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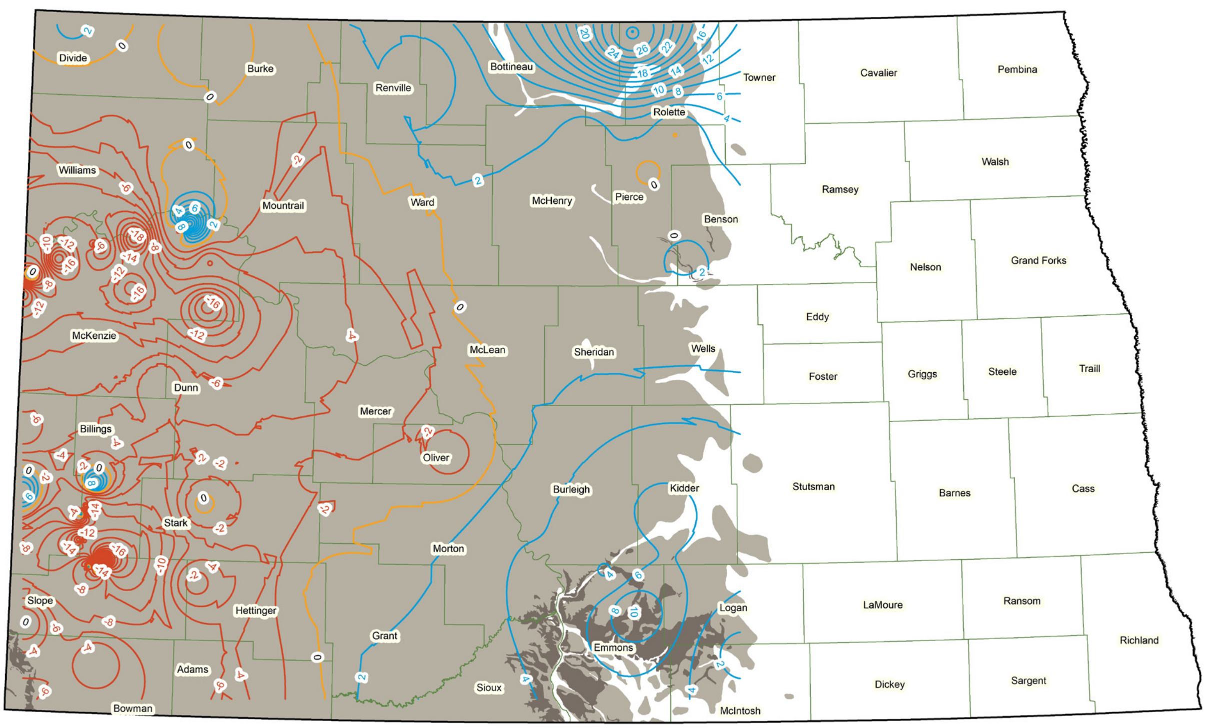
FOX HILLS – HELL CREEK AQUIFER 2016 CONDITIONS: PRESSURE HEAD AND WATER QUALITY



By
Bassel Timani, Ph.D., Water Resource Engineer

Water Resources Investigation No. 66
North Dakota State Water Commission
Project File No. 1442
2020

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INTRODUCTION

This report summarizes the 2016 conditions of the Fox Hills – Hell Creek aquifer in the western half of North Dakota (Figure 1). North Dakota lawmakers have tasked the Office of the State Engineer with monitoring, analyzing, and publishing the findings about extending the longevity and improving the conditions of flowing heads in artesian aquifers. North Dakota Century Code (N.D.C.C.) **§ 61-20-06. Duties of state engineer** states,

The state engineer shall advise the citizens of the state as to the practicability of measures affecting the underground waters of this state. The state engineer shall:

1. *Counsel and consult with the owner and assist the owner to work out the most desirable control and use of the owner's well.*
2. *Select at least three representative flowing wells in each county having that number, and as many more as it may deem advisable.*
3. *Cause the record of their flows and pressures to be taken, from time to time, to learn as much as possible of the decline, fluctuations, and permanence of the artesian supply.*
4. *Plan and conduct such other investigations as it may find advisable to ascertain the best method of prolonging the utility of the same.*
5. *Keep a record of the location, size, depth, flow, size of flow, character of water, construction, and history of all artesian wells of the state, and keep it on file for public reference.*
6. *Secure the enforcement of all laws pertaining to artesian and phreatic waters of the state.*
7. *Publish from time to time, as it may deem advantageous, bulletins containing information concerning the artesian wells and phreatic waters of the state.*

The state engineer may make such additional reasonable rules and regulations governing such wells as it shall determine.

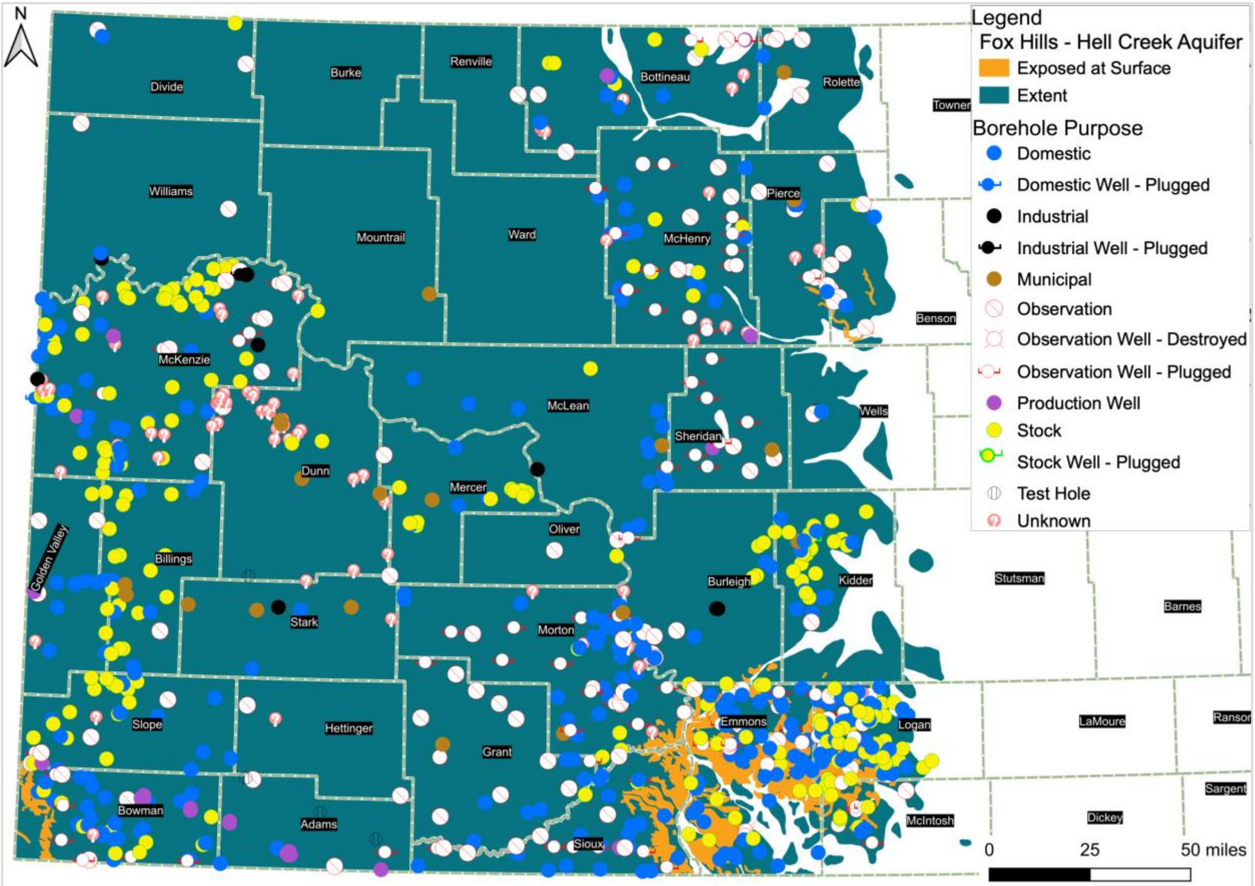

Figure 1: Extent of Fox Hills – Hell Creek Aquifer in North Dakota

N.D.C.C. § 61-20-06 dictates that the Office of State Engineer shall monitor the existing flowing artesian aquifers to learn as much as possible of the decline, fluctuations, and permanence of the artesian supply. An aquifer may have a flowing well in one location but not in another location. In this report, a flowing-head well or flowing well refers to a well that has a static potentiometric surface elevation or water level above the top of the well-casing, thereby allowing natural flow from the aquifer. Monitoring the water level in the aquifer provides the means for the Office of the State Engineer to promote water supply conservation and suggest steps to reduce the rate of decline in the aquifer's pressure head. Being a flowing artesian aquifer, the Fox Hills – Hell Creek aquifer is a valuable resource in western North Dakota. Flowing wells in low-lying areas provide some water users access to groundwater without the need for pumps.

Restrictions on large-scale water use have been applied to the Fox Hills – Hell Creek aquifer to avoid increasing the rate of aquifer pressure head decline. Increasing the rate of pressure head decline shortens the time flowing-head wells will continue to flow. Because of the small diameter construction of most flowing-head Fox Hills – Hell Creek wells, once the pressure head declines below ground surface the wells will no longer be useable as a water source. While not a water right, the flowing pressure head of Fox Hills – Hell Creek wells in low-lying areas of western North Dakota is recognized as a valuable asset to many area ranchers (Office of the State Engineer 2013).

In order to preserve flowing pressure head in low-lying areas, it is the policy of the Office of the State Engineer to restrict industrial access to the Fox Hills – Hell Creek aquifer where other suitable sources are available. The restriction is not a moratorium on future Fox Hills – Hell Creek water use, but takes into consideration the quantity of water needed and the proximity of flowing-head wells to the proposed water use (Office of the State Engineer 2013). To fulfill this responsibility, the Office of the State Engineer has monitored the trends in the aquifer's pressure head and groundwater chemistry on a decadal frequency for over 50 years. The aquifer conditions were last analyzed in 2006 (Honeyman 2007a-c). This report presents the 2016 conditions without geographically-based grouping of the wells (site locations) as done in Honeyman 2007a-c.

FOX HILLS – HELL CREEK AQUIFER

The Fox Hills – Hell Creek aquifer extends throughout western North Dakota into Montana, South Dakota, and Wyoming. The aquifer consists of the marine Fox Hills formation and the overlying non-marine Hell Creek formation. The Fox Hills formation includes sand and gravel deposits from ancestral beaches and river deltas and offshore deposits with occasional marine fossils. The Hell Creek formation, on the other hand, includes the back-beach and river flood plain landform deposits. Recharge to the aquifer most likely occurs in southwestern North Dakota (Bowman County), northwestern South Dakota, southeastern Montana, and northeastern Wyoming (Fischer 2013). Aquifer discharge occurs mainly via flowing wells. Because the uncontrolled discharge rate from all naturally flowing wells that are screened in the aquifer is larger than the recharge rate, the aquifer head continues to decline (Long et al. 2018). The total precipitation in Bowman County between 2006 and 2016 is 20% more than the total precipitation between 1996 and 2006.

Using the depths of test holes and the screen bottom of the 907 boreholes screened in the aquifer (Figure 1), the spatial distribution of the Fox Hills – Hell Creek well depths is displayed in Figure 2. In general, the aquifer is deeper in western North Dakota. The well depth ranges from less than 50 feet below ground surface along its eastern extent to about 2,000 feet below ground surface towards its western extent in North Dakota. Contoured depths close to a cluster of boreholes are more accurate than contours in areas with scarce boreholes.

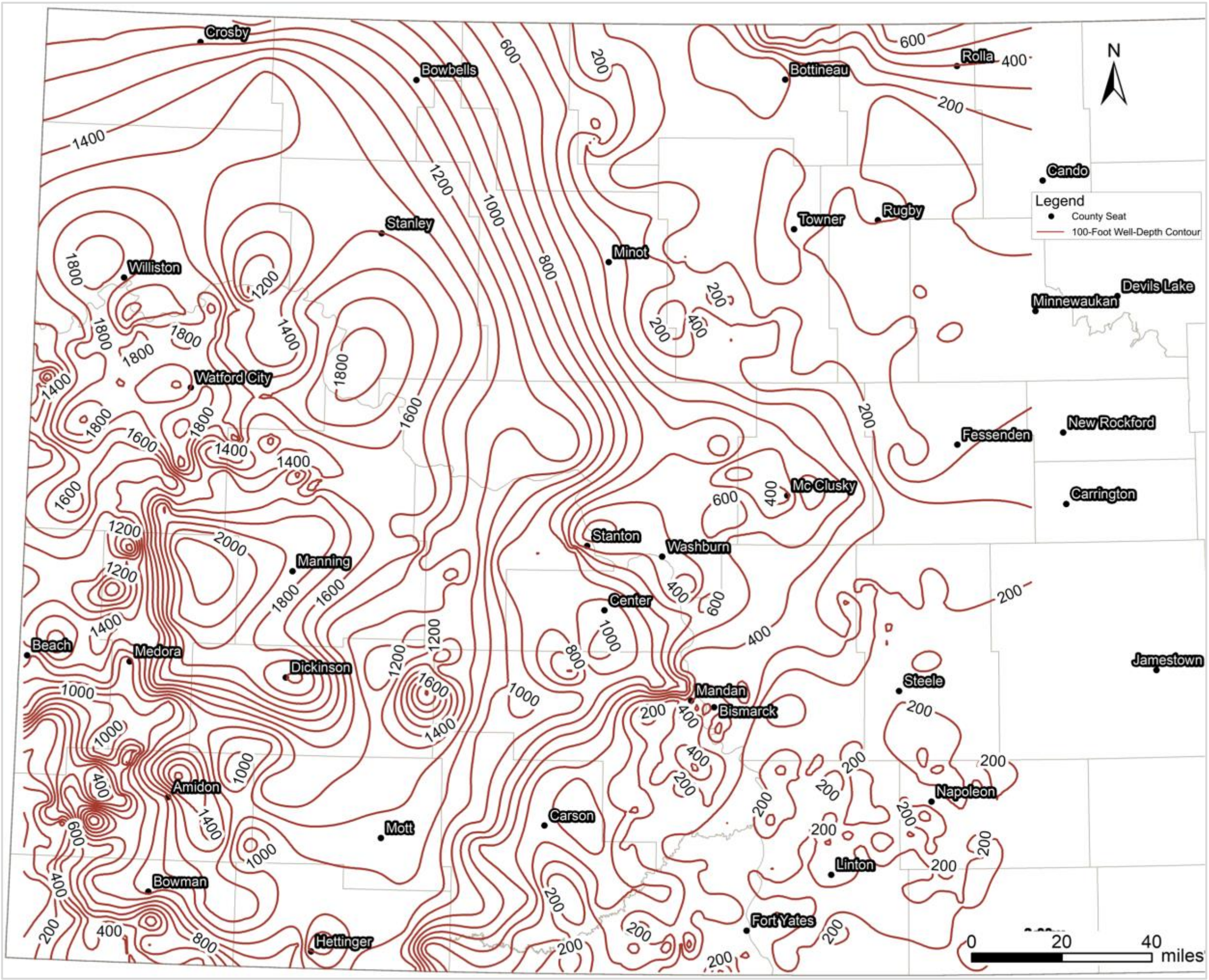

Figure 2: Depth of Wells Installed in the Fox Hills – Hell Creek Aquifer

Reported water use from the aquifer has decreased since 1990. Municipal use has decreased more than industrial water use (Figure 3). The fluctuation in the reported annual use for industrial purposes can be attributed to changes in oil activity in western North Dakota that uses water for desalinization in oil wells. The appropriated municipal water use from the aquifer has been declining since the mid 1990s because of Southwest Water Authority’s regional water supply. The reported water use before 2007 has been updated since Honeyman (2007a-c) published his findings.

