Groundwater Response in the Sandstones of the Wasatch and Fort Union Formations, Powder River Basin, Wyoming

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

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Cover photo: Southeastern Powder River Basin near Wright, Wyoming. The Rochelle Hills can be seen in the background. Photo courtesy of James E. Stafford, WSGS, 2006.

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Abbreviations, acronyms, and symbols used in this report

AF	acre-feet
bbl	barrel (*42 U.S. gallons)*
bcf	billion cubic feet *(a measure of natural gas volume)*
BLM	U.S. Bureau of Land Management
CBNG	coalbed natural gas
CFS	cubic feet per second
DGW	depth to groundwater
ft	feet
GIS	Geographic Information System
GWL	groundwater level
mcf	thousand cubic feet *(most commonly used standard measure of natural gas volume)*
mmcf	million cubic feet *(a measure of natural gas volume)*
POR	period of record
PRB	Powder River Basin
WOGCC	Wyoming Oil and Gas Conservation Commission
WSGS	Wyoming State Geological Survey

INTRODUCTION

Coalbed natural gas (CBNG) production has been recorded in Wyoming's Powder River Basin (PRB) since 1980 when the Wyoming Oil and Gas Conservation Commission (WOGCC) first began keeping records. Production grew slowly into the 1990s but by 1997, the PRB was producing more than one mmcf of CBNG per month (WOGCC, 2016). Annual CBNG production in the PRB peaked in 2009 at more than 556 bcf, or 2.1 percent of all U.S. natural production for that year. CBNG production rates started a decline in late 2010 that has continued into the present; annual production fell to 197 bcf during 2015, a decline of nearly 65 percent.

CBNG is produced by reducing the water pressure within a targeted coal seam. This typically requires the extraction of large amounts of groundwater from the seam, effectively lowering the water level. As water pressure decreases, microscopic films of natural gas that adhere to the surfaces of pores and fractures cleats in the coal desorb and coalesce into bubbles. Both water and free natural gas are pumped to the surface where they are separated. The CBNG, generally measured in volumes of thousand cubic feet (mcf), is transported to market through a series of compressor stations and pipelines. Produced water, measured in units of barrels (bbls), is used for irrigation or livestock, reinjected into deeper geologic formations, or discharged into evaporation/infiltration pits and streambeds. Between 2001 and 2014, the PRB in Wyoming produced nearly 5.6 trillion cubic feet of CBNG and more than 7.4 billion barrels (nearly 954,000 AF) of groundwater (EIA, 2016; WOGCC, 2016; fig. 1).

A typical production profile for a CBNG well is shown in figure 2. During the dewatering stage, in some instances water levels in coal seam aquifers may decline several hundred feet. In most cases, a period of stable gas and water production follows for several years. In time, as gas production declines below the rate at which the methane can be profitably produced, the volumes of water pumped from the well may be reduced to very low rates, or pumping may cease altogether and the well may be shut in or plugged and abandoned. As groundwater pumping declines or ceases, water levels in the targeted coal seam aquifer(s) may rise, or recover, in response. These fluctuations in groundwater level (GWL) are not restricted to just the developed coal

