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Groundwater Quality and Age of Secondary Bedrock Aquifers in the Glaciated Portion of Eastern Nebraska, 2016–18

Scientific Investigations Report 2021–5055

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By Christopher M. Hobza and Amanda T. Flynn

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
Flow rate		
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Radioactivity		
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Activities for radioactive constituents in water are given in picocuries per liter (pCi/L).

Results for measurements of stable isotopes of an element (with symbol E) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope (iE) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Abbreviations

^{14}C	carbon-14
^{1}H	hydrogen-1
^{2}H	hydrogen-2 (deuterium)
^{3}H	tritium
^{16}O	oxygen-16
^{18}O	oxygen-18
$\delta^{2}H$	hydrogen-2-to-hydrogen-1 isotopic ratio or delta deuterium of water
$\delta^{18}O$	oxygen-18-to-oxygen-16 isotopic ratio or delta oxygen-18 of water
AEM	airborne electromagnetic
ENWRA	Eastern Nebraska Water Resources Assessment
EPA	U.S. Environmental Protection Agency
H	hydrogen
LMWL	local meteoric water line
NRD	Natural Resources District
NWIS	National Water Information System
O	oxygen
pMC	percent Modern Carbon
USGS	U.S. Geological Survey

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Abstract

The Eastern Nebraska Water Resources Assessment (ENWRA) project was initiated in 2006 to assist water managers by developing a hydrogeologic framework and water budget for the glaciated portion of eastern Nebraska. Within the ENWRA area, the primary groundwater sources for municipal, domestic, and irrigation water needs are provided by withdrawals from alluvial, buried paleovalley, and the High Plains aquifer (where present). Generally, other bedrock aquifers are considered a secondary water source. However, in some areas, such as parts of Sarpy and Nemaha Counties, these secondary bedrock aquifers are the only source of water within glaciated upland areas. To improve the understanding of the quality, geochemistry, and age of groundwater from bedrock aquifers, the U.S. Geological Survey (USGS), in cooperation with the ENWRA group, which includes the Lewis and Clark, Lower Elkhorn, Lower Platte North, Lower Platte South, Nemaha, and Papio-Missouri River Natural Resources Districts, designed a study to sample 31 wells completed in the secondary bedrock aquifers and analyze samples for major ions, physical properties, nutrients, stable isotopes, and selected age tracers. Of the 31 samples collected for this report, 22 samples were collected from the Dakota aquifer contained in the Dakota Sandstone, 3 from the Niobrara aquifer contained in the Niobrara Formation of Colorado Group, and 6 from Paleozoic aquifers contained in undifferentiated Paleozoic-age units.

The results of this study indicate that major ion data collected from the Dakota aquifer can be used for assessing the quality, recharge source, and age of groundwater. Calcium bicarbonate dominant samples were characterized as modern or mixed, indicating that, in these areas, groundwater is unconfined and is recharged by precipitation and (or) surface water. If groundwater extraction rates exceed recharge rates, total dissolved solid concentrations may increase as a result of upwelling of groundwater from deeper units or formations, which can adversely affect groundwater quality. Sampling results presented in this report indicate water quality is good, but that groundwater in the Dakota aquifer with calcium bicarbonate water type may be vulnerable to surface contamination.

In contrast, groundwater sampled from the Dakota aquifer, having a dominant water type other than calcium bicarbonate, generally has low dissolved oxygen and nitrate concentrations, and higher concentrations of total dissolved solids and trace elements, including iron and strontium. The geochemical characteristics of noncalcium bicarbonate samples from the Dakota aquifer indicated confining conditions and limited groundwater recharge from local precipitation. Apparent groundwater ages estimated from radiocarbon (carbon-14) sampling of noncalcium bicarbonate samples from the Dakota aquifer indicated that the time of groundwater recharge to the Dakota aquifer occurred during Pleistocene time. Depleted stable isotopes results indicate recharge during a colder climate. Groundwater under confined conditions is not easily recharged from precipitation or surface water. Future groundwater-level monitoring in locations where the Dakota aquifer appears to be confined could provide information to evaluate whether groundwater supplies remain sufficient to meet future municipal, domestic, and irrigation needs.

For the Niobrara aquifer and Paleozoic aquifers, the dominant water type was not a diagnostic indicator of recharge source, age, and groundwater quality as with the Dakota aquifer. Most likely this is because the host formation was dominated by calcium-carbonate-rich rocks; however, few samples were collected from these aquifers to be able to confirm this interpretation. Samples collected from wells completed in the Niobrara aquifer and Paleozoic aquifers and characterized as calcium sulfate water type have statistically significantly higher concentrations of total dissolved solids compared to other samples from the Niobrara aquifer and Paleozoic aquifers characterized as calcium bicarbonate. Given that six of the nine of samples collected from the Niobrara and Paleozoic aquifers indicated modern recharge, these secondary bedrock aquifers are reliant on precipitation to sustain groundwater levels and may be vulnerable to a multiyear drought. Well yields of the Niobrara and Paleozoic aquifers are dependent on the presence of secondary porosity and these units offer little storage. Samples collected from wells completed in Paleozoic aquifers were the most isotopically enriched and similar to modern precipitation and had the highest concentrations of nitrate, indicating that groundwater is affected by agricultural

activities. Future groundwater sampling would be beneficial to characterize groundwater-quality changes within the Niobrara and Paleozoic aquifers over time.

Introduction

The Eastern Nebraska Water Resources Assessment (ENWRA) project was initiated to assist water managers by developing a hydrogeologic framework and water budget for the area of eastern Nebraska overlain by glacial deposits (Divine and others, 2009). The ENWRA area (fig. 1) covers more than 8,000,000 acres across the Lewis and Clark, Lower Elkhorn, Lower Platte North, Lower Platte South, Nemaha, and Papio-Missouri River Natural Resources Districts (NRDs) and roughly coincides with the extent of glacial till within Nebraska (fig. 2). Since 2007, airborne electromagnetic (AEM) geophysical surveys have been a focus of ENWRA to map the extents and characteristics of aquifers for ground-water resource assessments, better understand vulnerability of aquifers to surface contamination, and examine the con-nectivity of groundwater and surface water (Smith and others, 2008; Divine and others, 2009; Carney and others, 2015a, 2015b). The AEM geophysical surveys generally have focused on mapping the alluvial, buried paleovalley; upland area; and bedrock aquifers (Divine and others, 2009). However, in 2014, widely spaced reconnaissance flights collected AEM data for deeper Paleozoic- and Cretaceous-age geologic units and bed-rock aquifers (Carney and others, 2015a, 2015b).

Municipal, domestic, and irrigation water needs in the ENWRA area are primarily met from alluvial and buried paleovalley aquifers and the High Plains aquifer within Nebraska, and generally, other bedrock aquifers are consid-ered a secondary water source (Divine and Sibray, 2017); however, in some ENWRA areas, such as parts of Sarpy and Nemaha Counties, bedrock aquifers are the only source of water within the upland areas overlain by glacial deposits (Divine and Sibray, 2017). Within eastern Nebraska, popula-tion growth has led to increased development of groundwater resources for domestic and municipal needs (Maupin and others, 2014; Dieter and others, 2018). Groundwater pump-ing for irrigation during recent droughts (2000–6; 2012) has reduced streamflows and strained drinking-water supplies for some towns and cities (Laukaitis, 2012). In response to some of these concerns, water resource managers have been evaluating the use of secondary bedrock aquifers to meet future municipal and domestic-water needs. The AEM surveys and subsequent hydrostratigraphic interpretation have filled an important data gap by mapping the extents and lithologic characteristics of bedrock aquifers within eastern Nebraska; however, the quality, chemical characteristics, and age of groundwater within secondary bedrock aquifers have not been adequately characterized. Unconfined bedrock

aquifers that are in hydrologic connection to surface water or surficial alluvial aquifers may receive adequate recharge to handle additional development, but the aquifer also can be vulnerable to surface contamination. Conversely, confined bedrock aquifers generally have lower recharge rates and, therefore, are potentially sensitive to increased groundwater development. To improve the understanding of the quality, geochemistry, and age of groundwater from bedrock aquifers, the U.S. Geological Survey (USGS), in cooperation with the ENWRA group, which includes the Lewis and Clark, Lower Elkhorn, Lower Platte North, Lower Platte South, Nemaha, and Papio-Missouri River NRDs, designed a study to sample 31 wells completed in the secondary bedrock aquifer and analyze samples for major ions, physical properties, nutrients, stable isotopes, and selected age tracers. The interpretation of these sampling results can provide water resource managers with additional information regarding the quality, age, and sustainability of secondary bedrock aquifers within eastern Nebraska, which are needed for future water resource plan-ning and management.

Purpose and Scope

The purpose of this report is to characterize the quality, geochemistry, and age of groundwater in selected secondary bedrock aquifers in the ENWRA area of eastern Nebraska. Samples were collected from 31 existing monitoring, domes-tic, and stock wells for major ions, physical properties, nutrients, stable isotopes, and selected age tracers. Of the 31 samples collected for this report, 22 samples were collected from wells completed in the Dakota aquifer (also known as the Maha aquifer; Korus and Joeckel, 2011), which is contained in Early Cretaceous-age Dakota Sandstone, 3 from wells com-pleted in the Niobrara aquifer contained in Late Cretaceous-age Niobrara Formation of Colorado Group, and 6 from wells completed in Paleozoic aquifers contained in undifferentiated Paleozoic units. The proportion of samples used in this study roughly reflects the proportion of water use of these bedrock aquifers, with the Dakota aquifer being the most widely used of the aquifers sampled. The groundwater sampling approach and well selection process is described in the "Well Selection and Identification" section of this report. The results and interpretations from this study supplement the findings from previous studies by including additional sampling locations and constituents and providing a more current assessment of groundwater-quality conditions. Constituent concentrations from each of the sampled aquifer were compared with current U.S. Environmental Protection Agency (EPA) drinking-water regulations (U.S. Environmental Protection Agency, 2018) and assessed by aquifer. This report also summarizes interpreta-tions from stable isotope and age tracer sampling and analyses from the 31 wells sampled.
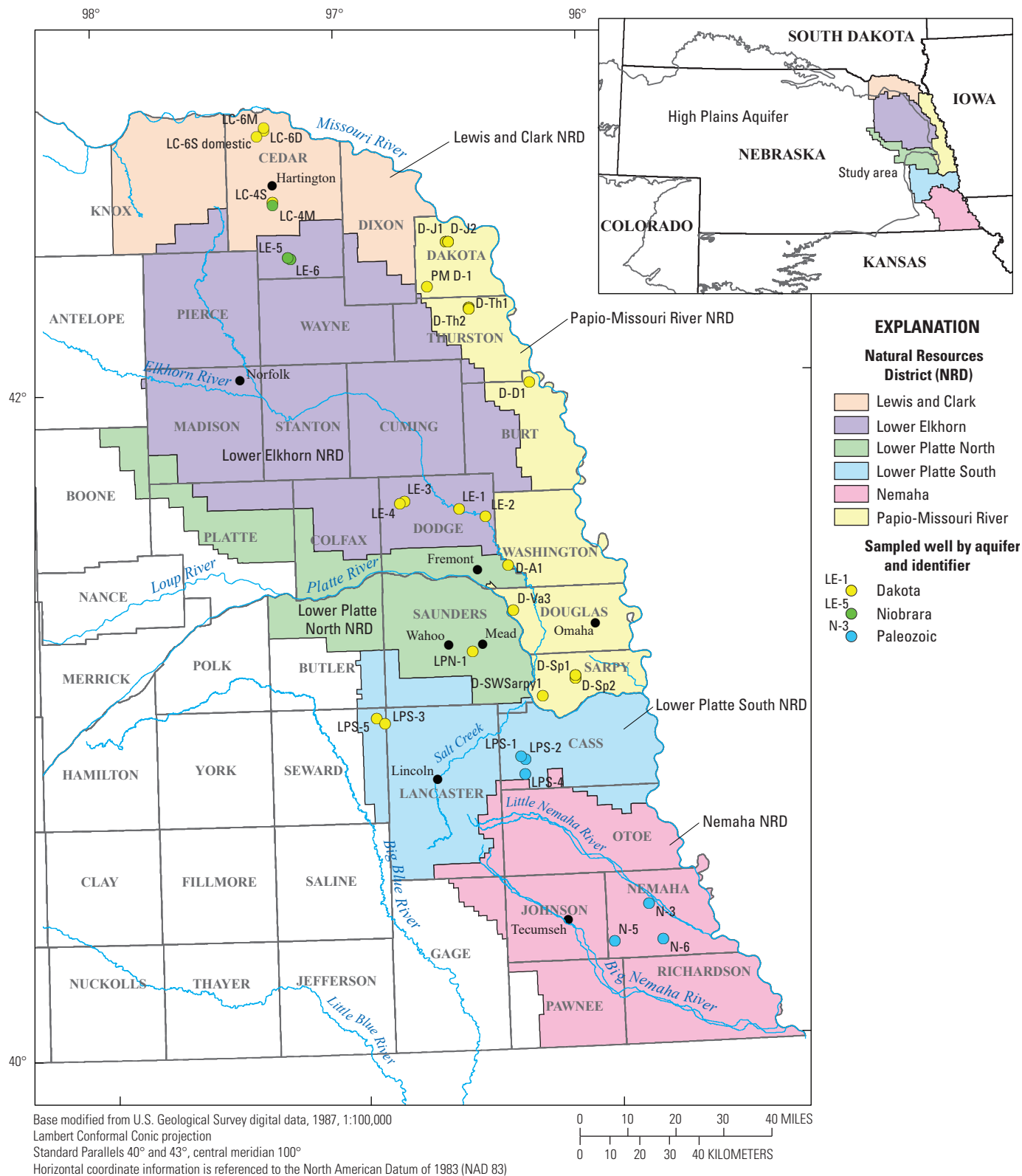
Figure 1. The Eastern Nebraska Water Resources Assessment (ENWRA) study area and location of sampled wells, eastern Nebraska.
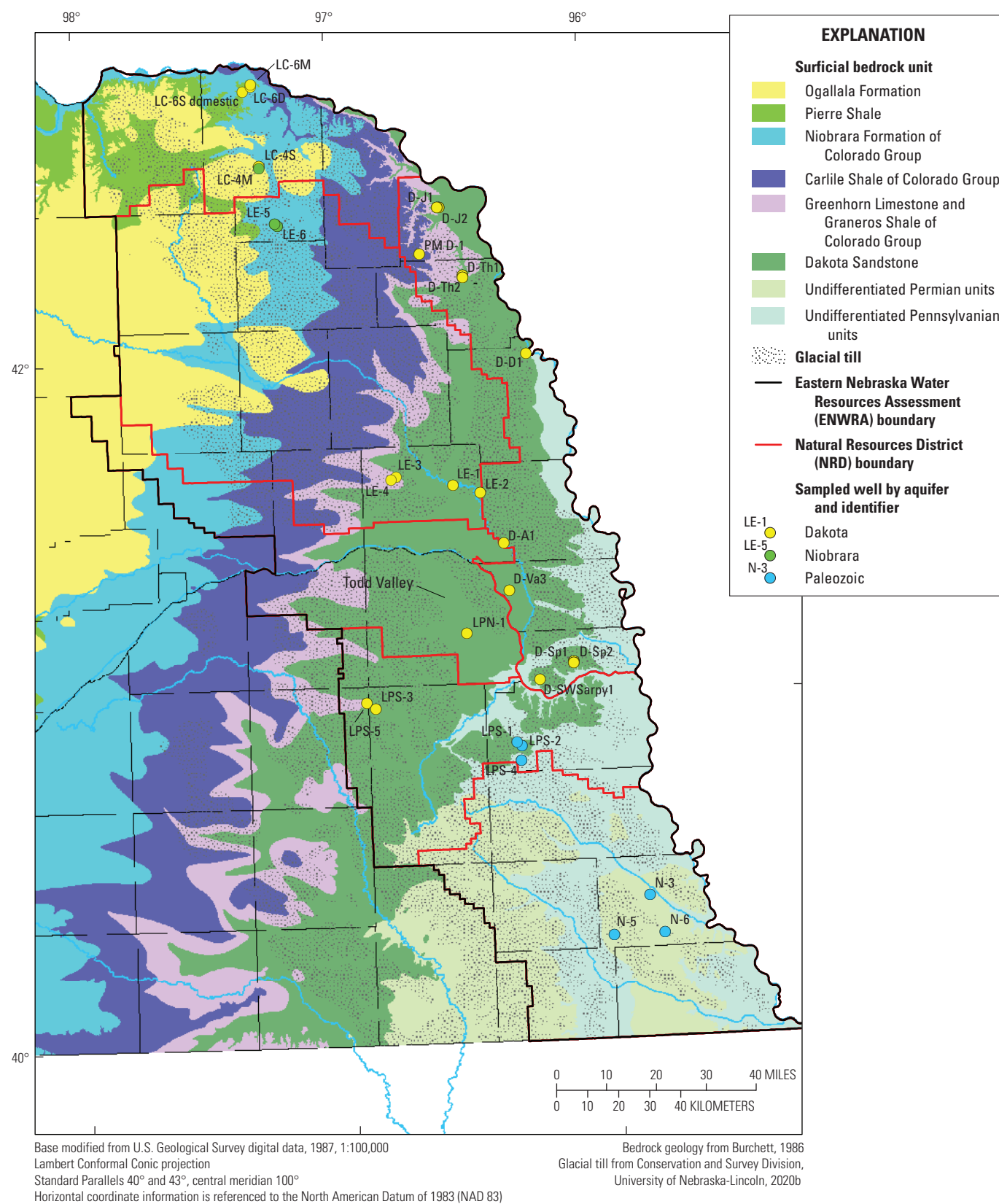
Figure 2.   Bedrock geology and location of sampled wells, eastern Nebraska.

Study Area Description

The study area for this report is the ENWRA area, which includes the Lewis and Clark, Lower Elkhorn, Lower Platte North, Lower Platte South, Nemaha, and Papio-Missouri River NRDs (fig. 1). The western boundary of the study area roughly coincides with the western extent of glacial till and overlaps onto the eastern margin of the High Plains aquifer (figs. 1 and 2). The study area is bounded by the Missouri River on the north and east and by the Kansas border to the south (fig. 1). The major streams of the study area include the Platte River, which flows from west to east across the center of the study area; the Elkhorn River, which is the largest tributary of the Platte River and flows southeast across the northern part of the study area to its confluence with the Platte River, south of Fremont, Nebraska; and the Little Nemaha and Big Nemaha Rivers, which drain the southern part of the study area (fig. 1).

Much of the study area is at the western edge of the Central Lowlands physiographic province (not shown on any maps) and is characterized as dissected till plains; however, the western parts of the Lewis and Clark, Lower Elkhorn, and Lower Platte North NRDs (fig. 1) are along the eastern margin of the Great Plains physiographic province (not shown on any maps; Fenneman and Johnson, 1946). The study area consists of gently rolling to steep upland areas that flank the major streams within the study area (Conservation and Survey Division, University of Nebraska-Lincoln, 2020c). The upland areas consist of loess-covered glacial deposits that can be deeply dissected by numerous small drainages (Verstraeten and Ellis, 1995; Druliner and Mason, 2000).

The climate in the study area is typical of continental midlatitude locations, characterized by cold winters and warm summers (National Center for Environmental Information, 2020). From 1981 to 2010, at Fremont, Nebr. (fig. 1), the average annual low temperature for the winter was −9.2 degrees Celsius (°C) and the average annual high temperature was 28.4 °C (National Center for Environmental Information, 2020). During that same period, the average annual precipitation was 30 inches per year (National Center for Environmental Information, 2020). In the study area, nearly 75 percent of the annual precipitation falls from April through September (National Center for Environmental Information, 2020), which is considered to be the growing season for crops.