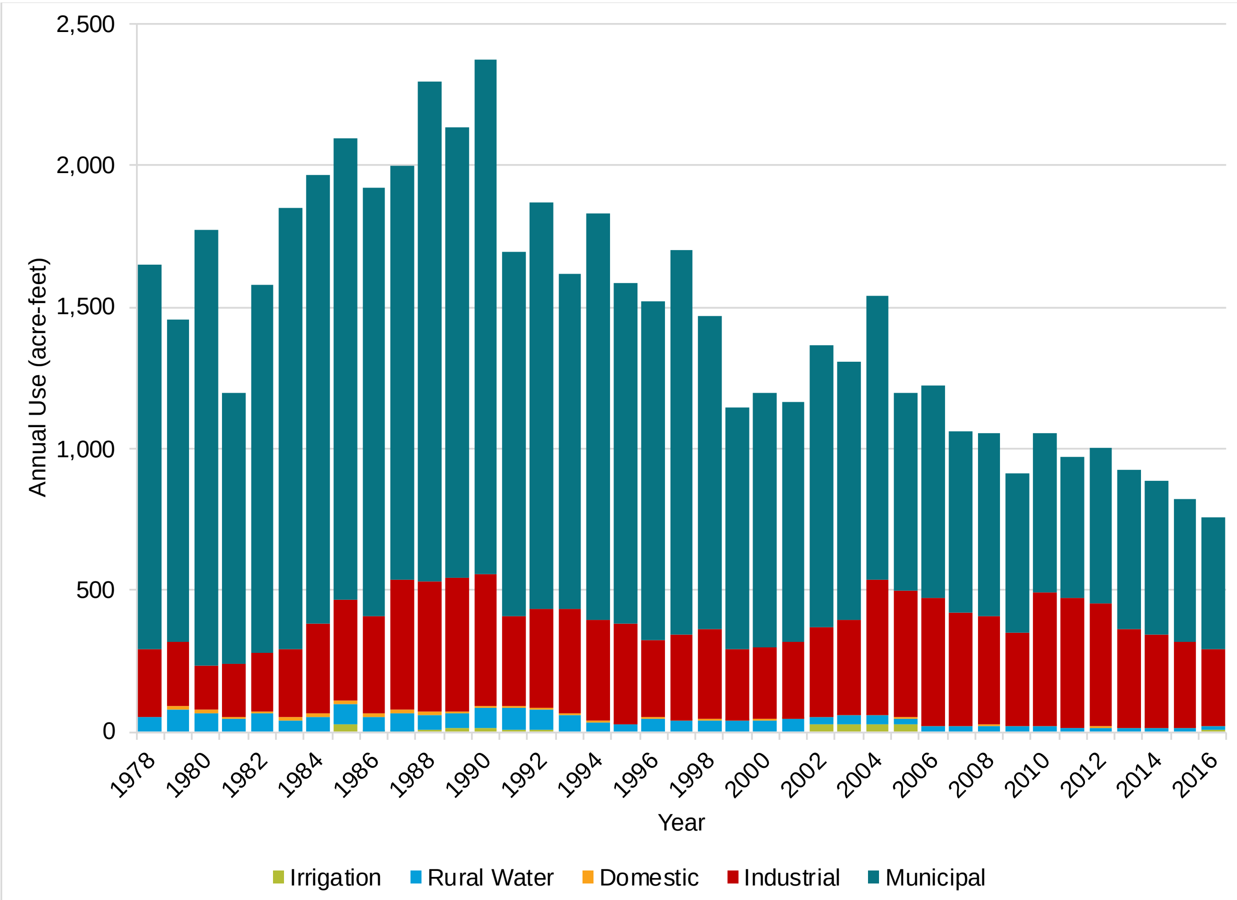

Figure 3: Reported Water Use from Fox Hills – Hell Creek Aquifer

DATA ACQUISITION

Aquifer pressure head, flow rate, and water quality samples were collected from observation and private wells for the analysis. The State Water Commission (SWC) installs and maintains observation wells for groundwater monitoring. The private wells complement the information observation wells provide. Private wells were constructed as water supply wells rather than for monitoring changes in the aquifer. Completion of a consent form was required prior to shutting in any private well to give the owner the opportunity to assess the condition of their well before volunteering to be part of this study.

The SWC measured potentiometric surface elevation or collected groundwater samples for analysis of the 2016 conditions at 107 Fox Hills – Hell Creek wells (Table 1). Additional well information is listed in the appendix. The wells include 74 SWC observation wells monitored until at least 2016. The wells also include 33 private wells (four which were not flowing). The plumbing on two of the private wells (14408510CCA and 15209824CCC) prevented measuring their shut-in pressure heads. The head at 14309014DDA dropped below ground surface prior to 2016. The appendix lists the range of dates during which potentiometric surface elevation measurements were taken during 2016 and the historic date range during which groundwater samples were collected for quality analysis, and the respective count of each event. The SWC monitors the potentiometric surface elevations and collects water samples for quality analysis on different rotations. While potentiometric surface elevations are measured on monthly, seasonal or annual basis, groundwater quality samples from a well are collected and analyzed approximately once every five years. Some of the observation wells listed in the appendix have been plugged since 2016. Burke, Bottineau, Mountrail, Ward, McLean, Sheridan, and Adams counties have no Fox Hills – Hell Creek wells that were measured as part of this study. Public data about any of the listed wells can be accessed with resources available at http://swc.nd.gov. The site location gives the legal description of a well location. For example, well 13207022BBB is located in the NW¼NW¼NW¼ of Section 22, Township 132 North, Range 70 West. The letters represent quarter sections with A, B, C, and D representing the NE, NW, SW, and SE quarters, respectively.

About 34% of the measured wells reported in Honeyman (2007a-c) were not included in this report (Figure 4) because the deteriorating conditions of the casings or the plumbing of some wells, wells no longer exist, or well owners could not be reached or abstained from signing the consent form. Figure 4 also shows the private wells that were used for the 2016 field measurements but not for 2006. The figure also displays the purpose of the private wells and if they were flowing in 2006 or 2016. Table 1 identifies the wells that were flowing in 2016 (text continues on page 11).

Table 1: Wells Used for Monitoring 2016 Conditions of Fox Hills – Hell Creek Aquifer

Site Location	County	Date Installed	Casing Material	Diameter (inches)	Screened Interval (feet bgs)	Flowing in 2016
12908023DDD	Sioux	6/5/73	PVC	1.25	138 - 142	no
12908101BAB	Sioux	6/5/73	ABS	1.25	98 - 104	no
12910434ADA2	Bowman	9/30/10	PVC	2	520 - 540	no
13008517DAA	Sioux	10/23/72	ABS	2	219 - 244	no
13008628CCC1	Sioux	6/11/73	Steel	2	406 - 424	no
13008628CCC2	Sioux	6/11/73	PVC	1.25	204 - 210	no
13108930AAA	Grant	6/16/73	Steel	2	791 - 809	no
13110207DDD1	Bowman	7/10/72	Steel	2	951 - 963	no
13207022BBB1	McIntosh	8/26/76	ABS	1.25	158 - 164	no
13209128DDD	Hettinger	8/26/68	Steel	4	NA - 1030	no
13210516BDB2	Bowman	10/3/11	PVC	2	575 - 595	no
13210516BDB3	Bowman	10/12/11	PVC	2	428 - 448	no
13308031CCD1	Sioux	5/10/73	PVC	1.25	168 - 180	no
13308312ADA1	Grant	5/16/73	ABS	1.25	218 - 230	no
13310613ADB2	Slope	7/6/77	PVC	1.25	223 - 229	no
13407515BBB	Emmons	10/24/72	ABS	1.25	97 - 103	no
13408236DCD	Sioux	8/23/71	Steel	2	145 - 157	no
13507315DCC	Logan	11/15/78	PVC	1.25	99 - 105	no
13509023BBB1	Grant	5/7/73	Steel	2	1029 - 1047	no
13509704DCA	Hettinger	9/3/68	Steel	4	1320 - 1360	no
13607316CBC1	Logan	6/12/79	PVC	1.25	158 - 164	no
13607322AAA	Logan	11/3/78	PVC	1.25	197 - 203	no
13607607BCC	Emmons	10/17/72	ABS	1.25	77 - 83	no
13607807BDB	Emmons	9/2/71	ABS	1.25	227 - 239	no
13608107DDC1	Morton	10/8/74	Steel	2	445 - 457	no

13608107DDC2	Morton	10/9/74	Steel	2	357 - 369	no
13608130BBB	Morton	5/19/11	PVC	2	150 - 160	no
13608225DDA1	Morton	5/17/11	PVC	2	267 - 287	no
13608225DDD	Morton	5/18/11	PVC	2	142 - 152	no
13610211BBB	Slope	NA	Steel	1.25	NA	yes
13610211DAD	Slope	1/1/69	Steel	1.25	NA	yes
13610221DBD	Slope	1/1/69	Steel	1.25	NA	yes
13610324AAB	Slope	1/1/69	Steel	1.25	800 - 840	yes
13610324ACC	Slope	NA	Steel	1.25	NA	yes
13710206CAC	Billings	NA	Steel	1.25	NA	yes
13710207AAD	Billings	9/29/80	Steel	1.25	1010 - 1040	yes
13710312BAB	G. Valley	NA	Steel	1.25	NA	yes
13808002BCA2	Burleigh	5/4/06	PVC	2	433 - 453	no
13808002BCA3	Burleigh	8/27/08	PVC	2	70 - 80	no
13810301BAB	G. Valley	NA	Steel	1.25	NA	yes
13907317CDBA	Kidder	10/19/98	PVC	2	228 - 238	no
13907317CDBA2	Kidder	10/20/98	PVC	2	125 - 135	no
13907927DCA	Burleigh	3/25/76	ABS	1.25	412 - 418	no
13908731DDA	Morton	6/28/13	PVC	2	1034 - 1054	no
13909607AA	Stark	6/8/81	Steel	8	1713 - 1962	no
13910217CAC2	Billings	7/25/73	Steel	1.25	1054 - 1104	yes
13910220DAD	Billings	NA	Steel	1.25	NA	yes
13910231BBB	Billings	NA	Steel	1.25	NA	yes
14010210DCA	Billings	6/21/84	Steel	8	1155 - 1280	yes
14010530CCC6	G. Valley	9/27/84	Steel	4	1050 - 1130	no
14109019CCD	Mercer	4/19/67	Steel	4	1142 - 1142	no
14208424BBA	Oliver	11/29/67	Steel	4	966 - 966	no
14308918ACC	Mercer	8/1/64	Steel	2	NA - 1380	yes
14308919ACB	Mercer	NA	Steel	2	NA - 1280	yes

14309014DDA	Mercer	11/12/74	Steel	2	1361 - 1445	no
14309024ABC	Mercer	NA	Steel	2	NA	yes
14309024BAB	Mercer	1/1/64	Steel	2	NA - 1280	yes
14310533BAB	G. Valley	8/25/75	Steel	2	1153 - 1177	no
14408510CCA	Mercer	1/1/66	Steel	2	900 - 900	no
14408914CDD	Mercer	1/1/69	Steel	0	1241 - 1281	yes
14409004BBA	Mercer	7/25/64	Steel	2	1265 - 1265	yes
14409110CBC	Dunn	11/2/76	Steel	9	1450 - 1575	yes
14410322CCD	G. Valley	NA	Steel	4	1239 - 1280	yes
14509803DDD1	McKenzie	8/14/81	Steel	2	1659 - 1683	no
14609020CCC	Mercer	6/18/68	Steel	4	1540 - 1574	no
14610227BCA	McKenzie	2/12/74	Steel	1.25	1260 - 1310	yes
14710020DDB2	McKenzie	11/28/72	Steel	1.25	1290 - 1330	yes
14807336AAA	Wells	6/4/14	PVC	2	48 - 53	no
14909509CDD	McKenzie	7/17/84	Steel	2	1539 - 1564	no
14910406ADB	McKenzie	7/6/71	Steel	1.25	1192 - 1220	yes
15009922BBA1	McKenzie	9/1/80	Steel	2	1742 - 1772	no
15010404AAB	McKenzie	7/25/77	Steel	2	1340 - 1380	yes
15107009ACA1	Benson	6/16/15	PVC	2	55 - 60	no
15109504DBD2	McKenzie	5/26/83	Steel	2	1407 - 1432	no
15110311AAA	McKenzie	5/7/85	Steel	4	1680 - 1753	no
15110404AAA	McKenzie	12/26/73	Steel	1.25	1342 - 1405	yes
15207104BBA1	Benson	6/2/15	PVC	2	68 - 73	no
15207105ADA1	Benson	6/2/15	PVC	2	40 - 45	no
15207105CCCC1	Benson	8/4/98	PVC	2	72 - 77	no
15209824CCC	McKenzie	6/21/75	Steel	2	1680 - 1730	no
15209903ABC	McKenzie	8/19/74	Steel	2	1560 - 1610	yes
15210114DCA	McKenzie	7/3/76	Steel	2	1735 - 1855	yes
15210115ADD	McKenzie	6/22/82	Steel	2.5	1532 - 1547	yes

15307119AAAA1	Benson	8/5/98	PVC	2	73.5 - 78.5	no
15307129AAB1	Benson	6/16/15	PVC	2	63 - 68	no
15307133DDD1	Benson	6/17/15	PVC	2	46 - 51	no
15307133DDD2	Benson	6/17/15	PVC	2	16 - 21	no
15307203DDD	Pierce	11/15/68	PVC	1.25	58 - 61	no
15309423CCC1	McKenzie	8/5/80	Steel	2	1743 - 1767	no
15309611ADA	McKenzie	6/17/87	Steel	4	1289 - 1370	no
15309620DCB1	McKenzie	7/28/84	Steel	4	1433 - 1500	no
15407111AAD1	Benson	8/14/68	ABS	1.25	42 - 45	no
15407836AAA3	McHenry	7/31/00	PVC	2	282 - 292	no
15407836AAA4	McHenry	8/1/00	PVC	2	211 - 221	no
15407836AAA5	McHenry	8/2/00	PVC	2	107 - 112	no
15607312CCC	Pierce	10/25/67	PVC	4	73 - 78	no
15607722CCC	McHenry	7/30/75	ABS	1.25	78 - 81	no
15609620DCD	Williams	9/6/84	Steel	4	1302 - 1350	no
15707534BBB	McHenry	8/20/12	PVC	2	174 - 179	no
15807116DDD	Pierce	8/9/68	ABS	1.25	67 - 73	no
15807624DAC3	McHenry	6/4/03	PVC	2	70 - 80	no
15910216AAD	Williams	6/6/85	Steel	4	1302 - 1372	no
16108424DDD	Renville	8/30/79	Steel	2	470 - 488	no
16209523CCC1	Divide	6/17/85	Steel	4	1440 - 1475	no
16307311CCC1	Rolette	8/22/78	Steel	2	406 - 412	no
16307311CCC2	Rolette	8/23/78	Steel	2	269 - 275	no
16310116DDD	Divide	10/4/82	Steel	2	1055 - 1079	no

G. Valley = Golden Valley; NA = not available; bgs = below ground surface

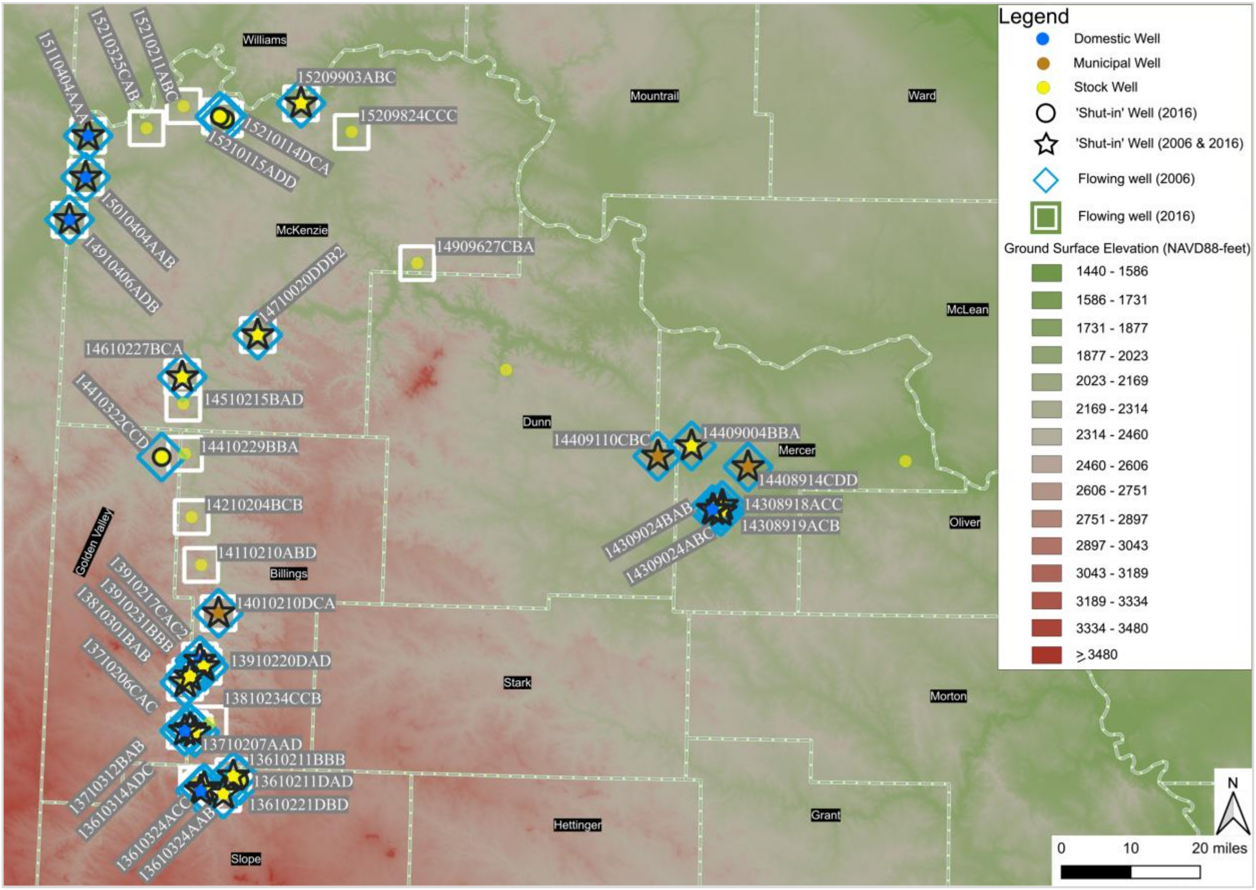

Figure 4: Participant Fox Hills – Hell Creek Wells Imposed on Ground Surface Elevation

AQUIFER PRESSURE HEAD AND UNCONTROLLED FLOW RATE

To obtain analogous iso-potentiometric contours between 2006 and 2016 (Figure 5), only the 65 wells that were measured in both 2006 and 2016 were included. These include observation wells, and flowing and non-flowing private wells. None of the observation wells monitored by the SWC are flowing above ground surface. By placing observation wells in locations higher in elevation than the pressure head, the SWC can monitor the aquifer conditions without the added cost of maintaining flowing wells during the winter season and eliminate the negative impacts (e.g. increasing soil saturation, soil salinity, and soil erosion) on the local landscape. All of the flowing (private) wells are located in low-lying areas along the Little Missouri River, Yellowstone River, or Knife River. A pressure gauge was used to measure pressure head at the wells after an 'unrestricted' flow rate measurement was taken.

