STATE OF SOUTH DAKOTA
Dennis Daugaard, Governor

DEPARTMENT OF ENVIRONMENT AND NATURAL RESOURCES
Steven M. Pirner, Secretary

DIVISION OF FINANCIAL AND TECHNICAL ASSISTANCE
James Feeney, Director

GEOLOGICAL SURVEY PROGRAM
Derric L. Iles, State Geologist

REPORT OF INVESTIGATIONS 118

EXAMINATION OF ISOTOPES IN SELECTED WATERS IN EASTERN SOUTH DAKOTA

DERRIC L. ILES

TOM RICH

Akeley-Lawrence Science Center
University of South Dakota
Vermillion, South Dakota

2017

GEOLOGICAL SURVEY PROGRAM

DEPARTMENT OF ENVIRONMENT AND NATURAL RESOURCES
AKELEY-LAWRENCE SCIENCE CENTER, USD
414 EAST CLARK STREET
VERMILLION, SOUTH DAKOTA 57069-2390
(605) 677-5227

Derric L. Iles, M.S., C.P.G.	State Geologist
Timothy C. Cowman, M.S.	Environmental Scientist Manager
Priscilla E. Young, B.S.	Senior Secretary
Sarah A. Chadima, M.S., C.P.G.	Geologist
Wesley P. Christensen, B.S.	Geologist
Stevie L. Holmes, B.S.	Geologist
Ann R. Jensen, B.S.	Geologist
Darren J. Johnson, M.S.	Geologist
Nicholas J. Krohe, M.S.	Geologist
Thomas R. Marshall, Ph.D.	Geologist
Matthew T. Noonan, B.S.	Hydrologist
Thomas B. Rich, M.S.	Hydrologist
Layne D. Schulz, B.S.	Geologist
Scott W. Jensen	Civil Engineering Technician
Ted R. Miller, B.S.	Civil Engineering Technician
James R. Olson, B.S.	Civil Engineering Technician
Lori L. Roinstad	Cartographer

RAPID CITY OFFICE
2050 WEST MAIN, SUITE 1
RAPID CITY, SOUTH DAKOTA 57702-2493
(605) 394-2229

Brian A. Fagnan, M.S,, C.P.G.	Geologist
Mark D. Fahrenbach, Ph.D.	Geologist
Joanne M. Noyes, M.S., P.E.	Hydrologist

CONTENTS

CONTENTS -- continued

FIGURES

Page

TABLES

Page

APPENDIX

Page

INTRODUCTION

Several radiocarbon ages have been previously determined for ground water from glacially derived aquifers in eastern South Dakota that are consistent with a Late Wisconsin age (glacial-age water). These ages suggested that the water sampled was connate, or entrapped within the sediments comprising the aquifers since the time of deposition of those sediments. In some buried, glacially derived aquifers, existing information suggested that there was mixing of meteoric water with connate water. In the context of this report, meteoric water is water that has entered the ground-water system in a timeframe of decades before present rather than a timeframe measured in millennia. The recharge of meteoric water to aquifers has commonly been inferred by the presence of water-level gradients in an aquifer, a rise in water levels as measured in monitoring wells, and quality of the water. However, there has been uncertainty as to the source areas of recharge of meteoric water to some of these ground waters as well as uncertainty as to the locations of their discharge areas.

The amount of mixing of connate and meteoric waters is relevant to the understanding of the flow of water from areas of recharge to areas of discharge from these aquifers as well as having a practical application in terms of the amount of water that can be sustainably withdrawn. South Dakota Codified Law 46-6-3.1 requires that annual withdrawal of ground water is not to exceed recharge. Additional topics to which recharge information may be applied are land-use zoning and source water protection efforts.

The naturally occurring ratios of hydrogen isotopes $^{2}H/^{1}H$ and oxygen isotopes $^{18}O/^{16}O$ (hereafter referred to as the stable-isotope ratios) in ground water have been used to trace movement within aquifers (Terwey, 1984). In addition, these stable-isotope ratios occurring in water of a known origin can be used as standards to compare with stable-isotope ratios occurring in ground waters in which the amount of mixing of meteoric and connate waters is unknown.

The radioactive isotopes carbon-14 and tritium are useful in determining the residence time of ground water in an aquifer where no mixing of waters of different sources has occurred. Carbon-14 is useful in gaining insight as to whether ground water present in glacially derived sediments is at least in part more recently derived meteoric water. Tritium is useful in determining whether any meteoric water has entered a ground-water system since the early 1950s.

This study specifically included sampling and analyses to determine (1) the departure from Vienna Standard Mean Ocean Water (VSMOW) for the stable-isotope ratios, (2) the isotope of carbon-14, and (3) the isotope of tritium.

OBJECTIVES

One objective of this study was to directly sample atmospheric precipitation from different times during the year and to analyze those samples for the stable-isotope ratios of hydrogen isotopes $^{2}H/^{1}H$ and oxygen isotopes $^{18}O/^{16}O$ so that a meteoric water line could be established for eastern South Dakota. By collecting samples at different times, any effects of seasonality would be accounted for. A meteoric water line is a convenient reference line for the understanding and tracing of local ground-water origins and movements (Mazor, 1991). In each hydrochemical investigation, the local meteoric line has to be established from samples of individual rain events (Mazor, 1991). The meteoric water line is used as a standard of comparison for samples in which the relative quantity of meteoric water is not known.

A second objective was to sample and analyze water that is inferred to be connate glacial water based on hydrogeological and geological criteria. Where radiocarbon ages have not been established for these waters, carbon-14, tritium, and the stable-isotope ratios were to be tested for.

A third objective was to sample and analyze ground water in which the amount of mixing of meteoric and connate water was more uncertain. Prior sampling in some glacially derived aquifers for carbon-14 yielded Late Wisconsin ages, suggesting that the sampled water was connate. However, other evidence suggests modern recharge to these aquifers. This objective was to examine the apparent conflict between the radiocarbon ages and evidence for recent recharge.

A fourth objective was to obtain samples from various sources of surface water and test the samples for the stable-isotope ratios. Variation in stable-isotope ratios in surface-water bodies may accommodate tracing of recharge sources, particularly in aquifers where a substantial portion of the recharge is derived from bodies of surface water and not from the direct infiltration of precipitation.

ISOTOPES EVALUATED IN THIS STUDY AND THEIR USES

Isotopes are different versions of a single element. The essential difference between isotopes is the number of neutrons in the nucleus of an atom of a particular element. The isotopes considered in this report are those of hydrogen, oxygen, and carbon.

The three relevant isotopes of hydrogen are hydrogen itself, which has a single neutron, deuterium, which has two neutrons, and tritium which has three neutrons. Tritium has a half-life of only 12.43 years (Clark and Fritz, 1997) and decays radioactively to helium. A half-life of a radioactive material is the time it takes for a given concentration of that material to decay to half its initial value. The other two isotopes of hydrogen are stable (do not decay radioactively).

The relevant isotopes of oxygen are oxygen-18 and oxygen-16. Both of these isotopes are stable (do not decay radioactively).

Stable-isotope ratios of hydrogen and oxygen are temperature dependent. Precipitation falling in areas with lower temperatures tend to have lower stable-isotope values (Fetter, 1988). The lightest (most negative) ratios correspond with cold temperatures and the heaviest (least negative) ratios correspond with warm temperatures. The significance of this temperature dependency is that the composition of precipitation is reflected in the isotopic composition of ground water (Mazor, 1991). These stable isotope ratios are therefore useful for tracing ground-water movement and recording the temperature of the water when it entered the ground as recharge. Tritium content is used to interpret the presence or absence of post-1950 water (Bradbury, 1991).

The relevant isotopes of carbon are carbon-14, carbon-13, and carbon-12. Carbon-14 has a half-life of 5,730 years (Mazor, 1991) and decays radioactively to nitrogen-14. The other two isotopes of carbon are stable. The radioactive isotope of carbon is useful in evaluating residence time of ground water (Mazor, 1991).

A major source of additional carbonate in an aquifer is solution of carbonate minerals. The method described by Mazor (1991) for applying delta carbon-13 to correct apparent radiocarbon ages was used to correct changes to the sampled water caused by interactions with carbonate rocks.

Mixing of waters can be suggested by seemingly incongruent isotope combinations, such as heavy stable-isotope ratios and old radiocarbon dates or by an incongruent mixture of radiocarbon dates and tritium data (Mazor, 1991). The absence of tritium, Late Wisconsin age radiocarbon ages, and small ratios of the stable isotopes would suggest the presence of connate waters in some glacial aquifers.

SAMPLING METHODS

The following description of sampling methods refers to work conducted in 2015 and 2016. Methods employed in previous isotope studies are described in other reports. Sixty–two samples were collected for this study from July 18, 2015, through November 2, 2016.

Sampling of rainfall was conducted in all seasons except winter so that precipitation condensing at a variety of temperatures could be sampled. Collection of rainfall samples was achieved by setting out an array of five gallon buckets during precipitation events. The water was then transferred into a 100-milliliter sample bottle. If necessary, contents of multiple buckets were combined to obtain a sufficient quantity of water for sampling. Rainfall samples were not filtered.

Samples of water from streams, lakes, and wetlands were obtained by dipping a 5-gallon bucket into the water, with one exception. A sample taken from Twin Lakes in Spink County (app. A) was collected through use of a Van Dorn sampler, which is a device specifically designed for collecting samples of water at the bottom of lakes or streams. The water collected from streams, lakes, and wetlands was then passed through a sampling barrel fitted with a 0.45-micron capsule filter. Water was gravity drained through this apparatus into a 1-liter polyethylene bottle.

All wells were sampled using a submersible pump except for wells TU-77H and R2-2007-45 which were sampled using a bailer and the Dennis Mutch well which was free-flowing. Water was tested during well purging for stabilization of pH, conductivity, and temperature. Samples for isotope analysis were not collected until these parameters had stabilized over three consecutive measurements and a minimum of three well volumes had been withdrawn from the well. Water collected using a submersible pump was passed through a 0.45-micron capsule filter connected directly to the pump apparatus. Water collected using a bailer and water from the Dennis Mutch well were collected directly from the well and then passed through a barrel filter fitted with a 0.45-micron capsule filter. All well samples were collected in 1-liter polyethylene bottles.

All sample bottles were filled leaving as little head space as possible to avoid exposure to air. To further avoid exposure to air, all sample bottles were placed in a zip-lock bag. Any necessary rinsing of sampling devices during sampling was done with the very water being sampled rather than deionized water because in the context of isotope sampling, deionized water is a potential contaminant. Samples were shipped to Isotech Laboratories Inc. of Champagne, Illinois, for analyses of stable-isotope ratios and tritium and to Beta Analytic of Miami, Florida, for radiocarbon testing.

SAMPLE LOCATIONS

The locations of wells completed in certain aquifers, for which a good understanding of subsurface hydrogeology existed due to recent investigations, dictated where ground-water samples were collected. The locations from which samples of ground water, surface water, and precipitation were collected in 2015 and 2016 are shown on figures 1, 2, and 3. More descriptive locations of those samples are provided in appendix A along with the locations of samples collected for previous investigations.

HYDROGEOLOGIC UNITS

Sioux Quartzite

The Precambrian-age Sioux Quartzite in Minnehaha County was described as a silica-cemented sand consisting “of predominantly orthoquartzite with minor comglomerate and mudstone layers. The orthoquartzite portion of the formation, typically pale red to moderate red in color, consists predominantly of pink-colored, fine grains of quartz sand cemented to a nonporous quartzite by silica ….. Scattered layers of claystone to silty mudstone are found within the Sioux Quartzite. These mudstone beds are commonly called pipestone or catlinite ….. ranges in color from a red to a dark purple, and is composed predominantly of sericite, quartz, and hematite ….. The Sioux Quartzite is broken into blocks by well-developed jointing, both vertical and horizontal. Spacing of the joints varies greatly in exposures from a few inches to several feet apart” (Tomhave, 1994). In Lincoln County, the quartzite was similarly described as “extremely well indurated pink to white, fine-grained to conglomeritic orthoquartzite with occasional beds of red to purple catlinite” (McCormick and Hammond, 2004).

The Sioux Quartzite underlies the entire area in which water samples from the quartzite were collected in Lincoln and Minnehaha Counties. The Sioux Quartzite is exposed at land surface in several areas in Minnehaha County near where water samples were collected (Well or well-owner name Q10, Q1, Q2a, Q6, and Q9 in app. A; pl. 2 in Tomhave, 1994). The quartzite is the first bedrock unit under the unconsolidated glacial-aged sediments at seven, possibly eight, of the nine sample locations in Minnehaha County (Well or well-owner name Q10, Q1, Q2a, Q4, Q5, Q6, Q7, and possibly Q9 in app. A; pl. 2 in Tomhave, 1994). At one sample site in Minnehaha County and at the only sample site in Lincoln County, the quartzite directly underlies sediments of Cretaceous age (Well or well-owner name G. Steever and Q8 in app. A; Tomhave, 1994; McCormick and Hammond, 2004).