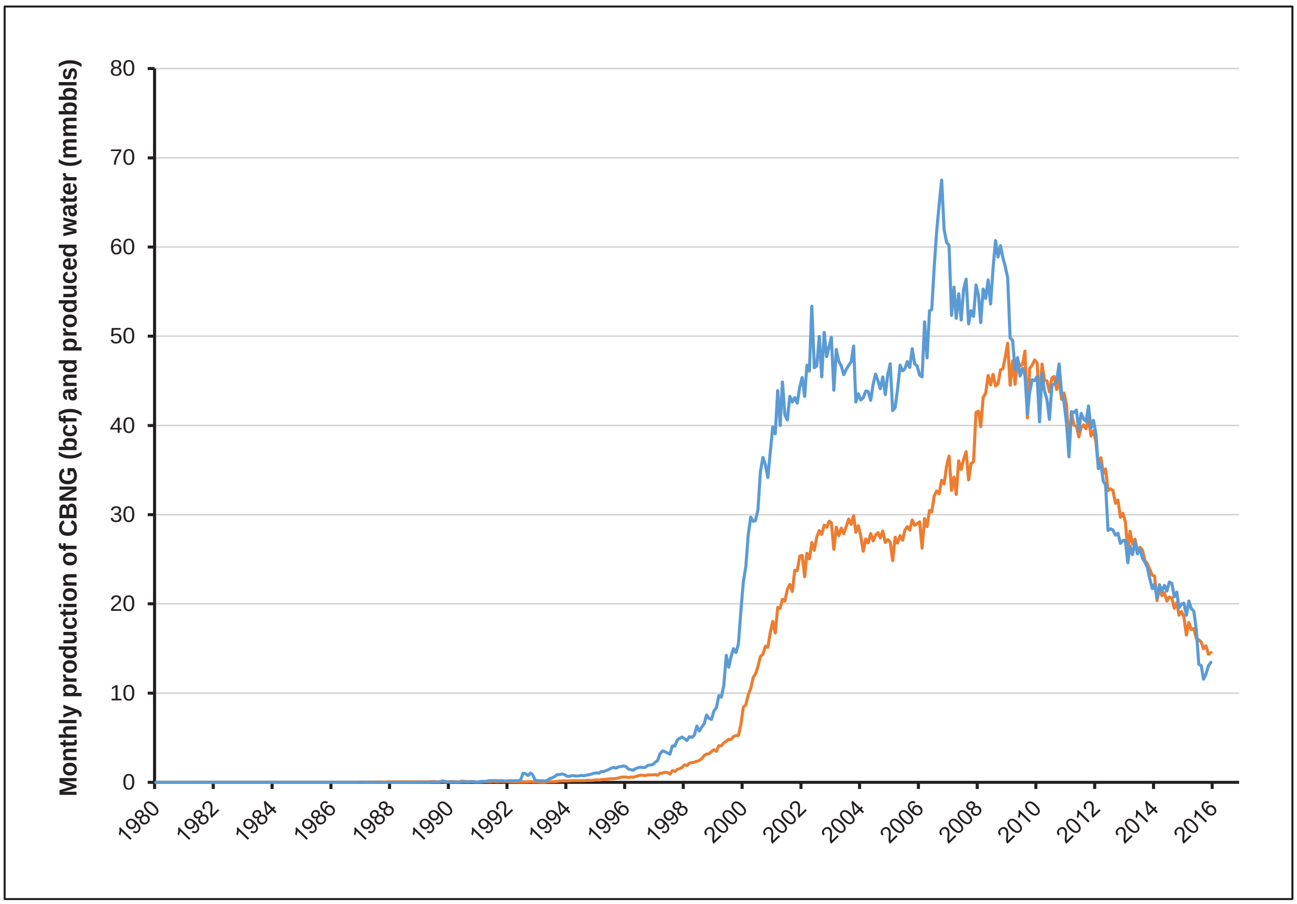

Figure 1. Monthly volumes of CBNG (red, in bcf) and produced water (blue, in mmbbls) produced in the PRB in Wyoming from 1980-2016 (WOGCC, 2016).

