of the White River Group, which crops out extensively in northwestern Nebraska and southwestern South Dakota, and is also present in parts of Wyoming, Colorado, and North Dakota. The silt in the "Brown Siltstone" consists mostly of volcanic glass shards that were derived from volcanic eruptions that occurred in the Great Basin (eastern Nevada and western Utah) 33.3 to 30 million years ago (Larson and Evanoff, 1998), and is probably equivalent to the Sharps Formation in South Dakota (Souders et al., 1980). The Brown Siltstone has some permeability and is the source of water for some stock and domestic wells in the Niobrara River Drainage in Box Butte County, Sioux County, and Dawes County. The Brule Formation generally has low permeability; some wells are drilled 300 feet (91 m) into the Brule Formation with open hole completions that yield less than 3 gpm (11 lpm).

Fractures in the Brule Formation are present at relatively shallow depths in the Pumpkin Creek valley and Lodgepole Creek Valley. In this area, the Brule Formation is considered to be hydraulically well-connected with the shallow Quaternary alluvial aquifers on the basis of water chemistry and age dating (Steele et al., 2007). Fractures in the Brule Formation also occur at shallow depths in some of the areas along the North Platte Valley and the Niobrara Valley in the Nebraska Panhandle.

The Brule sand-sandstone aquifer discussed in this report refers to parts of the formation that consist of sand, gravel, and sandstone, excluding the fractured areas discussed above. These sediments were deposited in ancient valleys, one of which in Cheyenne County is at least six miles long, a half mile wide, and has a maximum thickness of 60 feet (18 m) (Steele et al., 2007). The Brule sand-sandstone aquifer is used mostly in the Nebraska Panhandle (Fig. 10d).

## How extensively is the Brule sand-sandstone aquifer used in Nebraska?

The Brule sand-sandstone aquifer is used mostly for domestic (55%) and livestock (31%) purposes, although limited irrigation development has occurred where the paleovalley deposits are relatively thick (Fig. 17). Recent test hole drilling and review of geophysical logs from oil and gas wells indicate that there is some potential for Brule sand-sandstone aquifer development in part of southwestern Kimball County that has seen little development previously.

