Groundwater Level Recovery in the Sandstones of the Lower Tertiary Aquifer System of the Powder River Basin, Wyoming

Karl G. Taboga, James E. Stafford, and James R. Rodgers

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Cover photo: Groundwater level monitoring well (in the background) and equipment storage hut at the Napier well site, Campbell County, Wyoming. Photo by Richard Hays, WSGS, 2010.

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INTRODUCTION

This report updates and supersedes the Wyoming State Geological Survey (WSGS) Report of Investigations 74 (Taboga and others, 2017). That study examined groundwater level (GWL) changes in Wasatch and Fort Union Formation sandstones, henceforth referred to as the lower Tertiary aquifer system (Thamke and others, 2014), resulting from coal bed natural gas (CBNG) production in Wyoming's Powder River Basin (PRB). This report contains additional data from the Bureau of Land Management (BLM) and Wyoming Oil and Gas Conservation Commission (WOGCC) collected during 2017–2020. Furthermore, this study estimates the duration of groundwater recovery in some affected sandstone aquifers, and examines the relations between GWLs in the sandstone and associated coal seam aquifers; those are two analyses that were not provided in the previous investigation.

Between 2001 and 2019, the PRB in Wyoming produced more than 6.1 trillion cubic feet of CBNG and 8.0 billion barrels (about 1,000,000 acre-feet) of groundwater (WOGCC, 2020) from coal seams in the lower Tertiary aquifer system. Annual CBNG production in the PRB peaked in 2009 at more than 556 billion cubic feet (bcf), or 2.1 percent of all U.S. natural gas production for that year (WOGCC, 2020; U.S. Energy Information Administration [EIA], 2020). Since then, annual production has declined by 83 percent to 92.6 bcf during 2019 (fig. 1).

CBNG is produced by pumping large volumes of groundwater from a targeted coal seam, reducing both the water level and water pressure. This allows microscopic films of natural gas within the pores and fractures of the coal to coalesce into bubbles just as carbon dioxide effervesces from a newly opened bottle of seltzer. Produced water and free natural gas are pumped to the surface and separated at the wellhead. The CBNG is transported through pipelines to a series of compressor stations and then to market. Good-quality produced water is used for agricultural applications or discharged into unlined evaporation/infiltration

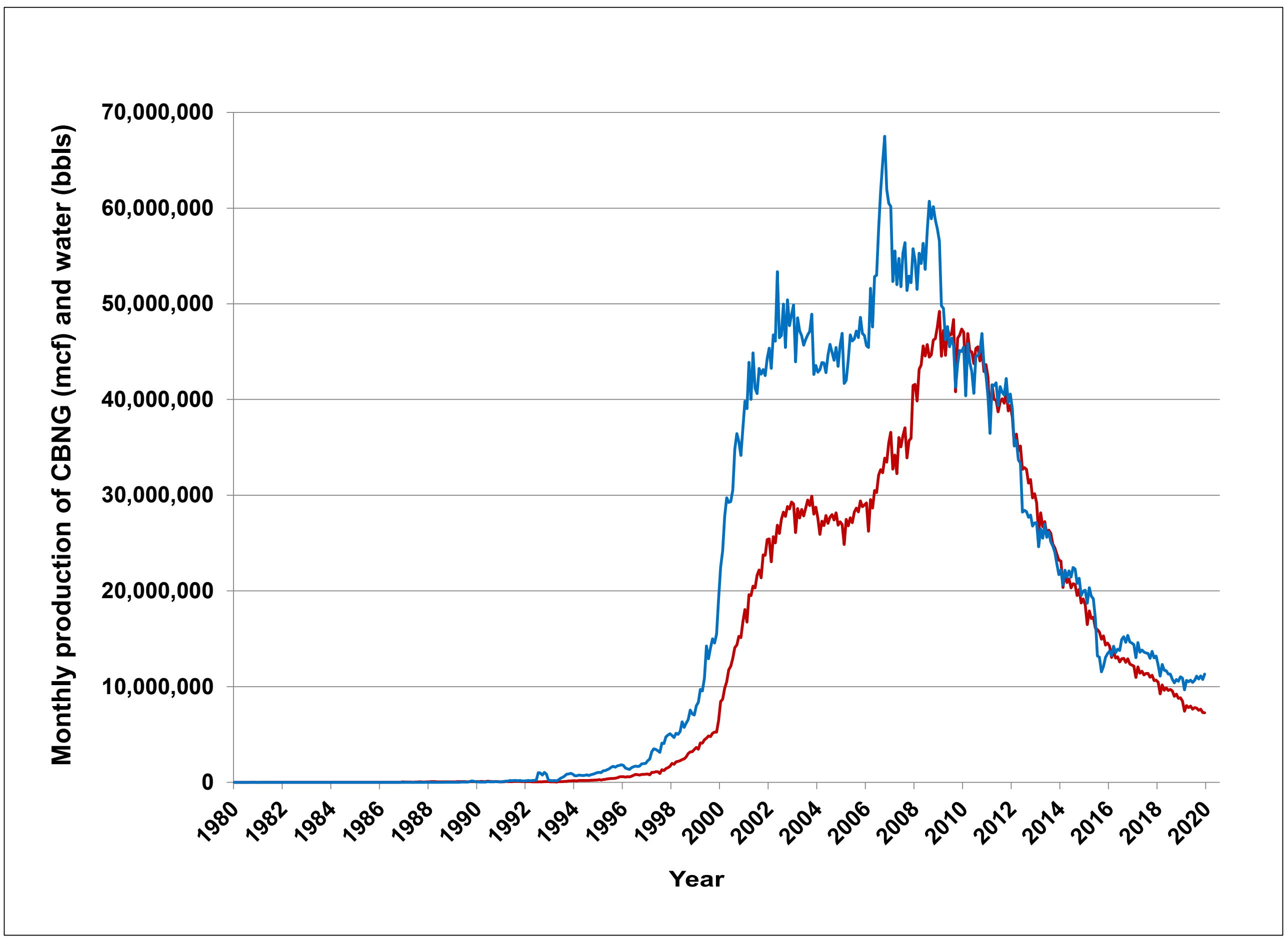

Figure 1. Monthly production volumes of coal bed natural gas (red line), in thousand cubic feet (mcf), and groundwater (blue line), in barrels (bbls), in the Wyoming portion of the Powder River Basin from 1980–2019 (WOGCC, 2020).

pits and streambeds. Poorer-quality water is reinjected into deeper geologic formations, pumped into lined evaporation pits, or treated and discharged to surface drainages.

During the dewatering stage, GWLs in coal seam aquifers may be lowered by several hundred feet. As the rate of pumping declines or ceases, water levels in the targeted coal seam frequently rise (recover); however, in some cases GWLs remain the same or continue to decline (Taboga and others, 2015, 2017). These fluctuations are not restricted to the producing coal seam but frequently extend to adjacent sandstone aquifers (Clarey and others, 2010; McLaughlin and others, 2012; Stafford and Wittke, 2013; Taboga and Stafford, 2014; Taboga and others, 2017). The potential impact on GWLs in the overlying sandstone aquifers, which supply many of the PRB's 14,000 domestic, municipal, and agricultural wells, rapidly became a point of concern (BLM, 2004; Bredehoeft, 2004) during the early stages of CBNG development in the PRB. Since then, there has been considerable speculation about the occurrence, magnitude, and timing of groundwater depletion and recovery in the shallow sandstone aquifers.

In partial response to these concerns, the BLM Field Office in Buffalo, Wyoming, expanded its GWL monitoring program in the Wyoming portion of the PRB. The program, which began recording GWLs in the coal zone and proximal sandstone aquifers near coal mines in the eastern PRB in the 1990s, grew to more than 60 monitoring sites scattered across the basin by 2008. In the past, the BLM contracted the WSGS to publish periodic reports for this program (Clarey and others, 2010; McLaughlin and others, 2012; Stafford and Wittke, 2013; Taboga and Stafford, 2014). Additionally, the WSGS has used the BLM data to investigate GWL recovery in the Upper Wyodak coal zone (Taboga and others, 2015) and in the associated sandstone aquifers (Taboga and others, 2017).

Previous WSGS studies provide summary descriptions of the geologic setting and hydrostratigraphy of the PRB (Taboga and others, 2015, 2017). U.S. Geological Survey (USGS) investigations in the PRB provide timely descriptions of the basin's hydrogeology (Thamke and others, 2014; Long and others, 2014) and coal stratigraphy (Flores and others, 2010; Luppens and others, 2015). USGS reports can be downloaded from the USGS publications website, https://pubs.er.usgs.gov/. A detailed description of the area's hydrostratigraphy (Taboga and others 2019, chap. 7) is available on the Wyoming Water Development Commission's website, https://waterplan.state.wy.us/plan/powder/2016/gw-finalrept/gw_toc.html.

METHODS

This report uses GWL data collected manually and with instrumentation by the BLM Buffalo Field Office from 40 Fort Union coal zone and 58 associated sandstone aquifer monitoring wells located at 39 monitoring sites (fig. 2, table 1) previously examined in the 2017 report (Taboga and others, 2017). The Palo monitoring site, closed in 2016, is not included in this study. Additionally, monitoring has been suspended at the Buffalo SE (September 2018) and Bull Creek (October 2017) sites. Updated data from those sites not included in the 2017 report are presented here.

Most analyses in this study use the manual GWL measurements because automated collection of GWL data requires regular inspection and calibration of the pressure transducers and data loggers used. Regular maintenance of this equipment is not always possible given the large number of monitoring wells in the BLM network and extreme weather conditions that can prevent access to remote sites for months at a time. Furthermore, transducers can malfunction between periodic calibrations resulting in spurious readings and lost data. Moreover, obtaining GWL data from manual measurements presents its own set of challenges, particularly in wells that are more than 100 ft deep. Damaged well casings, cascading groundwater, and data recording errors can result in seemingly anomalous manual measurements. These factors may explain some of the apparent irregularities observed in the hydrographs contained in this report. The complete GWL dataset is available from the BLM Buffalo Field Office by request, https://www.blm.gov/office/buffalo-field-office.

After review, the WSGS selected monitoring sites with a relatively complete record of quarterly manual water level measurements in one or more sandstone aquifer wells and in an associated well completed in the closest coal seam aquifer. It should be noted that several coal seam monitoring wells in this study lack measurements during periods when GWLs fell below the total depth of the wellbore or because CBNG pressures at the wellhead rose to unsafe levels. Monitoring wells with documented mechanical problems, such as wellbore packer failures or compromised well casings, were excluded from this study.

This report focuses on four aspects of GWL changes in the sandstone monitoring wells:

- How do maximum water level changes relate to the depth of the completed sandstone interval and its vertical distance to the associated coal seams?
- How do water levels respond to the decline or cessation of water production in relation to the depth of the completed sandstone interval and its vertical distance to the associated coal seams?
- How might seasonal changes affect GWLs?
- How are hydraulic responses in the sandstone and associated coal seam aquifers related?

The monitoring site hydrographs (figs. A1-1 through A1-10 and A2-1 through A2-29 in the appendices) used to answer these questions plot depths-to-groundwater (vertical axis) as a function of time (horizontal axis). Values on the vertical axis are given in reverse order, that is, the top of the vertical axis (shown as "0") represents the land surface. This is a more intuitive approach than showing GWLs in terms of altitude, particularly for non-technical readers of this report. The vertical distance between sandstone and coal seam aquifers is the thickness of the intervening sediments (interburden) between the two monitored units (Table 2).

Water Production Data

For this study, ArcGIS® Geographic Information System (GIS) software was used to identify CBNG wells located within a 3-mile-wide circular production area centered on each BLM monitoring site (Meredith and others, 2009; Stafford and Wittke, 2013). Then, WOGCC data (WOGCC, 2020) were used to calculate monthly water production from monitored coal seams in each production area into the year 2020. CBNG wells generally target the Wyodak coal zone and the subsidiary Andersen and Canyon coal seams in the eastern PRB, the Cook and Wall zones in the northcentral basin, and the Big George zone (also known as the Wyodak Rider) in the western portion of the basin.

In this report, water production volumes from wells completed in several coal zones, previously assigned to "multiple" zone production (Stafford and Wittke, 2013), were added to production volumes from monitored coal zones. It has been a common practice for CBNG operators to apply for multiple zone production knowing that the greatest portion of water and CBNG would be extracted from the most productive coal (usually the Wyodak or Big George coal zones). Monitoring sites were determined to be in "producing" areas if total CBNG well water production exceeded 1,000 barrels (bbls)/month (about 1 gallon per minute [gpm] for the entire production area) after June 2019. The remaining sites were considered to be sited in "nonproducing" areas.

GWL Changes and Recent Rates of Recovery/Decline

BLM hydrographs were evaluated in Microsoft Excel for this study. In this report, declining GWL trends are shown as negative values and recovering trends as positive values. Maximum GWL changes were determined by subtracting the greatest depth to groundwater measurement from the initial level. The maximum GWL changes were then compared to the well's depth of completion and the vertical distance between the monitored sandstone and nearest monitored coal seam.

For monitoring sites in producing areas, annual rates of GWL change (recovery or decline) were calculated by linear regression over a three-year period, usually 2017–2020. In contrast, annual recovery/decline rates in nonproducing areas were determined from the month when total water production consistently fell below 1,000 bbl/month (~1 gpm) or ceased completely.

Time Series Decomposition—Seasonality, Trend, and Noise

Selected sandstone aquifer hydrographs were analyzed for seasonal fluctuations with software from http://www.wessa.net/tsa.wasp. The software is a collection of time series analysis modules written in R code that requires data collected at regularly spaced time intervals. Water levels for the first day of each month were obtained from monitoring sites that had three or more years of continuous daily automated (pressure transducer/datalogger) measurements. First, a spectral analysis module (Wessa, 2017) was applied to GWL data recorded for sandstone aquifers exhibiting periodic water level variations around 365 days (one calendar year). Then a seasonal decomposition module (Wessa, 2013) was used to determine the seasonal, trend, and noise components of the transducer data (Cleveland and others, 1990).

GWL Time-to-Recovery

GWL time-to-recovery to 95 percent of the initial measurement was calculated for nine sandstone wells using the calculated recovery/decline rates described previously. The wells in this analysis are completed in the closest sandstones that overlie or underlie the monitored coal seam, and all are recovering at an annual rate of more than 0.1 ft/year. The 95 percent recovery level was calculated by multiplying

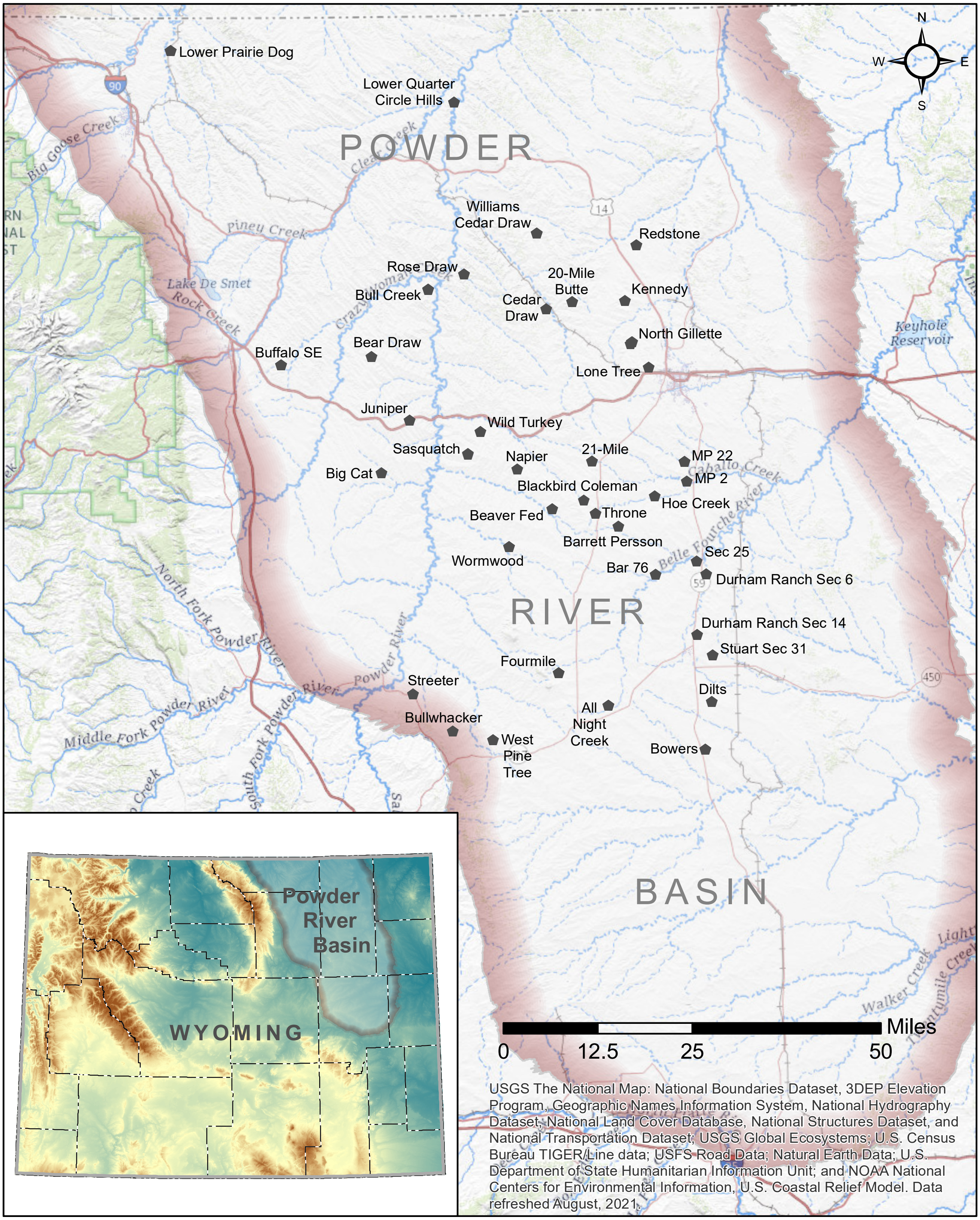

Figure 2. Location of 39 BLM sandstone and coal seam monitoring sites in the Powder River Basin of Wyoming.

Table 1. Bureau of Land Management groundwater monitoring site locations examined in this study. [Abbreviations: Qtr/Qtr, quarter/quarter; Sec., section; Twn., township; Rng., range; N, north; W, west; and ft, feet]

County	Monitoring site name	Public Land Survey System location				Coal seam intervals	Completed sandstone intervals	Approximate elevation (ft)	Start date (month-year)
		Qtr/Qtr	Sec.	Twn.	Rng.				
Monitoring sites centered in nonproducing zones									
Campbell	20-Mile Butte	SE SE	32	52 N	74 W	Anderson	1	4,557	Jan-2004
	21-Mile	NE NE	22	48 N	74 W	Big George	1	5,037	Aug-2001
	All Night Creek	NW SW	36	43 N	74 W	Big George	4	5,220	Mar-2001
	Bar 76	NE SE	1	45 N	73 W	Wyodak	1	4,768	Sep-1997
	Barrett Persson	SW SW	32	47 N	73 W	Wyodak	1	4,945	Dec-2000
	Blackbird Coleman	SW SE	5	47 N	74 W	Wyodak	1	4,778	Jul-2000
	Bowers	SE SW	36	42 N	72 W	Wyodak	4	5,018	Jan-1998
	Cedar Draw	NE SW	2	51 N	75 W	Wall	1	4,268	Jan-2004
	Dilts	SE NW	31	43 N	71 W	Wyodak	1	4,929	Mar-1999
	Durham Ranch Section 6	SW NE	6	45 N	71 W	Wyodak	1	4,697	Nov-1997
	Durham Ranch Section 14	SE NE	14	44 N	72 W	Wyodak	1	4,861	Jan-1998
	Fourmile	NW NE	11	43 N	75 W	Big George	2	5,358	Nov-2007
	Hoe Creek	SW SW	7	47 N	72 W	Wyodak	1	4,734	Jan-1998
	Kennedy	SE SE	33	52 N	73 W	Anderson	1	4,489	May-2000
	Lone Tree	SW SE	13	50 N	73 W	Wall	1	4,760	Feb-2000
	MP 2	NW NW	2	47 N	72 W	Wyodak	1	4,554	May-1993
	MP 22	SE NE	22	48 N	72 W	Wyodak	3	4,561	Feb-1993
	North Gillette	SW NE	34	51 N	73 W	Anderson	1	4,380	Sep-2001
	Redstone	SENW	26	53 N	73 W	Canyon	1	4,155	Oct-1998
	Section 25	SW SW	25	46 N	72 W	Wyodak	1	4,659	Nov-1996
	Stuart Section 31	NE SE	31	44 N	71 W	Wyodak	2	4,933	Aug-1997
	Throne Ranch	NW NW	26	47 N	74 W	Wyodak	1	5,029	Sep-2000
	Williams Cedar Draw	NE SW	15	53 N	75 W	Smith, Anderson	2	4,130	Apr-2007
Johnson	Buffalo SE	NW NW	12	50 N	81 W	Smith	4	4,542	Aug-2001
	Bull Creek	NW SE	12	52 N	77 W	Anderson	2	3,909	Nov-2005
	Rose Draw	NE SE	19	52 N	77 W	Wall	2	3,914	May-2009
	Streeter Road	SE NW	22	43 N	78 W	Big George	1	4,761	Aug-2004
Sheridan	L Quarter Circle Hills	NE SE	14	56 N	77 W	Cook	1	3,618	Apr-2005
	Lower Prairie Dog	SE NE	10	57 N	83 W	Anderson	2	3,715	Aug-2000
Monitoring sites centered in producing zones									
Campbell	Beaver Federal	SE NW	23	47 N	75 W	Big George	1	4,783	Apr-2003
	Napier	SE SE	24	48 N	76 W	Big George	1	4,803	May-2001
	Sasquatch	NE SW	12	48 N	77 W	Big George	1	4,472	Jan-1998
	West Pine Tree	SE SE	20	42 N	76 W	Big George	1	5,181	Sep-2007
	Wormwood	NWNE	14	46 N	76 W	Big George	2	4,574	Dec-2006
Johnson	Bear Draw Unit	SW NW	1	50 N	79 W	Big George	1	4,624	Mar-2006
	Big Cat	SE SE	24	48 N	79 W	Big George	1	4,480	Jul-2003
	Bullwhacker	NW SE	16	42 N	77 W	Big George	1	5,050	Apr-2002
	Juniper	SW SW	14	49 N	78 W	Big George	2	4,428	Mar-2001
	Wild Turkey	NE SW	29	49 N	76 W	Big George	1	4,344	Nov-2004

the maximum drawdown observed during the hydrograph period of record by 0.95. The time to recovery was determined from the month that water production ceased. The number of years to 95 percent recovery and corresponding calendar year were calculated from the year water production ceased at each monitoring site.

RESULTS AND DISCUSSION

The well hydrographs, figs. A1-1 through A1-10 and A2-1 through A2-29, in the appendices show that BLM technicians made manual depth-to-groundwater measurements at roughly three-month intervals at most monitoring sites into 2020. Gaps in the monitoring record may be the result of unsafe conditions such as dangerous weather or elevated wellbore gas pressures, landowner-restricted access to the monitoring site, or when obstructions in the wellbore prevented measurement. Several of the monitoring sites monitor multiple sandstone and coal strata with nested wells, wellbore packers, or a combination of the two. The hydrographs in this study show GWLs in monitored sandstone and coal seam aquifers, and monthly water production from CBNG wells located within the 1.5-mile radius production area of each monitoring site. Further detailed information regarding well completion zones and depths, CBNG gas production rates, interburden thicknesses, and area CBNG wells can be found in Taboga and Stafford (2014).

The tables in this section show sandstone and coal seam aquifer wells in stratigraphic order, from shallowest to deepest. The closest sandstone that overlies a monitored coal seam is always numbered as “sandstone 1.” At the few sites that monitor multiple overlying sandstones, shallower units are numbered consecutively, increasing as one approaches the surface. A sandstone that underlies a monitored coal aquifer is always referred to as an “underburden sandstone.”

Ten of the monitoring sites examined in this report are in zones that were actively producing CBNG and water during 2019 (table 1). Producing wells at all of these sites extract CBNG and produced water from Big George wells located on tributary drainages (WOGCC, 2020) of the upper Powder River mainstem (Hydrologic Unit Code 8 [HUC8] 10090202; WOGCC, 2020). During 2018–2019, CBNG wells completed in the Big George coal zone located in the upper Powder River drainage accounted for 97 percent of all gas and 90 percent of all water produced in the PRB (WOGCC, 2020).

The remaining 29 monitoring sites are in “nonproducing” zones (table 1), that is, monthly water production in the circular production area did not exceed 1,000 bbls/month, or 1 gpm, later than June 2019. In fact, no water production has been recorded at 25 of the nonproducing sites since July 2016. CBNG wells in the production areas of these monitoring sites are completed in the Upper and Lower Wyodak, Big George, Cook, and Wall coal zones.

Initial GWL Measurements

Initial GWLs were obtained by the BLM prior to the onset of water production at five monitoring sites centered on currently producing areas and 13 monitoring sites in nonproducing areas (table 2). Hydrographs from these sites show predevelopment hydraulic conditions in the lower Tertiary aquifer system that allow a complete assessment of the effects of CBNG production on sandstone and coal seam aquifers.

With one exception at site MP22 (fig. A2-21), the monitored coal seams and sandstones shown in table 2 are confined, or artesian, aquifers. That is, they are “immediately overlain by a low-permeability unit (confining layer; Sharp, 2007). The primary indication of a confined aquifer is that groundwater levels in a cased well rise above the top of the aquifer (Heath, 1983). In contrast, sandstone 3 of the MP22 site is an unconfined, or water table, aquifer above which there are unsaturated layers of sand, gravel, and soil. In fact, MP22 sandstone 3 is the only unconfined aquifer examined in this report.

Maximum GWL Changes

Tables 3 and 4 list GWL data for sandstone and coal seam aquifers at monitoring sites in producing and nonproducing areas, respectively. Additionally, coal seam water production data are shown for the corresponding production area around each monitoring site.

Maximum-recorded GWL changes in sandstone wells varied from a 36-ft rise at West Pine Tree (fig. A1-8) to a 567-ft decline in the underburden sandstone at the Wormwood site (fig. A1-10; table 3). The average maximum change for all sandstone wells is -89 ft (decline) compared to a previous average of -82 ft (Taboga and others, 2017). Since 2017, GWLs declined to new maximum lows in eight of 12 sandstones at monitoring sites located in producing areas (table 3) and in 16 of 46 sandstones at monitoring sites centered in nonproducing areas (table 4). The new maximum low GWLs are expected in the producing area monitoring sites; water production from surrounding CBNG wells averaged 59,000 bbls (~2.5 million gallons) per month in these areas during 2017–2019. Part of the declines observed in the producing area sites may be the result of regional drawdown in the Big George coal zone of the upper Powder River drainage.