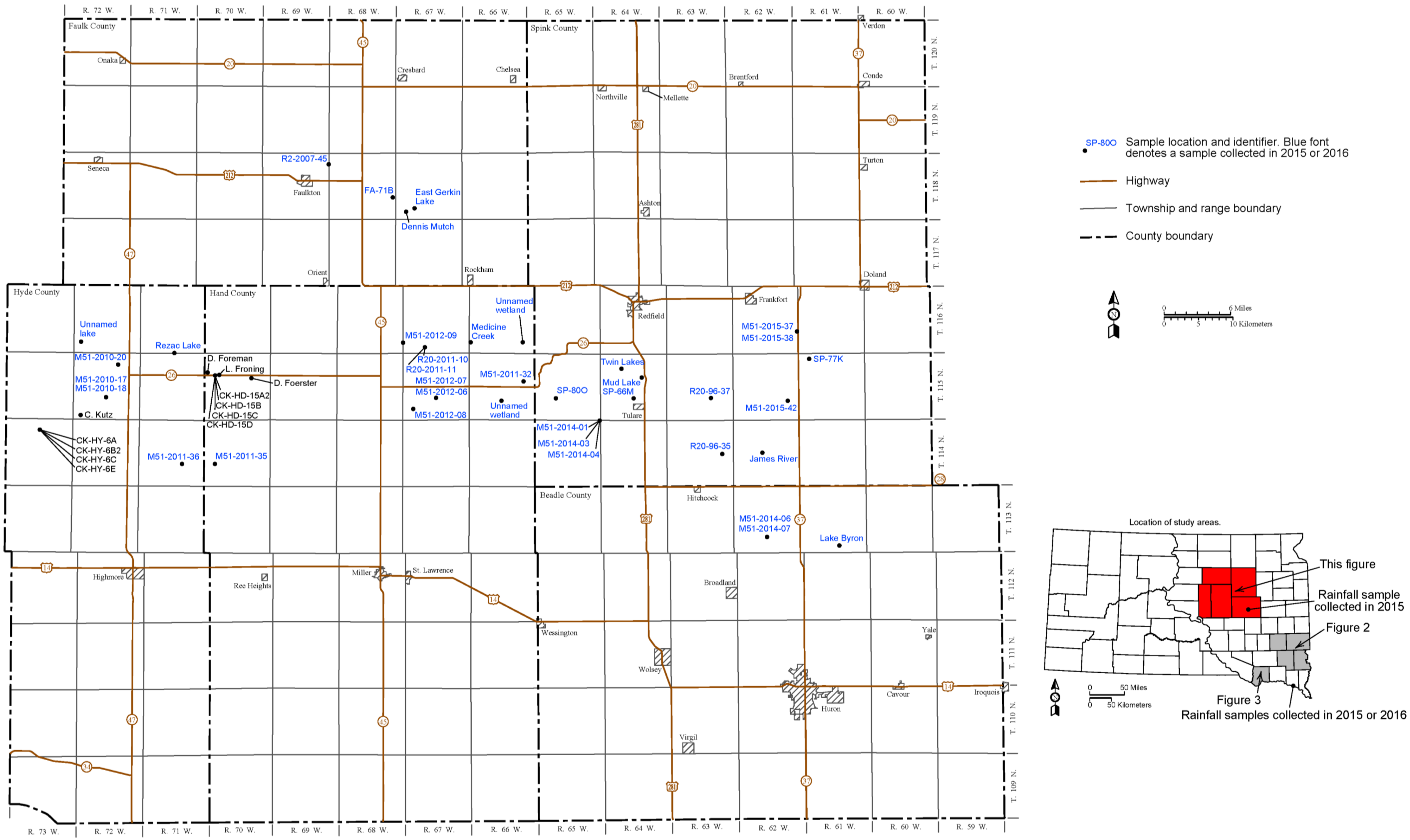

Figure 1. Sample locations in Faulk, Hyde, Hand, Spink, and Beadle Counties.

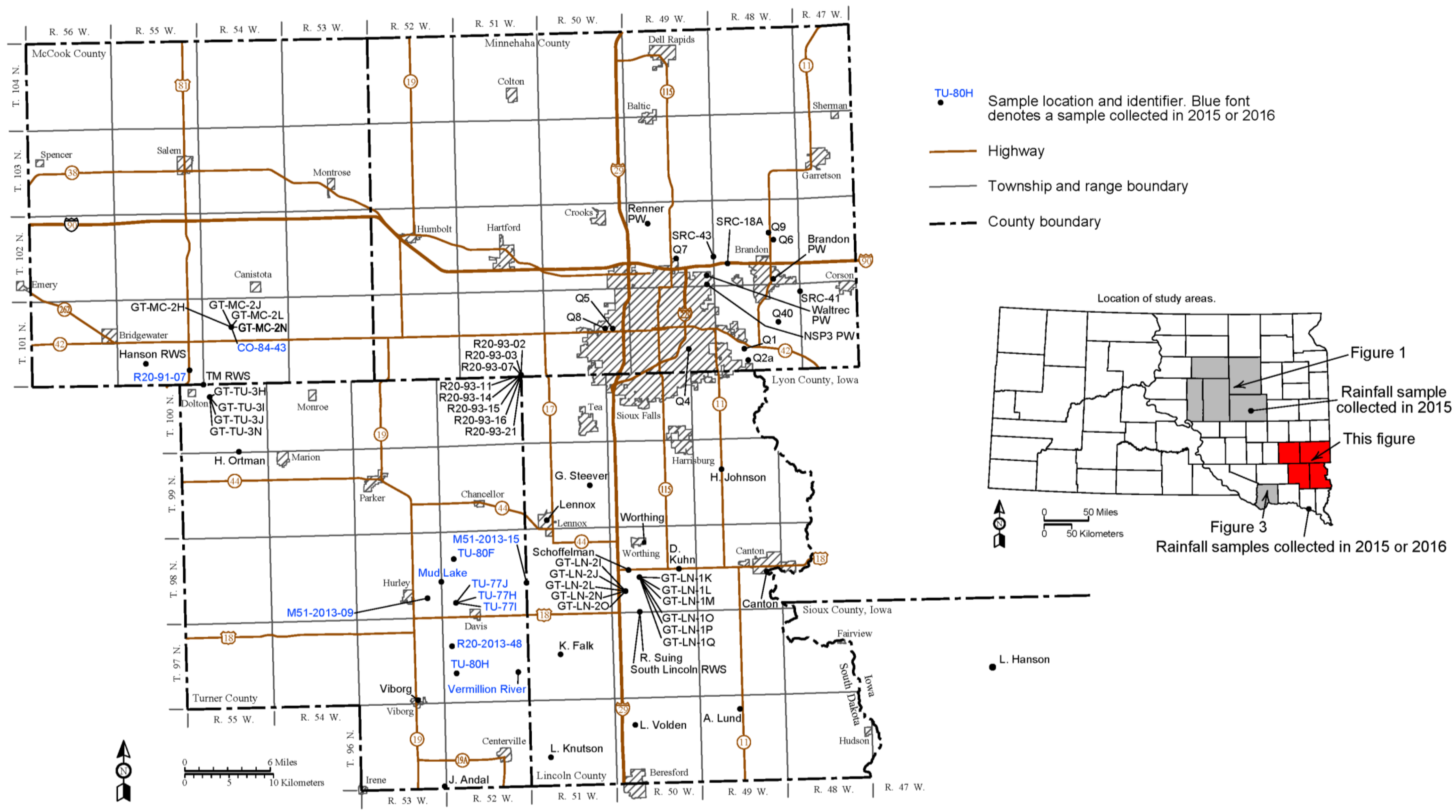

Figure 2. Sample locations in McCook, Minnehaha, Turner, and Lincoln Counties.

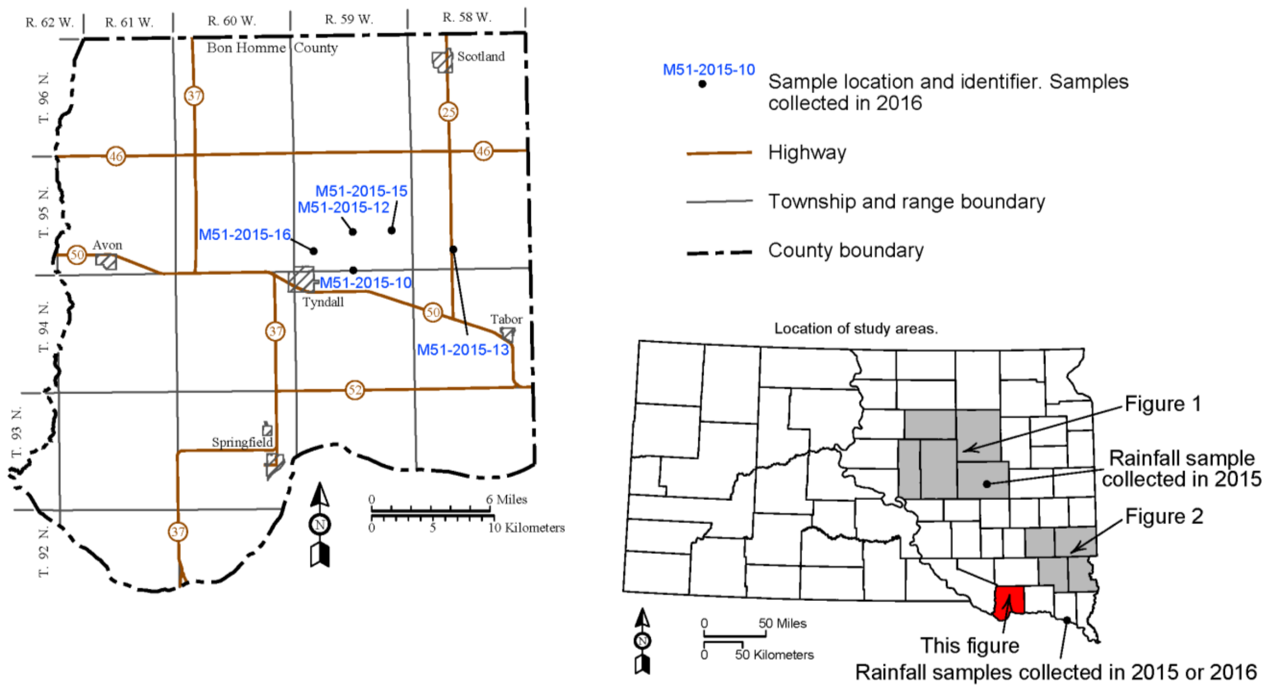

Figure 3. Sample locations in Bon Homme County.

Dakota Sandstone

The Cretaceous-age Dakota Sandstone, in the area of the water samples that were collected from this unit, is probably best described as "coarse to medium sandstones interbedded with massive gray to light gray mudstone intervals" (McCormick and Hammond, 2004). The commonly complex interfingering of sandstones with mudstone layers is due to the stream-dominated landscapes in which they were formed. The sandstones, especially in the lower portions of the Dakota Sandstone in the area which was sampled were deposited mainly in meandering, sluggish river channels. Mudstones were deposited as overbank flood deposits, oxbow fills, and other fine-grained alluvial fill (Witzke and Ludvigson, 1996).

The Dakota Sandstone is present in much of Lincoln County (see fig. 6 in McCormick and Hammond, 2004) and is laterally continuous eastward into Iowa and westward into parts of Turner County, South Dakota. Eight of the 10 samples collected from this unit were collected in Lincoln County and 1 sample each in Iowa and in Turner County.

Split Rock Creek Formation

The Cretaceous-age Split Rock Creek Formation has been described as attaining "a maximum thickness of nearly 100 meters, and consists of a sequence of sandy diamictites and quartz sandstones overlain by laminated organic claystones which grade upward into interbedded opaline sediments and massive cherts" (Ludvigson and others, 1981). The Split Rock Creek Formation "can be considered an age-equivalent to strata from the Dakota Formation upward through the Niobrara Formation" according to Kairo (1987). Tomhave (1994) suggested that the Pierre Shale may also be age equivalent to the Split Rock Creek Formation in Minnehaha County.

The Split Rock Creek Formation is a suite of embayment fill and other nearshore facies deposited along the irregular paleoshore of the Sioux Ridge (Ludvigson and others, 1981). The Split Rock Creek Formation lies directly on top of the Sioux Quartzite (Tomhave, 1994). The seven water samples collected from this hydrogeologic unit in 1988-1991 were collected from what Tomhave (1994) describes as the Brandon embayment.

Codell Sandstone Member of the Carlile Shale

The Cretaceous-age Codell Sandstone Member of the Carlile Shale in Bon Homme County is described as "a gray to green, fine to medium sandstone. It may be very tightly cemented or noncemented and is sometimes cross bedded" (Christensen, 1974). In the two wells that were sampled, the sand was described as hard and/or cemented.

Niobrara Formation

The Cretaceous-age Niobrara Formation is described in Spink County, where one of the two water samples was collected, as "light- to dark-gray, pyritic, calcarenite, chalk, and calcareous shale, with some bentonite" (Tomhave, 1997). A report from a county adjacent to where the other water sample from this unit was collected describes the Niobrara Formation as “medium-to dark-gray interbedded chalk, limestone, and calcareous shale, weathering to white and pale-yellow or tan” (McCormick and Hammond, 2004).

Although the Niobrara Formation exists as a contiguous unit over much of South Dakota, the water sample collected in Turner County is from a part of the Niobrara Formation that is an isolated erosional remnant that is not connected to the larger extent of the formation (Tomhave and Schulz, 2004; Holmes and Filipovic, 2015).

Buried Outwash

Outwash is material that has been transported and deposited by glacial meltwater. It is typically composed of sand to gravel sized clasts with minor amounts of silt and clay sized particles. Outwash in this category is classified as such because the top of the outwash body is some depth beneath ground level.

Most of the water samples from buried outwash were taken from formally named aquifers, but eighteen wells from which samples were collected are completed in unnamed buried outwash bodies occurring beneath Hand, Hyde, Lincoln, and Turner Counties. The depth to outwash from land surface ranges from 30 to 140 feet in 12 of these 18 wells and averaged 107 feet. Logs were not available for the other six wells but their reported well depths in feet are 70, 90, >110, 116, 117, and unknown.

The Vermillion-Missouri aquifer is a body of primarily buried outwash located mainly in Turner and Clay Counties. The eastern fringe of the aquifer lies in westernmost Lincoln County. This aquifer lies within a north-south trending bedrock valley (Holmes and Filipovic, 2015). In certain areas, the Vermillion-Missouri aquifer lies directly beneath the Parker-Centerville aquifer (Holmes and Filipovic, 2015), which is comprised of surficial outwash. Five water samples were collected from this aquifer. The depth to outwash from land surface ranges from 1 to 114 feet in the 5 sampled wells.

Deposits that comprise the Tulare aquifer were defined in Hamilton and Howells (1996) to “include not only surface and near-surface irregular sheets of outwash and other fluvio-glacial materials, but also older, more deeply buried valley-fill outwash and other permeable, hydraulically connected fill in the deep valleys in the bedrock surface.” This definition came from their report on Spink County, South Dakota, where 9 of the 11 water samples attributed to the Tulare aquifer were collected for isotopic analysis. Work performed in Hand and Hyde Counties by the Geological Survey Program subsequent to Hamilton and Howells (1996) shows that the Tulare aquifer does not exist as previously defined in those counties and that the extents of buried, connected outwash bodies are far less than defined in previous reports. Another lesson learned is that it is uncommon that there is significant vertical hydraulic interconnection of various outwash bodies contained in the sequence of glacial sediments, which is in contrast to the unsupported assumptions of Hamilton and Howells (1996). Thus, the definition of the deposits that comprise the Tulare aquifer put forth by Hamilton and Howells (1996) is inclusive of far too many of the outwash bodies known at the time of their report. The present understanding of the Tulare aquifer indicates that it is located in south-central and southwestern Spink County, northern Beadle County, and beneath about 20 square miles in northeastern Hand County. In this area, the location of the James River has been used as a boundary between different management units of the Tulare aquifer. West of the James River, the aquifer is discontinuous. The base of the outwash west of the James River is typically positioned well above the bedrock surface. East of the James River, the Tulare aquifer rests directly on the bedrock surface and appears from lithologic data to be laterally continuous. Future investigations may result in yet a different understanding of the Tulare aquifer. Eleven water samples were collected from wells attributed to this aquifer. The depth to outwash from land surface ranges from 1 to 107 feet in the 11 sampled wells.