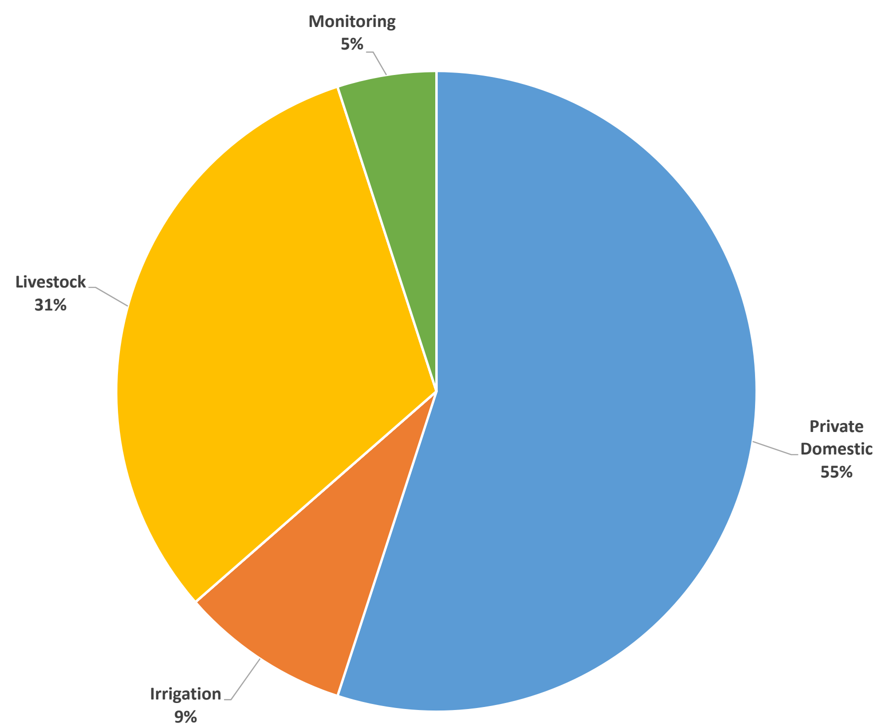



*Figure 17. Distribution of well use type for the Brule sand-sandstone aquifer.*

## What are the average well depth, depth to water and yield of Brule sand-sandstone wells in Nebraska?

The average well depth of Brule sand-sandstone wells is 246 feet (75 m) and average depth to water is 73 feet (22 m). The average irrigation well yield is 470 gpm (1,780 lpm), with a maximum reported pumping rate of 900 gpm (3,407 lpm).

## Where are the recharge and discharge areas of the Brule sand-sandstone aquifer?

Recharge and discharge areas of the Brule sand-sandstone aquifer are both local and regional in extent. Local recharge probably occurs in upland areas such as the Cheyenne Tablelands, the Wildcat Ridge, Box Butte and Sioux counties, and the Pine Ridge. There is also probably a regional component from upland areas to the west in Wyoming. In the North Platte valley, recharge may occur from leaking irrigation canals. Discharge in other areas is typically to local streams or wetlands located at lower elevations in valleys that are eroded into the Brule Formation. Discharge areas include Pumpkin Creek, the North Platte River and its tributaries, the Niobrara River, Lodgepole Creek and the White River.

## What is the water quality in the Brule sand-sandstone aquifer in Nebraska?

Water quality in the Brule sand-sandstone aquifer is generally good with low total dissolved solids (TDS) reported in Cheyenne County (Steele et al., 2007), Pumpkin Creek valley (Steele et al., 2005), and the North Platte valley (Vertraeten et al., 1995). The water type in the Brule sand-sandstone aquifer generally varies from sodium bicarbonate to calcium bicarbonate (Fig. 18). Age dates in low-yielding Brule sand-sandstone wells vary from 5,000 to 30,000 years old (Harvey and Sibray, 2001; Steele et al., 2007). The fractured upper part of the Brule Formation in Pumpkin Creek valley (not considered part of the Brule sand-sandstone aquifer) also has calcium bicarbonate chemistry, but much younger water, dating from the 1970s to modern (Steele et al., 2005).