The iso-potentiometric contours indicate no drastic changes in pressure head over the past decade. There is more variation in the iso-potentiometric contours over the western portion of the aquifer where the pressure head declined between 2006 and 2016 than over its eastern portion (Figure 5). The figure clearly shows that the aquifer head continues to decline over the area where it is naturally flowing and the aquifer head is recovering where the aquifer head is below ground surface. The more data points available for constructing the iso-potentiometric contours, the more accurate the contours are expected to be. Sampling the same locations over a long period of time is better for comparative analysis. Having more data points with diverse and wide spatial distribution can improve the approximation of the contours. The SWC continues to replace old wells and maintain a spatial distribution of sample points over all portions of the aquifer to accommodate the duties of the State Engineer as described in N.D.C.C. **§ 61-20-06**.

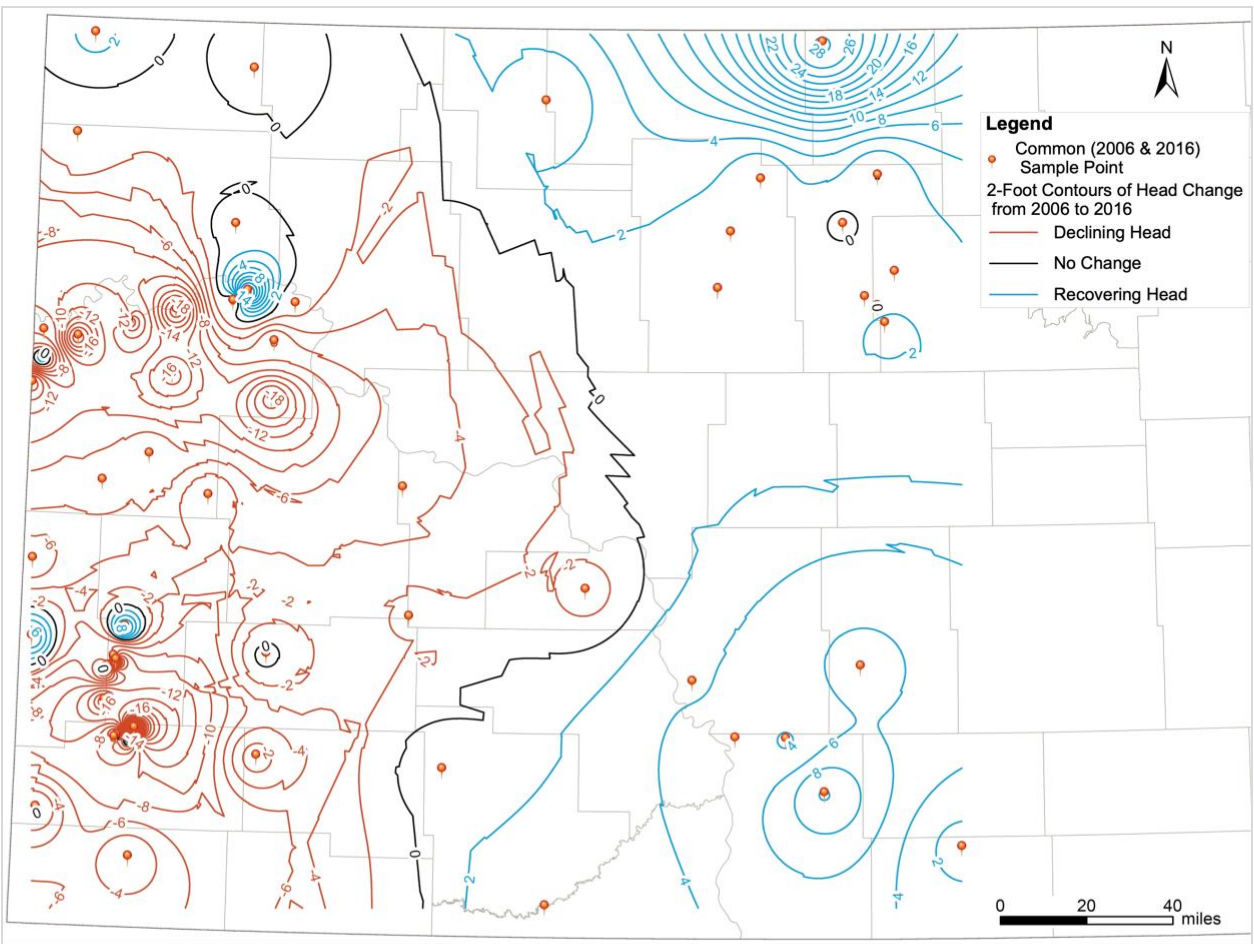

Figure 5: Two-Foot Contours of Decadal Changes in Fox Hills – Hell Creek Aquifer Head

The pressure heads versus shut-in time, and the measured flow rates of the 29 flowing private wells are summarized in Table 2. Data collection for pressure head measurements took place in August, October, and November of 2016. Pressure heads were recorded up to two hours (120 minutes) after shut in. However, pressure head at most wells stabilized within 60 minutes of shut in. Moreover, wells supplying households were not measured for the full two hours because no water could be used when the pressure head is measured. The absence of pressure head recovery (no change) or negative pressure head recovery implies corroded well casing through which water is leaking and pressure head is lost. The flow rates ranged between 1 and 30 gallons per minute. The pressure heads at the wells where head did not stabilize within 60 minutes of shut in are:

- At 70 minutes after shut in, the pressure head was 31.5, 32.6, 133.0, and 15.6 feet at 13610211BBB, 14308918ACC, 15209903ABC, and 15210114DCA, respectively.
- At 80 minutes after shut in, the pressure head was 32.5, 33.0, 134.0, and 15.6 feet at 13610211BBB, 14308918ACC, 15209903ABC, and 15210114DCA, respectively.
- At 100 minutes after shut in, the pressure head was 32.5, 33.5, 134.0, and 15.7 feet at 13610211BBB, 14308918ACC, 15209903ABC, and 15210114DCA, respectively.
- At 120 minutes after shut in, the pressure head was 33.0, 34.0, 134.0, and 16.0 feet at 13610211BBB, 14308918ACC, 15209903ABC, and 15210114DCA, respectively.

Table 2: Flow Rate and Shut-In Pressure Head (feet) at Participating Wells

Site Location	Average Flow Rate (gpm)	Shut-In Time (min)															
		1	2	3	4	5	7	9	12	15	20	25	30	35	40	50	60
13610211BBB	2	25	25.5	26	26.5	26.5	27	27.5	28	28.5	29	29.5	30	30	30.5	31	31.5
13610211DAD	6	24.5	24.5	24.5	24.5	25	25	25	25	25.5	25.5	25.5	26	26	26	26.5	
13610221DBD	3	47	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
13610324AAB	1	9	9	9.5	9.5	9.5	10	10.5	10.5	10.5	11	11	11	11	11.5	11.5	11.5
13610324ACC	1	3.5	3.5	4	4.5	4.5	4.5	4.5	4.5	5	5	5	5	5	5	5	5
13710206CAC	30	85	85	85	85	85	85	86	86	86	86	86	80	81	85	85	85
13710207AAD	2	5	5	5	5	5	5.1	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.6	5.5	
13710312BAB	10	63	64	64	64	65	65	65	65	65	65	65	65	65	65	65	65
13810301BAB	8	40	40	40	40	40	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5
13910217CAC2	14	45	45	45	45	45	45	46	46	46	46	46	46	46	46	46	46
13910220DAD	7	38	38	38	38.2	39	39.5	40	40	40	40	40	41	41	41	41	42
13910231BBB	8	39.5	40	41	41	41	41	41	41	41	41	41	41	41	41	41	41
14010210DCA	NA	128	128	128	128	129	128	129	129	129	128	129	129	129	129	129	129
14308918ACC	NA	25.5	26	27	27.4	27.8	28	28.5	29	29.5	29.8	30.5	30.7	31	31.4	31.8	32.3
14308919ACB	3	58	59	60	60	60	61	62	61	61	63	62	62	63	63	63	
14309024ABC	5	15.5	15.5	15.6	15.6	15.7	15.9	16	16	16	16.2	16.4	16.5	16.5	16.5	16.6	16.6
14309024BAB	2	11.5	12.1	12.4	12.5	12.5	13	13	13	13.2	13.4	13.4	13.4	13.5	13.5	13.5	13.5
14408914CDD	14	134	135	136	136	136	136	136	136	136	136	136	136	136	136	136	136
14409004BBA	1	3.5	3.5	3.6	3.7	4	4.1	4.4	4.5	4.7	5.1	5.5	5.6	5.6	5.6	5.6	5.6
14409110CBC	8	56	57	58	58	57	57	57	56	56	56	56	57	57	57	57	57
14410322CCD	12	42	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
14610227BCA	5	28	28	28	28	28	28	28	28	28	28	28	28	29	29	29	29
14710020DDB2	22	120	122	122	122	123	124	124	124	124	124	124	124	124	124	124	124
14910406ADB	15	94	94	95	95	95	95	96	97	97	97	98	100	103	108	108	108
15010404AAB	30	138	138	138	138	138	138	138	138	138	138	138	138	138	138	138	138
15110404AAA	30	158	159	159	159	159	159	159	159	159	159	159	159	159	159	159	159
15209903ABC	25	129	130	130	130	130	130	130	130	131	131	131	131	132	132	133	133
15210114DCA	1	12.5	13	13.5	13.5	14	14.2	14.4	14.5	15	15.1	15.1	15.1	15.2	15.4	15.5	15.5
15210115ADD	NA	73	74	74	74	74	74	74	74	75	75	75	76	76	76	76	76

Figure 6 through Figure 10 show the historic trends in the potentiometric surface elevations at select locations of the Fox Hills – Hell Creek aquifer. The hydrographs show wells that had at least three pressure head measurements prior to 2016. Figure 6 displays the hydrographs of wells with potentiometric surface elevations between 1950 and 2250 feet (Township 143 North through Township 152 North) without any warning signs of the onset of well issues developing between 2006 and 2016. However, the first reading of 15210115ADD seems to be erroneous.

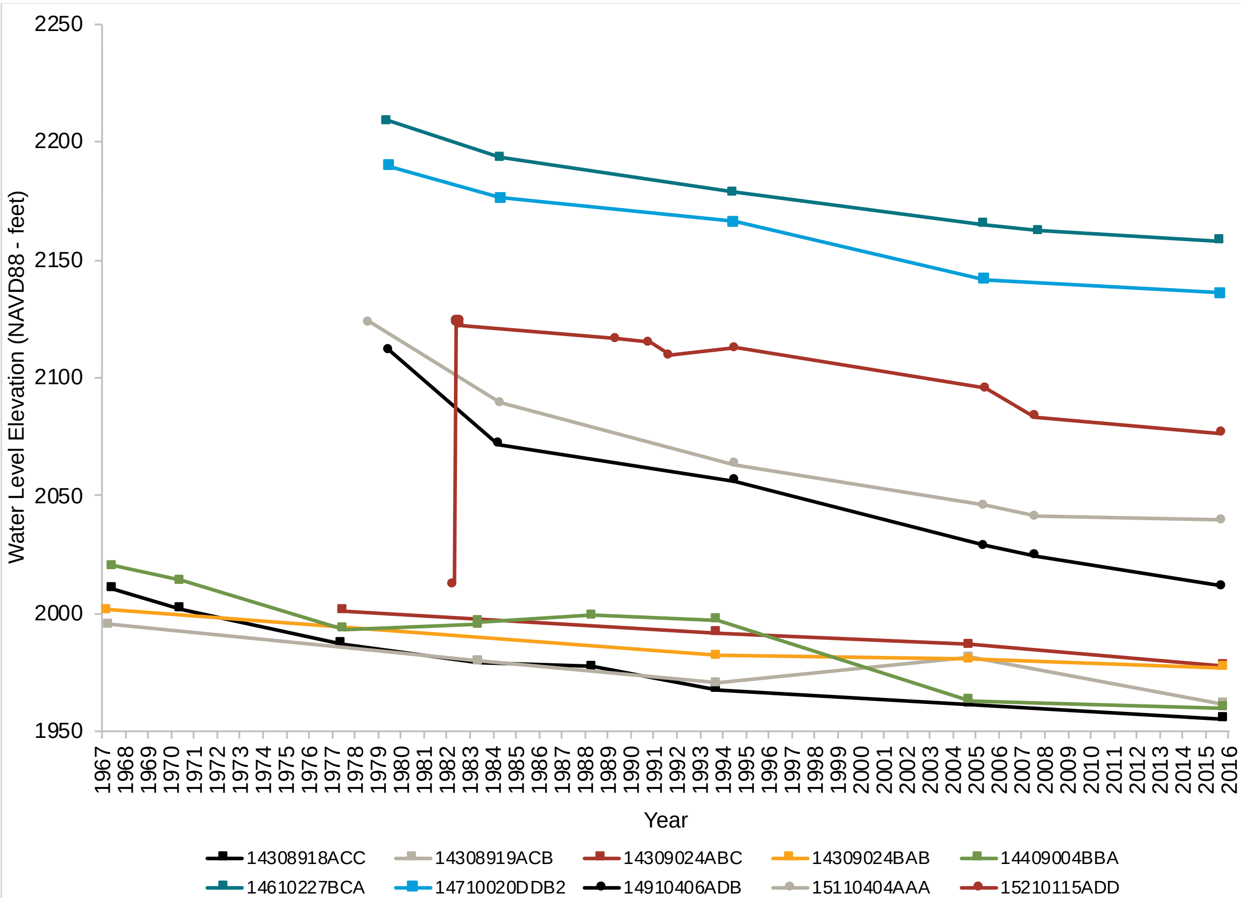

Figure 6:Trends in Potentiometric Surface Elevations (1950 – 2250 feet) at Select 'Private' Fox Hills – Hell Creek Wells with Signs of Pressure Head Decline

Figure 7 shows the hydrographs of wells with increasing pressure heads since 2006. Recovery in the pressure head is likely an indication there has been less discharge from the aquifer or increase in recharge at local areas. Less discharge can be the result of wells that are no longer in use, decreasing efficiency of nearby wells, wells ceasing to flow, or better conservation of water by shutting in wells when not in use could all lead to a recovery in the pressure heads. Between 1994 and 2005, municipal well 14409110CBC noticed a recovery in pressure head because the City of Dodge connected to Southwest Water Authority's regional water supply reducing its need to use its municipal well. That in turn lead to the recovery of pressure head at the well. Because the city of Zap started using alternative sources to satisfy its water demand, domestic well 14408914CDD noticed similar effects. The effects on the pressure head at 14408914CDD are not as pronounced as they were on 14409110CBC, because the City of Zap continued using the municipal well sporadically. Stock well 14308919ACB showed recovery in pressure head between 1994 and 2005 too but because it was shut in.

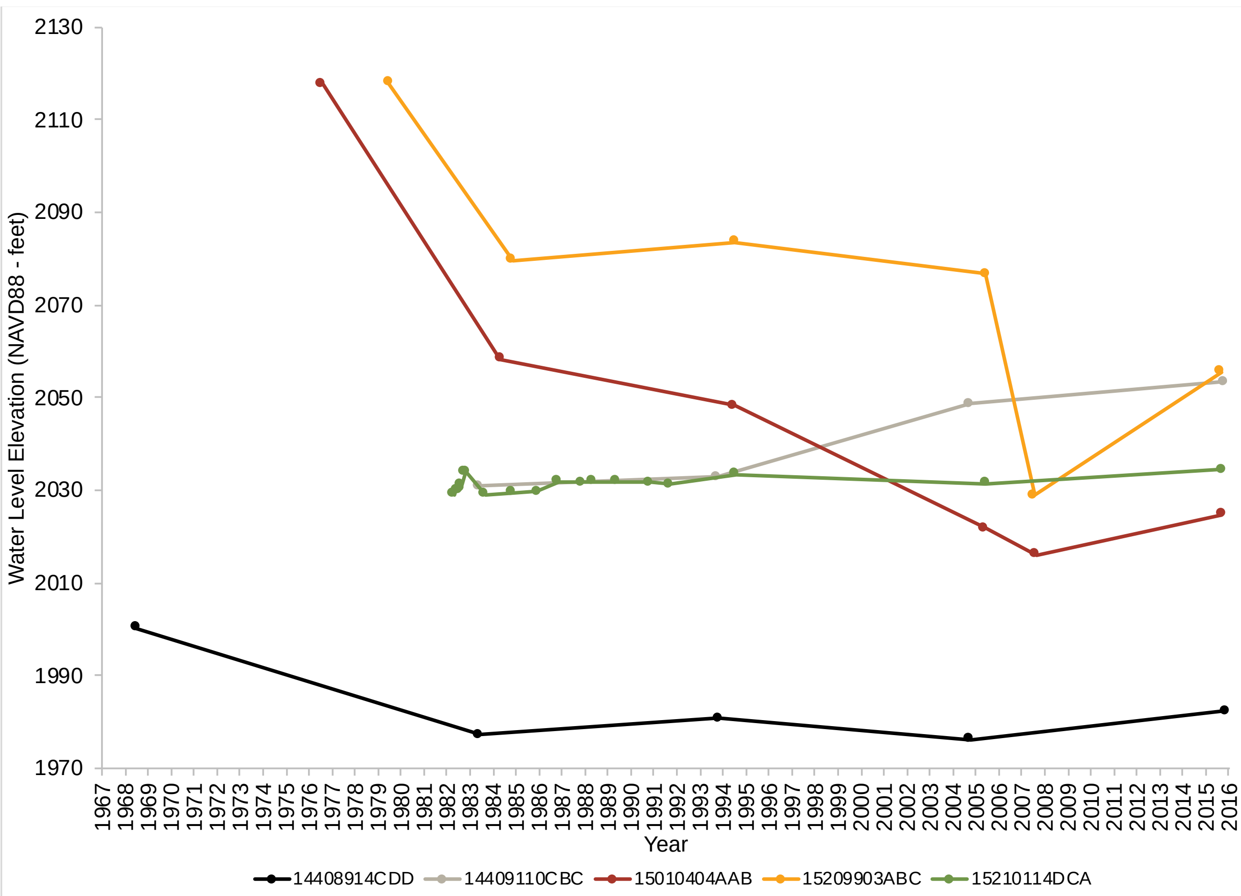

Figure 7: Trends in Potentiometric Surface Elevations (1950 – 2250 feet) at Select 'Private' Fox Hills – Hell Creek Wells with Signs of Pressure Head Recovery

Figure 8 shows the hydrographs of wells with potentiometric surface elevations between 2350 and 2550 feet (Township 136 North through Township 140 North). Because the trends in the potentiometric surface elevations at 13610221DAD and 13610221DBD are not similar to those at 13610211BBB, Figure 9 clearly shows that the erratic trend in the potentiometric surface elevations at 13610211BBB is related to the well rather than the aquifer.

