STATE OF SOUTH DAKOTA

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

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GEOLOGICAL SURVEY PROGRAM
Derric L. Iles, State Geologist

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HYDROGEOLOGIC INVESTIGATION OF THE UPPER-VERMILLION-MISSOURI AQUIFER

STEVIE L. HOLMES

DRAGAN FILIPOVIC

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

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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
Jeffrey J. Allen, B.A.	Geologist
Sarah A. Chadima, M.S., C.P.G.	Geologist
Wesley P. Christensen, B.S.	Geologist
Timothy C. Cowman, M.S.	Environmental Scientist Manager
Dragan Filipovic, M.S.	Hydrologist
Stevie L. Holmes, B.S.	Geologist
Ann R. Jensen, B.S.	Geologist
Darren J. Johnson, 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
Christopher A. Lanoue, B.A.	Natural Resources Technician
Ted R. Miller, B.S.	Civil Engineering Technician
James R. Olson, B.S.	Civil Engineering Technician
Lori L. Roinstad	Cartographer
Priscilla E. Young, B.S.	Senior Secretary

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

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INTRODUCTION

Investigation of the Upper-Vermillion-Missouri aquifer was undertaken to provide more information to the Water Rights Program, Department of Environment and Natural Resources, that would help make better-informed decisions regarding the allocation of water from this aquifer for irrigation. Data compiled from previous investigations and information from this study has enabled a better understanding of the Upper-Vermillion-Missouri aquifer. This aquifer and the Parker-Centerville aquifer are the principal sources of water for irrigation, municipal use, industry, and domestic use in the study area. The study area is located in southeastern South Dakota, and has an area of 1,050 square miles (fig. 1).

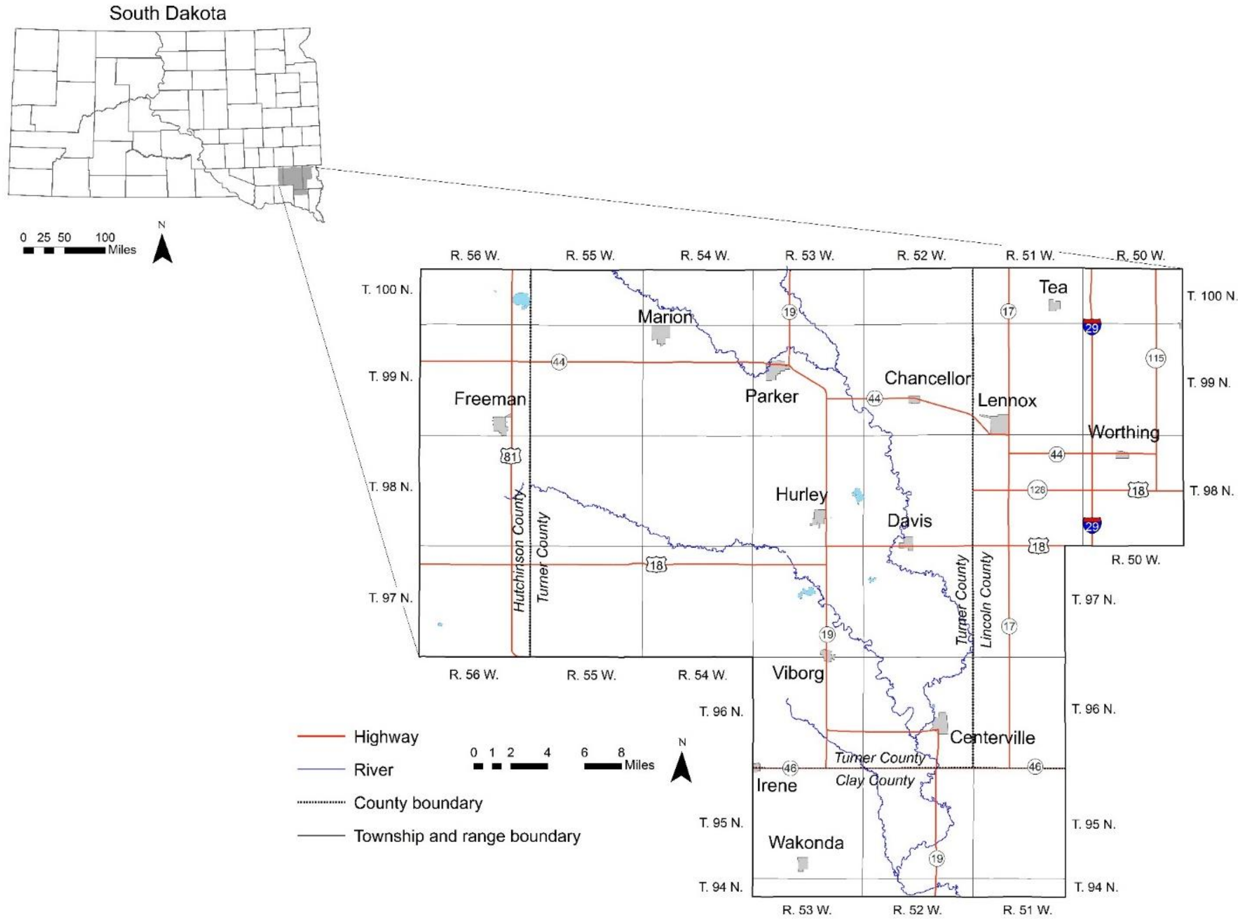


Figure 1. Index map of the study area.

The boundaries of the Upper-Vermillion-Missouri and Parker-Centerville aquifers were modified as a result of this investigation. Two of the most significant modifications that will be illustrated in this report are (1) that a large portion of the area previously assigned as part of the Upper-Vermillion-Missouri aquifer was determined not to be part of the aquifer and (2) that there is no scientific justification for the distinction (boundary) between the Upper-Vermillion-Missouri and Lower-Vermillion-Missouri aquifers. Rather, the two aquifers are one and the name proposed herein for the single aquifer is the Vermillion-Missouri.

METHODS

Field work was conducted from May 2013 through April 2014 and included the drilling of 83 test holes, 21 of which were completed as wells in the formerly interpreted Upper-Vermillion-Missouri aquifer, 4 of which were completed as wells in the Parker-Centerville aquifer, 8 of which were completed as wells in the Niobrara aquifer, and 12 of which were completed as wells in other glacial sands and gravels. Water samples were collected from 85 wells for analysis of water quality.

The general geologic setting of the study area was determined using available geologic maps and logs of test holes and wells, reviewing literature, and drilling and logging additional test holes and wells. The map of bedrock geology for eastern South Dakota (Tomhave and Schulz, 2004) was the base used for creating a new, more detailed map of bedrock type and topography in the study area. This study included the assessment of over 3,000 test holes and wells drilled in Clay, Turner, and Lincoln Counties for private use and various Geological Survey Program projects (Geological Survey Program, 2014; Water Rights Program, 2014, 2014b).

Water level data from 1956 through 2014 were obtained from 47 dedicated observation wells maintained by the Water Rights Program, Department of Environment and Natural Resources. Water level data were also collected from 45 additional wells installed for this study. These 92 wells provided information from the following aquifers: the formerly interpreted Upper-Vermillion-Missouri aquifer (37 wells); the Parker-Centerville aquifer (23 wells); the Niobrara aquifer (9 wells); the formerly interpreted Lower-Vermillion Missouri aquifer (1 well); and other glacial sands and gravels (22 wells) (app. A).

Chemical analyses were performed on water samples collected from 85 wells: 39 wells installed for this study, 43 wells which are part of the Water Rights Program observation-well network, and 3 wells installed for other studies. The number of wells that were sampled in each aquifer is as follows: formerly interpreted Upper-Vermillion-Missouri (35); Parker-Centerville (21); Niobrara (8); and other glacial sands and gravels (21). The South Dakota Department of Health Laboratory performed the analyses (app. B).

CLIMATE

The study area is characterized by cold winters and hot summers. Average annual precipitation for climate station *Centerville 6 SE* in Turner County from 1980 to 2013 was approximately 26 inches (National Oceanic and Atmospheric Administration, 2014) (fig. 2).

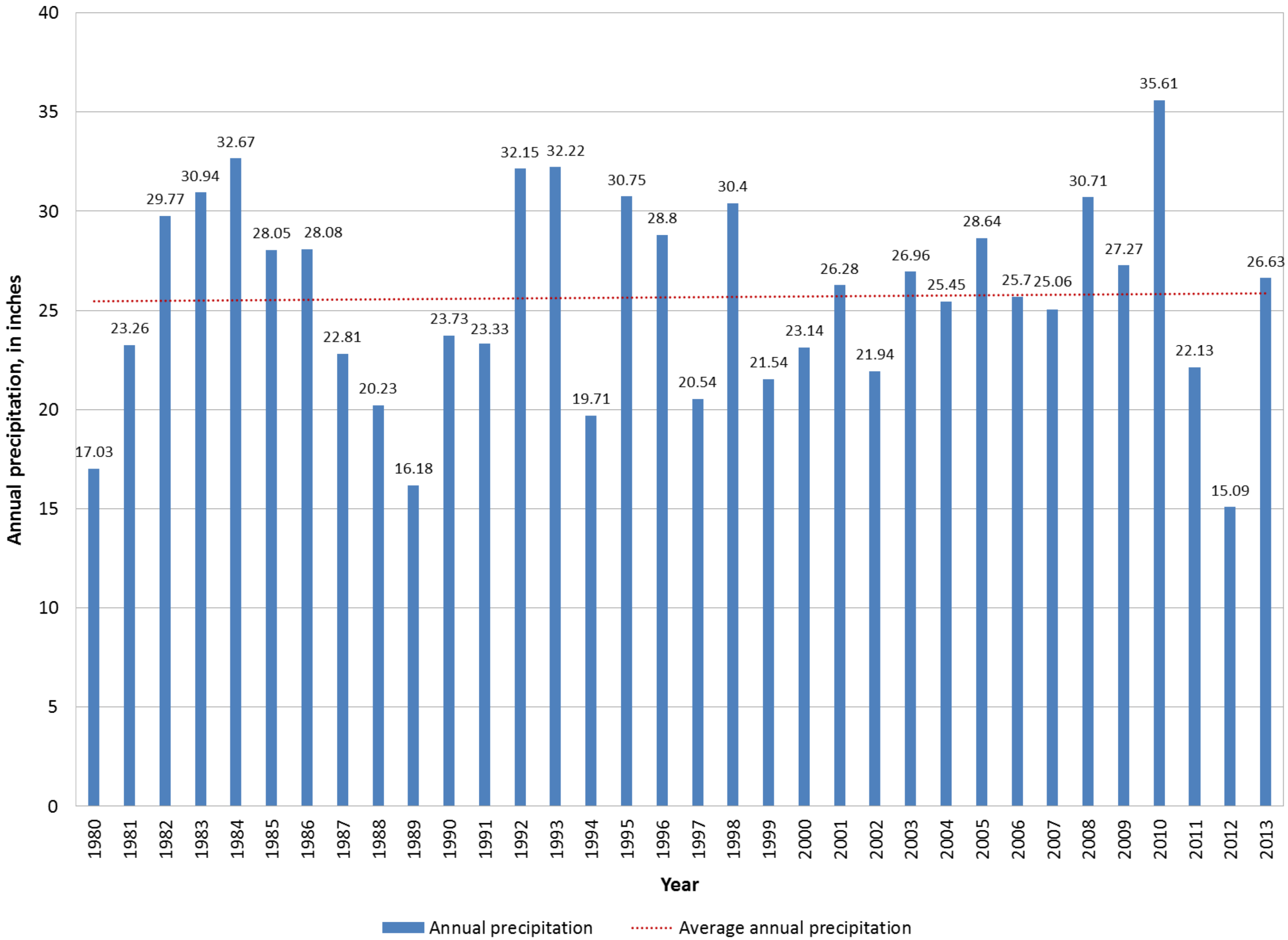


Figure 2. Annual precipitation from climate station Centerville 6 SE, 1980-2013.

RESULTS OF INVESTIGATION

Geology

Bedrock Geology

The bedrock topography provides the framework within which the Vermillion-Missouri aquifer was deposited. Plate 1 shows the type and configuration of the bedrock surface, which underlies the glacial deposits. Plates 2 and 3 contain cross sections that illustrate the distribution of the geologic units in the study area. Below are brief descriptions of the bedrock units, from oldest to youngest, that occur in the study area.

The Sioux Quartzite is a Precambrian-age orthoquartzite, typically pink to red in color due to trace amounts of iron (Baldwin, 1949). It underlies the entirety of the study area.