Table 2. Sandstone and coal seam aquifer monitoring sites with predevelopment water levels. Negative values indicate that the monitored coal seam aquifer had a higher initial GWL than the associated sandstone aquifer(s). [Abbreviations: ft bgs, feet below ground surface; GWL, groundwater level; ft, feet; -----, not applicable or no data]

Monitoring site name	Monitored aquifer	Depth, top of aquifer (ft bgs)	Initial GWL (ft bgs)	GWL difference between coal and sandstone aqufers (ft)	Vertical distance between coal and sandstone aquifers (ft)
Monitoring sites centered in nonproducing zones with predevelopment water levels					
Bar 76	Sandstone 1	659	176.0	-14.2	47
	Upper Wyodak coal	726	161.8	-----	-----
Blackbird Coleman	Sandstone 1	670	250.9	120.0	736
	Upper Wyodak coal	1,426	370.9	-----	-----
Buffalo SE	Sandstone 4	55	47.8	233.2	1,458
	Sandstone 3	155	143.8	137.2	1,358
	Sandstone 2	520	419.2	-138.2	993
	Sandstone 1	1,482	337.5	-56.5	90
	Smith coal	1,588	281.0	-----	-----
Dilts	Sandstone 1	260	119.8	220.8	280
	Upper Wyodak coal	580	340.6	-----	-----
Durham Ranch Section 6	Sandstone 1	255	96.2	22.0	43
	Upper Wyodak coal	328	118.2	-----	-----
Hoe Creek	Sandstone 1	150	100.9	130.4	620
	Upper Wyodak coal	830	231.3	-----	-----
MP 2	Sandstone 1	260	52.0	111.1	26
	Upper Wyodak coal	336	163.1	-----	-----
MP 22	Sandstone 3	15	20.2	153.6	358
	Sandstone 2	107	38.3	135.5	253
	Sandstone 1	340	83.9	89.9	38
	Upper Wyodak coal	438	173.8	-----	-----
Redstone	Sandstone 1	160	24.7	8.1	56
	Lower Wyodak coal	241	32.8	-----	-----
Section 25	Sandstone 1	134	28.1	20.2	250
	Upper Wyodak coal	420	48.3	-----	-----
Streeter Road	Sandstone 1	522	213.5	-54.7	621
	Big George coal	1,351	158.8	-----	-----
Stuart Section 31	Sandstone 1	555	253.0	82.9	89
	Upper Wyodak coal	664	335.9	-----	-----
	Underburden sandstone	794	322.0	13.9	14
Throne Ranch	Sandstone 1	1,400	566.7	-16.9	56
	Wyodak coal	1,506	549.8	-----	-----

Table 2 continued.

Monitoring site name	Monitored aquifer	Depth, top of aquifer (ft bgs)	Initial GWL (ft bgs)	GWL difference between coal and sandstone aqufers (ft)	Vertical distance between coal and sandstone aquifers (ft)
Monitoring sites centered in producing zones with pre-development water levels					
Big Cat	Sandstone 1	862	356.6	-156.4	1,082
	Big George coal	1,970	200.2	-----	-----
Juniper	Sandstone 2	550	428.5	-260.0	908
	Sandstone 1	1,086	342.0	-173.5	418
	Big George coal	1,548	168.5	-----	-----
Napier	Sandstone 1	1,462	402.5	29.5	63
	Big George coal	1,585	432.0	-----	-----
Sasquatch	Sandstone 1	1,296	225.0	4.8	75
	Big George coal	1,435	229.8	-----	-----
Wild Turkey	Sandstone 1	998	128.1	139.6	187
	Big George coal	1,205	267.7	-----	-----

Table 3. Initial depth to groundwater, maximum change in GWL, and water production for monitoring sites in producing areas. Red text indicates maximum low GWL change that occurred since the previous report (Taboga and others, 2017). [Abbreviations: ft, feet; ft bgs, feet below ground surface; GWL, groundwater level; and GWL declines and rises marked with minus (-) and plus (+) signs, respectively]

					Change in GWL (ft)		Water Production		
Monitoring site name	Monitored aquifer	Depth to top of aquifer (ft bgs)	Period monitored	Initial GWL (ft bgs)	Maximum GWL change (ft) during period [Date]	Last measured GWL change (ft) [Date]	Period of recorded water production	Maximum water production (bbls/month) [Date]	Average production 2018 (bbls/month)
Bear Draw Unit	Sandstone 1	2,052	Mar 2006–Jul 2020	494	-542 [Jul 2020]	-542 [July 2020]	-------	-------	-------
	Big George coal	2,205	Mar 2006–Jul 2020	499	781 [Jul 2020]	-781 [July 2020]	May 2005–May 2020	194,637 [May 2011]	88,731
Beaver Federal	Sandstone 1	552	Aug 2003–Feb 2020	246	-10 [Jan 2019]	-10 [Jan 2020]	-------	-------	-------
	Big George coal	1,186	Aug 2003–May 2009	402	-433 [May 2009]	-433 [May 2009]	Jun 2006–May 2020	141,699 [Jan 2007]	6,635
Big Cat	Sandstone 1	862	July 2003–Mar 2020	357	-11 [Nov 2008]	-6 [Mar 2020]	-------	-------	-------
	Big George coal	1,970	July 2003–Mar 2020	200	-1,533 [Mar 2020]	-1,533 [July 2020]	May 2004–May 2020	446,647 [Jul 20040]	70,495
Bullwhacker	Sandstone 1	1,202	Apr 2002–Jan 2016	25	-312 [Apr 2020]	-312 [Apr 2020]	-------	-------	-------
	Big George coal	1,338	Apr 2002–Dec 2009	93	-1,267 [Aug 2017]	-1,265 [Apr 2019]	Aug 2001–May 2020	368,412 [Jan 2003]	51,111
Juniper	Sandstone 2	550	Mar 2002–Dec 2019	429	-3 [Aug 2008]	-3 [Mar 2016]	-------	-------	-------
	Sandstone 1	1,086	Jun 2001–Dec 2019	342	-51 [Apr 2020]	-51 [Apr 2020]	-------	-------	-------
	Big George coal	1,548	Mar 2001–Sep 2019	168	-1,446 [June 2008]	-1,446 [Apr 2020]	July 2002–May 2020	445,330 [Sep 2004]	53,350
Napier	Sandstone 1	1,462	May 2001–Mar 2020	403	-341 [Sep 2017]	-320 [Mar 2020]	-------	-------	-------
	Big George coal	1,585	May 2001–Aug 2012	432	-500 [Aug 2012]	-500 [Aug 2012]	Sep 2004–May 2020	130,330 [Dec 2012]	17,545

Table 3 continued.

Monitoring site name	Monitored aquifer	Depth to top of aquifer (ft bgs)	Period monitored	Initial GWL (ft bgs)	Change in GWL (ft)		Water Production		
					Maximum GWL change (ft) during period [Date]	Last measured GWL change (ft) [Date]	Period of recorded water production	Maximum water production (bbls/month) [Date]	Average production 2018 (bbls/month)
Sasquatch	Sandstone 1	1,296	Jul 2001–Mar 2020	225	-434 [Mar 2020]	-434 [Mar 2020]	-------	-------	-------
	Big George coal	1,435	Jan 1998–Mar 2020	230	-619 [Mar 2020]	-619 [Mar 2020]	Feb 2002–May 2020	790,079 [Jun 2005]	20,298
West Pine Tree	Sandstone 1	538	Sep 2007–Apr 2020	272	36 [Nov 2010]	33 [Apr 2020]	-------	-------	-------
	Big George coal	1,347	Sep 2007–Apr 2020	272	-728 [Aug 2019]	-705 [Apr 2020]]	Jul 2007–May 2020	141,249 [Feb 2009]	36,046
Wild Turkey	Sandstone 1	998	Nov 2004–Apr 2020	128	-254 [Apr 2020]	-254 [Apr 2020]	-------	-------	-------
	Big George coal	1,205	Nov 2004–Aug 2016	268	-937 [Feb 2013]	-907 [Aug 2016]	Oct 2005–May 2020	1,425,974 [Jul 2006]	5,360
Wormwood	Sandstone 1	478	Dec 2006–Apr 2020	77	6 [Mar 2009]	-3 [Apr 2020]	-------	-------	-------
	Big George coal	1,074	Dec 2006–Apr 2020	262	-838 [Apr 2020]	-838 [Apr 2020]	Aug 2006–May 2020	504,162 [Mar 2007]	112,147
	Underburden sandstone	1,287	Dec 2006–Apr 2020	115	-567 [Apr 2018]	-556 [Apr 2020]	-------	-------	-------

Table 4. Initial depth to groundwater, maximum change in GWL, and water production for monitoring sites in nonproducing areas. Red text indicates maximum GWL change that occurred since the previous report (Taboga and others, 2017). [Abbreviations: ft, feet; ft bgs, feet below ground surface; GWL, groundwater level; -----, not applicable or no data; and GWL declines and rises marked with minus (-) and plus (+) signs, respectively]

					Change in GWL (ft)		Water Production		
Monitoring site name	Monitored aquifer	Depth to top of aquifer (ft bgs)	Period monitored	Initial GWL (ft bgs)	Maximum GWL change (ft) during period [Date]	Last measured GWL change (ft) [Date]	Period of recorded water production	Maximum water production (bbls/month) [Date]	Average production 2018 (bbls/month)
20-Mile Butte	Sandstone 1	500	Jan 2004–May 2020	363	-43 [Dec 2017]	-33 [May 2020]	-------	-------	-------
	Anderson coal	896	Jan 2004–May 2020	545	-161 [May 2020]	-122 [May 2020]	Apr 2001–Feb 2015	57,681 [Nov. 2001]	-------
21-Mile	Sandstone 1	799	Aug 2001–Mar 2020	533	-15 [Sep 2019]	-14 [Mar 2020]	-------	-------	-------
	Big George coal	1,278	Aug 2001–Mar 2020	627	-270 [Nov 2015]	-280 [Mar 2020]	Apr 2001–Dec 2010	60,017 [Oct 2006]	0
All Night Creek	Sandstone 4	200	Mar 2002–May 2020	95	-2 [Nov 2010]	-1 [May 2020]	-------	-------	-------
	Sandstone 3	350	Mar 2002–May 2020	201	+3 [Nov 2011]	+1 [May 2020]	-------	-------	-------
	Sandstone 2	580	Mar 2002–May 2020	252	-17 [Apr 2020]	-11 [May 2020]	-------	-------	-------
	Sandstone 1	840	Mar 2002–May 2020	321	-4 [Oct 2019]	+11 [May 2020]	-------	-------	-------
	Big George coal	984	Mar 2001–Nov 2007	440	-611 [May 2007]	-611 [May 2020]	Sep 2000–Jul 2016	472,319 [Dec 2002]	0
Bar 76	Sandstone 1	659	Sep 1997–May 2020	176	-274 [May 2016]	-265 [May 2020]	-------	-------	-------
	Wyodak coal	726	Sep 1997–May 2020	162	-616 [Feb 2008]	-314 [May 2020]	Oct 2001–Nov 2013	284,679 [July. 2002]	0
Barrett Persson	Sandstone 1	1,180	May 2001–May 2020	508	-306 [Feb 2011]	-259 [May 2020]	-------	-------	-------
	Wyodak coal	1,266	May 2001–May 2020	826	-215 [Jun 2008]	-63 [May 2020]	Nov 1999–Nov 2013	1,139,396 [Feb 2000]	0

Table 4 continued.

Monitoring site name	Monitored aquifer	Depth to top of aquifer (ft bgs)	Period monitored	Initial GWL (ft bgs)	Change in GWL (ft)		Water Production		
					Maximum GWL change (ft) during period [Date]	Last measured GWL change (ft) [Date]	Period of recorded water production	Maximum water production (bbls/month) [Date]	Average production 2018 (bbls/month)
Blackbird Coleman	Sandstone 1	670	Jul 2000–Mar 2020	251	-13 [Mar 2020]	-13 [Mar 2020]	-------	-------	-------
	Wyodak coal	1,426	Jul 2000–Mar 2020	371	-208 [Mar 2020]	-208 [Mar 2020]	Dec 2000–Aug 2018	180,049 [Jul. 2004]	79
Bowers	Sandstone 4	65	May 2002–May 2020	60	-12 [Mar 2005]	-3 [May 2020]	-------	-------	-------
	Sandstone 3	265	May 2002–May 2020	257	-3 [Dec 2005]	1 [May 2020]	-------	-------	-------
	Sandstone 2	352	May 2002–May 2020	301	-17 [May 2012]	-1 [May 2020]	-------	-------	-------
	Sandstone 1	520	Apr 2002–May 2020	335	-25 [May 2012]	-16 [May 2020]	-------	-------	-------
	Wyodak coal	722	Jan 1998–Jan 2005	420	-234 [Jan 2005]	-234 [Jan 2005]	Jul 1998–Nov 2015	244,670 [Mar. 2001]	0
Buffalo SE	Sandstone 4	55	May 2002–May 2007	48	-4 [Feb 2006]	-4 [May 2007]	-------	-------	-------
	Sandstone 3	155	Nov 2001–Sep 2018	144	+1 [Nov 2008]	1 [Sep 2018]	-------	-------	-------
	Sandstone 2	520	Mar 2002–Sep 2018	419	+21 [Sep 2013]	20 [Sep 2018]	-------	-------	-------
	Sandstone 1	1,482	Aug 2001–Sep 2018	338	+10 [Jun 2006]	4 [Sep 2018]	-------	-------	-------
	Smith coal	1,588	Oct 2001–Sep 2018	281	-55 [May 2008]	-26 [Sep 2018]	Jun 2003–Sep 2003	1,800 [Aug 2003]	0
Bull Creek	Sandstone 2	480	Dec 2005–Oct 2017	Flowing	-22 [Oct 2017]	-22 [Oct 2017]	-------	-------	-------
	Sandstone 1	876	Dec 2005–Oct 2017	92	-94 [Oct 2017]	-94 [Oct 2017]	-------	-------	-------
	Anderson coal	974	Dec 2005–Oct 2017	215	-177 [Aug 2012]	-177 [Oct 2017]	May 2004–Dec 2011	20,155 [Sep 2006]	0

Table 4 continued.

Monitoring site name	Monitored aquifer	Depth to top of aquifer (ft bgs)	Period monitored	Initial GWL (ft bgs)	Change in GWL (ft): Maximum GWL change (ft) during period [Date]	Change in GWL (ft): Last measured GWL change (ft) [Date]	Water Production: Period of recorded water production	Water Production: Maximum water production (bbls/month) [Date]	Water Production: Average production 2018 (bbls/month)
Cedar Draw	Sandstone 1	1,390	Feb 2004–May 2020	227	-538 [Sep 2011]	-335 [May 2020]	-------	-------	-------
	Wall coal	1,577	Feb 2004–May 2020	231	-641 [Sep 2011]	-331 [May 2020]	June 2003–Feb 2015	542,823 [Nov 2006]	0
Dilts	Sandstone 1	260	Apr 1999–May 2020	120	-7 [Jan 2009]	-4 [Jan 2020]	-------	-------	-------
	Wyodak coal	580	Apr 1999–May 2020	341	-317 [Feb 2008]	-317 [Jan 2020]	Apr 2001–Jun 2013	235,302 [Aug 2004]	0
Durham Ranch Section 14	Sandstone 1	666	Jan 1998–May 2020	25	-29 [Dec 2015]	-2 [May 2020]	-------	-------	-------
	Wyodak coal	716	Jan 1998–May 2020	268	-548 [Jan 2004]	-209 [May 2020]	May 1999–May 2010	394,439 [Jul 2002]	0
Durham Ranch Section 6	Sandstone 1	255	Nov 1997–May 2020	96	-90 [Nov 2019]	-91 [May 2020]	-------	-------	-------
	Wyodak coal	328	Nov 1997–May 2020	118	-245 [Mar 2007]	-181 [May 2020]	Jul 1999–Oct 2011	433,717 [Feb 2001]	0
Fourmile	Sandstone 1	778	Nov 2007–May 2020	427	-5 [Aug 2015]	-2 [May 2020]	-------	-------	-------
	Big George coal	1,359	Nov 2007–May 2020	867	-52 [Jan 2020]	-54 [May 2020]	Feb 2004–Jul 2018	121,256 [May 2006]	225
	Underburden sandstone	1,546	Nov 2007–May 2020	810	-20 [Jan 2020]	-22 [May 2020]	-------	-------	-------
Hoe Creek	Sandstone 1	150	Jan 1998–Apr 2020	101	-13 [Mar 2018]	-12 [Apr 2020]	-------	-------	-------
	Wyodak coal	830	Jan 1998–Apr 2020	231	-679 [Feb 2008]	-290 [Apr 2020]	Apr 1998–Nov 2010	535,378 [Jan 2000]	N/A (0) Last data 2012

Table 4 continued.

Monitoring site name	Monitored aquifer	Depth to top of aquifer (ft bgs)	Period monitored	Initial GWL (ft bgs)	Change in GWL (ft)		Water Production		
					Maximum GWL change (ft) during period [Date]	Last measured GWL change (ft) [Date]	Period of recorded water production	Maximum water production (bbls/month) [Date]	Average production 2018 (bbls/month)
Kennedy	Sandstone 1	520	Jul 2000–Apr 2020	270	-18 [Aug 2009]	-10 [Apr 2020]	-------	-------	-------
	Anderson coal	707	Jul 2000–Apr 2020	428	-222 [Sep 2008]	-46 [Apr 2020]	May 1999–Jan 2010	146,083 [Jan 2001]	0
Lone Tree	Sandstone 1	490	Feb 2000–Apr 2020	286	-9 [Mar 2005]	+3 [Apr 2020]	-------	-------	-------
	Wyodak coal	647	Feb 2000–Nov 2017	453	-207 [Nov 2012]	-196 [Nov 2017]	Mar 1992–Jun 2013	223,975 [Sep 2006]	0
Lower Prairie Dog	Sandstone 2	235	Jan 2002–Apr 2020	193	-4 [May 2010]	1 [Apr 2020]	-------	-------	-------
	Sandstone 1	352	Aug 2000–Apr 2020	197	-20 [May 2010]	-10 [Apr 2020]	-------	-------	-------
	Anderson coal	638	Aug 2000–Aug 2018	168	-477 [Dec 2013]	-459 [Aug 2018]	Mar 2000–June 2015	883,431 [Jan 2002]	0
L Quarter Circle Hills	Sandstone 1	493	Apr 2005–Apr 2020	41	-26 [Feb 2016]	-25 [Apr 2020]	-------	-------	-------
	Cook coal	684	Apr 2005–Apr 2020	23	-268 [Nov 2011]	-170 [Apr 2020]	Mar 2002–June 2015	130,515 [Apr 2002]	0
MP 2	Sandstone 1	260	May 1993–Apr 2020	52	-67 [Mar 2018]	-67 [Apr 2020]	-------	-------	-------
	Wyodak coal	336	May 1993–Apr 2020	163	-242 [May 2004]	-135 [Apr 2020]	July 2003–Mar 2009	796,332 [Apr 2001]	0 Last data 2011
MP 22	Sandstone 3	15	Apr 1998–Apr 2020	20	-3 [Sep 2010]	-3 [Apr 2020]	-------	-------	-------
	Sandstone 2	107	Apr 1998–Apr 2020	38	-3 [Jun 2018]	-3 [Apr 2020]	-------	-------	-------
	Sandstone 1	340	Feb 1993–Apr 2020	84	-61 [Jun 2018]	-61 [Apr 2020]	-------	-------	-------
	Wyodak coal	438	Mar 1993–Apr 2020	174	-316 [Jan 2002]	-142 [Apr 2020]	Mar 1993–Mar 2008	624,794 [Mar 2000]	0 Last data 2012

Table 4 continued.

Monitoring site name	Monitored aquifer	Depth to top of aquifer (ft bgs)	Period monitored	Initial GWL (ft bgs)	Change in GWL (ft)		Water Production		
					Maximum GWL change (ft) during period [Date]	Last measured GWL change (ft) [Date]	Period of recorded water production	Maximum water production (bbls/month) [Date]	Average production 2018 (bbls/month)
North Gillette	Sandstone 1	215	Sep 2001–Jun 2020	122	-6 [Aug 2007]	-6 [Jun 2020]	-------	-------	-------
	Anderson coal	534	Sep 2001–Jun 2020	500	-75 [Feb 2003]	106.7 [Jun 2020]	Aug 1999–Jan 2011	635,349 [May 2000]	0 Last data 2014
Redstone	Sandstone 1	160	Oct 1998–Apr 2020	25	+5 [Apr 2001]	1 [Apr 2020]	-------	-------	-------
	Canyon coal	241	Oct 1998–Apr 2020	33	-225 [Mar 2002]	-63 [Apr 2020]	Jul 1999–Jun 2012	445,936 [Jan 2000]	0 Last data 2012
Rose Draw	Sandstone 1	989	May 2009–Apr 2020	67	-24 [Dec 2015]	-24 [Feb 2016]	-------	-------	-------
	Wall coal	1,774	May 2009–Apr 2020	51	-186 [Feb 2012]	-57 [Feb 2016]	Apr 2008–Oct 2012	153,402 [Apr 2010]	0 Last data 2012
	Underburden sandstone	1,840	Sep 2009–Apr 2020	13	-92 [Jan 2020]	-67 [Feb 2016]	-------	-------	-------
Section 25	Sandstone 1	134	Nov 1996–May 2020	28	-6 [Jul 2018]	-6 [May 2020]	-------	-------	-------
	Wyodak coal	420	Nov 1996–May 2020	48	-405 [Feb 2005]	-215 [May 2020]	Oct 1999–Jun 2012	536,697 [Mar 2007]	0 Last data 2012
Streeter Road	Sandstone 1	522	Aug 2004–Apr 2020	214	-11 [May 2012]	-2 [Apr 2020]	-------	-------	-------
	Big George coal	1,351	Aug 2004–Apr 2020	159	-179 [Jan 2020]	-180 [Apr 2020]	Oct 2007–Jan 2011	18,518 [Apr 2009]	0 Last data 2011
Stuart Section 31	Sandstone 1	555	Oct 1997–May 2020	253	-79 [Dec 2009]	-63 [May 2020]	-------	-------	-------
	Wyodak coal	664	Sep 1997–May 2020	322	-458 [Jan 2004]	--209 [May 2020]	Mar 2000–June 2011	1,455,235 [Apr 2000]	0 Last data 2011
	Underburden sandstone	794	Oct 1997–May 2020	129	-459 [Sep 2010]	-393 [May 2020]	-------	-------	-------
Throne Ranch	Sandstone 1	1,400	May 2001–Jun 2020	567	-335 [Sep 2008]	-171 [Jun 2020]	-------	-------	-------
	Wyodak coal	1,506	May 2001–Jun 2020	815	-573 [May 2006]	-326 [Jun 2020]	Aug 2000–Jun 2012	248,161 [Jun 2003]	0 Last data 2012

Table 4 continued.

Monitoring site name	Monitored aquifer	Depth to top of aquifer (ft bgs)	Period monitored	Initial GWL (ft bgs)	Change in GWL (ft)		Water Production		
					Maximum GWL change (ft) during period [Date]	Last measured GWL change (ft) [Date]	Period of recorded water production	Maximum water production (bbls/month) [Date]	Average production 2018 (bbls/month)
Williams Cedar Draw	Smith coal	410	April 2007–Apr 2020	169	-16 [Apr 2017]	-15 [Apr 2020]	-------	-------	-------
	Sandstone 1	166	April 2007–Apr 2020	116	-7 [May 2018]	-7 [Apr 2020]	-------	-------	-------
	Anderson coal	735	April 2007–Apr 2020	244	-364 [Oct 2017]	-312 [Apr 2020]	Oct 2000–Dec 2015	58,920 [Jun 2009]	0 Last data 2017
	Underburden sandstone	564	April 2007–Apr 2020	371	-264 [Oct 2017]	-232 [Apr 2020]	-------	-------	-------

The maximum low GWLs seen in sandstone aquifers at the nonproducing monitoring sites (table 4) likely result from hydraulic connections between sandstone and coal seam aquifers. For example, hydrographs at monitoring sites such as Bar 76 (fig. A2-4) and Bull Creek (fig. A2-9) suggest that groundwater is flowing downward from overlying sandstone aquifers into adjacent coal seam aquifers. Likewise, GWLs in underburden sandstones at the Fourmile (fig. A2-14) and Rose Draw (fig. A2-24) sites show similar rates of decline to those in overlying coal seams. In fact, GWLs at the Stuart Section 31 site (fig. A2-27) declined in both the overlying and underlying sandstones in apparent response to dewatering of the associated coal seam aquifer. New maximum low GWLs, recorded since 2017 at the 20-Mile Butte (fig. A2-1), Blackbird Coleman (fig. A2-6), Hoe Creek (fig. A2-15), MP2 (fig. A2-20), and Section 25 (fig. A2-25) monitoring sites, are small magnitude changes that are not readily apparent at the scales shown on their hydrographs. The slow but persistent decline in GWLs at these sites are possibly the result of slow leakage into underlying aquifers, the extended severe drought (Martin and others, 2020) in the PRB during 2000–2007, or both.

Figure 3 shows the relation between the midpoint depth of the monitored sandstone thickness and maximum changes in GWLs during the monitoring site period of record. The use of the midpoint, or center, depth of the sandstone unit removes the need to discuss unit thickness. As noted previously, all sandstone units shown are confined aquifers with the exception of sandstone 3 at the MP22 site, which is an unconfined aquifer.

GWL declines of more than 250 ft occurred in 12 deep (>500 ft bgs) sandstone aquifers (fig. 3). Yet, GWLs dropped below the top of the aquifer only in the underburden sandstone at Williams Cedar Draw (fig. A2-29). Still, even moderate declines of a few feet may drop GWLs below the total depths of some older livestock and domestic wells (Taboga and others, 2019).