The Tyndall management unit of the Choteau aquifer and Scotland management unit of the Lower-James-Missouri aquifers consist of buried outwash located beneath east central Bon Homme County. These two bodies of outwash may be connected to one another. The outwash comprising these aquifers is situated within an east trending valley on the bedrock surface. Two water samples were collected from the Choteau aquifer and one was collected from the Lower-James-Missouri aquifer. The depths to outwash from land surface in the two sampled wells in the Choteau aquifer are 167 and 186 feet. The depth to outwash from land surface in the well completed in the Lower-James-Missouri aquifer is 225 feet.

The Grand aquifer has been described as outwash in a basal position relative to the glacial sediments. That means that the outwash lies at or very near the base of the glacial sediments and on or very near the bedrock surface. Some fairly recent work by the Geological Survey Program has determined that this “aquifer” is actually comprised of multiple unconnected bodies of buried outwash that directly overlie the bedrock surface and is not a single, contiguous aquifer. The outwash body sampled for the current study is elongate in a west-northwesterly direction for about 20 miles in central and southeastern Faulk County. Three water samples were collected from this body of outwash. The depths to outwash from land surface in the three sampled wells are 70, 91, and 170 feet.

The Dolton aquifer is located in south-central McCook County and northwestern Turner County in the vicinity of the towns of Dolton and Canistota. It consists of buried outwash that is usually underlain by till but occasionally occurs as a basal outwash (Holly and others, 1993). Five water samples have been collected from this aquifer; three for a previous investigation and two for the recent work. The depths to outwash from land surface in 3 of the 5 sampled wells are 137,146, and 158 feet. Logs were not available for the other two wells but their reported well depths are 165 and 172 feet.

The Deep James aquifer consists of buried outwash located in bedrock valleys beneath northern Spink County (Hamilton and Howells, 1996). This outwash sits directly or, nearly on, the bedrock surface. Two water samples were collected from this aquifer. The depths to outwash from land surface in the two sampled wells were 142 and 174 feet.

The Bad-Cheyenne aquifer has been described as deeply buried outwash extending from northern Hyde County to southeastern Hand County. A re-evaluation of this outwash aquifer by the Geological Survey Program has determined this “aquifer” consists of unconnected outwash bodies that directly overlie the bedrock surface. Two of these bodies of outwash were sampled for this study. One of these bodies is located in north-central Hyde County, while the other is located along the county line between northern Hyde and Hand Counties. Three water samples were collected from these outwash bodies. The depths to outwash from land surface in the three sampled wells are 170, 186, 277 feet.

Surface Outwash

The Parker-Centerville aquifer is the only surface outwash that was sampled for isotopes. Its boundary closely aligns with the Vermillion River Valley in Turner County (Holmes and Filipovic, 2015). It usually occurs at land surface but at its northern extent it is overlain by some till. Two water samples were collected from this aquifer.

Till

Till is nonsorted, nonstratified sediment deposited by a glacier with minimal transport by water. It typically consists of particles from silt to boulder-size in a clay matrix (Tomhave, 1994).

Unweathered till is characterized by the lack of oxidation and fractures and by its gray color and low permeability. Weathered till generally overlies unweathered till and is characterized by oxidation, the presence of fractures, an orange to brown color due to the oxidation, and a higher permeability than unweathered till. Transition-zone till, as the name implies, is transitional in position and can exhibit physical character of both weathered and unweathered till.

STREAMS, LAKES, AND WETLANDS

The James River, Medicine Creek, and the Vermillion River, as well as seven lakes and two wetlands were sampled (figs. 1 and 2; app. A) where they occurred over or near outwash bodies that were also sampled for isotopes. These water bodies were sampled to allow a comparison of isotope values from flowing surface water, standing surface water, and ground water.

RESULTS AND DISCUSSION

Results show that water having a certain radiocarbon age cannot be assumed to have certain stable-isotope ratios. Figure 4 clearly illustrates this point. Thus, an assumption, for example, that glacial-age water should be expected to exhibit stable-isotope ratios indicative of a cold climate is unfounded. The hydrogeologic history of aquifers sampled for this study is often complex as reflected in the isotopic data.

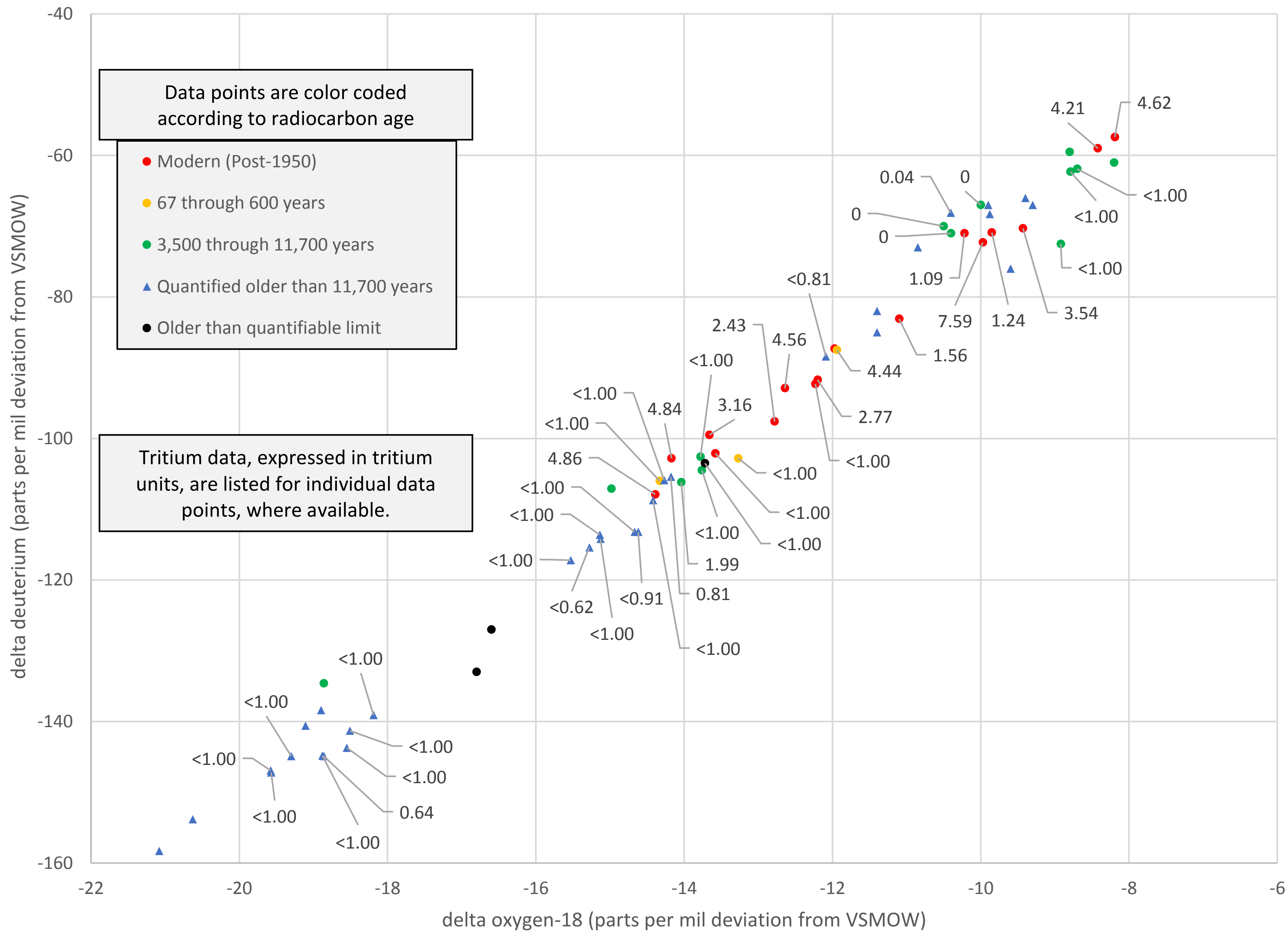

Figure 4. Isotope data from wells completed in aquifers.

Rainfall and Surface Water

A line of best fit to data from rainfall samples is referred to as the local meteoric water line and serves as a reference to the contemporary climate. This best-fit line (meteoric water line) appears on figures 5, 6, and 7. Data from rainfall and surface water are presented in appendix A and are summarized in table 1.

The data points representing samples collected from streams, lakes, and wetlands plot in distinctly different clusters than data points representing the samples collected from outwash and bedrock, indicating these surface water bodies are not well connected to the ground water (figs. 6 and 7).

Till

All three samples from weathered till that were radiocarbon dated had modern (post-1950) dates (app. A). Tritium was detected in all 15 of the samples collected from this source that were tested for this isotope. Some of the stable-isotope data from weathered till are generally similar to present rainfall, as shown on figure 5. The stable-isotope data, along with the presence of tritium and modern radiocarbon ages, indicate that the weathered till receives modern recharge.

The transition-zone till is difficult to characterize because only two wells completed in this unit were sampled (app. A). The radiocarbon dates of greater than 9,000 years before present combined with the relatively heavy stable-isotope ratios as shown on figure 5 and the very low tritium concentrations suggest some mixing of older and younger waters which is consistent with the heterogeneity of the material. The data indicate minimal modern recharge.

Results from wells completed in unweathered till are known to be problematic. The entry of young, shallow waters into the borehole during well construction is known to have made some water sampled in unweathered till appear younger and isotopically heavier than it really is. However, much of the results for stable isotopes shows that water from the unweathered till is isotopically lighter than meteoric water (fig. 5) and that the mean radiocarbon age determined from 19 samples was 12,300 years before present (table 2). All data for unweathered till are presented in appendix A. Additional work performed by Barari and others (1987), Davis and others (1997), and Iles and others (1996) indicate that unweathered till is very low in permeability. The collective body of data indicates that there is very minimal entry of modern water into unweathered till.

Surface Outwash

The two samples of water from surface outwash were collected from the Parker-Centerville aquifer (app. A). The modern radiocarbon dates, the tritium concentrations, and the relatively heavy ratios of stable isotopes as shown on figure 6 and in table 2 all indicate this surface outwash is recharged by modern, meteoric water.

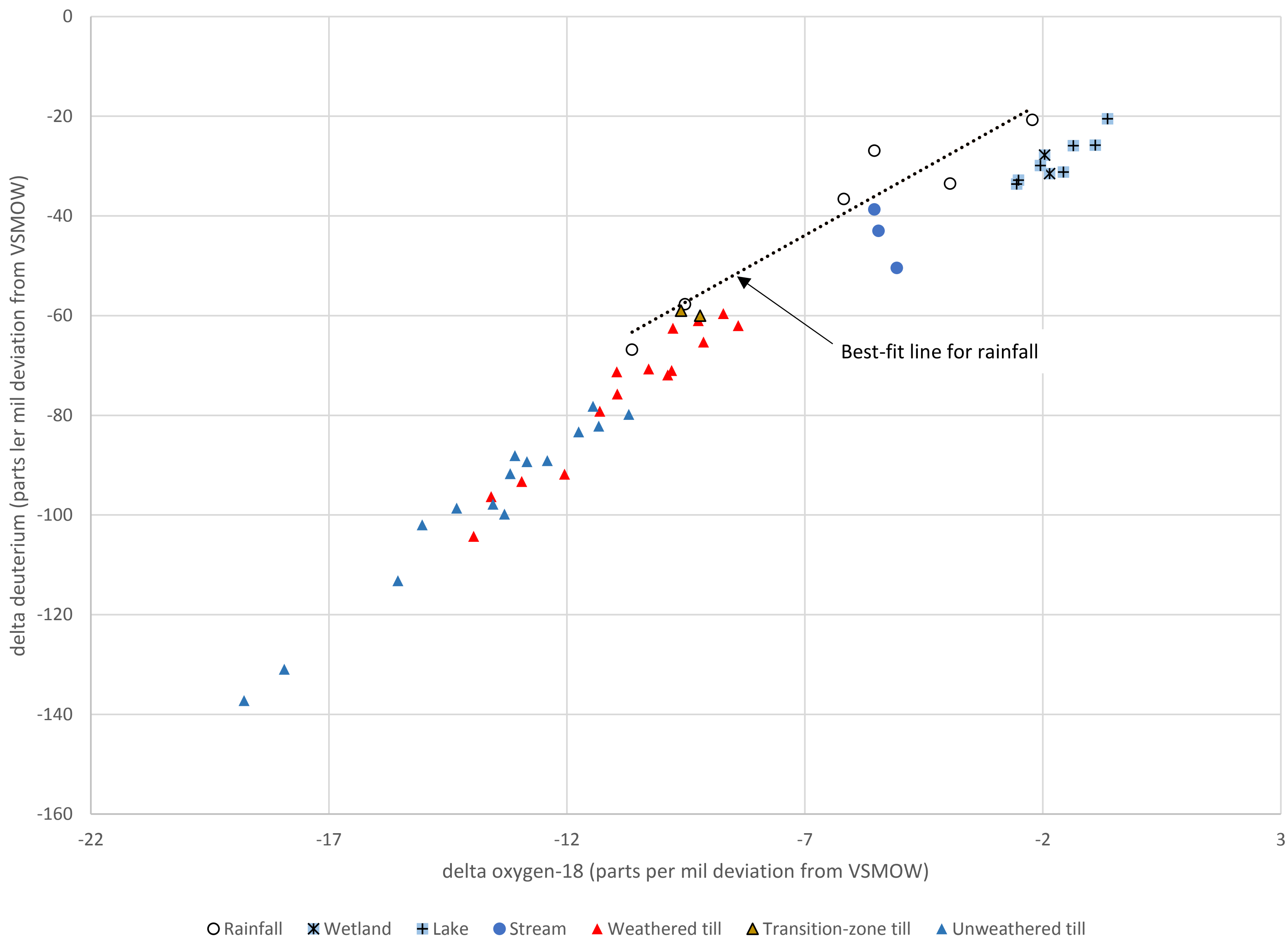

Figure 5. Delta deuterium versus delta oxygen-18 for samples collected from till, surface water, and rainfall.