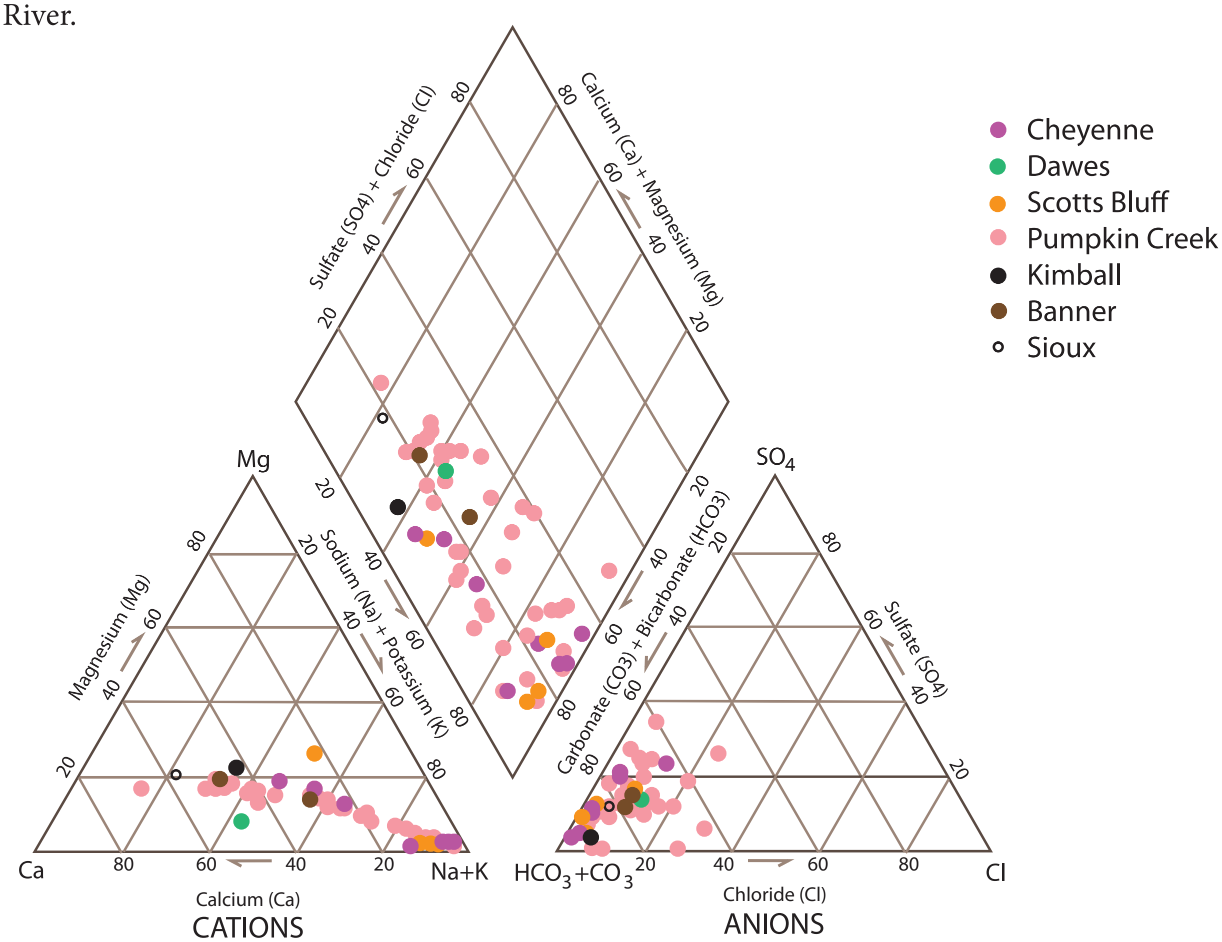



*Figure 18. Piper diagram depicting water chemistry for wells in the Brule sand-sandstone aquifer, western Nebraska. Proportions of positively charged (cations) and negatively charged (anions) ions are plotted separately on the triangles, with the overall major ion chemistry shown in the central diamond. Data are from Steele et al. (2007), Steele et al. (2005), Harvey and Sibray (2001), and Verstraeten et al. (1995).*

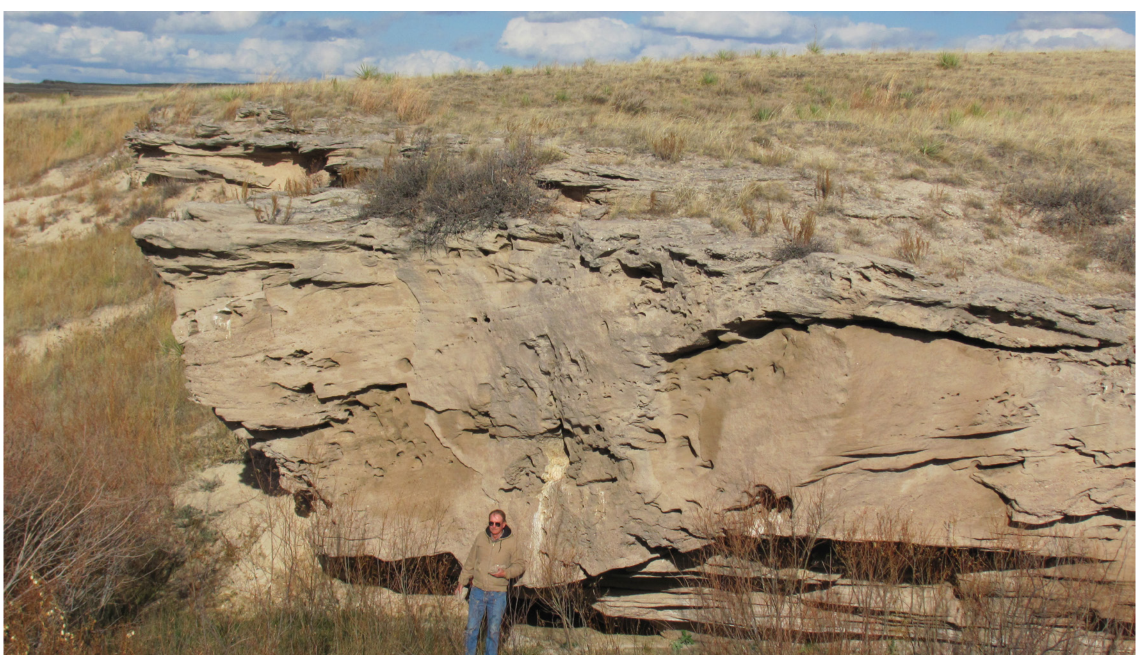
### What are the potential problems associated with using the Brule sand-sandstone aquifer in Nebraska?