Undifferentiated sediments of Cretaceous age occur along the margins of the Sioux Quartzite shown on plate 1. For this report, these sediments include the quartzite wash, marls, sandstones, shales, and sediment identified as "near-shore facies equivalent," referring to the equivalents of the standard Cretaceous depositional sequence (Ludvigson and others, 1981; Tomhave, 1994). Although the processes of weathering of Sioux Quartzite and deposition of quartzite wash may have occurred in times other than the Cretaceous Period, sediments described as "quartzite wash" are lumped into the category of undifferentiated Cretaceous-age sediments for the purposes of this report.

The Dakota Sandstone likely underlies all of the study area except where the Sioux Quartzite and the flanking undifferentiated Cretaceous-age sediments have been mapped as the first bedrock encountered. The Dakota Sandstone is comprised of interbedded sandstones and shales, representative of varying periods of terrestrial, fluvial, and marine environments (Schoon, 1971). The Dakota Sandstone does not lie in contact with the Vermillion-Missouri aquifer in the study area.

The Graneros Shale is a medium-gray, noncalcareous, silty shale, with interbedded silts and sands (McCormick and Hammond, 2004). This geologic unit is known to be present in the study area from previous drilling but was never the first bedrock encountered.

The Greenhorn Limestone is a fossiliferous gray limestone bounded at its upper and lower contacts by dark gray shale (Christensen, 1967). It directly underlies the glacial deposits in bedrock valleys at the southern border of the study area.

The Carlile Shale is a gray, greasy clay and was found to be calcareous and noncalcareous depending on locality. The Carlile Shale directly underlies glacial sediments throughout much of the study area.

The Niobrara Formation is typically a medium-gray chalk with thin interbeds of calcareous shale. However, varicolored weathering surfaces are common, as are fractures. The Niobrara

Formation unconformably overlies the Carlile Shale (Fahrenbach and others, 2010). The distribution of the Niobrara Formation is shown on plate 1.

The Pierre Shale underlies the glacial sediments in the southwestern part of the study area. Generally, the Pierre Shale is a medium to dark gray fissile shale, with thin bentonite seams (Johnson and McCormick, 2005).

Undifferentiated sediments of Tertiary age are present in the southwestern part of the study area. The sediments consist of peach-colored fine sand and silt (Johnson and McCormick, 2005).

Glacial Deposits

Till is the primary glacial deposit lying in contact with the bedrock surface throughout most of the study area. Till is nonstratified sediment deposited by a glacier. Within the area of study, it is a mixture of silt to boulder-size clasts in a dense clay matrix (Tomhave, 1994).

Outwash is comprised of clay to boulder size clasts that have been transported by glacial meltwater. In the study area, the outwash was found to be dominated by sand to gravel size clasts with minor amounts clay and silt.

Hydrology

For this investigation, 83 test holes were drilled with 45 completed as wells (plate 4). Forty-seven wells previously completed and maintained by the Water Rights Program, Department of Environment and Natural Resources, were also used for measuring water levels and collecting water samples. In all, 92 wells were used to monitor water levels (app. A, plate 5) and 85 wells were sampled and analyzed for general inorganic chemistry (app. B; plate 6).

Bedrock Aquifers

Within the area of study, there are two bedrock aquifers: the Dakota aquifer and the Niobrara aquifer. Previous drilling in the study area has shown that the Dakota aquifer is not in direct contact with the glacial aquifers. Therefore, the hydrologic characteristics of the Dakota aquifer are not addressed in this report.

The Niobrara aquifer is in direct contact with glacially derived sands and gravels (outwash) based on data collected for this study and previous investigations (plates 2 and 3). The Niobrara aquifer underlies 490 square miles of the study area. For this study, eight wells were drilled and installed in the Niobrara Formation. Water levels in the Niobrara aquifer were measured from November 2013 to April 2014 in these eight wells and one Water Rights Program well (TU-79D). Samples were collected for water-quality analyses from seven of the eight wells installed for this study and from a previously installed well (plate 6). Ground water from the Niobrara aquifer is calcium-magnesium-sulfate-bicarbonate type (fig. 3). Total dissolved solids concentrations ranged

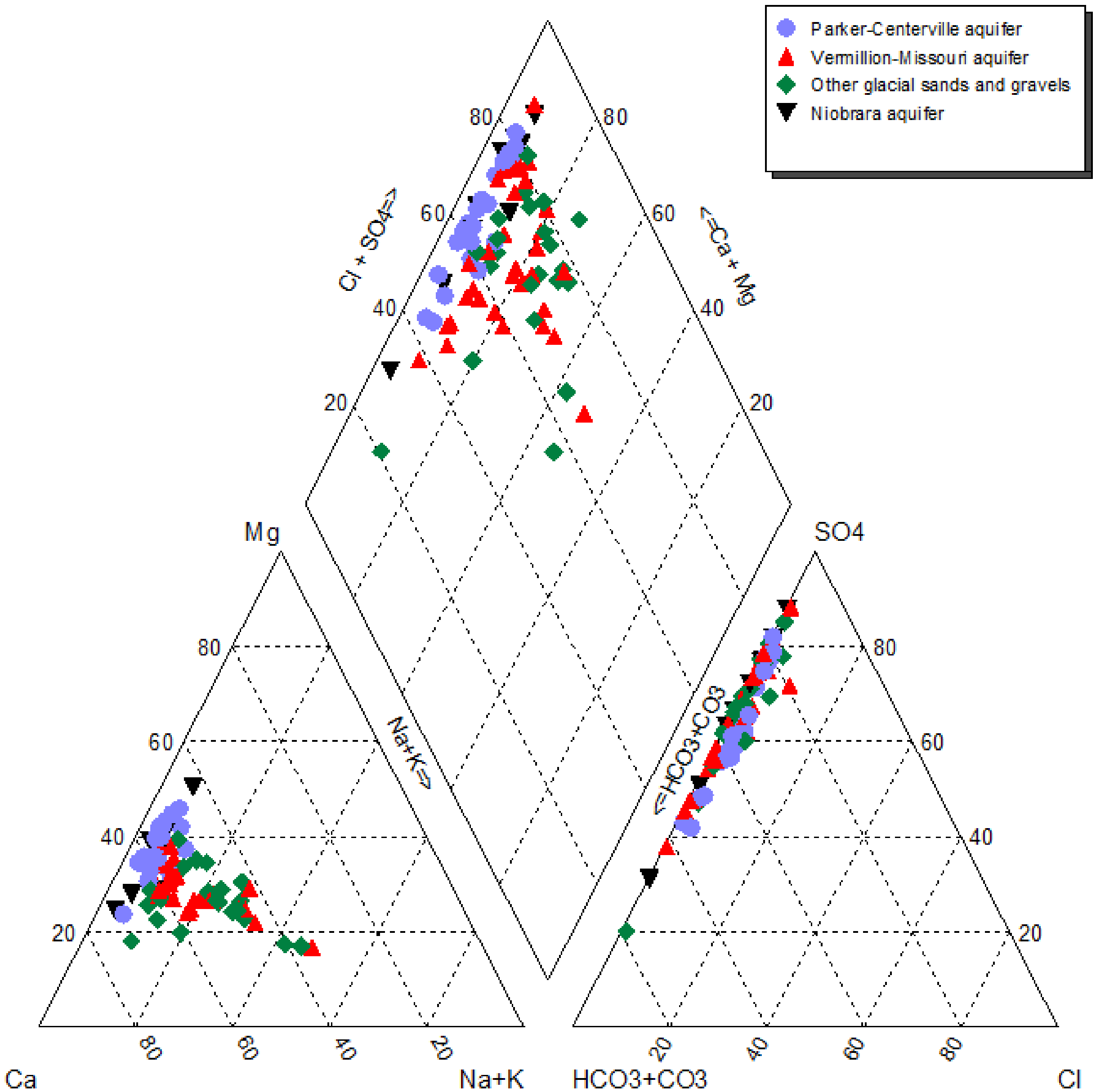


Figure 3. Piper diagram showing water quality of all sampled aquifers.

from 645 to 3,642 milligrams per liter (mg/L) and hardness ranged from 719 to 3,451 mg/L (app. B).

Glacial Aquifers

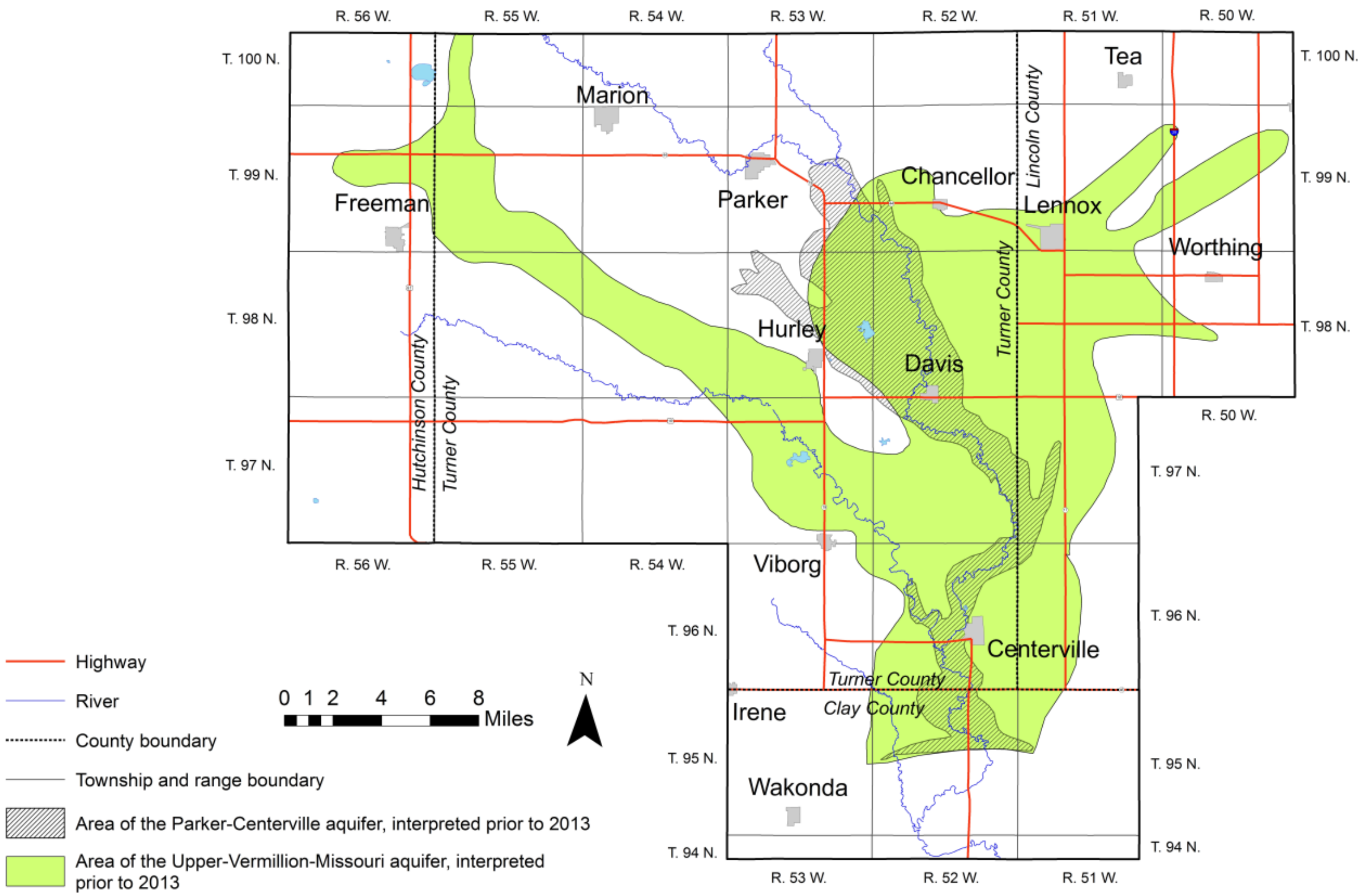
The glacially derived outwash aquifers are the primary sources of water for irrigation, domestic, municipal, industrial, and livestock use within the area of study. They include the Parker-Centerville aquifer and previously defined Upper-Vermillion-Missouri aquifer. Tipton (1957) investigated the extent and characteristics of the Parker-Centerville aquifer which is a surface outwash body. Lindgren and Hansen (1993) and Niehus (1997) examined the Upper-Vermillion-Missouri aquifer which is a primarily buried outwash body. These three investigations were the basis for the aquifer boundaries as they were known previously (fig. 4).