In the study area, most of the land is used for agricultural purposes (Center for Advanced Land Management Information Technologies, 2007). Approximately 48 percent of the study area is classified as dryland cropland; 28 percent pasture; 13 percent irrigated crops; 7 percent open water, riparian woodlands, and wetlands; and 4 percent urbanized (Center for Advanced Land Management Information Technologies, 2007).

Geologic and Hydrogeologic Setting

This section of the report describes the geologic setting and hydrogeology of the study area. Geologic units important to the groundwater flow system are discussed with special attention applied to sampled bedrock aquifers and with limited discussion of overlying surficial units. The ages and geologic and hydrogeologic characteristics of geologic and hydrostratigraphic units, including the sampled bedrock aquifers, are described in table 1. The sampled bedrock aquifers within the study area are contained in geologic units that can be generally categorized as either Paleozoic or Cretaceous in age (fig. 2, table 1; Burchett, 1986). Bedrock formations generally have a subcrop along a northeast to southwest trendline with younger units to the western part of the study area and older units to the south and east (fig. 2).

Undifferentiated Pennsylvanian- and Permian-age units have subcrops in the Nemaha and the Lower Platte South NRDs in southeast part of the study area and to the east along the Missouri River valley in the Papio-Missouri River NRD (Burchett, 1986; Divine, 2014; fig. 2). For the purposes of this report, surficial Pennsylvanian- and Permian-age units described here are described as "aquitards with local low-yield aquifers" by Korus and Joeckel (2011) and are referred to hereinafter as "Paleozoic aquifers" and overlie the Western Interior Plains aquifer system (table 1). Pennsylvanian units are described as predominantly shale or interbedded limestone and are semi-confined or confined (Tanner and Steele, 1991). Permian-age units are described as limestone, shale, mudstone, and evaporites and are unconfined to semi-confined (table 1; Korus and Joeckel, 2011). Wells completed in the Paleozoic aquifers can yield up to 20 to 50 gallons per minute (gal/min) and yields are dependent on fracturing and the development of secondary porosity (Tanner and Steele, 1991). Water use for the Paleozoic aquifers is generally limited to domestic or stock wells (Korus and Joeckel, 2011).

Cretaceous-age units cover much of the study area and include the Dakota Sandstone (also called the Dakota Group), Greenhorn Limestone of Colorado Group, Graneros Shale of Colorado Group, Carlile Shale of Colorado Group, Niobrara Formation of Colorado Group, and Pierre Shale (fig. 2; Korus and Joeckel, 2011). In the study area, the oldest of these units and most hydrologically important is the Dakota Sandstone. The Dakota Sandstone was deposited 100 to 145 million years ago along the margin of the Western Interior Seaway (not shown on any maps). Within the study area, the Dakota Sandstone is described as a highly variable series of sandstones, shales, siltstones, and mudstones that reflect a complex pattern of deposition and erosion that are associated with fluvial, near-shore, and beach depositional environments (table 1; Gosselin and others, 2001). The Dakota Sandstone covers a large geographic area, which includes large parts of Nebraska, Kansas, and Colorado, and has highly variable

Table 1. Description of geologic and hydrostratigraphic units, eastern Nebraska.

[Ma, millions of years ago; NRD, Natural Resources District; gal/min, gallon per minute; mg/L, milligram per liter]

Period	Epoch	Age (Ma)	Geologic unit	Geologic description[1]	Hydrostratigraphic unit		Hydrogeologic description[1]
Quaternary	Holocene	Present to 0.01	Undifferentiated Quaternary deposits	Loess, till, eolian sand, and alluvial deposits	High Plains aquifer system	Alluvial and eolian deposits	Primary water source for much of study area, located along major river and stream valleys including the Platte River, Elkhorn River, and Big Nemaha River.
Quaternary	Pleistocene	0.01 to 2.6	Undifferentiated Quaternary deposits	Loess, till, eolian sand, and alluvial deposits	High Plains aquifer system	Paleovalley aquifers	Coarse sediments deposited from eastward drain-ing Pleistocene-age streams in eroded valleys in exposed bedrock, often capped with glacial till, primary water source where present.
Tertiary	Miocene	5.3 to 19	Ogallala Formation	Poorly sorted mixture of sand, silt, clay, gravel, sandstone, and siltstone	High Plains aquifer system	Ogallala aquifer	Moderate- to high-yielding water-bearing units. Heterogeneous mix of sand, silt, gravel, sandstone, and clay. Yields vary greatly by locality. Principal aquifer in western parts of the Lower Elkhorn and Lewis and Clark NRDs.
Cretaceous	Upper Cretaceous	65 to 99.6	Pierre Shale	Gray to black marine shale	Pierre Shale confining unit		Confining unit, not a source of water.
Cretaceous	Upper Cretaceous	65 to 99.6	Niobrara Formation of the Colorado Group	Shaley chalk, lime-stone	Niobrara aquifer[2]		Secondary bedrock aquifer. Largest concentration of wells is in Cedar County where well yields aver-age 400 gal/min, also a water source in Pierce and Madison Counties, where fractured.
Cretaceous	Upper Cretaceous	65 to 99.6	Carlile Shale of the Colorado Group	Shale with minor limestone	Carlile Shale confining unit		Predominantly shale, part of Great Plains confin-ing system, but includes a sandstone unit in Knox County, which is called the Codell aquifer (Miller and Appel, 1997; Divine and Sibray, 2017).
Cretaceous	Upper Cretaceous	65 to 99.6	Greenhorn Limestone and Graneros Shale of the Colorado Group	Limestone and shale	Greenhorn Limestone and Graneros Shale confining unit		Not typically used as a water source, part of Great Plains confining system (Miller and Appel, 1997)
Cretaceous	Lower Cretaceous	99.6 to 145.5	Dakota Sandstone	Sandstone, with intervals of interbedded shale and mudstone	Dakota aquifer[2]		Unconfined to confined, wells can yield up to 750 gal/min in northeast Nebraska, most widely used bedrock aquifer in eastern Nebraska. The Dakota aquifer, which is also called the Maha aquifer, is the uppermost aquifer of the Great Plains aquifer system; the underlying aquifer in the Great Plains aquifer system is the Apishapa aquifer, which is not present in the study area (Miller and Appel, 1997).

Table 1. Description of geologic and hydrostratigraphic units, eastern Nebraska.—Continued

[Ma, millions of years ago; NRD, Natural Resources District; gal/min, gallon per minute; mg/L, milligram per liter]

Period	Epoch	Age (Ma)	Geologic unit	Geologic description[1]	Hydrostratigraphic unit	Hydrogeologic description[1]
Permian		245 to 286	Undifferentiated Permian units	Limestone, shale, mudstone, and evaporites	Paleozoic aquifers[2]	Able to supply water to domestic and stock wells, yield depends on degree of fracturing.
Pennsylvanian		286 to 318	Undifferentiated Pennsylvanian units	Limestone, shale, mudstone, and sandstone		
Mississippian		318 to 359	Multiple undifferentiated units	Limestone, sandy limestone, dolomite, silty dolomite, shaly dolomite, shale, siltstone, and chert	Western Interior Plains aquifer system	Secondary aquifers with poor water quality, water is saline to brine with estimated total dissolved solid concentrations ranging from 11,000 to 200,000 mg/L.
Devonian		359 to 416				
Silurian		416 to 444				
Ordovician		444 to 488				
Cambrian		488 to 542				

[1]Geologic and hydrogeologic descriptions modified from Korus and Joeckel (2011), Divine and Sibray (2017), and Tanner and Steele (1991).

[2]Sampled secondary bedrock aquifer.

lithologic characteristics. The stratigraphic and hydrostrati-graphic organization of this unit varies by state and location. The Dakota Sandstone hosts the Great Plains aquifer system, which is composed of the hydrostratigraphically distinct Maha and Apishapa aquifers (Helgesen and others, 1993). Within eastern Nebraska, only the Maha aquifer is present (Helgesen and others, 1993). In Nebraska, the Maha aquifer is locally referred to as the Dakota Sandstone or Dakota aquifer (Divine, 2014); in this report the Maha aquifer will hereinafter be referred to as the Dakota aquifer. Helgesen and others (1993) reported that more than 75 percent of the Dakota Sandstone thickness is described as a sandstone in the southern part of the study area, compared with only 50 percent for the northern part of the study area.

The Dakota aquifer is the most widely used secondary bedrock aquifer within eastern Nebraska. As of 2015 there were approximately 3,400 registered wells completed within the Dakota aquifer (Divine and Sibray, 2017). The Dakota aquifer is often relied on for domestic purposes where nearly 75 percent of the registered wells are used for domestic pur-poses. Since 1993, the number of registered domestic wells screened in the Dakota aquifer has increased by approximately 130 per year (Divine and Sibray, 2017). Most of the Dakota aquifer wells are located along the southwest to northeast belt from southwestern Lancaster County into Sarpy and Douglas Counties (fig. 1). Well completed within the Dakota aquifer are also concentrated within counties that border the Missouri River upstream from Douglas County (Divine and Sibray, 2017). Quaternary-age deposits directly overlie the Dakota aquifer along both of these locations. Roughly 10 percent of wells completed in the Dakota aquifer are located west of the subcrop belt where Late Cretaceous-age shales overlie the Dakota aquifer and restrict its recharge from precipitation. In Cedar County in the Lewis and Clark NRD (fig. 2), well yields can exceed 750 gal/min, which are the highest yields for any well completed in the Dakota aquifer (Divine and Sibray, 2017).

Overlying the Dakota aquifer are the Greenhorn Limestone and the Graneros Shale of the Colorado Group and the Carlile Shale of the Colorado Group (table 1). The Greenhorn Limestone and the Graneros Shale of the Colorado Group units are not used as a water source across the study area and are part of the Great Plains confining system (Miller and Appel, 1997). The Carlile Shale of the Colorado Group is also part of the Great Plains confining system (Miller and Appel, 1997), is predominantly shale and, in parts of Boyd and Knox Counties, hosts the Codell aquifer, which is composed of a sandstone unit (Divine and Sibray, 2017).

The Niobrara Formation of the Colorado Group is locally described as a shaley chalk or limestone and hosts the Niobrara aquifer (table 1; Korus and Joeckel, 2011). The larg-est concentration of wells completed in the Niobrara aquifer is in Cedar County in the Lewis and Clark NRD (fig. 2; Divine and Sibray, 2017). Within Cedar County, approximately half of the 150 registered wells, which are screened in the Niobrara aquifer, are irrigation wells that on average can yield more

than 400 gal/min (Divine and Sibray, 2017). In some locations, where fractures are present, such as in Pierce and Madison Counties (fig. 1), the Niobrara aquifer can yield water to domestic, stock, and municipal wells (Gutentag and oth-ers, 1984). There is little, if any, information available about recharge to the Niobrara aquifer; however, the average well depth for wells completed in the Niobrara aquifer is a little more than 100 feet (ft). Therefore, it has been inferred that the Niobrara aquifer is only used as a water source where the unit is unconfined and precipitation or surface water from a losing stream provide adequate recharge (Divine and Sibray, 2017). In northeastern Nebraska, recharge to the Niobrara aquifer is through glacial deposits or in bedrock outcrop areas (Engberg and Druliner, 1987).

The Pierre Shale is the regional confining unit for the western part of the study area separating secondary bedrock aquifers from overlying Pleistocene- or Quaternary-age depos-its (fig. 2; Korus and Joeckel, 2011; Carney and others, 2015a, 2015b). The Pierre Shale is described as a shale with minor shaley chalk, siltstone, and sandstone intervals (table 1; Korus and Joeckel, 2011). Geologic units that are used as secondary bedrock aquifers east of the Pierre Shale subcrop area are not as extensively used to the west (fig. 2). In those areas, ground-water generally is too brackish for domestic purposes likely partly because the Pierre Shale restricts the recharge from precipitation (Engberg and Druliner, 1987).

The Ogallala Formation is the principal geologic unit in the High Plains aquifer system and is parts of the Lewis and Clark, Lower Elkhorn, and Lower Platte North NRDs (fig. 2). The Ogallala Formation consists of a poorly sorted mixture of sand, silt, clay, and gravel (Condra and Reed, 1943) and is generally unconsolidated or weakly consolidated but can contain layers of sandstone cemented by calcium carbonate or limestone. Within the study area, the Ogallala Formation has not been subdivided into stratigraphic units recognized in other areas because of the difficulty correlating these units in the subsurface with available test-hole data.

Paleovalleys are an important hydrogeologic feature that were formed by eastward draining Pleistocene-age streams that, prior to glaciation, incised valleys into exposed bedrock (Divine and others, 2009). With time, paleovalleys were gradually filled with often coarse sediments creating locally important aquifer systems. These sediments are capped by glacial till deposits and Pleistocene-age loess deposits (Korus and others, 2012; Cannia and others, 2017; Conservation and Survey Division, University of Nebraska-Lincoln, 2020a). The distribution and thickness of glacial outwash and till deposits are important in this study because overlying till deposits can form a confining cap to underlying Pleistocene-age sand and gravel deposits, preventing surface contamination into the aquifer and limiting groundwater/surface-water interaction (Cannia and others, 2017).

Alluvial aquifers located along major modern river and stream valleys are the primary water source for much of the study area (Divine and others, 2009; Korus and Joeckel, 2011). The highest density of high-capacity irrigation wells

are located within the stream valleys of the Platte, Elkhorn, and Big Nemaha Rivers (fig. 1; Divine and others, 2009). The largest cities in the study area, Lincoln and Omaha, Nebr., receive much of their water from the Platte River alluvial aquifer (Divine and others, 2009). Another major alluvial aquifer system underlies the Todd Valley in Saunders County (fig. 2), this major alluvial aquifer system is hosted within deposits of a former channel of the Platte River that was abandoned during the late Pleistocene and filled with alluvial sediments (Divine, 2015).

Previous Studies

Previous studies have focused on describing the hydrogeologic characteristics of secondary bedrock aquifers and assessing groundwater quality within the study area (Engberg, 1984; Miller and Appel, 1997; Divine and Sibray, 2017). Divine and Sibray (2017) published a report describing the hydrogeology, water use, and water-quality characteristics of secondary bedrock aquifers in Nebraska, including the Western Interior Plains, Dakota, Codell, and Niobrara aquifers. Miller and Appel (1997) provided maps of aquifer characteristics and cross-sections of all major aquifer systems within Nebraska as well as maps of water type and total dissolved solid concentrations of the Dakota aquifer. Engberg (1984) analyzed water-quality data for aquifers completed in Cretaceous- and Paleozoic-age deposits within Nebraska and provided summary statistics and maps for major constituents.

For some studies, the geochemistry and water quality of secondary bedrock aquifers was not the primary focus, rather they were part of more comprehensive groundwater-quality assessments (Tanner and Steele, 1991; Verstraeten and Ellis, 1995; McGuire and others, 2012). Tanner and Steele (1991) collected groundwater samples from confined and unconfined Paleozoic aquifers as part of a groundwater-quality reconnaissance of the Nemaha NRD. Verstraeten and Ellis (1995) sampled 58 wells within the Papio-Missouri River NRD including 13 completed in the Dakota aquifer. McGuire and others (2012) sampled 133 wells completed in various aquifers from 1994 through 2009, including 38 wells completed in the Dakota aquifer, for major ions, trace elements, nutrients, stable isotopes, and selected age tracers. Groundwater sampled from the Dakota aquifer in the Papio-Missouri River NRD was characterized as being a calcium-sulfate water type that had recharged approximately 20 to 40 years ago (McGuire and others, 2012).

The groundwater chemistry of the Dakota aquifer has been the focus of several recent studies (Stotler, 2000; Gosselin and others, 2001; Harvey and others, 2007; Stotler and others, 2010). Gosselin and others (2001) analyzed the major ion concentrations from previously collected groundwater samples from 203 wells in eastern Nebraska (most of the wells were within the study area). Additional groundwater samples were collected to analyze strontium isotopic ratios and stable isotopic ratios of oxygen-18/oxygen-16 (δ^{18}O) and hydrogen-2 (deuterium)/hydrogen-1 (δ^{2}H). Using these datasets, three different water types were identified within the Dakota aquifer in eastern Nebraska. The first water type, which is characterized as Pleistocene-age recharge, is present within the Lewis and Clark NRD in Knox and Cedar Counties (fig. 1). Because the Dakota aquifer is confined and not easily recharged, the aquifer is vulnerable to overdevelopment and more active management may be necessary (Gosselin and others, 2001). The second water type is present in groundwater within Lancaster, Sarpy, and Saunders Counties (fig. 1) and is characterized as primarily local meteoric recharge (precipitation); in these areas, groundwater development would need to be balanced to ensure extraction does not exceed recharge (Gosselin and others, 2001). The final water type was identified as a mix of local meteoric precipitation and upwelling sodium chloride-type brines in Dakota and Thurston Counties (fig. 1). Gosselin and others (2001) noted that in Dakota and Thurston Counties it is important that groundwater extraction does not exceed local recharge to ensure that the freshwater/saline-water interface does not migrate farther upward and adversely affect drinking-water quality (Gosselin and others, 2001).

Stotler and others (2010) examined the geochemical characteristics to determine the origin of groundwater in the Dakota aquifer in northern and northeastern Nebraska. Using selected major ions, age tracers, and stable isotopes, it was determined the source of water from sampled wells with a calcium-sulfate water type likely was the Madison aquifer (not shown in table 1) in the Black Hills in South Dakota (not shown on any maps). Groundwater sampled in wells in northwest Dixon County and areas to the west into Boyd County (not shown on any maps) was likely recharged in the Madison aquifer more than 25,000 years ago. Groundwater sampled in southeastern Dixon County and Dakota and Thurston Counties is likely the result of modern recharge (Stotler and others, 2010).

Harvey and others (2007) examined sources of groundwater discharge within eastern Nebraska's saline wetlands, which supports a unique ecosystem home to several threatened and endangered species. The saline wetlands are located along the northern edge of Lincoln, Nebr., and within the Salt Creek drainage in Lancaster and Saunders Counties (fig. 1) and are the result of saline groundwater discharge from the underlying Dakota aquifer and other Pennsylvanian-age units. The researchers determined that wetlands are sustained by groundwater flows along regional flow paths during the course of thousands to tens of thousands of years (Harvey and others, 2007).

Study Design and Methods

This section describes the study design and methods used to collect groundwater-quality and age tracer samples and the analytical approaches used to describe and interpret these data. Groundwater levels were measured and groundwater samples were collected using the guidelines and protocols described in Cunningham and Schalk (2011) and in the USGS National Field Manual (U.S. Geological Survey, variously dated).

Well Selection and Identification

Well selection for this study was a collaborative process between the USGS, the coordinator of the ENWRA group, geologists from the University of Nebraska Conservation and Survey Division, and staff from the participating NRDs. Wells selected for sampling were chosen from the Nebraska Department of Natural Resources registered well database (Nebraska Department of Natural Resources, 2020). A detailed, reliable driller's log was required to ensure that the chosen well was screened within the targeted aquifer (Nebraska Department of Natural Resources, 2020). Monitoring wells were preferred over other well types because the depth and length of the screened interval is usually based on lithologic descriptions and geophysical logs collected by a professional geologist (Conservation and Survey Division, University of Nebraska-Lincoln, 2020a). In many instances, a monitoring well was not available and domestic or stock wells were chosen for sampling. Wells with relatively short screen intervals (10 ft or less) were preferred to ensure a representative sample from a specific interval within the aquifer. The type of well, aquifer sampled, and screen interval are listed in table 2. One well, LC–6S domestic, was not completed as a screened well, rather a casing was installed through 40 ft of unconsolidated deposits until the borehole reached competent bedrock, then the borehole was left open to the formation from 40 to 95 ft below land surface (table 2).