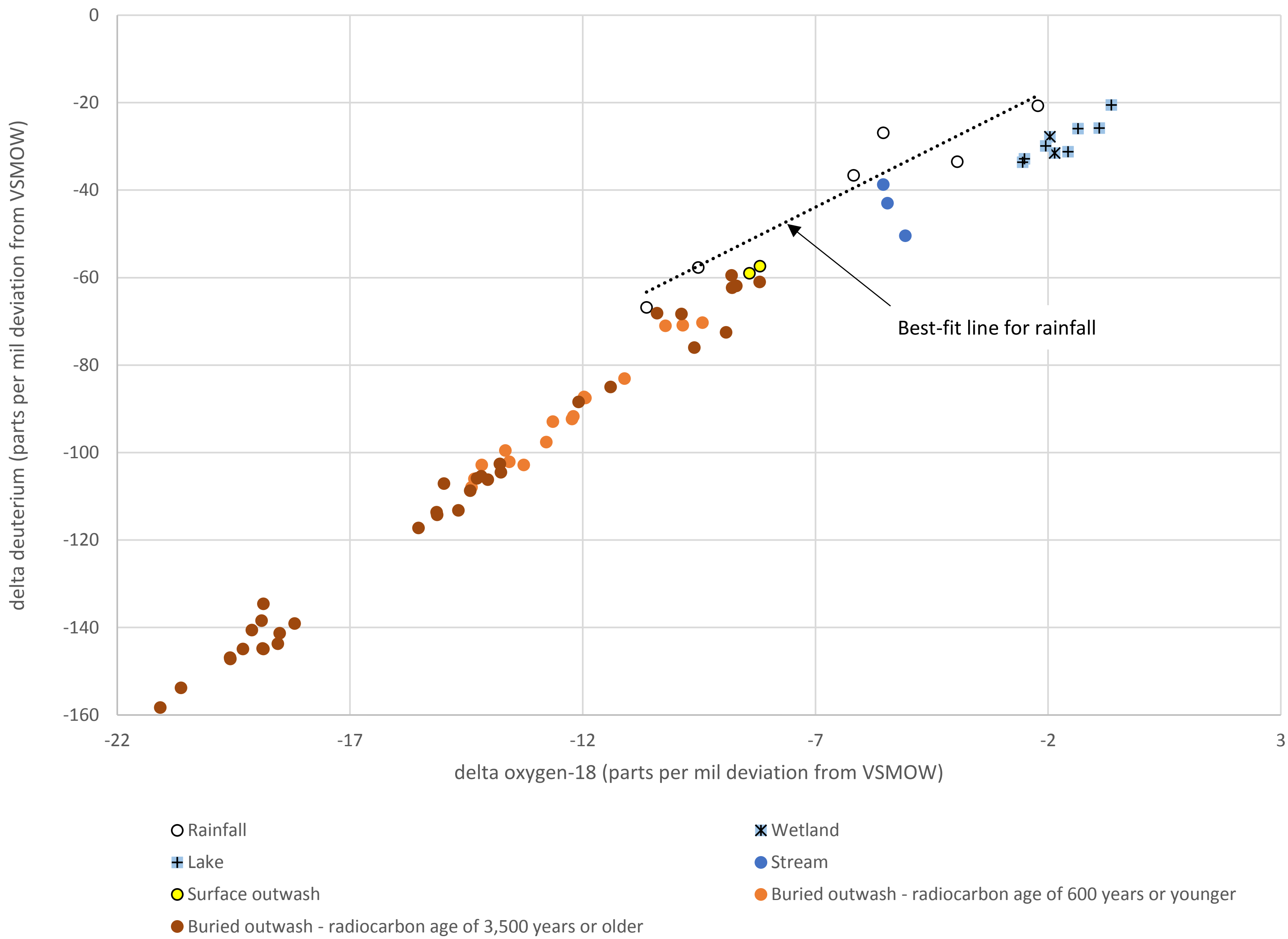

Figure 6. Delta deuterium versus delta oxygen-18 for samples collected from outwash, surface water, and rainfall.

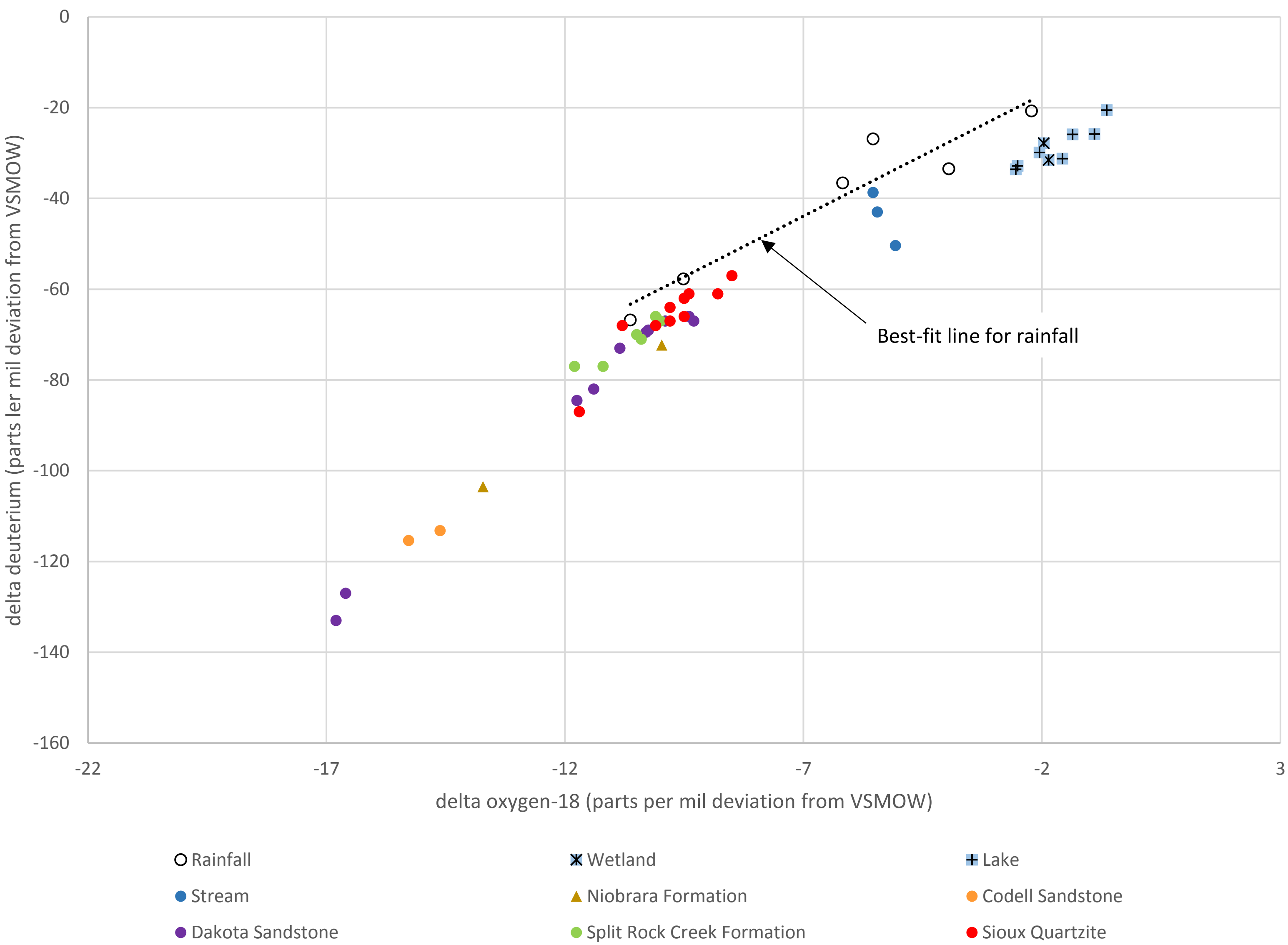

Figure 7. Delta deuterium versus delta oxygen-18 for samples collected from bedrock, surface water, and rainfall.

Table 1. Summary of isotope data by atmospheric and surface-water source

Surface water source and number of samples	Delta oxygen-18				Delta deuterium				Radiocarbon age				Tritium			
	Maximum	Minimum	Mean	Std. dev.	Maximum	Minimum	Mean	Std. dev.	Maximum	Minimum	Mean	Std. dev.	Maximum	Minimum	Mean	Std. dev.
Rainfall • Number of samples = 6	-2.22	-10.63	-6.34	3.22	-20.7	-66.8	-40.4	18.0	No data				No data			
Stream • Number of samples = 3	-5.07	-5.54	-5.35	0.249	-38.7	-50.4	-44.0	5.92	No data				No data			
Lake • Number of samples for delta oxygen-18 and delta deuterium = 7 • Number of samples for radiocarbon age and tritium = 1	-0.64	-2.55	-1.65	0.751	-20.5	-33.6	-28.5	4.69	Modern		---	---	8.58		---	---
Wetland • Number of samples = 2	-1.86	-1.96	-1.91	0.071	-27.8	-31.5	-29.7	2.61	No data				No data			

Table 2. Summary of isotope data by hydrogeologic source

Hydrogeologic source and number of samples	Delta oxygen-18				Delta deuterium				Radiocarbon age				Tritium			
	Maximum	Minimum	Mean	Std. dev.	Maximum	Minimum	Mean	Std. dev.	Maximum	Minimum	Mean	Std. dev.	Maximum	Minimum	Mean	Std. dev.
Weathered till • Number of samples for delta oxygen-18, delta deuterium, and tritium = 15 • Number of samples for radiocarbon age = 3	-8.4	-13.96	-11	0.163	-59.6	-104.3	-76	14	Modern				118	0.57	37	34
Transition-zone till • Number of wells sampled = 2	-9.2	-9.6	-9.4	0.28	-59	-60	-60	0.71	12,082	9,299	10,690	1968	0.62	0.58	0.60	0.03
Unweathered till • Number of samples for delta oxygen-18, delta deuterium, and radiocarbon age = 19 • Number of samples for tritium = 21 ○ 20 samples with numeric results ○ 1 sample with a "less than" value (less than lab detection limit) ▪ Numeric information shown assumes a concentration of half of the lab detection limit for this sample	-9.5	-18.78	-13	2.5	-63	-137.2	-91	20	22,410	503	12,300	6180	17.3	-0.6	3	5
Surface outwash • Number of samples = 2	-8.19	-8.42	-8.31	0.163	-57.4	-59.0	-58.2	1.13	Modern				4.62	4.21	4.42	0.300
Buried outwash with a radiocarbon age of 600 years or younger • Number of samples for delta oxygen-18 and delta deuterium = 16 • Number of samples for radiocarbon age = 16 ○ 3 samples with numeric results ○ 13 samples with a modern radiocarbon age • Number of samples for Tritium = 15 ○ 11 samples with numeric results ○ 4 samples with "less than" values (less than lab detection limit)	-9.43	-14.4	-12.4	1.57	-70.3	-108	-91.6	12.5	600	Modern			4.86	<1.00	---	---
Buried outwash with a radiocarbon age of 3,500 years or older • Number of samples for delta oxygen-18, delta deuterium, and radiocarbon age = 34 • Number of samples for tritium = 23 ○ 4 samples with numeric results ○ 19 samples with "less than" values (less than lab detection limit)	-8.2	-21	-15	4.1	-60	-160	-110	32	35,000	3,500	16,000	9,000	1.99	<0.81	---	---
Niobrara Formation • Number of samples = 2	-9.97	-13.72	-11.8	2.65	-72.3	-103.5	-87.9	22.1	>43,500	Modern	---	---	7.59	<1.00	---	---
Codell Sandstone Member of the Carlile Shale • Number of samples = 2	-14.62	-15.28	-14.95	0.467	-113.2	-115.4	-114.3	1.556	23,500	23,000	23,000	350	<0.91	<0.62	---	---
Split Rock Creek Formation • Number of samples for delta oxygen-18 and delta deuterium = 6 • Number of samples for radiocarbon age = 4 • Number of samples for tritium = 5	-10	--12	-11	0.70	-66	-77	-71	4.8	10,600	3,400	7,500	3100	0	0	---	---
Dakota Sandstone • Number of samples for delta oxygen-18 and delta deuterium = 10 • Number of samples for radiocarbon age = 7 ○ 5 samples with numeric results ○ 2 samples with water too old to date using carbon-14 (i.e., >34,700 and >37,000)	-9.3	-16.8	-12	2.8	-66	-133	-84	25	38,200	27,130	---	---	No data			
Sioux Quartzite • Number of samples for delta oxygen-18 and delta deuterium = 10 • Number of samples for radiocarbon age = 1	-8.5	-11.7	-9.8	0.93	-57	-173	-75	8.2	23,370				No data			

Buried Outwash with Water having a Radiocarbon Age of 600 Years or Younger

Results of the analyses of samples of water in buried outwash can be separated into two categories. One category is water from buried outwash with radiocarbon ages of 600 years before present or younger (table 2). With two exceptions, these radiocarbon ages are much younger than those of water from unweathered till (app. A), which commonly overlies and underlies these outwash bodies. The two exceptions are radiocarbon dates of 503 and 732 years before present determined using water from unweathered till (app. A). However, these dates may not actually be representative of water in unweathered till as explained in the description of results from unweathered till. Outwash sources yielding radiocarbon dates in the category of "600 years or younger" include the Vermillion-Missouri aquifer, unnamed outwash in northern Hyde County, unnamed outwash in northeastern Hand County, and the Tulare aquifer.

The isotopically heaviest water (least negative stable-isotope ratios) in this category of buried outwash, represented by three data points on figure 6, was sampled from the Vermillion-Missouri aquifer (app. A, wells TU-77H, TU-77I, & M51-2013-09). The stable-isotope ratios of these three samples indicates a strong influence by modern meteoric water. The remainder of the samples collected from this category of buried outwash exhibit water that is isotopically lighter than the three data points just mentioned (fig. 6). This suggests less influence by modern meteoric water in these remaining samples even though all of the samples from this category have radiocarbon ages of "modern" or 400-600 years (app. A). Tritium was detected in 11 of the 15 water samples collected from this category of buried outwash and analyzed for tritium.

Buried outwash containing water with radiocarbon ages 600 years before present or younger is dominated by recharge occurring since the outwash was deposited. This is consistent with the conclusion of Holmes and Filipovic (2015) that a portion of the Vermillion-Missouri aquifer, a buried outwash, is being recharged by the Parker-Centerville aquifer, a surface outwash, in the vicinity of the three wells mentioned in the previous paragraph.