Results of this investigation do not support a distinction between the Upper-Vermillion-Missouri and Lower-Vermillion-Missouri aquifers. Results also show that the Upper-Vermillion-Missouri aquifer is smaller than was previously interpreted. Additionally, the boundary of the Parker-Centerville aquifer was altered as a result of this investigation. The areal extent (Hedges and others, 1982) and potentiometric surface of the Upper-Vermillion-Missouri aquifer, as they were commonly interpreted prior to work performed for this investigation, are shown on plate 7. Plate 8 shows the newly defined areal extent of these three aquifers in addition to the naming of the combined Upper-Vermillion-Missouri and Lower-Vermillion-Missouri aquifers as the Vermillion-Missouri aquifer.

VERMILLION-MISSOURI AQUIFER

The Vermillion-Missouri aquifer is an outwash body deposited in a generally north-south trending bedrock valley. The valley extends from south of Chancellor toward Centerville and southward into Clay County (compare plates 1 and 8). The outwash lies in direct contact with five bedrock units throughout the study area. Along the northern margin of the aquifer, the outwash overlies the Sioux Quartzite and the undifferentiated Cretaceous-age sediments. The main body of the aquifer is deposited directly on the Carlile Shale. Along the southern boundary of the area of study, the outwash overlies the Greenhorn Limestone. These bedrock units may act as lower confining layers. The aquifer lies in direct contact laterally with the Niobrara Formation (plates 2 and 3).

Most of the aquifer is overlain by till ranging from approximately 160 feet in thickness to nonexistent. In the eastern part of the aquifer, there is a layer of till ranging from 30 to 100 feet thick that occurs between layers of outwash that are part of aquifer (plates 2 and 3). The outwash itself is not of uniform composition having layers of clay, a variable sand-gravel ratio, and interfingering till deposits. This variability is indicative of a dynamic depositional environment developed from braided-stream-like systems or anastomosing channels (Shaver and Pusc, 1992) and multiple episodes of deposition.



Area of the Upper-Vermillion-Missouri aquifer from Buhler (2012)

Area of the Parker-Centerville aquifer from Hedges and others (1982)

Figure 4. Previously interpreted areas of the Upper-Vermillion-Missouri and Parker-Centerville aquifers.

The Vermillion-Missouri aquifer is under confined and unconfined hydraulic conditions. The elevation and configuration of the potentiometric surface of the aquifer are shown on plate 8. The general direction of ground water flow is from north to south.

North of the town of Davis, the approximate horizontal hydraulic gradient is 5 feet per mile. One mile south of Davis, an area of lower permeability is indicated by a higher hydraulic gradient. This area has an approximate hydraulic gradient of 10 feet per mile. A third area extending from 5 miles north of the town of Centerville to the southern boundary of the aquifer has an approximate hydraulic gradient of 3 feet per mile (plate 8). Similar interpretations regarding these areas of differing hydraulic gradients were presented in Buhler (2014). The distribution of irrigation and other high-capacity production wells (fig. 5) is consistent with the three areas of differing hydraulic gradient just described.

Water samples were taken from 35 wells installed in the Vermillion-Missouri aquifer and analyzed for general inorganic chemistry (app. B). The total dissolved solids ranged from 567 (well M51-2013-27) to 3,205 (well R20-2013-46) mg/L, and hardness ranged in concentration from 415 (well M51-2013-27) to 2,363 (well R20-2013-46) mg/L. The concentration of nitrate plus nitrite as nitrogen in all 35 samples was less than 0.2 mg/L (app. B) and is compliant with the South Dakota Drinking Water Standard of 10 mg/L.

Within the area interpreted to contain the Vermillion-Missouri aquifer, two wells (M51-2013-01 and M51-2013-02) in T. 96 N., R. 51 W. (plate 4) were installed at a depth consistent with surrounding sand and gravel. However, both of these wells yielded very minimal quantities of water. It is not known whether these wells are representative of low-permeability zones within the aquifer or if the wells were completed in isolated occurrences of sand and gravel that are not truly part of the aquifer.

Test hole (M51-2013-34) was drilled in section 35, T. 98 N., 52 W. (plate 4) within the area of the Vermillion-Missouri aquifer and encountered flowing conditions in a sand and gravel unit from 58 to 70 feet. This sand and gravel is not interpreted to be part of the aquifer because it is shallower than the Vermillion-Missouri aquifer and flowing conditions are not evident elsewhere in the Vermillion-Missouri aquifer.

PARKER-CENTERVILLE AQUIFER

The Parker-Centerville aquifer is a shallow deposit of outwash and alluvium. Its boundary very closely aligns with the Vermillion River Valley. Throughout most of its areal extent, the Parker-Centerville aquifer occurs at land surface with the exception of its northern boundary where it is overlain by some till.

Ground water in the Parker-Centerville aquifer is under unconfined conditions. The elevation and configuration of the water table of the Parker-Centerville aquifer are shown on plate 8. The general direction of ground water flow is from the north to south.

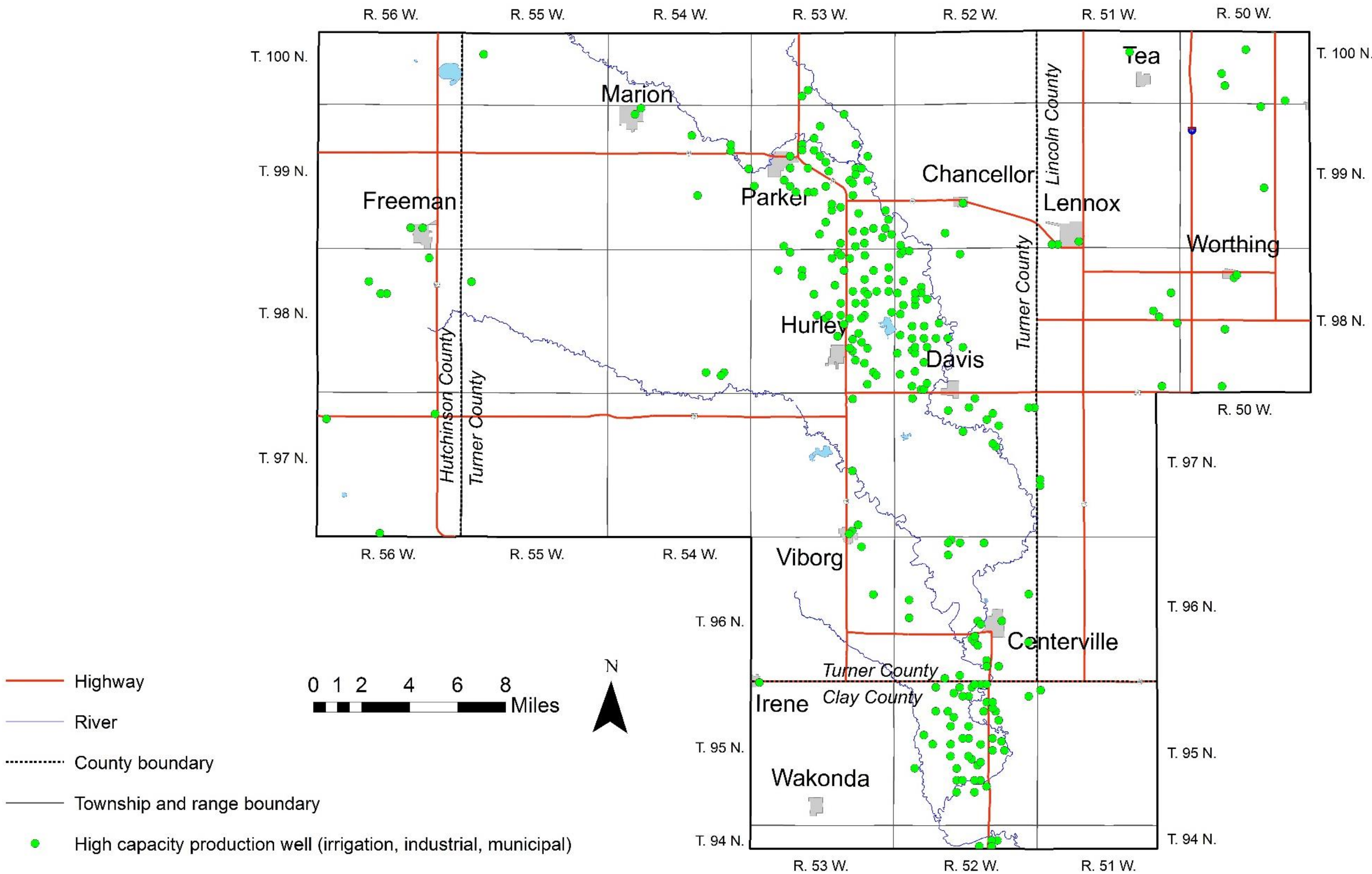


Figure 5. Locations of irrigation wells and other high capacity production wells in the study area.

Samples from 21 wells installed in the Parker-Centerville aquifer were analyzed for inorganic chemistry (app. B). The total dissolved solids ranged from 671 (well LN-78D) to 2,834 mg/L (well TU-80E), and hardness ranges in concentration from 545 (well TU- 77K) to 2,145 mg/L (well TU-80E). From 21 samples from the Parker Centerville aquifer concentrations of nitrate plus nitrite as nitrogen are less than the South Dakota Drinking Water Standard of 10 mg/L with one exception. The exception is a sample collected from Water Rights Program well TU-79C which had a nitrate plus nitrite as nitrogen concentration of 11 mg/L.

OTHER GLACIAL AQUIFERS

Occurrences of sand and gravel at various depths and locations were documented by Beffort (1969) for a portion of the study area near Lennox. However, Beffort found these sands and gravels to often be limited in lateral extent. The present investigation found similar limited occurrences of glacial sands and gravels over much of the study area. An examination of the quality of water from these other glacial sands and gravels found them to collectively contain calcium-magnesium-sulfate-bicarbonate type water (fig. 3). These sands and gravels could not be shown on a map due to their spatial variability and undocumented lateral extent.

Previous investigations included sand and gravel deposited in a bedrock channel extending from just north of Viborg to the northwest (fig. 4). The spatial relationship of the northwest-southeast trending bedrock channel to what is herein interpreted to be the Vermillion-Missouri aquifer can be seen in plates 1 and 8. Observations from drilling and measurements of water levels from wells show that there is a very poor hydraulic connection between the main body of the aquifer and the northwest-trending channel. This area of poor hydraulic connection was also noted in Buhler (2014). It is possible that the transport of sediments via glacial meltwaters resulted in a transverse hydraulic barrier (area of lower permeability) at the confluence of the two channels (Shaver and Pusc, 1992).

DISCUSSION

The Parker-Centerville aquifer, throughout most of its extent, overlies the outwash of the Vermillion-Missouri aquifer. Locally, the two outwash aquifers lie in direct contact with each other causing the aquifers to be hydraulically connected (plate 8). The Vermillion-Missouri aquifer is generally under confined conditions, except where there is direct physical connection with the Parker-Centerville aquifer and unconfined conditions exist (plates 2, 3, and 8). The Parker-Centerville aquifer is under unconfined conditions.

Water levels in the Vermillion-Missouri aquifer and the Parker-Centerville aquifer measured on April 28, 2014, can be considered to approximate static ground-water levels because aquifer-wide water use is generally low this time of the year. There is a great similarity in ground-water elevations of the Vermillion-Missouri and Parker-Centerville aquifers in the area where ground-water elevations range from approximately 1,230 to approximately 1,270 feet (pl. 8). In this same area, some direct physical connection between the two aquifers has been interpreted (pl. 8). The similarity in ground-water elevations supports the interpretation of direct connection between the two aquifers.

The saturated thickness of the Vermillion-Missouri aquifer in the study area was interpreted using test-drilling data, the elevation map of the bedrock surface (pl. 1), and the cross sections (pls. 2 and 3). Saturated thickness of the Vermillion-Missouri aquifer in the study area was interpreted to range from approximately 184 feet in well TU-77N to approximately 10 feet in wells TU-77W and M51-2013-23 (table 1, plate 9).

The three areas of differing horizontal hydraulic gradient in the Vermillion-Missouri aquifer (plate 8) are presumed to be the result of differing permeability in the outwash sediments. The area south of Davis where the hydraulic gradient is approximately 10 feet per mile is interpreted to be caused by outwash sediments having a lower permeability than either the area to the north or to the south.

Recharge to the Vermillion-Missouri aquifer and the Parker-Centerville aquifer is most likely from precipitation rather than inflow from other buried aquifers. The leakage from the overlying Parker-Centerville aquifer to the Vermillion-Missouri aquifer is the likely source of recharge where the two aquifers are in direct contact (plates 2, 3, and 8).