Drawdowns may be large because the paleovalleys are often small and hydraulically confined. Special attention may also need to be given to the well gravel packs to prevent the wells from pumping silt and very fine sand.

### What do cuttings from strata hosting the Brule sand-sandstone aquifer look like?

The sands and gravels in the paleovalleys are typically white to light brown with pink feldspar and granite clasts. Where fine-grained sandstones are present, registered well logs often describe them as brown to tan and "granular."

*Brule sand and gravel characteristic of paleovalley fills. Pink and white feldspar and granite are common. Scotts Bluff County, Nebraska.*



*Outcrop of Brule sandstone in Scotts Bluff County, Nebraska, described by N.H. Darton in 1898.*

## ACKNOWLEDGMENTS

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## REFERENCES

Barkley, R.C., 1953, Artesian conditions in area surrounding the Sioux Quartzite Ridge: South Dakota State Geological Survey, Report of Investigations No. 72, 68 p.

Burchett, R.R., 1986, Geologic Bedrock Map of Nebraska: Conservation and Survey Division, University of Nebraska, scale 1:1,000,000, Geologic Maps and Charts (GMS)-1.

Burkart, M.R., 1984, Availability and quality of water from the Dakota aquifer, Northwest Iowa, In D. G. Jorgensen (Ed.), Geohydrology of the Dakota aquifer: Proceedings of the first C.V. Theis conferences on geohydrology: National Water Well Association, 56-61.

Busch, J.D., 1976. Geology, depositional environments, diagenesis, and economic potential of the Codell Sandstone (Upper Cretaceous) in western Nebraska and eastern Wyoming: Unpublished Masters' thesis, University of Nebraska, Lincoln, NE, 75 p.

Carlson, M.P., Nodine-Zeller, D.E., Thompson, T.L., and Witzke, B.J., 1986, Correlation of stratigraphic units in North America: Mid-Continent Region correlation chart, American Association of Petroleum Geologists.

Carlson, M.P. and Sibray, S.S., 1992, Older groundwater reservoirs in Nebraska: A description of Pre-Cenozoic hydrostratigraphic units to include their distribution, thickness, depth, and water quality: Conservation and Survey Division, University of Nebraska, Open File Report 75, 37 p.

Case, H.L. 1984, Hydrology of Inyan Kara and Dakota-Newcaste aquifer system, South Dakota, *In* D. G. Jorgensen (Ed.), Geohydrology of the Dakota aquifer: Proceedings of the first C.V. Theis conferences on geohydrology: National Water Well Association, 38-40.

Christensen, C.M., 1974, Geology and water resources of Bon Homme County, South Dakota: Part I; Geology: Department of Natural Resource Development—Geological Survey, Bulletin 21, Part I, 48 p.

Condra, G.E. and Reed, E.C., 1959, The Geologic Section of Nebraska: Nebraska Geological Survey, University of Nebraska, Bulletin 14A, 82 p.

Cussey, R. and Friedman, G.M., 1977, Patterns of porosity and cement in ooid reservoirs in Dogger (Middle Jurassic) of France: *The American Association of Petroleum Geologists Bulletin*, v. 61, p. 511-518.