This report uses three different methods of well identification. The first method uses the USGS site number, which is a 15-digit number (table 2). The 15-digit USGS site number is particularly useful for accessing available water-quality or water-level data for a given well in the USGS National Water Information System (NWIS; U.S. Geological Survey, 2020b). The next identification method is the USGS station name. The station name uses the legal description of the well location and a local well name, which is the well name typically used by participating NRDs (hereinafter referred to as the well's "field name"), such as 19N 8E 20AD (LE–1). The last well identification method is the field name, such as LE–1 (table 2).

For this report, a total of 31 wells were sampled from the three secondary bedrock aquifers. Of these 31 wells, 22 wells were sampled from wells completed in the Dakota aquifer, 3 were sampled from wells completed in the Niobrara aquifer, and 6 were sampled from wells completed in Paleozoic aquifers (table 2, fig. 2). Well depths for sampled wells completed in the Dakota aquifer ranged from 95 to 750 ft below land surface. Well depths for sampled wells completed in the Niobrara aquifer ranged from 120 to 180 ft below land surface. Well depths for sampled wells completed in the Paleozoic aquifers ranged from 79 to 172 ft below land surface (table 2). Of the 22 sampled wells completed in the Dakota aquifer, 15 were monitoring wells and 7 were domestic wells. Two monitoring wells and one domestic well were sampled for the Niobrara aquifer. One stock and five domestic wells were sampled for the Paleozoic aquifers (table 2).

Sample Collection

Groundwater samples were collected from August 9, 2016, to June 20, 2018 (table 2). Sample collection procedures followed the guidelines and protocols set forth in the USGS "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated), the USGS Menlo Park Tritium Laboratory (U.S. Geological Survey, 2020c), and the USGS Reston Stable Isotopes Laboratory (U.S. Geological Survey, 2020d). The sampling protocols described in this section ensured that a representative sample of groundwater was collected at each well and that the samples were collected and handled in a way that minimized contamination.

Prior to sampling monitoring wells, the water level was measured to the nearest 0.01 ft using a graduated electric tape following guidelines and protocols described in Cunningham and Schalk (2011). For domestic and stock wells, water level and well depth were not measured because the wells generally were in operation prior to sampling. Groundwater samples were collected from monitoring wells using a stainless-steel submersible pump. Groundwater samples from domestic or stock wells were collected at a hydrant or spigot closest to the well so that water was sampled prior to reaching a pressure tank or any other water treatment such as water softeners. Groundwater was sampled through Tygon tubing connected to the submersible groundwater pump or the chosen hydrant or spigot. Samples were collected in-line so that groundwater samples were not exposed to the atmosphere prior to collection.

Groundwater from all sampled wells was pumped into a flow-through chamber to facilitate the monitoring of the physical properties of the water to ensure that enough water was purged from the well casing prior to the collection of a representative sample. The physical properties—specific conductance, pH, water temperature, and dissolved oxygen—were measured in the field at 3-minute intervals by a multiparameter sonde (YSI Incorporated, 2020). Representative samples were collected after three well volumes had been purged from the well and after sequential readings of the physical parameters stabilized within limits described by USGS "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated).

Table 2. Sampled well location, date sampled, completion information, and sampled aquifer, eastern Nebraska, 2016–18.

[USGS, U.S. Geological Survey; Legal description as township number and direction, range number and direction, section number, and 2–4 quarters: N, north; W, west; E, east; ABCD, codes for the quarter section, as A, B, C, and D, respectively from largest to smallest quarter, where A is northeast, B is northwest, C is southwest, and D is southeast quarter of the next larger unit; D, domestic; M, monitoring; S, stock. Horizontal datum is referenced to the North American Datum of 1983]

Site number	USGS station name[1]	Field name	Date sampled	County	Latitude, in decimal degrees	Longitude, in decimal degrees	Well type	Well depth, in feet below land surface	Screen interval, in feet below land surface	Aquifer sampled
413618096322901	19N 8E 20AD (LE–1)	LE–1	8/25/2016	Dodge	41.62611111	−96.553889	D	181	161–181	Dakota
413639096274901	19N 8E 24AA (LE–2)	LE–2	8/25/2016	Dodge	41.60005556	−96.450056	M	220	205–220	Dakota
413912096462201	19N 6E 6AA (LE–3)	LE–3	8/24/2016	Dodge	41.65333333	−96.772778	D	526	506–526	Dakota
413828096465801	19N 6E 6CD (LE–4)	LE–4	8/24/2016	Dodge	41.65666667	−96.7925	D	239	219–239	Dakota
424611097185201	32N 1E 9BA (LC–6S domestic)	LC–6S domestic	8/11/2016	Cedar	42.79388889	−97.310556	D	95	40–95*	Dakota
423317097160901	30N 1E 25BB (LC–4M)	LC–4M	8/10/2016	Cedar	42.57027778	−97.266889	M	730	712–730	Dakota
424713097170101	33N 1E 35CC (LC–6M)	LC–6M	8/9/2016	Cedar	42.78338889	−97.290556	M	520	500–520	Dakota
424713097170102	33N 1E 35CC (LC–6D)	LC-6D	8/9/2016	Cedar	42.78777778	−97.294167	M	750	730–750	Dakota
421730096390001	27N 7E 30AA (PM D–1)	PM D–1	8/11/2016	Dakota	42.29916667	−96.65	D	440	410–440	Dakota
410002096551101	12N 4E 24 AB (LPS–5)	LPS–5	10/27/2016	Seward	41.00013889	−96.916778	D	162	136–161	Dakota
411005096311701	14N 8E 22CB (LPN–1)	LPN–1	4/11/2017	Saunders	41.19277778	−96.5225	M	206	201–206	Dakota
410335096150101	13N 10E 36BB (D–SWSarpy1)	D–SWSarpy1	10/3/2016	Sarpy	41.05022222	−96.250167	M	117	107–117	Dakota
410613096071101	13N 11E 12DD (D–Sp1)	D–Sp1	9/28/2016	Sarpy	41.10008333	−96.116889	M	215	205–215	Dakota
410613096071102	13N 11E 12DD (D–Sp2)	D–Sp2	9/28/2016	Sarpy	41.10005556	−96.116917	M	125	115–125	Dakota
411845096211203	16N 9E 36NESE (Valley City Park deep)	D–Va3	3/9/2018	Douglas	41.3125	−96.353333	M	204	194–204	Dakota
412758096222801	17N 9E 2DC (D–A1)	D–A1	11/2/2016	Washington	41.45016667	−96.366889	M	297	287–297	Dakota
415958096152201	23N 10E 2DA (D–D1)	D–D1	6/20/2018	Burt	41.99944444	−96.250194	M	180	170–180	Dakota
421406096294901	26N 8E 11CC (D–Th1)	D–Th1	10/14/2016	Thurston	42.23355556	−96.4835	M	370	360–370	Dakota
421406096294902	26N 8E 11CC (D–Th2)	D–Th2	10/14/2016	Thurston	42.23341667	−96.483583	M	275	265–275	Dakota
422616096343801	29N 7E 35DC (D–J1)	D–J1	10/13/2016	Dakota	42.43352778	−96.566861	M	470	460–470	Dakota
422616096343802	29N 7E 35DC (D–J2)	D–J2	10/13/2016	Dakota	42.4335	−96.566833	M	280	270–280	Dakota
405921096535101	12N 5E 19DC (LPS–3)	LPS–3	11/10/2016	Lancaster	40.98344444	−96.883444	D	212	192–212	Dakota
423317097161001	30N 1E 25BB (LC–4S)	LC–4S	8/10/2016	Cedar	42.55022222	−97.273889	M	120	80–120	Niobrara
422344097120801	28N 2E 16DC(LE–5)	LE–5	8/23/2016	Cedar	42.39555556	−97.202222	D	157	137–157	Niobrara
422409097124601	28N 2E 16BC (LE–6)	LE–6	8/23/2016	Cedar	42.4025	−97.212778	M	180	170–180	Niobrara
405139096194801	10N 10E 5CB (LPS–1)	LPS–1	10/6/2016	Cass	40.86083333	−96.33	D	116	104–114	Paleozoic

[USGS, U.S. Geological Survey; Legal description as township number and direction, range number and direction, section number, and 2–4 quarters: N, north; W, west; E, east; ABCD, codes for the quarter section, as A, B, C, and D, respectively from largest to smallest quarter, where A is northeast, B is northwest, C is southwest, and D is southeast quarter of the next larger unit; D, domestic; M, monitoring; S, stock. Horizontal datum is referenced to the North American Datum of 1983]

Site number	USGS station name[1]	Field name	Date sampled	County	Latitude, in decimal degrees	Longitude, in decimal degrees	Well type	Well depth, in feet below land surface	Screen interval, in feet below land surface	Aquifer sampled
405213096205001	10N 10E 6BB (LPS–2)	LPS–2	10/6/2016	Cass	40.87027778	−96.347222	D	130	120–130	Paleozoic
402313095512401	5N 14E 21 BC (N–3)	N–3	10/5/2016	Nemaha	40.41083333	−95.866389	D	160	120–160	Paleozoic
401759096003301	4N 13E 19BC(N–5)	N–5	11/8/2016	Nemaha	40.29972222	−96.009167	S	172	152–172	Paleozoic
404950096205501	10N 10E 18CC (LPS–4)	LPS–4	10/5/2016	Cass	40.81691667	−96.333444	D	110	95–115	Paleozoic
401819095493701	4N 14E 15DD (N–6)	N–6	11/8/2016	Nemaha	40.30016667	−95.81675	D	79	69–79	Paleozoic

[1]The station name uses the legal description of the well location and a local well name (referred to as the well's "field name").

*Indicates well is not screened; instead is open to the formation at the interval given.

Sample Analysis and Reporting

Water samples from all sites were analyzed for major ions, trace elements, nutrients including nitrate, and stable isotopes. Age tracers (tritium [^{3}H] and carbon-14 [^{14}C]) were analyzed for a subset of sampled wells. The constituent, analyzing laboratory, references to methods used, and field preservation procedures are given in table 3. Sampling results from all analyses are available online in the USGS NWIS (U.S. Geological Survey, 2020b). For the convenience of the reader, selected results are presented in this report to support the interpretations and conclusions.

For this report, conventional nomenclature was used to describe analyses of water samples for stable isotopes. The composition of stable isotopes of low-mass (light) of oxygen (O) and hydrogen (H) commonly are reported as "δ" (delta) values, which indicate parts per thousand or per mil. The reported value is compared to the isotopic ratio of the Vienna Standard Mean Ocean Water (Clark and Fritz, 1997). The general expression for the δ value is calculated by the following equation (Clark and Fritz, 1997):

$$\delta \text{ (in per mil)} = \left[\frac{Rx}{Rs} - 1\right] * 1{,}000 \qquad (1)$$

where

- Rx is the ratio of the heavy to light isotope of the sample; and
- Rs is the ratio of the heavy to light isotope of the standard (Vienna Standard Mean Ocean Water).

A negative δ value indicates that the sample is depleted of the rare isotope relative to the standard; that is, the sample is isotopically "light." A positive δ value indicates that the sample is enriched in the rare isotope relative to the standard; that is, the sample is isotopically "heavy."

Understanding and interpreting the stable isotopic composition of groundwater samples is aided by understanding hydrologic processes that can affect isotopic ratios. Isotopic fractionation occurs where the isotopic composition is altered by chemical, biological, or physical processes that may result in the preferential enrichment or depletion of one isotope over another. This fractionation process partitions isotopes as a function of the differences in the masses of the isotopes. Because the heavier isotope has a stronger molecular bond (oxygen-18 [^{18}O] has a stronger molecular bond than oxygen-16 [^{16}O] and deuterium [^{2}H] has a stronger molecular bond than hydrogen-1 [^{1}H]), the liquid phase of water generally is isotopically "heavier" than the gaseous phase (Kendall and Caldwell, 1998). As a result, evaporation is a major fractionation process in which the lighter isotope is concentrated in water vapor, whereas the heavier isotope enriches the aqueous phase. Additional information on isotopes and their presence in the environment can be found in references such as Clark and Fritz (1997).

Data-Analysis Procedures

Data-analysis procedures included general statistical analyses, creation of Piper diagrams (Piper and Garrett, 1953), scatter plots, and summary tables. This report only contains selected plots and tables necessary to support the interpretations and conclusions presented herein. Analyses of stable isotope data and age tracer results, including radiocarbon dating procedures, are also described in this section of the report.

Statistical analyses were completed to determine if differences in the concentrations of selected constituent were significant between aquifers. Two nonparametric tests were performed for this report: Kruskal-Wallis and Wilcoxon Rank Sum (Helsel and others, 2020). The Kruskal-Wallis test was used to determine differences between distribution of concentrations of selected constituents in samples by aquifer. For this report, this test was performed on samples from wells screened in the Dakota, Niobrara, or Paleozoic aquifers. The null hypothesis for the test was that the distributions for the groups are identical, and the alternative hypothesis was that at least one of the group medians is different from the others (Helsel and others, 2020). The Wilcoxon Rank Sum test (Helsel and others, 2020) was used to determine if differences between distributions of the two subsets of samples collected from the Dakota aquifer were significant. Water samples collected from the Dakota aquifer were divided into two groups based on the dominant water type, which is discussed in further detail in the "Major Ions and Trace Elements" subsection later in this report. The null hypothesis for the test was that the distributions for the groups are identical, and the alternative hypothesis was that at least one of the distributions is different from the others (Helsel and others, 2020). For both types of nonparametric statistical tests, the null hypothesis was rejected when the calculated p-value was less than an alpha value (α) of 0.05, which indicates a 95-percent confidence level that the probability value from the statistical test generated an accurate representation of the populations being tested (Helsel and others, 2020). A p-value is defined as the measure of the probability that an observed difference occurred by random chance (Helsel and others, 2020). If a calculated p-value is less than 0.05, then it can be inferred there is a significant difference between the medians of the sample groups with 95-percent confidence.

Nonparametric statistical methods rely on the conversion of data to ranked values and do not require that the data be distributed normally (Helsel and others, 2020). Censored data, which have values less than the reporting limit of the analytical procedure, were kept for analyses. In this report, for the nonparametric statistical analyses, each censored value was assigned a value equal to one-half the reporting limit. A value of one-half the reporting limit ensures that the censored data are smaller than the smallest number above the reporting limit. Because the tests performed are nonparametric and compare independent populations by ranking the data, assigning a minimum value to the censored data does not affect the hypothesis-test results (Helsel and others, 2020).

Table 3. Laboratory analytical methods and field preservation procedures for water-quality constituents.

[USGS, U.S. Geological Survey; μm, micrometer; NWQL, National Water Quality Laboratory (Denver, Colorado); °C, degree Celsius; <, less than; HNO_3; nitric acid; RSIL, Reston Stable Isotope Laboratory (Reston, Virginia); MPTL, Menlo Park Tritium Laboratory (Menlo Park, California); WHOI, Woods Hole Oceanographic Institution (Woods Hole, Massachusetts)]

Analyte(s)	Analyzing laboratory	Analytical method	Reference	Field preservation procedure	Number of samples collected
Physical properties	Analyzed onsite	Various methods	USGS (variously dated)	None	31
Carbonate alkalinity	Analyzed onsite	Inflection point titration	USGS (variously dated)	Filter through 0.45-μm filter	31
Nutrients	USGS NWQL	Various methods	Fishman (1993)	Filter through 0.45-μm filter, chill, and maintain at 4 °C	31
Major ions	USGS NWQL	Inductively coupled plasma	Fishman and Friedman (1989); Fishman (1993)	Anions: filter through 0.45-μm filter, Cations: filter through 0.45-μm filter, acidify sample to pH <2 with nitric acid (HNO_3)	31
Trace elements	USGS NWQL	Inductively coupled plasma, atomic absorption spectrometry	Fishman and Friedman (1989); Fishman (1993); Garbarino (1999); Struzeski and others (1996); Garbarino and Damrau (2001); Garbarino and others (2006)	Filter through 0.45-μm filter, acidify sample to pH <2 with nitric acid (HNO_3)	31
Stable isotopes	USGS RSIL	Mass spectrometry	USGS (2020d)	Fill bottle two-thirds full	21
Tritium	USGS MPTL	Electrolytic enrichment and liquid scintillation	USGS (2020c)	Fill bottle to top, seal with cap and wrap with electrical tape	13
Carbon-14	WHOI	Accelerator mass spectrometry	WHOI (2020)	Filter through 0.45-μm filter, bottom fill bottle flushing two volumes before capping and sealing with electrical tape, chill and maintain at 4 °C	25

Stable Isotopes

In terrestrial waters, the ratio of the two most common isotopes of O and H ($\delta^{18}O$ and $\delta^{2}H$) are covariant and vary by a factor of 5 and 2 percent, respectively (Coplen and Kendall, 2000). Craig (1961) determined that for fresh water, isotopic composition of precipitation worldwide could be correlated on a global scale and could be described using the global meteoric water line, which is given as $\delta^{2}H=8\ \delta^{18}O+10$. The global meteoric water line is the average of many local or regional meteoric water lines that differ in slope and $\delta^{2}H$ intercept (Clark and Fritz, 1997). Variations in the slope and $\delta^{2}H$ intercept for local and regional meteoric water lines are affected by many factors such as season and climate. For a given area, precipitation during cold seasons is depleted in ^{2}H and ^{18}O, whereas precipitation in warm seasons is typically isotopically enriched. Precipitation falling in cold regions and climates is isotopically depleted and precipitation falling in with warmer regions and climates is isotopically enriched (Clark and Fritz, 1997).

This report uses a local meteoric water line (LMWL) established by Harvey (2001) from analysis of precipitation samples collected at Mead, Nebr. (fig. 1). Harvey (2001) reported the LMWL as $\delta^{2}H=7.40\ \delta^{18}O+7.32$. Although Mead (fig. 1) is approximately at the center of the study area, it is more than 100 miles from the northern most sample and approximately 70 miles from the southernmost sample, so it is assumed that the LMWL at Mead, Nebr., adequately represents the study area used in this report.

Age Tracers

Estimating the age of groundwater is an increasingly common approach to inform water-resource-management strategies. Groundwater age is often used to estimate groundwater recharge rates, examine the sustainability of groundwater resources, and assist in groundwater model calibration (Kazemi and others, 2006). Groundwater age can also complement studies focused on groundwater quality. Aquifers containing primarily recently recharged groundwater are vulnerable to contamination from anthropogenic sources. Conversely, if an aquifer contains waters that are determined to be premodern (recharged prior to 1950), naturally occurring contaminants such as arsenic can be elevated because longer residence times in the aquifer can result in higher concentrations of dissolved constituents in groundwater (Lindsey and others, 2019). For this study, ^{3}H and ^{14}C samples were collected from selected wells. Data-analysis procedures, including the ^{3}H classification approach and radiocarbon adjustments of ^{14}C data, are discussed in the following subsections.