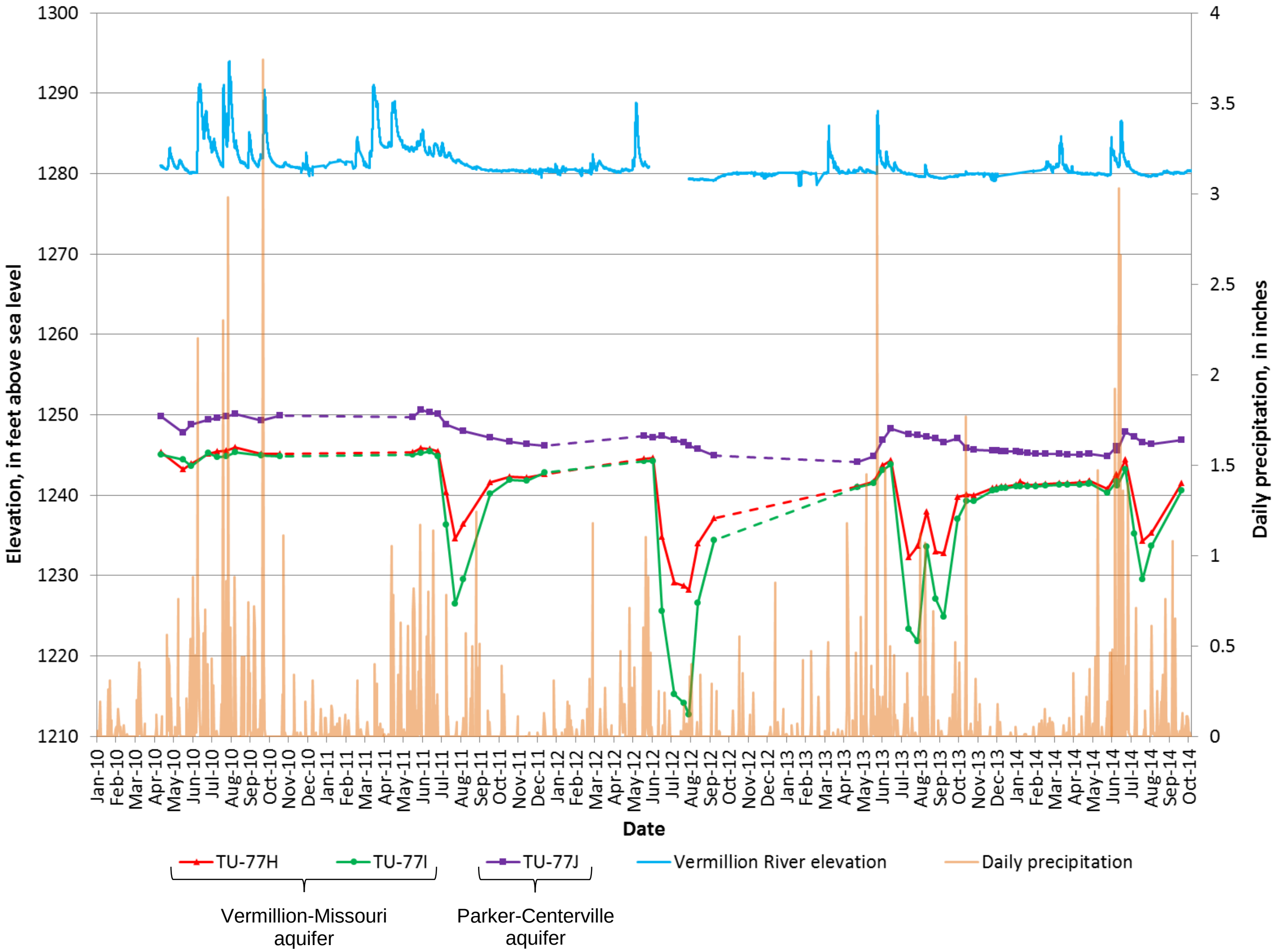
Water from the Vermillion-Missouri aquifer in the study area is discharged through generally southward movement of ground water through the aquifer and through pumping for irrigation, private and public water supplies, livestock, and an ethanol plant. Water from the Parker-Centerville aquifer is discharged through generally southward ground water flow through the aquifer, direct evaporation, transpiration by plants, seepage laterally into surface bodies of water, localized leakage downward to the Vermillion-Missouri aquifer, and through pumping for irrigation, private and public water supplies, and livestock. Figure 6 illustrates the typical water levels and response to pumping from 2010 through 2014 in the two aquifers as compared to daily precipitation and Vermillion River elevation. The elevation data for the Vermillion River were obtained from an automatic sensor operated and maintained by the Watershed Protection Program, Department of Environment and Natural Resources, located on a bridge near Chancellor. Figure 7 illustrates water levels in the two aquifers from 1980 through 2014 in comparison to annual precipitation. Drawdown shown in the Vermillion-Missouri aquifer on figures 6 and 7 is due primarily to pumping for irrigation and perhaps from the pumping of two production wells for the ethanol plant at Chancellor.

Measurement frequency in Water Rights Program wells is typically one to three times per month for seven to eight months each year but with no regular measurements during the winter. Therefore, the hydrographs do not show the exact time when irrigation and other production wells in the vicinity of measured wells started or stopped pumping. It is also notable that ground water levels in the Parker-Centerville aquifer continue to decline after irrigation pumping stops, even when the water level in the Vermillion-Missouri aquifer is significantly recovering. The reason for this simultaneous behavior in both aquifers is probably that leakage from the overlying Parker-Centerville aquifer provides recharge to the Vermillion-Missouri aquifer. Figures 6 and 7 show a similar pattern of water-level fluctuation in the Vermillion River and the Parker-Centerville aquifer. Based on the limited data available, the Vermillion River is probably a recharge source to

Table 1. Estimated saturated thickness of the Vermillion-Missouri aquifer

Well name	Location				Estimated elevation of the bottom of the outwash	Estimated saturated thickness, in feet, on 4-14-2014
	Quarter section[1]	Section	Township	Range		
M51-2013-48	SW SW SW NW	1	95 N	52 W	1039	150
CL-80K	NE NE NE NE	12	95 N	52 W	1115	74
R20-2013-44	NW NW NE NW	17	95 N	52 W	1059	114
M51-2013-50	NW NW NW NE	19	95 N	52 W	1060	102
CL-66AR	NE NE NE NE	21	95 N	52 W	987	180
M51-2013-02	SW SW SW SW	7	96 N	51W	1005	180
M51-2013-01	SE SE NE SE	18	96 N	51W	991	179
M51-2013-10	SE SE NE SE	18	96 N	51 W	991	182
R20-2013-45	SW NW NW SW	19	96 N	51 W	999	137
M51-2013-45	NE NE NW NW	1	96 N	52 W	990	156
TU-77M	NW NW NW NW	10	96 N	52 W	1027	116
M51-2013-06	NE NW NW NW	16	96 N	52 W	1070	120
R20-2013-43	NW NE NE NW	29	96 N	52 W	1062	121
TU-77N	SW SW SW SW	34	96 N	52 W	995	184
M51-2013-47	SE NE NE NW	35	96 N	52 W	1036	101
LN-78B	NW NW NW NW	19	97 N	51 W	1009	82
R20-2013-40	SW SW NW NE	29	97 N	51 W	1020	79
TU-77L	SW SW SW SW	1	97 N	52 W	994	132
TU-80H	SW SW SW SW	20	97 N	52 W	1026	143
R20-2013-46	SW SW SW SW	20	97 N	52 W	1029	138
TU-78B	NW NW NW NW	24	97 N	52 W	986	160
TU-80I	SW SW SW SW	26	97 N	52 W	1059	98
R20-2013-54	NW NW NE NE	33	97 N	52 W	1044	96
M51-2013-16	SW SW NW SW	19	98 N	51 W	1035	118
R20-2013-04	NE NE NE NW	11	98 N	52 W	1047	137
TU-77F	SW SW SW SW	17	98 N	52 W	1047	126
TU-77G	SW SW SW SW	17	98 N	52 W	1047	126
TU-77W	NE NE NE NE	22	98 N	52 W	1126	10
TU-77H	NW NW NW NW	32	98 N	52 W	1060	78
TU-77I	NW NW NW NW	32	98 N	52 W	1060	78
M51-2013-28	NW NW NE NE	33	98 N	52 W	1012	122
TU-77Y	NW NW NW NW	35	98 N	52 W	1001	117
M51-2013-23	NE NW NE NW	3	98 N	53 W	1212	10
M51-2013-29	SE SW SE SE	10	98 N	53 W	1096	126
TU-77D	NW NW NW NW	14	98 N	53 W	1062	146?
M51-2013-27	NE NE SE SE	24	98 N	53 W	1043	100
M51-2013-09	SE NE NE SE	26	98 N	53 W	1140	65?
TU-77B	NE NE NE NE	36	99 N	53 W	1130	40

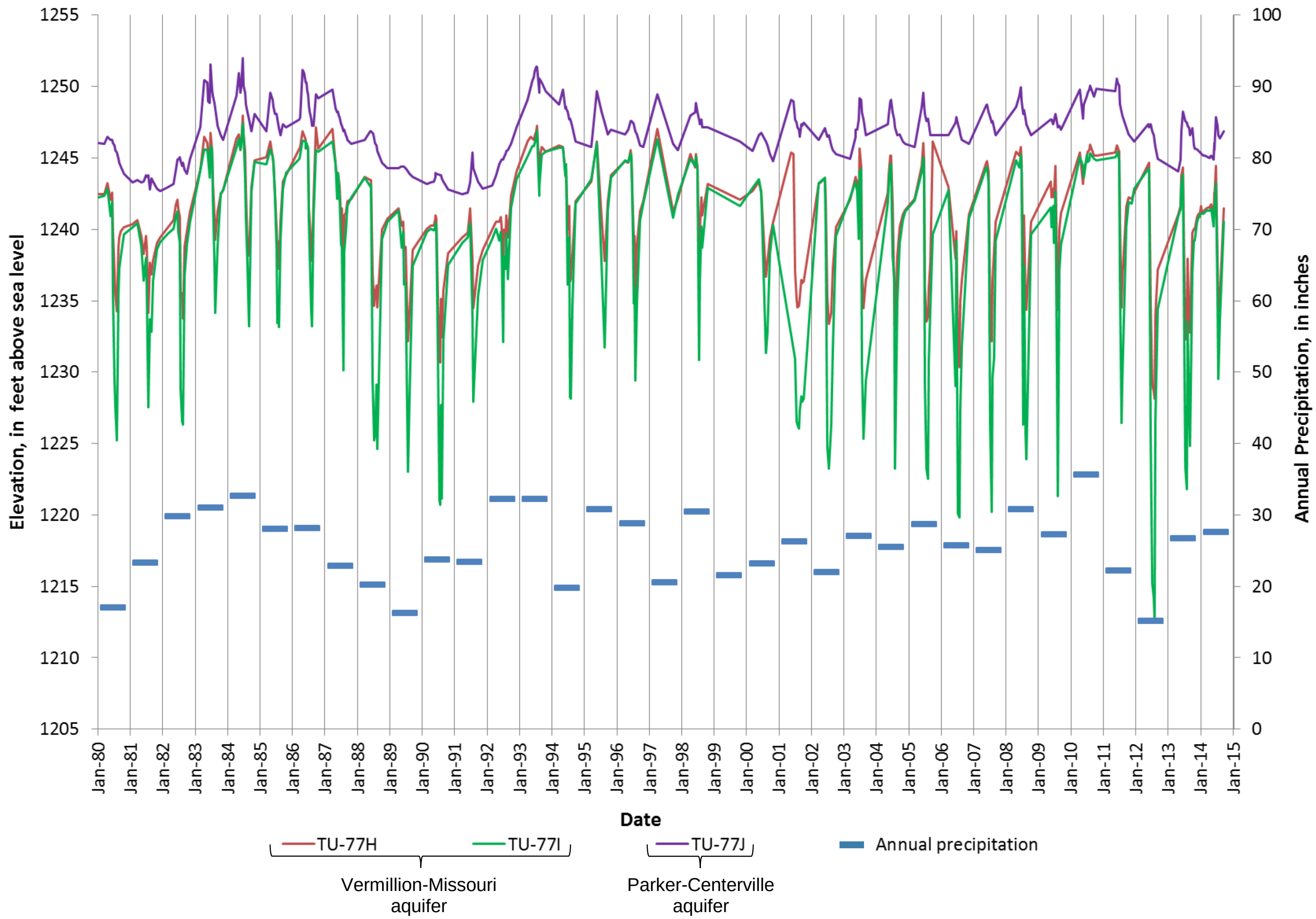
[1] Using the first well in the table (M51-2013-48) as an example, the quarter-section portion of the location would be read as the SW¼ of the SW¼ of the SW¼ of the NW¼.