Darton, N.H., 1899, Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian, *In* C.D. Walcott, Nineteenth annual report of the United States Geological Survey to the Secretary of the Interior, 1897-1898; Part IV, Hydrography: U.S. Geological Survey Report 19, pt. 4, p. 719-785

Darton, N. H., 1905, Preliminary report on the geology and underground water resources of the central Great Plains: U.S. Geological Survey, Professional Paper 32, 433 p.

DeGraw, H.M., 1969, Subsurface relations of the Cretaceous and Tertiary in western Nebraska: Unpublished Master's Thesis, University of Nebraska, Lincoln, NE, 137 p.

Diaz, E., Prasad, M., Mavko, G., and Dvorkin, J., 2003, Effect of glauconite on the elastic properties, porosity, and permeability of reservoir rocks: *The Leading Edge*, v. 22, p. 42-45.

Diffendal, R.F., Jr., and Voorhies, M.R., 1994, Geologic framework of the Niobrara River drainage basin and adjacent areas in South Dakota generally east of the 100th Meridian west longitude and west of the Missouri River: Conservation and Survey Division, School of Natural Resources, University of Nebraska, Report of Investigations 9, 13 p.

Divine, D.P., 2014, The groundwater atlas of Lancaster County, Nebraska: Conservation and Survey Division, School of Natural Resources, University of Nebraska, Resource Atlas 7, 39 p.

Divine, D.P., 2015, The groundwater atlas of Saunders County, Nebraska: Conservation and Survey Division, School of Natural Resources, University of Nebraska, Resource Atlas 9, 37 p.

Divine, D.P., Joeckel, R.M., and Korus, J.T., 2015, Basic guide for description of cuttings from boreholes in Nebraska: Conservation and Survey Division, School of Natural Resources, University of Nebraska, Educational Circular 25, 36 p.

Divine, D.P., Joeckel, R.M., Lackey, S.O., 2016, Aquifers of Nebraska I: The Codell aquifer in northeastern Nebraska: Conservation and Survey Division, University of Nebraska, Bulletin (New Series) 7, 21 p.

Drever, J.I., 1997, The geochemistry of natural waters: Surface and groundwater environments, Third Edition: Prentice-Hall Inc., Englewood Cliffs, NJ, 436 p.

Dvorak, B.I., Skipton, S.O., Woldt, W., and Kahle, A., 2014, Drinking water: Arsenic: University of Nebraska Extension, NebGuide G1552 (Revised August 2014), 3 p.

Ellis, M.J., 1984, Overview of the Dakota aquifer system in Nebraska, *In* D. G. Jorgensen (Ed.), Geohydrology of the Dakota aquifer: Proceedings of the first C.V. Theis conferences on geohydrology: National Water Well Association, 48-55.

Engberg, R.A. and Druliner, A.D., 1987, Nebraska ground water quality: U.S. Geological Survey, Open File Report 87-0737, 9 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice Hall Inc., Englewood Cliffs, NJ, 604 p.

Gannon, J.M. and Vogelgesang, J.A., undated, Groundwater resource evaluation of the lower Dakota aquifer in north-central and southwest Iowa: Iowa Geological Survey, Water Resources Investigation Report 12, 19 p.

Gjelsteen, T.W., and Collings, S.P., 1988, Relationship between groundwater flow and uranium mineralization in the Chadron Formation, northwest Nebraska, *In* Diedrich, R.P., Dyka, M.A.K, and Miller, W.R., Wyoming Geological Association 39th Field Conference Guidebook, Eastern Powder River Basin—Black Hills, p. 271-284.

Gosselin, D.C., Harvey, F.E., and Frost, C.D., 2001, Geochemical evolution of ground water in the Great Plains (Dakota) Aquifer of Nebraska: Implications for the management of a regional aquifer system: *Ground Water,* v. 39, p. 98-108.

Gosselin D., Klawer L., and Noe A., 2004, Arsenic in Nebraska's Groundwater and Public Water Systems: Conservation and Survey Division, University of Nebraska, Earth Science Notes 7, 8 p.