Tritium

^{3}H is a naturally occurring radioactive isotope of hydrogen with a half-life of 4,500 days (12.3 years; Kazemi and others, 2006) and is directly related to the time since substantial thermonuclear testing in the 1950s and 1960s. The use of ^{3}H in groundwater age studies is well established and valuable because isotope concentrations of the hydrogen atoms in the water molecule are measured rather than concentrations of a dissolved constituent; however, because of the time that has lapsed since substantial thermonuclear testing, this age tracer may not be as useful as other tracers (Kazemi and others, 2006). ^{3}H was present in the atmosphere prior to thermonuclear testing in the 1950s and 1960s as a result of natural production in the upper atmosphere through the bombardment of nitrogen by neutrons in cosmic radiation (Solomon and Cook, 2000). The natural background activity of ^{3}H in precipitation prior to 1952 ranges from about 1 to 10 tritium units with each unit equal to one ^{3}H atom in 1,018 atoms of hydrogen (Kazemi and others, 2006). Beginning in 1952, large amounts of ^{3}H were added to the atmosphere from aboveground testing of thermonuclear devices, and ^{3}H combined with O to form tritiated water, which dispersed throughout the hydrosphere. After the onset of thermonuclear testing, large increases of ^{3}H concentrations in precipitation were noticed and continued to rise until an international treaty banned atmospheric thermonuclear testing in 1963 (Solomon and Cook, 2000). The concentration of ^{3}H in precipitation remained high for decades, but recently (since 2010) concentrations have leveled off, indicating a return to near prebomb (prior to 1953) concentrations (Lindsey and others, 2019).

Sampled wells were classified based on the concentration of ^{3}H in groundwater using an approach described in Lindsey and others (2019). The classification is based on a general understanding of how ^{3}H concentrations change in groundwater in response to changes in ^{3}H concentrations in precipitation. The three ^{3}H concentration classifications are modern (recharged in 1953 or later), premodern (recharged prior to 1953), and mixed (a mixture of waters recharge prior to 1953 and after 1953). Concentrations of ^{3}H in groundwater that has recharged before 1953 would have a much lower concentration than the measured background concentration because of radioactive decay during the time that elapsed between recharge and sampling. A threshold was calculated by correcting the 1953 ^{3}H background concentration (the most recent concentrations prior to thermonuclear testing) reported in Michel and others (2018) for radioactive decay (Lindsey and others, 2019). If the ^{3}H concentration of the groundwater sample is less than the calculated threshold, it can be inferred that the water was recharged prior to 1953. In addition, ^{3}H concentrations from a groundwater sample that are greater than any of the postbomb (after 1963) peak concentrations in precipitation that have been reduced by the radioactive decay that would have occurred from the precipitation date to the date of sampling must have recharged in 1953 or later and are classified as modern. If a sample concentration is between these upper and lower bounds, then a sample is classified as a mixture of premodern and modern waters (Lindsey and others, 2019).

The calculated thresholds for premodern and modern vary slightly across the study area because of differences in ^{3}H concentration in precipitation. Michel and others (2018) estimated ^{3}H concentrations in precipitation for the conterminous United States in quadrangles for every 2 degrees in latitude and every 5 degrees in longitude. The premodern and modern thresholds for samples collected in wells in the northern part of the study area were slightly higher than samples in the southern part of the study area.

Carbon-14

Measurements of ^{14}C concentrations in groundwater are often used for dating premodern waters with long residence times. Age dating with ^{14}C techniques uses the dissolved organic or inorganic carbon in water and not the water molecule itself (Clark and Fritz, 1997). Wang and others (1998) reported the natural production of ^{14}C in the atmosphere by the interaction of cosmic-ray-produced neutrons with nitrogen (Kalin, 2000). Once produced, ^{14}C becomes incorporated into carbon dioxide and assimilates into the hydrosphere. The half-life of ^{14}C (5,730 years) and the ubiquity of carbon make it an ideal tracer to date groundwater that can be thousands to tens of thousands of years old (Kalin, 2000).

Analyses of ^{14}C are typically reported as percent Modern Carbon (often referred to as pMC). Prior to the thermonuclear testing in the 1950s and 1960s, atmospheric composition of ^{14}C was relatively constant (A_0 in eq. 2) and is designated as 100 pMC (Parkhurst and Plummer, 1993). Apparent groundwater age can be determined by examining the ^{14}C in dissolved inorganic carbon within a groundwater sample. If the concentration of ^{14}C in the atmosphere is known at the time of recharge, then the age of groundwater sample can be estimated. The age of the water was determined by the following equation (modified from Parkhurst and Plummer, 1993):

$$ t = \frac{5,730}{\ln(2)} \ln\left(\frac{Ao}{A}\right) \tag{2} $$

where

t	is the estimated age of the groundwater, in years;
5,730	is the half-life of ^{14}C, in years;
Ao	is the starting concentration of ^{14}C in the water, in percent Modern Carbon; and
A	is the concentration of ^{14}C in the sample, in percent Modern Carbon.

The initial concentration of ^{14}C in precipitation (A_0) is modified through several processes that need to be accounted for to provide meaningful estimates of apparent groundwater age. NetPathXL (Parkhurst and Charlton, 2008) was used to account for geochemical processes such as isotopic exchange in the unsaturated zone. NetPathXL provides several radiocarbon adjustment models to estimate the initial concentration of ^{14}C. For this report, the initial concentrations of ^{14}C in precipitation were estimated using the revised Fontes and Garnier (1979) radiocarbon adjustment model (Han and Plummer, 2013) within NetPathXL (Parkhurst and Charlton, 2008). It was assumed that there was carbon isotopic exchange with solid carbonate mineral within the saturated zone. Ages derived from ^{14}C age-dating analyses generally are on the order of hundreds to tens of thousands of years and results are reported in years before present. Radiocarbon adjustments are complicated, and many details are not described in this report. However, details on the use and limitations of ^{14}C in dating of groundwater can be found elsewhere, such as Clark and Fritz (1997) and Kazemi and others (2006).

Quality Assurance and Quality Control

Quality control samples were collected for this study and included field blanks and field replicates. Quality control samples were collected to evaluate and determine if samples had been contaminated or if the data were biased by the collection, processing, storage, or analysis of the samples. For this study, six field blanks and five field replicate samples were collected. Selected statistics for the field blank results and the relative percent difference between replicate samples are shown in table 4. The relative percent difference is calculated using equation 3 given below.

$$ RPD = \frac{S_1 - S_2}{\left(\dfrac{S_1 + S_2}{2}\right)} \times 100 \tag{3} $$

where

S_1	is the concentration of field replicate sample 1;
S_2	is the concentration of field replicate sample 2; and
RPD	is the relative percent difference between field replicate samples 1 and 2.

Field blanks are collected to determine the occurrence and magnitude of sample contamination from collection, processing, storage, and analysis. Field blanks are collected using water that has been certified to be free of inorganic constituents and were analyzed for major ions, trace elements, and nutrients. Generally speaking, few detections, or "hits," were analyzed from the field blanks (table 4). Most detections were within an order of magnitude of the lower detection limit for the specific constituent; however, two blank samples, D–SWSarpy1 and LC–4S, had concentrations of cobalt and zinc, respectively, that exceed an order of magnitude of the detection limit. Concentrations of copper were detected in blank samples that exceeded an order of magnitude of the detection limit for wells D–SWSarpy1 and D–Sp2 (table 4).

Five field replicate samples were collected to assess the variability in analytical results. The relative percent difference in the concentrations of the replicate samples for major ions all were 5 percent or less of each other, with the exception of the concentration of magnesium, sodium, and fluoride in one

Table 4. Selected statistics of field blank samples and relative percent difference between replicate samples, eastern Nebraska, 2016–18.

[mg/L, milligram per liter; --, not applicable or not sampled; <, less than; NH_3, ammonia; NH_4^+, ammonium; N, nitrogen; µg/L, microgram per liter; ^{14}C, carbon-14; %, percent; pCi/L, picocurie per liter; $\delta^{13}C$, carbon isotope ratio in per mil Vienna Peedee belemnite; δ^2H, hydrogen isotope ratio in per mil Vienna Standard Mean Ocean Water; $\delta^{18}O$, oxygen isotope ratio in per mil Vienna Standard Mean Ocean Water]

| Constituent | Type of constituent | Field blank sample | | | | Replicate sample | | |
| | | | | | | Relative percent difference | | |
		Unit	Median	Maximum	Lower detection limit	Minimum	Median	Maximum
Total dissolved solids	--	mg/L	<20	<20	20	0.0	1.3	3.3
Calcium	Major ion	mg/L	<0.022	0.058	0.022	0.5	1.4	2.7
Magnesium		mg/L	<0.011	<0.011	0.011	0.0	1.8	5.1
Potassium		mg/L	<0.06	<0.06	0.06	0.0	0.0	2.7
Sodium		mg/L	<0.10	<0.10	0.10	0.4	1.8	5.9
Chloride		mg/L	<0.02	0.04	0.02	0.7	0.9	3.0
Fluoride		mg/L	<0.01	<0.01	0.01	0.0	0.0	7.7
Silica		mg/L	<0.018	0.11	0.018	0.0	0.8	2.4
Sulfate		mg/L	<0.02	<0.02	0.02	0.0	1.8	4.8
Ammonia ($NH_3+NH_4^+$)	Nutrient	mg/L	<0.01	0.01	0.01	0.0	0.0	0.0
Nitrate plus nitrite, as N		mg/L	<0.040	<0.040	0.040	0.0	1.7	9.8
Nitrite, water, as N		mg/L	<0.001	0.002	0.001	0.0	0.0	32.3
Orthophosphate, as phosphorus		mg/L	<0.004	<0.004	0.004	0.0	0.0	3.5
Aluminum	Trace element	µg/L	<3.0	<3.0	3.0	0.0	0.0	0.0
Barium		µg/L	<0.10	<0.10	0.10	0.0	1.5	3.4
Beryllium		µg/L	<0.010	<0.050	0.050	0.0	0.0	0.0
Cadmium		µg/L	<0.030	<0.030	0.030	0.0	0.0	11.8
Chromium		µg/L	<0.6	<0.6	0.6	0.0	0.0	7.1
Cobalt		µg/L	0.03	0.16	0.03	0.0	0.3	9.5
Copper		µg/L	0.31	0.41	0.02	0.0	8.0	16.2
Iron		µg/L	<5.0	<10.0	5	1.0	7.8	28.1
Lead		µg/L	<0.020	<0.020	0.020	0.0	0.0	0.0
Lithium		µg/L	<0.15	<0.15	0.15	0.0	2.2	5.9
Manganese		µg/L	<0.40	<0.40	0.40	0.0	1.7	13.9
Molybdenum		µg/L	<0.050	<0.100	0.050	2.9	4.5	5.9
Nickel		µg/L	<0.20	0.21	0.20	0.0	3.3	12.8
Silver		µg/L	<1.00	<1.00	1.00	0.0	0.0	0.0
Strontium		µg/L	<0.50	<0.50	0.50	1.5	1.9	6.0
Vanadium		µg/L	<0.10	<0.10	0.10	0.0	0.0	11.0
Zinc		µg/L	<2.0	10.4	2.0	0.0	0.0	4.0
Arsenic		µg/L	<0.05	<0.05	0.05	0.0	3.7	6.5
Boron		µg/L	<2.0	<2.0	2.0	0.6	2.0	4.7
Selenium		µg/L	<0.05	<0.05	0.05	0.0	0.0	3.4
Uranium		µg/L	<0.010	<0.010	0.01	1.2	1.3	4.7

Table 4.   Selected statistics of field blank samples and relative percent difference between replicate samples, eastern Nebraska, 2016–18.—Continued

[mg/L, milligram per liter; --, not applicable or not sampled; <, less than; NH_3, ammonia; NH_4^+, ammonium; N, nitrogen; µg/L, microgram per liter; ^{14}C, carbon-14; %, percent; pCi/L, picocurie per liter; $\delta^{13}C$, carbon isotope ratio in per mil Vienna Peedee belemnite; δ^2H, hydrogen isotope ratio in per mil Vienna Standard Mean Ocean Water; $\delta^{18}O$, oxygen isotope ratio in per mil Vienna Standard Mean Ocean Water]

| Constituent | Type of constituent | Field blank sample | | | | Replicate sample | | |
| | | | | | | Relative percent difference | | |
		Unit	Median	Maximum	Lower detection limit	Minimum	Median	Maximum
^{14}C	Isotope	% modern	--	--	--	0.1	1.2	1.5
Tritium		pCi/L	--	--	--	0.1	12.1	24.0
$\delta^{13}C$		per mil	--	--	--	0.2	0.9	1.1
δ^2H		per mil	--	--	--	0.4	0.7	1.7
$\delta^{18}O$		per mil	--	--	--	0.4	0.5	1.9

set of replicate samples, which were 5.1, 5.9, and 7.7 percent, respectively (table 4). It should be noted that when concentrations for replicate samples are low, small differences in concentration can result in higher relative percent differences. For nutrients, the relative percent differences in the concentrations of the replicate samples for most nutrients were less than 5 percent or within an order of magnitude of the detection limit. Notable exceptions included the concentration of nitrate plus nitrite in one set of replicate samples that had a 9.8-percent (0.39 milligram per liter [mg/L]) difference and nitrite in one set of samples which had a 32.3-percent (0.005 mg/L) difference (table 4). For trace elements, the six trace elements with the greatest maximum relative percent differences were copper (16.2 percent), iron (28.1 percent), cadmium (11.8 percent), manganese (13.9 percent), nickel (12.8 percent), and vanadium (11.0 percent); however, the associated differences in concentration were within one order of magnitude of the lower detection limit (table 4). It is important to note that because the concentrations of these constituents are low, the calculated relative percent difference values can be anomalously high. For the trace element cobalt, the maximum relative percent difference was calculated at 9.5 percent, which was an order of magnitude greater than the detection limit. Exceeding the order of magnitude threshold indicates the possibility that some samples may have a positive bias. The median relative percent difference for all replicate samples was 0.3 percent. The median relative percent difference for iron was 7.8 percent but the difference in concentrations was within an order of magnitude of the lower detection limit (table 4). Replicates were only collected for two ^3H samples (D–A1 and D–SWSarpy1). The relative percent difference was not calculated for D–A1 because the ^3H concentrations were below the detection limit. The relative percent difference calculated for ^3H in the sample from well D–SWSarpy1 was 24, which was due to the fact that ^3H concentrations were fairly low and differences between samples are close to the lower detection limit.

Quality and Age of Groundwater

This section of the report describes the water quality, geochemical characteristics, and groundwater age of the samples collected from wells screened in the Dakota aquifer, Niobrara aquifer, and the Paleozoic aquifers. Presented in this section are descriptions of the groundwater sampling results, statistical analyses, stable isotope and age tracer interpretations, and a discussion of groundwater management implications. Much of the groundwater sampling results are summarized in a series of maps, graphs, and tables. Results from groundwater sampling not presented in this report are provided in the USGS NWIS database (U.S. Geological Survey, 2020b).

Major Ions and Trace Elements

Major ion concentrations for each sample are plotted as a Piper diagram (Piper and Garrett, 1953) shown in figure 3. Analysis of the major ion concentrations indicates samples collected from the Dakota aquifer show no single primary water type; however, the two most common water types within the Dakota aquifer are calcium bicarbonate (10 samples) and calcium sulfate (7 samples; figs. 3 and 4, table 5). Samples that were characterized as calcium bicarbonate generally had lower specific conductance and concentrations of total dissolved solids (table 5A). This is consistent with previous studies, which determined that calcium bicarbonate was the dominant water type where the Dakota aquifer was unconfined and groundwater was recharged from local precipitation (Gosselin and others, 2001). Sampled wells that are not characterized as calcium bicarbonate water type typically had higher concentrations of total dissolved solids and lower dissolved oxygen concentrations (table 5A). Calcium sulfate water types often are present where Cretaceous-age shales overlie the Dakota aquifer, such as in Cedar County in the northern part of the study area (fig. 4). In Dakota County, wells D–J1 and D–J2 are characterized as
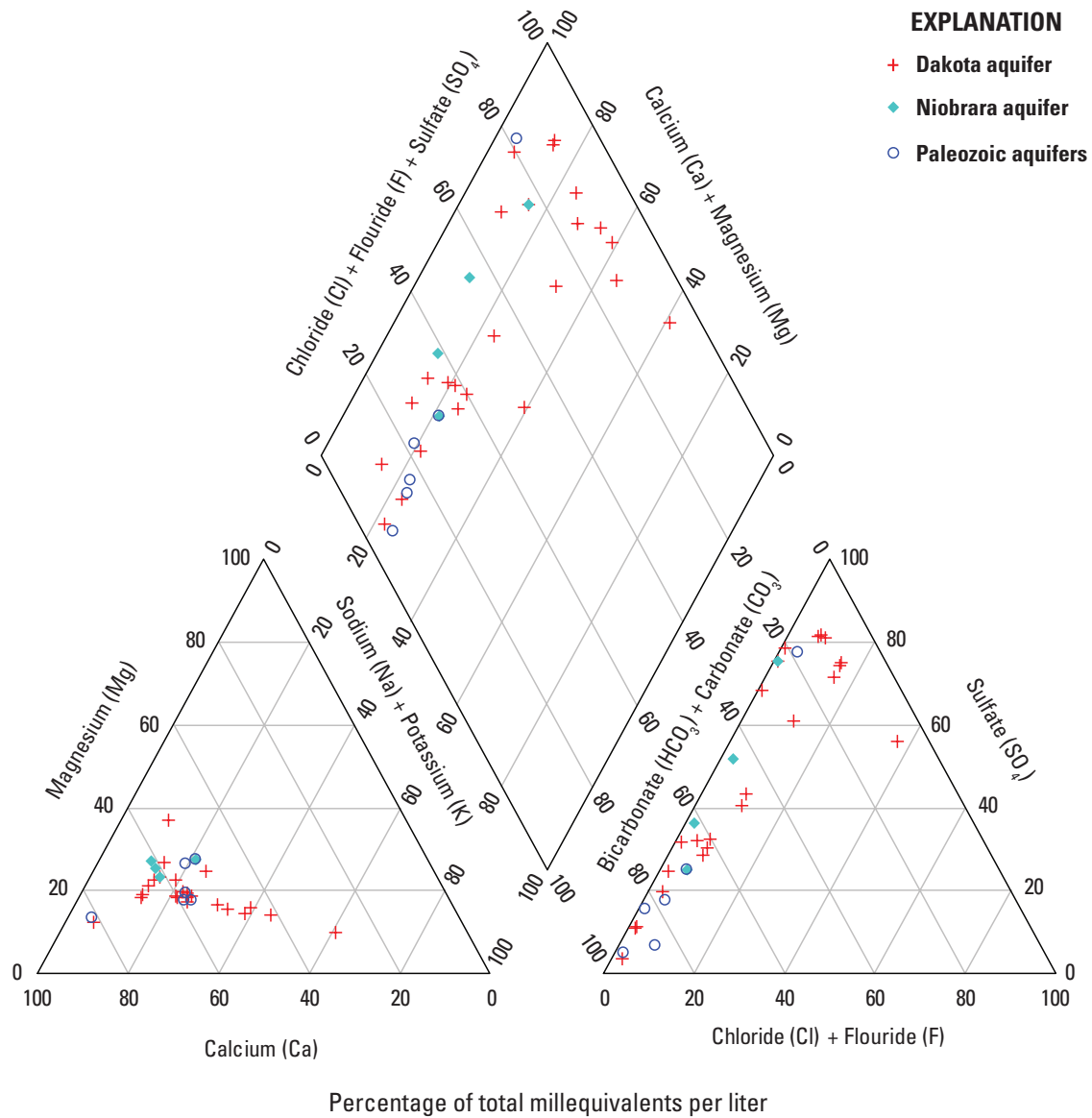
Figure 3.   Ionic composition of groundwater from Dakota aquifer, Niobrara aquifer, and Paleozoic aquifers, eastern Nebraska, 2016–18.