Vermillion River elevation data measured from a bridge located at NW¼ NE¼ NE¼ NE¼, sec. 25, T. 99 N., R. 53. W.

Daily precipitation data from climate station Centerville 6 SE located at NW¼ NW¼ SW¼ SW¼, sec. 17, T. 95 N., R. 51 W.

Figure 6. Graph showing Vermillion River elevation, daily precipitation from climate station Centerville 6 SE, and water levels in wells TU-77H, TU-77I, and TU-77J, 2010 through 2014.



Annual precipitation data from climate station Centerville 6 SE which is located at NW¼ NW¼ SW¼ SW¼, sec. 17, T. 95 N., R. 51 W.

Figure 7. Graph showing annual precipitation from climate station Centerville 6 SE and water levels in wells TU-77H, TU-77I, and TU-77J, 1980 through 2014.

the Parker-Centerville aquifer in the growing season, and a discharge area for ground water in the non-growing season.

The results of ground-water analyses in the study area were compared for concentrations of total dissolved solids and major ions (plates 10, 11 and 12; app. B). In the Vermillion-Missouri aquifer, the highest concentrations of total dissolved solids and major ions were commonly found to be near the edges of the aquifer. In the area where the Parker-Centerville aquifer overlies the Vermillion-Missouri aquifer, concentrations of total dissolved solids and major ions have the same range.

The water quality in the Vermillion-Missouri aquifer indicates that the velocity of ground water flow is probably greater away from the edges of the aquifer. In the part of the aquifer where flow velocity is likely greater, ground water has a shorter period of contact with the sand and gravel. Therefore, the dissolving process has less time to act on the minerals in the outwash. This factor probably accounts for lower concentrations of total dissolved solids and major ions away from the edges of the aquifer.

Locally, the Niobrara Formation lies in direct contact with the Vermillion-Missouri and Parker-Centerville aquifers (plates 1, 2, 3, and 8). However, the water-level data and water quality analyses do not indicate that ground water from the Niobrara Formation has a significant influence on the Vermillion-Missouri or Parker-Centerville aquifers (plates 10, 11, and 12).

A well monitored by the Water Rights Program (TU-77B) has been assumed to be monitoring the Vermillion-Missouri aquifer. Cross sections A-A’ and BB-BB’ (plates 2 and 3), in conjunction with the map of bedrock topography (plate 1), show that it may be reasonable to interpret that the sand and gravel in this well is part of the Vermillion-Missouri aquifer. However, the water level from this well is lower than the interpreted potentiometric surface to the south (plate 8) when it would be expected to be higher, under static conditions, than water levels to the south in the aquifer. The lower water level in this well as compared to the larger body of the aquifer to the south may be the result of a lower permeability zone in the sand and gravel separating the area of well TU-77B from the aquifer to the south. It may also be because the sand and gravel in well TU-77B represents an aquifer that is largely unconnected to the Vermillion-Missouri aquifer. The water level from this well was not used in interpreting the potentiometric surface for the Vermillion-Missouri aquifer on plate 8.

CONCLUSIONS

Prior to work performed for this study, the Upper-Vermillion-Missouri aquifer and its southern counterpart, the Lower-Vermillion-Missouri aquifer, were considered to be two hydrogeologic units. However, results of this study show that the two are actually a single hydrogeologic unit, herein named the Vermillion-Missouri aquifer. The drilling and hydrogeologic data generated through this study provide sufficient information available to alter the aquifer areas and names shown on figure 4 to those shown on plate 8.

The Upper-Vermillion-Missouri aquifer within the area of study previously had a delineated areal extent of 318 square miles while the newly interpreted Vermillion-Missouri aquifer now has an area of 172 square miles within the area of study. The Parker-Centerville aquifer was previously defined as 76 square miles within the study area but it now is interpreted to include an area of 56 square miles.

Work performed for this study leads to the conclusion that the sand and gravel deposit coincident with the northwest-southeast trending bedrock valley northwest of Viborg (plate 1) is not part of the Vermillion-Missouri aquifer. This conclusion is supported by the high lateral ground-water gradient shown east-northeast of Viborg on plate 7 and test drilling that indicates the presence of clayey outwash sediment in the same area.

Interpretation of the drilling data reveals that there are local connections between the Parker-Centerville aquifer and the Vermillion-Missouri aquifer. Plate 8 shows the observed areas of physical connection between the two aquifers. These connections probably act as zones of recharge for the buried Vermillion-Missouri aquifer.

The quality of water in the Vermillion-Missouri and Parker-Centerville aquifers meets the South Dakota Drinking Water Standard with exception of a single observed nitrate-nitrogen concentration of 11 mg/L in Water Rights Program well TU-79C. Calcium and sulfate are the dominant ions in the ground water from the Vermillion-Missouri and Parker-Centerville aquifers. Both aquifers have similar concentrations of total dissolved solids. Total dissolved solids ranged from 567 to 3,205 mg/L in the Vermillion-Missouri aquifer and from 671 to 2,834 mg/L in the Parker Centerville aquifer. The ground water from both aquifers can be described as low salinity to slightly saline. Hardness of ground water from the Vermillion-Missouri aquifer ranged from 415 to 2,363 mg/L. Hardness in the Parker-Centerville aquifer ranged from 545 to 2,145 mg/L. Both are classified as very hard (Durfor and Becker, 1964).

Further work is needed to more completely document the relationship between the Vermillion-Missouri aquifer, the Parker-Centerville aquifer, and the Vermillion River. Work should address leakage between the two aquifers, the recharge-discharge relationship between the Parker-Centerville aquifer and the Vermillion River, and the zones of lower hydraulic conductivity in the two aquifers and their areal extents. The work should include year-round documentation of ground-water levels and water quality. To definitively determine the existence of hydraulic barriers and low permeability zones, and their influence on general hydrogeology of the aquifers studied, it is necessary to perform aquifer tests in the future in conjunction with more test drilling and well installation.

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Appendix A. Ground-water elevations

Well name	Location				Elevation of casing top[2]	Date and elevation of water in feet above sea level												
	Quarter section[1]	Section	Township	Range		11-26-2013	12-3-013	12-10-2013	12-17-2013	1-3-2014	1-9-2014	1-21-2014	2-3-2014	2-19-2014	3-13-2014	3-26-2014	4-14-2014	4-28-2014
Vermillion-Missouri aquifer																		
M51-2013-48	SW SW SW NW	1	95 N	52 W	1234.11	Not measured	1179.00	1178.91	1178.84	1178.97	1178.86	1178.77	1178.69	1178.70	1178.67	1178.85	1179.04	1179.26
CL-80K	NE NE NE NE	12	95 N	52 W	1254.17	1177.70	1177.94	1177.84	1177.69	1178.32	1177.99	1177.60	1177.65	1177.63	1177.70	1178.05	1177.52	1178.03
R20-2013-44	NW NW NE NW	17	95 N	52 W	1231.98	1172.81	1173.24	1173.01	1172.85	1173.25	1172.99	1172.54	1172.69	1172.74	1172.78	1173.18	1172.75	1173.34
M51-2013-50	NW NW NW NE	19	95 N	52 W	1239.48	1169.73	1169.98	1169.83	1169.65	1170.10	1169.81	1169.56	1169.46	1169.60	1169.68	1169.91	1169.74	Not measured
CL-66AR	NE NE NE NE	21	95 N	52 W	1231.07	1169.57	1169.85	1169.70	1169.56	1170.11	1169.81	1169.42	1169.50	1169.47	1169.58	1169.99	1169.48	1169.94
M51-2013-02	SW SW SW SW	7	96 N	51W	1255.30	1189.82	1190.01	1189.97	1189.92	1189.99	1189.94	1189.76	1189.85	1189.91	1189.92	Not measured	1189.84	1190.11
M51-2013-01	SE SE NE SE	18	96 N	51W	1263.78	1187.64	1187.77	1187.69	1187.66	1187.99	1187.80	1187.77	1187.47	1187.76	1187.69	1187.82	1187.51	1187.67
M51-2013-10	SE SE NE SE	18	96 N	51 W	1264.01	1188.11	1188.29	1188.22	1188.18	1188.48	1188.33	1188.17	1188.15	1188.22	1188.21	1188.34	1188.02	1188.28
R20-2013-45	SW NW NW SW	19	96 N	51 W	1245.06	1186.33	1185.33	1186.41	1186.34	1186.71	1186.53	1186.31	1186.35	1186.38	1186.40	1186.55	1186.21	1186.51
M51-2013-45	NE NE NW NW	1	96 N	52 W	1237.66	Not measured	Not measured	Not measured	Not measured	1194.75	1194.70	1194.64	1194.66	1194.75	1194.72	1194.76	1194.68	1194.97
TU-77M	NW NW NW NW	10	96 N	52 W	1251.27	1192.96	1193.16	1193.11	1193.11	1193.19	1193.14	1193.06	1193.06	1193.19	1193.15	1193.19	1193.09	1193.33
M51-2013-06	NE NW NW NW	16	96 N	52 W	1247.12	1189.85	1190.11	1190.03	1190.01	1190.08	1190.02	1189.94	1189.93	1190.04	1190.00	1190.06	1190.08	1190.21
R20-2013-43	NW NE NE NW	29	96 N	52 W	1229.20	1184.15	1184.34	1184.24	1184.18	1184.31	1184.21	1184.05	1184.08	1184.13	1184.14	1184.26	1184.11	1184.38
TU-77N	SW SW SW SW	34	96 N	52 W	1187.75	1179.69	1179.65	1179.56	1179.54	1179.51	1179.45	1179.41	1179.35	1179.30	1179.34	1179.46	1179.56	1179.52
M51-2013-47	SE NE NE NW	35	96 N	52 W	1228.82	Not measured	1182.37	1182.27	1182.20	1182.36	1182.24	1182.04	1182.11	1182.11	1182.14	1182.32	1182.16	1182.42
LN-78B	NW NW NW NW	19	97 N	51 W	1225.52	1205.02	1205.21	1205.22	1205.27	1205.42	1205.38	1205.37	1205.39	1205.50	1205.51	1205.56	1205.48	1205.70
R20-2013-40	SW SW NW NE	29	97 N	51 W	1247.33	1200.54	1200.71	1200.69	1200.72	1200.68	1200.88	1200.79	1200.81	1200.93	Not measured	1200.93	1200.87	1201.21
TU-77L	SW SW SW SW	1	97 N	52 W	1239.63	1227.24	1227.47	1227.58	1227.67	1227.93	1227.91	1227.77	1227.95	1228.10	1228.16	1228.21	1228.14	1228.29
TU-80H	SW SW SW SW	20	97 N	52 W	1279.92	1196.96	1197.17	1197.07	1197.20	1197.67	1197.17	1197.02	1197.07	1197.15	1197.20	1197.17	1197.07	1197.35
R20-2013-46	SW SW SW SW	20	97 N	52 W	1276.79	1198.72	1199.17	Not measured	1199.28	Not measured	1199.00	Not measured	1198.96	1199.04	Not measured	1199.08	1199.04	1198.68
TU-78B	NW NW NW NW	24	97 N	52 W	1228.57	1206.19	1206.39	1206.38	1206.42	1206.57	1206.54	1206.52	1206.52	1206.64	1206.67	1206.71	1206.61	1206.83
TU-80I	SW SW SW SW	26	97 N	52 W	1261.19	1196.78	1196.97	1196.89	1196.90	1196.99	1196.94	1196.88	1196.88	1196.98	1196.97	1196.99	1196.90	1197.15
R20-2013-54	NW NW NE NE	33	97 N	52 W	1266.72	Not measured	Not measured	Not measured	Not measured	1195.89	1195.83	1195.76	1195.76	1195.88	1195.83	1195.86	1195.75	1196.01
M51-2013-16	SW SW NW SW	19	98 N	51 W	1288.28	1238.75	1239.13	1239.29	Not measured	1239.80	1239.86	1240.00	1240.06	1240.26	1240.33	1240.37	1240.31	1240.48
R20-2013-04	NE NE NE NW	11	98 N	52 W	1318.66	1243.11	1243.62	1243.78	1243.97	1244.51	1244.53	1244.64	1244.79	1245.04	1245.09	1245.16	1245.03	1245.33
TU-77F	SW SW SW SW	17	98 N	52 W	1264.89	1244.01	1244.71	1244.98	1244.99	1244.56	1244.87	1244.77	1244.51	1244.99	Not measured	1244.52	1244.60	1244.64
TU-77G	SW SW SW SW	17	98 N	52 W	1265.55	1244.30	1244.64	1244.90	1244.95	1245.05	1245.03	1244.95	1244.90	1245.05	1245.40	1245.03	1244.94	1245.00
TU-77W	NE NE NE NE	22	98 N	52 W	1283.14	1239.87	1240.16	1240.35	1240.41	1240.68	1240.67	1240.66	1240.72	1240.84	1240.95	1240.94	1240.89	1240.99
TU-77H	NW NW NW NW	32	98 N	52 W	1253.96	1240.87	1240.99	1241.10	1241.11	1241.25	1241.66	1241.28	1241.27	1241.36	1241.46	1241.52	1241.54	1241.68
TU-77I	NW NW NW NW	32	98 N	52 W	1254.83	1240.52	1240.71	1240.87	1240.89	1241.10	1241.09	1241.08	1241.08	1241.19	1241.29	1241.32	1241.30	1241.41
M51-2013-28	NW NW NE NE	33	98 N	52 W	1253.58	1237.33	1237.55	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	1238.24	1238.36
TU-77Y	NW NW NW NW	35	98 N	52 W	1263.89	1235.69	1235.95	1236.11	1236.18	1236.44	1236.44	1236.49	1236.49	1236.62	1236.72	1236.74	1236.70	1236.81
M51-2013-23	NE NW NE NW	3	98 N	53 W	1291.62	1274.27	1274.44	Not measured	1274.50	Not measured	1274.67	Not measured	1274.67	1274.64	1274.79	1274.76	1274.66	1274.70
M51-2013-29	SE SW SE SE	10	98 N	53 W	1273.47	1256.86	1257.04	1257.14	1257.17	1257.31	1257.33	1257.30	1257.29	1257.38	1257.39	1257.47	1257.40	1257.50
TU-77D	NW NW NW NW	14	98 N	53 W	1273.33	Not measured	1255.88	1255.94	1255.97	1256.18	1256.12	1256.13	1256.09	1256.19	1256.18	1256.18	1256.21	1256.30
M51-2013-27	NE NE SE SE	24	98 N	53 W	1255.73	1243.85	1244.11	1244.05	1244.29	1244.47	1244.44	1244.41	1244.36	1244.50	1244.54	1244.54	1244.50	1244.57
M51-2013-09	SE NE NE SE	26	98 N	53 W	1257.36	1248.75	1247.82	Not measured	Not measured	Not measured	Not measured	1247.94	1247.84	1247.83	1247.94	1248.10	1248.36	1248.63
TU-77B	NE NE NE NE	36	99 N	53 W	1290.11	1256.04	1256.59	1256.69	1256.72	1257.10	1257.06	1256.75	1257.09	1256.94	1256.96	1256.85	1256.53	1256.70