Hamilton, L.J., 1984, Water resources of Aurora and Jerauld counties, South Dakota: South Dakota Geological Survey, Water Resources Investigations Report 84-4030, 58 p.

Hamilton, L.J., 1989, Water resources of Brookings and Kingsbury counties, South Dakota: South Dakota Geological Survey, Water Resources Investigations Report 88-4185, 82 p.

Hansen, D.S., 1983, Water resources of Hanson and Davison counties, South Dakota: South Dakota Geological Survey, Water Resources Investigations Report 83-4108, 55 p.

Hansen, D.S., 1986, Water resources of Lake and Moody counties, South Dakota: South Dakota Geological Survey, Water Resources Investigations Report 84-4209, 51 p.

Harvey, F.E., Ayers, J.F., and Gosselin, D. C., 2007, Ground water dependence of endangered ecosystems: Nebraska's eastern saline wetlands: *Ground Water,* v. 45, p. 736-752.

Harvey, F.E., and Sibray, S.S., 2001, Delineating ground water recharge from leaking irrigation canals using water chemistry and isotopes: *Ground Water,* v. 39, p. 408-421.

Hedges, L.S., 1975, Geology and water resources of Charles Mix and Douglas counties, South Dakota, Part I: Geology: South Dakota Geological Survey Bulletin 22, 43 p.

Helgesen, J.O., Jorgensen, D.G., and Leonard, R.B., 1984, Regional study of the Dakota aquifer (Darton's Dakota revisited), *In* D. G. Jorgensen (Ed.), Geohydrology of the Dakota aquifer: Proceedings of the first C.V. Theis conferences on geohydrology: National Water Well Association, 69-73.

Helgesen, J.O., Leonard, R.B., and Wolf, R.J., 1993, Hydrology of the Great Plains Aquifer System in Nebraska, Colorado, Kansas, and adjacent areas: U. S. Geological Survey Professional Paper 1414-E, 80 p.

Joeckel, R.M., Wally, K.D., Ang Clement, B.J., Hanson, P.R., Dillon, J.S., and Wilson, S.K., 2011, Secondary minerals from extrapedogenic *per latus* acidic weathering environments at geomorphic edges, eastern Nebraska, USA: *Catena*, v. 85, p. 253-266.

Jorgensen, D.G., 1971, Geology and water resources of Bon Homme County, South Dakota, Part II: Water Resources: South Dakota Geological Survey, Bulletin 21, Part II, 61 p.

Kelly, B.B., 2011, Using electrical resistivity imaging (ERI) to map saline groundwater and subaqueous spring discharge: An example from the saline wetlands of eastern Nebraska, Unpublished Masters' thesis, University of Nebraska: Lincoln, NE, 150 p.

Knauth, L.P., 1979, A model for the origin of chert in limestone, *Geology*, v. 7, p. 274-277.

Koch, N.C., and McGarvie, S.D., 1988, Water resources of Miner County, South Dakota: South Dakota Geological Survey, Water Resources Investigations Report 86-4035, 37 p.

Korus, J.T., 2013, Type log showing stratigraphic units of the Forest City basin in Nebraska: Conservation and Survey Division, University of Nebraska, Correlations and Cross Sections (CCS) 19, 1 p.

Korus, J.T., Howard, L. M., Young, A. R., Divine, D. P., Burbach, M. E., Jess, J. M., and Hallum, D. R., 2013, The groundwater atlas of Nebraska: Conservation and Survey Division, University of Nebraska, Resources Atlas 4b/2013, Third (revised) edition, 64 p.

Korus, J.T. and Joeckel, R.M., 2011, Generalized geologic and hydrostratigraphic framework of Nebraska 2011, ver. 2: Conservation and Survey Division, University of Nebraska, Geologic Maps and Charts (GMC)-38, 1 p.

Kume, J., 1977, Geology and water resources of Charles Mix and Douglas Counties, South Dakota, Part II: Water Resources: South Dakota Geological Survey, Bulletin 22, 31 p.