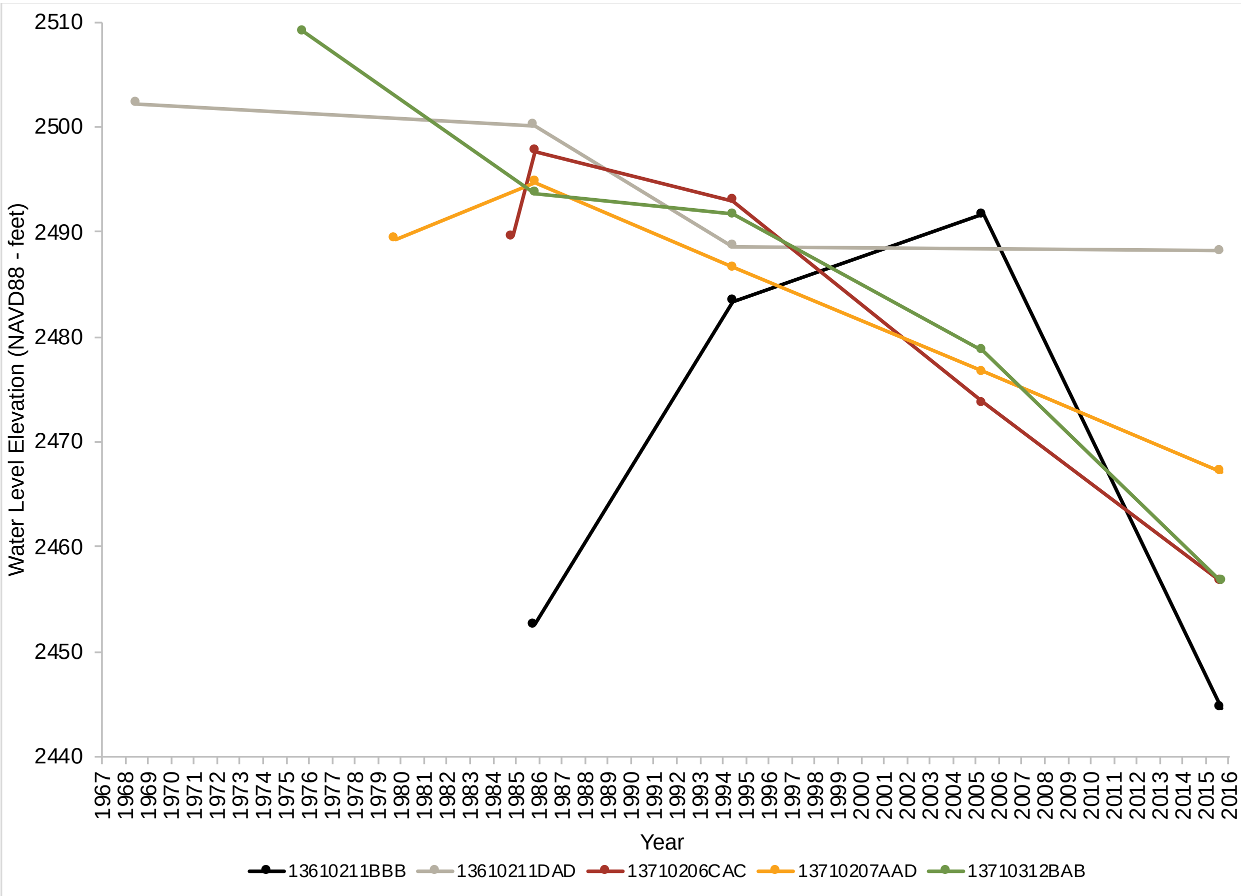

Figure 8: Trends in Potentiometric Surface Elevations (2350 – 2550 feet) at Select ‘Private’ Fox Hills – Hell Creek Wells with Signs of Pressure Head Decline

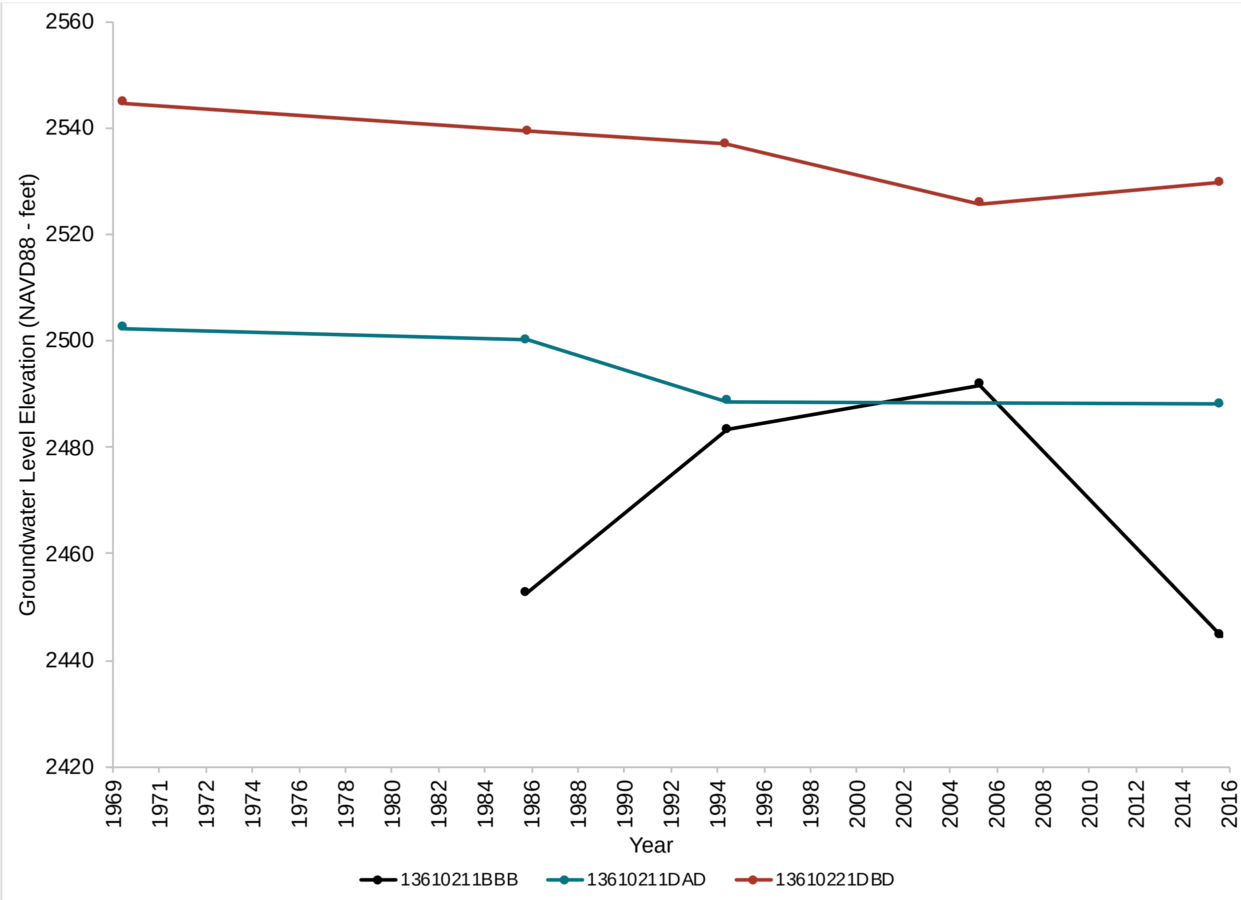

Figure 9: Inconsistent Aquifer Behavior in Township 136 North, Range 102 West

Figure 10 shows the hydrographs of wells with potentiometric surface elevations within the same range that have increased since 2006. Extrapolating based on two values provides frivolous results at best. Better statistical measures and approximations are usually associated with larger pool of data points. The wells 13610324ACC, 13810301BAB, 13910220DAD, 13910231BBB, and 14410322CCD were excluded from the elevation trend charts, because each well has only one or two potentiometric surface elevation measurements.

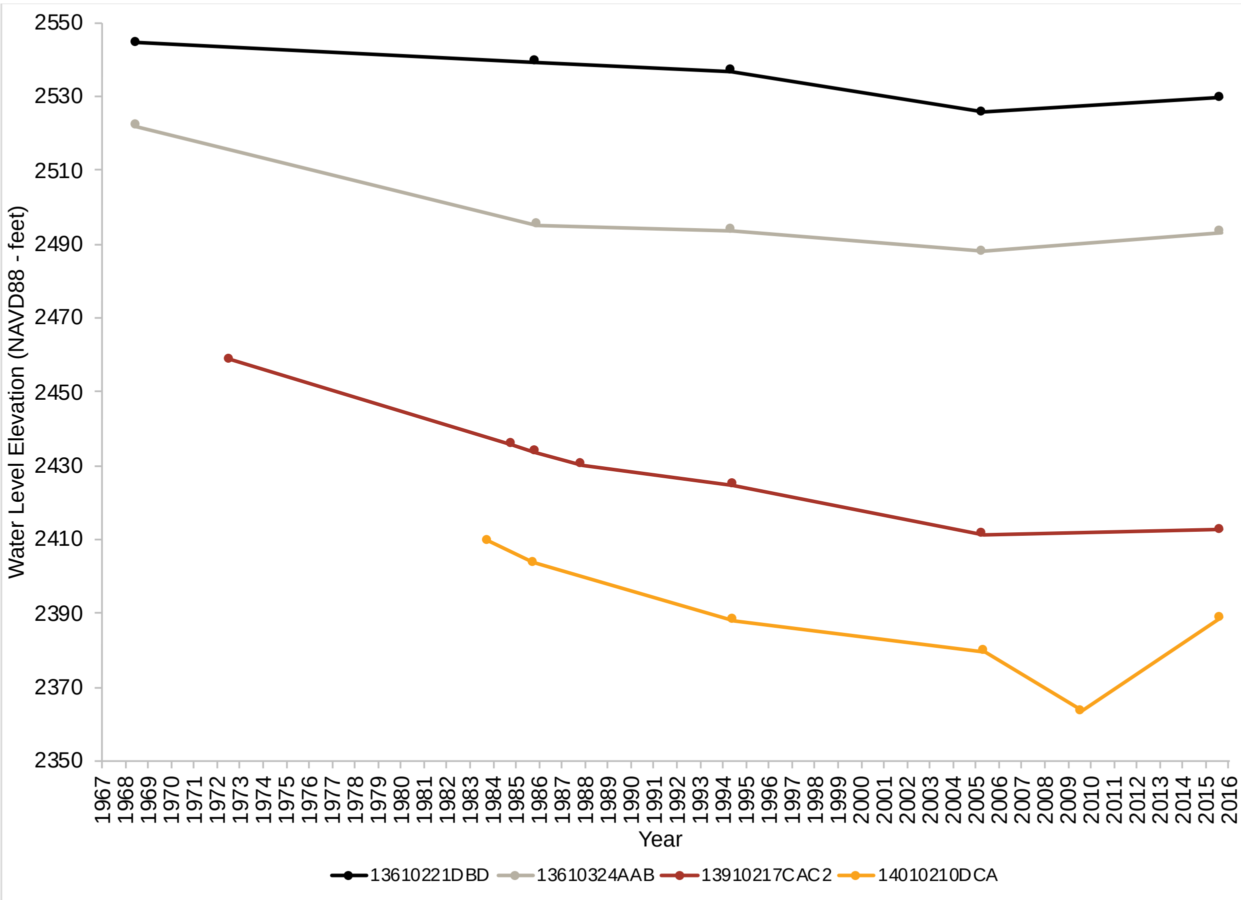

Figure 10: Trends in Potentiometric Surface Elevations (2350 – 2550 feet) at Select ‘Private’ Fox Hills – Hell Creek Wells with Signs of Pressure Head Recovery

Figure 11 through Figure 13 show the inconsistency in the behavior of potentiometric surface elevations at select locations. Figure 11 shows that the rate of decline in the head at the Fox Hills – Hell Creek aquifer at 13110207DDD1 since 1990 is slower than the rate of decline until the early 1990s. Moreover, the potentiometric surface elevations appear to be approaching a quasi-equilibrium state. The decline in potentiometric surface elevations at this location is associated with the appropriated irrigation use of groundwater in that quarter section. Figure 12 clearly shows similar behavior change at 15309611ADA and 15309620DCB1 after the release of trapped gas (Honeyman 2007b). Figure 13 shows the response of the aquifer potentiometric surface elevation to aquifer recharge and discharge processes along the northeastern edge of the aquifer. The figure also shows that factors besides the proximity of two wells to each other influence measured aquifer response. Figure 14 displays the location of the private and observation wells discussed above (*text continues on page 23*).