EXPLANATION

Surficial bedrock unit

- Ogallala Formation
- Pierre Shale
- Niobrara Formation of Colorado Group
- Carlile Shale of Colorado Group
- Greenhorn Limestone and Graneros Shale of Colorado Group
- Dakota Sandstone
- Undifferentiated Permian units
- Undifferentiated Pennsylvanian units
- Glacial till
- Eastern Nebraska Water Resources Assessment (ENWRA) boundary
- Natural Resources District (NRD) boundary

Water type for sampled well by aquifer and identifier

- LE-1 — Dakota—Calcium bicarbonate
- LC-4M — Dakota—Calcium sulfate
- D-Th1 — Dakota—Calcium sulfate bicarbonate
- LE-3 — Dakota—Calcium sodium sulfate
- D-Va3 — Dakota—Calcium sodium sulfate bicarbonate
- LPN-1 — Dakota—Sodium sulfate
- LC-4S — Niobrara—Calcium bicarbonate
- LE-5 — Niobrara—Calcium sulfate
- N-5 — Paleozoic—Calcium bicarbonate
- N-3 — Paleozoic—Calcium sulfate

Base modified from U.S. Geological Survey digital data, 1987, 1:100,000
Lambert Conformal Conic projection
Standard Parallels 40° and 43°, central meridian 100°
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Bedrock geology from Burchett, 1986
Glacial till from Conservation and Survey Division, University of Nebraska-Lincoln, 2020b

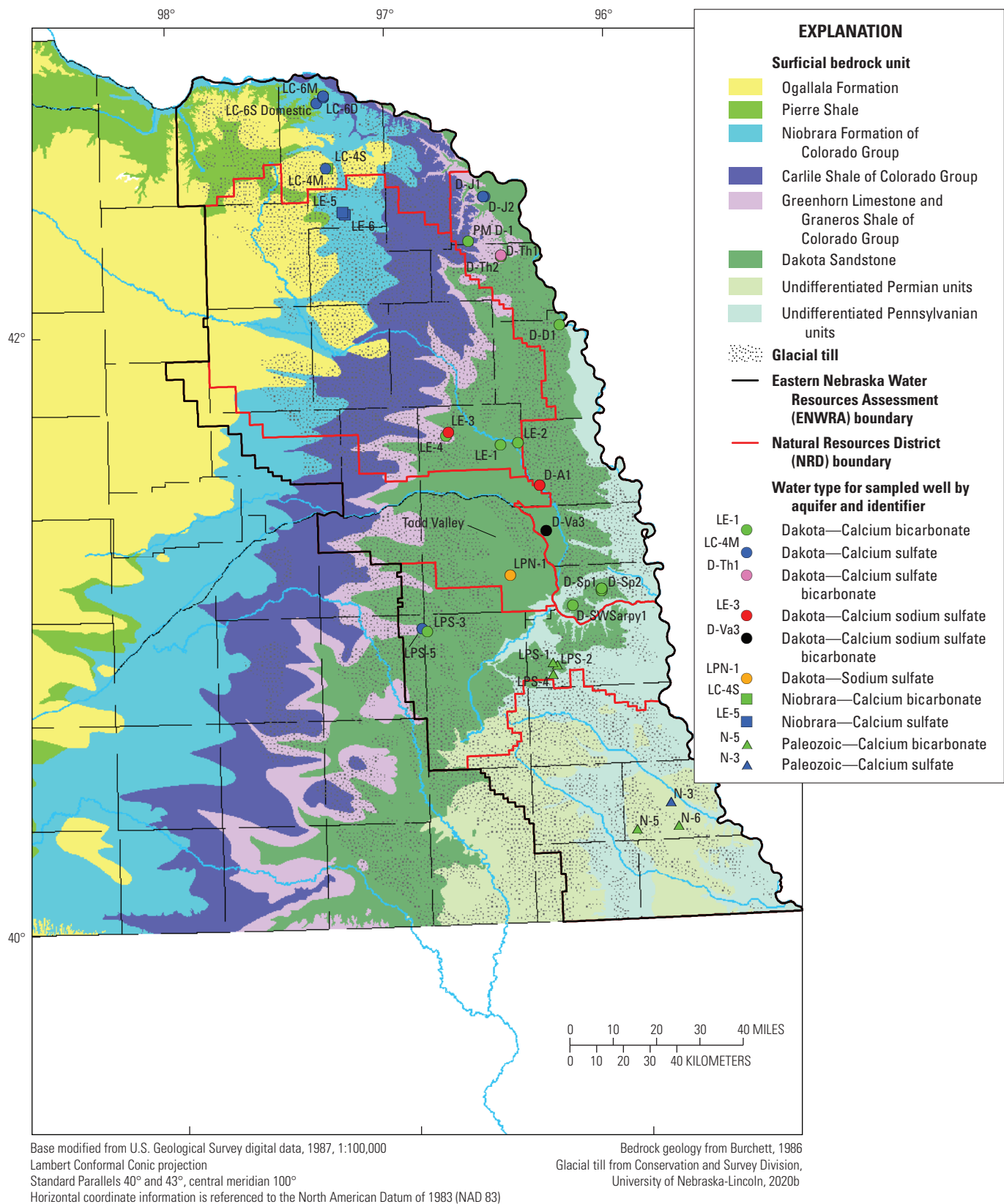**Figure 4.**   Dominant water type for wells completed in the Dakota aquifer, Niobrara aquifer, and Paleozoic aquifers, eastern Nebraska, 2016–18.

calcium sulfate waters (fig. 4). Both wells are screened beneath sequences of clay, claystone, siltstone, and sand deposits, indicating the Dakota aquifer is at least partially confined in this location and meteoric recharge would be limited.

Sodium was the dominant cation for one sample (LPN–1; fig. 4, table 5A) and a subdominant cation for three samples (LE–3, D–Va3, and D–A1), all from the Dakota aquifer. With the exception of D–Va3, these sodium dominant and subdominant samples display higher specific conductance and concentrations of the total dissolved solids concentration compared to most samples collected in the study area (table 5A). The Dakota aquifer in these locations is confined by interbedded mudstone or shales within the Dakota or by overlying Late Cretaceous-age shales (Conservation and Survey Division, University of Nebraska-Lincoln, 2020a; Katie Cameron, Eastern Nebraska Water Resources Assessment, written commun., 2019), which can limited meteoric recharge (fig. 4).

In some locations, the dominant water type of the Dakota aquifer varied by depth. Domestic wells LE–4 and LE–3 are located in northwest Dodge County (fig. 1) and are approximately 1 mile apart. Well LE–4 is 239 ft deep and screened in the upper part of the Dakota aquifer, and well LE–3 is 526 ft and is completed in the lower part of the Dakota aquifer. Sampling data indicate that groundwater sampled from well LE–4 is calcium bicarbonate water type and likely recharged by meteoric water (fig. 4). Well LE–3 is a calcium sodium sulfate water type and underlies interbedded shale units within the Dakota aquifer (Conservation and Survey Division, University of Nebraska-Lincoln, 2020a; Katie Cameron, Eastern Nebraska Water Resources Assessment, written commun., 2019) where meteoric recharge is likely limited. The total dissolved solids concentration of well LE–3 was more than four times greater than that of well LE–4 (table 5A).

Samples collected from wells completed in the Niobrara aquifer and Paleozoic aquifers were characterized as either calcium bicarbonate or calcium sulfate water types (figs. 3 and 4, table 5A). Of the three samples collected from the Niobrara aquifer, one sample (LC–4S) was characterized as calcium bicarbonate and two samples (LE–5 and LE–6) were characterized as calcium sulfate. The sample characterized as calcium bicarbonate water type (LC–4S) had the lowest concentration of total dissolved solids compared to the other two samples (table 5A). The sample collected at well LE–5 indicated higher concentration of total dissolved solids and lower concentrations of dissolved oxygen when compared to well LE–6. Well LE–5 had a well depth of 157 ft and was screened below a thick sequence of clay; this clay layer may be restricting meteoric recharge to the aquifer at this location. A clay layer was not encountered when drilling well LE–6, which has a well depth of 180 ft and is about 0.75 mile northwest of well LE–5 (Nebraska Department of Natural Resources, 2020).

Of the six samples collected from wells screened in Paleozoic aquifers, all but one sample were characterized as calcium bicarbonate water type (well N–3; fig. 3, table 5A).

Well N–3 was characterized as calcium sulfate water type and had much higher total dissolved solids compared to other Paleozoic aquifers wells. The calcium-sulfate-rich water may be explained by the dissolution of gypsum, which was noted in the driller's log (Nebraska Department of Natural Resources, 2020). Except for well N–5, all Paleozoic aquifers water samples indicated oxic conditions (dissolved oxygen greater than 0.5 mg/L).

The Kruskal-Wallis test was performed on selected constituents to determine if a group of samples collected from each of the three aquifers (Dakota aquifer, Niobrara aquifer, or Paleozoic aquifers) had significantly different distributions from the others. The calculated p-values from the tests are presented in table 6. For this report, all values less than 0.05 are considered significant with 95-percent confidence. Results indicated that the distributions of one of the three aquifer sample groups were significantly different for specific conductance; dissolved oxygen; iron; strontium; uranium; and nutrients, including nitrate plus nitrite as N, ammonia ($NH_3+NH_4^+$), and orthophosphate as phosphorus (table 6). Because the Kruskal-Wallis test is unable to discern which of the three groups' distributions were significantly different, there is some ambiguity in the results; however, some useful insights can be interpreted. Examining the water-quality data presented in tables 5A and 5B, it can be determined that most of the samples collected from the Paleozoic aquifers were calcium bicarbonate water type and typically had high dissolved oxygen concentrations, low specific conductance, and low concentrations of trace elements including iron and uranium.

Samples collected from wells completed in the Dakota aquifer were subdivided into two groups based on water type: calcium bicarbonate and all other water types. The Wilcoxon Rank Sum test was completed to determine if the distributions of selected constituent were statistically significant between the two Dakota aquifer subgroups. The p-values are presented in table 6 and indicate that differences between the distributions for all selected field properties and constituents are significant. Given these results, the samples from the Dakota aquifer were subdivided into two groups when discussed in the remainder of this report: (1) Dakota aquifer (noncalcium bicarbonate water type) and (2) Dakota aquifer (calcium bicarbonate water type).

A Wilcoxon Rank Sum test was completed to determine if the distributions of selected constituents were statistically significant between two samples groups for the Niobrara and Paleozoic aquifers: (1) calcium bicarbonate dominant samples and (2) calcium sulfate dominant samples (table 6). The p-values presented in table 6 indicate that differences between the distributions for all selected field properties and constituents are insignificant, with the exception of specific conductance. Given these results, samples dominated by calcium sulfate had higher specific conductance, and by inference total dissolved solids, compared to samples dominated by calcium bicarbonate.

[ft, foot; BLS, below land surface; SC, specific conductance; µS/cm, microsiemen per centimeter; WT, water temperature; °C, degrees Celsius; mg/L, milligram per liter; DO, dissolved oxygen; TDS, total dissolved solids; Ca, calcium; Mg, magnesium; K, potassium; Na, sodium; CaCO₃, calcium carbonate; HCO₃, bicarbonate; SO₄, sulfate; M, dissolved oxygen reading from instrument was negative, indicating the actual dissolved oxygen value was less than 0.1 mg/L; Na, sodium]

Site number	Field name	Well depth (ft BLS)	Date sampled	Dominant water type	pH, standard units	SC (µS/cm)	WT (°C)	Concentration, in mg/L						Alkalinity, as CaCO₃
								DO	TDS	Ca	Mg	K	Na	
Dakota aquifer														
413618096322901	LE–1	181	8/25/2016	Ca - HCO₃	7.3	624	12.3	M	305	82	15.3	6.38	30.1	292
413639096274901	LE–2	220	8/25/2016	Ca - HCO₃	7	867	12	0.2	425	116	23	10	52.3	333
413912096462201	LE–3	526	8/24/2016	Ca-Na - SO₄	6.8	2,500	13.9	0	1,880	279	51.9	30.9	246	185
413828096465801	LE–4	239	8/24/2016	Ca - HCO₃	6.8	851	13.7	0	402	128	27.9	7.74	28.6	365
424611097185201	LC–6S domestic	95	8/11/2016	Ca - SO₄	6.7	1,750	11.1	0.1	1,360	388	36.1	6.27	28.7	303
423317097160901	LC–4M	730	8/10/2016	Ca - SO₄	7.1	1,560	19.5	0.1	1,170	219	39.2	24.2	91.7	149
424713097170101	LC–6M	520	8/9/2016	Ca - SO₄	7.1	1,470	17.2	M	1,150	242	41.8	17	46.7	138
424713097170102	LC–6D	750	8/9/2016	Ca - SO₄	6.9	1,610	18.2	0	1,300	275	45.3	15.7	53.3	137
421730096390001	PM D–1	440	8/11/2016	Ca - HCO₃	7	739	14	M	367	115	22.9	9.3	22.6	344
410002096551101	LPS–5	162	10/27/2016	Ca - SO₄	6.8	1,400	13.1	0.4	943	183	78.5	15	32	337
411005096311701	LPN–1	206	4/11/2017	Na - SO₄	7.2	3,600	14	0.1	2,540	232	47.1	32.3	537	186
410335096150101	D–SWSarpy1	117	10/3/2016	Ca - HCO₃	6.7	473	12.9	9.1	212	64.7	13.5	4.41	25.9	252
410613096071101	D–Sp1	215	9/28/2016	Ca - HCO₃	6.5	493	14.2	5.4	273	65.1	18	3.02	16.9	245
410613096071102	D–Sp2	125	9/28/2016	Ca - HCO₃	6.9	456	15.8	0.7	276	55.9	11.5	2.98	24.4	211
411845096211203	D–Va3	204	3/9/2018	Ca-Na -SO₄-HCO₃	7.6	580	11.3	0.6	351	57.4	12.2	7.01	53	184
412758096222801	D–A1	297	11/2/2016	Ca-Na - SO₄	7.2	2,030	14.2	M	1,440	195	40	12.6	231	208
415958096152201	D–D1	180	6/20/2018	Ca - HCO₃	6.5	808	11.4	0.1	414	109	25.6	7.5	37	334
421406096294901	D–Th1	370	10/14/2016	Ca - SO₄-HCO₃	6.5	1,000	12.6	0.3	505	134	25.9	16.8	53.3	300
421406096294902	D–Th2	275	10/14/2016	Ca - HCO₃	6.9	867	13.1	0.1	409	121	22.8	14.3	40.6	333
422616096343801	D–J1	470	10/13/2016	Ca - SO₄	7.1	2,060	13.8	0.6	1,570	242	44.8	27	172	176
422616096343802	D–J2	280	10/13/2016	Ca - SO₄	6.9	1,340	16.1	0.2	981	174	35.2	16.9	81.9	323
405921096535101	LPS–3	212	11/10/2016	Ca - HCO₃	7.1	866	12.9	2.8	402	99	29.4	10.1	49.8	365

Table 5A. Results of water-quality analyses for selected constituents, eastern Nebraska, 2016–18.—Continued

[ft, foot; BLS, below land surface; SC, specific conductance; μS/cm, microsiemen per centimeter; WT, water temperature; °C, degrees Celsius; mg/L, milligram per liter; DO, dissolved oxygen; TDS, total dissolved solids; Ca, calcium; Mg, magnesium; K, potassium; Na, sodium; CaCO₃, calcium carbonate; HCO₃, bicarbonate; SO₄, sulfate; M, dissolved oxygen reading from instrument was negative, indicating the actual dissolved oxygen value was less than 0.1 mg/L; Na, sodium]

| Site number | Field name | Well depth (ft BLS) | Date sampled | Dominant water type | pH, standard units | SC (μS/cm) | WT (°C) | Concentration, in mg/L | | | | | | Alkalinity, as CaCO₃ |
								DO	TDS	Ca	Mg	K	Na	
						Niobrara aquifer								
423317097161001	LC–4S	120	8/10/2016	Ca - HCO₃	7	706	12.7	0.3	397	100	25.2	11	18.6	272
422344097120801	LE–5	157	8/23/2016	Ca - SO₄	7	1,820	13.6	0.1	1,380	287	66	16.9	73.4	340
422409097124601	LE–6	180	8/23/2016	Ca - SO₄	7	1,090	11.9	1.6	646	148	39.9	6.3	27.7	306
						Paleozoic aquifers								
405139096194801	LPS–1	116	10/6/2016	Ca - HCO₃	6.9	542	15.2	7.6	297	70.2	13.2	2.01	34.5	289
405213096205001	LPS–2	130	10/6/2016	Ca - HCO₃	6.1	667	12.7	5.9	260	89.3	16.4	2.88	39.3	304
402313095512401	N–3	160	10/5/2016	Ca - SO₄	6.9	1,910	13.8	3	1,480	397	39.8	1.98	28.3	294
401759096003301	N–5	172	11/8/2016	Ca - HCO₃	6.9	928	13.3	M	392	113	37	6.33	50.1	396
404950096205501	LPS–4	110	10/5/2016	Ca - HCO₃	6.9	654	12.7	11	422	86	17.7	1.96	37.9	291
401819095493701	N–6	79	11/8/2016	Ca - HCO₃	7.1	663	13.5	8.5	332	80.6	23.7	1.36	32.2	243

Table 5B.   Results of water-quality analyses for selected constituents, eastern Nebraska, 2016–18.