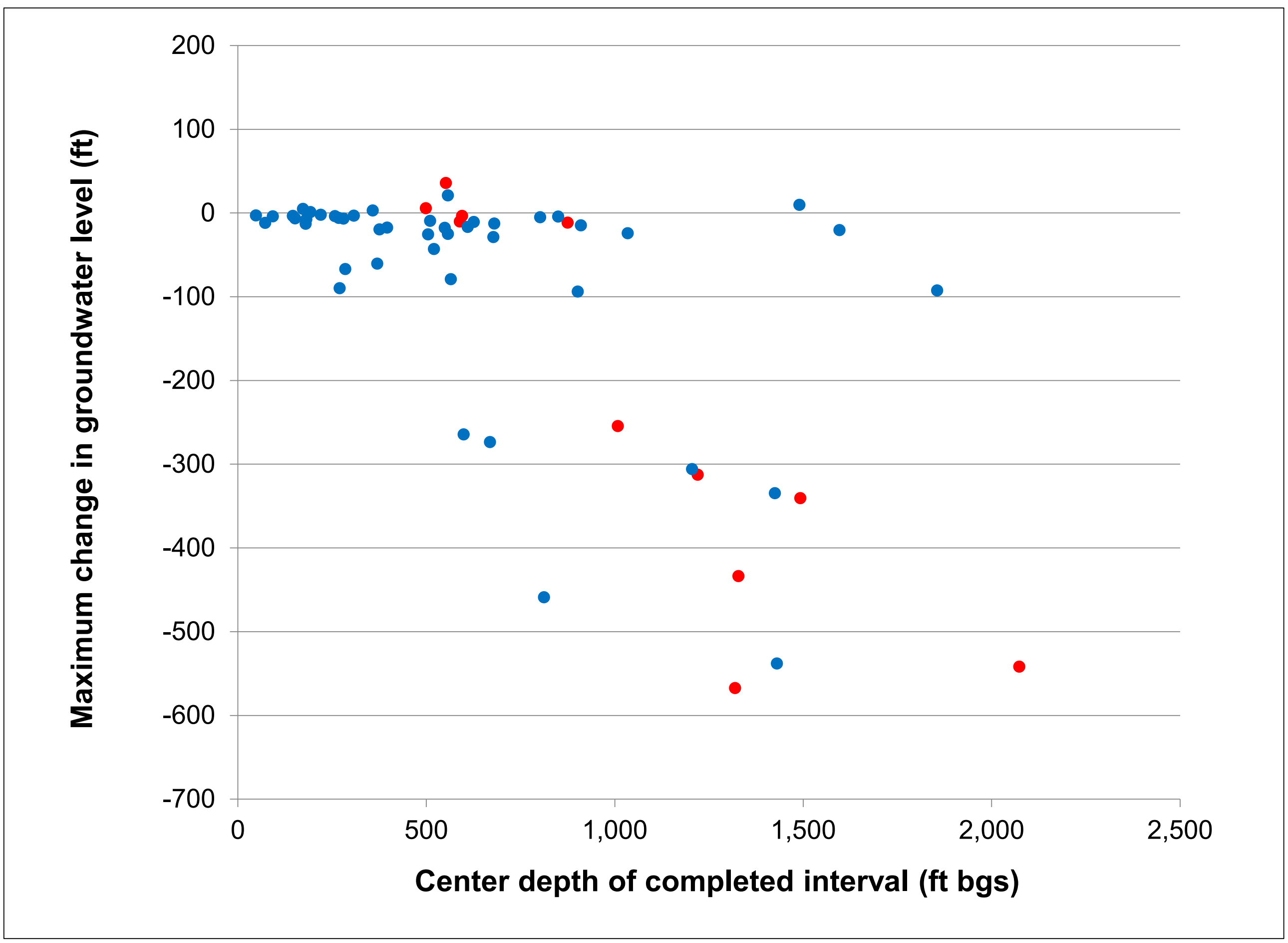

Figure 3. Maximum observed change in GWLs during the period of record versus the center depth of sandstone aquifer in sandstone monitoring wells in currently producing (red dots) and nonproducing areas (blue dots). [Abbreviations: ft, feet; ft bgs, feet below ground surface]

The maximum observed GWL change is closely related to the vertical distance between the monitored sandstone and associated coal seam aquifers (fig. 4). All GWL declines of 60 ft or more occurred in sandstones separated from the nearest monitored coal seam by less than 200 vertical ft. Ross and Zoback (2008) observed this relationship early during CBNG development using many of the same wells as this study. They attributed this to vertical hydraulic connection between some narrowly separated sandstone and coal seam aquifers. However, other sandstone aquifers within this thin (<200 ft) separation interval exhibited moderate declines of less than 30 ft, and in two cases, small GWL rises (wells Buffalo SE in Sandstone #4 [fig. A2-8] and Redstone [fig. A2-23]). This wide variation of GWL response in this separation interval (<200 ft) demonstrates the wide range of hydraulic properties present in the interbedded sandstones and shales of the lower Tertiary aquifer system (Thamke and others, 2014; Long and others, 2014). In contrast, maximum GWL changes in sandstones separated from a monitored coal seam by more than 200 ft varied from a 51-ft decline (well Juniper #2 [fig. A1-5]] to a 36-ft rise (well West Pine Tree [fig. A1-8]).

Figures 3 and 4 show that deep (>500 ft bgs) sandstone aquifers that are vertically separated from an associated coal seam aquifer by 200 ft or less are most likely to experience substantial drawdown. Fifteen of the 23 wells that meet both criteria had GWL declines of more than 75 ft, and 12 had declines of 200 ft or greater. The large GWL declines observed in these deep proximal sandstone aquifers were predicted by hydrogeologists and federal agencies (Bredehoeft, 2004; BLM, 2004) at the onset of CBNG development in the PRB.

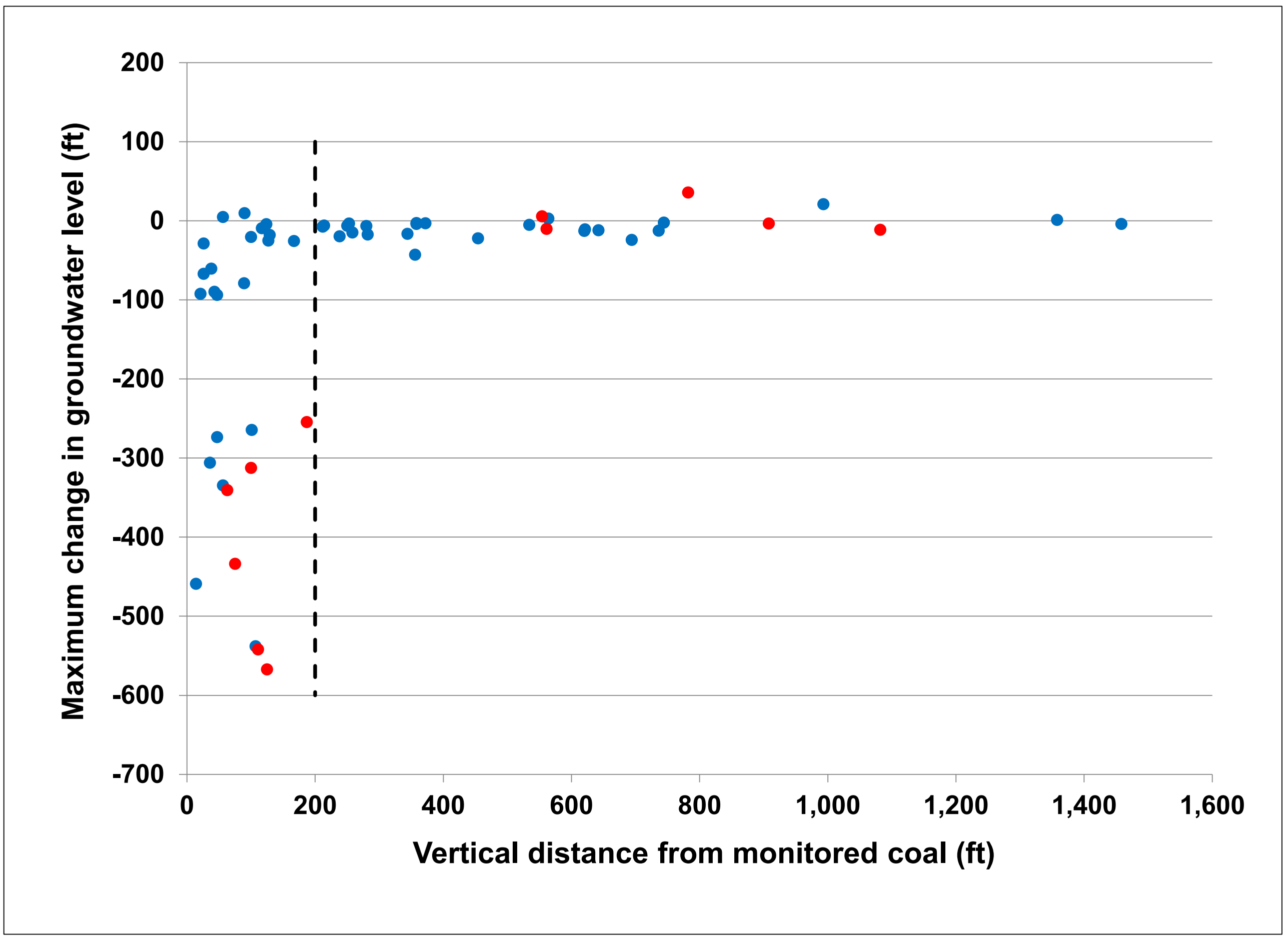

Figure 4. Maximum observed change in GWLs in sandstone monitoring wells during the period of record versus the vertical separation distance from the associated coal seam in currently producing areas (red dots) and nonproducing (blue dots). [Abbreviations: ft, feet]

Rates of GWL Recovery/Decline

Annual rates of GWL change (fig. 5), calculated by linear regression to the nearest 0.1 ft, are shown separately for sites in currently producing (table 5; red markers on fig. 5) and nonproducing (table 6; blue markers on fig. 5) areas. Overall, GWLs are declining in 32 monitored sandstone aquifers, rising in 16, and static (zero change) in 8 aquifers. Similar to maximum drawdowns, sandstone aquifers separated from a monitored coal aquifer by 200 ft or less show the widest variation in annual rate of recovery or decline.

As expected, the highest rates of GWL decline occur in the sandstone wells sited in producing areas (table 5) such as Bear Draw (-63.1 ft/year; fig. A1-1), Wild Turkey (-13.2 ft/year; fig. A1-9), and Sasquatch (-10.1 ft/year; fig. A1-7). Water level declines in producing area sandstones average 8.9 ft/year. The robust recovery (8.5 ft/year) at the Napier sandstone well (fig. A1-6) follows a continual decline in water production to less than 1,000 bbls/month during April 2017–October 2019. However, this rapid recovery rate will probably not continue because water production has risen to almost 40,000 bbls/month since then.

In nonproducing areas (blue dots, fig. 5), GWLs are recovering in 12 sandstones, declining in 18, and stable (<0.1 ft/year recovery/decline) in 13. Again, however, the largest variation in annual rates of change is observed in the 20 sandstones separated from a monitored coal by 200 ft or less. In those units, GWL recovery and decline rates average 5.6 ft/year and 2.2 ft/year, respectively. In comparison, average rates of change in sandstones separated from a coal by more than 200 ft are 0.6 ft/year in recovering aquifers and 1.2 ft/year in declining sandstone aquifers.

In nonproducing areas, the number of sandstone aquifers with declining GWLs (12) outnumber those with rising levels (5). GWLs are stable (-0.1≤GWL rate≤+0.1 ft/year) in seven wells, which suggests that there is no apparent hydraulic connection between those sandstone and coal seam aquifers.

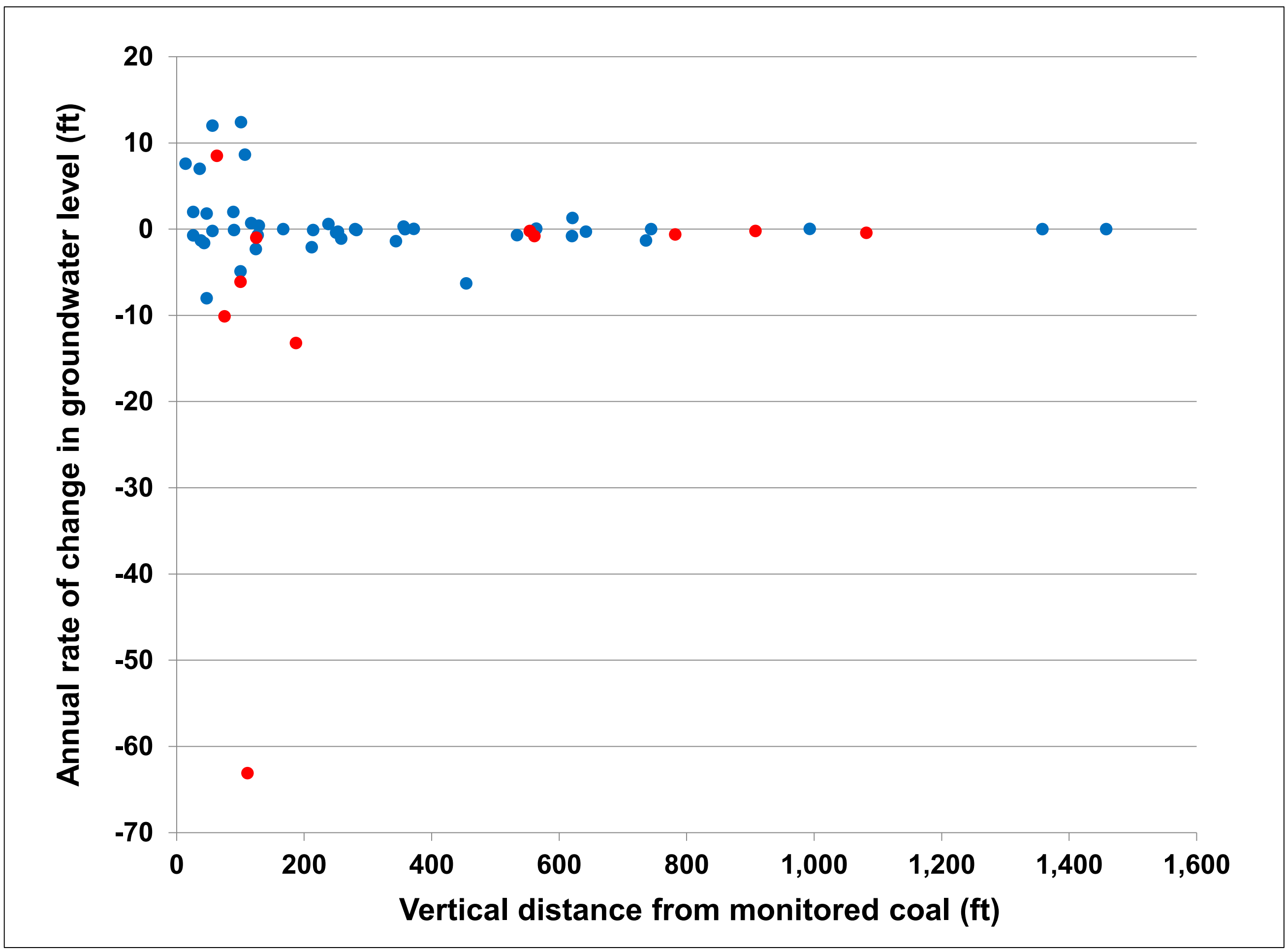

Figure 5. Annual rate of change (by linear regression) in GWLs in sandstone monitoring wells during the period of record versus the vertical separation distance from the associated coal seam in currently producing (red dots) and nonproducing areas (blue dots). [Abbreviations: ft, feet]

Table 5. Rates of GWL decline (negative values) and recovery (positive values) observed in sandstone aquifers sited in producing areas. [Abbreviations: GWL, groundwater level; ft., feet; R^2, coefficient of determination].

Monitoring site name Coal seam aquifer GWL trend	Monitored aquifer	Direction of GWL trend	GWL trend interval [~36 months]	Annual rate of GWL change [ft/year]	Regression model [R^2]
Bear Draw Big George_Recovering	Sandstone 1	Declining	Jun 2017–July 2020	-63.1	Linear model [R^2= 0.990]
Beaver Federal Big George_Insuf Data	Sandstone 1	Declining	Feb 2017–Feb 2020	-0.8	Linear model [R^2= 0.204]
Big Cat Big George_Insuf Data	Sandstone 1	Declining	Mar 2017–Mar 2020	-0.4	Linear model [R^2= 0.879]
Bullwhacker Big George_Insuf Data	Sandstone 1	Declining	Apr 2017–Apr 2020	-6.1	Linear model [R^2= 0.995]
Juniper Big George_Well Dry	Sandstone 2	Declining	Feb 2017–Apr 2020	-0.2	Linear model [R^2= 0.485]
	Sandstone 1	Declining	Feb 2017–Apr 2020	-2.2	Linear model [R^2= 0.988]
Napier Big George_Insuf Data	Sandstone 1	Recovering	Sep 2017–Mar 2020	+8.5	Linear model [R^2= 0.920]
Sasquatch Big George_Declining	Sandstone 1	Declining	Jul 2016–Dec 2019	-10.1	Linear model [R^2= 0.998]
West Pine Tree Big George_Declining	Sandstone 1	Declining	May 2016–Jan 2020	-0.6	Linear model [R^2= 0.560]
Wild Turkey Big George_Declining	Sandstone 1	Declining	Feb 2017–Apr 2020	-13.2	Linear model [R^2= 0.959]
Wormwood Big George_Declining	Sandstone 1	Declining	Apr 2017–Apr 2020	-0.2	Linear model [R^2= 0.303]
	Underburden sandstone	Declining	Apr 2017–Apr 2020	-1.0	Linear model [R^2= 0.020]

Care must be taken when using linear regression analysis to model "current" groundwater recovery/decline rates. The hydrograph of the Cedar Draw monitoring site (figs. 6, A2-10) provides a good example. The linear regression (black trendline) for the entire post-production period of record (2012–2020) estimates the annual rate of recovery at 23.9 ft/year with a coefficient of determination (R^2) of 0.844 even though the linear regression is not a good fit for the hydrograph and the recovery rate is slowing with time. Anscombe (1973) used a similar example of this misapplication of regression analysis to point to the importance of visually examining the data and regression for goodness-of-fit. The rate of recovery shown in table 6 was estimated by linear regression of data from 2017–2020 (fig. 6, green markers), although this rate will probably continue to decrease over time as it has compared to earlier intervals (fig. 6, blue and red markers).

Visual examination of sandstone hydrographs indicated water levels at some monitoring sites likely exhibited periodic (seasonal) variations (fig. 7). R^2 values for linear regression models in these wells are low when compared to their linear hydrographs. Application of spectral analysis (Wessa, 2017) to available transducer data at six monitoring sites (table 7) confirmed the presence of a seasonal component with periodicities of approximately 360 days, or 12 months. Subsequently, the hydrographs of those sandstone aquifers were separated into their seasonal, trend, and remainder components by use of an online decomposition model (Wessa, 2013). Figure 7 shows the decomposition of monthly transducer data collected between May 2008 and August 2011 at the 20-Mile Butte sandstone-monitoring site (fig. A2-1). The R^2 value of the observed data (red line in top panel, R^2=0.065) is greatly improved when the trend, which represents the action of long-term processes (second panel, R^2=0.453, linear regression line not shown), is regressed after the seasonal (third panel from the top) and remainder (lowermost panel) components are removed. The "remainder" component consists of random, unexplained, and irregular influences such as an isolated snowmelt or rain event, measurement errors, or unexplained "white noise." Note that the similar slopes of the regression equations for both the raw data (0.0025 ft/day) and the trend component (0.0021 ft/day) yield comparable annual rates of change, 0.80 and 0.90 ft/year, respectively (table 7). The agreement between rates of change for the observed and decomposed hydrographs (table 7) indicates that the seasonal component has little effect on the slopes of the regressions at the six monitoring sites shown.

Table 6. Rates of GWL decline (negative values) and recovery (positive values) observed in sandstones sited in nonproducing areas. [Abbreviations: GWL, groundwater level; ft., feet; R^2, coefficient of determination]

Monitoring site name Coal seam aquifer GWL trend	Monitored aquifer	Direction of GWL trend	GWL trend interval [variable]	Annual rate of GWL change [ft/year]	Regression model [R^2]
20-Mile Butte Anderson_recovering	Sandstone 1	Recovering	Mar 2015–May 2020	+0.3	Linear model, seasonal signal at 375 days [R^2= 0.013]
21-Mile Big George_declining	Sandstone 1	Declining	Aug 2012–Mar 2020	-1.1	Linear model [R^2= 0.154]
All Night Creek Big George well dry	Sandstone 4	Stable	May 2012–May 2020	0.0	Linear model [R^2= 0.118]
	Sandstone 3	Stable	May 2012–May 2020	+0.1	Linear model [R^2= 0.187]
	Sandstone 2	Declining	May 2012–May 2020	-1.4	Linear model [R^2= 0.804]
	Sandstone 1	Declining	May 2012–May 2020	-2.3	Linear model [R^2= 0.957]
Bar 76 Wyodak_recovering	Sandstone 1	Recovering	Oct 2015–May 2020	+1.8	Linear model [R^2= 0.957]
Barrett Persson Wyodak_recovering	Sandstone 1	Recovering	Dec 2013–May 2020	+7	Linear model [R^2= 0.992]
Blackbird Coleman Wyodak_declining	Sandstone 1	Declining	Jun 2017–Oct 2019	-1.2	Linear model [R^2= 0.988]
Bowers Wyodak_insufficient data	Sandstone 4	Declining	Dec 2015–May 2020	-0.3	Linear model [R^2= 0.665]
	Sandstone 3	Stable	Dec 2015–May 2020	0.0	Linear model [R^2= 0.001]
	Sandstone 2	Stable	Dec 2015–May 2020	-0.1	Linear model [R^2= 0.402]
	Sandstone 1	Declining	Dec 2015–May 2020	-0.7	Linear model [R^2= 0.188]
Buffalo SE Smith_stable Wellsite closed Sep 2018	Sandstone 4	Insufficient data	Feb 2004–May 2007	+0.5	Linear model [R^2= 0.511]
	Sandstone 3	Stable	Jun 2009–Sep 2018	0.0	Linear model [R^2= 0.171]
	Sandstone 2	Stable	Feb 2004–Sep 2018	0.0	Linear model [R^2= 0.034]
	Sandstone 1	Stable	Feb 2004–Sep 2018	-0.1	Linear model [R^2= 0.100]
Bull Creek Anderson_recovering Wellsite closed Oct 2017	Sandstone 2	Declining	Mar 2016–Oct 2017	-6.3	Linear model [R^2= 0.994]
	Sandstone 1	Declining	Mar 2016–Oct 2017	-8.0	Linear model [R^2= 0.990]

Table 6 continued.

Monitoring site name Coal seam aquifer GWL trend	Monitored aquifer	Direction of GWL trend	GWL trend interval [variable]	Annual rate of GWL change [ft/year]	Regression model [R^2]
Cedar Draw Wall_recovering	Sandstone 1	Recovering	Jun 2017–May 2020	+9.8	Linear model [R^2= 0.993]
Dilts Wyodak _well dry	Sandstone 1	Stable	Jun 2013–Jan 2020	0.0	Linear model. seasonal signal at 360 days [R^2= 0.006]
Durham Ranck Section 14 Wyodak_recovering	Sandstone 1	Recovering	Jun 2010–May 2020	+2	Linear model [R^2= 0.389]
Durham Ranck Section 6 Wyodak_insufficient data	Sandstone 1	Declining	Mar 2016–May 2020	-1.6	Linear model [R^2= 0.988]
Fourmile Big George_declining	Sandstone 1	Declining	Nov 2016–May 2020	-0.7	Linear model [R^2= 0.466]
	Underburden sandstone	Declining	Nov 2016–May 2020	-4.9	Linear model [R^2= 0.980]
Hoe Creek Wyodak_recovering	Sandstone 1	Declining	Dec 2010–Apr 2020	-0.8	Linear model [R^2= 0.877]
Kennedy Anderson_recovering	Sandstone 1	Recovering	Mar 2010–Apr 2020	+0.4	Linear model [R^2= 0.433]
Lone Tree Wyodak_recovering	Sandstone 1	Recovering	Jul 2013–Apr 2020	+0.7	Linear model [R^2= 0.679]
Lower Prairie Dog Anderson_recovering	Sandstone 2	Stable	Aug 2015–Apr 2020	0.0	Linear model [R^2= 0.069]
	Sandstone 1	Recovering	Aug 2015–Apr 2020	+0.6	Linear model [R^2= 0.903]
L Quarter Circle Hills Cook_recovering	Sandstone 1	Stable	Jul 2015–Apr 2020	0.0	Linear model [R^2= 0.003]
MP 2 Wyodak_recovering	Sandstone 1	Declining	Jun 2009–Apr 2020	-0.7	Linear model [R^2= 0.923]
MP 22 Wyodak_recovering	Sandstone 3	Stable	Feb 2008–Apr 2020	0.0	Linear model, seasonal signal at 360 days [R^2= 0.046]
	Sandstone 2	Declining	Feb 2008–Apr 2020	-0.3	Linear model [R^2=0.722]
	Sandstone 1	Declining	Feb 2008–Apr 2020	-1.3	Linear model [R^2= 0.984]
North Gillette Anderson_recovering	Sandstone 1	Stable	Mar 2010–Jun 2020	-0.1	Linear model [R^2= 0.923]
Redstone Canyon_recovering	Sandstone 1	Declining	Aug 2012–Apr 2020	-0.2	Linear model, seasonal signal at 360 days [R^2= 0.366]
Section 25 Wyodak_recovering	Sandstone 1	Declining	Aug 2012–May 2020	-0.4	Linear model, seasonal signal at 370 days [R^2= 0.821]
Streeter Road Big George_declining	Sandstone 1	Recovering	Mar 2011–Apr 2020	+1.3	Linear model [R^2= 0.837]

Table 6 continued.