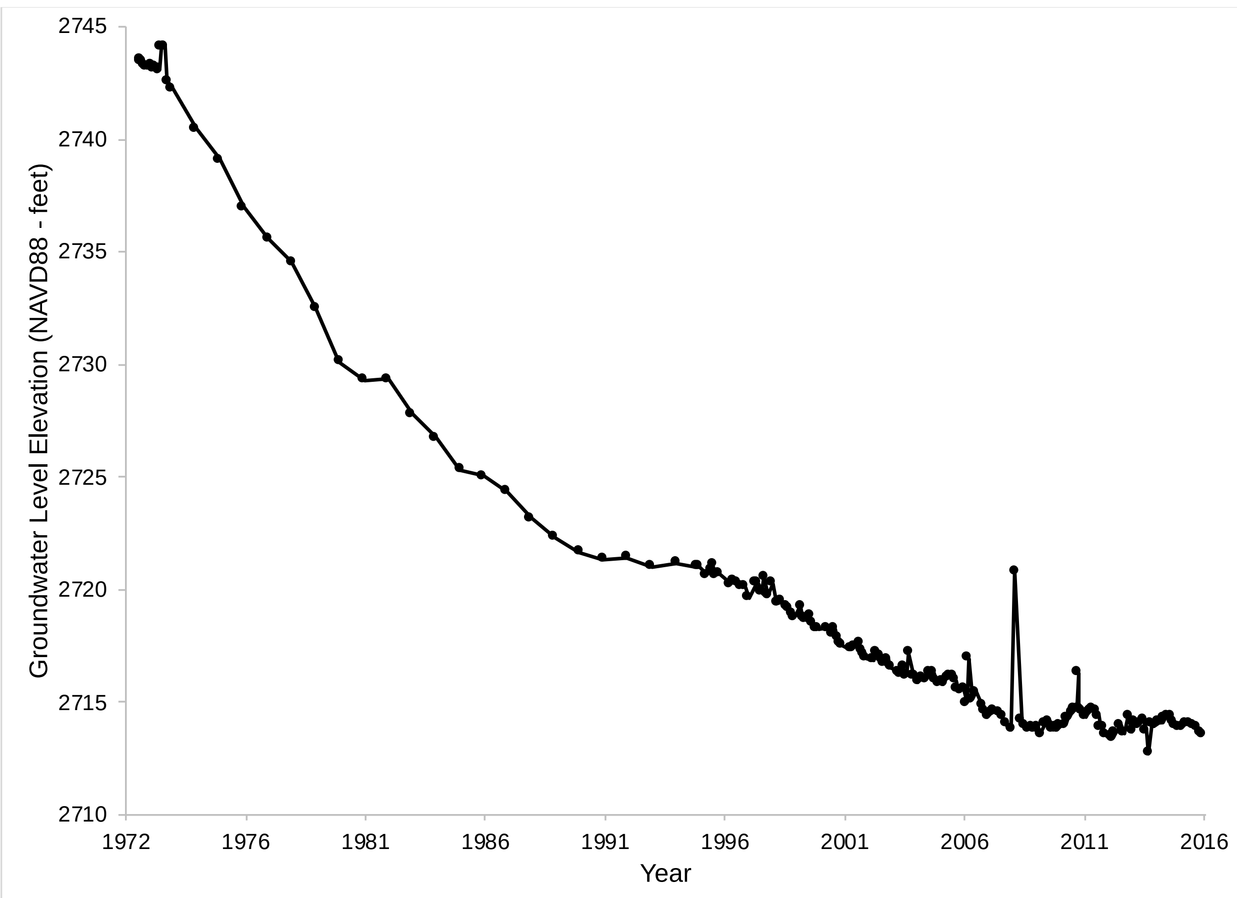

Figure 11: Potentiometric Surface Elevations at 13110207DDD1

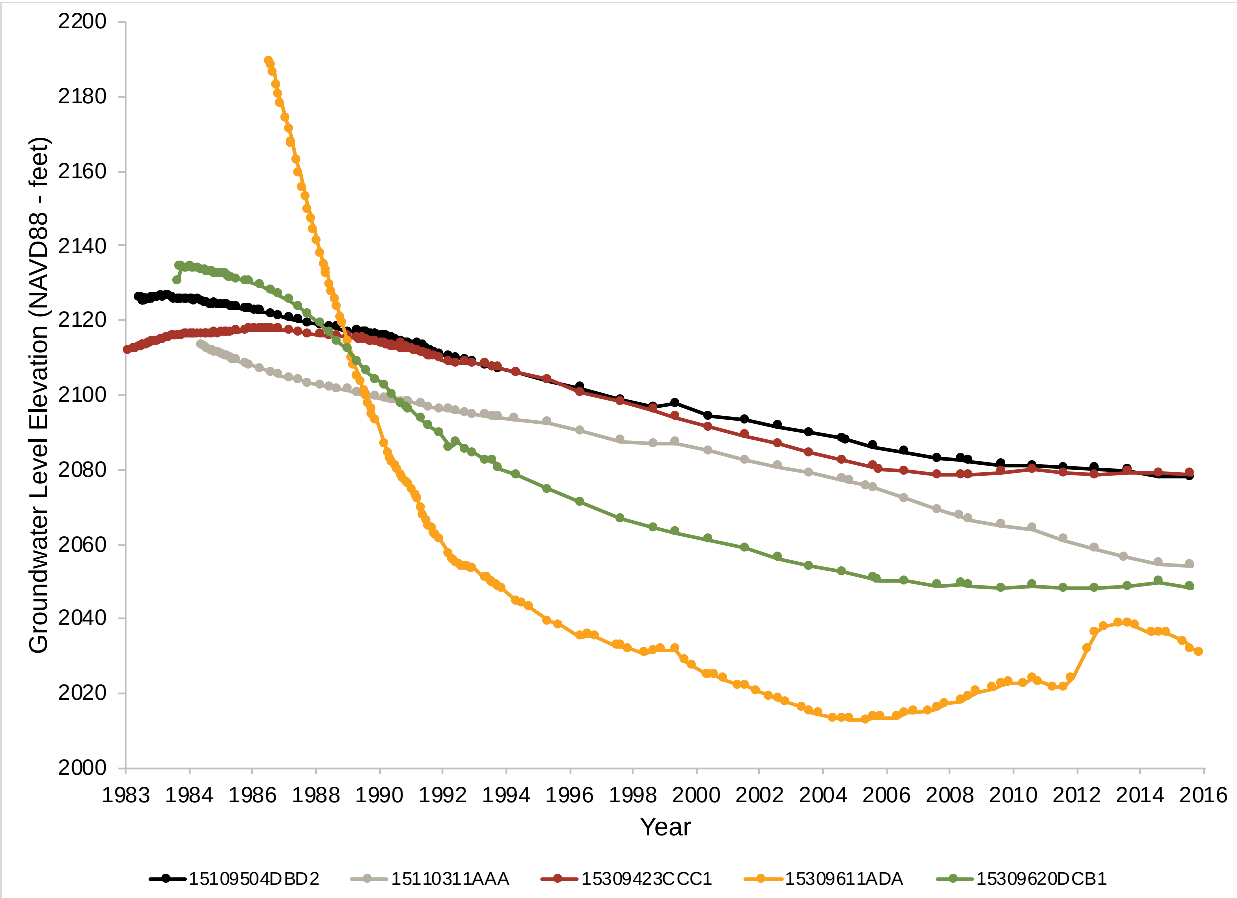

Figure 12: Potentiometric Surface Elevations at Select Fox Hills – Hell Creek Observation Wells

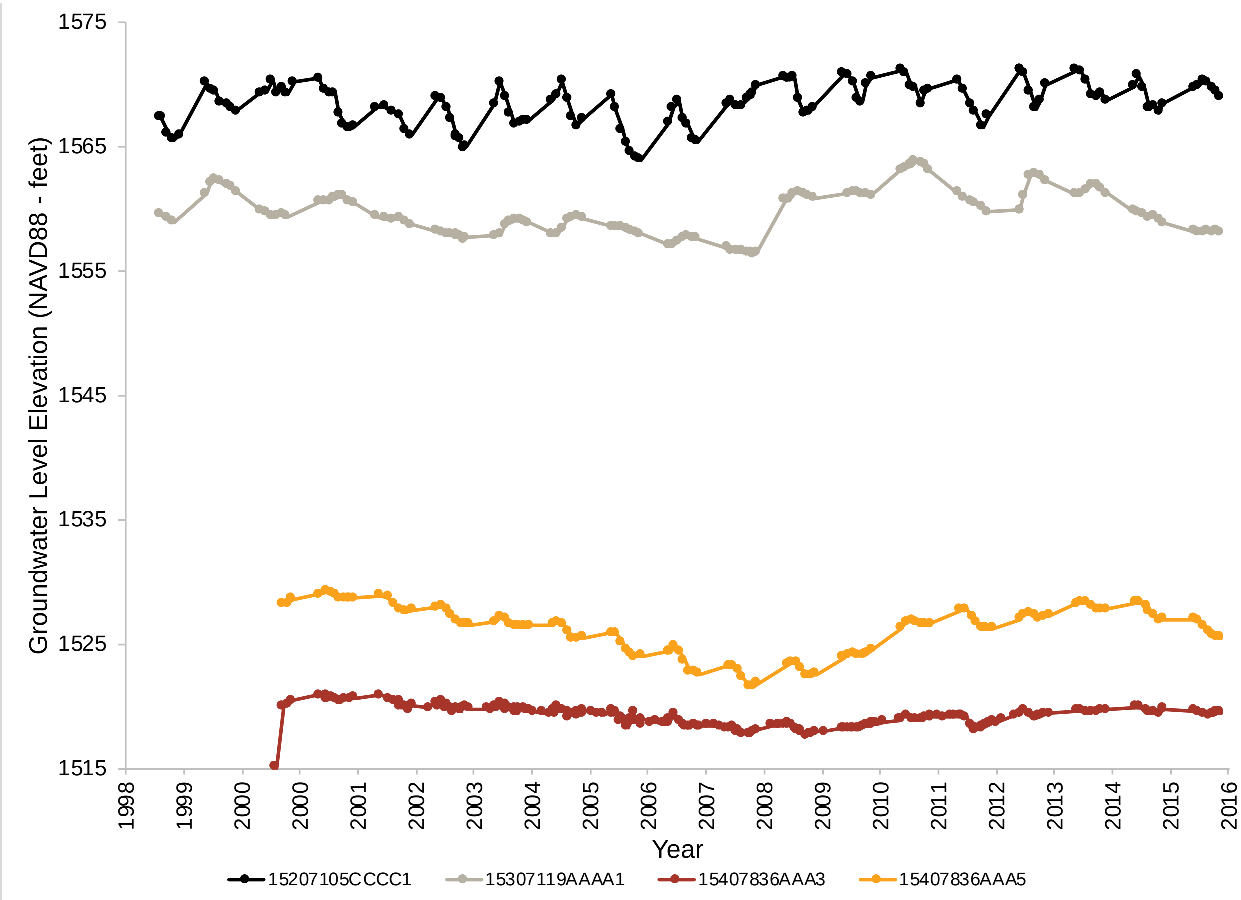

Figure 13: Potentiometric Surface Elevations at Select Fox Hills – Hell Creek Observation Wells

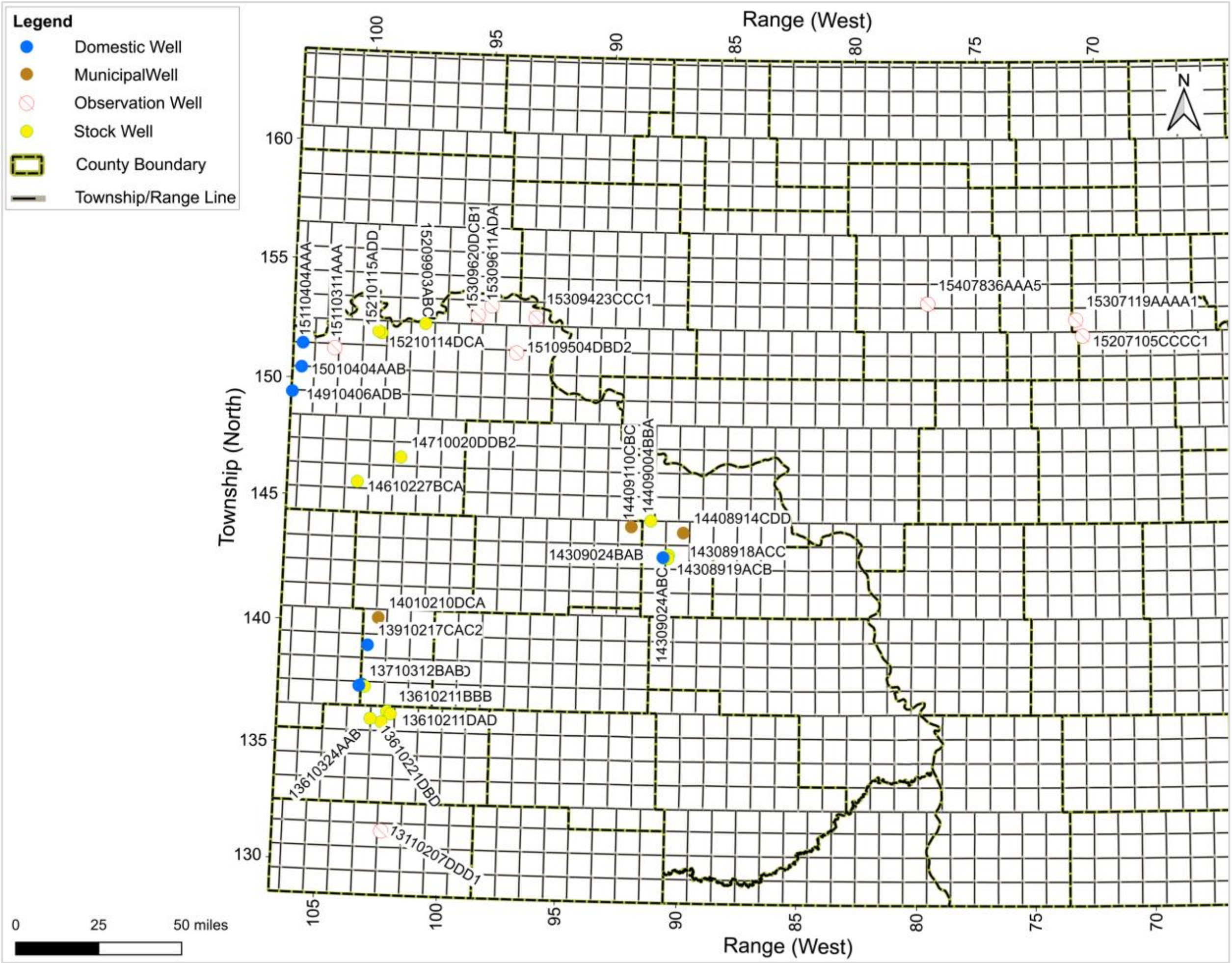

Figure 14: Locations of Select Fox Hills – Hell Creek Wells

PRESSURE HEAD CHANGE RATE

The pressure head change rate is dependent on the timeframe over which it is calculated. Three calculations are made for each well: linear regression using all measurements, first and last measurements, and last two measurements. The linear regression option is the most rigorous option because it includes all measurements and reflects the historic decadal variation in the trend. The decadal variation is absent from the other two options. A positive change implies recovering pressure head and a negative change rate implies declining pressure head.

The linear regression equations and some pertinent information of each well location are listed in Table 3. Each equation takes the general form of Head Elevation = Rate of Change * Year + Intercept. Regression equations with positive change rate are highlighted in Table 3. For each well in Table 3, all available measurements were considered when constructing the equation. The third column in Table 3 gives the flowing head above respective ground surface of each well. The average annual pressure head was calculated and used for wells with multiple measurements during a year. Pressure head change rate and groundwater elevation can be used to approximate when the aquifer would stop flowing naturally at respective locations. Better approximations are associated with well-maintained wells having a longer period over which their pressure heads were measured. Because the aquifer conditions are summarized on a decadal basis, the intra- and inter-annual changes in the aquifer conditions are not considered. In other words, the fluctuations in the aquifer conditions that occurred within the ten years between 2006 and 2016 are not considered.

Table 3: Regression Parameters and Other Pertinent Information of Select Fox Hills – Hell Creek Wells

Site Location	GSE	FH16	Regression Equation	R^2
13610211BBB	2412	33	-0.1836x + 2835.4	1%
13610211DAD	2462	27	-0.332x + 3156.1	76%
13610221DBD	2482	48	-0.3824x + 3297.8	83%
13610324AAB	2482	12	-0.616x + 3727	68%
13710206CAC	2372	85	-1.1861x + 4851.6	88%
13710207AAD	2462	6	-0.7023x + 3885.2	88%
13710312BAB	2412	45	-1.2028x + 4886.4	94%
13910217CAC2	2367	46	-1.0464x + 4514.8	88%
14010210DCA	2259	130	-0.9756x + 4339.7	60%
14308918ACC	1921	34	-1.1134x + 4193.6	92%
14308919ACB	1898	63	-0.5801x + 3134.1	71%
14309024ABC	1961	17	-0.5944x + 3177.2	99%
14309024BAB	1963	14	-0.516x + 3015.1	94%
14408914CDD	1846	136	-0.3489x + 2679.1	42%
14409004BBA	1954	6	-1.2092x + 4397	87%
14409110CBC	1996	57	0.7782x + 485.19	92%
14610227BCA	2129	29	-1.395x + 4965.4	96%
14710020DDB2	2012	124	-1.5164x + 5189.3	97%
14910406ADB	1904	108	-2.554x + 7154.5	94%

15010404AAB	1887	138	-2.3005x + 6643.8	81%
15110404AAA	1881	159	-2.2075x + 6478.1	90%
15209903ABC	1922	134	-1.6713x + 5413.6	62%
15210114DCA	2019	16	0.1148x + 1802.9	51%
15210115ADD	1997	79	-1.1778x + 4454.5	76%

GSE = Ground Surface Elevation (NAVD88 - feet); FH16 = 2016 pressure head in feet above ground surface; R^2 = correlation coefficient

The decadal variation in the change rate at select wells and the effect of the number of measurements used in approximating a year when a well stops flowing can be inferred from Table 4 and Figure 15. Positive rates of change and corresponding years are highlighted in Table 4. The 'FLM' (First and Last Measurement) column uses the first and last measurement of each well. The 'LTM' (Last Two Measurement) column uses the last two measurements of each well. Including the 1995-2006 rates of change, 50% of the 24 wells that had their shut-in pressure head measured showed negative head change. The well count increases to 14 if the 1995-2006 change rates are excluded. Because recovery in the pressure head may reflect decrease in discharge from the aquifer, preliminary statistical measures were calculated using all of the 24 wells. When regression analysis ('RA' column) was used for calculating the pressure head rate change, the range of head change is between -2.55 and 0.78 feet/year with an average rate of -0.95 feet/year. Regression analysis indicates that well 14409004BBA is the first well expected to cease flowing above the ground surface subsequent to 2016.

The regression analysis also indicates that the aquifer is recovering at 14409110CBC and 15210115ADD. When the first and last measurements were used for calculating the rate of head change, the range of head change is between -2.78 and 0.70 feet/year with an average rate of -0.96 feet/year. When the last two measurements were used for calculating the rate of head change, the range of head change is between -4.70 and 4.18 feet/year with an average rate of -0.26 feet/year. The 2006 – 2016 change rate ranged between -4.70 and 0.90 feet/year with an average of -0.76 feet/year. Because the last two pressure head measurements were not necessarily taken in 2006 and 2016 for each well, the statistical measures of the last two groups are not the same.

Figure 15 plots the various rates of change of each well, where a positive change implies aquifer recovery in the vicinity of the well. The rate of head change at wells 13610211BBB and 14308919ACB switched from positive between 1995 and 2006 to negative between 2006 and 2016. The rate of head change at wells 13610221DBD, 13610324AAB, 13910217CAC2, 14010210DCA, 14408914CDD, and 15010404AAB switched from negative between 1995 and 2006 to positive between 2006 and 2016. However, the regression analysis indicates that the respective rates of head change continue to be negative. The rate of head change at 15210114DCA switched from negative between 1995 and 2006 to positive between 2006 and 2016 irrespective of analysis (Figure 15). The rate of head change at 14409110CBC is positive irrespective of analysis (Figure 15). The magnitude of the negative rate of head change between 2006 and 2016 is smaller than the magnitude of the negative rate of head change between 1995 and 2006 at 13710206CAC, 14409004BBA, 14610227BCA, 14710020DDB2, 14910406ADB, and 15110404AAA. The magnitude of the negative rate of head change between 2006 and 2016 is larger than the magnitude of the negative rate of head change between 1995 and 2006 at 13710312BAB, 15209903ABC, and 15210115ADD. Irrespective of the analysis used to calculate the rate of head change at 13710207AAD, 14308918ACC, 14309024ABC, and 14309024BAB, the rate of head change continues to be between 0 and about –1 foot per year. It was not possible to calculate the rate of head change at 13610211DAD well. Compared to the 1995 – 2006 decadal changes, the number of wells showing aquifer recovery between 2006 and 2016 increased and the average rate of head change increased by 18% (from -0.92 feet/year to -0.76 feet/year). However, the minimum rate of change dropped from -3.09 to -4.70 feet/year.