Larson, E.E., and Evanoff, E., 1998, Tephrostratigraphy and source of the stuffs of the White River sequence, *In* Terry, D.O., Jr., LaGarry, H.E., and Hunt, R.M. (Eds.), Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America): Geological Society of America Special Paper 325, p. 1-4.

Macfarlane, P.A., 2000, Revisions to the nomenclature for Kansas aquifers, Kansas Geological Survey: *Current Research in Earth Sciences*, v. 244, p. 1-14.

Maher, H.D., Jr., 2014, Distributed normal faults in the Niobrara chalk and Pierre Shale of the central Great Plains of the United States: *Lithosphere*, v. 6, p. 319-334.

McGovern, H.E., 1984, Overview of Dakota aquifer in Kansas, *In* D. G. Jorgensen (Ed.), Geohydrology of the Dakota aquifer: Proceedings of the first C.V. Theis conferences on geohydrology: National Water Well Association, p. 58-61.

Miller, D.E. and Vandike, J.E., 1997, Groundwater resources of Missouri: Missouri Resources Report 46, Missouri State Water Plan Series Volume II, Missouri Department of Natural Resources, 210 p.

Miller, J.A. and Appel, C.L., 1997, Ground water atlas of the United States: Segment 3, Kansas, Missouri, and Nebraska: U.S. Geological Survey, Hydrologic Investigations Atlas 730-D, 24 p.

Munter, J.A., Ludvigson, G.A., and Bunker, B.J., 1983, Hydrogeology and stratigraphy of the Dakota Formation in northwest Iowa: Iowa Geological Survey, Water Supply Bulletin Number 13, 55 p.

Murray, R.C., 1960, Origin of porosity in carbonate rocks: *Journal of Sedimentary Research*, v. 30, p. 59-84.

Nebraska Department of Natural Resources, undated, Registered Ground Water Wells Data Retrieval, URL: https://dnr.nebraska.gov/data/groundwater-data, accessed July 19, 2016.

Nebraska Department of Water Resources, 1976, Transcript of hearing in the matter of the Department of Water Resources public hearing concerning the establishment of a groundwater control area, October 5, 1976, Scottsbluff, NE.

Olcott, P.G., 1992, Ground water atlas of the United States: Segment 9, Iowa, Michigan, Minnesota, Wisconsin: U. S. Geological Survey, Hydrologic Investigations Atlas 730-J, 31 p.

Pipes, J.W., 1987, The hydrogeologic framework of the Paleozoic aquifers of the Papio Natural Resources District, Nebraska: Unpublished Masters' thesis, University of Nebraska, Lincoln, NE, 106 p.

Prior, J.C., Boekhoff, J.l., Howes, M.R., Libra, R.D., and VanDorpe, P.E., 2003, Iowa's groundwater basics: A geological guide to the occurrence, use, & vulnerability of Iowa's aquifers: Iowa Department of Natural Resources, Iowa Geological Survey Educational Series 6, 83 p.

Robson, S.G., and Banta, E.R., 1995, Ground water atlas of the United States: Segment 2, Arizona, Colorado, New Mexico, Utah: U.S. Geological Survey, Hydrologic Investigations Atlas 730-C, 32 p.

Schoon, R.A., 1984, Overview of South Dakota's Dakota aquifer, *In* D. G. Jorgensen (Ed.), Geohydrology of the Dakota aquifer: Proceedings of the first C.V. Theis conferences on geohydrology: National Water Well Association, 38-40.

Sibray, S.S., 2011, White River Group paleosols as source rocks for uranium mineralization in western Nebraska: *The Mountain Geologist*, v. 48, p. 9-21.

Sibray, S.S., unpublished, Water quality results from two samples collected in 2016.

Souders, V.L., Smith, F.A., and Swinehart, J.B., 1980, Geology and groundwater supplies of Box Butte County, Nebraska: Conservation and Survey Division, University of Nebraska, Water Survey Paper 47, 203 p.

Spalding, R.F., Druliner, A.D., Whiteside, L.S., and Struempler, A.W., 1984, Uranium geochemistry in groundwater from tertiary sediments: *Geochimica et Cosmochimica Acta*, v. 48, p. 2679-2692.