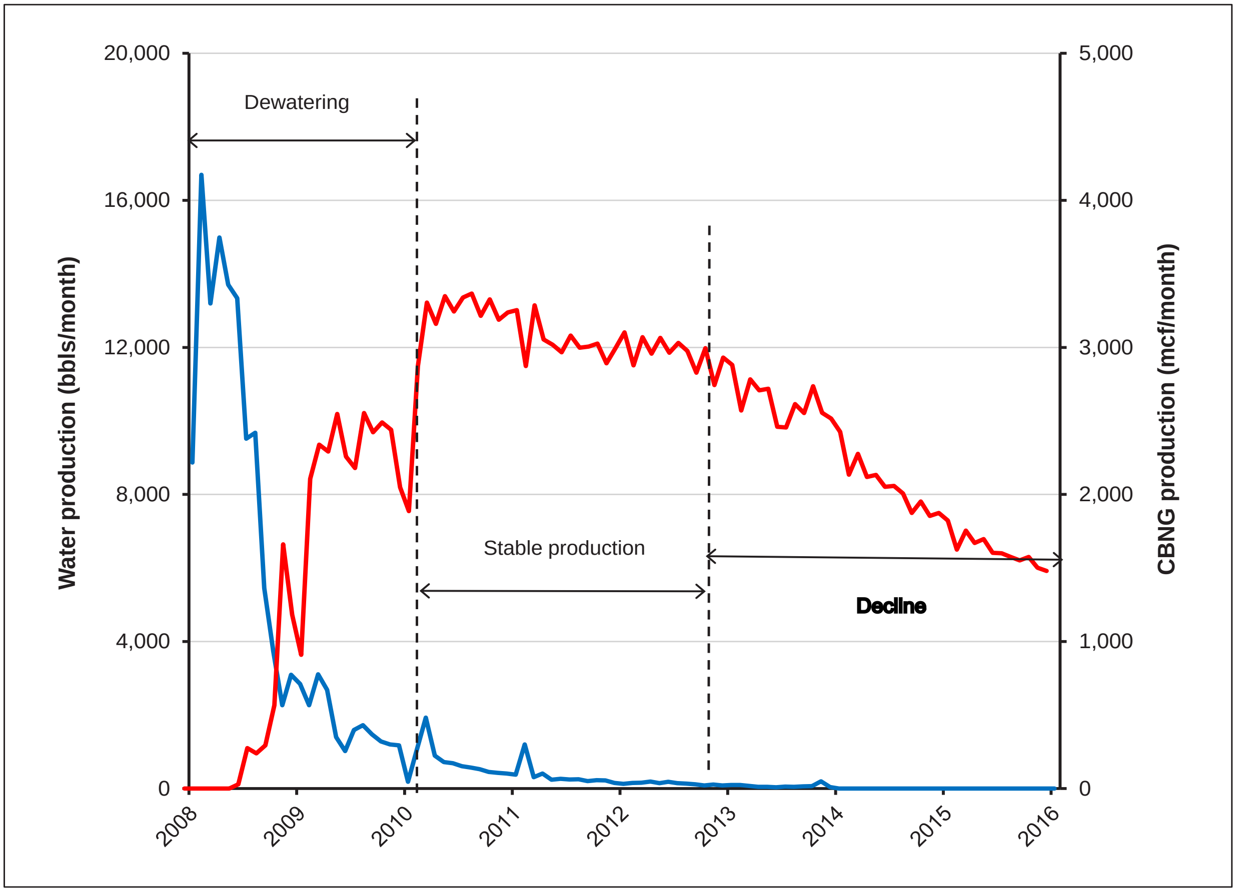

Figure 2. CBNG (in red) and water production (in blue) curves from the Hartzog Federal 32-31-4575BG well (API#-49-005-55783) located in the central PRB in Wyoming (WOGCC, 2016).

seam aquifers but extend, in some cases, to adjacent sandstone aquifers as well (Taboga and Stafford, 2014; Stafford and Wittke, 2013).

More than 36,000 CBNG wells have been drilled in the PRB. During peak development in 2008, more than 24,000 wells were producing (WOGCC, 2016). Over time, about 11,000 CBNG wells have been permitted for other uses, mostly as livestock wells (SEO, 2016; WDEQ, 2016). In comparison, nearly 14,000 permitted non-CBNG groundwater wells designated for domestic, municipal, agricultural, and/or livestock uses are completed in PRB aquifers (table 1); most of these water rights were granted prior to CBNG development. The impact that production has had on pre-development water levels in the sandstone aquifers that overlie the gas-rich coal zones is a concern

Table 1. Permitted non-CBNG groundwater rights grouped by depth of completion in the PRB (SEO, 2016). NR = no record.

	Depth (ft)						
Use	1-49	50-99	100-499	500-999	≥1,000	NR	Totals
Domestic	723	485	2,720	465	75	81	4,549
Municipal	0	0	7	3	7	11	28
Irrigation	5	2	6	0	9	4	26
Livestock	867	481	4,304	843	222	243	6,960
Multi-use	248	167	1,369	367	96	149	2,396
Totals	**1,843**	**1,135**	**8,406**	**1,678**	**409**	**488**	**13,959**

to many of the holders of these water rights (Bredehoeft, 2004; BLM, 2004).

Since the early 1990s, the BLM Field Office in Buffalo, Wyoming, has operated a network of groundwater monitoring well sites in the Wyoming portion of the PRB. This monitoring network, which currently includes 65 sites, collects groundwater level data from the Wyodak Rider (Big George), Upper Wyodak, Lower Wyodak, Cook, and Wall coal zones and sandstone aquifers. Under contract to the BLM, the Wyoming State Geological Survey (WSGS) reported groundwater level changes at the monitoring sites (Taboga and Stafford, 2014; Stafford and Wittke, 2013; McLaughlin and others, 2012; Clarey and others, 2010; Clarey, 2009). WSGS previously examined groundwater level recovery in the Upper Wyodak coal zone (Taboga and others, 2014).

This report examines GWL changes in the sandstone aquifers of the Wasatch and Fort Union Formations associated with coal seams that were developed for CBNG extraction. GWL changes in 58 sandstone wells located at 40 monitoring sites (fig. 3, table 2) are evaluated with respect to water production from CBNG development within 1 ½-mile radius buffer zones centered on each monitoring well site. Monitoring in the wells examined in this study began as early as 1992 and has continued into the present.

Special focus is placed on aquifer responses to recent declines in water production. Coal seam water production data were obtained from the WOGCC website, http://wogcc.state.wy.us/.

POWDER RIVER STRUCTURAL BASIN, WYOMING

Geologic Setting

The Powder River Structural Basin (PRB) is an elongate Laramide foreland basin that measures nearly 120 miles east to west by 200 miles north to south. In Wyoming, the basin is bound by the Black Hills, Hartville Uplift, Laramie Range, Casper Arch, and Bighorn Mountains. The Pryor Uplift, Porcupine Dome, and Miles City Arch flank the northern third of the basin in Montana (Thamke and others, 2014). The structural basin is asymmetric; it dips gently westward (~1.5°) from its eastern margin for about 90 miles to the basin's axis where it reaches its greatest depths (~18,000 ft below the surface). The axis is located within 10 miles of its western edge and generally parallels the ridge of the Bighorn Mountains.