[ft, foot; BLS, below land surface; mg/L, milligram per liter; µg/L, microgram per liter; Cl, chloride; Fl, fluoride; SO$_4$, sulfate; N, nitrogen; NH$_3$, ammonia; NH$_4^+$, ammonium; P, phosphorus; Fe, iron; Mn, manganese; Mo, molybdenum; Sr, strontium; As, arsenic; U, uranium; δ^{2}H, hydrogen isotope ratio in per mil Vienna Standard Mean Ocean Water; δ^{18}O, oxygen isotope ratio in per mil Vienna Standard Mean Ocean Water; <, less than; --, analyte not sampled]

Site number	Field name	Well depth (ft BLS)	Concentration, in mg/L							Concentration in µg/L					Stable isotopes	
			Cl	Fl	SO$_4$	Nitrate plus nitrite, as N	Ammonia (NH$_3$ + NH$_4^+$)	Ortho-phosphate, as P	Fe	Mn	Mo	Sr	As	U	δ^{2}H, per mil	δ^{18}O, per mil
							Dakota aquifer									
413618096322901	LE–1	181	5.21	0.29	47.8	<0.040	0.22	0.057	786	530	1.3	639	0.09	0.05	−54.9	−8.13
413639096274901	LE–2	220	17.1	1.22	116	<0.040	0.35	0.033	756	224	2.3	1,790	4.7	1.05	−58.6	−8.58
413912096462201	LE-3	526	133	1.96	927	<0.040	0.82	<0.004	1,650	111	3.81	6,850	1.7	0.14	−109	−14.45
413828096465801	LE-4	219	3.2	0.33	111	0.179	0.6	0.032	417	303	2.22	1,340	0.34	1.04	−63.7	−9.26
424611097185201	LC–6S domestic	95	5.41	0.46	746	1.58	0.01	<0.004	35.8	3.42	55.6	2,100	0.71	37.8	−66.7	−9.64
423317097160901	LC–4M	730	37.5	2.33	672	<0.040	0.69	<0.004	1,550	74.8	2.88	5,130	2.5	0.07	−126	−16.71
424713097170101	LC–6M	520	38.5	1.9	653	<0.040	0.13	<0.004	1,630	156	5.28	4,510	2.7	<0.050	−126	−16.97
424713097170102	LC–6D	750	51.3	1.61	699	<0.040	0.07	<0.004	1,640	150	5.36	4,590	3	0.07	--	--
421730096390001	PM D–1	440	3.24	0.68	74.5	0.042	0.29	0.019	358	224	1.28	1,670	0.13	0.32	−68	−9.89
410002096551101	LPS–5	162	4.6	0.37	486	<0.040	1.24	0.052	879	817	2.69	1,690	2.2	1.18	−59.1	−8.95
411005096311701	LPN–1	206	472	1.9	976	<0.040	1.17	0.006	1,300	197	4.32	6,940	2.5	0.189	−112	−14.76
410335096150101	D–SWSarpy1	117	2.37	0.29	6.19	2.14	<0.01	0.205	7.7	<0.40	2.34	275	0.8	3.13	--	--
410613096071101	D–Sp1	215	1.63	0.23	19.9	3.11	<0.01	0.145	33.3	2.18	2.47	258	1.5	1.61	--	--
410613096071102	D–Sp2	125	1.44	0.24	17.5	2.55	<0.01	0.117	29.6	223	6.78	261	1.8	1.37	--	--
411845096211203	D–Va3	204	16.9	0.67	98.2	<0.040	0.15	0.006	604	83.9	1.54	873	0.37	0.096	--	--
412758096222801	D–A1	297	112	0.77	723	<0.040	0.51	0.014	1,020	681	3.44	3,400	1.9	0.746	−92.4	−12.49
415958096152201	D–D1	180	11	0.6	110	<0.040	0.15	0.013	795	142	0.89	1,400	0.56	3.9	--	--
421406096294901	D–Th1	370	27.3	1.34	178	<0.040	0.42	0.038	993	143	1.87	2,960	1.3	0.08	--	--
421406096294902	D–Th2	275	17.5	1.26	106	<0.040	0.37	0.009	861	158	2.05	2,340	0.74	0.09	--	--
422616096343801	D–J1	270	116	2.26	804	0.045	0.63	0.029	1,420	316	6.38	6,540	1.3	0.219	--	--
422616096343802	D–J2	280	50.5	1.27	375	<0.040	0.45	0.056	622	435	6.78	3,130	1.6	0.614	--	--
405921096535101	LPS–3	212	20	0.42	105	<0.040	1.12	0.01	348	420	4.03	905	18	0.751	−58.9	−8.84

Table 5*B*. Results of water-quality analyses for selected constituents, eastern Nebraska, 2016–18.—Continued

[ft, foot; BLS, below land surface; mg/L, milligram per liter; µg/L, microgram per liter; Cl, chloride; Fl, fluoride; SO₄, sulfate; N, nitrogen; NH₃, ammonia; NH₄⁺, ammonium; P, phosphorus; Fe, iron; Mn, manganese; Mo, molybdenum; Sr, strontium; As, arsenic; U, uranium; δ^2H, hydrogen isotope ratio in per mil Vienna Standard Mean Ocean Water; δ^{18}O, oxygen isotope ratio in per mil Vienna Standard Mean Ocean Water; <, less than; --, analyte not sampled]

Site number	Field name	Well depth (ft BLS)	Concentration, in mg/L							Concentration in µg/L					Stable isotopes	
			Cl	Fl	SO₄	Nitrate plus nitrite, as N	Ammonia (NH₃ + NH₄⁺)	Ortho-phosphate, as P	Fe	Mn	Mo	Sr	As	U	δ^2H, per mil	δ^{18}O, per mil
							Niobrara aquifer									
423317097161001	LC–4S	120	2.65	0.71	103	<0.040	0.03	0.008	319	147	15.3	957	1.7	1.71	−81.1	−11.4
422344097120801	LE-5	157	5.32	0.32	700	<0.040	0.05	0.035	9.9	868	4.88	1,510	1.4	41.3	−61.6	−8.83
422409097124601	LE-6	180	8.9	0.28	225	13.6	<0.01	0.059	8.5	<0.40	1.82	757	1.1	21.4	−68.3	−10.07
							Paleozoic aquifers									
405139096194801	LPS–1	116	2.58	0.31	9.62	1.89	<0.01	0.061	<5.0	<0.40	0.83	355	0.41	3.34	−42.7	−6.75
405213096205001	LPS–2	130	13.2	0.32	15	<0.040	0.16	0.082	761	99.7	2.1	627	8.5	0.065	−49.7	−7.71
402313095512401	N–3	160	32.6	0.27	807	4.17	<0.01	0.009	19.3	1.54	14.8	6,150	1.2	3.74	−44.5	−6.92
401759096003301	N–5	172	15.1	0.49	93	1.77	0.36	0.035	45	200	45.4	1,010	10.9	3.43	−43.9	−6.88
404950096205501	LPS–4	110	2.08	0.32	35	10.4	<0.01	0.351	5.6	1.31	0.12	726	19.8	23.5	−46.9	−7.34
401819095493701	N–6	79	6.59	0.31	35.9	16.8	<0.01	0.025	7.4	<0.40	0.536	415	0.88	0.504	−41.4	−6.45

Table 6. Results from the Krustal-Wallis and Wilcoxon Rank Sum statistical tests for selected field properties and constituents.

[SC, specific conductance; DO, dissolved oxygen; Fe, iron; Mn, manganese; As, arsenic; Mo, molybdenum; Sr, strontium; Se, selenium; U, uranium; Dakota, Dakota aquifer; Niobrara, Niobrara aquifer; Paleozoic, Paleozoic aquifers; N, nitrogen; NH$_3$, ammonia; NH$_4^+$, ammonium]

| Group | Statistical test | Statistical test results (*p*-values) for selected field properties and constituents | | | | | | | | | | | | |
| | | SC | DO | Trace element | | | | | | | Nutrient | | |
				Fe	Mn	As	Mo	Sr	Se	U	Nitrate plus nitrite, as N	Ammonia (NH$_3$+NH$_4^+$)	Ortho-phosphate, as phosphorus
Dakota, Niobrara, and Paleozoic (all water types)	Kruskal-Wallis	[1]0.0030	[1]0.0241	[1]0.0006	0.1040	0.3861	0.1859	[1]0.0025	0.2882	[1]0.0268	[1]0.0210	[1]0.0085	[1]0.0409
Dakota (calcium bicarbonate) and Dakota (noncalcium bicarbonate)	Wilcoxon Rank Sum	[1]0.0005	[1]0.0137	[1]0.0005	[1]0.0005	[1]0.0025	[1]0.0005	[1]0.0005	[1]0.0023	[1]0.0025	[1]0.0012	[1]0.0005	[1]0.0023
Niobrara and Paleozoic (calcium bicarbonate) and Niobrara and Paleozoic (calcium sulfate)	Wilcoxon Rank Sum	[1]0.0238	0.3810	1.0000	0.8955	0.5476	0.7143	0.0952	0.6973	0.0952	0.8955	0.6714	0.6041

[1]Statistically significant difference.

Nutrients

Sampling results for nutrients, which include nitrate plus nitrite as nitrogen (hereinafter referred to as "nitrate") and orthophosphate as phosphorous (hereinafter referred to as "orthophosphate"), are presented in table 5B. Of the 31 samples collected from the three bedrock aquifers, 18 wells had concentrations of nitrate that were below the detection limit of 0.040 mg/L. In general, nitrate concentrations for the Dakota aquifer were the lowest of the three aquifer groups and all samples were below the EPA maximum contaminant level of 10 mg/L. One of the three samples collected for the Niobrara aquifer and two of the six samples collected from the Paleozoic aquifers exceeded the 10 mg/L EPA maximum contaminant level for nitrate (table 5).

Nitrate in groundwater is often the primary contaminant of concern for local water managers and users because land use in eastern Nebraska is dominated by row-crop agriculture. For this report, the background nitrate concentration is assumed to be less than 2 mg/L (Mueller and Helsel, 1996). Denitrification may play a role in reducing nitrate concentrations in secondary bedrock aquifers in eastern Nebraska. Denitrification is an important microbially mediated natural attenuation process where anaerobic microorganisms, in the absence of dissolved oxygen, reduce nitrate to generate energy and nitrogen gas (Green and Bekins, 2010). Dissolved oxygen measurements can be used to assess the prevalence of denitrification and to predict the extent to which natural attenuation may help control nitrate concentrations in groundwater.

Dissolved oxygen and nitrate concentrations are plotted against well depth for water samples from both Dakota aquifer subgroups, the Niobrara aquifer, and the Paleozoic aquifers (figs. 5A and 5B, table 5A and 5B). Of the 31 wells sampled, 12 wells had dissolved oxygen concentrations of 0.5 mg/L or greater and 7 sampled wells had nitrate concentrations that exceeded 2.0 mg/L (figs. 5A and 5B). For this report, groundwater with dissolved oxygen concentrations less than 0.5 mg/L is considered anoxic. Samples in table 5 were coded as "M" when the instrument used measured dissolved oxygen concentrations of less than 0 mg/L. The less than 0 mg/L measured values for dissolved oxygen occurred because the 1-point calibration of the sensor was completed at 100-percent saturation (U.S. Geological Survey, 2020a) and, therefore, may not predict the dissolved oxygen concentration as accurately when values approach 0 mg/L. Samples coded as "M" were assumed to be 0 mg/L for statistical analyses and in figure 5A. Generally, groundwater samples collected from wells screened deeper than 220 ft had dissolved oxygen concentration that were less than or approximately equal to 0.5 mg/L, and all wells screened deeper than 270 ft had dissolved oxygen concentrations less than 0.5 mg/L. Of the 10 Dakota aquifer (calcium bicarbonate) wells, 4 have dissolved oxygen concentrations greater than 0.5 mg/L, compared to only 2 of the 12 Dakota aquifer (noncalcium bicarbonate) wells. The highest dissolved oxygen concentration for Dakota aquifer (calcium bicarbonate) wells was 9.1 mg/L and for the Dakota aquifer (noncalcium bicarbonate) wells was 0.6 mg/L (table 5A).

Nitrate concentrations plotted against well depth indicate that concentrations for wells deeper than 200 ft are below the background concentration of 2 mg/L (Mueller and Helsel, 1996) and are often below the detection limit of 0.040 mg/L. Of the 12 Dakota aquifer (noncalcium bicarbonate) wells sampled, only two wells had nitrate concentrations above the detection limit, and all were below the background concentration of 2 mg/L (Mueller and Helsel, 1996; fig. 5B). Three of the 10 Dakota aquifer (calcium bicarbonate) wells had nitrate concentrations above the background concentration of 2 mg/L (fig. 5B, tables 5A and 5B). The only Niobrara aquifer sample with measurable dissolved oxygen concentrations had a nitrate concentration of 13.6 mg/L, which exceeds the EPA maximum contaminant level of 10 mg/L (fig. 5A and 5B, tables 5A and 5B). Sampled wells completed in Paleozoic aquifers, which have well depths that range from 79 to 172 ft, had some of the highest concentrations of nitrate compared to the other aquifer groups, with nitrate in three of the six wells exceeding the background nitrate concentration of 2 mg/L, and nitrate concentrations in two of the six wells exceeding the EPA maximum contaminant level of 10 mg/L (fig. 5B, tables 5A and 5B).

Stable Isotopes

Stable isotope data from samples collected from wells completed in the Dakota aquifer (including both subgroups), Niobrara aquifer, and Paleozoic aquifers tend to cluster together along the LMWL from Mead, Nebr. (fig. 6; Harvey, 2001). Generally, samples collected in the northern part of the study area are isotopically depleted, and samples collected in the southern part of the study area are isotopically enriched (table 5B). The latitudinal effect described in Clark and Fritz (1997) states that for every degree of increase in latitude, $\delta^{18}O$ decreases by approximately 0.6 per mil. The latitude effect explains some, but not all, of the variability in $\delta^{18}O$ values in figure 6.

The seasonality of recharged groundwater likely plays a role because the northern part of the study area receives more snow fall compared to the southern part of the study area. Examining the data from both Dakota aquifer subgroups, the samples from the Dakota aquifer (noncalcium bicarbonate) subgroup are generally more isotopically depleted compared to the samples from the Dakota aquifer (calcium bicarbonate) subgroup (fig. 6). Some of the most isotopically depleted water samples were collected in Lewis and Clark NRD in the northern part of the study area (fig. 1), which is consistent with samples collected by Gosselin and others (2001) in that area. Values of $\delta^{18}O$ are known to be temperature dependent; globally colder regions have more isotopically depleted $\delta^{18}O$ compared to more temperate regions (Clark and Fritz, 1997). The values of the most isotopically depleted samples from the
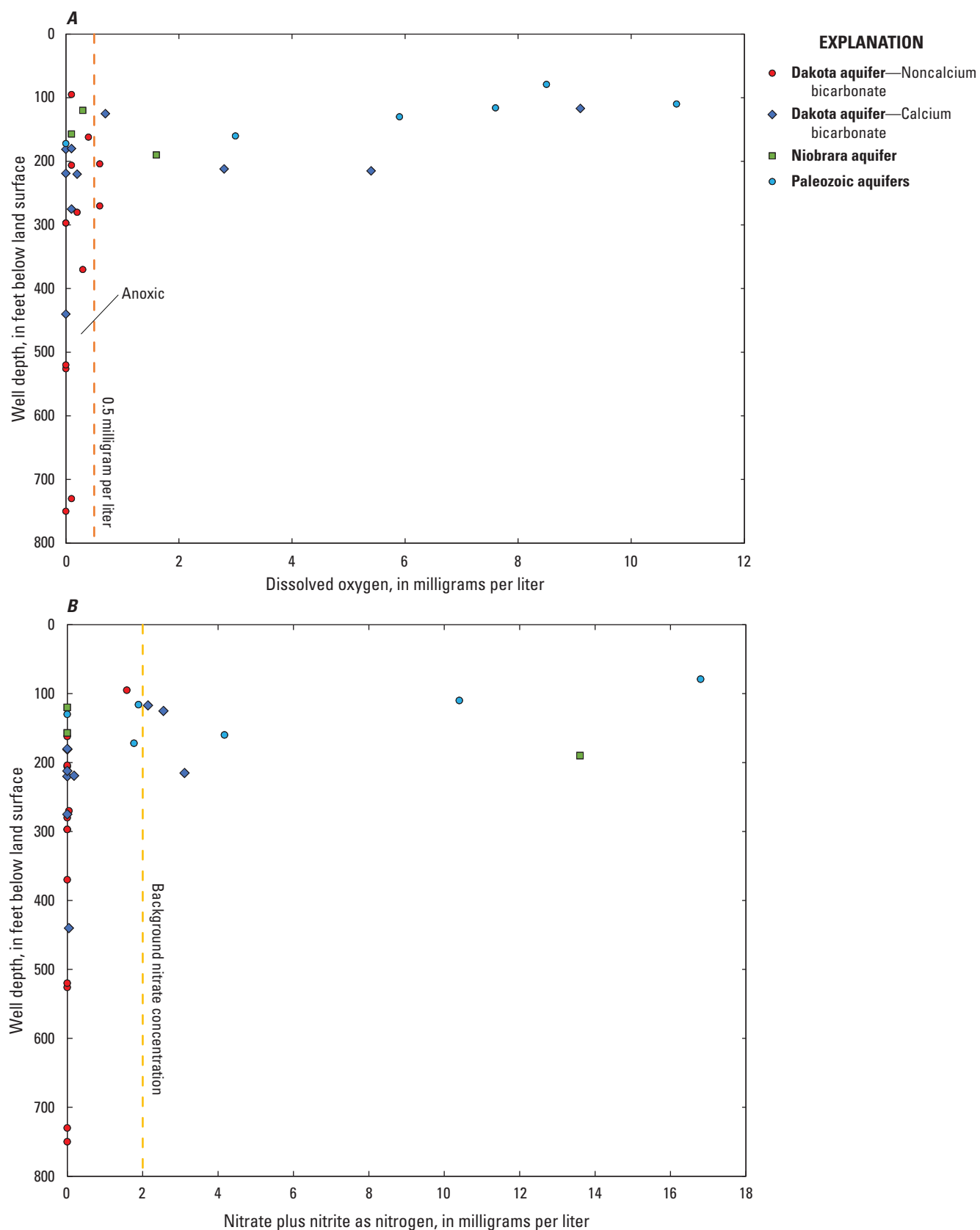
Figure 5.   Concentrations from sampled wells against well depth, eastern Nebraska, 2016–18. *A*, Dissolved oxygen. *B*, Nitrate plus nitrite as nitrogen.
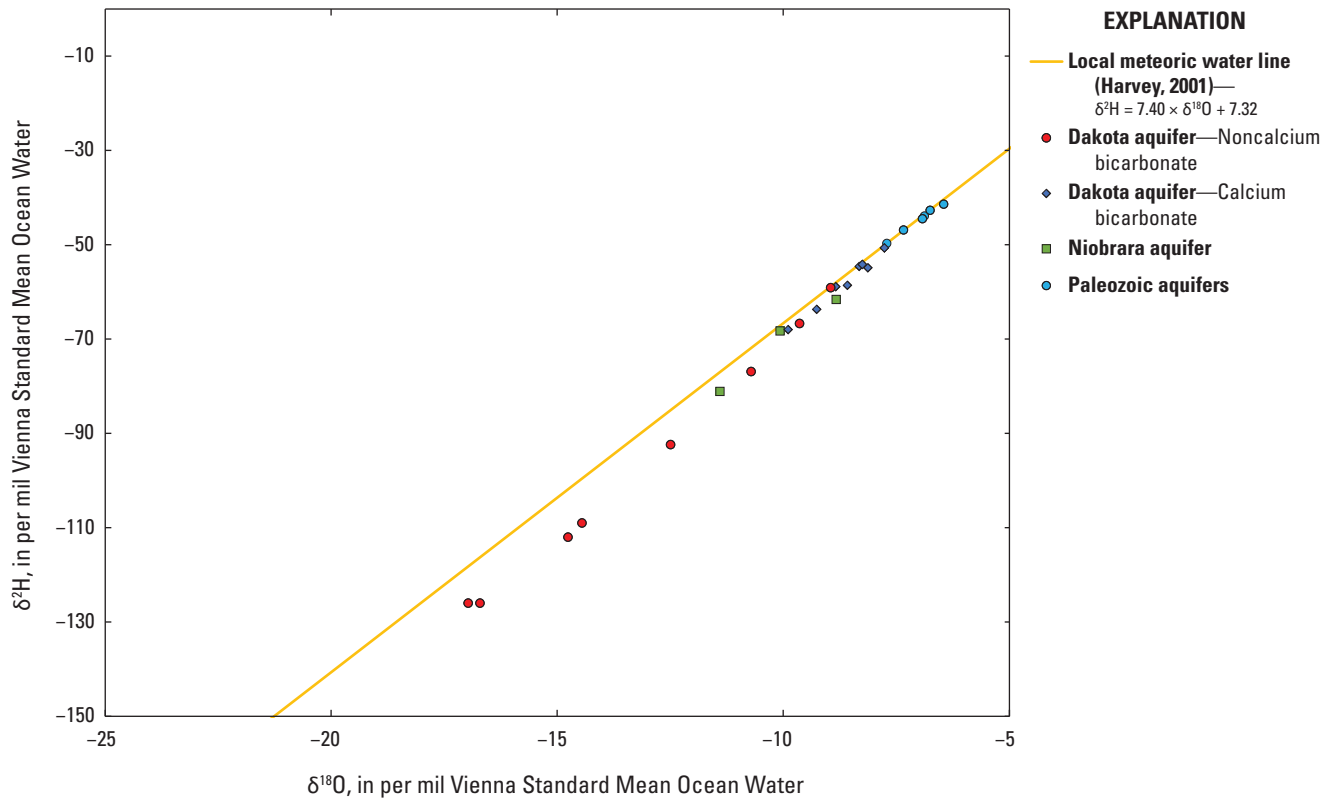
Figure 6.   Stable isotopes of oxygen (δ¹⁸O) and hydrogen (δ²H) from sampled wells, eastern Nebraska, 2016–18.