Steele, G.V., Cannia, J.C., Sibray, S.S., and McGuire, V.L., 2005, Age and quality of ground water and sources of nitrogen in the surficial aquifers in Pumpkin Creek Valley, western Nebraska, 2000: U.S. Geological Survey, Scientific Investigations Report 2005-5157, 68 p.

Steele, G.V., Sibray, S.S., and Quandt, K.A., 2007, Evaluation of ground water near Sidney, western Nebraska, 2004-05: U.S. Geological Survey, Scientific Investigations Report 2007-5086, 54 p.

Stotler, R., Harvey, F.E., and Gosselin, D.C., 2010, A Black Hills-Madison aquifer origin for Dakota aquifer groundwater in northeastern Nebraska: *Ground Water,* v. 48, 448-464.

Swinehart, J.B., Souders, V.L., DeGraw, H.M., and Diffendal, R.F., Jr., 1985, Cenozoic paleogeography of western Nebraska, *In* Flores, R.M., and Kaplan, S.S. (Eds.) Cenozoic paleogeography of the west central United States, Special Publication, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 209-229.

Terry, D.O., Jr., and Evans, J.E., 1994, Pedogenesis and paleoclimatic implications of the Chamberlain Pass Formation, basal White River Group, Badlands of South Dakota: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 110, p. 197-215.

Terry, D.O., Jr., LaGarry, H.E., and Wells, W.B., 1995, The White River Group revisited: Vertebrate trackways, ecosystems, and lithostratigraphic revision, redefinitions, and redescription, Field Trip no. 4, *In* C.A. Flowerday, ed., Geologic Field Trips in Nebraska and Adjacent Parts of Kansas and South Dakota, Guidebook no. 10: Conservation and Survey Division, University of Nebraska, p. 43-57.

U.S. Environmental Protection Agency (EPA), 2012, 2012 Edition of the drinking water standards and health advisories, EPA 822-S-12-001, 12 p.

U.S. Geological Survey, undated, National Water Information System: Web Interface, URL: https://waterdata.usgs.gov/nwis/qw, accessed December 12, 2016

Verstraeten, I.M., Sibray, S.S., Cannia, J.C., and Tanner, D.Q., 1995, Reconnaissance of ground water quality in the North Platte Natural Resources District, western Nebraska, June-July 1991: U.S. Geological Survey, Water Resources Investigation Report 94-4057, 114 p.

Walker, E.H., 1956, Ground water resources of the Hopkinsville Quadrangle, Kentucky: U.S. Geological Survey, Water Supply Paper 1328, 98 p.

Weigand, R.C., 1991, Hydrogeology of the Codell Sandstone Member, Carlile Shale (Upper Cretaceous), in western Kansas: Unpublished Masters' thesis, Fort Hays State University, Fort Hays, KS, 87 p.

Wenzel, L.K., Cady, R.C., and Waite, H.A., 1946, Geology and groundwater resources of Scotts Bluff County, Nebraska, U.S. Geological Survey, Water Supply Paper 943, 150 p.

Whitehead, R.L., 1996, Ground water atlas of the United States: Segment 8, Montana, North Dakota, South Dakota, Wyoming, U.S. Geological Survey, Hydrologic Investigations Atlas 730-I, 24 p.

Whittemore, D.O., Macfarland, P.A., and Wilson, B.B., 2014, Water resources of the Dakota aquifer in Kansas: Kansas Geological Survey, Bulletin 260, 60 p.

Witzke, B.J., undated, unpublished hydrostratigraphic chart for western Iowa.

Witzke, B.J., Ludvigson, G.A., Poppe, J.R., and Ravn, R.l., 1983, Cretaceous paleogeography along the eastern margin of the Western Interior Seaway, Iowa southern Minnesota, and eastern Nebraska and South Dakota: *In* M. W. Reynolds and E. D. Dolly (Eds.), Mesozoic Paleogeography of west-central United States, Rocky Mountain Paleogeography Symposium 2: Rock Mountain Section SEPM, p. 225-252.

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