Monitoring site name Coal seam aquifer GWL trend	Monitored aquifer	Direction of GWL trend	GWL trend interval [variable]	Annual rate of GWL change [ft/year]	Regression model [R^2]
Stuart Section 31 Wyodak_recovering	Sandstone 1	Recovering	Sep 2011–May 2020	+2	Linear model, seasonal signal at 360 days [R^2= 0.714]
	Underburden sandstone	Recovering	Sep 2011–May 2020	+7.6	Linear model [R^2= 0.989]
Throne Ranch Wyodak_recovering	Sandstone 1	Recovering	Sep 2010–Jun 2020	+12	Linear model [R^2= 0.976]
Williams Cedar Draw Wyodak_recovering	Sandstone 1	Declining	Oct 2017–Apr 2020	-2.1	Linear model [R^2= 0.252]
	Underburden sandstone	Recovering	Oct 2017–Apr 2020	+12.4	Linear model [R^2= 0.960]

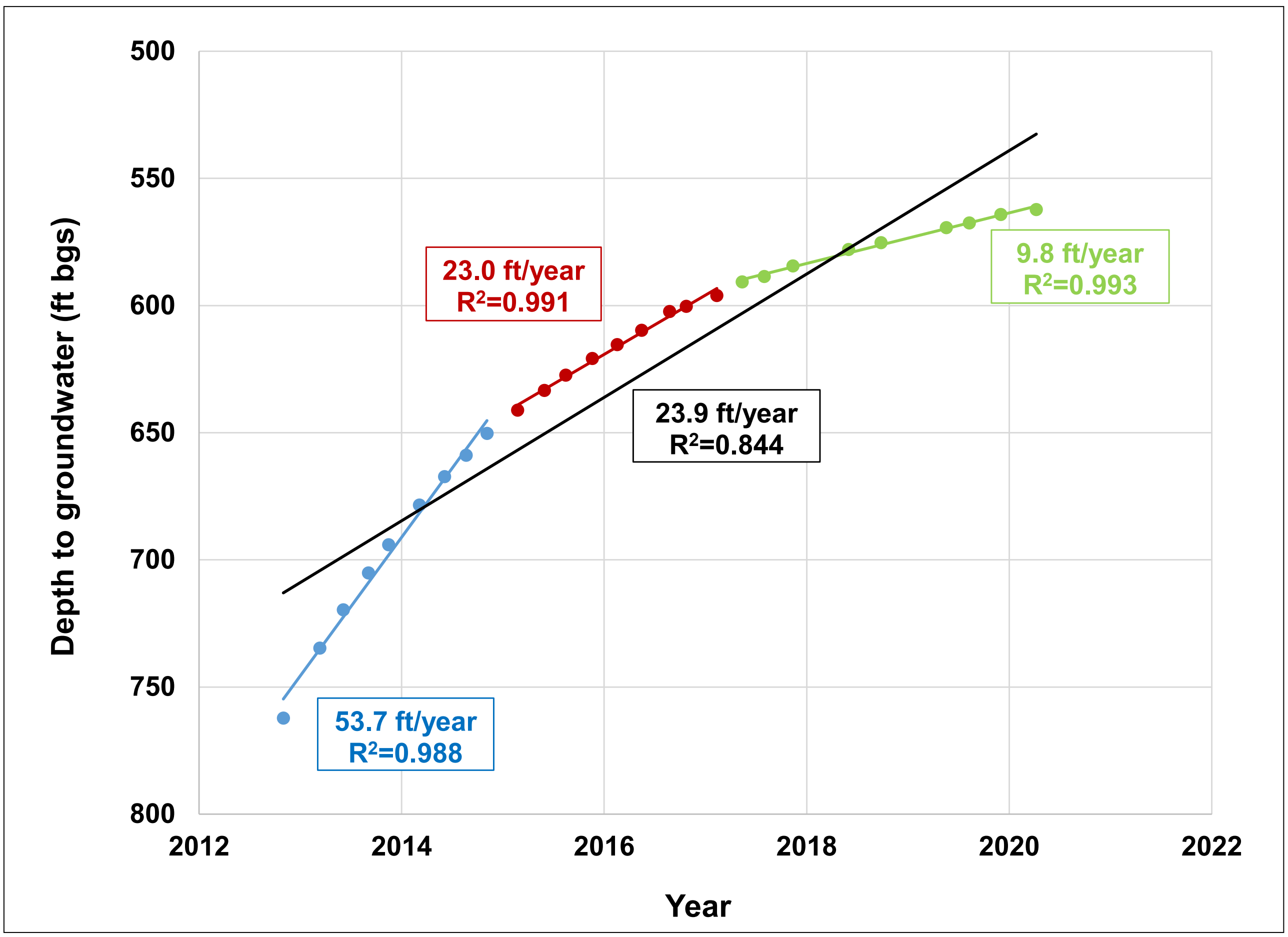

Figure 6. Comparative linear regressions of the Cedar Draw sandstone hydrograph for various CBNG post-production periods of record (shown in blue [2012-2014], red [2015-2017], and green [2018-2020]) with predicted annual recovery rates and coefficients of determination (R2) shown. The linear regression for the entire post-production period (2012–2020), shown in black does not provide an accurate prediction of the slowing recovery rate. [Abbreviations: ft, feet; ft bgs, feet below ground surface; R^2, coefficient of determination]

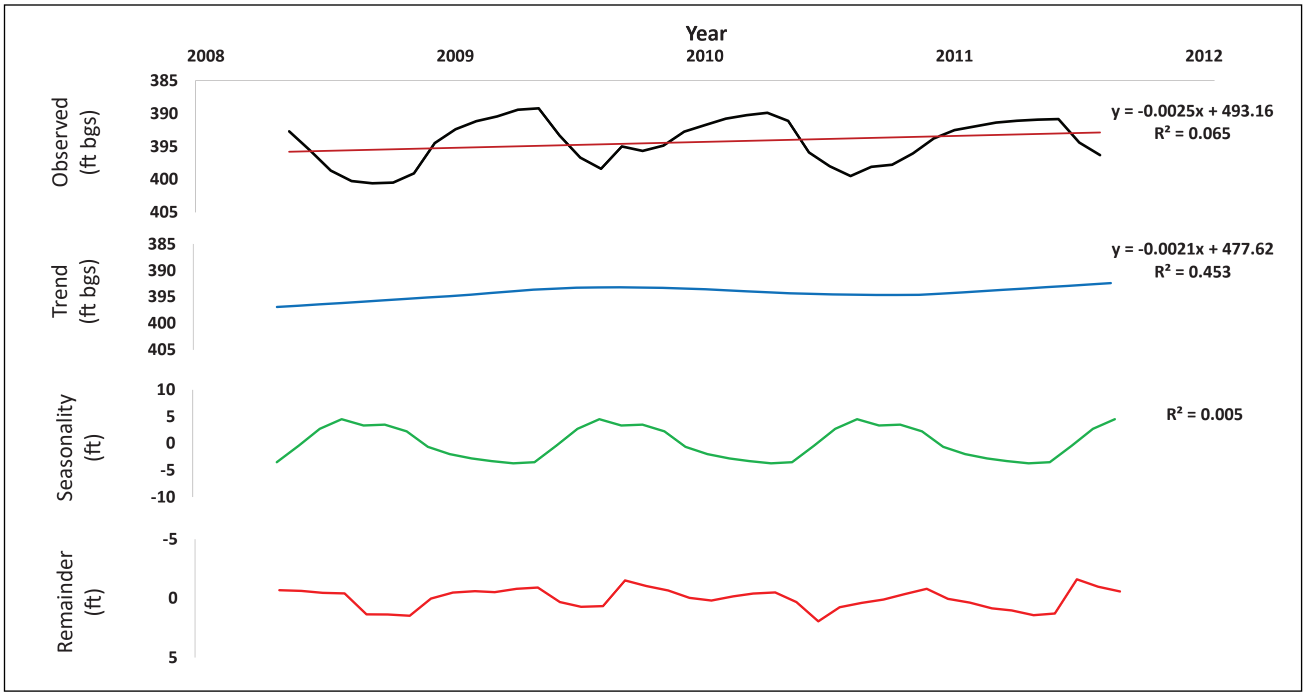

Figure 7. Monthly hydrograph of the 20 Mile monitoring site showing the observed time series (top panel) decomposed into trend, seasonal, and remainder (white noise) components. Linear regression line plotted for observed data only; regression data shown for trend and seasonality. [Abbreviations: ft, feet; ft bgs, feet below ground surface; R^2, coefficient of determination]

Table 7. Statistics for raw and decomposed hydrographs in selected sandstone wells with continuous transducer data. [Abbreviations: ft., feet; R^2, coefficient of determination].

Monitoring site name	Sandstone aquifer	Time interval	Raw hydrograph rate-of-change (ft/year)	Trend component rate-of-change (ft/year)	Raw/decomposed R^2	Range of seasonal component (ft)
20-Mile Butte	Sandstone 1	May 2008–Aug 2011	0.80	0.90	0.065 / 0.453	-3.7–4.5
Dilts	Sandstone 1	Sep 2013–Feb 2017	0.03	0.02	0.004 /0.004	-0.31–0.35
MP 22	Sandstone 1	July 2008–Apr 2013	0.02	0.02	0.004 / 0.078	-0.61–0.35
Redstone	Sandstone 1	Sep 2009–Apr 2015	0.37	0.37	0.651 / 0.833	-0.31–0.29
Section 25	Sandstone 1	Jun 2016–May 2020	0.22	0.22	0.722 / 0.867	-0.09–0.10
Stuart Section 31	Sandstone 1	Aug 2012–Dec 2017	2.66	2.70	0.745 / 0.866	-2.57–1.19

Decomposition also improved the fit (R^2 value) of the regressions at the Redstone (fig. A2-23), Section 25 (fig. A2-25), and Stuart Section 31 (fig. A2-27) monitoring sites (table 7) but not at the Dilts site (fig. A2-11) where the trend component is a single concave-down curve (fig. 8). This shows that decomposition can improve goodness-of-fit for hydrographs that already have a relatively linear trend component. The hydrograph from the 20-Mile Butte (fig. A2-1) monitoring site raises the possibility that the low R^2 values for some shallower units (table 6) such as All Night Creek (sandstones 3 and 4; fig. A2-3), Bowers (sandstone 3; fig. A2-7), and Lower Prairie Dog (sandstone 2; fig. A2-19) may result, at least in part, from the influence of a seasonal component or noise. Unfortunately, the continuous transducer data required for decomposition is unavailable for these wells.

The magnitude of the seasonal component varied from 0.2 ft (Section 25 site; fig. A2-25) to 8.2 ft (20-Mile Butte site; fig. A2-1). Previous studies (Lee and Lee, 2000; LaFare and others, 2016) indicate that GWL variations are controlled by factors that affect recharge dynamics (amount and timing of recharge inputs, groundwater/surface water interactions, and seasonal pumping) and by the physical properties of the aquifer (lithology, intergranular and fracture porosity, vertical and horizontal heterogeneity, and storage characteristics). In the broadest sense, the wide range of seasonal variations observed in these six wells points to the great heterogeneity present in the lower Tertiary aquifer system as well as the many hydrogeological and environmental drivers that influence groundwater response even in deeper units. For these reasons, the rates provided in tables 5 and 6 are provisional and will likely change as new data become available.

Estimated Times for Recovery

The number of years for water levels to recover 95 percent of the maximum GWL decline (table 4) is shown for 10 sandstone wells (table 8) using the rates of recovery obtained by linear regression (table 6). The wells in this analysis are completed in the closest sandstones that overlie or underlie the associated coal seam and are recovering at an annual rate of more than 0.1 ft/year. One site in table 6 that met these criteria (Durham Ranch 14; fig. A2-12) was disqualified because water levels in the sandstone well exhibited an unexplained abrupt but persistent change of more than 20 ft during the period of record.

Calculated times of 95 percent recovery vary from 20–144 years with a mean value of 52 years. This assumes that recharge and climatic conditions are similar to those that occurred in the PRB over the last decade. The 95 percent value was used because GWL recovery rates frequently slow with time (fig. 6).

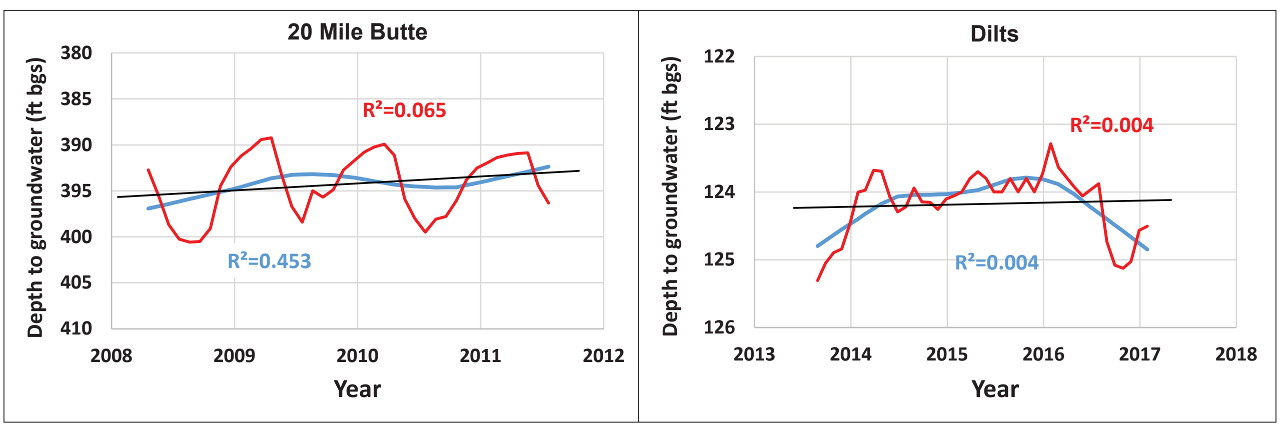

Figure 8. Comparative coefficient of determination (R2) values for the observed sandstone hydrographs (red line) and the decomposed trend component (blue line) for the 20 Mile Butte (left) and Dilts (right) sites. The black line represents the linear regression for both hydrograph and trend. The R^2 value is greatly improved for the relatively linear trend at 20 Mile Butte but remains the same for the concave-down curve of the Dilts monitoring well. [Abbreviations: ft, feet; ft bgs, feet below ground surface; R^2, coefficient of determination]

Table 8. Estimated time to 95 percent recovery using recovery rates determined by linear regression for 10 sandstones sited in nonproducing areas. The rate of recovery shown for Cedar Draw, calculated for the years 2017–2020 (fig. 6), will likely continue to slow with time. [ft bgs, feet below ground surface; ft, feet; R^2, coefficient of determination]

Monitoring site name	Monitored aquifer	Transducer data interval	Depth-to-groundwater at 95% recovery (ft bgs)	Number of years to 95% reccovery	Year of expected recovery	Annual rate of recovery [ft/year]	Regression model [R^2]
20-Mile Butte	Sandstone 1	Mar 2015–May 2020	364.9	109	2124	+0.3	Linear model [R^2= 0.013]
Bar 76	Sandstone 1	Oct 2015–May 2020	189.2	144	2159	+1.8	Linear model [R^2= 0.957]
Barrett Persson	Sandstone 1	Dec 2013–May 2020	523.1	41	2054	+7	Linear model [R^2= 0.992]
Cedar Draw	Sandstone 1	Jun 2017–May 2020	254.3	35	2052	+9.8	Linear model [R^2= 0.993]
Kennedy	Sandstone 1	Mar 2010–Apr 2020	271.1	33	2043	+0.4	Linear model [R^2= 0.433]
Lower Prairie Dog	Sandstone 1	Aug 2015–Apr 2020	197.9	21	2036	+0.6	Linear model [R^2= 0.903]
Stuart Section 31	Sandstone 1	Sep 2011–May 2020	257.0	38	2049	+2	Linear model [R^2= 0.714]
	Underburden sandstone	Sep 2011–May 2020	151.7	57	2068	+7.6	Linear model [R^2= 0.98]
Throne Ranch	Sandstone 1	Sep 2010–Jun 2020	616.3	20	2030	+12	Linear model [R^2= 0.976]
Williams Cedar Draw	Underburden sandstone	Oct 2017–Apr 2020	385.1	20	2037	+12.4	Linear model [R^2= 0.960]

Depressed Coal Seam GWLs Effect on Recovery in Sandstone Aquifers

Figure 9 shows four monitoring sites in nonproducing areas where initial groundwater levels were obtained prior to or shortly after the start of CBNG development. Water production at these sites ceased between August 2012 (Throne Ranch; fig. A2-28) and August 2017 (Cedar Draw; fig. A2-10). These sandstone and coal seam aquifers are separated by 47–107 ft of vertical distance and GWL recovery in each coal seam aquifer is non-linear, slowing with time and apparently stabilizing at greater depths than measured initially. The hydrographs in figure 9 illustrate the varying degree of hydraulic connectivity between the sandstone and coal seam aquifer at each monitoring site. High-level hydraulic connections are clearly observed at the Bar 76 (fig. A2-4), Cedar Draw (fig. A2-10), and Throne Ranch (fig. A2-28) sites where the sandstone aquifer hydrographs follow the form of the associated coal seam hydrographs. By comparison, the hydrographs at the Redstone (fig. A2-23) monitoring site indicate lower hydraulic connectivity between the sandstone and coal seam aquifers. Shortly after the onset of CBNG production in 1999, GWLs in the sandstone aquifer there began a steady decline of 0.2 ft/year that continued into 2020.

The hydrographs in figure 9 also illustrate the changing hydraulic relations between the monitored coal seams and the proximal sandstone aquifers. For example, the vertical hydraulic gradients at the Bar 76 (fig. A2-4) and Throne Ranch (fig. A2-28) sites were reversed during CBNG production. Prior to development, GWLs in the coal seam aquifers at those sites were higher than in the overlying sandstone aquifers and water flowed upward. During production, however, GWLs in the coal seams quickly declined below those in the sandstone aquifers, at which point, groundwater flow reversed direction to move downward from the sandstone into the underlying coal seam. At the Cedar Draw and Redstone sites, the small downward hydraulic gradients at the Cedar Draw and Redstone sites increased greatly during production. The GWL trends observed in the sandstone aquifers at the four sites (fig. 9) will likely persist for years in response to the slowing recovery rates of the associated coal seams. This arcuate type of coal seam recovery is also observed at the Durham Ranch Section 14 (fig. A2-12), Hoe Creek (fig. A2-15), Kennedy (fig. A2-16), MP 22 (fig. A2-21), North Gillette (fig. A2-22), and Section 25 (fig. A2-25) monitoring sites and in Gillette area monitoring wells managed by the Wyoming State Engineer's Office (pers commun., Jeremy Manley).

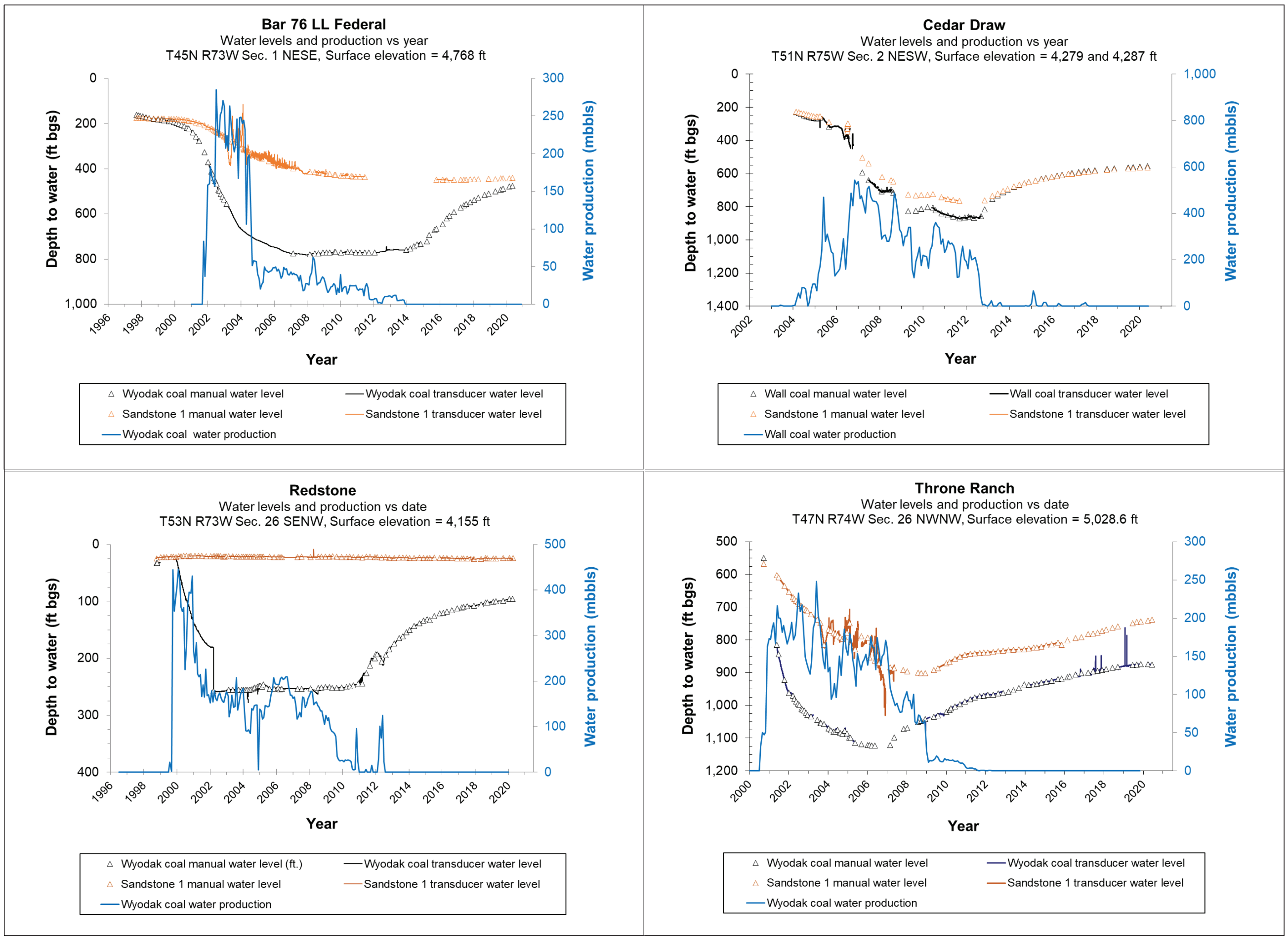

Figure 9. Examples of sandstone aquifer responses coincident with slowing GWL recovery in associated coal seams. Sandstone aquifer GWLs, which declined several hundred feet, are recovering at Cedar Draw and Throne Ranch, and have stabilized at the Bar 76 site following the cessation of water production from nearby CBNG wells. By comparison, the sandstone aquifer at the Redstone site shows a more muted but persistent response to depressed GWLs in the associated coal seam aquifer. [Abbreviations: ft bgs, feet below ground surface; mbbls, thousand barrels]

CONCLUSION

The analyses presented herein confirm the groundwater recovery trends observed in the previous WSGS report (Taboga and others, 2017). Historic GWL declines are highest in sandstone aquifers that are more than 500 ft bgs and located within 200 vertical feet of an associated coal seam aquifer. These aquifers also exhibit the greatest annual rates of recovery and decline. As expected, the highest rates of GWL decline are observed in sandstone aquifers sited in areas currently producing CBNG from the Big George coal in the upper Powder River drainage. In contrast, the highest recovery rates are seen in wells sited in nonproducing areas.

Apparent seasonal variations in sandstone aquifer GWLs at six monitoring sites were confirmed by spectral analysis of daily transducer data. Generally, R^2 values for linear regression models of post-production data in these wells were low despite the fact that their hydrographs appeared to be linear. Subsequent application of a seasonal decomposition model separated the time series hydrographs into trend, seasonal, and noise components. Linear regression models of the trend component yielded calculated annual rates of recovery/decline that did not differ significantly from the rates of change determined from observed data but did show improved R^2 values. This suggests that the low R^2 values observed on the recovery/decline estimates in some sandstone units result from the influence of a seasonal component and/or noise.

The number of years for water levels to recover to 95 percent of the initial measurement was estimated for nine sandstone wells using the rates of recovery previously obtained from linear regression. The calculated times of recovery, which vary from 20–144 years with a mean value of 52 years, probably represent best-case estimates because the calculations assume that environmental and hydrological conditions will largely remain unchanged from those of the last decade. Furthermore, slowing recovery rates commonly observed in some coal seam aquifers may impede the return to predevelopment water levels in the proximal sandstones.

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Appendices

Appendix 1

Figures A1-1 through A1-10 in Appendix 1 are hydrographs for monitoring sites in producing areas showing depth-to-groundwater (left vertical axis, feet below ground surface=ft bgs) and monthly water production (right vertical axis, per thousand barrels=mbbls) as functions of time (horizontal axis) at monitoring site labeled at the top of each figure. [T.: township, N.: north, R.: range, W.: west, Sec.: section, S.: south, W.: west, Ft.: feet]