Potentiometric surface elevations at 13610324ACC, 13810301BAB, 13910220DAD, and 13910231BBB were measured only twice to date. Moreover, there is no specified datum for 13910220DAD or 13910231BBB. Potentiometric surface elevations at 14410322CCD were measured only once to date. Using the two potentiometric surface elevation readings of wells 13610324ACC and 13910220DAD indicate that they will cease to flow above ground surface in 2021 and 2029, respectively. Wells 14309014DDA, 14408510CCA, and 15209824CCC have not been measured since 1994, 2005, and 2008, respectively. Well 13909607AA was not flowing when the data was collected.

Table 4: Approximate Year Each Well Stops Flowing

Site Location	95-06		06-16		FLM		LTM		RA	
	Rate	Year	Rate	Year	Rate	Year	Rate	Year	Rate	Year
13610211BBB	0.75	–	- 4.70	2024	- 0.27	2140	- 4.70	2024	- 0.18	2308
13610211DAD	NA	NA	NA	NA	- 0.30	2105	- 0.02	3129	- 0.33	2092
13610221DBD	- 1.03	2063	0.40	–	- 0.32	2167	0.40	–	- 0.38	2135
13610324AAB	- 0.52	2038	0.53	–	- 0.61	2035	0.53	–	- 0.62	2022
13710206CAC	- 1.75	2065	- 1.70	2066	- 1.06	2097	- 1.70	2066	- 1.19	2091
13710207AAD	- 0.90	2023	- 0.95	2022	- 0.61	2025	- 0.95	2022	- 0.70	2027
13710312BAB	- 1.18	2055	- 2.20	2037	- 1.31	2051	- 2.20	2037	- 1.20	2058
13910217CAC2	- 1.20	2055	0.13	1648	- 1.07	2059	0.13	–	- 1.05	2053
14010210DCA	- 0.75	2189	0.90	1872	- 0.66	2215	4.18	–	- 0.98	2134
14308918ACC	- 0.59	2074	- 0.55	2079	- 1.15	2046	- 0.55	2079	- 1.11	2041
14308919ACB	1.00	1953	- 1.82	2051	- 0.71	2105	- 1.82	2051	- 0.58	2131
14309024ABC	- 0.45	2053	- 0.81	2037	- 0.61	2044	- 0.81	2037	- 0.59	2046
14309024BAB	- 0.15	2106	- 0.34	2056	- 0.51	2043	- 0.34	2056	- 0.52	2039
14408914CDD	- 0.41	2349	0.55	–	- 0.38	2372	0.55	–	- 0.35	2387
14409004BBA	- 3.09	2018	- 0.30	2035	- 1.26	2021	- 0.30	2035	- 1.21	2021
14409110CBC	1.43	–	0.43	–	0.70	1935	0.43	–	0.78	–
14610227BCA	- 1.25	2040	- 0.70	2058	- 1.42	2037	- 0.56	2068	- 1.40	2034
14710020DDB2	- 2.22	2072	- 0.61	2221	- 1.50	2099	- 0.61	2221	- 1.52	2096
14910406ADB	- 2.50	2060	- 1.70	2080	- 2.78	2055	- 1.59	2085	- 2.55	2056
15010404AAB	- 2.42	2074	0.30	–	- 2.38	2074	1.07	1888	- 2.30	2068
15110404AAA	- 1.59	2116	- 0.60	2281	- 2.26	2087	- 0.19	2864	- 2.21	2083
15209903ABC	- 0.64	2227	- 2.10	2080	- 1.73	2094	3.32	–	- 1.67	2090
15210114DCA	- 0.18	2104	0.30	–	0.10	–	0.30	–	0.11	–
15210115ADD	- 1.55	2068	- 1.90	2058	- 0.87	2108	- 0.90	2105	- 1.18	2087

Rate = Rate of Change (feet per year); FLM = First and Last Measurement; LTM = Last Two Measurements; RA = Regression Analysis; Year = Year pressure head falls below ground surface

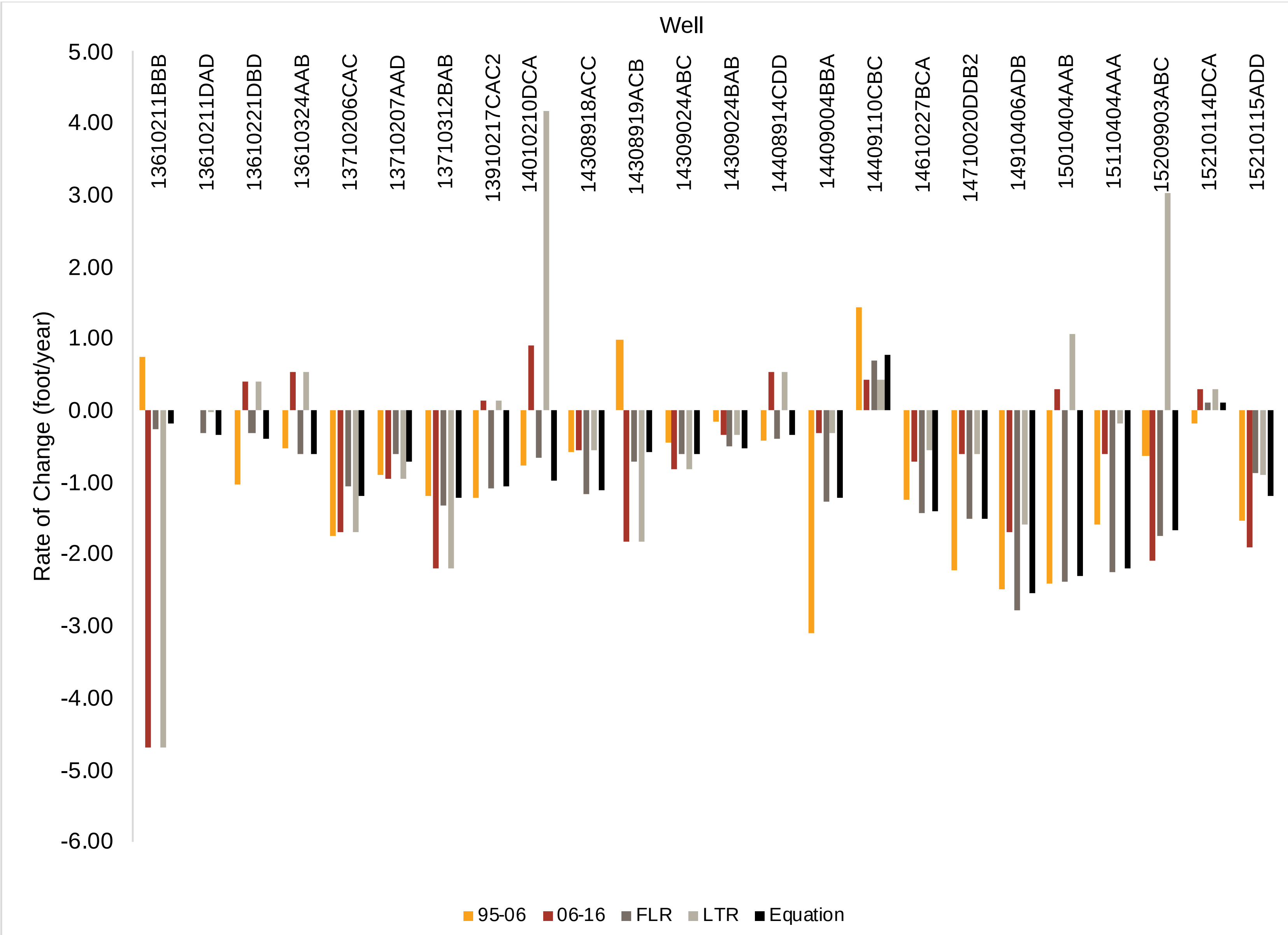

Figure 15: Rate of Change at Select 'Private' Fox Hills – Hell Creek Wells

WATER QUALITY

Groundwater samples were collected from a total of 45 wells for the 2016 groundwater quality analysis. In addition to the 44 wells listed in the appendix as being sampled during 2016, a groundwater sample was also collected from 13407515BBB in 2016 and 2018. As a standard operating procedure, SWC flushes observation wells prior to collecting a water sample. The private wells were flowing prior to the field visit, so flushing of a well was not required to collect a representative sample. Flushing a well requires pumping out the water from the well casing so that fresh inflow of aquifer water can replace it. The time that it takes to flush a well is dependent on the depth of the well and the pumping rate. Thus, the time it takes to obtain representative water samples can vary from a few minutes to a few days. Moreover, the time that private wells were flowing is unknown. Flushing wells is assumed to provide representative aquifer water samples for analysis. Collecting representative water samples from the few wells that were shut in prior to the field visit in a timely manner was infeasible.

Analysis of the groundwater quality was based on standards that differ per the intended use of the water. The Environmental Protection Agency (EPA) regulates the standards of water quality for human consumption. The EPA sets the concentrations of various contaminants of concern in water for human consumption using the 'National Primary Drinking Water Regulations' (NPDWR) and 'National Secondary Drinking Water Regulations' (NSDWR) (EPA 2018a, b). The NPDWR take the form of maximum contaminant levels (MCLs) and are legally-enforceable standards of public water systems. Even though some wells might not be part of a public supply system, the MCLs can still be used to evaluate the quality of water for human consumption. The MCLs are posed to prevent adverse public health issues from the persistent and extended use of contaminated water. The NSDWR guidelines, on the other hand, are non-enforceable guidelines for contaminants that are known to cause cosmetic or aesthetic effects. Other limits and guidelines (Soltanpour and Raley 1999) were used to examine the water quality for livestock consumption. These guidelines are used because some Fox Hills – Hell Creek wells are used primarily for livestock purposes. Concentrations above respective guidelines for livestock consumption are considered toxic and water should be treated before being consumed by livestock for extended periods of time.

The MCLs, NSDWR guidelines, and the livestock guidelines and limits are listed in Table 5. None of the three guidelines provide limits on calcium, carbonate, magnesium, or sodium. Chlorine refers to the liquified gas that is usually used in the treatment of municipal water supplies. Chloride refers to the ionized form of the chlorine atom. For example, table salt (sodium chloride) gives chloride ions and sodium ions when dissolved in water. Table 6 lists the potential health effects and sources of contaminants of concern. The potential health effects are from human consumption of water with concentrations of one or more contaminants of concern above respective MCLs. Erosion of natural deposits is a common source of each contaminant listed in the table. The table lists additional sources of the listed contaminants. Table 7 lists the cosmetic and aesthetic effects of consuming water with concentrations of contaminants of concern in exceedance of respective NSDWRs.

Table 5: Guidelines and Limits of Contaminants of Concern in milligrams per liter (mg/l)

Analyte	Guideline Limit (mg/l)		
	MCL	NSDWR	Livestock
Aluminum	N/A	0.05 - 0.2	5
Arsenic	0.01	N/A	0.2
Boron	N/A	N/A	5
Cadmium	0.005	N/A	0.05
Chlorine (Cl_2)	4	N/A	N/A
Chloride (Cl^-)	N/A	250	N/A
Chromium	0.1	N/A	1
Copper	1.3	1	0.5
Fluoride	4	2	2
Iron	N/A	0.3	N/A
Lead	0.015	N/A	0.1
Manganese	N/A	0.05	N/A
Mercury	0.002	N/A	0.01
Nitrogen	10	N/A	100
Selenium	0.05	N/A	0.05
Silver	N/A	0.1	N/A
Sulfate	N/A	250	N/A
Zinc	N/A	5	24
TDS	N/A	500	1000
pH	N/A	6.5 – 8.5	N/A

Table 6: Source of Contaminants and Potential Health Effects of MCL Exceedance

Contaminant	Potential Health Effects*	Additional Sources of Contaminant
Arsenic	Skin damage or problems with circulatory systems & may have increased risk of getting cancer	Runoff from orchards; Runoff from glass & electronics-production wastes
Cadmium	Kidney damage	Corrosion of galvanized pipes; Discharge from metal refineries; Runoff from waste batteries & paints
Chlorine (Cl_2)	Eye/nose irritation; stomach discomfort	Water additive used to control microbes
Chromium$	Allergic dermatitis	Discharge from steel & pulp mills
Copper	Short term exposure: Gastrointestinal distress Long term exposure: Liver or kidney damage	Corrosion of household plumbing systems
Fluoride	Bone disease (pain and tenderness of the bones); Children may get mottled teeth	Water additive which promotes strong teeth; Discharge from fertilizer & aluminum factories
Lead	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems
Mercury#	Kidney damage	Discharge from refineries and factories; Runoff from landfills and croplands
Nitrate^	Infants less than six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; Leaking from septic tanks, sewage
Nitrite^	same as nitrate	same as nitrate
Selenium	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; Discharge from mines

** = from long-term exposure above the MCL (unless specified as short-term); $ = total chromium; # = organic mercury; content from EPA 2018a*

Table 7: Cosmetic and Aesthetic Effects from Concentrations Exceeding NSDWR guidelines

Analyte	Effects of NSDWRs Exceedance
Aluminum	Colored water
Chloride (Cl^-)	Salty taste
Copper	Metallic taste; blue-green staining
Fluoride	Tooth discoloration
Iron	Rusty color; Sediment; Metallic taste; Reddish or orange staining
Manganese	Black to brown color; Black staining; Bitter metallic taste
Silver	Skin discoloration; Graying of the white part of the eye
Sulfate	Salty taste
Zinc	Metallic taste
pH	Low pH: bitter metallic taste; Corrosion
	High pH: slippery feel; Soda taste; Deposits
TDS*	Hardness; Deposits; Colored water; Staining; Salty taste

**TDS = Total Dissolved Solids; content from EPA 2017*

Table 8 lists the date range and preliminary statistical measures of contaminant concentrations of concern using the 32 sampled private wells and 13 sampled observation wells. Average values in Table 8 do not include ‘below detection limit’ (BDL) values. Table 9 and Table 10 list the historic range and 2016 contaminant concentration of concern at each private and observation well, respectively. Nitrogen was not included in either table because it was orders of magnitude lower than the MCL in each of the private wells. Observation wells 15107009ACA1 and 15307133DDD2 showed nitrogen concentrations of 12.4 and 37.1 mg/l, respectively, in 2016. All other nitrogen concentrations were below MCL. Groundwater samples from the last six observation wells listed in Table 10 were collected for the first time in 2016. Therefore, no range of concentrations were listed for any of these wells. The detection limit listed in any of the tables is the detection limit used for a particular analyte. However, the detection limit can vary for the same analyte per the analysis method. Except for nitrogen (nitrate), the two groups of wells have relatively similar ranges of respective concentrations (*text continues on page 37*).