Appendix A – continued

Well name	Location				Elevation of casing top[2]	Date and elevation of water in feet above sea level												
	Quarter section[1]	Section	Township	Range		11-26-2013	12-3-013	12-10-2013	12-17-2013	1-3-2014	1-9-2014	1-21-2014	2-3-2014	2-19-2014	3-13-2014	3-26-2014	4-14-2014	4-28-2014
Parker-Centerville aquifer																		
M51-2013-53	NW SE SE SW	2	96 N	52 W	1212.07	1200.76	1200.76	1200.71	1200.81	1200.95	1200.94	1200.89	1201.00	1201.10	1201.52	1201.60	1201.20	1201.07
LN-78A	NW NW NW NW	19	97 N	51 W	1225.48	1216.83	Not measured	1216.76	1216.72	1216.73	1216.70	1216.67	1216.67	1216.78	1216.92	1216.99	1217.02	1217.07
LN-78D	SW SW SW SW	30	97 N	51 W	1221.60	Not measured	1210.55	1210.39	1210.38	1210.36	1210.24	1210.24	1210.28	1210.27	Not measured	Not measured	1210.68	Not measured
TU-80G	SE NE NE SE	5	97 N	52 W	1244.50	1235.04	1235.09	1235.07	1235.17	1235.30	Not measured	1235.39	1235.44	1235.42	1235.58	1235.88	1235.64	1235.60
TU-77K	NE NE NW NE	10	97 N	52 W	1240.10	1227.80	1227.81	1227.78	Not measured	1228.02	1228.03	1228.09	1228.18	1228.35	1228.51	1228.76	1228.44	1228.33
TU-78A	NW NW NW NW	24	97 N	52 W	1228.27	1219.13	1219.17	1219.16	1219.30	1219.47	1219.52	1219.70	1219.82	1220.03	1220.26	1220.14	1219.67	1219.58
TU-80F	SE SE SE SE	7	98 N	52 W	1265.76	1258.81	1258.78	Not measured	1258.65	Not measured	Not measured	Not measured	1258.38	1258.37	1258.34	1258.34	1258.28	1258.43
TU-77J	NW NW NW NW	32	98 N	52 W	1254.07	1245.58	1245.54	1245.48	1245.43	1245.40	1245.33	1245.26	1245.16	1245.16	1245.10	1245.07	1245.00	1245.12
TU-56D	SW SW SW NW	1	98 N	53 W	1286.30	1270.44	1270.49	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured	Not measured
M51-2013-26	NW SW SW SW	2	98 N	53 W	1281.26	1262.61	1262.77	1262.83	1262.94	1263.17	1263.21	Not measured	1263.32	1263.30	Not measured	Not measured	1263.56	1263.67
TU-79C	SE SE SW SW	5	98 N	53 W	1302.73	1290.63	1290.65	1290.59	1290.54	1290.61	1290.42	1290.44	1290.24	1290.21	1290.04	1290.03	1290.00	1290.11
TU-80E	NW NW NW NW	10	98 N	53 W	1279.83	1274.61	1274.61	1274.43	1274.53	1274.55	1273.88	1273.90	1273.94	1274.48	1273.46	1273.93	1274.31	1274.87
TU-77C	SW SW SW SW	12	98 N	53 W	1274.42	1255.48	1255.52	1255.50	1255.57	1255.67	1255.65	1255.72	1255.73	1255.78	1255.84	1255.87	1255.91	1256.08
TU-56H	NW NW NW NE	13	98 N	53 W	1275.10	1257.62	1257.71	1257.68	1257.79	1257.88	1257.93	1257.95	1257.95	1257.95	1258.09	1258.14	1258.18	1258.20
M51-2013-31	SW SW SW NW	13	98 N	53 W	1268.74	1251.79	1251.83	1251.83	1251.84	1251.94	1251.92	1251.95	1251.89	1251.94	1251.92	1252.07	1252.21	1252.33
TU-79F	SW SW SW SW	15	98 N	53 W	1269.36	1262.87	1263.06	1262.86	1262.91	1262.95	1262.73	1262.69	1262.41	1262.43	1262.40	1262.41	1263.40	1263.42
TU-56F	NE NE NE NE	16	98 N	53 W	1276.58	1265.88	1265.95	1266.05	1266.03	1266.35	1266.31	Not measured	Not measured	1266.73	1266.93	1267.04	1267.18	1267.32
TU-77E	NE NE NE NW	26	98 N	53 W	1261.08	1250.82	1250.90	1250.92	1250.97	1251.01	1251.06	1250.96	1250.92	1250.95	1250.99	1251.11	1251.66	1251.56
R20-2013-47	SE SE NE NE	23	99 N	53 W	1299.96	1284.90	1284.94	1284.94	1284.93	1284.92	1284.97	1284.92	1284.90	1284.88	1285.03	1285.28	1285.11	1285.05
TU-77A	NE NE NE NW	23	99 N	53 W	1311.27	1288.63	1289.69	1289.69	1289.73	1289.76	1289.77	1289.75	1289.74	1289.74	1289.81	1289.87	1289.83	1289.75
TU-80D	SE SE SE SE	27	99 N	53 W	1295.92	1280.03	1280.08	1280.07	1280.06	1280.14	Not measured	Not measured	1280.02	1280.07	1280.02	1280.04	1280.05	1280.07
TU-79A	SE SE SE SE	28	99 N	53 W	1318.25	1292.58	1292.56	1292.51	1292.49	1292.50	1292.39	1292.29	1292.14	1292.07	1291.95	1291.94	1291.95	1291.67
TU-79E	NE NE NE NE	35	99 N	53 W	1296.97	1280.66	1280.67	1280.62	1280.65	1280.68	1280.48	1280.40	1280.32	1280.26	1280.21	1280.17	1280.08	1280.08
Niobrara aquifer																		
R20-2013-41	SW SE SE SE	8	95 N	51 W	1302.95	1289.45	1289.53	1289.29	1289.04	1289.23	1288.96	1290.02	1288.57	1288.48	1288.41	1288.29	1288.46	1288.47
M51-2013-51	NW NW NE NE	24	95 N	53 W	1266.51	1245.14	1245.26	1245.22	1245.21	1245.28	1245.21	1245.21	1245.14	1245.35	1245.18	1245.31	1244.91	1245.08
R20-2013-37	NE NE NE NW	33	96 N	51 W	1302.81	1290.46	1290.50	1290.38	1290.23	1290.21	1290.05	1289.83	1289.82	1289.78	1289.87	1289.76	1289.61	1289.68
M51-2013-05	SE SE SW SW	19	96 N	52 W	1264.90	1242.55	1242.76	1242.63	1242.49	1242.57	1242.33	1242.15	1242.04	1241.99	1242.02	1242.19	1242.08	1242.38
M51-2013-04	NE NE NW NW	31	96 N	52 W	1249.09	1228.75	1228.79	1228.62	1228.43	1228.44	1228.24	1227.99	1227.78	1227.73	1227.60	1227.55	1227.28	1227.38
M51-2013-35	NE NW NE NE	10	97 N	53 W	1299.51	1263.52	1263.71	1263.51	1263.35	1263.49	1263.24	1263.03	1262.78	1262.79	1262.56	1262.53	1262.07	1262.13
R20-2013-48	NW NW NW NE	18	97 N	52 W	1295.23	Not measured	1279.73	1279.43	Not measured	1279.49	1278.44	1277.89	1277.51	1277.12	1277.04	1277.60	1277.44	1277.84
TU-79D	SE SE SW SW	5	98 N	53 W	1302.61	1285.25	1286.76	1287.89	1287.64	Not measured	1290.25	1290.29	1290.87	1290.76	1291.20	1291.26	1291.31	1291.37
M51-2013-08	NE NW NW NW	21	98 N	53 W	1303.01	1283.82	1283.88	1283.70	1283.59	1283.48	1283.52	1283.08	1282.94	1282.80	1282.61	1282.56	1282.33	1282.37