Buried Outwash with Water having a Radiocarbon Age of 3,500 Years or Older

Another category of water from buried outwash is water with radiocarbon dates of 3,500 years before present or older (table 2). Ten of the 34 samples in this category for which radiocarbon ages were determined had ages less than 11,700 years before present (app. A), the commonly accepted boundary between glacial times and post-glacial times. The other 24 samples for which radiocarbon ages were determined were glacial aged (12,000-35,000 years, app. A). Water in this category of buried outwash is older than water from surface outwash and weathered till (table 2). Nineteen of the 23 water samples analyzed for tritium from this source were untritiated, 3 samples exhibited 0.81 tritium units or less, and 1 sample had 1.99 tritium units (app. A). The range in stable-isotope ratios for this category of buried outwash (fig. 6) is greater than the range for any other source of water sampled for this investigation, indicating a varied history of recharge since deposition of the outwash.

If the data for water in buried outwash having a radiocarbon date of 3,500 years or older are sorted on the parameter of delta deuterium, then five groupings of data become evident (table 3, fig. 8). The two groupings having the heaviest (least negative) stable-isotope ratios exhibit a strong influence by modern meteoric water. The grouping in the lower left-hand corner of figure 8, and at the bottom of table 3, exhibits the lightest (most negative) stable-isotope ratios, including delta oxygen-18 values of less than -17 parts per mil deviation from VSMOW. This grouping on figure 8 and at the bottom of table 3 probably represents connate, or dominantly connate, water that fell as precipitation in a climate significantly colder than the present climate. Glacial meltwaters studied in the upper Midwest, with which minimal mixing with more modern waters has occurred, have delta oxygen-18 values of less than -17 parts per mil deviation from VSMOW (Siegel and Mandle, 1984). The delta oxygen-18 values of the Laurentide ice sheet have been estimated to be as high as -15 to as low as -38 parts per mil deviation from VSMOW (Ferguson and Jasechko, 2015). This grouping of data points has radiocarbon ages that range from 11,532 through 35,000 years before present and reflect water from the Bad-Cheyenne, Dolton, Grand, and Lower-James-Missouri aquifers and an unnamed outwash (app. A).

Since water that is both pre-modern and isotopically heavy may be meteoric, distinguishing pre-modern meteoric water from mixtures of waters of different ages on the basis of radiocarbon dates and stable-isotope data is problematic. As stated previously, mixing of waters of different origin can be indicated by an incongruent mixture of radiocarbon dates and tritium data (Mazor, 1991). Twenty-three samples of water from the category of “buried outwash with a radiocarbon age of 3,500 years or older” were analyzed for both radiocarbon age and tritium (app. A). Of these 23 samples, only 4 had a detection of tritium (0.04, 0.64, 0.81, and 1.99 tritium units; app. A). Data from this category of buried outwash indicate only very minimal mixing of modern and pre-modern waters.

Simplicity and certainty are seldom an aspect of isotopic data such as examined in this report. For example, table 3 shows that the water that is isotopically the lightest does not always have the oldest radiocarbon ages. The lack of a close correspondence between stable isotope values and radiocarbon ages may also reflect sources of uncertainty in the radiocarbon method. Unknown mixing events of waters of different origin and age have likely resulted in many of the seemingly discordant combinations of stable-isotope ratios and radiocarbon ages. The data do, however, indicate that modern recharge to buried outwash has been negligible in most of the water sampled from this category of buried outwash.

Niobrara Formation

Only two water samples were collected from the Cretaceous-age Niobrara Formation. The hydrogeologic settings represented by these two samples are very different from one another. A sample collected in Spink County was collected from a portion of the Niobrara Formation that is regionally contiguous with a large area of the Niobrara Formation. This water sample proved to be too old to be dated using the radiocarbon method and was also untritiated (table 2, app. A). In addition, it was very light isotopically, as shown on figure 7. These data indicate that the water from which this sample was collected has not been significantly influenced by modern recharge.

Table 3. Isotope data from water in buried outwash having a radiocarbon age of 3,500 years before present or older, sorted on delta-deuterium values

Aquifer	Aquifer management unit	Location					Well or well-owner name	Depth to top of outwash in feet[1]	Well depth in feet below land surface	Date sampled	delta oxygen-18 ‰	delta deuterium ‰	Radiocarbon age in years before present	Tritium units
		County	Quarter section	Section	Township	Range								
---	---	Lincoln	SW¼ SW¼ SW¼ SW¼	33	98 N	50 W	R. Suing	---	70	7/26/1984	-8.8	-59.5	7,269	---
---	---	Lincoln	SW¼ SE¼ SE¼ SW¼	8	96 N	50 W	L. Volden	140	157	10/28/1983	-8.2	-61	10,630	---
Vermillion-Missouri aquifer	---	Lincoln	SW¼, SW¼, NW¼, SW¼	19	98 N	51 W	M51-2013-15	67	79	9/19/2016	-8.70	-61.9	5,500	<1.00
Vermillion-Missouri aquifer	---	Turner	SW¼, SW¼, SW¼, SW¼	20	97 N	52 W	TU-80H	108	228.4	8/25/2015	-8.79	-62.3	4,000	<1.00
---	---	Lincoln	NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	Sweeter	---	>110	7/15/1986	-10.405	-68.1	12,602	0.04
---	---	Lincoln	NE¼ NE¼ NW¼ NW¼	20	98 N	50 W	Schoffelman	---	90	7/25/1984	-9.88	-68.3	13,543	---
Tulare aquifer	Hitchcock	Beadle	SW¼, NW¼, NW¼, SW¼	27	113 N	62 W	M51-2014-06	27	59.5	4/4/2016	-8.92	-72.5	8,000	<1.00
---	---	Turner	SE¼ SW¼ NW¼ SW¼	35	97 N	53 W	Viborg	---	117	10/21/1983	-9.6	-76	15,260	---
---	---	Lincoln	NW¼ SE¼ SW¼ NE¼	32	99 N	51 W	Lennox	---	?	11/3/1983	-11.4	-85	21,300	---
Choteau aquifer	Tyndall	Bon Homme	SW¼, SW¼, SW¼, SW¼	29	95 N	59 W	M51-2015-16	136, 186	202.5	10/24/2016	-12.09	-88.4	13,500	<0.81
---	---	Hand	SE¼, SE¼, SE¼, SE¼	30	115 N	67 W	M51-2012-08	108	123.4	5/10/2016	-13.78	-102.6	5,000	<1.00
Deep James aquifer	---	Spink	NW¼, NE¼, NE¼, NE¼	1	114 N	65 W	M51-2014-04	76, 110, 142	167.3	4/6/2016	-13.76	-104.5	7,000	<1.00
Choteau aquifer	Tyndall	Bon Homme	NW¼, NW¼, NW¼, NW¼	27	95 N	59 W	M51-2015-12	167	227	10/24/2016	-14.18	-105.4	22,000	0.81
Dolton aquifer	---	McCook	NE¼, NE¼, NE¼, NE¼	17	101 N	54 W	CO-84-43	158	165	9/2/2015	-14.27	-105.9	17,500	<1.00
---	---	Hand	NW¼, NW¼, NW¼, NW¼	27	115 N	67 W	M51-2012-07	38	55	4/12/2016	-14.04	-106.2	3,500	1.99
---	---	Hand	SE¼ NE¼ NW¼ NW¼	14	115 N	70 W	D. Foerster	78	90	8/8/1984	-14.98	-107.1	4,892	---
---	---	Hand	NW¼, NW¼, NW¼, NW¼	27	115 N	67 W	M51-2012-06	96	109.6	4/12/2016	-14.42	-108.7	12,000	<1.00
Tulare aquifer	Western Spink	Hand	NE¼, NE¼, NE¼, SE¼	14	115 N	66 W	M51-2011-32	23, 69	97	4/12/2016	-14.67	-113.2	13,000	<1.00
Tulare aquifer	Western Spink	Spink	NE¼, NE¼, NE¼, NE¼	29	115 N	65 W	SP-80O	61	122.5	5/10/2016	-15.14	-113.6	13,000	<1.00
Deep James aquifer	---	Beadle	SW¼, NW¼, NW¼, SW¼	27	113 N	62 W	M51-2014-07	174	185.7	4/4/2016	-15.13	-114.2	29,000	<1.00
---	---	Hand	NW¼, NW¼, NW¼, NW¼	31	116 N	67 W	M51-2012-09	139	156	5/10/2016	-15.53	-117.2	22,000	<1.00
---	---	Hand	SW¼ SE¼ SE¼ SW¼	8	115 N	70 W	L. Froning	---	116	8/8/1984	-18.86	-134.6	11,532	---
---	---	Hand	SE¼ NE¼ SW¼ SW¼	7	115 N	70 W	D. Foreman	80	105	8/7/1984	-18.9	-138.4	26,503	---
Bad-Cheyenne aquifer	---	Hyde	SE¼, SE¼, SE¼, SE¼	21	115 N	72 W	M51-2010-17	277	299.4	4/5/2016	-18.19	-139.1	29,000	<1.00
Dolton aquifer	---	McCook	SE¼ SE¼ SE¼ NE¼	29	101 N	55 W	Hanson RWS	137	180	7/31/1984	-19.11	-140.6	13,526	---
Grand aquifer	---	Faulk	NE¼, NE¼, NE¼, NE¼	12	118 N	69 W	R2-2007-45	170	183	5/18/2016	-18.51	-141.3	27,000	<1.00
Bad-Cheyenne aquifer	---	Hyde	SW¼, SW¼, SW¼, SW¼	23	114 N	71 W	M51-2011-36	170	230	4/5/2016	-18.55	-143.7	29,000	<1.00
Bad-Cheyenne aquifer	---	Hand	SW¼, SW¼, SW¼, SW¼	20	114 N	70 W	M51-2011-35	186	204	4/5/2016	-18.88	-144.8	29,000	<1.00
Dolton aquifer	---	McCook	SW¼, SW¼, SW¼, SW¼	25	101 N	55 W	R20-91-07	146	182.73	9/2/2015	-19.30	-144.9	16,000	<1.00
Lower-James-Missouri aquifer	Scotland	Bon Homme	NE¼, NW¼, NW¼, NW¼	33	95 N	58 W	M51-2015-13	225	246	10/26/2016	-18.86	-144.9	15,000	0.64
Grand aquifer	---	Faulk	NE¼, NE¼, SE¼, NE¼	31	118 N	67 W	Dennis Mutch	70	100	7/28/2015	-19.58	-146.9	35,000	<1.00
Grand aquifer	---	Faulk	SE¼, SE¼, SW¼, SE¼	24	118 N	68 W	FA-71B	91	149.2	5/11/2016	-19.57	-147.2	35,000	<1.00
Dolton aquifer	---	Turner	SE¼ SE¼ SE¼ SE¼	34	100 N	55 W	H. Ortman	---	165	8/1/1984	-20.63	-153.8	16,126	---
Dolton aquifer	---	Turner	NW¼ NE¼ NW¼ NE¼	8	100 N	55 W	TM RWS	---	172	8/2/1984	-21.08	-158.3	14,778	---

[1] Depth is presented in feet below land surface.
See figure 8 for a graphical representation of data for delta deuterium and delta oxygen-18.

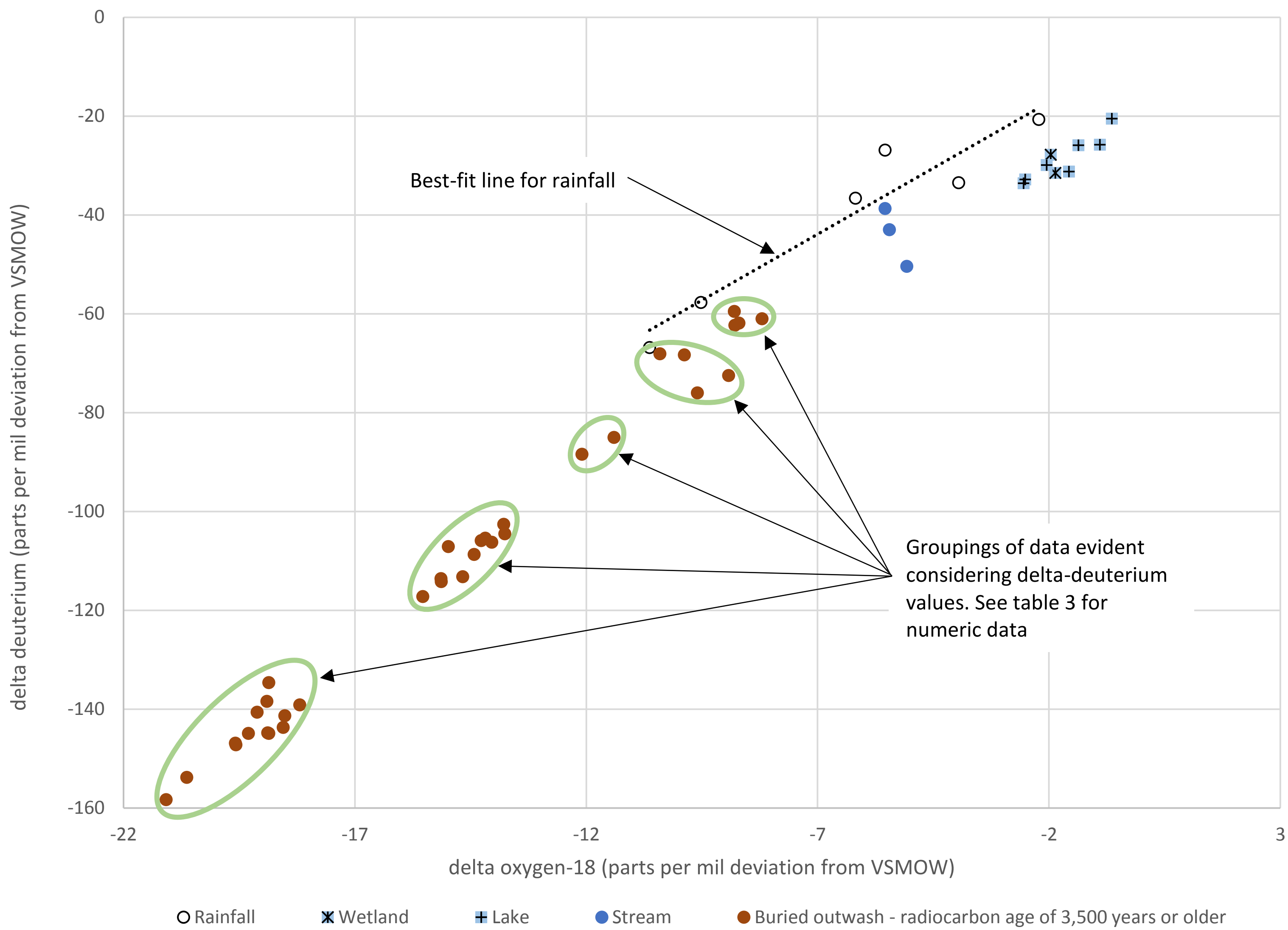

Figure 8. Delta deuterium versus delta oxygen-18 for samples collected from outwash having water with a radiocarbon age of 3,500 years or older, surface water, and rainfall.