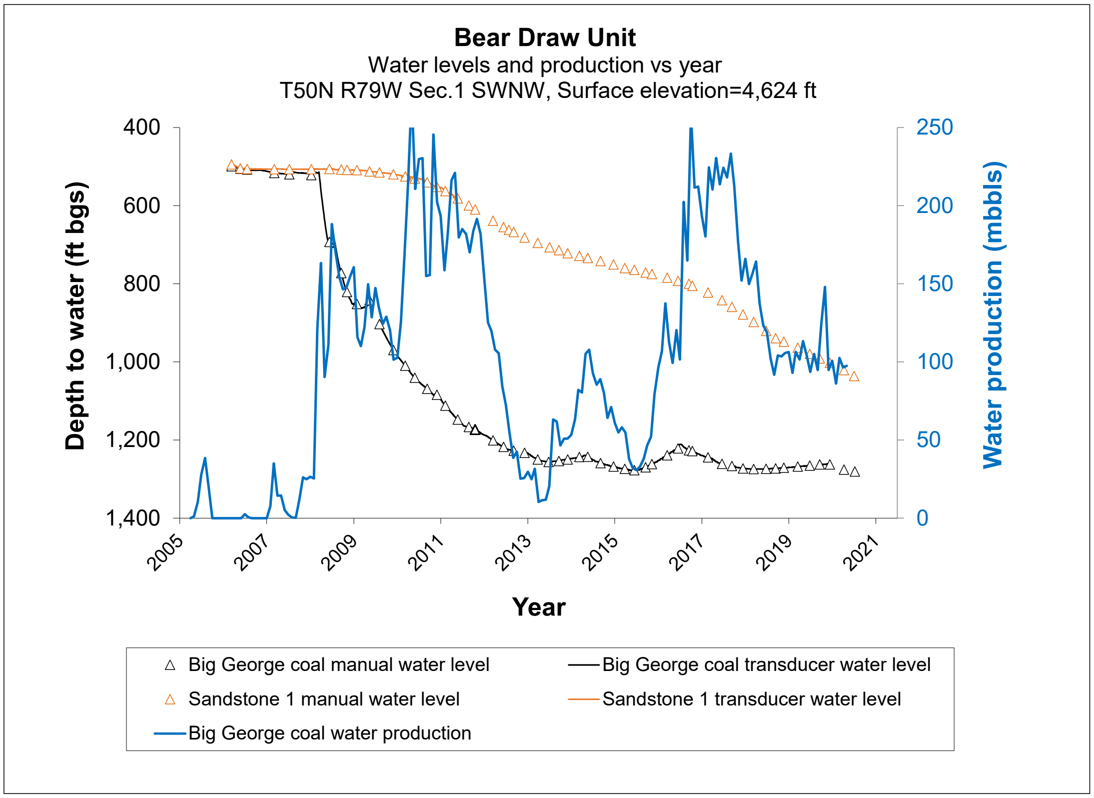

Figure A1–1. Bear Draw Unit

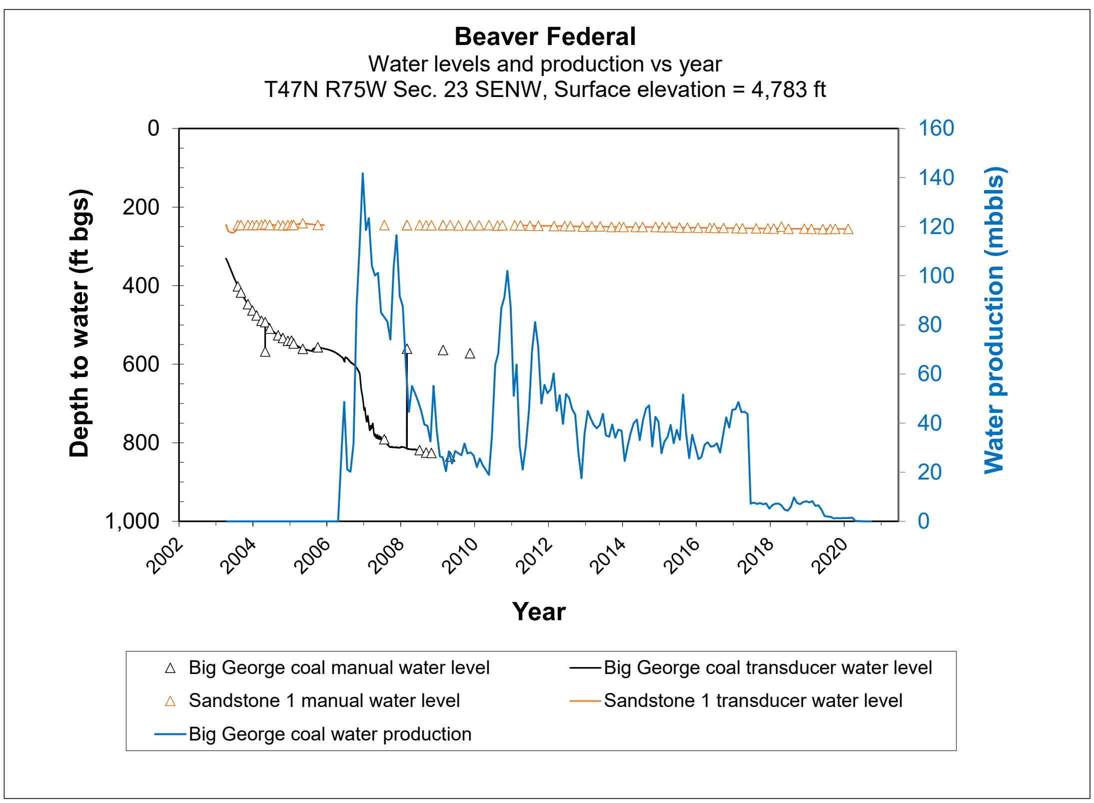

Figure A1–2. Beaver Federal

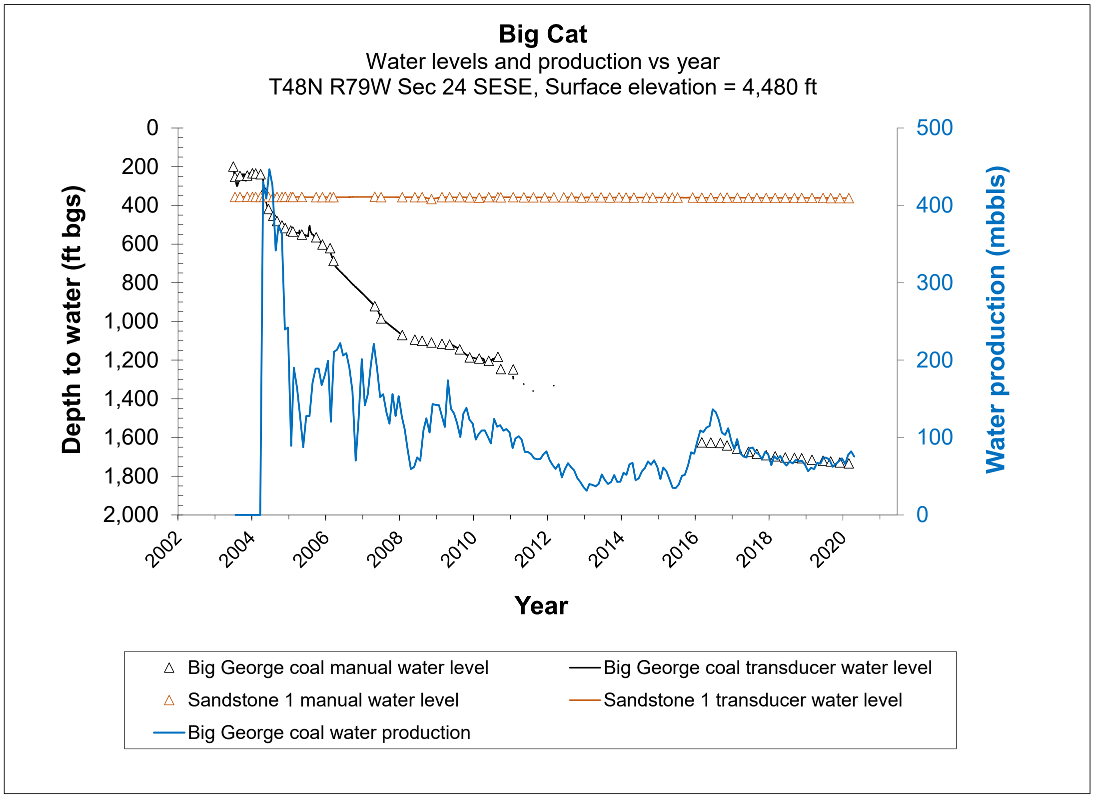

Figure A1–3. Big Cat

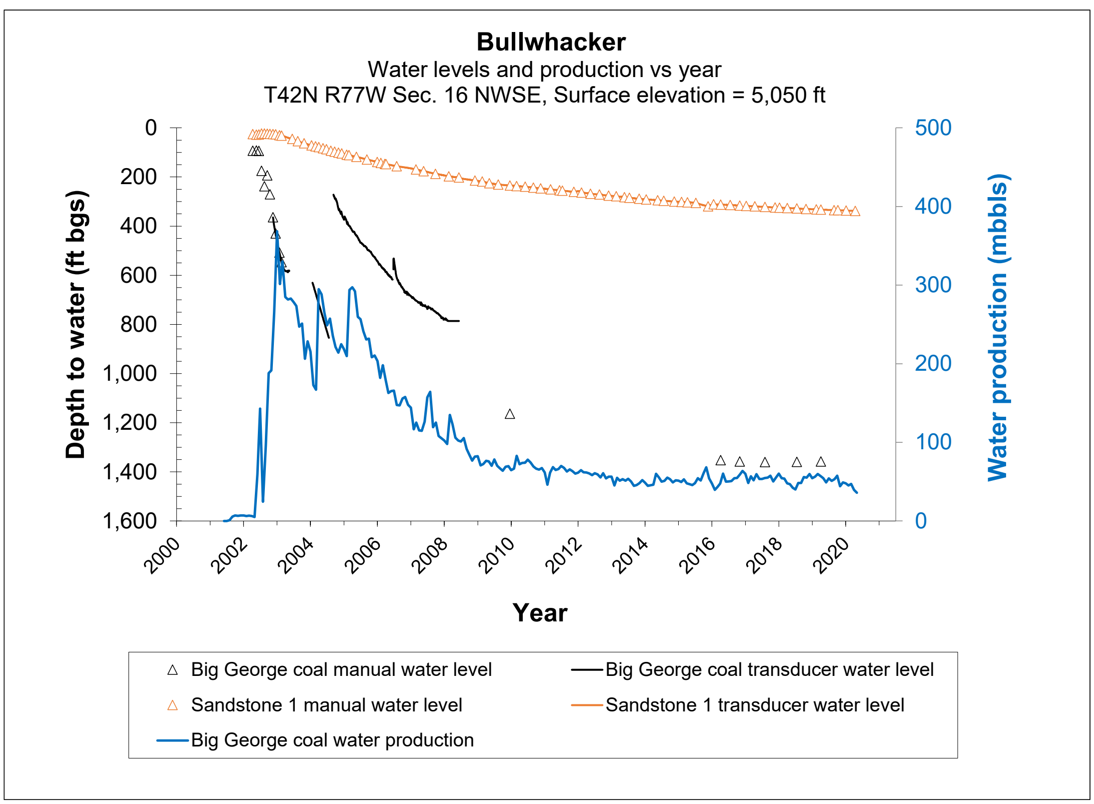

Figure A1–4. Bullwacker

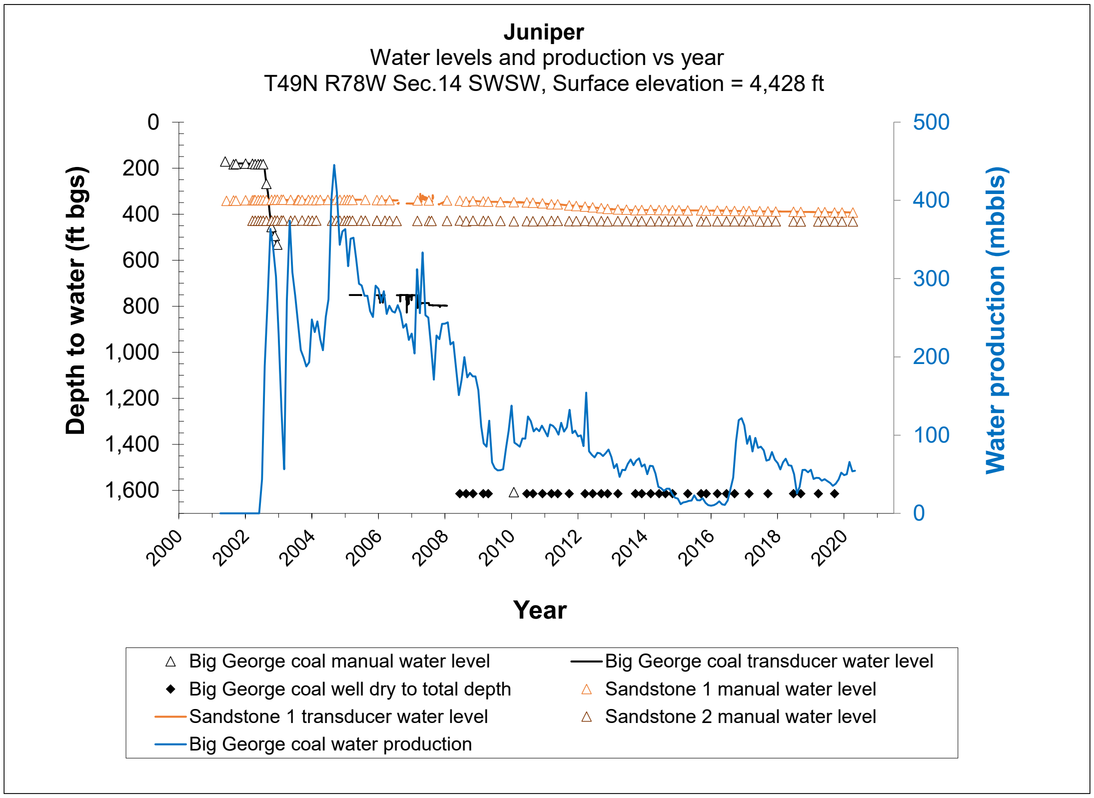

Figure A1–5. Juniper

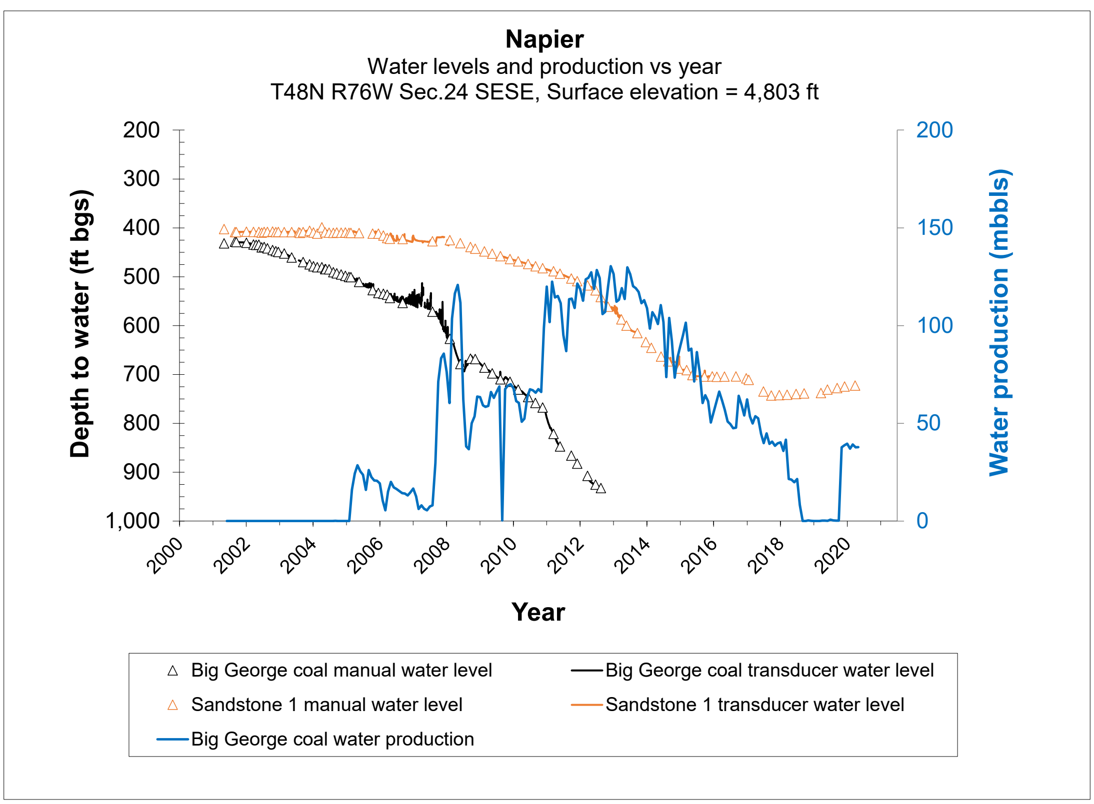

Figure A1–6. Napier

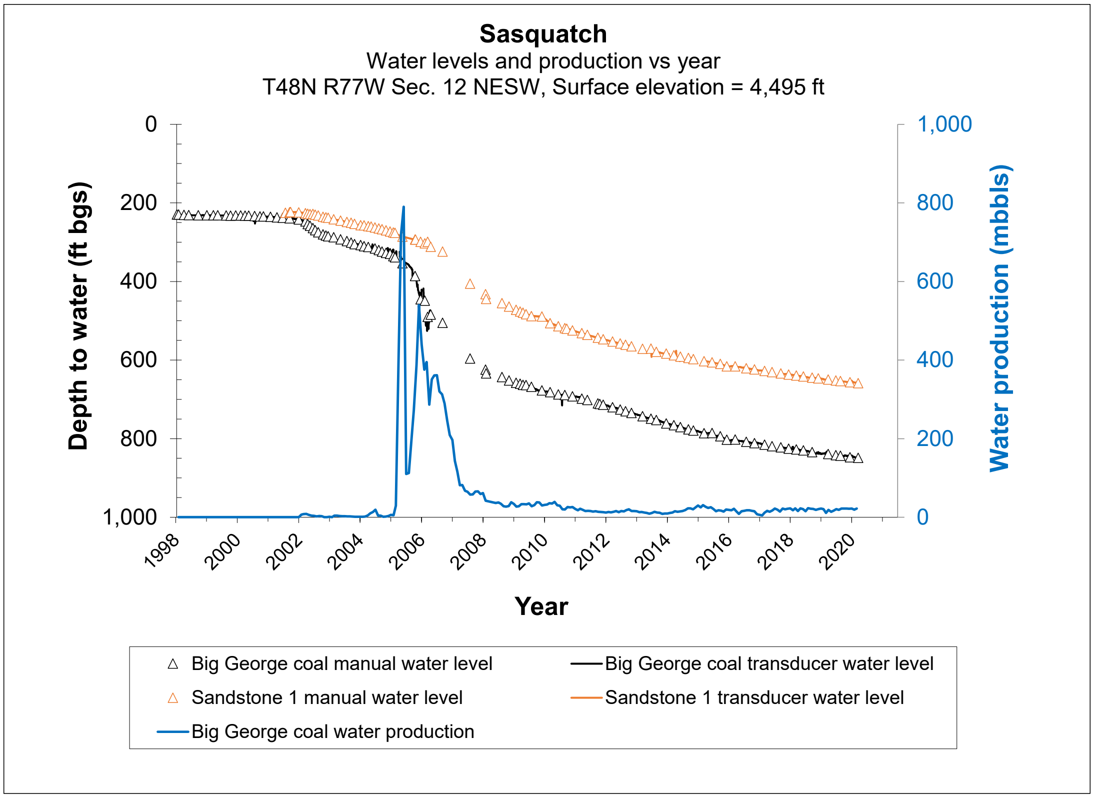

Figure A1–7. Sasquatch

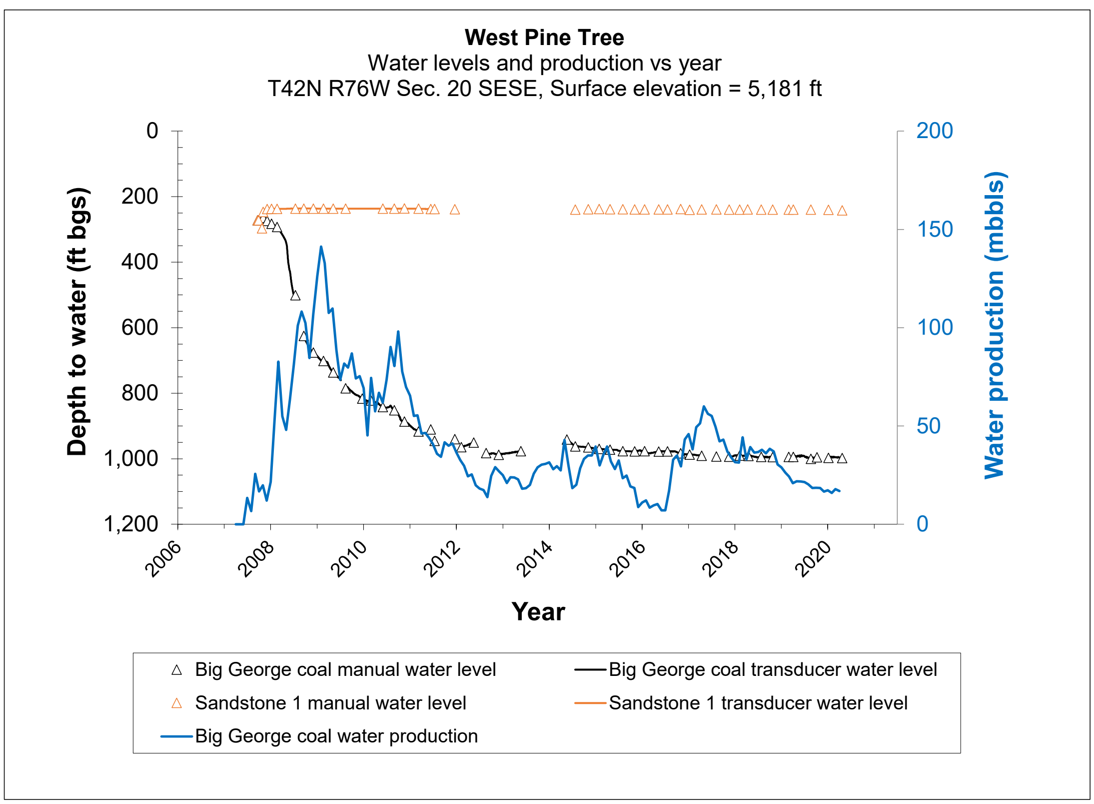

Figure A1–8. West Pine Tree

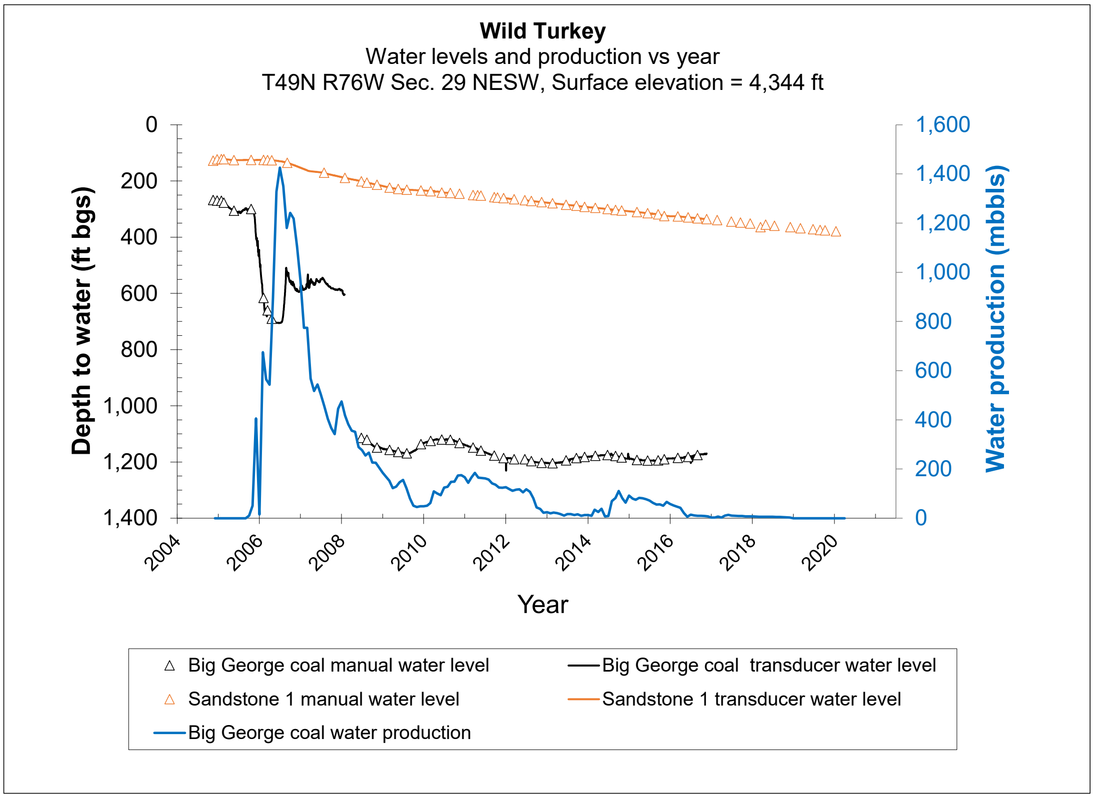

Figure A1–9. Wild Turkey

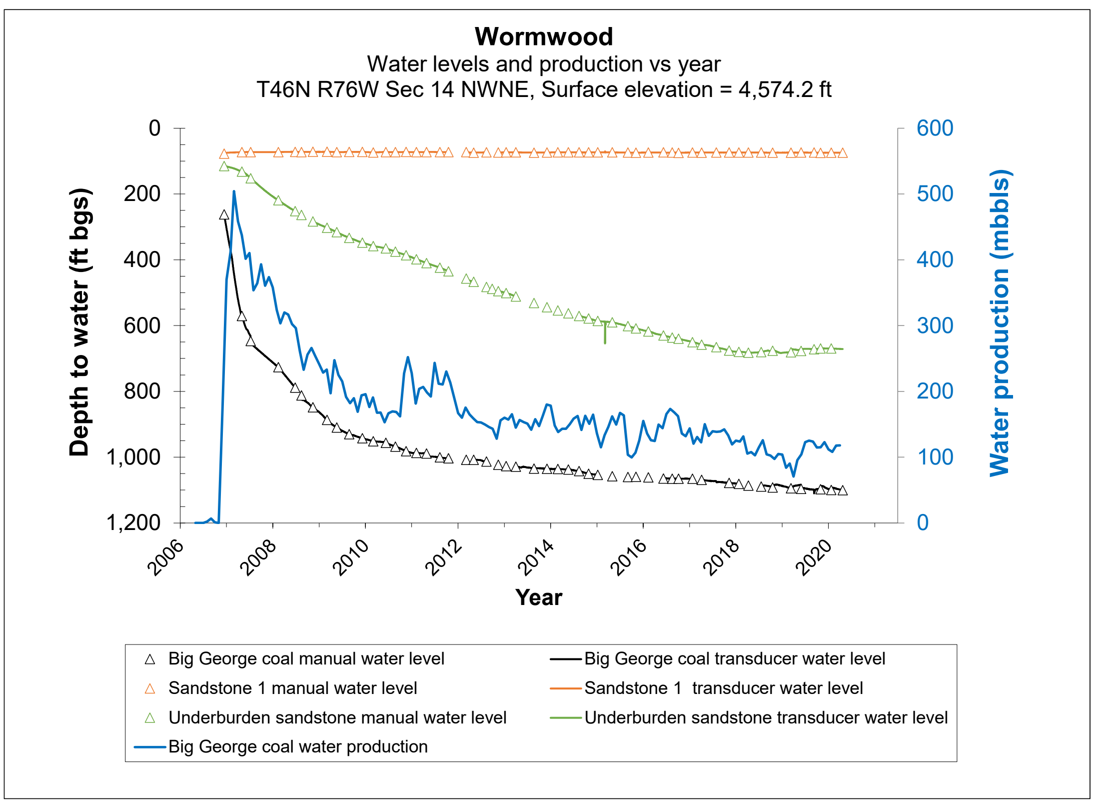

Figure A1–10. Wormwood

Appendix 2

Figures A2-1 through A2-29 in Appendix 2 are hydrographs for monitoring sites in nonproducing areas showing depth-to-groundwater (left vertical axis, feet below ground surface=ft bgs) and monthly water production (right vertical axis, per thousand barrels=mbbls) as functions of time (horizontal axis) at monitoring site labeled at the top of each figure. [T.: township, N.: north, R.: range, W.: west, Sec.: section, S.: south, W.: west, Ft.: feet]