Earliest formation of the structural basin likely occurred in the middle Paleocene when rapid subsidence (Curry, 1971) created Lake Lebo that was in-filled through fluvial, deltaic, paludal (marshy), and lacustrine sedimentation. During the middle through late Paleocene, the lake was filled by sediments deposited by fluvial-deltaic systems around the margins, forming the Tongue River Member of the Fort Union Formation (Ayers, Jr., 1986). Nearby orogenic uplifts constricted the basin and provided sediment sources for the coal-bearing formations in the upper part of the Tongue River Member. Eocene fluvial Wasatch Formation sediments occupy the center of the PRB axis, while the Paleocene lacustrine and fluvial-deltaic Fort Union Formation sediments crop out around the basin margins (Tyler and others, 1995).

The type of the depositional environment responsible for the formation of the PRB's extensive coal beds has been controversial. Interpreted depositional environments include northeastward-flowing fluvial systems of braided, meandering, and anastomosed streams in the basin center and alluvial fans at the basin margin (Flores and Ethridge, 1985), or bounded by backswamp and flood plain facies (Flores, 1986). Peat accumulated in low-lying swamps and raised mires, in fluvial flood plains, abandoned channels, and interchannel environments (Flores and others, 1999).

In contrast, Jones (2010) proposed a late Paleocene (60 million—55 million years ago [mya]) drainage system that included rivers and flowing channels but was dominated by an extensive palustrine (marshy) environment similar to the Pantanal wetlands in present-day Brazil, Bolivia, and Paraguay. During palustrine episodes, the low energy southwest to northeast flow gradient did not support effective clastic transport, and organic sediments formed as decaying vegetation collected below the water table under anoxic conditions. During wetter conditions, lacustrine environments prevailed as higher energy flows carried clastics from neighboring uplifts into the basin. Organic material decayed rapidly in the oxygenated waters, and clastic sediments formed.

Hydrostratigraphy

The Lower Tertiary Wasatch and Fort Union Formations, and Upper Cretaceous Lance Formation and Fox Hills Sandstone are the dominant stratigraphic units in the PRB (table 3). These units cover more than 93 percent of the bedrock surface area in the Wyoming portion of the PRB and reach a maximum combined thickness of more than 8,600 ft along the axis of the PRB just south of Crazy Woman Creek (Denson and others, 1995).

Sedimentary units underlying the Fox Hills consist of earlier Mesozoic- and Paleozoic-aged marine shales, sandstones, and carbonates total 6,800 to 10,000 ft thick.

Table 2. List of BLM groundwater monitoring site locations examined in this study.