Appendix A – continued

Well name	Location				Elevation of casing top[2]	Date and elevation of water in feet above sea level												
	Quarter section[1]	Section	Township	Range		11-26-2013	12-3-013	12-10-2013	12-17-2013	1-3-2014	1-9-2014	1-21-2014	2-3-2014	2-19-2014	3-13-2014	3-26-2014	4-14-2014	4-28-2014
Other glacial sands and gravels																		
M51-2013-07	NE NW NW NW	16	96 N	52 W	1247.08	1229.38	1223.17	1222.94	1222.82	1223.26	1222.99	1222.78	1222.69	1223.01	1222.89	1222.96	1222.47	1223.01
LN-78E	NW NW NW NW	20	97 N	51 W	1246.02	1203.82	1204.01	1204.01	1204.06	1204.21	1204.17	1204.16	1204.18	1204.29	1204.30	1204.32	1204.27	1204.52
TU-77Z	SE SE SE SE	5	97 N	53 W	1280.29	1258.94	1259.07	1258.98	1258.93	1258.89	1258.81	1258.72	1258.59	1258.63	1258.42	1258.34	1258.17	1258.18
M51-2013-40	SE SW SW SW	13	97 N	53 W	1261.76	Not measured	Not measured	Not measured	Not measured	1237.26	1237.14	1237.11	1236.92	1236.98	1236.89	1236.91	1236.66	1236.73
M51-2013-42	SE SE SE SE	17	97 N	53 W	1280.48	1260.67	1261.29	1261.66	1261.82	1262.33	1262.52	1262.51	1262.54	1262.54	1262.56	1262.54	1262.47	1262.58
M51-2013-37	SE SW SW SE	20	97 N	53 W	1291.15	1245.35	1245.46	1245.37	1245.33	1245.34	1245.24	1245.19	1245.09	Not measured	1245.12	1245.13	1244.94	1245.11
M51-2013-12	SW SW SW SE	22	97 N	53 W	1279.24	1244.79	1244.90	1244.82	1244.79	1244.80	1244.69	1244.63	1244.53	1244.58	1244.56	1244.58	1244.41	1244.58
R20-2013-52	NE SE NE NE	26	97 N	53 W	1268.35	Not measured	Not measured	Not measured	Not measured	1244.30	1244.21	1244.13	1244.06	1244.12	1244.09	1244.11	1243.96	1244.12
TU-77T	SE SE SE SE	27	97 N	53 W	1282.38	1244.57	1244.68	1244.61	1244.56	1244.58	1244.50	1244.42	1244.33	1244.40	1244.36	1244.37	1244.20	1244.38
LN-80O	SE SE SE SE	14	98 N	51 W	1310.03	1255.77	1256.17	1256.06	1256.10	1256.24	1256.23	1256.23	1256.33	1256.57	1256.54	1256.50	1256.50	1256.81
M51-2013-15	SW SW NW SW	19	98 N	51 W	1287.96	1269.05	1269.26	1269.09	Not measured	1269.04	1268.98	1268.98	1268.94	1269.05	1268.96	1268.88	1268.83	1269.05
R20-2013-50	NW SW SW NW	28	98 N	51 W	1286.78	Not measured	1238.96	1239.17	1239.37	1239.87	1239.95	1240.10	1240.30	1240.56	1240.69	1240.79	1240.78	1240.97
TU-80B	NE NE NE NE	2	98 N	52 W	1331.58	1246.44	1246.96	1247.07	1247.28	1247.84	1247.82	1247.94	1248.06	1248.32	1248.36	1248.45	1248.33	1248.61
M51-2013-18	SE NE SE NE	5	98 N	52 W	1298.94	1266.95	1267.44	1267.65	Not measured	1268.34	1268.32	1268.36	1268.48	1268.71	1268.61	1268.89	1269.02	1269.42
R20-2013-58	NW NE NW NW	14	98 N	52 W	1301.16	Not measured	1242.20	1242.41	1242.71	1243.07	1243.21	1243.43	1243.59	1243.81	1244.32	1244.84	1245.65	1246.54
TU-77X	NW NW NW NW	35	98 N	52 W	1265.89	1253.84	1253.89	1253.88	1253.88	1253.91	1253.89	1253.84	1253.80	1253.86	1253.79	1253.79	1253.70	1253.77
LN-81G	NW NW SW SW	35	99 N	51 W	1339.51	1267.60	1267.97	1268.10	1268.27	1268.66	1268.69	1268.83	1268.93	1269.13	1269.14	1269.16	1269.12	1269.28
TU-77P	NE NE NE NE	19	99 N	52 W	1343.64	1291.70	1292.10	1292.21	1292.29	1292.58	1292.62	1292.72	1292.82	1293.22	1293.35	1293.37	1293.34	1293.43
M51-2013-11	SE SE SE NE	27	99 N	52 W	1352.17	1292.24	1293.10	1292.86	1292.88	1292.93	1292.90	1292.97	1292.98	1293.35	1293.17	1293.06	1293.05	1293.54
TU-77U	NE NE NE NE	31	99 N	52 W	1308.47	1255.76	1256.37	1256.47	1256.53	1257.00	1257.01	1256.65	1257.00	1256.89	1256.96	1256.88	1256.51	1256.75
TU-77V	SE SE SE SE	33	99 N	52 W	1327.85	1248.47	1249.56	Not measured	1249.75	1250.81	1250.62	Not measured	1250.73	1251.25	1251.34	1251.55	1250.97	1251.80
M51-2013-17	SE SW SW SE	34	99 N	52 W	1327.45	1244.53	1245.04	1245.16	1245.35	Not measured	Not measured	Not measured	1246.15	1246.43	1246.50	1246.60	1246.43	1246.78

[1] Using the first well in the table (M51-2013-48) as an example, the quarter-section portion of the location would be read as the SW¼ of the SW¼ of the SW¼ of the NW¼.

[2] Casing-top elevation is in feet above sea level.

Appendix B. Results of water-quality analyses

Well name	Location				Sample collection date	Lab pH	Conductivity (micromhos per centimeter)	Constituent and concentration in milligrams per liter															
	Quarter section[1]	Section	Township	Range				Total dissolved solids	Calcium	Magnesium	Sodium	Potassium	Chloride	Total alkalinity	Bicarbonate	Sulfate	Fluoride	Ammonia	Nitrate + nitrite as nitrogen	Iron	Manganese	Total phosphorous	Hardness
Vermillion-Missouri aquifer																							
M51-2013-48	SW SW SW NW	1	95 N	52 W	10-31-2013	8.24	1520	1072	121	34.9	183	10.4	29	280	342	505	0.53	0.5	<0.2	3.84	0.80	0.426	446
CL-80K	NE NE NE NE	12	95 N	52 W	10-7-2013	7.70	3100	3040	486	192	95	15.7	4	399	487	1730	0.44	0.25	<0.2	5.46	2.73	0.108	2004
R20-2013-44	NW NW NE NW	17	95 N	52 W	9-23-2013	7.66	1990	1692	280	93.1	56.6	13.0	9	258	315	932	0.29	0.98	<0.2	5.08	1.04	0.020	1082
M51-2013-50	NW NW NW NE	19	95 N	52 W	11-20-2013	7.40	2520	2240	407	147	60.8	18.6	4	340	415	1270	0.45	1.9	<0.2	9.22	1.55	0.029	1621
M51-2013-10	SE SE NE SE	18	96 N	51 W	9-24-2013	7.88	2370	2013	336	106	136	16.2	9	342	417	1090	0.29	1.5	<0.2	7.36	1.21	0.127	1275
R20-2013-45	SW NW NW SW	19	96 N	51 W	9-23-2013	7.80	2160	1715	247	80.1	169	10.8	19	399	487	848	0.31	0.64	<0.2	5.08	0.92	0.022	946
M51-2013-45	NE NE NW NW	1	96 N	52W	10-28-2013	7.67	1200	861	132	44.9	62.4	7.4	10	268	327	360	0.25	0.29	<0.2	4.44	0.92	0.039	514
TU-77M	NW NW NW NW	10	96 N	52 W	10-7-2013	7.84	1250	966	181	57.1	38.3	8.5	<3	306	373	389	0.27	0.78	<0.2	4.98	1.43	0.028	687
M51-2013-06	NE NW NW NW	16	96 N	52 W	9-24-2013	7.91	2700	2406	409	150	73.8	23.4	4	431	526	1290	0.36	2.19	<0.2	11.7	0.85	0.037	1639
R20-2013-43	NW NE NE NW	29	96 N	52 W	9-23-2013	7.54	2150	1785	300	104	65.7	21.2	3	411	501	884	0.22	1.77	<0.2	8.79	0.62	0.040	1177
M51-2013-47	SE NE NE NW	35	96 N	52 W	10-24-2013	7.75	1210	880	163	43.8	57.9	8.4	7	288	351	390	0.28	0.59	<0.2	4.17	1.28	0.023	587
LN-78B	NW NW NW NW	19	97 N	51 W	10-7-2013	7.71	2050	1703	286	84.6	106	11.0	11	423	516	798	0.32	0.38	<0.2	4.35	1.88	0.111	1062
R20-2013-40	SW SW NW NE	29	97 N	51 W	9-24-2013	8.00	2430	2082	341	108	148	13.7	9	388	473	1080	0.27	1.05	<0.2	3.35	1.41	0.040	1296
TU-77L	SW SW SW SW	1	97 N	52 W	10-16-2013	7.75	1820	1409	235	75.6	114	10.8	26	323	394	711	0.39	0.77	<0.2	2.01	2.84	0.064	898
R20-2013-46	SW SW SW SW	20	97 N	52 W	9-25-2013	7.71	3230	3205	574	226	51.9	14.3	13	248	302	1920	1.26	<0.05	0.9	0.59	0.34	0.040	2363
TU-80H	SW SW SW SW	20	97 N	52 W	10-8-2013	7.57	2730	2558	406	174	60.0	20.9	<3	419	511	1480	0.35	0.73	<0.2	12.6	0.39	0.065	1730
TU-78B	NW NW NW NW	24	97 N	52 W	10-23-2013	7.76	1260	954	179	50.0	45.9	7.1	7	316	386	401	0.28	0.61	<0.2	3.43	1.61	0.076	653
TU-80I	SW SW SW SW	26	97 N	52 W	10-7-2013	7.87	939	696	138	39.8	23.9	5.8	<3	284	346	249	0.25	0.34	<0.2	1.84	1.27	0.059	508
R20-2013-54	NW NW NE NE	33	97 N	52 W	10-21-2013	8.16	1430	1074	146	48.7	107	10.1	7	280	342	553	0.32	0.97	<0.2	0.06	1.31	0.026	565
M51-2013-16	SW SW NW SW	19	98 W	51 W	9-26-2013	7.83	2010	1626	304	82.5	109	11.0	12	381	465	766	0.33	0.48	<0.2	0.52	3.18	0.084	1099
R20-2013-04	NE NE NE NW	11	98 N	52 W	9-30-2013	7.82	2990	2408	391	118	328	21.7	31	643	784	1320	0.51	0.36	0.6	13.9	6.12	3.04	1462
TU-77G	SW SW SW SW	17	98 N	52 W	10-15-2013	7.84	1270	979	184	68.1	27.5	7.1	<3	320	390	438	0.23	0.34	<0.2	1.06	2.09	0.054	740
TU-77F	SW SW SW SW	17	98 N	52 W	10-23-2013	8.12	875	615	122	34.6	24.4	8.6	<3	263	321	212	0.33	0.72	<0.2	0.16	1.68	0.026	447
TU-77W	NE NE NE NE	22	98 N	52 W	10-15-2013	8.20	2400	2030	229	96.9	175	11.8	32	341	416	1100	0.37	0.26	<0.2	1.34	4.40	0.234	971
TU-77I	NW NW NW NW	32	98 N	52 W	10-16-2013	7.92	1420	1091	208	73.3	42.8	8.2	<3	308	376	526	0.27	0.92	<0.2	1.63	2.32	0.028	821
TU-77H	NW NW NW NW	32	98 N	52 W	10-22-2013	8.07	929	649	139	38.0	24.4	6.8	4	277	338	249	0.29	0.64	<0.2	<0.03	1.85	0.031	503
M51-2013-28	NW NW NE NE	33	98 N	52 W	9-26-2013	7.42	1220	823	166	54.5	34.3	6.8	4	322	393	372	0.28	0.71	<0.2	0.43	1.63	0.068	639
TU-77Y	NW NW NW NW	35	98 N	52 W	10-16-2013	7.92	1610	1235	210	65.7	97.6	9.9	20	305	372	606	0.33	0.62	<0.2	2.18	2.21	0.055	795
M51-2013-23	NE NW NE NW	3	98 N	53 W	9-30-2013	7.93	1850	1454	263	88.5	116	19.2	4	357	436	711	0.43	3.81	<0.2	11.6	2.33	0.842	1021
M51-2013-29	SE SW SE SE	10	98 N	53 W	10-1-2013	7.63	2220	1958	318	146	34.7	7.9	10	342	417	1010	0.42	<0.05	<0.2	2.52	2.26	0.086	1395
TU-77D	NW NW NW NW	14	98 N	53 W	10-15-2013	7.74	1730	1442	259	108	25.3	6.9	3	294	359	788	0.23	<0.05	<0.2	1.68	1.55	0.089	1091
M51-2013-27	NE NE SE SE	24	98 N	53 W	10-3-2013	7.85	820	567	110	34.2	14.2	5.2	<3	295	360	175	0.21	0.84	<0.2	1.52	1.02	0.111	415
M51-2013-09	SE NE NE SE	26	98 N	53 W	10-3-2013	7.54	2200	1772	305	78.3	107	13.0	84	261	318	928	0.40	0.17	<0.2	5.29	1.24	0.066	1084
CO-91-62	NW NW NW NW	36	98 N	53 W	10-16-2013	7.30	2440	2167	426	132	47.2	14.9	10	361	440	1240	0.41	0.66	<0.2	7.61	0.99	0.032	1607
TU-77B	NE NE NE NE	36	99 N	53 W	10-9-2013	7.88	2370	1927	292	92.3	197	12.6	59	345	421	937	0.52	0.78	<0.2	0.10	2.99	0.071	1109