The other sample was collected from an isolated erosional remnant of Niobrara Formation in Turner County. This sample had a modern radiocarbon age, was tritiated, and was much heavier isotopically than the other sample from the Niobrara Formation in Spink County (fig. 7, app. A). The isotope data from the sample collected in Turner County indicates that the Niobrara Formation is being recharged by modern water in the area from which the sample was collected.

Codell Sandstone Member of the Carlile Shale

Only two samples were collected from the Cretaceous-age Codell Sandstone. Water sampled from the Codell Sandstone exhibited glacial-age radiocarbon ages and was untritiated (table 2, app. A). The stable-isotope ratios of water collected from the Codell Sandstone were among the lightest ratios found in samples collected from bedrock sources (fig. 7). These data indicate that there has been recharge to the Codell Sandstone since its time of deposition but the recharge does not exhibit characteristics of modern recharge.

Split Rock Creek Formation

The Split Rock Creek Formation is of Cretaceous age. However, the four samples of water collected from this bedrock sandstone had post-glacial radiocarbon ages (younger than 11,700 years before present) but were untritiated (table 2, app A). The stable-isotope ratios of samples drawn from this source were relatively heavy (fig. 7). These data imply recharge to the Split Rock Creek Formation, but that any modern recharge occurring is minimal.

Dakota Sandstone

The Dakota Sandstone is of Cretaceous age. Radiocarbon ages determined for samples collected from the Dakota Sandstone were older than those collected from the Codell Sandstone and Split Rock Creek Formation (table 2, app. A). Stable-isotope ratios from two of the samples collected from the Dakota Sandstone were much lighter than the stable-isotope ratios of the other eight samples collected from this source (fig. 7, app. A). The two samples with the lighter (more negative) stable-isotope ratios were the only samples analyzed for radiocarbon age from this source that were too old to be dated using this method. The other five samples from this source with radiocarbon ages exhibited ages that were glacial in age (app. A). All of the samples from the Dakota Sandstone were collected from an area in Lincoln County, South Dakota, or immediately adjacent to that area. The possibility of glacial-age recharge to this small part of the Dakota Sandstone was postulated in Iles (1984). These data indicate that there has been recharge to the Dakota Formation since its deposition but the recharge history has been varied in the area sampled and does not exhibit all of the characteristics of modern recharge.

Sioux Quartzite

The Sioux Quartzite is Precambrian in age. The one sample of water collected from the Sioux Quartzite that was analyzed for radiocarbon age was determined to be glacial aged (23,370 years before present). This single sample from which a radiocarbon age determination was made was somewhat lighter with regard to stable-isotope ratios than the nine other samples collected from this source (fig. 7, app. A), which exhibit some of the isotopically heaviest water from bedrock sources that were sampled (fig. 7). The stable-isotope ratios of the nine samples for which radiocarbon ages are not available (app. A) plot very near the local meteoric water line (fig. 7). There has been recharge to the Sioux Quartzite since its time of deposition but more radiocarbon and tritium data would be useful to determine the extent to which it is receiving modern recharge.

SUMMARY AND CONCLUSIONS

A program of sampling rainfall, lakes, wetlands, streams, glacial outwash, and bedrock aquifers for isotopes of hydrogen, oxygen, and carbon was undertaken in 2015 and 2016. The four isotope parameters determined from these analyses were delta oxygen-18, delta deuterium, radiocarbon age, and tritium content. The delta oxygen-18 and delta deuterium are useful as tracers of ground water movement due to their stability. Radiocarbon and tritium are useful in determining residence time in water because they decay radioactively. Data gathered in 2015 and 2016 were combined, and collectively analyzed with similar isotopic data collected by the Geological Survey Program in earlier studies.

Atmospheric precipitation from different times during the year was sampled and analyzed for the stable-isotope ratios. Results of this sampling allowed the determination of a local meteoric water line for eastern South Dakota which could be used to compare with stable-isotope results determined for various sources of surface-water and ground-water. All of the data points representing stable-isotope ratios determined for surface-water and ground-water samples plotted below the meteoric water line. Data points representing stable-isotope ratios from ground water plotting below the meteoric water line were explained by Fritz and others (1979) as reflecting evaporative fractionation of rainwater prior to infiltration into the ground or the presence of old waters that originated in a different climate regime.

Water that was thought, on the basis of geologic and hydrologic criteria, to be connate or dominantly connate glacial water was sampled and analyzed. Ground-water sources that were suspected of containing connate water were the Dolton, Bad-Cheyenne, and Grand aquifers. Results show that four of the five samples from the Dolton aquifer had stable-isotope ratios characteristic of connate glacial water. All five samples from the Dolton aquifer had radiocarbon ages ranging from 13,526 to 17,500 years before present (table 3, app. A). In addition, water sampled from the Lower-James-Missouri aquifer in Bon Homme County and unnamed buried outwash in northwestern Hand County exhibited characteristics of connate water.

Ground water for which the amount of mixing of meteoric and connate water was more uncertain was sampled and analyzed. This water came from unnamed buried outwash in Hand, Hyde, Lincoln, and Turner Counties (table 4, app. A). An examination of the stable-isotope,

Table 4. Isotope data from water collected from unnamed buried outwash, sorted on delta-deuterium values

Location					Well or well-owner name	Depth to top of outwash in feet[1]	Well depth in feet[1]	Date sampled	delta oxygen-18 ‰	delta deuterium ‰	Radiocarbon age in years before present	Tritium units
County	Quarter section	Section	Township	Range								
Hand	SE¼ NE¼ SW¼ SW¼	7	115 N	70 W	D. Foreman	80	140	8/7/1984	-18.9	-138.4	26,503	---
Hand	SW¼ SE¼ SE¼ SW¼	8	115 N	70 W	L. Froning	---	116	8/8/1984	-18.86	-134.6	11,532	---
Hand	NW¼, NW¼, NW¼, NW¼	31	116 N	67 W	M51-2012-09	139	156	5/10/2016	-15.53	-117.2	22,000	<1.00
Hand	NW¼, NW¼, NW¼, NW¼	27	115 N	67 W	M51-2012-06	96	109.6	4/12/2016	-14.42	-108.7	12,000	<1.00
Hand	SE¼ NE¼ NW¼ NW¼	14	115 N	70 W	D. Foerster	78	95	8/8/1984	-14.98	-107.1	4,892	---
Hand	NW¼, NW¼, NW¼, NW¼	27	115 N	67 W	M51-2012-07	38	55	4/12/2016	-14.04	-106.2	3,500	1.99
Hyde	SE¼, SE¼, SE¼, SE¼	21	115 N	72 W	M51-2010-18	130	154	4/5/2016	-13.27	-102.8	600	<1.00
Hand	SE¼, SE¼, SE¼, SE¼	30	115 N	67 W	M51-2012-08	108	123.4	5/10/2016	-13.78	-102.6	5,000	<1.00
Hyde	SW¼, NW¼, NW¼, NW¼	11	115 N	72 W	M51-2010-20	117	151	4/5 & 5/17/2016	-12.78	-97.6	Modern	2.43
Hand	SW¼, SW¼, SW¼, NW¼	33	116 N	67 W	R20-2011-11	85	93	5/10/2016	-12.23	-92.3	Modern	<1.00
Hand	SW¼, SW¼, SW¼, NW¼	33	116 N	67 W	R20-2011-10	30	40.4	5/10/2016	-12.20	-91.7	Modern	2.77
Hyde	NE¼ SE¼ NW¼ SE¼	31	115 N	72 W	C. Kutz	130	156	8/14/1984	-11.97	-87.3	Modern	---
Lincoln	NW¼ SE¼ SW¼ NE¼	32	99 N	51 W	Lennox	---	?	11/3/1983	-11.4	-85	21,300	---
Turner	SE¼ SW¼ NW¼ SW¼	35	97 N	53 W	Viborg	---	117	10/21/1983	-9.6	-76	15,260	---
Lincoln	NE¼ NE¼ NW¼ NW¼	20	98 N	50 W	Schoffelman	---	90	7/25/1984	-9.88	-68.3	13,543	---
Lincoln	NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	Sweeter	---	>110	7/15/1986	-10.405	-68.1	12,602	0.04
Lincoln	SW¼ SE¼ SE¼ SW¼	8	96 N	50 W	L. Volden	140	157	10/28/1983	-8.2	-61	10,630	---
Lincoln	SW¼ SW¼ SW¼ SW¼	33	98 N	50 W	R. Suing	---	70	7/26/1984	-8.8	-59.5	7,269	---

[1] Depth is presented in feet below land surface.

radiocarbon, and tritium data for this set of samples shows a range of results that exhibit connate-water characteristics to modern-water characteristics and many points in between (table 4). This means that recharge to each aquifer must be evaluated separately. To do this, however, will likely require more information on the hydrogeologic framework within which each aquifer exists and will certainly require more information on isotopic content of water contained in each aquifer.

Multiple sources of surface water (streams, lakes, wetlands) were sampled and analyzed for stable-isotope ratios. Variation in stable-isotope ratios in surface-water bodies may accommodate tracing of recharge sources (Mazor, 1991), particularly in aquifers where a substantial portion of the recharge is derived from bodies of surface water and not from the direct infiltration of precipitation. Results showed the wetlands and lakes that were sampled are substantially heavier with regard to the stable-isotope ratios than the ground water. Data from the three samples collected from streams plot in an intermediate position between data from wetlands and lakes and the data from ground water (figs. 5, 6, and 7). The data indicate that the surface waters that were sampled are isotopically distinct from the ground water that was sampled. However, some of the ground water exhibited isotopic signatures indicating the presence of some modern recharge. Yet, the amount of recharge or mixing of surface waters with ground water cannot be quantified with the available information.

Weathered till was interpreted to receive recharge from modern rainwater. Radiocarbon dating of samples of water from transitional till indicates minimal influence by modern recharge. Data available for unweathered till indicates minimal to no natural influence by modern recharge.

Water from the Cretaceous-age Niobrara Formation, Split Rock Creek Formation, Codell Sandstone Member of the Carlile Shale, and the Dakota Formation exhibited radiocarbon ages from thousands to tens of thousands of years old, with one exception (app. A), or much younger than the formations themselves. Although these waters are clearly not connate due to the radiocarbon ages, the isotope data do not exhibit all of the characteristics of modern recharge. Nine of the ten samples of water from the Sioux Quartzite indicate a strong influence by modern recharge but radiocarbon and tritium data from this water source are largely lacking to make a better conclusion.

The depth of burial of an outwash body is not always a good predictor as to whether the water within that body is largely meteoric or connate. For example, one of the wells yielding water that is interpreted to be connate from the Grand aquifer in Faulk County is installed in outwash that is only 70 feet below ground surface. Conversely, water with a modern radiocarbon age is observed to be present in outwash lying 130 feet below ground in northern Hyde County.

Results of this study affirm that each aquifer of glacial or bedrock origin must be evaluated individually in the context of its own hydrogeologic framework, hydrogeologic history, and water chemistry. Often, the information needed to make such evaluations is insufficient or non-existent. It is recommended, to the extent that budgets allow, that analyses of water be regularly performed in the future for relevant isotopic content in addition to the traditional analyses for common inorganic constituents. The routine addition of isotopic information into ground-water studies will lead to a better understanding of South Dakota's aquifers, more informed interpretations on sustainable water availability from those aquifers, and a better probability that South Dakota's ground-water resources will be available for future generations.

REFERENCES

Barari, A., Bender, A., Brohl, R., Doering, E., Lawson, J., Schaak, J., Verzah, J., 1987, *Comparison of irrigated land in southern Alberta, Canada, with the CENDAK area, South Dakota*: South Dakota Geological Survey Open-File Report 8-BAS, 212 p., 37 figs., 39 tables, 11 apps.

Bradbury, K.R., 1991, *Tritium as an indicator of ground-water age in central Wisconsin*: Ground Water, vol. 29, no. 3.

Christensen, C.M., 1974, *Geology and water resources of Bon Homme County South Dakota: Part I; Geology*: South Dakota Geological Survey Bulletin 21, 48 p., 7 pls., 16 figs., 3 tables, 1 app.

Clark, I.D., and Fritz, P., 1997, *Environmental Isotopes in Hydrogeology*: Boca Raton, Florida, CRC Press., 328 p.

Davis, R.K., Iles, D.L., Schaefer, V.R., Kortran, J.M., Koch, B., and Peterson, E.W., 1997, *Hydrogeology and hydrochemistry of clayey till at the Sioux Falls landfill, Sioux Falls, South Dakota*: South Dakota Geological Survey Open-File Report 9- BAS, 186 p., 47 figs., 5 tables, 8 app.

Ferguson, G., and Jasechko, S., 2015, *The isotopic composition of the Laurentide ice sheet and fossil groundwater*: Geophysical Research Letters, 42, American Geophysical Union.

Fetter, C., 1988, *Applied hydrogeology*: Columbus, Ohio, Merrill Publishing Company.

Fritz, P., Hennings, C.S., Suzulo, O. and Salati, E. 1979, *Isotope hydrology in northern Chile*: in Isotope Hydrology 1978, IAEA, Vienna, 2, p. 525-544.

Hamilton, L.J., and Howells, L.W., 1996, *Water resources of Spink County, South Dakota*: U. S. Geological Survey Water-Resources Investigations Report 96-4056, 68 p., 26 figs., 12 tables.

Holly, D.E., Iles, D.L., and Barari, A., 1993, *Ground-water study for the TM rural water District in the vicinities of Dolton and Parker, South Dakota*: South Dakota Geological Survey Open-File Report 65-UR, 112 p., 14 figs., 3 tables, 5 apps.

Holmes, S.L., and Filipovic, D., 2015, *Hydrogeologic investigation of the Upper-Vermillion-Missouri aquifer*: South Dakota Geological Survey Open-File Report 93-UR, 26 p., 12 plates, 7 figs., 1 table, 2 apps.

Iles, D., 1984, *Pleistocene recharge to Dakota Formation in Lincoln County, South Dakota*: in Geohydrology of the Dakota aquifer, Proceedings of the First C.V. Theis Conferences on Geohydrology, 12 p., 11 figs., 3 tables.

Iles, D.L., Barari, A., and Hedges, L.S., 1996, *Ground-water movement within till in Lincoln County, South Dakota*: South Dakota Geological Survey Open-File Report 4- BAS, 82 p., 18 figs., 7 tables, 7 app.

Kairo, S., 1987, *Sedimentology, stratigraphy, and depositional history of the Cretaceous Split Rock Creek Formation, Minnehaha County, South Dakota*: West Lafayette, Indiana, Purdue University, M.S. thesis, 122 p.