County	Well site name	Location				Coal seam intervals	Completed sandstone intervals	Approximate elevation (ft)	Start date
		Qtr/Qtr	Section	Township	Range				
Campbell	20 Mile Butte	SE SE	32	52 N	74 W	Anderson	1	4,557	Jan-04
	21 Mile	NE NE	22	48 N	74 W	BG	1	5,037	Aug-01
	All Night Creek	NW SW	36	43 N	74 W	BG	4	5,220	Mar-01
	Bar 76	NE SE	1	45 N	73 W	Wyodak	1	4,768	Sept-97
	Barrett Persson	SW SW	32	47 N	73 W	Wyodak	1	4,945	Dec-00
	Beaver Fed	SE NW	23	47 N	75 W	BG	1	4,783	Apr-03
	Blackbird Coleman	SW SE	5	47 N	74 W	Wyodak	1	4,778	Jul-00
	Bowers	SE SW	36	42 N	72 W	Wyodak	4	5,018	Jan-98
	Cedar Draw	NE SW	2	51 N	75 W	Wall	1	4,268	Jan-04
	Dilts	SE NW	31	43 N	71 W	Wyodak	1	4,929	Mar-99
	Durham Ranch Section 6	SW NE	6	45 N	71 W	Wyodak	1	4,697	Nov-97
	Durham Ranch Section 14	SE NE	14	44 N	72 W	Wyodak	1	4,861	Jan-98
	Fourmile (4-Mile)	NW NE	11	43 N	75 W	BG	2	5,358	Nov-07
	Hoe Creek	SW SW	7	47 N	72 W	Wyodak	1	4,734	Jan-98
	Kennedy	SE SE	33	52 N	73 W	Anderson	1	4,489	May-00
	Lone Tree	SW SE	13	50 N	73 W	Wall	1	4,760	Feb-00
	MP 2	NW NW	2	47 N	72 W	Wyodak	1	4,554	May-93
	MP 22	SE NE	22	48 N	72 W	Wyodak	3	4,561	Feb-93
	Napier	SE SE	24	48 N	76 W	BG	1	4,803	May-01
	North Gillette	SW NE	34	51 N	73 W	Anderson	1	4,380	Sept-01
	Palo	SE NE	22	56 N	74 W	Canyon	1	4,141	Feb-01
	Redstone	SENW	26	53N	73W	Canyon	1	4,155	Oct-98
	Section 25	SW SW	25	46 N	72 W	Wyodak	1	4,659	Nov-96
	Stuart Section 31	NE SE	31	44 N	71 W	Wyodak	2	4,933	Aug-97
	Throne	NW NW	26	47 N	74 W	Wyodak	1	5,029	May-01
	West Pine Tree	SE SE	20	42 N	76 W	BG	1	5,181	Sept-07
	Williams Cedar Draw	NE SW	15	53 N	75 W	Smith, Anderson	2	4,130	Apr-07
	Wormwood	NE NW	14	46 N	76 W	BG	2	4,574	Dec-06
Johnson	Bear Draw	SW NW	1	50 N	79 W	BG	1	4,624	Mar-06
	Big Cat	SE SE	24	48 N	79 W	BG	1	4,480	Jul-03
	Buffalo SE (1)	NW NW	12	50 N	81 W	Smith	4	4,542	Aug-01
	Bull Creek	NW SE	12	52 N	77 W	Anderson	2	3,909	Nov-05
	Bullwhacker	NW SE	16	42 N	77 W	BG	1	5,050	Apr-02
	Juniper	SW SW	14	49 N	78 W	BG	2	4,428	Mar-01
	Rose Draw	NE SE	19	52 N	77 W	Wall	2	3,914	May-09
	Sasquatch	NE SW	12	48 N	77 W	BG	1	4,472	Jan-98
	Streeter	SE NW	22	43 N	78 W	BG	1	4,761	Aug-04
	Wild Turkey	NE SW	29	49 N	76 W	BG	1	4,344	Nov-04
Sheridan	L Quarter Circle Hills	NE SE	14	56 N	77 W	Cook	1	3,618	Apr-05
	Lower Prairie Dog	SE NE	10	57 N	83 W	Anderson	2	3,715	Aug-00

(1) The shallow sand monitoring well has flowed intermittently during this period of record (POR) and was not considered in this study.

Figure 3. Location of BLM sandstone monitoring well sites in the PRB in Wyoming.

Table 3. Dominant hydrostratigraphic units, their lithologic types, and thicknesses in the PRB in Wyoming. [a] Thamke and others (2014); [b] Love and Christiansen (1985); [c] Hallberg and Case (1999a, b), Reheis (2007), Reheis and Williams (2007), Reheis and Coates (2007); [d] Flores and Bader (1999), Flores and others (2010); [e] Denson and others (1994, 1995).

Age	Hydrogeologic unit[a]	Units[b]		Primary lithologic types[b]	Thicknesses
Quaternary	Undivided	Surficial deposits		Residum on bedrock, slopewash, alluvial, and terrace deposits along streambeds, weathered bedrock outcrops, scoria, scattered colluvium, and landslide deposits	Generally, 25 ft[c] or less. Up to 100 ft locally in some valley, alluvial, and landslide deposits
Tertiary	Lower Tertiary aquifer system	Wasatch Formation (Eocene)		Drab sandstones and claystones; thin coals.	to 2,775 ft[e]
		Fort Union Formation (Paleocene)	Tongue River Member	Thick yellow and gray sandstones; light gray to tan shales; thick coal seams	Up to 1,860 ft[d]
			Lebo Shale Member	Gray mudstones; concretionary sandstones; carbonaceous shales and thin coals	Up to 2,600 ft[d]
			Tullock Member	Gray sandstones, carbonaceous shales, and mainly thin coal seams	Up to 740 ft[d]
Cretaceous	Upper Cretaceous aquifer system	Lance Formation		Thick beds of sandstone, drab to green shale, and thin conglomerate lenses	700-2,475 ft[e]
		Fox Hills Sandstone		Light colored sandstone and gray sandy shales	125-700 ft[e]
Earlier Mesozoic and Paleozoic	Basal confining unit	Thick series of Upper Cretaceous shales (Pierre, Mowry, Belle Fourche, and Carlile), shaly carbonate units (Greenhorn and Niobrara Formations), and older sedimentary formations[b]		Mostly marine shales, sandstones, and carbonates	6,800-10,000 ft[e]

Denson and others (1994, 1995) determined the thickness of units in the PRB that overly the Pierre Shale.