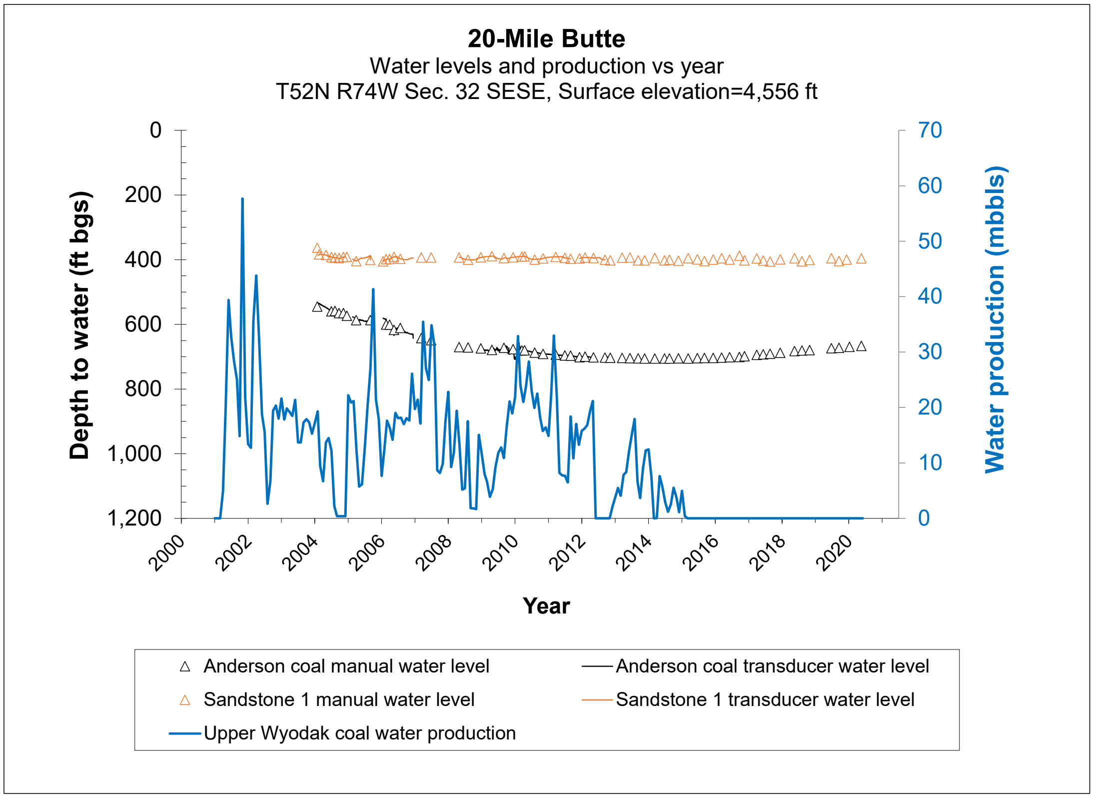

Figure A2–1. 20-Mile Butte

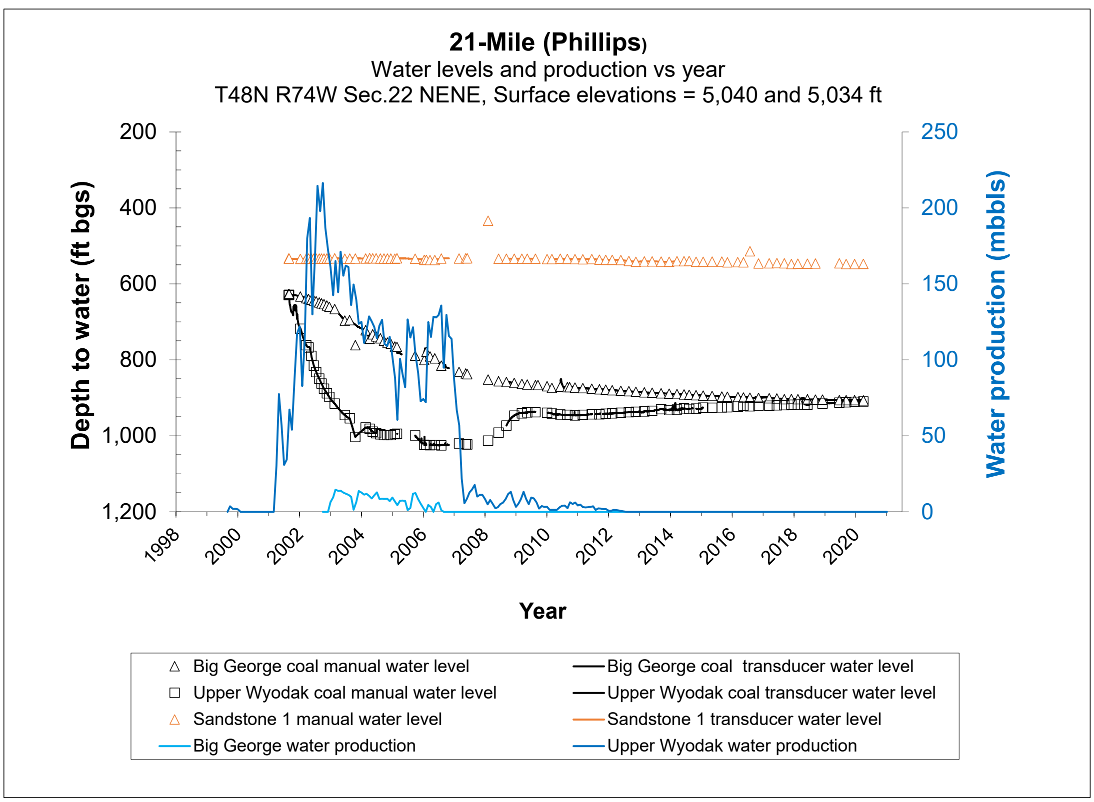

Figure A2–2. 21-Mile (Phillips)

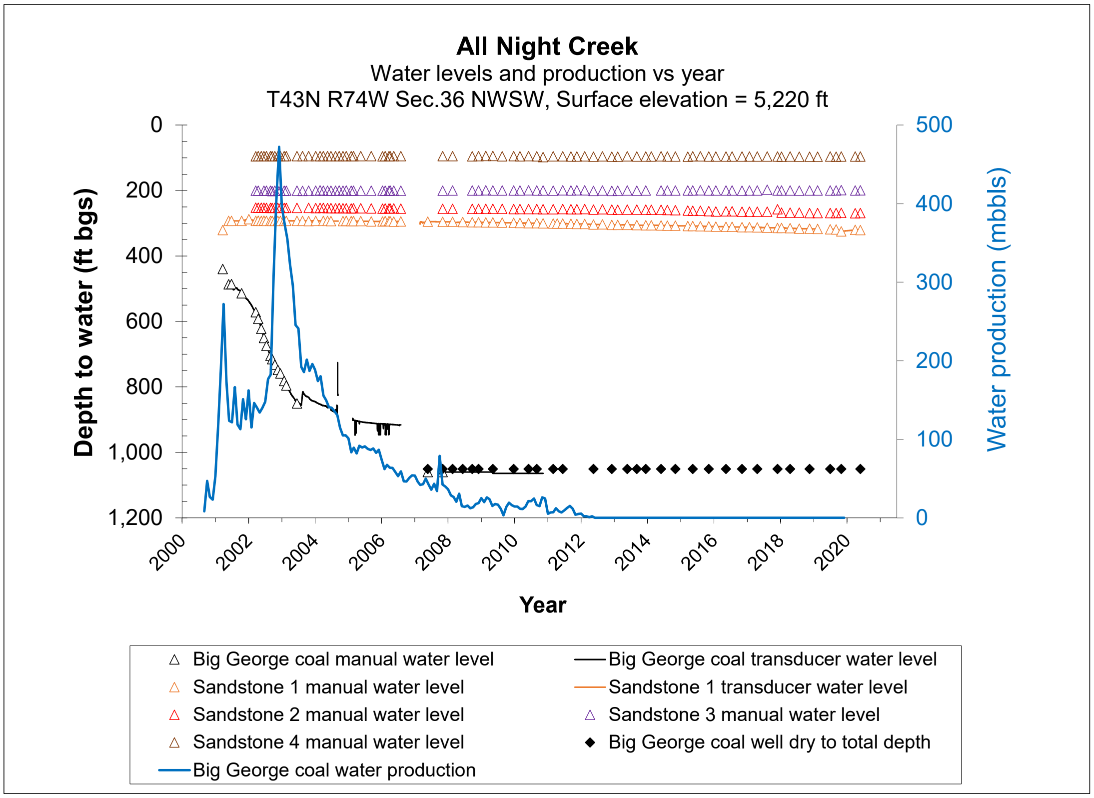

Figure A2–3. All Night Creek

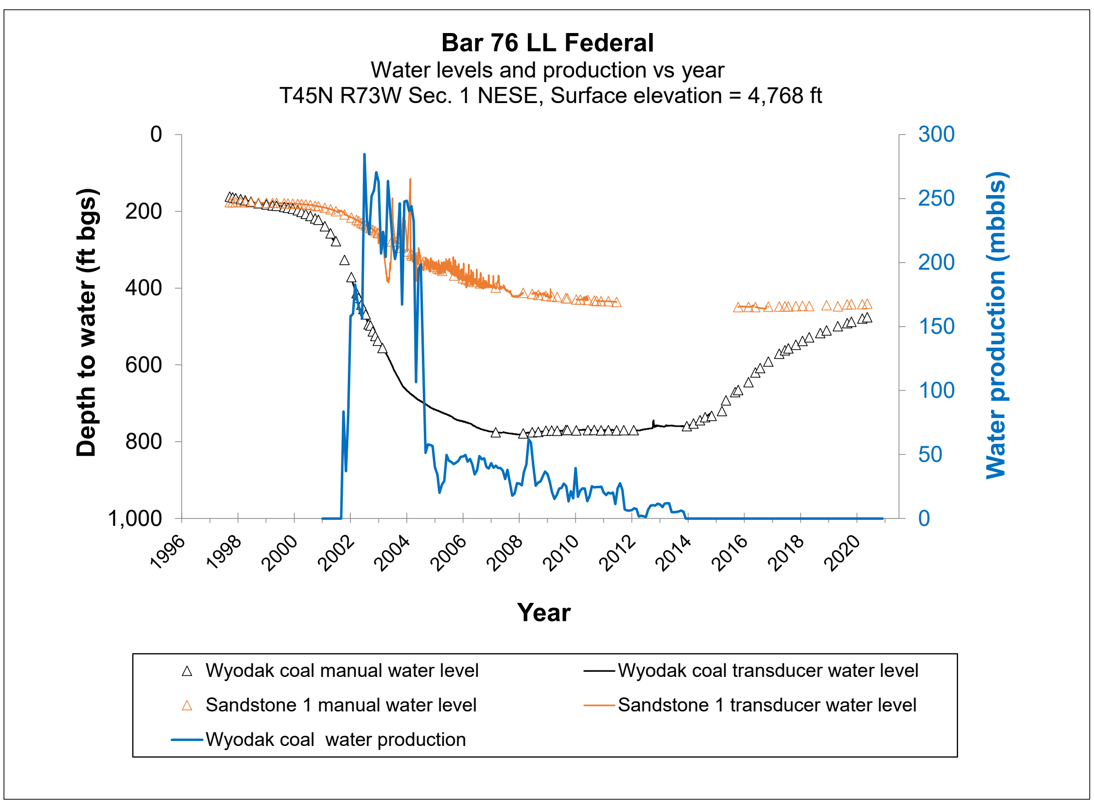

Figure A2–4. Bar 76 LL Federal

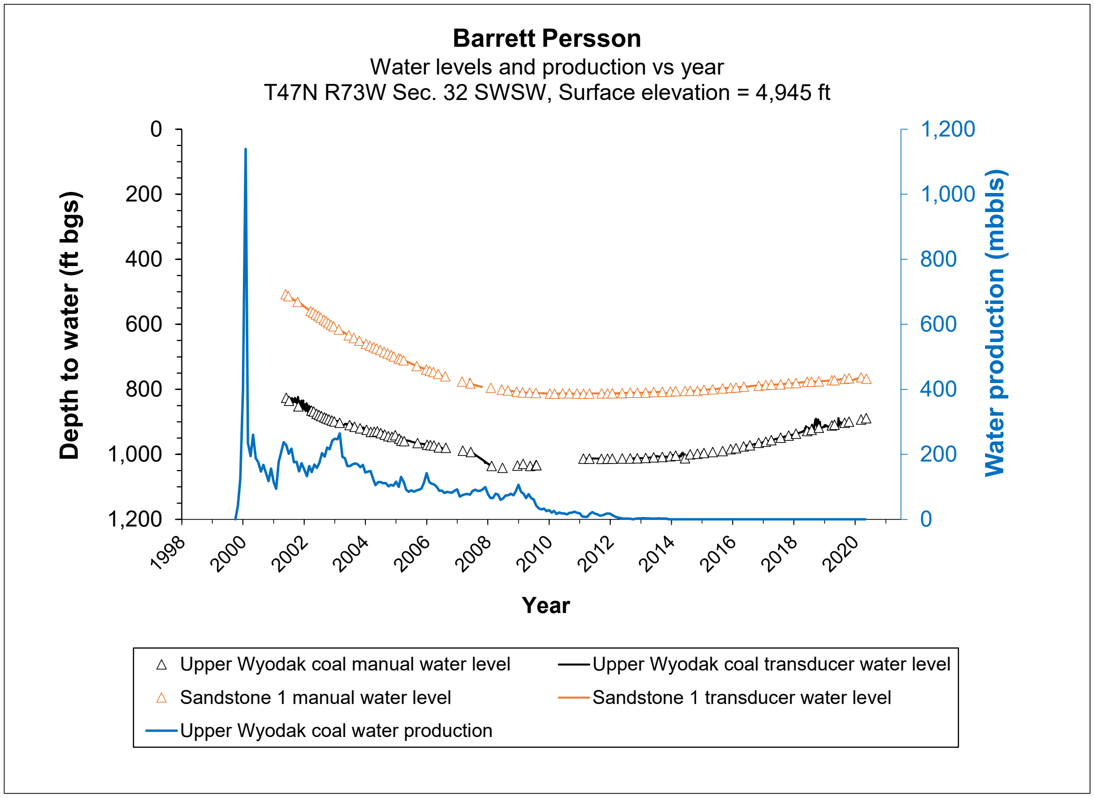

Figure A2–5. Barrett Persson

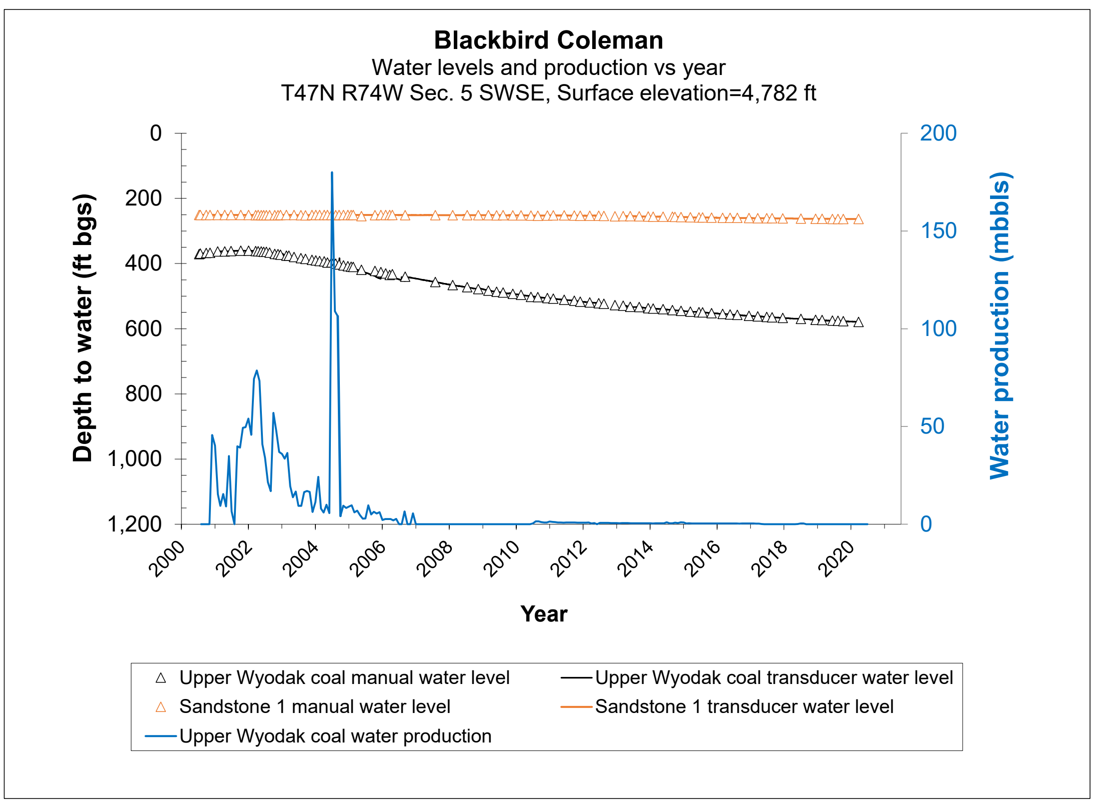

Figure A2–6. Blackbird Coleman

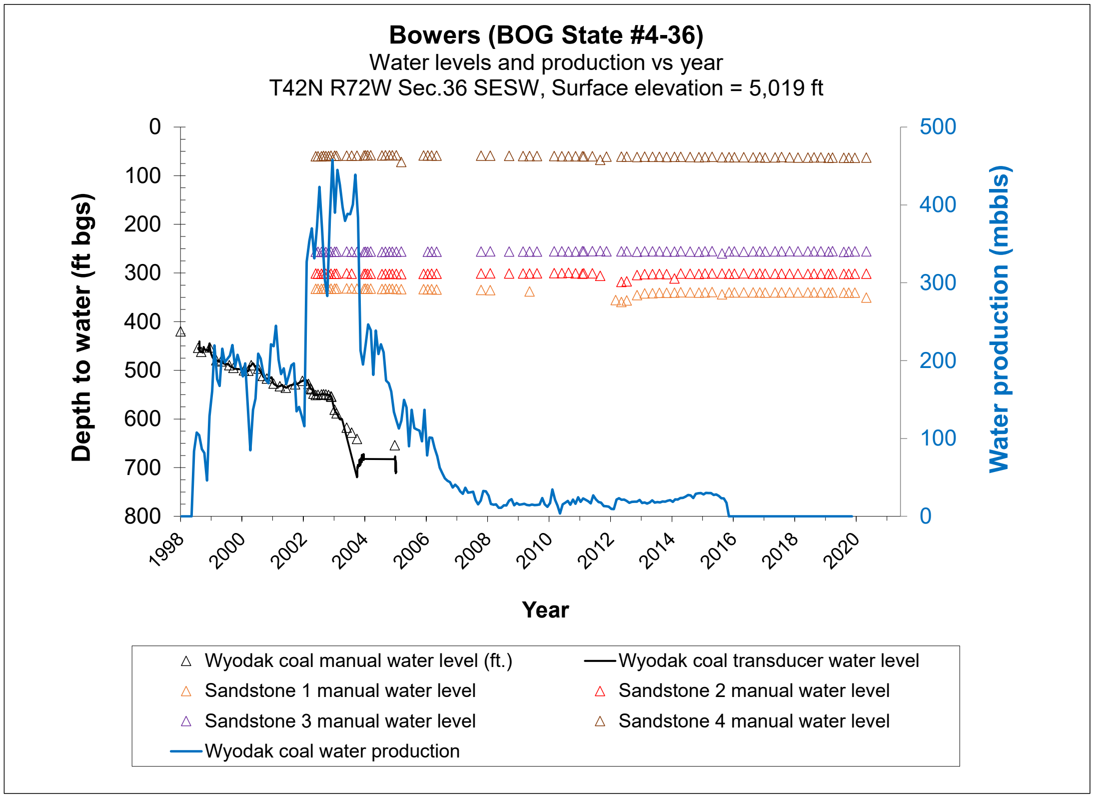

Figure A2–7. Bowers (BOG State #4-36)