Dakota aquifer (noncalcium bicarbonate) subgroup indicate the climate at the time of recharge was approximately 15 °C cooler than present day (2020) climate. Samples from the Dakota aquifer (calcium bicarbonate) subgroup are isotopically enriched and are similar to modern precipitation (fig. 6). Samples collected from Paleozoic units were the most isotopically enriched of any aquifer group, indicating groundwater is recharged by more summertime precipitation compared to other aquifer groups (table 5B).

Groundwater Age

Groundwater age tracer results indicated that samples from the Dakota aquifer (noncalcium bicarbonate) subgroup generally had lower values of percent Modern Carbon (fig. 7) and had older radiocarbon ages (table 7, fig. 8) compared to samples from the Dakota aquifer (calcium bicarbonate) subgroup. Of the 11 samples from the Dakota aquifer (noncalcium bicarbonate) subgroup where ^{14}C samples were collected, 3 were considered modern (post-1950). The oldest radiocarbon ages estimated in this report are from samples of four Dakota aquifer (noncalcium bicarbonate) subgroup wells located in Cedar County (figs. 1 and 8, table 7) and dated the time of recharge to the Pleistocene when continental ice sheets covered much of the study area. The oldest radiocarbon ages coincided with the most depleted stable isotope samples, indicating

groundwater from the Dakota aquifer in Cedar County was recharged from Pleistocene-age water, which is consistent with the findings by Gosselin and others (2001). One Dakota aquifer (noncalcium bicarbonate) subgroup well, LPN–1, which is within the Todd Valley (fig. 2), had a radiocarbon age of 30,500 years before present (table 7) with stable isotope values that were very isotopically depleted (table 5B). Groundwater sampled from LPN–1 likely had the same recharge history as wells in Cedar County farther to the north. Other samples from Dakota aquifer (noncalcium bicarbonate) subgroup wells, including D–A1 and LE–3 (fig. 1) with radiocarbon ages of 20,500 and 17,500 years before present (table 7), respectively, and isotopically depleted values (table 5B), also indicate Pleistocene-age recharge. Of the samples from the Dakota aquifer (noncalcium bicarbonate) subgroup, the three ^{3}H samples collected indicated that groundwater is considered premodern and likely to have recharged at least several hundred years ago (figs. 9 and 10, table 7).

Age tracer samples collected from the Dakota aquifer (calcium bicarbonate) subgroup indicate that nearly all samples have higher values for percent Modern Carbon compared to the Dakota aquifer (noncalcium bicarbonate) subgroup samples (table 7, fig. 7). Of the six ^{14}C samples from the Dakota aquifer (calcium bicarbonate) subgroup, all were considered modern (table 7). Of the five ^{3}H samples from the Dakota aquifer (calcium bicarbonate) subgroup, four were determined to be premodern and likely several hundred years old. The
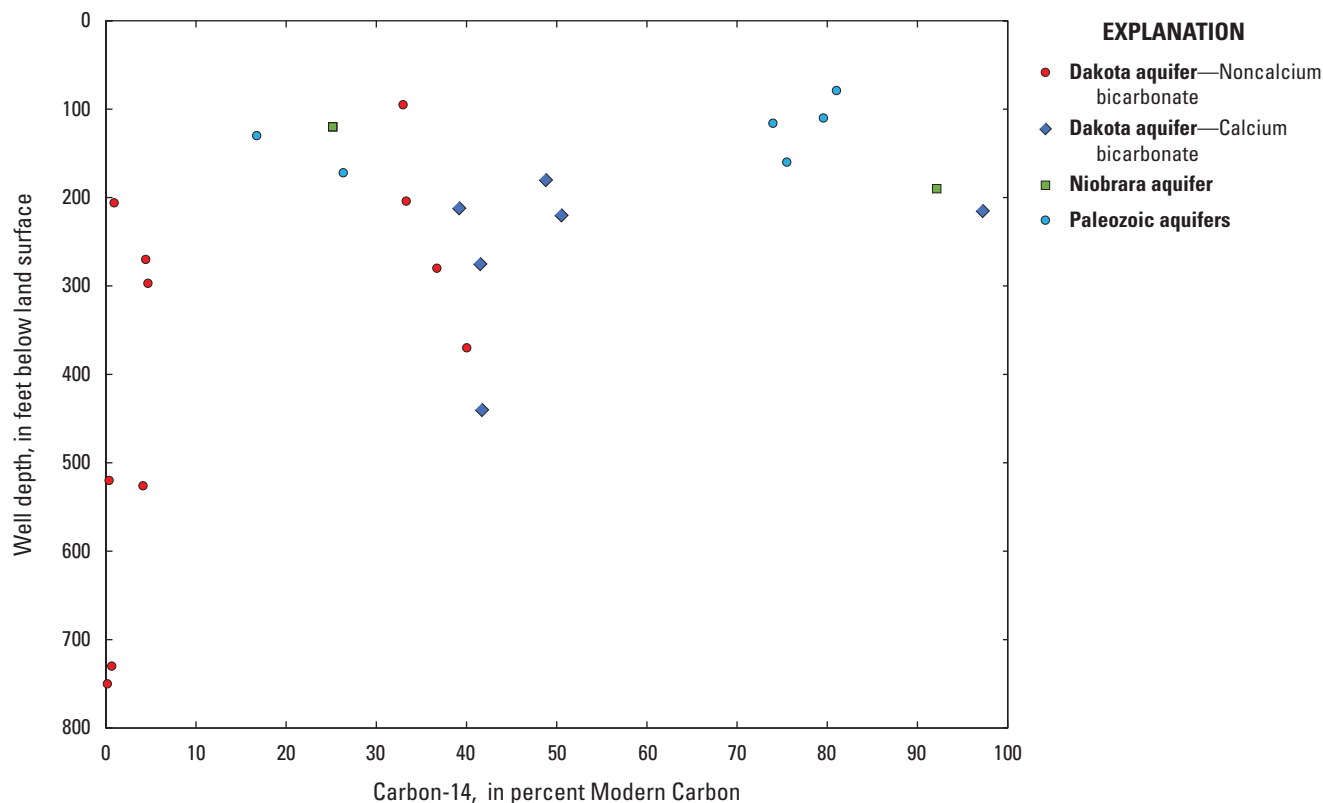
Figure 7.   Concentrations of carbon-14 (^{14}C), in percent Modern Carbon, against well depth, eastern Nebraska, 2016–18.

fifth sample is a mixture of modern and premodern waters (table 7). One sample (PM D–1) was considered modern based on ^{14}C sampling and premodern based on ^{3}H sampling; however, the difference in ^{3}H concentration between the measured ^{3}H concentration and premodern/mixed threshold was within the reported error of the analysis (U.S. Geological Survey, 2020c). Three samples (D–SWSarpy1, D–Sp1, D–Sp2) from the Dakota aquifer (calcium bicarbonate) subgroup had nitrate concentrations above the background concentration of 2 mg/L (table 5B), indicating some post–1952 water in each sample. These three samples were characterized as mixed, modern, and premodern, respectively (table 7).

Two of the three samples (LE–5 and LE–6) collected from wells completed in the Niobrara aquifer are considered modern based on ^{14}C and (or) ^{3}H sampling. Unlike samples collected from the Dakota aquifer subgroups, these younger samples were characterized as being calcium sulfate water type, which is most likely the result of weathering of pyrite and gypsum in the overlying Pierre Shale (Divine and Sibray, 2017). One Niobrara aquifer sample, LC–4S, had a radiocarbon age of 3,400 years before present (fig. 8, table 7) and is characterized as having a calcium bicarbonate water type. LC–4S is within a monitoring well cluster with a Dakota aquifer (noncalcium bicarbonate) subgroup well (LC–4M), which had a radiocarbon age of 31,000 years before present (fig. 8, table 7). Well LC–4S was more isotopically depleted and had the lowest concentration of total dissolved solids compared to

the other two samples from wells completed in the Niobrara aquifer (tables 5A and 5B). It is possible that the sample collected from LC–4S is a mixture of older Dakota aquifer water and recent recharge, but it is difficult to make that interpretation with the data available.

Four of the six samples collected from wells completed in Paleozoic aquifers were characterized as modern based on ^{14}C results (table 7). These four modern samples had dissolved oxygen concentrations that ranged from 3 to 10.8 mg/L and nitrate concentrations that ranged from 1.89 to 16.8 mg/L (tables 5A and 5B, figs. 5A and 5B), indicating that the Paleozoic aquifers have been affected by agricultural activities in these locations. Stable isotope results for samples from wells completed in Paleozoic aquifers were the most isotopically enriched samples collected for this report and plot close to the LMWL (fig. 6), which indicates that recharge to Paleozoic aquifers is from local precipitation and appears to occur during warmer months. The radiocarbon ages for samples LPS–2 and N–5 were 13,000 and 7,000 years before present, respectively (table 7; fig. 8). Both of these samples had nitrate concentrations that were below the background concentration of 2 mg/L (table 5B); however, their stable isotope values plotted very close to the LMWL and to other samples determined to be modern, indicating that these samples are likely a mixture of modern recharge and older water (table 5B, fig. 6). Three ^{3}H samples collected from the Paleozoic aquifers indicated that two samples (N–3 and LPS–4) were determined

Table 7. Calculated radiocarbon ages and tritium (^{3}H) age categories from sampled wells, eastern Nebraska, 2016–18.

[ft, foot; BLS, below land surface; δ^{13}C, ratio of carbon-13 to carbon-12 relative to Peedee belemnite; ^{14}C, carbon-14; pMC, percent Modern Carbon; ^{3}H, tritium; TU, tritium units; Dakota, Dakota aquifer; --, well not sampled for constituent or not applicable; Premodern, water is likely more than several hundred years old; Niobrara, Niobrara aquifer; Modern, water is likely less than 64 years old (water entered groundwater system after 1952); Paleozoic, Paleozoic aquifers; Mixed, water is likely a mixture of groundwater less than 64 years old and groundwater more than several hundred years old]

Site number	Field name	Well depth (ft BLS)	Aquifer sampled	Date sampled	δ^{13}C, per mil	^{14}C, in percent modern	Radiocarbon age, ^{14}C (pMC)	^{14}C apparent age in years before present	^{3}H (TU)	Premodern ^{3}H concentration threshold (TU)	Modern ^{3}H concentration threshold (TU)	^{3}H age category
413912096462201	LE–3	526	Dakota (non-calcium bicarbonate)	8/24/2016	−9.27	4	4.1	17,500	--	--	--	--
424611097185201	LC–6S domestic	95	Dakota (non-calcium bicarbonate)	8/11/2016	−10.02	31.98	33.0	1,100	--	--	--	--
423317097160901	LC–4M	730	Dakota (non-calcium bicarbonate)	8/10/2016	−7.82	0.64	0.7	31,000	--	--	--	--
424713097170101	LC–6M	520	Dakota (non-calcium bicarbonate)	8/9/2016	−7.03	0.35	0.4	35,000	--	--	--	--
424713097170102	LC–6D	750	Dakota (non-calcium bicarbonate)	8/9/2016	−7.2	0.17	0.2	41,000	--	--	--	--
410002096551101	LPS–5	162	Dakota (non-calcium bicarbonate)	10/27/2016	--	--	--	--	0.00	0.23	2.37	Pre-modern
411005096311701	LPN–1	206	Dakota (non-calcium bicarbonate)	4/11/2017	−9.95	0.9	0.9	30,500	0.03	0.22	2.24	Pre-modern
411845096211203	D–Va3	204	Dakota (non-calcium bicarbonate)	3/9/2018	−8.85	32.24	33.3	Modern (post-1950)	--	--	--	--
412758096222801	D–A1	297	Dakota (non-calcium bicarbonate)	11/2/2016	−10.65	4.54	4.7	20,500	0.09	0.23	2.37	Pre-modern
421406096294901	D–Th1	370	Dakota (non-calcium bicarbonate)	10/14/2016	−9.18	38.76	40.0	Modern (post-1950)	--	--	--	--
422616096343801	D–J1	470	Dakota (non-calcium bicarbonate)	10/13/2016	−7.82	4.28	4.4	15,500	--	--	--	--

Table 7. Calculated radiocarbon ages and tritium (^{3}H) age categories from sampled wells, eastern Nebraska, 2016–18.—Continued

[ft, foot; BLS, below land surface; δ^{13}C, ratio of carbon-13 to carbon-12 relative to Peedee belemnite; ^{14}C, carbon-14; pMC, percent Modern Carbon; ^{3}H, tritium; TU, tritium units; Dakota, Dakota aquifer; --, well not sampled for constituent or not applicable; Premodern, water is likely more than several hundred years old; Niobrara, Niobrara aquifer; Modern, water is likely less than 64 years old (water entered groundwater system after 1952); Paleozoic, Paleozoic aquifers; Mixed, water is likely a mixture of groundwater less than 64 years old and groundwater more than several hundred years old]

Site number	Field name	Well depth (ft BLS)	Aquifer sampled	Date sampled	δ^{13}C, per mil	^{14}C, in percent modern	Radiocarbon age, ^{14}C (pMC)	^{14}C apparent age in years before present	^{3}H (TU)	Premodern ^{3}H concentration threshold (TU)	Modern ^{3}H concentration threshold (TU)	^{3}H age category
422616096343802	D–J2	280	Dakota (non-calcium bicarbonate)	10/13/2016	−9.44	35.57	36.7	Modern (post-1950)	--	--	--	--
413618096322901	LE–1	181	Dakota (calcium bicarbonate)	8/25/2016	--	--	--	--	0.22	0.23	2.37	Pre-modern
413639096274901	LE–2	220	Dakota (calcium bicarbonate)	8/25/2016	−8.21	48.82	50.5	Modern (post-1950)	--	--	--	--
413828096465801	LE–4	239	Dakota (calcium bicarbonate)	8/24/2016	--	--	--	--	0.16	0.23	2.37	Pre-modern
421730096390001	PM D–1	440	Dakota (calcium bicarbonate)	8/11/2016	−9.36	40.39	41.7	Modern (post-1950)	0.16	0.23	2.37	Pre-modern
410335096150101	D–SWSarpy1	117	Dakota (calcium bicarbonate)	10/3/2016	--	--	--	--	0.34	0.23	2.37	Mixed
410613096071101	D–Sp1	215	Dakota (calcium bicarbonate)	9/28/2016	−7.55	93.83	97.2	Modern (post-1950)	--	--	--	--
410613096071102	D–Sp2	125	Dakota (calcium bicarbonate)	9/28/2016	--	--	--	--	0.03	0.23	2.37	Pre-modern
415958096152201	D–D1	180	Dakota (calcium bicarbonate)	6/20/2018	−8.86	47.21	48.8	Modern (post-1950)	--	--	--	--
421406096294902	D–Th2	275	Dakota (calcium bicarbonate)	10/14/2016	−9.3	40.2	41.5	Modern (post-1950)	--	--	--	--
405921096535101	LPS–3	212	Dakota (calcium bicarbonate)	11/10/2016	−9.61	37.97	39.2	Modern (post-1950)	--	--	--	--
423317097161001	LC–4S	120	Niobrara	8/10/2016	−10.09	24.41	25.2	3,400	--	--	--	--
422344097120801	LE–5	157	Niobrara	8/23/2016	--	--	--	--	3.29	0.23	2.37	Modern
422409097124601	LE–6	180	Niobrara	8/23/2016	−8.57	89.11	92.1	Modern (post-1950)	2.70	0.23	2.37	Modern
405139096194801	LPS–1	116	Paleozoic	10/6/2016	−6.54	71.25	74.0	Modern (post-1950)	0.22	0.19	1.97	Mixed
405213096205001	LPS–2	130	Paleozoic	10/6/2016	−14.07	16.36	16.7	13,000	--	--	--	--
402313095512401	N–3	160	Paleozoic	10/5/2016	−6.88	72.78	75.5	Modern (post-1950)	3.95	0.19	1.97	Modern

Table 7. Calculated radiocarbon ages and tritium (³H) age categories from sampled wells, eastern Nebraska, 2016–18.—Continued

[ft, foot; BLS, below land surface; δ13C, ratio of carbon-13 to carbon-12 relative to Peedee belemnite; 14C, carbon-14; pMC, percent Modern Carbon; 3H, tritium; TU, tritium units; Dakota, Dakota aquifer; --, well not sampled for constituent or not applicable; Premodern, water is likely more than several hundred years old; Niobrara, Niobrara aquifer; Modern, water is likely less than 64 years old (water entered groundwater system after 1952); Paleozoic, Paleozoic aquifers; Mixed, water is likely a mixture of groundwater less than 64 years old and groundwater more than several hundred years old]