Table 8: Concentration and Sampling Events Date Range of Analyzed Contaminants of Concern in Fox Hills – Hell Creek Wells

Analyte	Date		Concentration (mg/l, except pH)			
	Minimum	Maximum	Minimum	Average	Maximum	Detection limit
	Private Wells					
Aluminum	09/19/05	10/14/13	<	-	<	0.05
Arsenic	09/19/05	10/14/13	0.004	0.008	0.02	0.001
Boron	08/24/64	10/14/13	0.07	2.4	6.3	N/A
Cadmium	09/19/05	10/14/13	<	-	<	0.001
Chloride	08/24/64	11/02/16	7.4	162.4	1140.0	3.0
Chromium	09/19/05	10/14/13	0.002	0.003	0.005	0.001
Copper	09/19/05	10/14/13	0.004	0.006	0.002	N/A
Fluoride	08/24/64	11/02/16	0.2	4.0	6.6	N/A
Iron	08/24/64	11/02/16	0.02	0.2	2.0	0.05
Lead	09/19/05	10/14/13	<	0.001	0.001	0.001
Manganese	05/18/69	11/02/16	<	0.02	0.5	0.01
Mercury	-	-	-	-	-	-
Nitrogen	09/19/05	11/02/16	0.02	0.03	0.09	-
Selenium	09/19/05	10/14/13	0.009	0.03	0.07	0.001
Silver	09/19/05	10/14/13	<	-	<	0.001
Sulfate	08/24/64	11/02/16	<	100.9	284.0	3.0
Zinc	09/19/05	10/14/13	0.001	0.06	0.4	0.001
TDS	08/24/64	11/02/16	296.0	1334.8	2960.0	N/A
pH [ ]	08/24/64	11/02/16	7.4	8.5	9.0	N/A
Analyte	Observation Wells					
Aluminum	6/22/06	9/7/18	<	-	0.07	0.05
Arsenic	9/16/93	9/7/18	<	0.0017	0.002	0.001
Boron	6/6/67	9/7/18	0.2	1.6	3.4	N/A
Cadmium	6/22/06	9/7/18	<	<	<	0.001
Chloride	6/6/67	9/7/18	<	168.0	946.0	3.0
Chromium	6/22/06	9/7/18	<	<	<	0.001
Copper	6/22/06	9/7/18	0.003	0.006	0.007	N/A
Fluoride	6/6/67	9/7/18	0.08	2.4	6.8	N/A
Iron	6/6/67	9/7/18	<	0.8	14.0	0.05
Lead	9/16/93	9/7/18	<	-	0.002	0.001
Manganese	7/10/69	9/7/18	<	0.1	0.4	0.01
Mercury	9/16/93	8/28/01	<	<	<	-
Nitrogen	6/6/67	9/7/18	<	2.6	37.1	-
Selenium	9/16/93	9/7/18	<	0.005	0.008	0.001
Silver	6/22/06	9/7/18	<	<	<	0.001
Sulfate	6/6/67	9/7/18	<	96.1	713.0	3.0
Zinc	6/22/06	9/7/18	<	0.02	0.04	0.001
TDS	6/6/67	9/7/18	104.0	1188.0	2630.0	N/A
pH [ ]	6/6/67	9/7/18	7.1	8.5	9.7	N/A

Table 9: Range and 2016 Concentrations (mg/l, except pH) of Contaminants of Concern at the Sampled Private Wells

Site Location	Chloride		Fluoride		Iron		Manganese		Sulfate		TDS		pH [ ]	
	Range	2016	Range	2016	Range	2016	Range	2016	Range	2016	Range	2016	Range	2016
13610211BBB	11.0-12.0	11.5	3.6- 4.0	3.6	0.1- 0.2	0.06	BDL- 0.01	BDL	BDL-2.50	BDL	1070.0-1090.0	1070.0	8.4- 8.7	8.6
13610211DAD	27.9-29.0	27.9	2.0- 2.1	2.0	0.04-0.1	0.05	BDL- 0.01	BDL	223.0-230.0	228.0	1040.0-1080.0	1040.0	8.7- 8.9	8.7
13610221DBD	BDL-27.0	25.4	0.2- 2.5	2.7	0.04-0.1	0.05	BDL- 0.5	BDL	21.4-210.0	206.0	296.0-1040.0	1020.0	7.5- 8.8	8.7
13610324AAB	7.4- 8.0	7.6	4.6- 5.1	4.8	BDL-0.04	BDL	BDL	BDL	180.0-190.0	180.0	1020.0-1060.0	1020.0	8.7- 8.8	8.7
13610324ACC	23.1-23.1	23.1	2.2- 2.3	2.2	0.08-0.09	0.08	BDL	BDL	215.0-220.0	220.0	986.0-986.0	986.0	8.8	8.8
13710206CAC	25.8-26.0	26.0	1.7- 1.9	1.7	0.06-0.07	BDL	BDL- 0.01	BDL	266.0-272.0	272.0	1020.0-1040.0	1020.0	8.8- 8.9	8.8
13710207AAD	38.6-39.0	38.8	1.8- 2.0	1.9	BDL-0.03	BDL	BDL- 0.01	BDL	250.0-260.0	260.0	1030.0-1060.0	1030.0	8.8- 8.9	8.8
13710312BAB	34.0-35.0	34.5	1.6- 1.7	1.6	BDL-0.05	BDL	BDL- 0.01	BDL	279.0-284.0	284.0	1040.0-1070.0	1040.0	8.8- 8.9	8.8
13810301BAB	29.3-29.5	29.3	2.2- 2.4-	2.2	0.06-0.07	0.06	BDL	BDL	275.0-281.0	281.0	1070.0-1070.0	1070.0	8.7	8.7
13910217CAC2	32.0-33.0	32.6	2.3- 3.6	2.5	BDL-1.1	BDL	BDL- 0.04	BDL	248.0-260.0	252.0	1060.0-1100.0	1080.0	8.6- 9.0	8.8
13910220DAD	11.5-11.7	11.7	3.4- 3.7	3.4	0.08-0.10	0.10	BDL	BDL	BDL-1.1	BDL	1080.0-1080.0	1080.0	8.6	8.6
13910231BBB	28.9-29.5	28.9	2.9- 3.2	2.9	BDL-0.05	BDL	BDL	BDL	192.0-197.0	197.0	1080.0-1080.0	1080.0	8.7	8.7
14010210DCA	77.0-80.7	78.0	3.1- 3.4	3.1	0.1- 0.2	0.10	BDL- 0.01	BDL	94.0-105.0	103.0	1030.0-1050.0	1050.0	8.7- 8.8	8.8
14308918ACC	240.0-252.0	252.0	4.7- 5.1	4.7	BDL-0.1	BDL	BDL	BDL	BDL-0.4	BDL	1390.0-1530.0	1530.0	8.4- 8.7	8.5
14308919ACB	180.0-190.0	190.0	4.9- 6.0	4.9	0.1- 2.0	0.11	NAF, BDL-0.01	BDL	BDL-5.8	BDL	1270.0-1460.0	1430.0	8.4- 8.9	8.5
14309014DDA	207.0-215.0	215.0	4.1- 5.2	4.9	0.03-0.4	0.44	BDL- 0.01	0.01	BDL-12.4	12.4	1330.0-1450.0	1450.0	8.5	8.5

14309024ABC	190.0-197.0	197.0	4.8- 5.2	4.8	BDL-0.06	BDL	BDL- 0.01	BDL	BDL-0.4	BDL	1340.0-1440.0	1430.0	8.5- 8.6	8.5
14309024BAB	108.0-170.0	156.0	2.5- 4.3	2.8	0.1- 1.7	0.25	NAF, BDL-0.01	BDL	BDL-11.0	BDL	1440.0-1560.0	1560.0	7.9- 8.5	8.4
14408510CCA	266.0-284.0	266.0	3.9- 4.4	3.9	BDL-0.1	BDL	NAF, BDL-0.02	0.02	BDL-6.0	6.0	1440.0-1580.0	1580.0	8.3- 8.6	8.4
14408914CDD	237.0-1140.0	1120.0	2.6- 4.9	2.6	0.1- 0.9	0.13	BDL- 0.04	0.02	BDL-11.8	11.8	1440.0-2960.0	2960.0	8.0- 8.7	8.7
14409004BBA	117.0-120.0	119.0	2.7- 2.8	2.7	0.04-0.06	0.06	BDL- 0.01	BDL	BDL-0.4	BDL	1330.0-1500.0	1490.0	7.4- 8.5	8.5
14409110CBC	151.0-181.0	159.0	5.2- 5.5	5.2	0.1- 1.2	0.28	BDL- 0.01	BDL	BDL-1.2	BDL	1230.0-1340.0	1330.0	7.6- 8.9	8.9
14410322CCD	9.40-57.6	57.6	4.2- 6.3	4.2	BDL-0.1	BDL	BDL	BDL	127.0-210.0	127.0	1120.0-1230.0	1120.0	8.5- 8.7	8.7
14610227BCA	79.70-85.0	79.7	4.8- 5.1	4.8	BDL-0.1	BDL	BDL- 0.03	BDL	BDL-2.1	BDL	1070.0-1100.0	1080.0	8.6- 8.7	8.7
14710020DDB2	97.3-104.0	97.3	4.7- 5.2	4.7	BDL-0.5	BDL	BDL- 0.01	BDL	BDL-3.3	BDL	1100.0-1160.0	1150.0	8.3- 8.6	8.6
14910406ADB	132.0-140.0	132.0	5.0- 5.3	5.0	BDL-0.2	BDL	BDL- 0.01	BDL	BDL-2.5	BDL	1220.0-1270.0	1250.0	8.5- 8.7	8.6
15010404AAB	180.0-192.0	180.0	4.8- 5.3	4.8	BDL-0.02	BDL	BDL- 0.01	BDL	BDL-1.2	BDL	1290.0-1370.0	1360.0	8.6	8.6
15110404AAA	177.0-190.0	177.0	4.7- 5.5	4.9	BDL-0.1	BDL	BDL- 0.01	BDL	BDL-3.7	BDL	1310.0-1380.0	1370.0	8.3- 8.6	8.6
15209824CCC	309.0-440.0	401.0	3.8- 6.6	3.8	0.05-0.1	0.06	BDL- 0.03	BDL	BDL-3.3	BDL	1620.0-1970.0	1950.0	8.2- 8.5	8.4
15209903ABC	227.0-242.0	227.0	5.3- 5.8	5.4	BDL-0.5	0.08	BDL- 0.01	BDL	BDL-3.3	BDL	1510.0-1560.0	1550.0	8.1- 8.6	8.5
15210114DCA	220.0-241.0	223.0	3.0- 3.3	3.0	BDL-0.4	0.14	BDL- 0.01	BDL	BDL-3.7	BDL	1860.0-1930.0	1900.0	8.2- 8.4	8.4
15210115ADD	200.0-223.0	201.0	3.2- 6.6	5.1	0.1- 0.7	0.08	BDL- 0.05	BDL	BDL	BDL	1410.0-1480.0	1470.0	8.3- 8.5	8.5

BDL = below detection limit; NAF = not analyzed for

Table 10: Range and 2016 Concentrations (mg/l, except pH) of Contaminants of Concern at the Sampled Observation Wells

Site Location	Chloride		Fluoride		Iron		Manganese		Sulfate		TDS		pH [ ]	
	Range	2016	Range	2016	Range	2016	Range	2016	Range	2016	Range	2016	Range	2016
13008517DAA	251.0-289.0	284.0	2.3-2.9	2.5	0.04-4.0	0.1	BDL-0.03	BDL	0.6-18.0	6.2	1210.0 - 1320.0	1320.0	8.1-9.3	9.3
13407515BBB	BDL-8.8	BDL	0.1-0.4	0.1	BDL-0.8	0.8	0.1-0.4	0.2	21.4-194.0	21.4	104.0 - 716.0	104.0	7.1-8.2	7.1
13608107DDC1	3.9-7.0	5.7	2.1-2.3	2.1	0.2-0.4	0.3	BDL-0.02	BDL	115.0-130.0	115.0	1020.0 - 1070.0	1020.0	8.6-8.9	8.9
13608107DDC2	97.9-130.0	97.9	2.1-2.7	2.4	0.2-0.9	0.9	BDL-0.02	BDL	77.2-110.0	77.2	1380.0 - 1420.0	1420.0	8.5-9.1	9.1
13808002BCA2	922.0-946.0	922.0	0.4-0.7	0.5	0.1-0.8	0.8	0.03-0.1	0.1	BDL-21.2	21.2	2620.0 - 2630.0	2620.0	8.2-8.3	8.3
13808002BCA3	6.4-16.1	6.4	0.4-2.1	0.4	0.2-0.3	0.3	0.03-0.1	0.1	351.0-713.0	351.0	1070.0 - 1660.0	1070.0	7.9-8.2	7.9
14109019CCD	91.0-198.0	176.0	2.4-6.8	4.4	0.1-14.0	0.5	NAF, BDL-0.04	BDL	BDL-11.0	7.45	1290.0 - 1520.0	1430.0	8.1-9.7	8.9
15107009ACA1	1.9		0.2		0.3		0.4		65.6		389.0		7.8	
15207104BBA1	4.0		0.2		0.1		0.4		106.0		485.0		8.2	
15207105ADA1	6.1		0.2		1.2		0.4		141.0		565.0		7.7	
15307129AAB1	24.1		0.3		BDL		0.02		151.0		856.0		8.5	
15307133DDD1	4.1		0.4		0.1		0.1		76.3		534.0		8.4	
15307133DDD2	15.0		0.1		0.1		0.02		86.0		552.0		8.1	

BDL = below detection limit; NAF = not analyzed for

Table 5 through Table 10 can be used to analyze the quality of the groundwater samples of the Fox Hills – Hell Creek aquifer. Concentrations of aluminum, arsenic, boron, cadmium, chromium, copper, lead, selenium, silver and zinc were not analyzed in any of the groundwater samples collected from private wells in 2016. Groundwater samples collected from private wells were never analyzed for mercury. However, at least one of the groundwater samples collected from the listed observation wells was analyzed for mercury. The below analysis is provided by grouping analytes based on the available guidelines and using the historic ranges of concentrations. The first group includes analytes that have MCLs. Some analytes of this group can have NSDWR and/or livestock guidelines. The second group of analytes have livestock guidelines. Some analytes of this group may have NSDWR guidelines. The third group of analytes have only NSDWR guidelines. Contaminants, analytes, or macronutrients without any guidelines are included in the fourth group.

ANALYTES WITH MCLS

Each contaminant included in this group is associated with an MCL as set by the EPA. Some of the contaminants may be associated with the one or two other guidelines.

ARSENIC

Groundwater samples from private wells were last analyzed for arsenic in 2013. The samples from observation wells were analyzed for arsenic in 2016. Arsenic concentrations were at or above MCLs at 14408914CDD in 2005 and 2010. Water samples from all other private wells and all observation wells had arsenic concentrations lower than the MCL. The range of arsenic concentrations do not pose any toxicity to livestock. Because arsenic is linked to causing cancer (Evans et al. 2019), it is ideal for all water samples to be analyzed for arsenic.

CADMIUM, CHROMIUM, COPPER, LEAD, AND MERCURY

None of the analyzed groundwater samples from private or observation wells had concentrations above the respective MCL of cadmium, chromium, copper, lead, or mercury. With exception to the one sample from 13407515BBB in 2001, none of the groundwater samples from private wells were analyzed for mercury. However, the low concentrations did not raise enough concern to analyze for mercury since then. The range of concentrations for cadmium, chromium, lead, and mercury in analyzed groundwater samples do not raise a toxicity concern in livestock. Copper concentrations do not pose any concerns regardless of the guideline. However, people with Wilson's Disease are highly prone to copper concentrations exceeding the MCL (EPA 2018a).

FLUORIDE

The average and maximum concentrations of fluoride detected in groundwater samples from private wells are greater than the MCL. The average fluoride concentration in groundwater samples from observation wells is half the MCL. Only groundwater samples from observation well 14109019CCD contained fluoride in concentrations greater than MCL. Groundwater samples from 14 different private wells contained fluoride concentrations greater than MCL. Fluoride concentrations exceed the livestock and NSDWR guidelines in analyzed groundwater samples from all private and observation wells. The prolonged use of water with fluoride concentrations greater than 4 mg/l leads to bone disease and mottled teeth in children.

NITROGEN AS NITRATE

The nitrogen concentrations of analyzed groundwater samples from all private wells were three orders of magnitude smaller than the MCL and four orders of magnitude smaller than the livestock guideline. Among the sampled observation wells, the analyzed groundwater samples from 15107009ACA1 and 15307133DDD2 contained nitrogen concentrations greater than the MCL in 2016. This is because both these observation wells are in Benson County where the depth to the Fox Hills – Hell Creek aquifer is shallow and it may even be exposed to the surface. Nitrate dissipates and changes form as it percolates deeper into the ground. Elevated concentrations of nitrogen in the form of nitrates or nitrites are of concern especially if consumed by infants.

SELENIUM

Some of the groundwater samples from private and observation wells contained selenium in concentrations smaller than the detection limit. Among private and observation wells, 14408914CDD is the only private well with groundwater samples that had selenium concentrations greater than the MCL and livestock guidelines. These groundwater samples were collected in 2005 and 2010. The consumption of water with selenium concentrations greater than 0.05 mg/l can lead to circulatory problems for humans and is considered toxic to livestock.

ANALYTES WITH LIVESTOCK GUIDELINES

Each contaminant included in this group is associated with a livestock guideline. None of these contaminants has an MCL. However, some of the contaminants may be associated with NSDWR guidelines.

ALUMINUM

Groundwater samples from all private wells and all observation wells but one had aluminum concentrations smaller than the detection limit of the analysis method and the livestock guideline. The 2010 groundwater sample from 13608107DDC2 had aluminum concentration greater than the detection limit but smaller than the livestock guidelines. Moreover, that concentration falls within the range of NSDWR guidelines for aluminum.

BORON

Two groundwater samples from private wells contained elevated boron concentrations. All groundwater samples from observation wells contained boron in concentrations smaller than the livestock guideline. Groundwater samples collected from 14308918ACC and 14409004BBA in 2005 contained boron concentrations of 6.25 and 5.00 mg/l, respectively. Such boron concentrations maybe toxic to livestock.

ZINC

None of the analyzed groundwater samples contained alarming concentrations of zinc with respect to being consumed by livestock or causing any aesthetic effects on humans.

TOTAL DISSOLVED SOLIDS (TDS)

The average and maximum levels of TDS measured in the groundwater samples from private and observation wells are larger than the livestock ideal guideline and the NSDWR guideline. The range of the TDS (total dissolved solids) of the Fox Hills – Hell Creek water samples indicate that the water has relatively low – very satisfactory salinity. While the use of water with relatively low salinity is considered to be excellent for all classes of livestock and poultry, the use of water with very satisfactory salinity may cause temporary and mild diarrhea in livestock not accustomed to them and water droppings in poultry. Water with high TDS tends to be colored and have a salty taste and may cause staining.

ANALYTES WITH NSDWR GUIDELINES

Each contaminant included in this group is associated only NSDWR guidelines. None of these contaminants have an MCL or livestock guidelines.

CHLORIDE

Groundwater samples from private wells 14308918ACC, 14408510CCA, 14408914CDD, and 15209824CCC and from observation wells 13008517DAA and 13808002BCA2 had chloride concentrations greater than the NSDWR guidelines. Water with chloride concentrations greater than 250 mg/l tend to have salty taste.

IRON

None of the groundwater samples from private wells contained iron in concentrations larger than the NSDWR guidelines since 1982. The private wells that showed elevated iron concentrations before that are 13910217CAC2, 14308919ACB, 14309024BAB, 14710020DDB2, 15209903ABC, 15210114DCA, and 15210115ADD. However, groundwater samples from some observation wells showed elevated iron concentrations in 2016. These observation wells are 13407515BBB, 13608107DDC1, 13608107DDC2, 13808002BCA2, 13808002BCA3, 14109019CCD, and 15207105ADA1. Groundwater samples from the observation well 13008517DAA showed a single elevated iron concentration in the past. Water with iron concentration above 0.3 mg/l may have rusty color and a metallic taste, and may cause sedimentation and reddish or orange stains.