The Wasatch and Fort Union Formations form the Lower Tertiary aquifer system, which is the most widely utilized source of groundwater in the PRB. Wells completed in the Upper Cretaceous Lance Formation and Fox Hills Sandstone aquifer system supply groundwater along the basin's margin. Both systems are capable of providing sufficient amounts of high-quality groundwater adequate to meet the needs of domestic, municipal, agricultural, and livestock users.

Knowledge of the lithostratigraphic complexity in the Fort Union and Wasatch Formations advanced significantly during CBNG development when borehole data from thousands of wells became available. Combining the CBNG data with geophysical logs from oil and natural gas wells and coal boreholes, Flores and others (2010) plotted vertical and lateral lithostratigraphic variations along 17 cross sections spanning the PRB. Coal seams in the Wasatch and Fort Union Formations are generally continuous, but split and merge frequently as they dip westward until they split into multiple thin veins and pinch-out in the western PRB. The occurrence, distribution, shape, and spatial extents of sandstone bodies vary widely. In the northern PRB, they appear to be relatively discontinuous and lenticular, whereas south of Gillette, they are more continuous, extending for 10 or more miles.

CBNG Water Production in the PRB

Produced water management quickly became a pivotal environmental issue during CBNG development in the PRB. During the early years of development, much of the water was legally discharged under National Pollution Discharge Elimination System (NPDES) permits to the nearest surface drainage. As the Wyoming Department of Environmental Quality (WDEQ) refined the NPDES permitting process, produced water discharges were regulated largely by watershed through the Watershed-based WYPDES Permitting Program (WDEQ, 2016). In addition, the WOGCC tracked CBNG and water production by drainage; see NRCS (2016) for an overview of the Watershed Boundary Dataset and Hydrologic Unit Code (HUC) System.

Significant CBNG development began in eastern PRB drainages, primarily in the Upper Belle Fourche subbasin, and progressed westward (fig. 4). Water production rates in eastern subbasins (Upper Belle Fourche, Little Powder, and Upper Cheyenne Rivers) were highest during 2000–2003, comprising 55–85 percent of all CBNG-produced water in the PRB. As development moved westward, water production increased in the Upper and Middle Powder Rivers

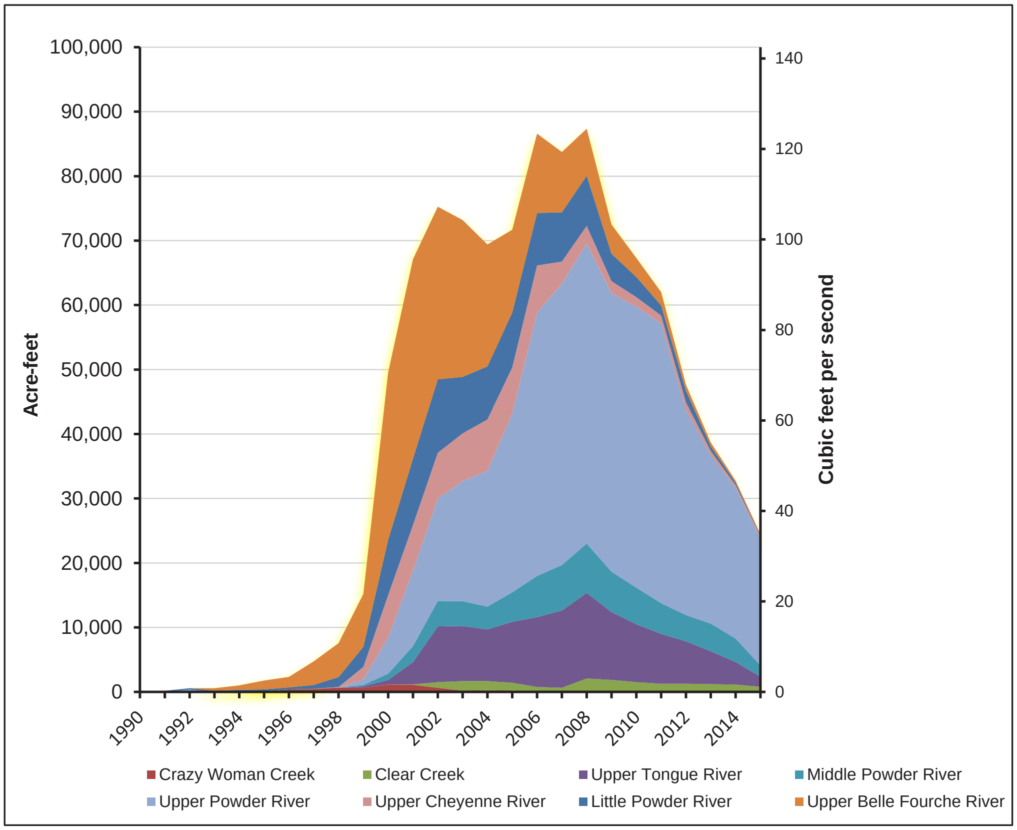

Figure 4. Cumulative area plot illustrating the temporal and geographic progression of annual water production in the PRB drainage subbasins (HUC 8s; WOGCC, 2016).