Ludvigson, G.A., McKay, R.M., Iles, D., and Bretz, R.F., 1981, *Lithostratigraphy and sedimentary Petrology of the Split Rock Creek formation, late Cretaceous, of southeastern South Dakota* in *Cretaceous stratigraphy and sedimentation in northwest Iowa, northeast*

Nebraska, & southeast South Dakota: Iowa Geological Survey Guidebook, Series Number 4, p. 77-104.
Mazor, E., 1991, *Applied Chemical and Isotopic Groundwater Hydrology*: New York, New York, John Wiley and Sons.
McCormick, K.A., and Hammond, R.H., 2004, *Geology of Lincoln and Union Counties, South Dakota*: South Dakota Geological Survey Bulletin 39, 43 p., 4 plates, 12 figs., 4 tables, 2 apps.
Pence, S.F., 1996, Hydrogeology and recharge of the Split Rock Creek aquifer, southeastern South Dakota: Grand Forks, N. Dak., University of North Dakota, M.S. thesis.
Siegel, D.I., and Mandle, R.J., 1984, *Isotopic evidence for glacial meltwater recharge to the Cambrian-Orovician aquifer, north-central United States*: Quaternary Research, 22, p. 328-335.
Terwey, J.L., 1984, *Isotopes in groundwater hydrology*: in Proceedings of the Harare Symposium, July 1984, Challenges in African hydrology and water resources, International Atomic Energy Agency, IAHS Publ. no. 144, p. 155-160, 2 figs. 1 table.
Tomhave, D.W., 1994, *Geology of Minnehaha County, South Dakota*: South Dakota Geological Survey Bulletin 37, 53 p., 4 plates, 19 figs., 2 tables.
_____, 1997, *Geology of Spink County, South Dakota*: South Dakota Geological Survey Bulletin 38, 61 p., 2 pls., 28 figs., 2 tables, 1 app.
Tomhave, D.W., and Schulz, L.D., 2004, *Bedrock geologic map showing configuration of the bedrock surface in South Dakota east of the Missouri River*: South Dakota Geological Survey General Map 9.
Witzke, B.J., and Ludvigson, G.A., 1996, *Mid-Cretaceous fluvial deposits of the eastern margin, western interior basin: Nishnabotna Member, Dakota Formation*: Geological Survey Bureau Guidebook Series no. 17, Iowa Department of Natural Resources.

Appendix A. Isotope data from water in eastern South Dakota

Sample source	Aquifer or surface-water body	Aquifer management unit	Location: County	Location: Quarter section	Location: Section	Location: Township	Location: Range	Well or well-owner name	Depth to top of outwash in feet[1]	Well depth in feet[1]	Date sampled	Delta oxygen-18 ‰	Delta deuterium ‰	Radiocarbon age[2]	Tritium units	Data source[3]
Rainfall	---	---	Beadle	NE¼, NE¼, NE¼, NE¼	13	110 N	62 W	---	---	---	9/23/2015	-9.52	-57.7	---	---	A
			Clay	NE¼, NE¼, NE¼, SE¼	19	92 N	51 W	---	---	---	7/18/2015	-2.22	-20.7			
											8/9/2015	-6.18	-36.6			
											4/18/2016	-5.54	-26.9			
											6/15/2016	-3.95	-33.5			
				NE¼, NE¼, NE¼, SW¼	14	92 N	52 W	---	---	---	10/11/2015	-10.63	-66.8			
Stream	James River	---	Spink	SE¼, SW¼, SW¼, SE¼	16	114 N	62 W	---	---	---	9/15/2015	-5.07	-50.4	---	---	A
	Medicine Creek	---	Hand	NW¼, NE¼, NW¼, NW¼	31	116 N	66 W	---	---	---	7/29/2015	-5.54	-38.7			
	Vermillion River	---	Turner	NW¼, NE¼, NW¼, NW¼	25	97 N	52 W	---	---	---	7/21/2015	-5.45	-43.0			
Lake	East Gerkin Lake	---	Faulk	SE¼, SE¼, SE¼, SE¼	29	118 N	67 W	---	---	---	7/28/2015	-1.57	-31.2	---	---	A
	Lake Byron	---	Beadle	SW¼, SW¼, SW¼, NE¼	34	113 N	61 W	---	---	---	9/15/2015	-2.55	-33.6			
	Mud Lake	---	Spink	SW¼, NW¼, NE¼, NE¼	15	115 N	64 W	---	---	---	7/29/2015	-2.51	-32.8			
	Mud Lake	---	Turner	SE¼, SE¼, SE¼, NE¼	24	98 N	52 W	---	---	---	7/21/2015	-0.64	-20.5			
	Rezac Lake	---	Hyde	SW¼, SW¼, SE¼, SW¼	34	116 N	71 W	---	---	---	7/28/2015	-1.36	-25.9			
	Twin Lakes	---	Spink	NE¼, NE¼, SE¼, NE¼	8	115 N	64 W	---	---	---	9/16/2015	-2.05	-29.9	Modern	8.58	
	---	---	Hyde	NE¼, NW¼, NW¼, NE¼	31	116 N	72 W	---	---	---	7/28/2015	-0.90	-25.8	---	---	
Wetland	---	---	Hand	SW¼, SW¼, NW¼, NW¼	27	115 N	66 W	---	---	---	9/15/2015	-1.86	-31.5	---	---	A
				SW¼, SE¼, SE¼, SE¼	26	116 N	66 W	---	---	---	7/29/2015	-1.96	-27.8			
Weathered till	---	---	Hand	NW¼ NW¼ NW¼ NW¼	17	115 N	70 W	CK-HD-15A2	---	13.1	7/22/1986	-13.96	-104.3	Modern	118	C
			Hyde	SW¼ SW¼ SW¼ SW¼	3	114 N	73 W	CK-HY-6A	---	13	7/22/1986	-13.59	-96.3	---	41.7	
			Lincoln	NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	GT-LN-1K	---	11	7/14/1986	-10.95	-71.25	Modern	64.7	D
				NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	GT-LN-1L	---	13	7/14/1986	-10.94	-75.7	---	51.3	
				NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	GT-LN-1M	---	16	7/15/1986	-9.88	-71.9	Modern	15.1	
				SE¼ SE¼ SE¼ NE¼	30	98 N	50 W	GT-LN-2I	---	11	7/15/1986	-11.31	-79.2	---	56	
				SE¼ SE¼ SE¼ NE¼	30	98 N	50 W	GT-LN-2J	---	13	7/15/1986	-10.28	-70.7	---	30.8	
			McCook	NE¼ NE¼ NE¼ NE¼	17	101 N	54 W	GT-MC-2H	---	11	7/23/1986	-9.77	-62.5	---	19.2	C
				NE¼ NE¼ NE¼ NE¼	17	101 N	54 W	GT-MC-2I	---	13	7/16/1986	-8.71	-59.6	---	4.59	
				NE¼ NE¼ NE¼ NE¼	17	101 N	54 W	GT-MC-2J	---	16	7/16/1986	-9.24	-61	---	0.57	
			Minnehaha	SW¼ NW¼ SE¼ SW¼	35	101 N	51 W	R20-93-07	---	16.9	3/1/1994	---	---	---	6.05	B
											7/14/1994	-9.8	-71	---	---	
				NE¼ SE¼ SW¼ SW¼	35	101 N	51 W	R20-93-21	---	21.6	3/1/1994	---	---	---	2.74	
											7/14/1994	-8.4	-62	---	---	
			Turner	NE¼ NE¼ NE¼ NE¼	17	100 N	55 W	GT-TU-3H	---	11	7/16/1986	-12.95	-93.3	---	73.3	C
				NE¼ NE¼ NE¼ NE¼	17	100 N	55 W	GT-TU-3I	---	13	7/16/1986	-12.05	-91.8	---	62	
				NE¼ NE¼ NE¼ NE¼	17	100 N	55 W	GT-TU-3J	---	17	7/16/1986	-9.13	-65.3	---	13.5	

Appendix A --- continued

Sample source	Aquifer or surface-water body	Aquifer management unit	Location					Well or well-owner name	Depth to top of outwash in feet[1]	Well depth in feet[1]	Date sampled	Delta oxygen-18 ‰	Delta deuterium ‰	Radiocarbon age[2]	Tritium units	Data source[3]
			County	Quarter section	Section	Township	Range									
Transition-zone till	---	---	Minnehaha	SE¼ NW¼ SW¼ SW¼	35	101 N	51 W	R20-93-11	---	29.3	3/1/1994	---	---	---	0.58	B
											7/14/1994	-9.2	-60	12,082	---	
				NW¼ NE¼ SW¼ SW¼	35	101 N	51 W	R20-93-16	---	28.6	3/1/1994	---	---	---	0.62	
											7/14/1994	-9.6	-59	9,299	---	
Unweathered till	---	---	Hand	NW¼ NW¼ NW¼ NW¼	17	115 N	70 W	CK-HD-15B	---	28.3	7/22/1986	-15.55	-113.2	10,068	17.3	C
				NW¼ NW¼ NW¼ NW¼	17	115 N	70 W	CK-HD-15C	---	53.1	7/22/1986	-17.935	-130.95	14,768	1.37	
				NW¼ NW¼ NW¼ NW¼	17	115 N	70 W	CK-HD-15D	---	69	7/22/1986	-18.78	-137.24	13,231	9.73	
			Hyde	SW¼ SW¼ SW¼ SW¼	3	114 N	73 W	CK-HY-6B2	---	28	7/22/1986	-11.75	-83.3	732	15	
				SW¼ SW¼ SW¼ SW¼	3	114 N	73 W	CK-HY-6C	---	33	7/22/1986	-10.7	-79.8	3,818	0.18	
				SW¼ SW¼ SW¼ SW¼	3	114 N	73 W	CK-HY-6E	---	97	7/22/1986	-13.09	-88.1	503	6.69	
			Lincoln	NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	GT-LN-1A	---	68	7/14/1986	-13.31	-99.8	16,869	-0.06	D
				NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	GT-LN-1O	---	36	7/15/1986	-12.41	-89.1	22,410	0.22	
				NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	GT-LN-1P	---	46	7/15/1986	-13.19	-91.7	10,798	0.75	
				NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	GT-LN-1Q	---	56	7/15/1986	-14.315	-98.6	10,433	0.19	
				SE¼ SE¼ SE¼ NE¼	30	98 N	50 W	GT-LN-2L	---	26	7/15/1986	-11.33	-82.18	10,942	1.14	
				SE¼ SE¼ SE¼ NE¼	30	98 N	50 W	GT-LN-2N	---	46	7/15/1988	-13.55	-97.85	9,068	1.99	
				SE¼ SE¼ SE¼ NE¼	30	98 N	50 W	GT-LN-2O	---	56	7/15/1986	-15.04	-101.98	13,581	3.06	
			McCook	NE¼ NE¼ NE¼ NE¼	17	101 N	54 W	GT-MC-2N	---	71	7/16/1986	-12.84	-89.3	16,477	0.14	C
			Minnehaha	SE¼ NW¼ SW¼ SW¼	35	101 N	51 W	R20-93-02	---	71.8	3/1/1994	---	---	---	0.15	B
											7/14/1994	-10.7	-69	21,829	---	
				SE¼ NW¼ SW¼ SW¼	35	101 N	51 W	R20-93-03	---	52.35	3/1/1994	---	---	---	1.31	
											6/30/1994	---	---	---	0.75	
											10/28/1994	-10.1	-69	17,880	---	
				NE¼ SE¼ SW¼ SW¼	35	101 N	51 W	R20-93-14	---	73.5	3/1/1994	---	---	---	2.37	
											6/30/1994	---	---	---	1.1	
											10/28/1994	-10.5	-63	10,933	---	
				NE¼ SE¼ SW¼ SW¼	35	101 N	51 W	R20-93-15	---	49.7	3/8/1994	---	---	---	<0.03	
											7/14/1994	-9.5	-67	19,085	---	
			Turner	NE¼ NE¼ NE¼ NE¼	17	100 N	55 W	GT-TU-3N	---	71	7/16/1986	-11.45	-78.2	11,043	0.58	C
Surface outwash	Parker-Centerville aquifer	---	Turner	SE¼, SE¼, SE¼, SE¼	7	98 N	52 W	TU-80F	0	14.2	8/26/2015	-8.19	-57.4	Modern	4.62	A
				NW¼, NW¼, NW¼, NW¼	32	98 N	52 W	TU-77J	0	20	9/10/2015	-8.42	-59	Modern	4.21	