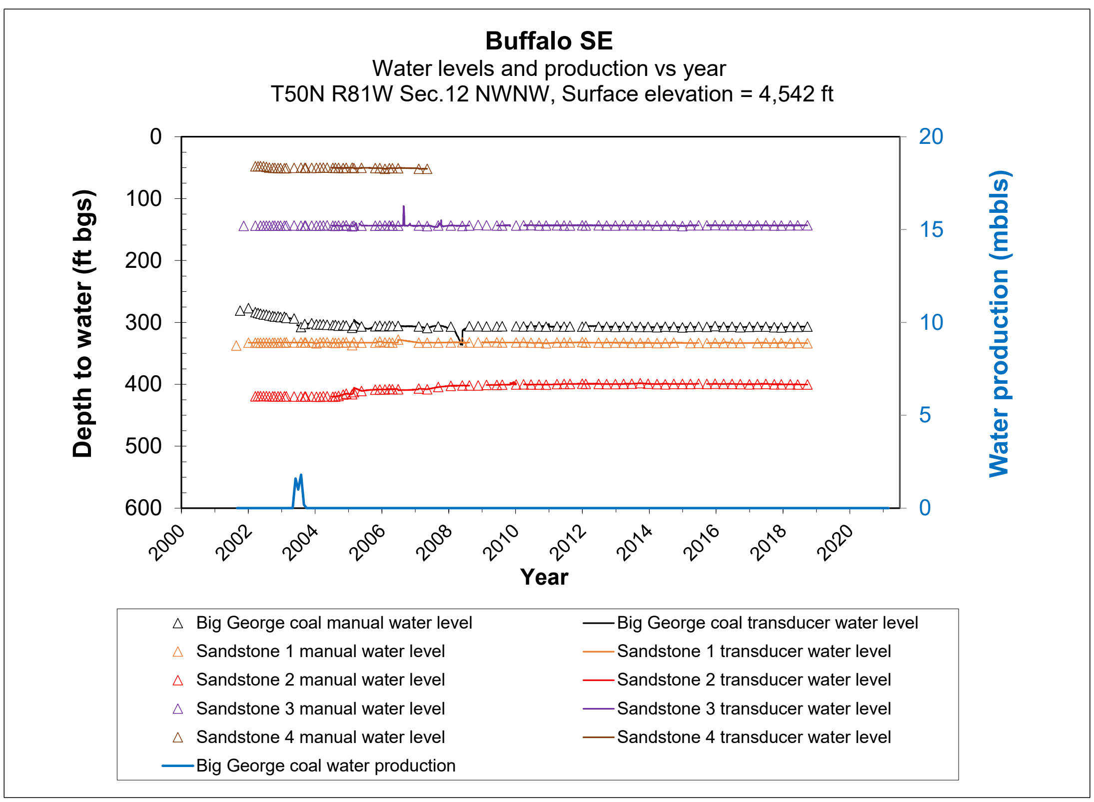

Figure A2–8. Buffalo SE

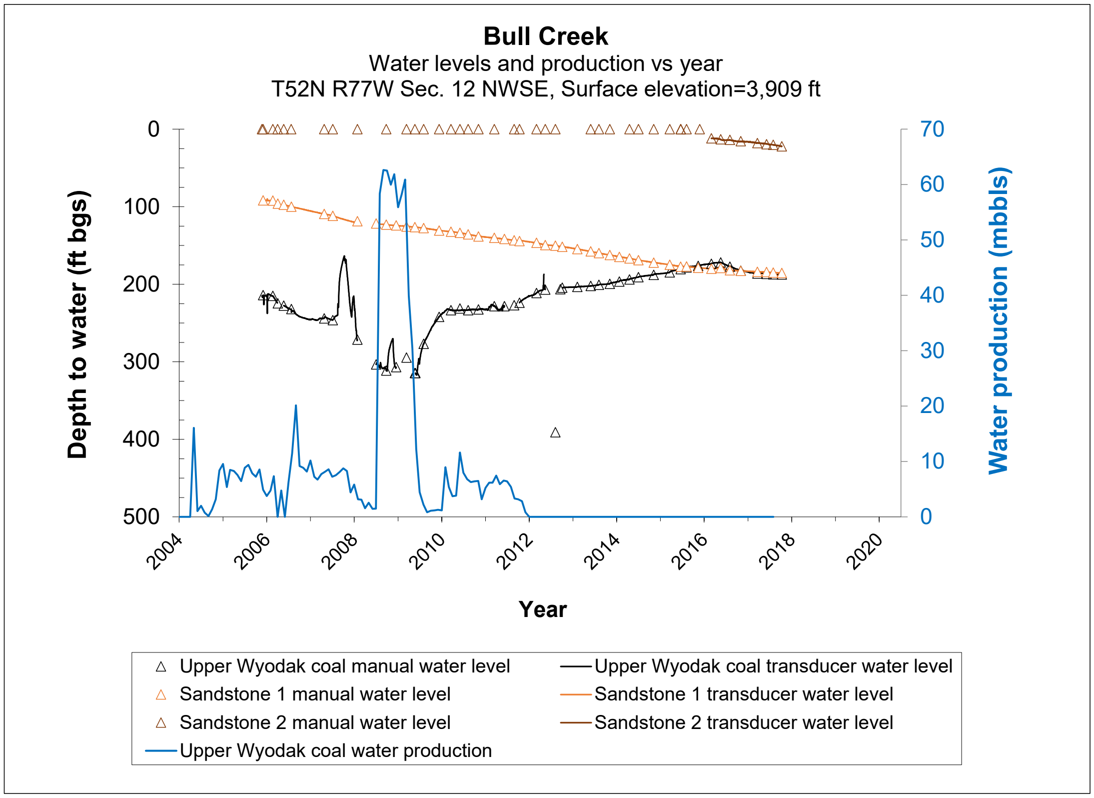

Figure A2–9. Bull Creek

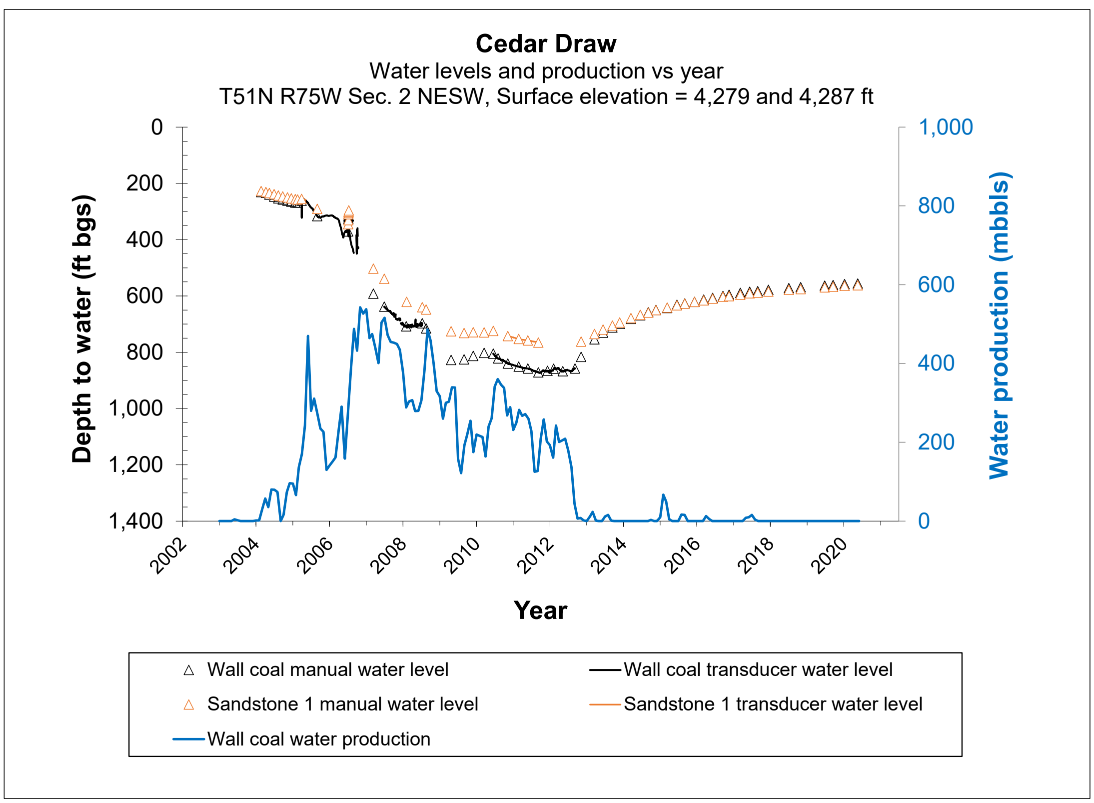

Figure A2–10. Cedar Draw

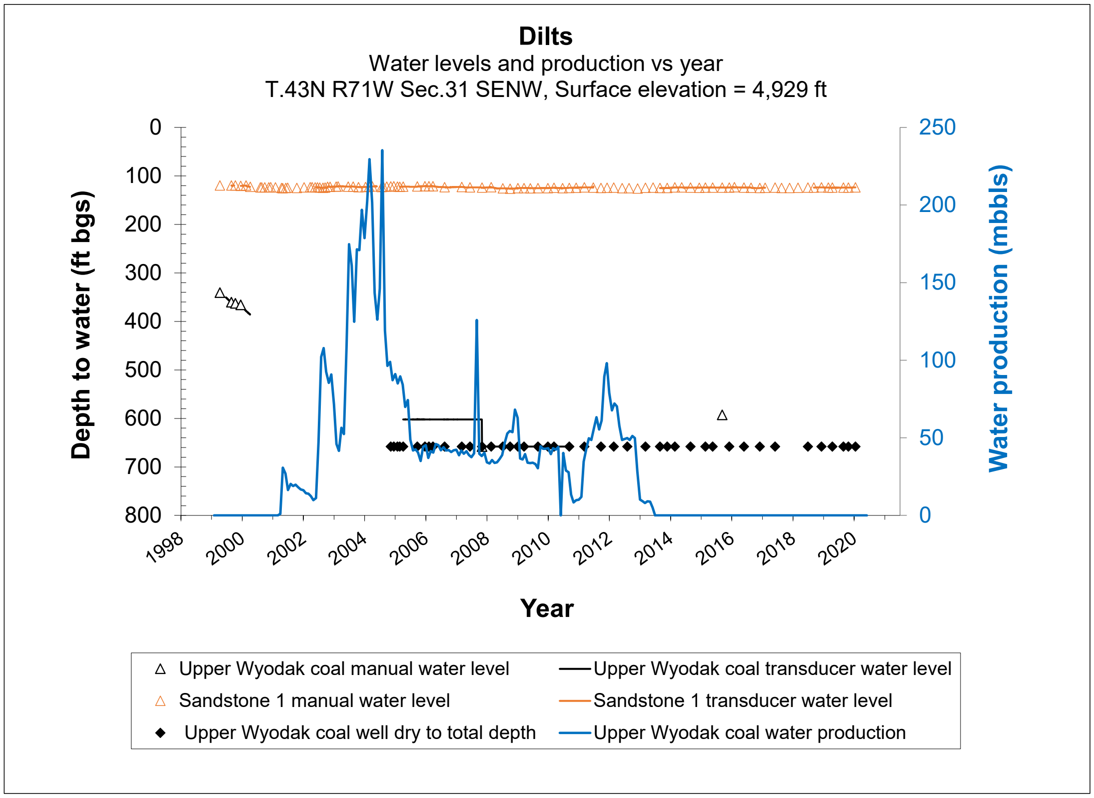

Figure A2–11. Dilts

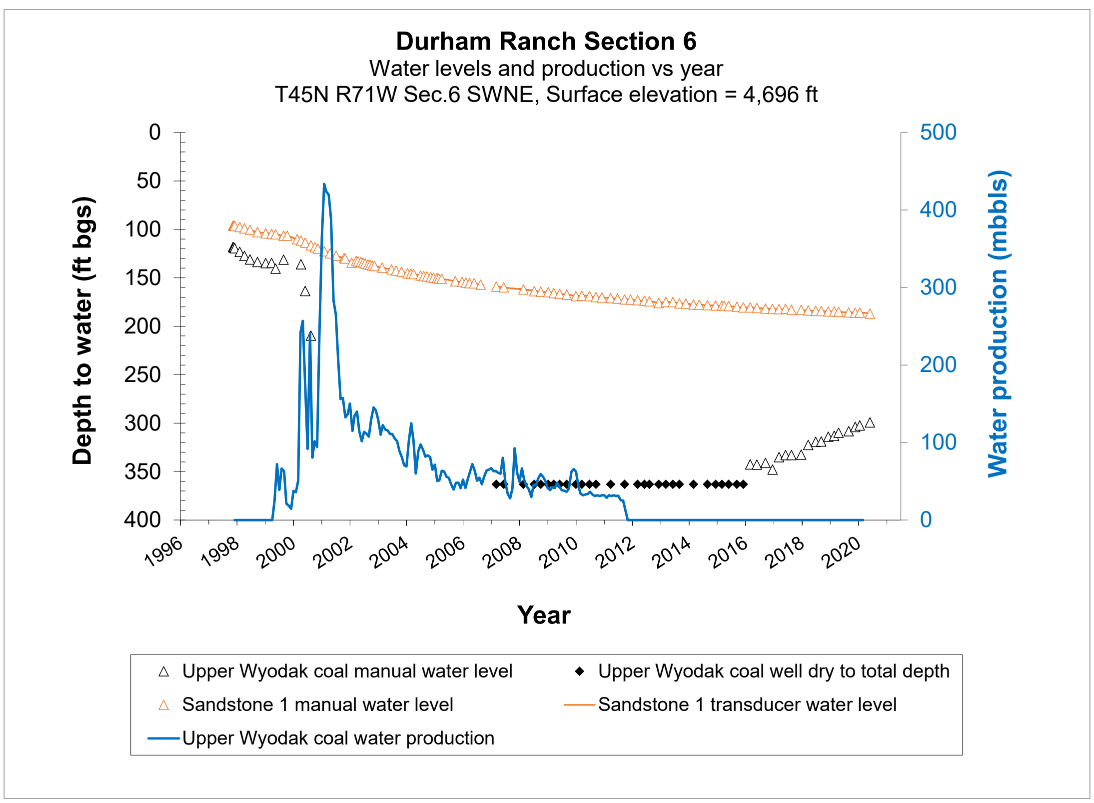

Figure A2–12. Durham Ranch Section 6

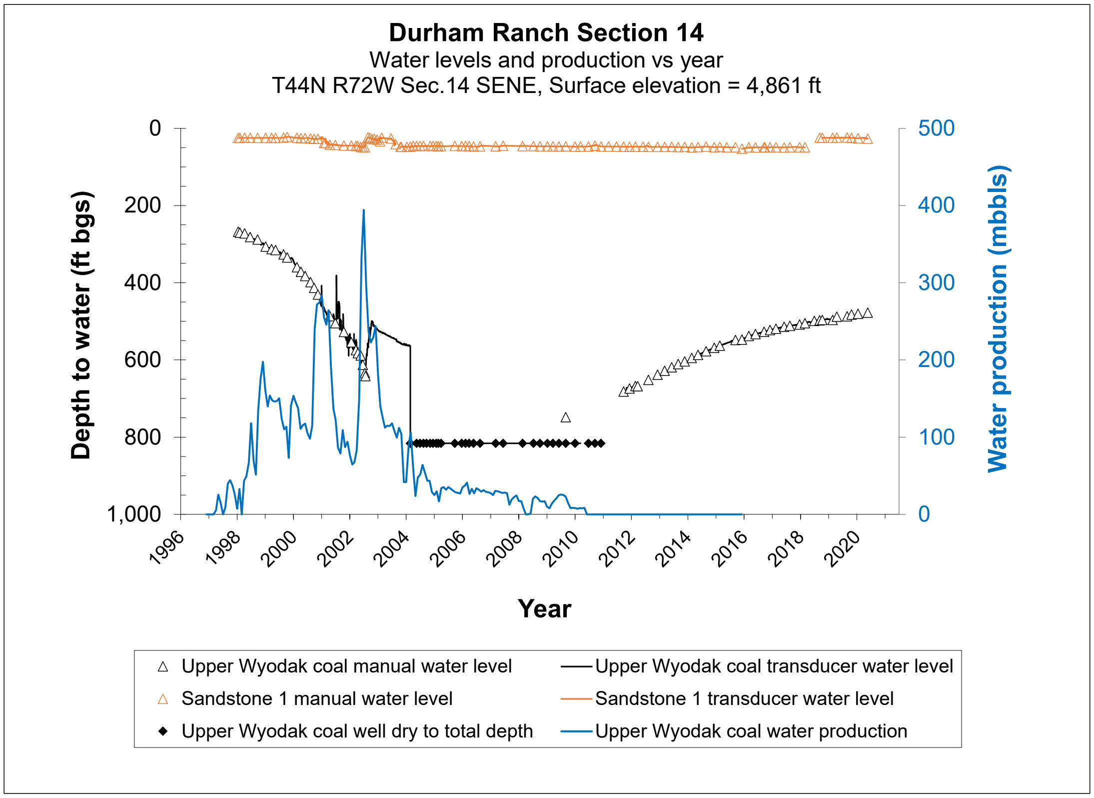

Figure A2–13. Durham Ranch Section 14

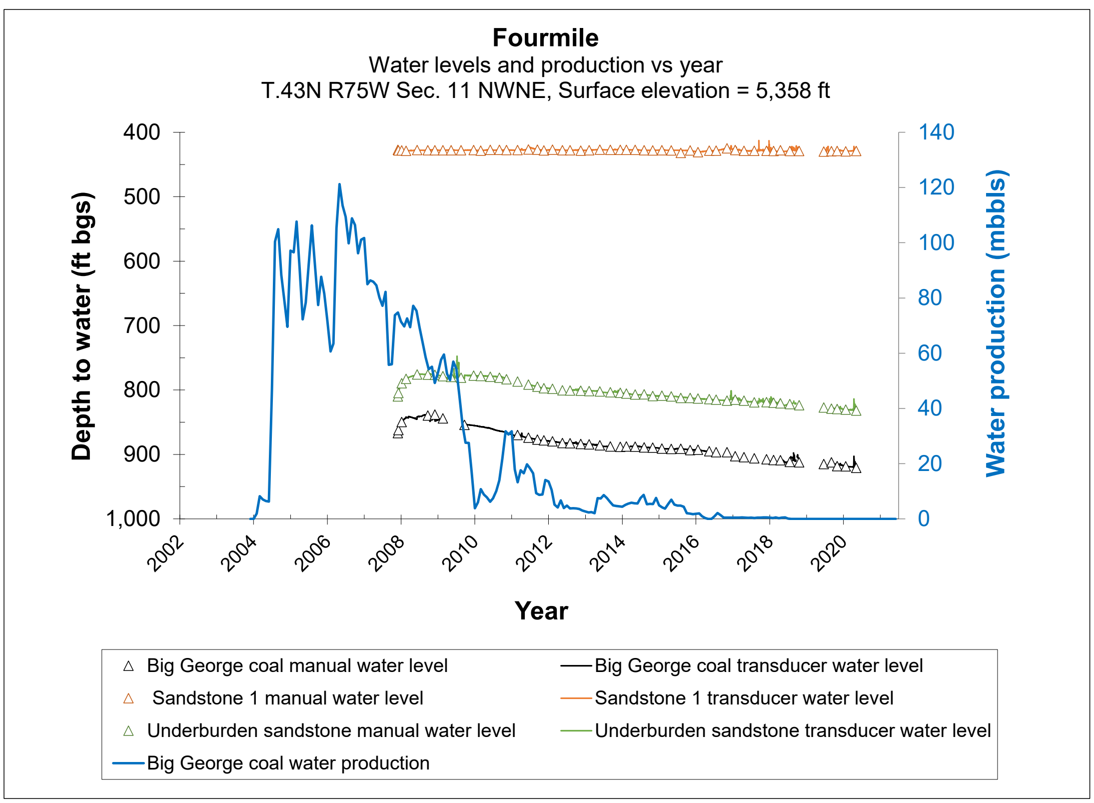

Figure A2–14. Fourmile

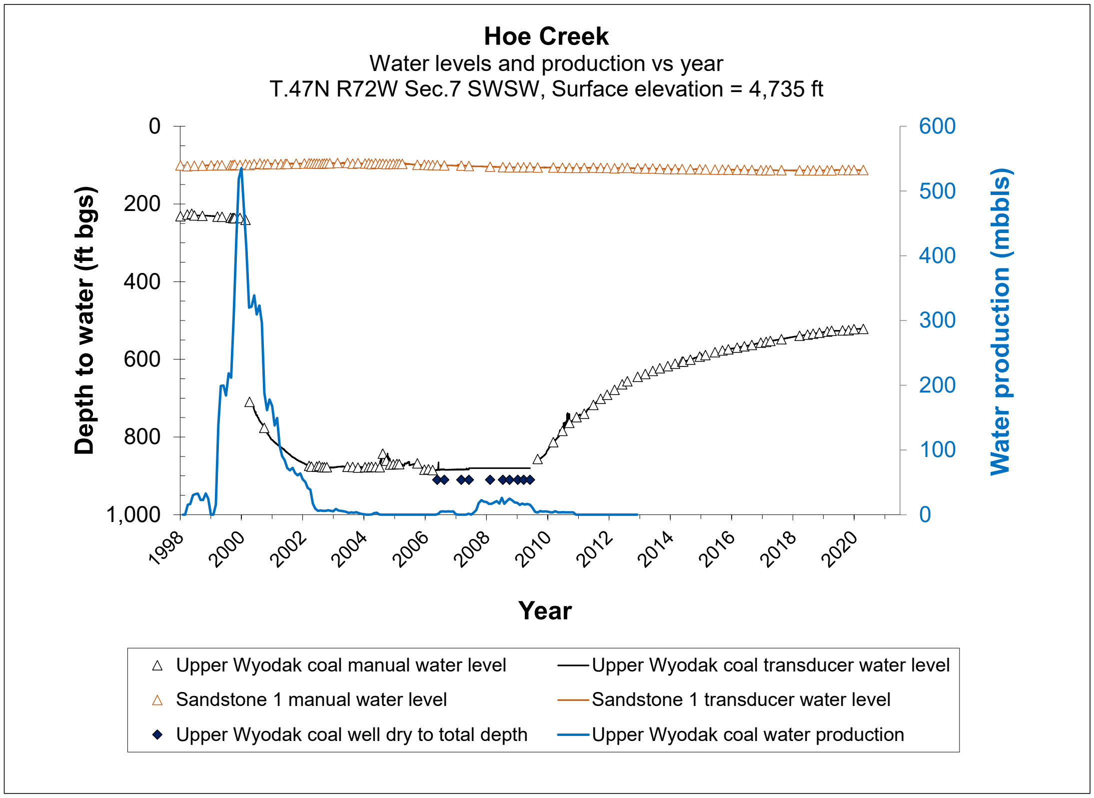

Figure A2–15. Hoe Creek

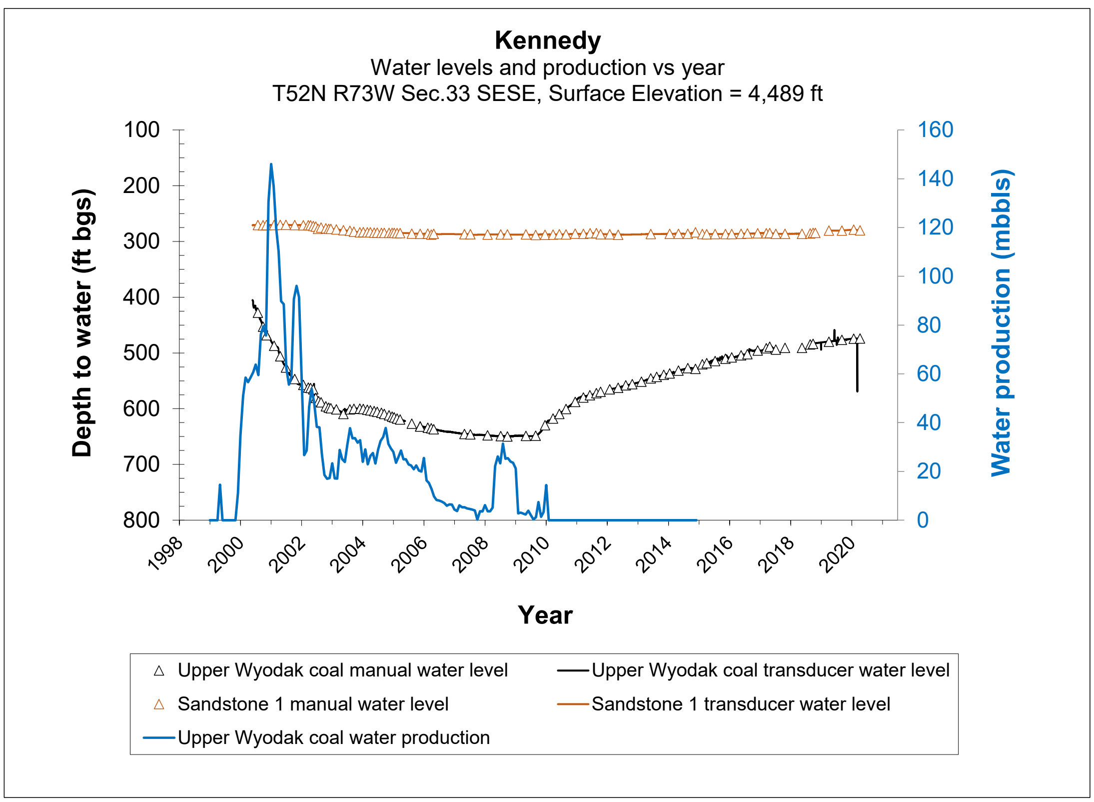

Figure A2–16. Kennedy

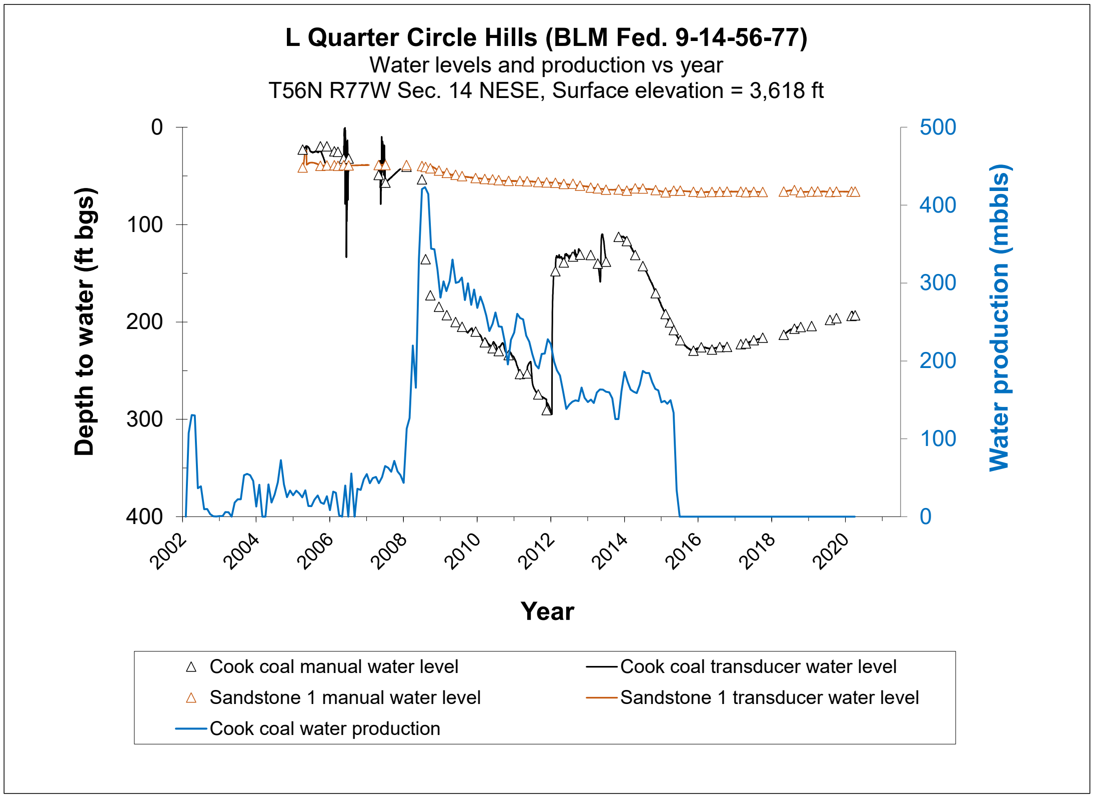

Figure A2–17. L Quarter Circle Hills (BLM Fed. 9-14-56-77)

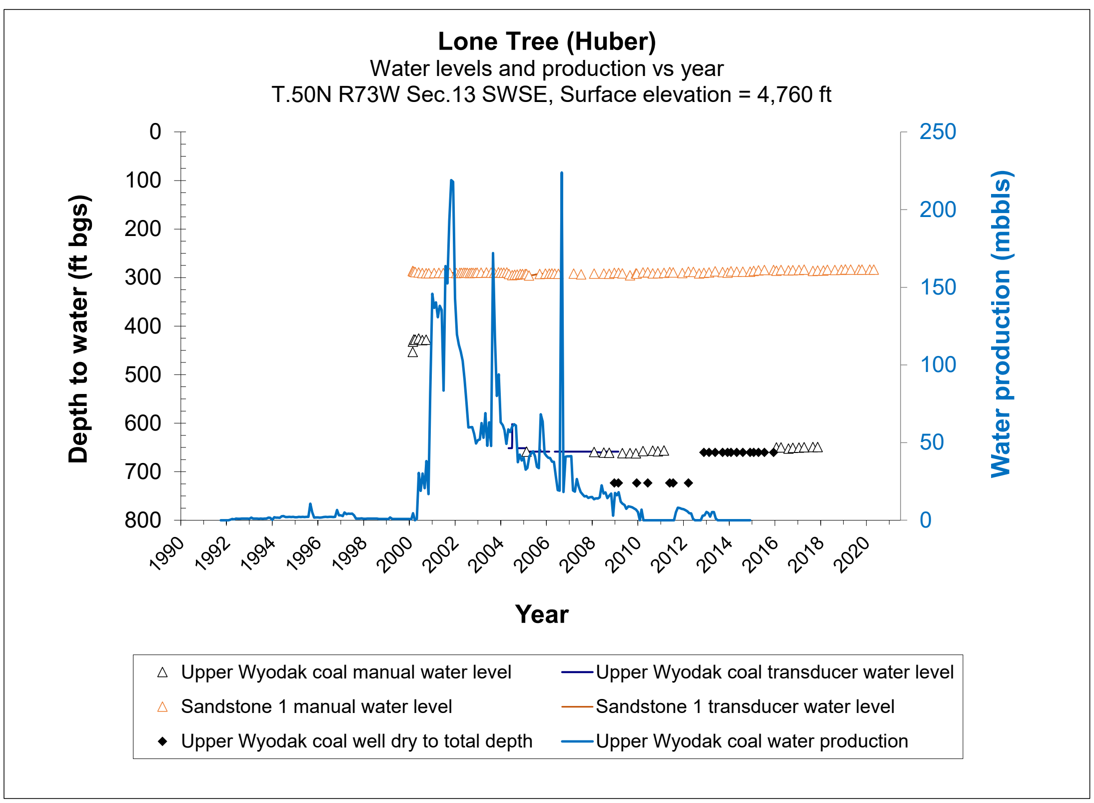

Figure A2–18. Lone Tree (Huber)

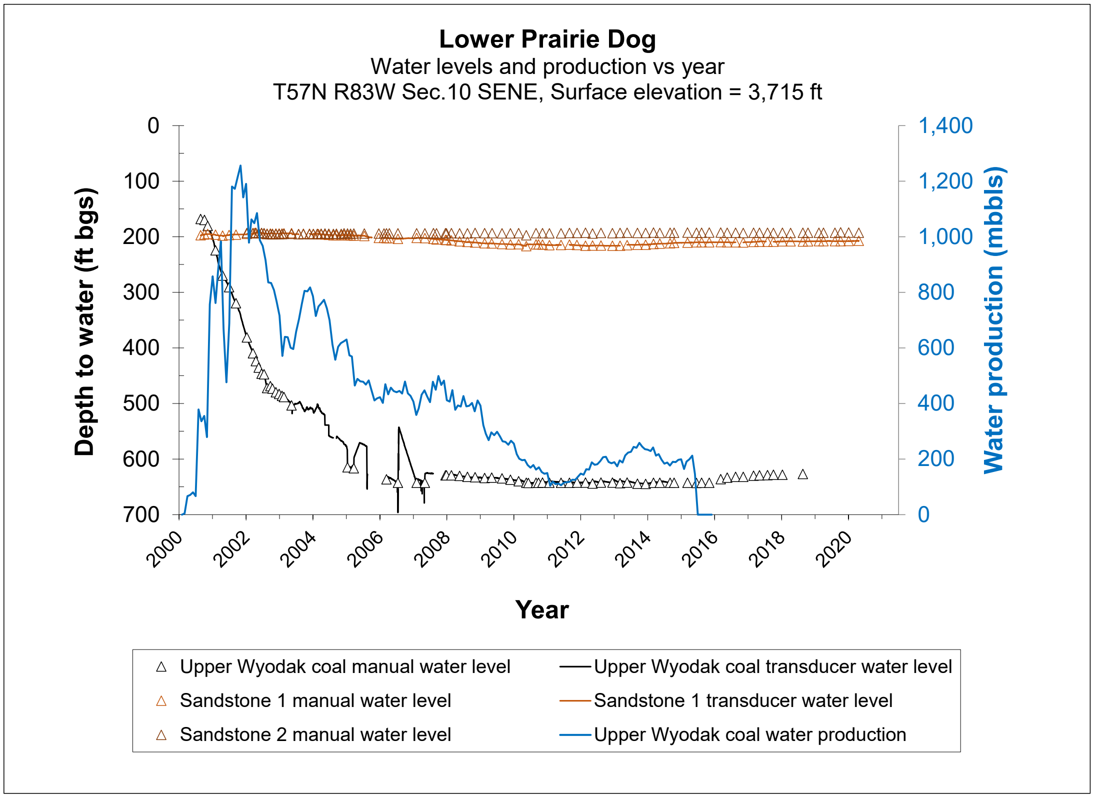

Figure A2–19. Lower Prairie Dog

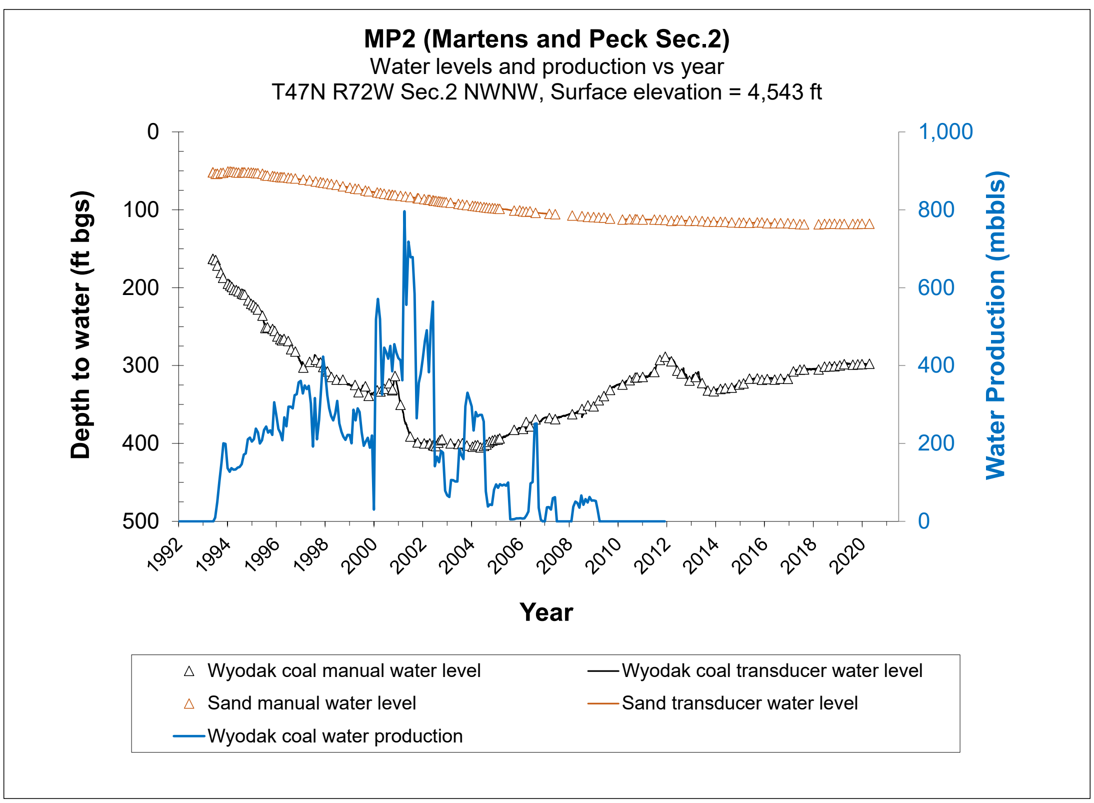

Figure A2–20. MP2 (Martens and Peck Sec.2)