and the Upper Tongue River drainages through the early part of the decade, reaching peak levels in 2008. Water production from Wyodak coals in the Upper Belle Fourche and Big George coals in the Upper Powder River subbasin, respectively, account for the peak produced water volumes observed in 2002 and in 2006–2008. During 2015, CBNG water production dropped to 24,600 AF/year; 80 percent (19,697 AF) was produced in the Upper Powder River Basin drainage. In comparison, only 662 AF (2.7 percent) of the total was pumped from the once productive Upper Belle Fourche River, Little Powder River, and Upper Cheyenne River drainages of the eastern PRB.

Water production varied widely among subbasins within the PRB (fig. 5, upper plot). Water production rates normalized to subbasin surface area (fig. 5, lower plot) show that large volumes of produced water per square mile were extracted from the Upper Belle Fourche, Upper Powder, Middle Powder, and Upper Tongue Rivers subbasins. The low production rates in the Crazy Woman Creek and Clear Creek drainages resulted from WDEQ and SEO production restrictions that were imposed following a WSGS report outlining poor water-gas ratios in those drainages (Surdham and others, 2007).

Hydrogeology of the Lower Tertiary Aquifer System

The Fort Union and Wasatch Formations that comprise the Lower Tertiary aquifer system of the interior PRB provide groundwater for domestic, municipal, agricultural, and livestock wells. In eastern portions of the basin, some of these wells have been completed in coal seam aquifers where groundwater quality meets state and federal water standards. As CBNG development progressed into the PRB, produced water from CBNG wells was used increasingly to provide water to livestock throughout the basin. About 10,000 groundwater rights in the PRB list "CBM/Livestock" as the well use (SEO, 2016).

The PRB is a semi-arid basin; average annual rainfall ranges from 10–26 inches (PRISM, 2016). Estimated recharge from direct precipitation is about 0.2 in/year (Long and others, 2014). Regional groundwater flow in the PRB is to the north or northeast (Thamke and others, 2014). U.S. Geological Survey (USGS) data obtained from numerous wells shows wide ranges in hydraulic parameters and total dissolved solids (TDS, table 4).

Thorough descriptions of the hydrogeology of the PRB can be found in recent studies by the USGS (Thamke and