Appendix A --- continued

Sample source	Aquifer or surface-water body	Aquifer management unit	Location					Well or well-owner name	Depth to top of outwash in feet[1]	Well depth in feet[1]	Date sampled	Delta oxygen-18 ‰	Delta deuterium ‰	Radiocarbon age[2]	Tritium units	Data source[3]
			County	Quarter section	Section	Township	Range									
Buried outwash with a radiocarbon age of 600 years or younger	Tulare aquifer	East James	Spink	SE¼, SE¼, SE¼, NE¼	6	115 N	61 W	SP-77K	107	143.1	4/11/2016	-14.39	-107.9	Modern	4.86	A
				NE¼, NE¼, SE¼, NE¼	26	115 N	62 W	M51-2015-42	12	51.1	11/2/2016	-11.10	-83.1	Modern	1.56	
				NW¼, NE¼, NE¼, NE¼	25	116 N	62 W	M51-2015-37	11	54.9	11/2/2016	-11.94	-87.5	500	4.44	
		Hitchcock	Spink	NE¼, NE¼, NE¼, NE¼	23	114 N	63 W	R20-96-35	13	25.8	4/4/2016	-12.64	-92.9	Modern	4.56	
				SW¼, SW¼, SW¼, SW¼	23	115 N	63 W	R20-96-37	1	22.4	5/9/2016	-13.66	-99.5	Modern	3.16	
		Western Spink	Spink	NE¼, NE¼, NE¼, NE¼	1	114 N	65 W	M51-2014-01	62	72.5	4/6/2016	-13.58	-102.1	Modern	<1.00	
				NW¼, NE¼, NE¼, NE¼	1	114 N	65 W	M51-2014-03	74, 90	105.4	4/6/2016	-14.33	-106.0	400	<1.00	
				SW¼, SW¼, SW¼, SW¼	22	115 N	64 W	SP-66M	29	59.6	5/9/2016	-14.17	-102.8	Modern	4.84	
	Vermillion-Missouri aquifer	---	Turner	NW¼, NW¼, NW¼, NW¼	32	98 N	52 W	TU-77H	63	71.5	9/10/2015	-9.85	-70.9	Modern	1.24	
				NW¼, NW¼, NW¼, NW¼	32	98 N	52 W	TU-77I	114	173.9	9/2/2015	-10.22	-71.0	Modern	1.09	
				SE¼, NE¼, NE¼, SE¼	26	98 N	53 W	M51-2013-09	1	89.7	8/26/2015	-9.43	-70.3	Modern	3.54	
	---	---	Hand	SW¼, SW¼, SW¼, NW¼	33	116 N	67 W	R20-2011-10	30	40.4	5/10/2016	-12.20	-91.7	Modern	2.77	
				SW¼, SW¼, SW¼, NW¼	33	116 N	67 W	R20-2011-11	85	93	5/10/2016	-12.23	-92.3	Modern	<1.00	
			Hyde	SW¼, NW¼, NW¼, NW¼	11	115 N	72 W	M51-2010-20	117	151	4/5/2016	---	---	Modern	---	
											5/17/2016	-12.78	-97.6	---	2.43	
				SE¼, SE¼, SE¼, SE¼	21	115 N	72 W	M51-2010-18	130	154	4/5/2016	-13.27	-102.8	600	<1.00	
				NE¼ SE¼ NW¼ SE¼	31	115 N	72 W	C. Kutz	130	156	8/14/1984	-11.97	-87.3	Modern	---	C
Buried outwash with a radiocarbon age of 3,500 years or older	Bad-Cheyenne aquifer	---	Hand	SW¼, SW¼, SW¼, SW¼	20	114 N	70 W	M51-2011-35	186	204	4/5/2016	-18.88	-144.8	29,000	<1.00	A
			Hyde	SW¼, SW¼, SW¼, SW¼	23	114 N	71 W	M51-2011-36	170	230	4/5/2016	-18.55	-143.7	29,000	<1.00	
				SE¼, SE¼, SE¼, SE¼	21	115 N	72 W	M51-2010-17	277	299.4	4/5/2016	-18.19	-139.1	29,000	<1.00	
	Choteau aquifer	Tyndall	Bon Homme	NW¼, NW¼, NW¼, NW¼	27	95 N	59 W	M51-2015-12	167	227	10/24/2016	-14.18	-105.4	22,000	0.81	
				SW¼, SW¼, SW¼, SW¼	29	95 N	59 W	M51-2015-16	136, 186	202.5	10/24/2016	-12.09	-88.4	13,500	<0.81	
	Deep James aquifer	---	Beadle	SW¼, NW¼, NW¼, SW¼	27	113 N	62 W	M51-2014-07	174	185.7	4/4/2016	-15.13	-114.2	29,000	<1.00	
			Spink	NW¼, NE¼, NE¼, NE¼	1	114 N	65 W	M51-2014-04	76, 110, 142	167.3	4/6/2016	-13.76	-104.5	7,000	<1.00	
	Dolton aquifer	---	McCook	NE¼, NE¼, NE¼, NE¼	17	101 N	54 W	CO-84-43	158	165	9/2/2015	-14.27	-105.9	17,500	<1.00	
				SW¼, SW¼, SW¼, SW¼	25	101 N	55 W	R20-91-07	146	182.7	9/2/2015	-19.30	-144.9	16,000	<1.00	
				SE¼ SE¼ SE¼ NE¼	29	101 N	55 W	Hanson RWS	137	180	7/31/1984	-19.11	-140.6	13,526	---	C
			Turner	NW¼ NE¼ NW¼ NE¼	8	100 N	55 W	TM RWS	---	172	8/2/1984	-21.08	-158.3	14,778	---	
				SE¼ SE¼ SE¼ SE¼	34	100 N	55 W	H. Ortman	---	165	8/1/1984	-20.63	-153.8	16,126	---	
	Grand aquifer	---	Faulk	NE¼, NE¼, SE¼, NE¼	31	118 N	67 W	Dennis Mutch	70	100	7/28/2015	-19.58	-146.9	35,000	<1.00	A
				SE¼, SE¼, SW¼, SE¼	24	118 N	68 W	FA-71B	91	149.2	5/11/2016	-19.57	-147.2	35,000	<1.00	
				NE¼, NE¼, NE¼, NE¼	12	118 N	69 W	R2-2007-45	170	183	5/18/2016	-18.51	-141.3	27,000	<1.00	
	Lower-James-Missouri aquifer	Scotland	Bon Homme	NE¼, NW¼, NW¼, NW¼	33	95 N	58 W	M51-2015-13	225	246	10/26/2016	-18.86	-144.9	15,000	0.64	
	Tulare aquifer	Hitchcock	Beadle	SW¼, NW¼, NW¼, SW¼	27	113 N	62 W	M51-2014-06	27	59.5	4/4/2016	-8.92	-72.5	8,000	<1.00	
		Western Spink	Hand	NE¼, NE¼, NE¼, SE¼	14	115 N	66 W	M51-2011-32	23, 69	97	4/12/2016	-14.67	-113.2	13,000	<1.00	
			Spink	NE¼, NE¼, NE¼, NE¼	29	115 N	65 W	SP-80O	61	122.5	5/10/2016	-15.14	-113.6	13,000	<1.00	
	Vermillion-Missouri aquifer	---	Lincoln	SW¼, SW¼, NW¼, SW¼	19	98 N	51 W	M51-2013-15	67	79	9/19/2016	-8.70	-61.9	5,500	<1.00	
			Turner	SW¼, SW¼, SW¼, SW¼	20	97 N	52 W	TU-80H	108	228.4	8/25/2015	-8.79	-62.3	4,000	<1.00	

Appendix A --- continued

Sample source	Aquifer or surface-water body	Aquifer management unit	Location					Well or well-owner name	Depth to top of outwash in feet[1]	Well depth in feet[1]	Date sampled	Delta oxygen-18 ‰	Delta deuterium ‰	Radiocarbon age[2]	Tritium units	Data source[3]
			County	Quarter section	Section	Township	Range									
Buried outwash with a radiocarbon age of 3,500 years or older	---	---	Hand	NW¼, NW¼, NW¼, NW¼	27	115 N	67 W	M51-2012-06	96	109.6	4/12/2016	-14.42	-108.7	12,000	<1.00	A
				NW¼, NW¼, NW¼, NW¼	27	115 N	67 W	M51-2012-07	38	55	4/12/2016	-14.04	-106.2	3,500	1.99	
				SE¼, SE¼, SE¼, SE¼	30	115 N	67 W	M51-2012-08	108	123.4	5/10/2016	-13.78	-102.6	5,000	<1.00	
				NW¼, NW¼, NW¼, NW¼	31	116 N	67 W	M51-2012-09	139	156	5/10/2016	-15.53	-117.2	22,000	<1.00	
				SE¼ NE¼ SW¼ SW¼	7	115 N	70 W	D. Foreman	80	140	8/7/1984	-18.9	-138.4	26,503	---	C
				SW¼ SE¼ SE¼ SW¼	8	115 N	70 W	L. Froning	---	116	8/8/1984	-18.86	-134.6	11,532	---	
				SE¼ NE¼ NW¼ NW¼	14	115 N	70 W	D. Foerster	78	95	8/8/1984	-14.98	-107.1	4,892	---	
		---	Lincoln	SW¼ SE¼ SE¼ SW¼	8	96 N	50 W	L. Volden	140	157	10/28/1983	-8.2	-61	10,630	---	
				NE¼ NE¼ NW¼ NW¼	20	98 N	50 W	Schoffelman	---	90	7/25/1984	-9.88	-68.3	13,543	---	D
				NE¼ NE¼ NE¼ SE¼	20	98 N	50 W	Sweeter	---	>110	7/15/1986	-10.405	-68.1	12,602	0.04	
				SW¼ SW¼ SW¼ SW¼	33	98 N	50 W	R. Suing	---	70	7/26/1984	-8.8	-59.5	7,269	---	
				NW¼ SE¼ SW¼ NE¼	32	99 N	51 W	Lennox	---	?	11/3/1983	-11.4	-85	21,300	---	C
			Turner	SE¼ SW¼ NW¼ SW¼	35	97 N	53 W	Viborg	---	117	10/21/1983	-9.6	-76	15,260	---	
Niobrara Formation		---	Spink	NW¼, NE¼, NE¼, NE¼	25	116 N	62 W	M51-2015-38	---	199.4	4/12/2016	-13.72	-103.5	>43,500	<1.00	A
			Turner	NW¼, NW¼, NW¼, NE¼	18	97 N	52 W	R20-2013-48	---	67	8/26/2015	-9.97	-72.3	Modern	7.59	
Codell Sandstone Member of the Carlile Shale		---	Bon Homme	SE¼, SE¼, SE¼, SE¼	23	95 N	59 W	M51-2015-15	---	236	10/24/2016	-14.62	-113.2	23,000	<0.91	A
				SW¼, SW¼, SW¼, SW¼	34	95 N	59 W	M51-2015-10	---	253.5	10/24/2016	-15.28	-115.4	23,500	<0.62	
Split Rock Creek Formation		---	Minnehaha	NW¼ NE¼ NW¼ SW¼	6	101 N	47 W	SRC-41	---	222	8/15/1991	-10.1	-66	---	---	F
				SE¼ SE¼ SE¼ NE¼	30	102 N	48 W	SRC-18A	---	115	8/15/1991	-11.8	-77	---	---	
				SE¼ NW¼NW¼ SW¼	35	102 N	48 W	Brandon PW	---	222	6/28/1989	---	---	6,900	0	
											8/15/1991	-10.5	-70	---	---	
				SW¼ SE¼ SE¼ NW¼	8	102 N	49 W	Renner PW	---	173	2/13/1989	---	---	---	0	
											2/14/1989	---	---	10,600	0	
				NE¼ SE¼ SE¼ SE¼	24	102 N	49 W	SRC-43	---	191	8/15/1991	-11.2	-77	---	---	
				NW¼ SE¼ SE¼ SW¼	36	102 N	49 W	NSP-3 PW	---	148	4/27/1988	---	---	3,400	0	
											8/15/1991	-10	-67	---	---	
				SW¼ SW¼ NW¼ NE¼	36	102 N	49 W	Watrec PW	---	≈130	4/27/1988	---	---	9,200	0	
											8/15/1991	-10.4	-71	---	---	
Dakota Sandstone		---	Lincoln	SW¼ SW¼ SE¼ SE¼	4	96 N	49 W	A. Lund	---	560	10/24/1983	-11.4	-82	27,130	---	C
				NW¼ NE¼ NE¼ NW¼	29	96 N	51 W	L. Knutson	---	400	10/26/1983	-16.6	-127	>34,700	---	
				SW¼ NW¼ SW¼ SW¼	16	97 N	51 W	K. Falk	---	338	2/2/1982	-11.75	-84.5	---	---	E
				NE¼ NE¼ SE¼ NE¼	23	98 N	49 W	Canton	---	415	2/2/1982	-10.25	-69	---	---	
				SW¼ NE¼ NW¼ NW¼	9	98 N	50 W	Worthing	---	479	2/2/1982	-10.3	-69.5	---	---	
				NW¼ NW¼ NE¼ NE¼	23	98 N	50 W	D. Kuhn	---	425	11/16/1983	-9.9	-67	32,700	---	C
				SE¼ SE¼ SE¼ SE¼	32	98 N	50 W	South Lincoln Rural Water System	---	654	2/2/1982	-10.85	-73	38,200	---	E
				SE¼ NE¼ NE¼ NE¼	17	99 N	49 W	H. Johnson	---	491	11/17/1983	-9.4	-66	27,490	---	C
			Turner	NW¼ SE¼ SE¼ SE¼	36	96 N	53 W	J. Andal	---	347	10/20/1983	-16.8	-133	>37,000	---	
			Sioux, Iowa	SE¼ NE¼ NW¼ SE¼	28	97 N	46 W	L. Hanson	---	590	11/1/1983	-9.3	-67	27,700	---	

Appendix A --- continued

Sample source	Aquifer or surface-water body	Aquifer management unit	Location					Well or well-owner name	Depth to top of outwash in feet[1]	Well depth in feet[1]	Date sampled	Delta oxygen-18 ‰	Delta deuterium ‰	Radiocarbon age[2]	Tritium units	Data source[3]
			County	Quarter section	Section	Township	Range									
Sioux Quartzite		---	Lincoln	NW¼ NE¼ NW¼ NE¼	23	99 N	51 W	G. Steever	---	170	11/1/1983	-11.7	-87	23,370	---	C
			Minnehaha	NE¼ SW¼	14	101 N	48 W	Q10	---	260	8/15/1991	-8.5	-57	---	---	F
				SE¼ NE¼	29	101 N	48 W	Q1	---	106	8/15/1991	-8.8	-61	---	---	
				NW¼	33	101 N	48 W	Q2a	---	208?	8/15/1991	-10.8	-68	---	---	
				NW¼	26	101 N	49 W	Q4	---	?	8/15/1991	-9.4	-61	---	---	
				SW¼	14	101 N	50 W	Q8	---	?	8/15/1991	-9.5	-66	---	---	
				SE¼	14	101 N	50 W	Q5	---	?	8/15/1991	-9.8	-67	---	---	
				SW¼	14	102 N	48 W	Q6	---	?	8/15/1991	-9.5	-62	---	---	
				SE¼	15	102 N	48 W	Q9	---	?	8/15/1991	-9.8	-64	---	---	
				SW¼	22	102 N	49 W	Q7	---	?	8/15/1991	-10.1	-68	---	---	

[1] Depth is presented in feet below land surface.

[2] Age is presented in years before present. "Modern" denotes a calculated age that is post 1950.

[3] Sources for the data are as follows.

A. This study

B. Davis, R.K., Iles, D.L., Schaefer, V.R., Kortran, J.M., Koch, B., and Peterson, E.W., 1997, *Hydrogeology and hydrochemistry of clayey till at the Sioux Falls landfill, Sioux Falls, South Dakota*: South Dakota Geological Survey Open-File Report 9-BAS

C. DENR Geological Survey Program files

D. Iles, D.L., Barari, A., and Hedges, L.S., 1996, *Ground water movement within till in Lincoln County, South Dakota*: South Dakota Geological Survey Open-File Report 4-BAS

E. Iles, D.L., 1984, *Pleistocene recharge to the Dakota Formation in Lincoln County, South Dakota*: in Geohydrology of the Dakota aquifer, Proceedings of the first C.V. Theis Conferences on Geohydrology

F. Pence, S.F., 1996, *Hydrogeology and recharge of the Split Rock Creek aquifer, southeastern South Dakota*: Grand Forks, N. Dak., University of North Dakota, M.S. thesis