Well name	Location				Sample collection date	Lab pH	Conductivity (micromhos per centimeter)	Constituent and concentration in milligrams per liter															
	Quarter section[1]	Section	Township	Range				Total dissolved solids	Calcium	Magnesium	Sodium	Potassium	Chloride	Total alkalinity	Bicarbonate	Sulfate	Fluoride	Ammonia	Nitrate + nitrite as nitrogen	Iron	Manganese	Total phosphorous	Hardness
Parker-Centerville aquifer																							
M51-2013-53	NW SE SE SW	2	96 N	52 W	11-20-2013	7.76	1300	976	166	74	39.5	6.5	21	256	312	462	0.41	0.14	<0.2	3.95	2.12	0.164	719
LN-78A	NW NW NW NW	19	97 N	51 W	10-7-2013	7.72	1220	923	151	77.8	26.3	4.8	14	296	361	403	0.40	<0.05	<0.2	5.29	1.42	0.204	697
LN-78D	SW SW SW SW	30	97 N	51 W	10-8-2013	8.03	942	671	178	62.4	14.4	6.1	6	325	396	240	0.40	<0.05	<0.2	9.86	4.20	1.66	701
TU-80G	SE NE NE SE	5	97 N	52 W	10-16-2013	7.69	1090	817	163	53.6	17.3	5.6	16	246	300	359	0.22	0.11	<0.2	4.25	0.88	0.050	628
TU-77K	NE NE NW NE	10	97 N	52 W	10-22-2013	7.91	1030	722	146	43.9	16.6	5.3	15	328	400	242	0.26	<0.05	<0.2	4.47	1.12	0.179	545
TU-78A	NW NW NW NW	24	97 N	52 W	10-8-2013	7.97	1020	756	141	52.7	16.5	4.7	10	300	366	281	0.40	<0.05	<0.2	2.69	1.42	0.096	569
TU-80F	SE SE SE SE	7	98 N	52 W	10-15-2013	7.88	1690	1370	231	134	29.0	7.8	28	342	417	696	0.55	<0.05	<0.2	12.3	2.65	0.692	1128
CO-83-159	SW SW SW SW	18	98 N	52 W	10-17-2013	7.83	1170	878	163	76.0	11.1	4.8	20	260	317	395	0.21	<0.05	<0.2	1.85	0.64	0.053	720
TU-77J	NW NW NW NW	32	98 N	52 W	10-22-2013	7.99	1000	730	144	51.8	8.0	4.6	12	239	292	312	0.19	<0.05	<0.2	1.77	0.77	0.052	573
M51-2013-26	NW SW SW SW	2	98 N	53 W	10-1-2013	7.96	1530	1259	204	103	17.7	6.1	14	239	292	624	0.24	0.08	<0.2	0.47	1.02	0.039	933
TU-79C	SE SE SW SW	5	98 N	53 W	10-10-2013	7.99	2260	2054	326	178	34.8	7.4	10	308	376	1090	0.99	<0.05	11.0	2.47	0.24	0.155	1546
TU-80E	NW NW NW NW	10	98 N	53 W	10-23-2013	7.62	3000	2834	503	216	38.1	12.0	5	371	453	1650	0.45	<0.05	<0.2	1.13	4.79	0.105	2145
TU-77C	SW SW SW SW	12	98 N	53 W	10-28-2013	7.88	1040	768	156	53.0	6.1	6.1	12	288	351	277	0.14	<0.05	<0.2	3.17	0.87	0.121	608
TU-56H	NW NW NW NE	13	98 N	53 W	10-15-2013	7.87	1240	971	167	81.6	13.2	5.2	18	246	300	484	0.20	<0.05	<0.2	1.67	0.59	0.028	753
M51-2013-31	SW SW SW NW	13	98 N	53 W	10-21-2013	7.88	1260	928	166	56.8	32.8	7.9	14	303	370	420	0.18	0.11	<0.2	2.31	0.94	0.048	648
TU-79F	SW SW SW SW	15	98 N	53 W	10-17-2013	7.50	2270	2016	442	90.1	34.5	11.2	21	296	361	1160	0.21	<0.05	<0.2	3.08	0.29	0.022	1474
TU-77E	NE NE NE NW	26	98 N	53 W	10-24-2013	7.89	1900	1652	301	113	30.6	7.4	19	260	317	908	0.24	<0.05	<0.2	3.45	1.54	0.043	1217
R20-2013-47	SE SE NE NE	23	99 N	53 W	9-30-2013	7.84	1260	984	180	77	13.6	5.2	23	247	301	435	0.21	<0.05	<0.2	1.71	0.98	0.077	766
TU-77A	NE NE NE NW	23	99 N	53 W	10-28-2013	7.91	1260	960	190	90.0	12.6	5.7	24	304	371	425	0.25	<0.05	<0.2	5.77	1.05	0.305	845
TU-80D	SE SE SE SE	27	99 N	53 W	10-10-2013	7.83	1300	1015	182	80.8	16.8	6.5	12	269	328	434	0.21	<0.05	<0.2	0.91	0.76	0.029	787
TU-79E	NE NE NE NE	35	99 N	53 W	10-10-2013	7.67	2090	1840	320	141	27.3	8.4	20	315	384	976	0.19	<0.05	<0.2	6.12	2.04	0.098	1379
Niobrara aquifer																							
M51-2013-51	NW NW NE NE	24	95 N	53 W	11-20-2013	7.54	2080	1764	334	98.1	60.4	21.8	4	369	450	935	0.64	1.7	<0.2	7.90	0.21	0.054	1238
R20-2013-37	NE NE NE NW	33	96 N	51 W	9-24-2013	7.72	3600	3642	784	363	83.9	19.1	<3	1403	1712	2320	1.13	0.07	<0.2	12.6	0.78	1.340	3451
M51-2013-05	SE SE SW SW	19	96 N	52 W	9-23-2013	7.80	3250	3202	530	218	61.3	15.5	4	267	326	1890	0.44	0.48	<0.2	10.4	0.50	0.059	2220
M51-2013-04	NE NE NW NW	31	96 N	52 W	9-23-2013	7.53	1620	1371	278	114	17.5	8.5	<3	367	448	699	0.70	<0.05	<0.2	2.47	0.15	0.187	1163
M51-2013-35	NE NW NE NE	10	97 N	53 W	9-25-2013	7.66	3580	3600	453	324	61.8	31.6	11	463	565	2050	0.72	0.72	<0.2	5.59	0.36	0.156	2464
R2-86-96	NE NW NE NE	18	97 N	52 W	10-8-2013	7.71	932	645	264	55.0	5.6	16.0	<3	580	708	254	0.76	<0.05	<0.2	7.33	0.88	0.649	886
R20-2013-48	NW NW NW NE	18	97 N	52 W	9-25-2013	7.73	2050	1820	331	137	15	12.8	5	303	370	992	0.53	<0.05	<0.2	2.88	0.34	0.062	1390
M51-2013-08	NE NW NW NW	21	98 N	53 W	10-1-2013	7.79	1070	822	203	51.6	12.5	10.4	4	340	415	342	0.63	0.09	<0.2	1.04	0.15	0.101	719

Appendix B – continued

Well name	Location				Sample collection date	Lab pH	Conductivity (micromhos per centimeter)	Constituent and concentration in milligrams per liter															
	Quarter section[1]	Section	Township	Range				Total dissolved solids	Calcium	Magnesium	Sodium	Potassium	Chloride	Total alkalinity	Bicarbonate	Sulfate	Fluoride	Ammonia	Nitrate + nitrite as nitrogen	Iron	Manganese	Total phosphorous	Hardness
Other glacial sands and gravels																							
M51-2013-07	NE NW NW NW	16	96 N	52 W	9-24-2013	7.50	4410	4277	554	239	376	31.8	24	428	522	2550	0.24	2.97	<0.2	4.80	4.55	0.104	2367
LN-78E	NW NW NW NW	20	97 N	51 W	10-7-2013	7.98	1850	1411	485	96.2	169	15.0	24	749	914	673	0.55	1.09	<0.2	44.8	6.79	6.13	1607
TU-77Z	SE SE SE SE	5	97 N	53 W	10-8-2013	7.49	1980	1674	314	84.1	58.4	18.6	<3	390	476	772	0.31	1.01	<0.2	9.22	0.84	0.032	1130
M51-2013-40	SE SW SW SW	13	97 N	53 W	10-3-2013	7.71	2060	1656	261	83.1	132	20.7	9	360	439	884	0.37	1.82	<0.2	6.05	0.62	0.496	994
M51-2013-42	SE SE SE SE	17	97 N	53 W	10-31-2013	7.96	1680	1214	1118	171	167	24.1	22	2198	2861	575	0.85	0.71	<0.2	42.5	23.2	8.210	3495
M51-2013-37	SE SW SW SE	20	97 N	53 W	9-25-2013	7.77	1680	1389	265	64.2	39.5	11.8	<3	307	374	677	0.69	0.79	<0.2	8.04	0.35	0.048	926
M51-2013-12	SW SW SW SE	22	97 N	53 W	9-25-2013	7.49	1730	1381	261	55.7	52.6	14.8	4	359	438	661	0.38	1.11	<0.2	4.94	0.77	0.024	881
TU-77T	SE SE SE SE	27	97 N	53 W	10-8-2013	7.83	1780	1560	290	80.8	34.2	22.3	<3	417	509	647	0.29	1.26	<0.2	7.39	0.35	0.026	1057
LN-80O	SE SE SE SE	14	98 N	51 W	10-9-2013	7.66	2550	2193	292	104	203	14.3	11	357	436	1170	0.38	1.12	<0.2	2.77	1.45	0.028	1157
M51-2013-15	SW SW NW SW	19	98 N	51 W	9-26-2013	7.43	3450	2838	452	197	173	24.8	4	444	542	1780	0.24	1.91	<0.2	4.39	3.41	0.104	1939
R20-2013-50	NW SW SW NW	28	98 N	51 W	10-21-2013	8.19	1450	1031	118	32.5	159	11.8	10	355	433	431	0.55	2.02	<0.2	0.78	0.83	0.067	428
TU-80B	NE NE NE NE	2	98 N	52 W	10-9-2013	7.78	2480	2169	370	119	190	15.6	17	496	605	1060	0.27	0.20	<0.2	2.45	1.36	0.125	1414
TU-77X	NW NW NW NW	35	98 N	52 W	10-16-2013	8.32	1480	1062	125	32.7	144	9.0	32	290	354	487	0.29	0.81	<0.2	2.65	1.42	0.246	447
TU-77R	SE SE SE SE	26	98 N	54 W	10-17-2013	7.82	2950	2765	460	214	87.4	11.1	68	386	471	1630	0.27	<0.05	<0.2	0.71	0.37	0.047	2029
TU-77S	NE NE NE NE	36	98 N	54 W	10-17-2013	7.45	2170	1783	289	97.7	121	24.9	3	304	371	1020	0.68	1.72	<0.2	9.90	0.33	0.030	1124
LN-81I	SE SE SE SE	17	99 N	50 W	10-9-2013	7.60	3750	3733	595	255	192	22.1	<3	609	743	2000	0.20	2.37	<0.2	9.16	5.6	0.089	2535
LN-81G	NW NW SW SW	35	99 N	51 W	10-9-2013	7.52	3250	3082	548	175	128	16.0	5	499	609	1670	0.18	1.34	<0.2	15.5	3.62	0.087	2088
TU-77P	NE NE NE NE	19	99 N	52 W	10-10-2013	7.95	1350	1039	168	51.9	105	13.2	<3	254	310	482	0.38	0.82	<0.2	0.88	1.40	0.062	633
M51-2013-11	SE SE SE NE	27	99 N	52 W	9-30-2013	7.59	3950	3946	822	314	213	31.1	6	1398	1706	2280	0.43	1.14	<0.2	29.7	12.00	3.89	3345
TU-77U	NE NE NE NE	31	99 N	52 W	10-9-2013	7.82	3000	2753	427	157	224	23.0	14	409	499	1340	0.22	1.12	<0.2	0.27	6.15	0.026	1712
M51-2013-17	SE SW SW SE	34	99 N	52 W	9-30-2013	7.80	2760	2370	309	93.4	232	11.5	17	391	477	1270	0.27	0.74	<0.2	1.33	0.70	0.179	1156

[1] Using the first well in the table (M51-2013-48) as an example, the quarter-section portion of the location would be read as the SW¼ of the SW¼ of the SW¼ of the NW¼.