| Site number	Field name	Well depth (ft BLS)	Aquifer sampled	Date sampled	δ13C, per mil	14C, in percent modern	Radiocarbon age, 14C (pMC)	14C apparent age in years before present	3H (TU)	Premodern 3H concentration threshold (TU)	Modern 3H concentration threshold (TU)	3H age category
401759096003301	N–5	172	Paleozoic	11/8/2016	−12.5	25.67	26.3	7,000	--	--	--	--
404950096205501	LPS–4	110	Paleozoic	10/5/2016	−6.96	76.71	79.6	Modern (post–1950)	3.54	0.19	1.97	Modern
401819095493701	N–6	79	Paleozoic	11/8/2016	−7.53	78.2	81.0	Modern (post–1950)	--	--	--	--
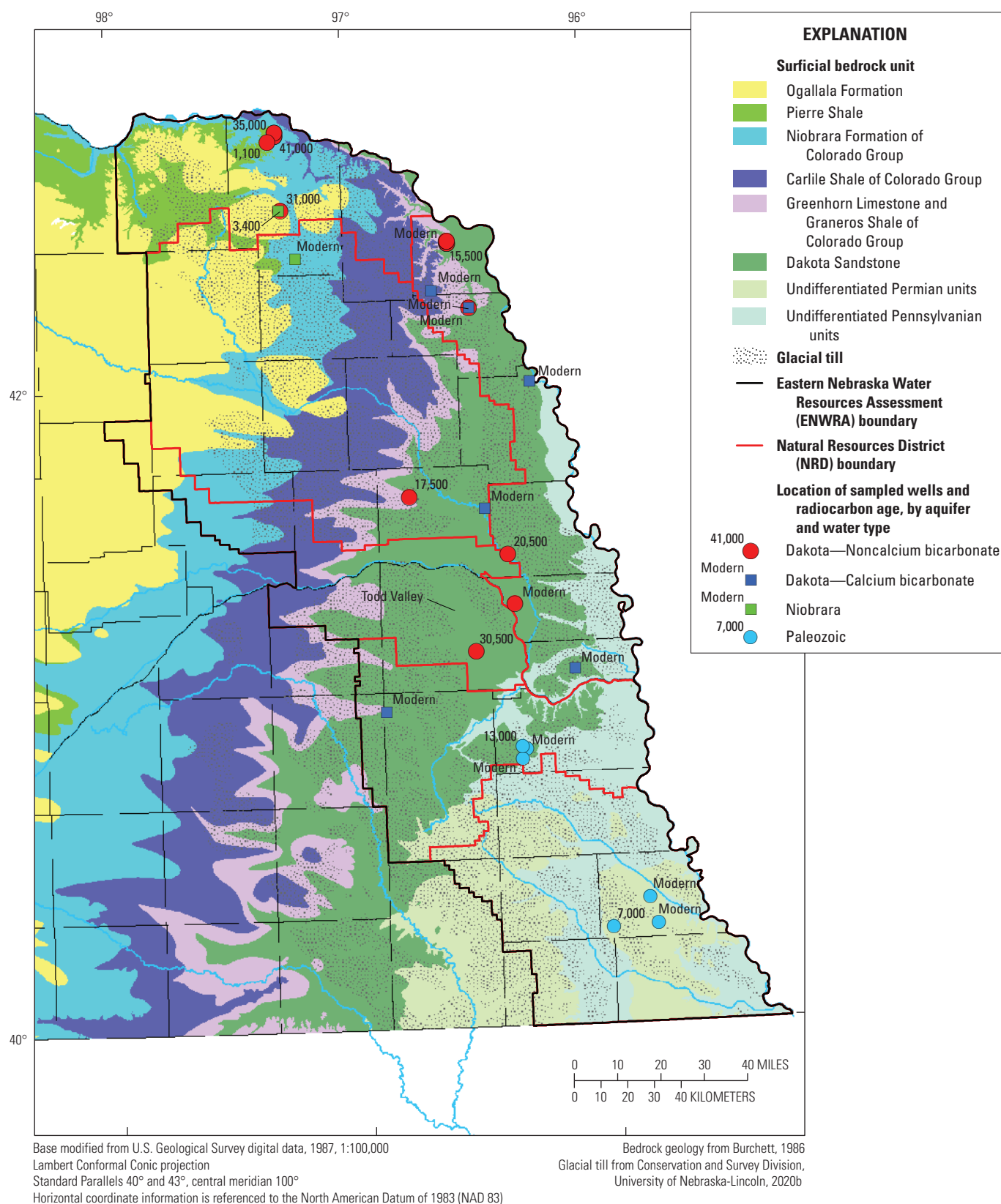
Figure 8.   Radiocarbon ages, in years before present, from sampled wells, eastern Nebraska, 2016–18.
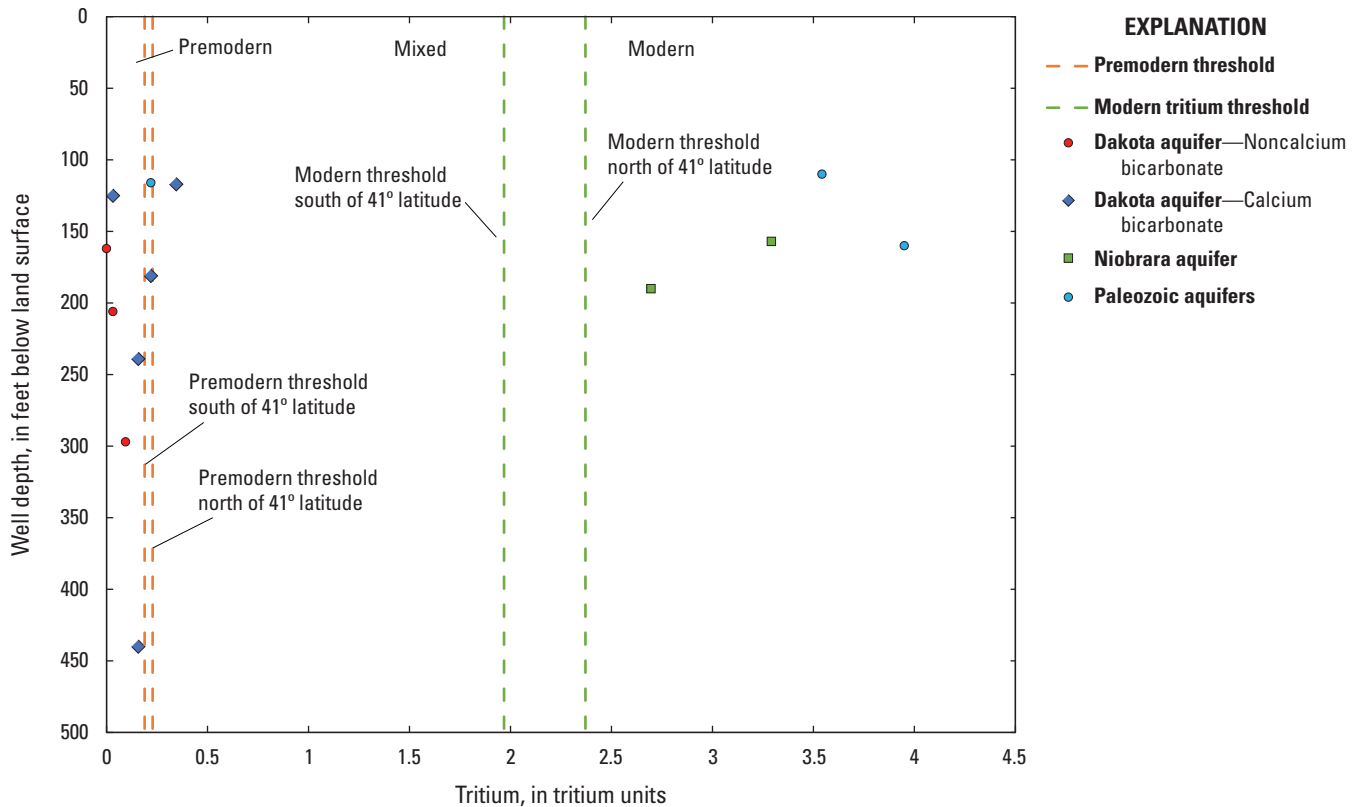
Figure 9.   Concentrations of tritium (^{3}H) against well depth, eastern Nebraska, 2016–18.

to be modern with elevated nitrate concentrations and one sample (LPS–1) was mixed with nitrate concentration below 2 mg/L (tables 5*B* and 7). Based on the six samples collected from the Paleozoic aquifers, water type did not appear to be diagnostic for determining the age and recharge history of groundwater in these aquifers.

Groundwater Management Implications

The results of this study indicate that the dominant water type determined from samples collected from the Dakota aquifer are diagnostic for assessing the quality, recharge source, and age of groundwater. Groundwater samples collected from the Dakota aquifer, where calcium bicarbonate was the dominant water type, show very different geochemical characteristics from samples with other water types. Calcium bicarbonate dominant samples from the Dakota aquifer were characterized as modern or mixed using radiocarbon results, indicating that in these areas, groundwater is unconfined and is recharged by precipitation and (or) surface water (table 7, figs. 7 and 8). Stable isotope ratios of calcium bicarbonate dominant samples from the Dakota aquifer were more isotopically enriched compared to other water types and were similar to modern precipitation values (tables 5*A* and 5*B*, fig. 6). If groundwater extraction rates exceed recharge rates, total dissolved solid concentrations may increase as a result of upwelling of

groundwater from deeper units, which can adversely affect groundwater quality. Concentrations of nitrate for calcium bicarbonate dominant samples from the Dakota aquifer were generally near or below background, but some wells indicated effects from agricultural activities (fig. 5*B*). It should be noted that seven samples were considered anoxic (dissolved oxygen less than 0.5 mg/L) and could indicate that denitrification is reducing nitrate concentrations in groundwater. Sampling results presented in this report indicate water quality in the Dakota aquifer with a calcium bicarbonate water type is good, but that the groundwater may be vulnerable to surface contamination. Future groundwater sampling plans could focus on understanding how groundwater quality in the Dakota aquifer with a calcium bicarbonate water type changes in the future.

In contrast, groundwater sampled from the Dakota aquifer, having a dominant water type other than calcium bicarbonate, generally has low dissolved oxygen and nitrate concentrations, and higher concentrations of total dissolved solids and trace elements, including iron and strontium. The geochemical characteristics of these samples indicated confining conditions and limited groundwater recharge from local precipitation. Of the 12 wells sampled from the Dakota aquifer where calcium bicarbonate was not the dominant water type, only 2 were characterized as modern. Similar to what Gosselin and others (2001) reported for Cedar County, apparent groundwater age estimated from ^{14}C sampling dates groundwater recharge to the Dakota aquifer to Pleistocene time. Depleted stable isotope
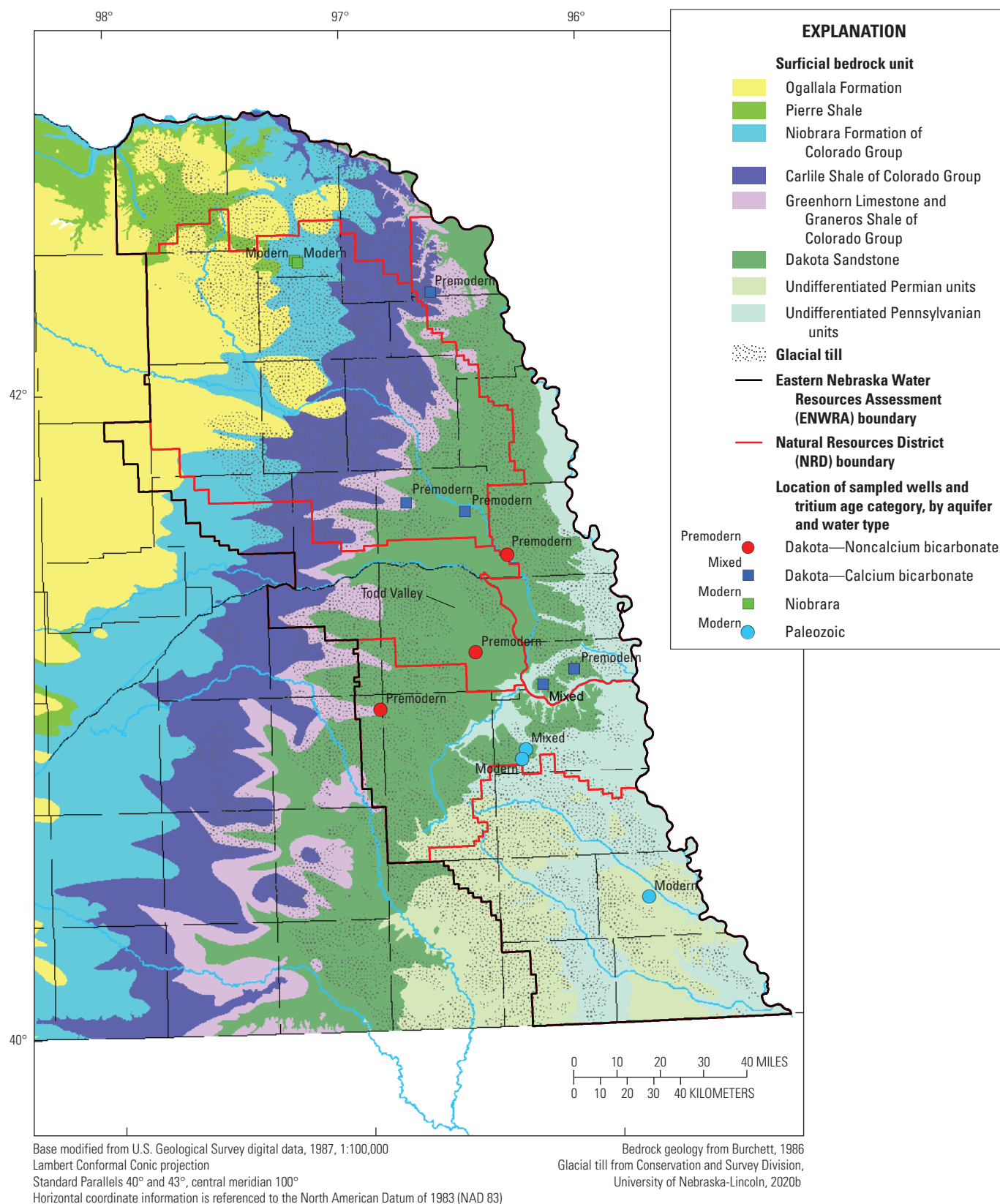
Figure 10.   Tritium (^{3}H) age category from sampled wells, eastern Nebraska, 2016–18.

results from these samples indicate recharge occurred during a colder climate. Other samples collected in wells completed in sandstone below layers of shale, mudstone, or clay within the Dakota aquifer (Dakota, Washington, Saunders, and Douglas Counties for this report) show similar geochemical and age characteristics. Groundwater in these areas is not easily recharged from precipitation or surface water. Future groundwater–level monitoring could provide information to evaluate whether groundwater supplies remain sufficient to meet future domestic and irrigation needs. Sampling results from the Dakota aquifer, having a dominant water type other than calcium bicarbonate, indicate that groundwater is not vulnerable to surface contamination; however, groundwater-quality issues include elevated concentrations of total dissolved solids and trace elements.

For the Niobrara aquifer and Paleozoic aquifers, the dominant water type was not a diagnostic indicator of recharge source, age, and groundwater quality as it was with the Dakota aquifer. Most likely this is because the host aquifer was dominated by calcium-carbonate-rich rocks, and prolonged rock-water interaction would result in higher concentrations of these major ions; however, relatively few samples were collected from these aquifers to be able to confirm this interpretation. Samples collected from wells completed in the Niobrara aquifer (2 wells) and Paleozoic aquifers (1 well) and characterized as calcium sulfate water type have statistically significantly higher concentrations of total dissolved solids compared to other samples from the Niobrara aquifer and Paleozoic aquifers characterized as calcium bicarbonate. Given that six of the nine of samples collected from the Niobrara and Paleozoic aquifers indicated modern recharge, these secondary bedrock aquifers are reliant on recharge from precipitation to sustain groundwater levels and may be vulnerable to a multiyear drought. Divine and Sibray (2017) state that yields to wells completed in the Niobrara are dependent on the presence of bedding planes, and Tanner and Steele (1991) noted that well yields in Paleozoic aquifers are dependent on fracturing and secondary porosity. It can be inferred that these units offer little storage and that the Niobrara and Paleozoic aquifers are susceptible to overpumping or a multiyear drought. Samples collected from wells completed in Paleozoic aquifers were the most isotopically enriched, isotopically similar to modern precipitation, and had the highest concentrations of nitrate. Sampling indicated that groundwater in Paleozoic and Niobrara aquifers is affected by agricultural activities and future groundwater sampling would be needed to characterize groundwater–quality changes with time.

Summary

The Eastern Nebraska Water Resources Assessment (ENWRA) project was initiated in 2006 to assist water managers by developing a hydrogeologic framework and water budget for the portion of eastern Nebraska overlain by glacial deposits. The study area covers more than 8,000,000 acres across the Lewis and Clark, Lower Elkhorn, Lower Platte North, Lower Platte South, Nemaha, and Papio-Missouri River Natural Resources Districts (NRDs) and roughly coincides with the extent of glacial till within Nebraska. Municipal, irrigation, and domestic groundwater needs are met from alluvial, buried paleovalley and the High Plains aquifer (where present) and generally, bedrock aquifers are considered a secondary water source; however, in some areas, such as parts of Sarpy and Nemaha Counties, bedrock aquifers are the only source of water within glaciated upland areas. Within eastern Nebraska, population growth has led to increased development of groundwater resources for domestic and municipal needs. Groundwater pumping for irrigation during recent droughts (2000–6; 2012) have reduced streamflows and strained drinking-water supplies for some towns and cities.

In response to some of these concerns, water resource managers have been evaluating the use of secondary aquifers to meet future drinking-water needs. To improve the understanding of the quality, geochemistry, and age of groundwater from selected bedrock aquifers in the ENWRA area, the U.S. Geological Survey, in cooperation with the ENWRA group, which includes the Lewis and Clark, Lower Elkhorn, Lower Platte North, Lower Platte South, Nemaha, and Papio–Missouri River NRDs, designed a study to sample 31 wells and analyze samples for major ions, physical properties, nutrients, stable isotopes, and selected age tracers. Of the 31 samples collected for this report, 22 samples were collected from wells completed in the Dakota aquifer contained in the Dakota Sandstone, 3 from wells completed in the Niobrara aquifer contained in the Niobrara Formation of Colorado Group, and 6 from wells completed in Paleozoic aquifer contained in undifferentiated Paleozoic-age units. The proportion of samples used in this study roughly reflects the proportion of water use of these bedrock aquifers, with the Dakota aquifer being the most widely used of the aquifers sampled.

The results of this study indicate that major ion data collected from the Dakota aquifer can be used for assessing the quality, recharge source, and age of groundwater. Calcium bicarbonate dominant samples were characterized as modern or mixed, indicating that in these areas, groundwater is unconfined and is recharged by precipitation and (or) surface water. Stable isotope ratios of calcium bicarbonate dominant samples were more isotopically enriched compared to other water types in the Dakota aquifer and were similar to modern precipitation values. If groundwater extraction rates from the Dakota aquifer exceed recharge rates, total dissolved solid concentrations may increase as a result of upwelling of groundwater from deeper units, which can adversely affect groundwater quality. Sampling results presented in this report indicate water quality from the Dakota aquifer with a calcium bicarbonate water type is good, but that groundwater may be vulnerable to surface contamination. Future groundwater sampling plans for the Dakota aquifer with a calcium bicarbonate water type could focus on understanding how groundwater quality changes in the future.

In contrast, groundwater sampled from the Dakota aquifer, having a dominant water type other than calcium bicarbonate, generally has low dissolved oxygen and nitrate concentrations, and higher concentrations of total dissolved solids and trace elements, including iron and strontium. The geochemical characteristics of these samples indicated confining conditions and groundwater recharge from local precipitation were limited. Apparent groundwater age estimated from ^{14}C (or radiocarbon) sampling dates groundwater recharge to the Dakota aquifer with noncalcium bicarbonate water type during Pleistocene time. Depleted stable isotopes indicate recharge occurred during a colder climate. Other samples collected in wells completed in sandstone below layers of shale, mudstone, or clay in the upper Dakota aquifer (Dakota, Washington, Saunders, and Douglas Counties for this report) show similar geochemical and age characteristics. Groundwater under confined conditions is not easily recharged from precipitation or surface water. Future groundwater-level monitoring of the Dakota aquifer with non-calcium bicarbonate water type could provide information to evaluate whether groundwater supplies remain sufficient to meet future domestic and irrigation needs. Sampling results indicate that groundwater from the Dakota aquifer with noncalcium bicarbonate water type is not vulnerable to surface contamination; however, groundwater-quality issues include elevated concentrations of total dissolved solids and trace elements.

For the Niobrara aquifer and Paleozoic aquifers, the dominant water type was not a diagnostic indicator of recharge source, age, and groundwater quality as with the Dakota aquifer. Most likely this is because the host formation was dominated by calcium-carbonate-rich rocks, and prolonged rock–water interaction would result in higher concentrations of these major ions; however, relatively few samples were collected from these aquifers to be able to confirm this interpretation. Samples collected from wells completed in the Niobrara aquifer and Paleozoic aquifers and characterized as calcium sulfate water type have statistically significantly higher specific conductance, and by inference, total dissolved solids compared to other samples from the Niobrara aquifer and Paleozoic aquifers characterized as calcium bicarbonate. Given that six of the nine of samples collected from the Niobrara and Paleozoic aquifers indicated modern recharge, these secondary bedrock aquifers are reliant on precipitation to sustain groundwater levels and may be vulnerable to a multiyear drought. Yields to wells completed in the Niobrara aquifer are dependent on the presence of bedding planes and yields in Paleozoic aquifers are dependent on fracturing and secondary porosity. It can be inferred that these units offer little storage and that the Niobrara and Paleozoic aquifers are susceptible to overpumping or a multiyear drought. Samples collected from wells completed in Paleozoic aquifers were the most isotopically enriched, isotopically similar to modern precipitation, and had the highest concentrations of nitrate. Sampling indicated that groundwater in Paleozoic and Niobrara aquifers is affected by agricultural activities and future groundwater sampling would be beneficial to characterize groundwater-quality changes with time.

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