MANGANESE

Among private wells, groundwater samples from the stock well 15210115ADD contained elevated manganese concentration in the past. Groundwater samples from the observation well 13407515BBB consistently contained elevated manganese concentrations. Groundwater samples from the other observation wells 13808002BCA2, 13808002BCA3, 15107009ACA1, 15207104BBA1, 15207105ADA1, and 15307133DDD1 contained elevated manganese concentrations in 2016. Water with manganese concentrations greater than 0.05 mg/l can become black to brown in color, have a bitter metallic taste, and may cause black staining.

SILVER

None of the groundwater samples contained silver concentrations that would cause any aesthetic effect.

SULFATE

The average sulfate concentrations in groundwater samples from the private wells and from observation wells do not exceed the NSDWR guidelines. The 2016 sulfate concentrations in groundwater samples collected from private wells 13710206CAC, 13710207AAD, 13710312BAB, 13810301BAB, and 13910217CAC2, and observation well 13808002BCA3 were greater than 250mg/l. Water with elevated sulfate concentrations has a salty taste.

pH

The preliminary statistical measures of pH levels in groundwater samples from private wells are similar to those from observation wells. The average pH levels are at the upper end of the NSDWR guideline limit and the maximum measured levels are just outside the range. Such levels of pH are expected to make the water feel slippery, give the water a soda taste, and cause deposits.

ANALYTES WITH NO GUIDELINES OR LIMITS

Calcium, carbonate, magnesium, and sodium have no suggested limits for human or livestock consumption. However, water sample chemical composition can be based on these ions. Figure 16 summarizes the water chemistry of the analyzed water samples from observation and private wells. There is more variation in the distribution of cations in water samples from observation wells than in water samples from private wells. That is most probably because there is more variation in the screened depth and the spatial distribution of observation wells than of private wells. Overall, the water is predominantly sodium-bicarbonate type that generally has less dissolved constituents than the overlying formations.

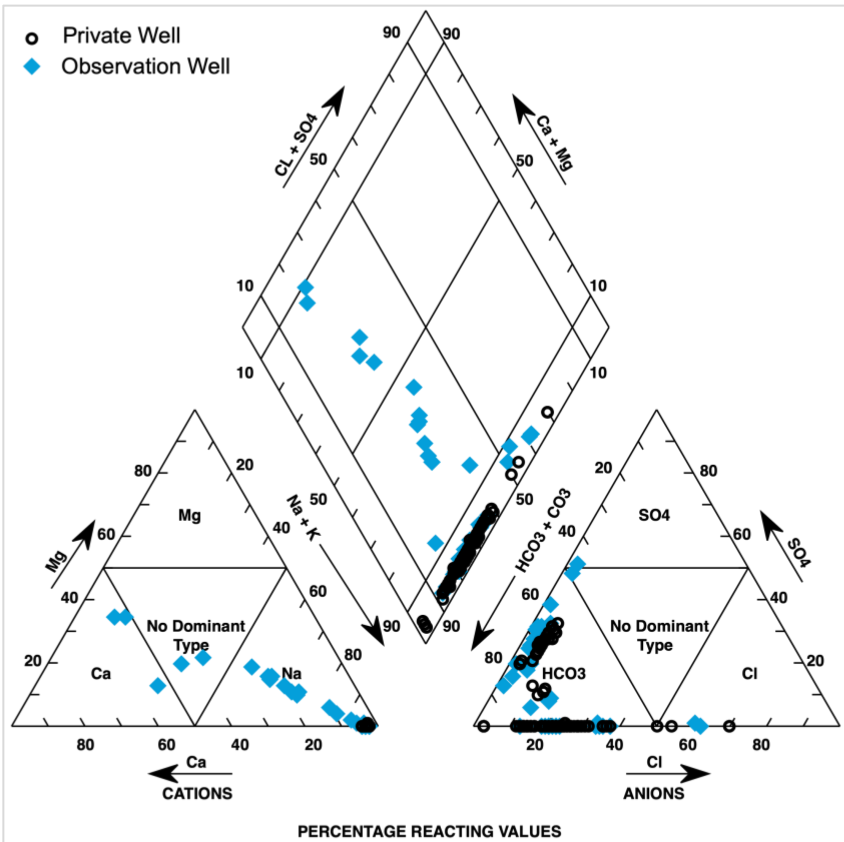

Figure 16: Piper Diagram of Analyzed Water Samples

SUMMARY AND RECOMMENDATIONS

The overall aquifer head declined at a slower rate (18% less) between 2006 and 2016 than between 1995 and 2006. However, the maximum rate of decline increased from 3.09 feet/year to 4.70 feet/year. The increase in the average rate of decline reflects decreasing aquifer discharge at local areas that is a result of out-of-use wells, wells with decreasing efficiency, or better conservation of water. The pressure head in the Fox Hills – Hell Creek aquifer continues to decline because discharge from the aquifer, primarily from flowing head and other production wells is greater than recharge to the system. If unmanaged or uncontrolled flow from many of the flowing head wells was diminished, the rate of decline could decrease more. In 2016, the aquifer flowing head is approximately declining at a maximum rate of 2.55 feet/year with an average of 0.95 feet/year. At the current rate of discharge, flowing wells are expected to cease flowing between 2022 and 2387.

Fox Hills – Hell Creek aquifer continues to be used predominantly for livestock purposes. The reported use of Fox Hills – Hell Creek water for domestic, irrigation and rural water purposes continued to diminish since 2006. The reported use of the aquifer water for municipal purposes continued to decrease but still is a major component of the total reported aquifer water used since 2006. The reported water use for industrial purposes did not decline with the same rate as that for municipal purposes.

The quality of the Fox Hills – Hell Creek groundwater samples continue to follow the general trend detected in previous analysis. In general, the quality of the groundwater improves closer to the recharge zones. Water from the Fox Hills – Hell Creek aquifer is primarily a sodium-bicarbonate type. Concentrations of arsenic are commonly found in samples collected from the aquifer. Because there is growing evidence that tie arsenic to cancer (Evans et al. 2019), arsenic should be analyzed in future field work and prior to any well being used for human consumption. Other constituents of concern with human consumption include chloride and fluoride with concentrations that are frequently greater than the respective MCL. Selenium might be elevated at some locations. High nitrate concentrations might be of concern in shallow wells. Among the constituents of concern with livestock guidelines, boron and TDS concentrations are the contaminants that are expected to be elevated. Aesthetic effects might occur from elevated iron manganese and sulfate concentrations. Even though erosion of natural deposits can result in the presence of barium, it was never analyzed for in any of the groundwater samples. Because beryllium, cyanide, and thallium are not present as a result of natural deposit erosion, they were never analyzed for in any of the samples. If attainable, the detection limit of the analysis method should always be smaller or equal to the most crucial guideline.

There has been fair representation of private wells in areas where the Fox Hills – Hell Creek aquifer is flowing along the Little Missouri River and its tributaries. Between the observation wells and private wells, each of the counties over which the aquifer extends has at least one Fox Hills – Hell Creek well except for Burke, Bottineau, Mountrail, Ward, McLean, Sheridan, and Adams Counties. Private wells 13910220DAD and 13910231BBB should be surveyed so that depth to groundwater measurements can be transposed into elevations coherent with the other wells.

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APPENDIX:

SAMPLING EVENTS SPAN AND COUNT OF SELECT FOX HILLS – HELL CREEK WELLS

Site Location	Purpose	Potentiometric Surface Elevation 2016 Measurement Events			Groundwater Quality Historic Sample Events		
		Range in Date		Count	Range in Date		Count
12908023DDD	O	5/5/16	10/27/16	3	10/19/73	4/19/17	3
12908101BAB	O	5/5/16	10/27/16	3	7/13/73	4/17/17	3
12910434ADA2	O	5/5/16	10/27/16	3	10/19/10	4/19/17	2
13008517DAA	O	5/3/16	10/27/16	4	11/16/72	10/13/16	9
13008628CCC1	O	1/29/16	11/18/16	7	7/5/73	8/8/17	5
13008628CCC2	O	1/29/16	11/18/16	7	7/10/73	9/23/11	5
13108930AAA	O	5/3/16	10/27/16	2	7/2/73	7/2/73	1
13110207DDD1	O	1/27/16	11/16/16	7	7/20/72	7/20/72	1
13207022BBB1	O	5/12/16	11/1/16	7	9/29/76	9/8/04	3
13209128DDD	O	5/3/16	10/27/16	3	8/30/68	11/12/87	2
13210516BDB2	O	5/5/16	10/27/16	3	11/1/11	4/19/17	2
13210516BDB3	O	5/5/16	10/27/16	3	11/1/11	4/19/17	2
13308031CCD1	O	5/5/16	10/27/16	3	5/15/73	9/22/10	2
13308312ADA1	O	5/5/16	10/27/16	3	5/17/73	4/17/17	3
13310613ADB2	O	5/5/16	10/27/16	3	9/21/77	4/19/17	7
13407515BBB*	O	1/5/16	12/13/16	8	10/25/72	9/7/18	10
13408236DCD	O	5/5/16	10/27/16	3	9/1/71	4/17/17	4
13507315DCC	O	5/9/16	11/1/16	7	11/21/78	5/2/18	5
13509023BBB1	O	1/26/16	10/4/16	6	5/30/73	5/30/73	1
13509704DCA	O	1/26/16	11/17/16	7	8/4/68	9/28/11	6
13607316CBC1	O	5/9/16	11/1/16	7	6/21/79	5/1/18	4
13607322AAA	O	5/9/16	11/1/16	7	5/2/79	5/1/18	4
13607607BCC	O	7/19/16	7/19/16	1	10/18/72	6/12/19	9
13607807BDB	O	5/18/16	11/10/16	7	9/3/71	6/12/19	9
13608107DDC1	O	5/3/16	10/27/16	8	6/2/75	10/13/16	3
13608107DDC2	O	5/3/16	10/27/16	8	6/23/75	10/13/16	3

13608130BBB	O	5/3/16	10/27/16	7	6/2/11	8/3/17	2
13608225DDA1	O	5/3/16	10/27/16	7	6/2/11	8/3/17	2
13608225DDD	O	5/3/16	10/27/16	7	6/2/11	8/3/17	2
13610211BBB	S	8/15/16	8/15/16	1	6/1/95	8/15/16	3
13610211DAD	S	8/16/16	8/16/16	1	6/1/95	8/16/16	3
13610221DBD	S	8/22/16	8/22/16	1	5/31/95	8/22/16	4
13610324AAB	S	8/16/16	8/16/16	1	5/25/95	8/16/16	3
13610324ACC	D	8/16/16	8/16/16	1	4/10/06	8/16/16	2
13710206CAC	D	8/16/16	8/16/16	1	6/6/95	8/16/16	3
13710207AAD	S	8/16/16	8/16/16	1	6/7/95	8/16/16	3
13710312BAB	D	8/31/16	8/31/16	1	6/6/95	8/31/16	3
13808002BCA2	O	5/17/16	11/9/16	7	5/15/06	10/12/16	3
13808002BCA3	O	5/17/16	11/9/16	7	9/2/08	10/12/16	3
13810301BAB	S	8/17/16	8/17/16	1	4/11/06	8/17/16	2
13907317CDBA	O	5/2/16	10/24/16	4	10/28/98	5/16/17	6
13907317CDBA2	O	5/2/16	10/24/16	4	10/27/98	5/16/17	6
13907927DCA	O	5/5/16	10/27/16	3	4/9/76	4/18/17	3
13908731DDA	O	1/26/16	11/15/16	10	8/27/14	7/27/17	3
13909607AA	M	5/5/16	5/5/16	1			
13910217CAC2	D	8/17/16	8/17/16	1	8/14/74	8/17/16	5
13910220DAD	S	8/17/16	8/17/16	1	4/11/06	8/17/16	2
13910231BBB	S	8/17/16	8/17/16	1	4/11/06	8/17/16	2
14010210DCA	M	8/18/16	8/18/16	1	6/14/95	8/18/16	4
14010530CCC6	O	1/27/16	12/20/16	6	10/3/84	10/3/84	1
14109019CCD	O	5/5/16	6/30/16	2	6/6/67	6/30/16	17
14208424BBA	O	2/25/16	11/16/16	6	12/7/67	8/22/68	2
14308918ACC	S	10/11/16	10/11/16	1	9/30/94	10/11/16	3
14308919ACB	S	10/11/16	10/11/16	1	8/24/64	10/11/16	4

14309014DDA	S				9/30/94	10/10/16	3
14309024ABC	S	10/11/16	10/11/16	1	9/28/94	10/11/16	3
14309024BAB	D	10/10/16	10/10/16	1	8/24/64	10/10/16	4
14310533BAB	O	8/2/16	8/2/16	1	11/5/76	10/13/06	4
14408510CCA	S				3/29/67	10/10/16	4
14408914CDD	M	11/2/16	11/2/16	1	5/18/69	11/2/16	5
14409004BBA	S	10/11/16	10/11/16	1	10/5/94	10/11/16	3
14409110CBC	M	10/10/16	10/10/16	1	10/5/94	10/10/16	4
14410322CCD	S	8/31/16	8/31/16	1	8/5/75	8/31/16	2
14509803DDD1	O	8/2/16	8/2/16	1	5/26/83	5/26/83	1
14609020CCC	O	2/10/16	10/17/16	6	6/28/68	9/29/11	5
14610227BCA	S	8/23/16	8/23/16	1	6/5/79	8/23/16	5
14710020DDB2	S	8/23/16	8/23/16	1	6/19/80	8/23/16	5
14807336AAA	O	5/24/16	11/8/16	7	9/25/14	9/25/14	1
14909509CDD	O	8/10/16	8/10/16	1	6/23/86	9/29/05	2
14910406ADB	D	8/30/16	8/30/16	1	6/29/95	8/30/16	4
15009922BBA1	O	8/10/16	8/10/16	1	9/25/80	11/9/05	2
15010404AAB	D	8/30/16	8/30/16	1	6/23/95	8/30/16	3
15107009ACA1	O	5/24/16	11/8/16	8	5/24/16	5/24/16	1
15109504DBD2	O	8/10/16	8/10/16	1	1/1/84	9/27/05	2
15110311AAA	O	8/10/16	8/10/16	1	5/20/85	11/8/05	3
15110404AAA	D	8/29/16	8/29/16	1	10/31/78	8/29/16	5
15207104BBA1	O	5/24/16	11/8/16	8	5/24/16	5/24/16	1
15207105ADA1	O	5/24/16	11/8/16	8	5/24/16	5/24/16	1
15207105CCCC1	O	5/24/16	11/8/16	7	8/13/98	5/8/19	5
15209824CCC	S				6/4/80	8/24/16	5
15209903ABC	S	8/24/16	8/24/16	1	6/18/80	8/24/16	5
15210114DCA	S	8/25/16	8/25/16	1	11/2/78	8/25/16	5

15210115ADD	S	8/25/16	8/25/16	1	6/24/82	8/25/16	5
15307119AAAA1	O	5/24/16	11/8/16	7	8/12/98	5/8/19	5
15307129AAB1	O	5/24/16	11/8/16	8	5/24/16	5/24/16	1
15307133DDD1	O	5/24/16	11/8/16	8	5/24/16	5/24/16	1
15307133DDD2	O	5/24/16	11/8/16	8	5/24/16	5/24/16	1
15307203DDD	O	5/24/16	11/8/16	7	5/15/69	5/15/69	1
15309423CCC1	O	8/10/16	8/10/16	1	9/25/80	10/4/06	2
15309611ADA	O	5/11/16	11/9/16	3	9/9/87	9/9/87	1
15309620DCB1	O	8/10/16	8/10/16	1	8/26/84	9/28/06	3
15407111AAD1	O	1/6/16	12/14/16	7			
15407836AAA3	O	5/24/16	11/9/16	7	8/3/00	10/3/17	9
15407836AAA4	O	5/24/16	11/9/16	7	8/3/00	7/26/12	7
15407836AAA5	O	5/24/16	11/9/16	7	8/3/00	10/2/17	7
15607312CCC	O	1/6/16	12/14/16	7	11/1/67	7/24/12	8
15607722CCC	O	5/25/16	11/9/16	7	8/5/75	5/15/19	6
15609620DCD	O	5/10/16	8/9/16	4	1/1/84	10/11/06	3
15707534BBB	O	5/25/16	11/9/16	7	10/6/14	5/14/19	2
15807116DDD	O	5/25/16	11/9/16	7	6/6/96	8/1/18	5
15807624DAC3	O	5/25/16	11/9/16	7	6/10/03	5/14/19	5
15910216AAD	O	8/9/16	8/9/16	1	6/6/85	10/20/05	3
16108424DDD	O	1/27/16	11/16/16	7	10/4/79	8/6/08	7
16209523CCC1	O	8/8/16	8/8/16	1	6/21/85	8/6/85	2
16307311CCC1	O	8/23/16	8/23/16	1	9/26/78	7/8/97	2
16307311CCC2	O	1/6/16	12/14/16	8	9/21/78	7/8/97	2
16310116DDD	O	7/13/16	7/13/16	1	4/20/83	10/11/06	4

*O = observation well; S = stock well; D = domestic well; M = municipal well; Purpose reflects the purpose in 2016; * = sampled in 2016 too.*