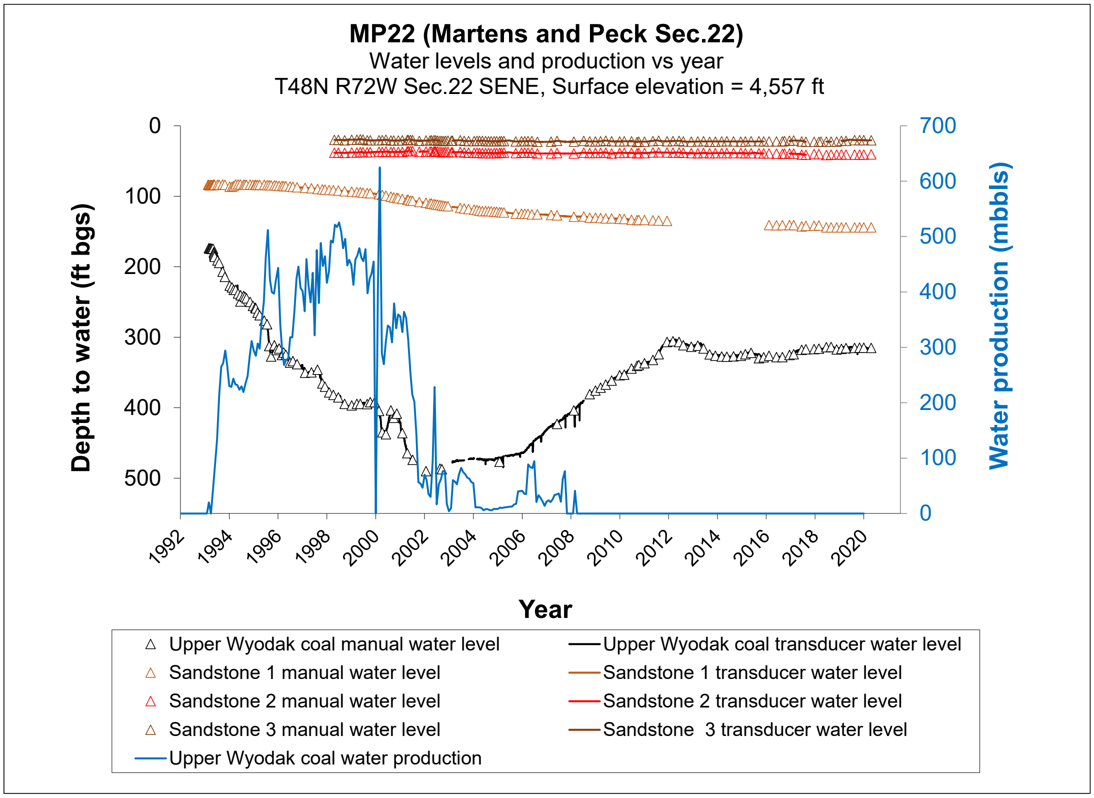

Figure A2–21. MP22 (Martens and Peck Sec.22)

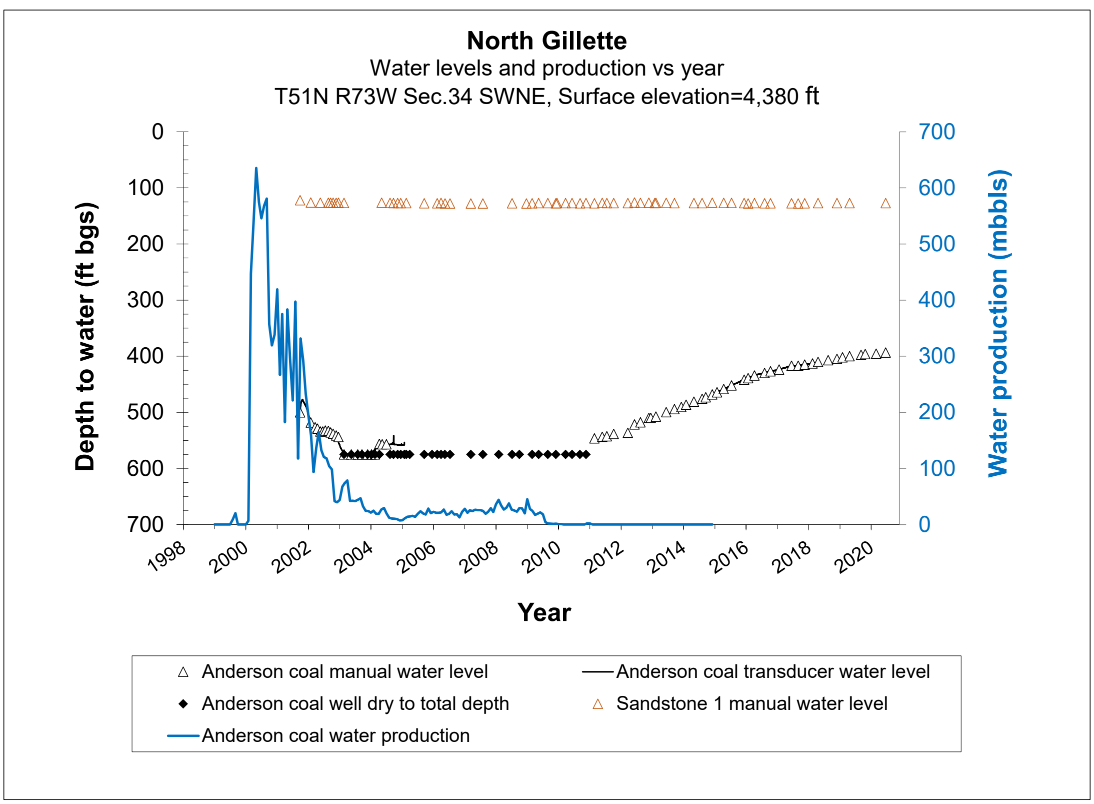

Figure A2–22. North Gillette

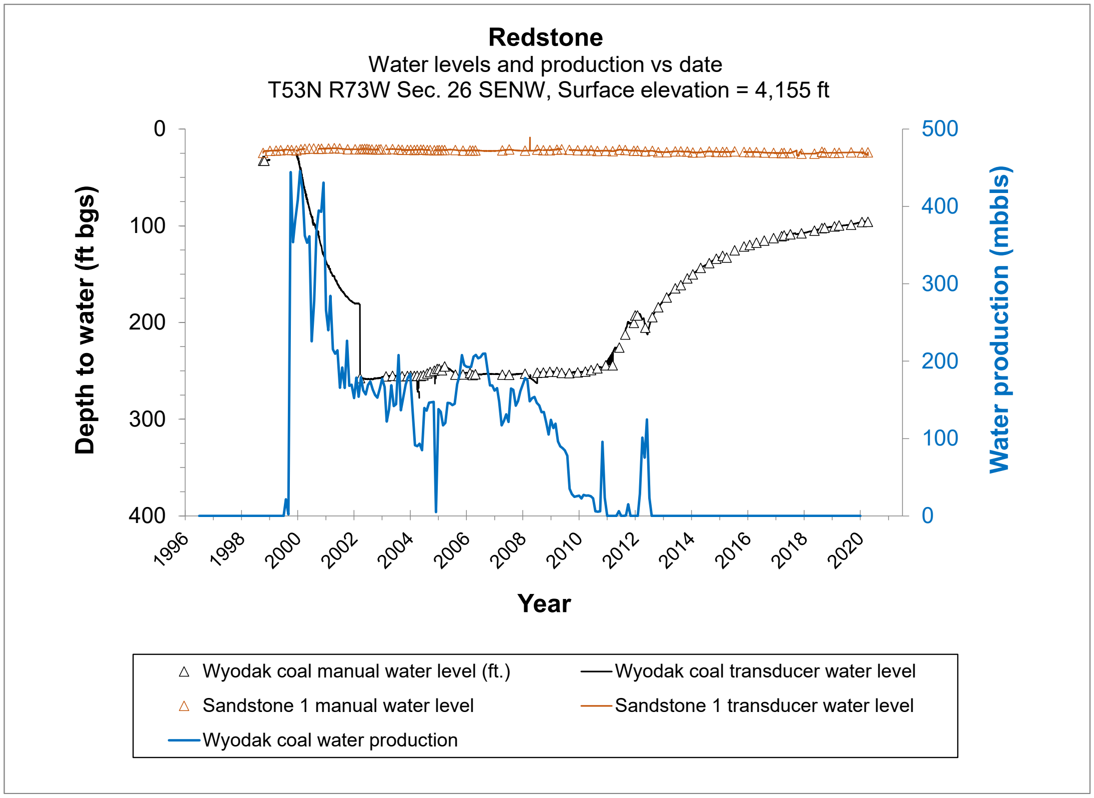

Figure A2–23. Redstone

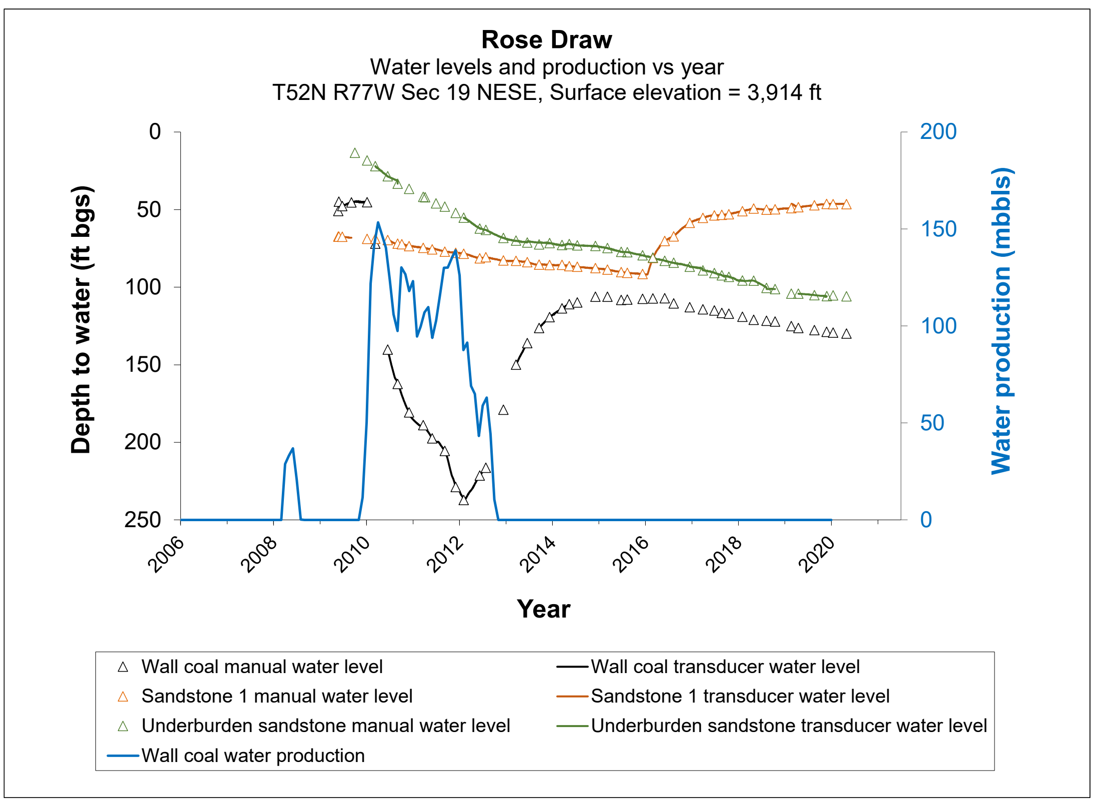

Figure A2–24. Rose Draw

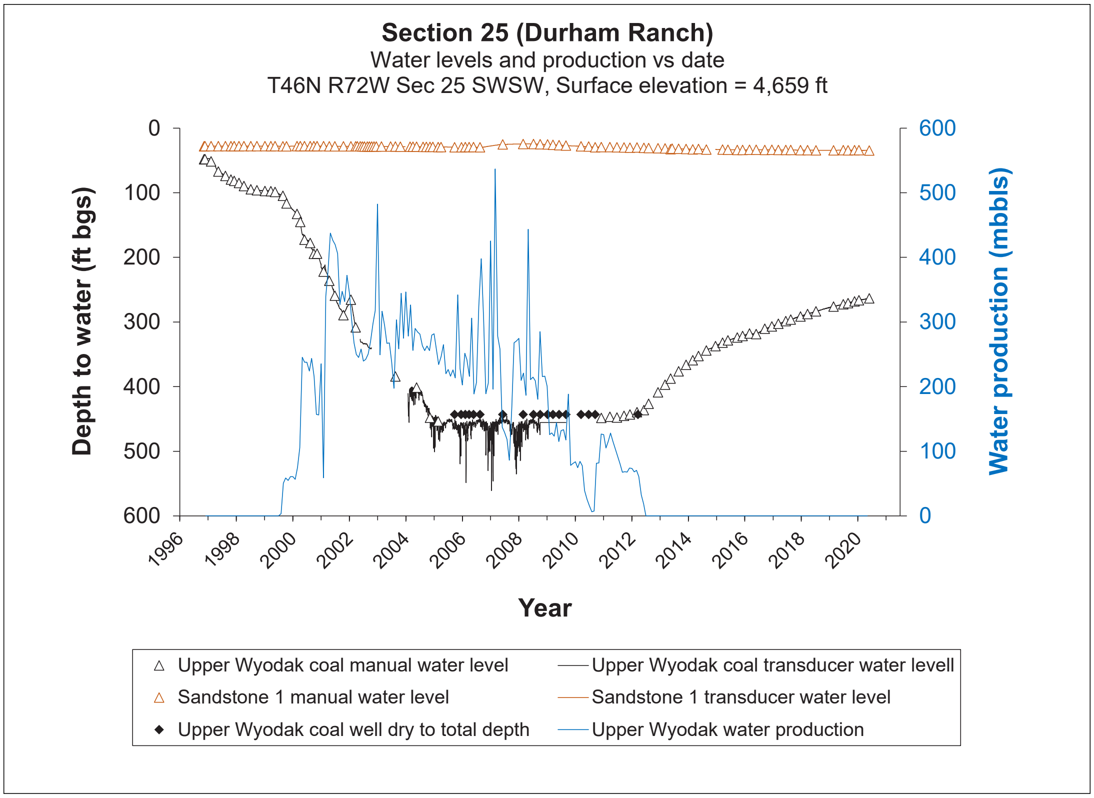

Figure A2–25. Section 25 (Durham Ranch)

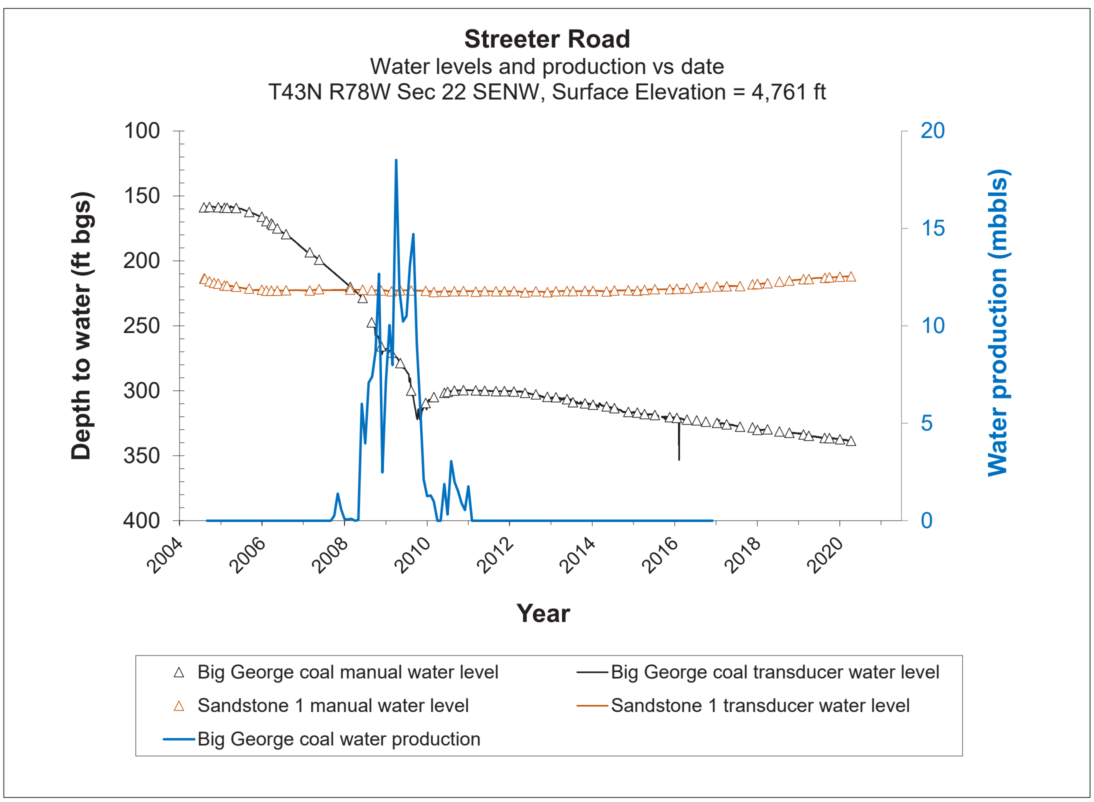

Figure A2–26. Streeter Road

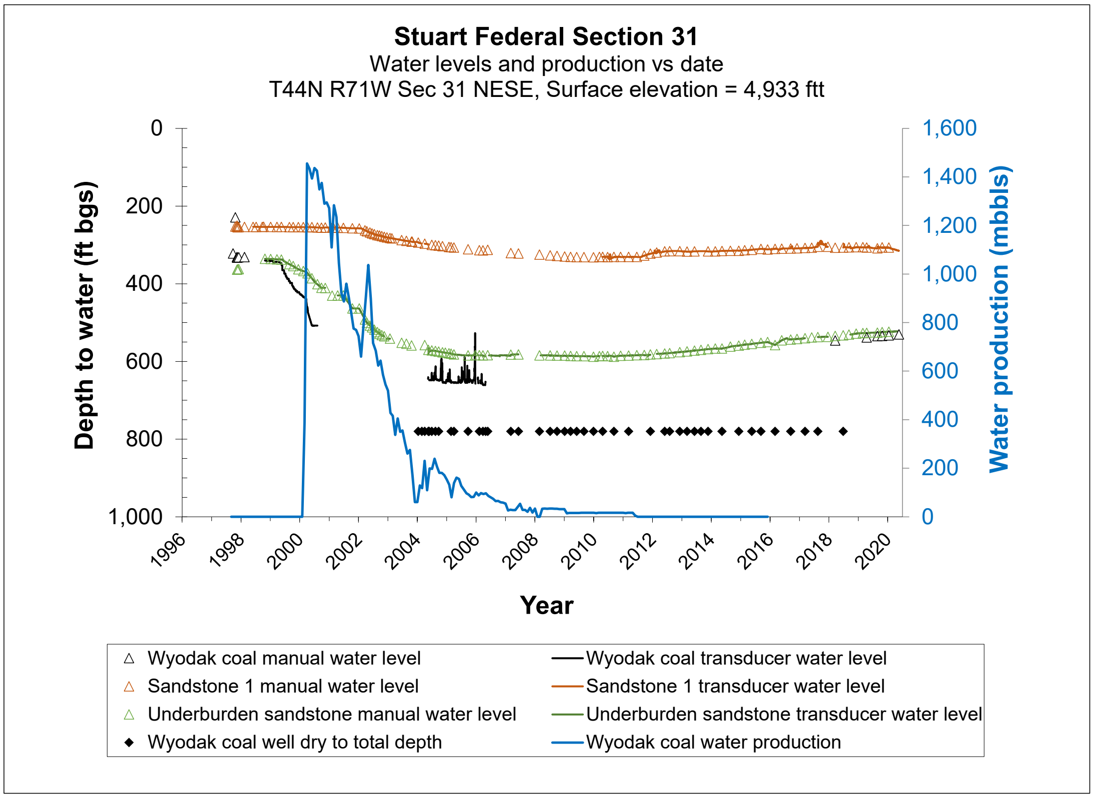

Figure A2–27. Stuart Federal Section 31

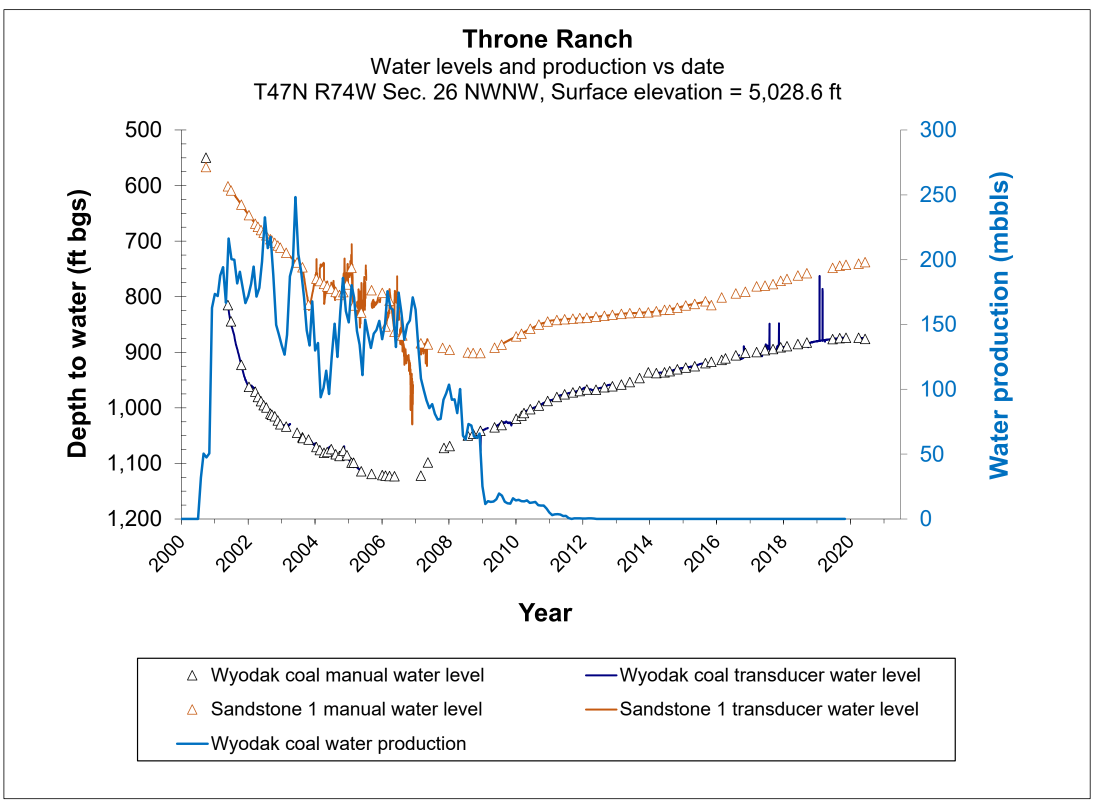

Figure A2–28. Throne Ranch

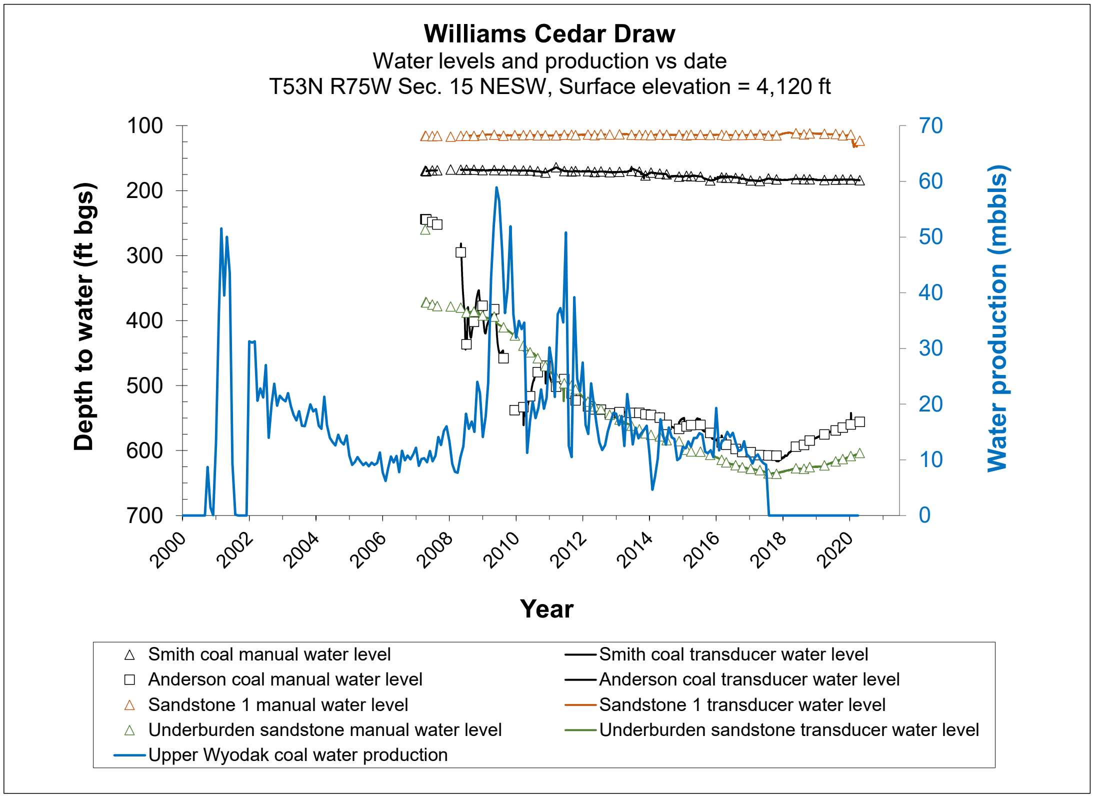

Figure A2–29. Williams Cedar Draw

Interpreting the past, providing for the future