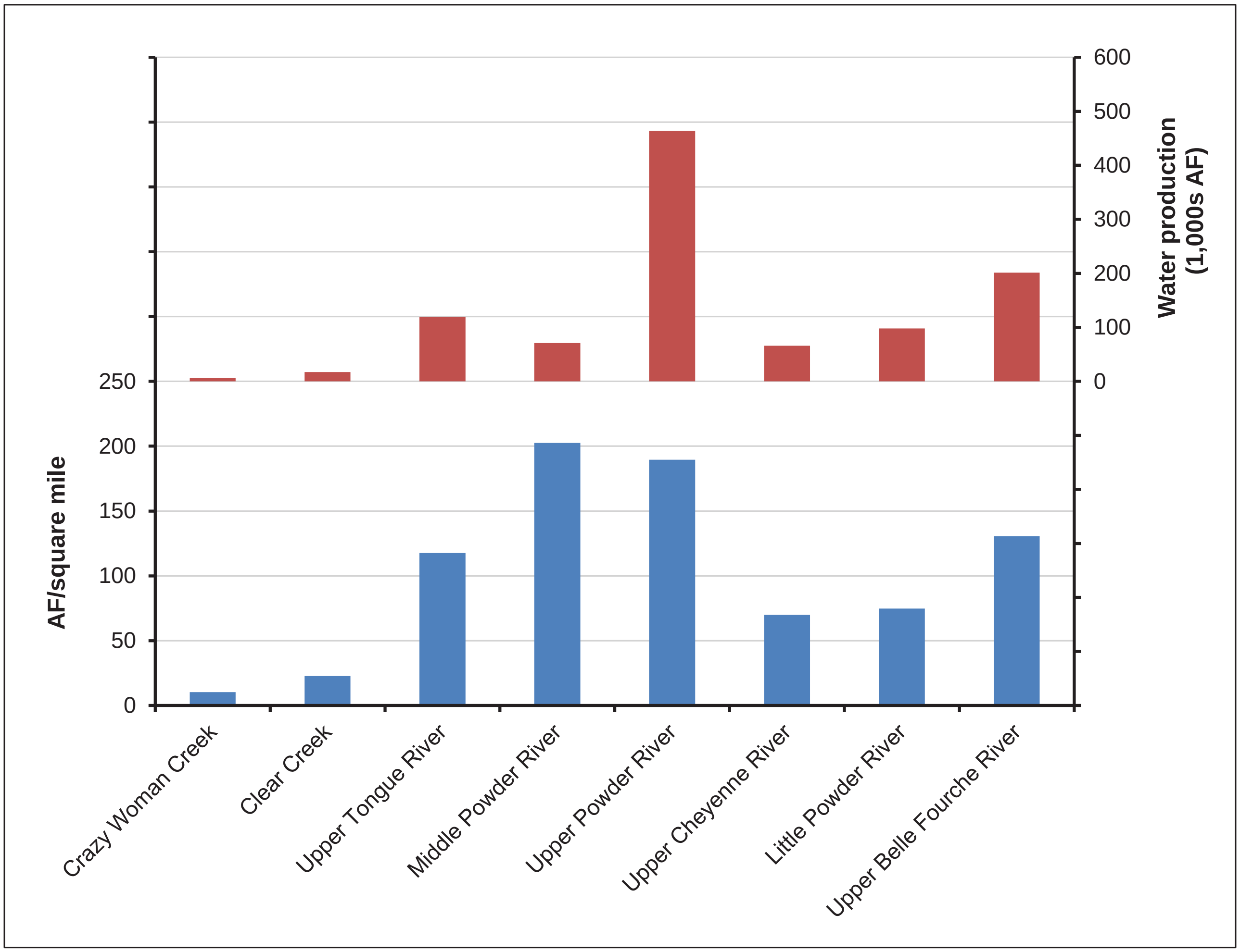

Figure 5. Bulk CBNG water production (in red) in AF and CBNG water production by unit area (in blue) in AF/square mile for principal drainages in the PRB in Wyoming (WOGCC, 2016).

others, 2014; Long and others, 2014). Both studies can be downloaded from the USGS Publications website.

Factors that Affect Water Level Responses to Pumping and Recovery

Numerous factors influence the manner in which GWLs in a well respond to pumping and subsequent recovery. Aquifers are complex environments where physical, spatial, and hydraulic characteristics are highly variable (anisotropic). Hydraulic properties are specific to the well site being tested and, in some cases, can only be estimated from measurements obtained during pump and recovery tests (Fetter, 2001). Factors that can affect drawdown and recovery include:

- Design and completion of the production wells: number of wells and locations
- Stratigraphic variations
- Production history: pumping rates, volumes, and duration
- Groundwater production from contiguous areas
- Type of aquifer(s) in which well is completed
- Local and regional groundwater flows
- Type, amount, and timing of recharge
- Hydraulic communication with adjacent hydrogeologic units
- Flow boundaries
- Geologic structure
- Presence of surface water bodies
- Variations in permeability and porosity including the presence of fractures

Table 4. Summary hydraulic and water quality data for Lower Tertiary and Upper Cretaceous aquifer systems in the PRB in Wyoming (adapted from Hallberg in Taboga and others, in press).

Aquifer	Well yield		Specific capacity		Transmissivity		TDS
	Count	Range (median) [gal/min]	Count	Range (median) [(gal/min)/ft]	Count	Range [ft²/day]	Range [mg/L]
Lower Tertiary aquifer system							
Wasatch aquifer	548	0.1–1,470 (7)	290	0.004–350 (0.19)	6	5.4–295	1,105–3,376
Fort Union aquifer	592	0.25–1,500 (10)	230	0.003–2,200 (0.39)	90	1.3–1,330	225–167,200
Coal seam aquifers	------						97–4,589
Upper Cretaceous aquifer system							
Lance aquifer	194	0.75–300 (10)	54	0.01–1.8 (0.24)	15	13.5–281	1,102–47,910
Fox Hills aquifer	46	2–5,000 (10)	23	0.03–4.9 (0.25)	3	214–324	325–6,758

When a production well is pumped at a constant rate, the pressure head will be depressed around the pumping well. An idealized plot of drawdown and recovery as a function of time (Theis, 1935) for an observation well located 1,000 ft from a typical CBNG production well is shown in figure 6 (Taboga and others, 2014). The general shape of the idealized curves is readily apparent in several of the monitoring well hydrographs shown in the appendix of this report. Others show near linear recovery phases or, in some cases, continued GWL declines even though water production was stopped years earlier. The unpredictable nature of groundwater response at these monitoring sites is due to the fact that producing CBNG well fields operate within highly variable environments. Wide variations in aquifer hydraulic properties, stratigraphy, geologic structure, and groundwater recharge and discharge occur in the PRB over local and regional scales.

The operation of a CBNG field is also complex. Water production rates at well fields are not constant but vary widely over time in response to market and operational conditions. The depression of the potentiometric surface in a CBNG well field is rarely a smooth radial cone but is, instead, a highly irregular surface that is the result of many irregularly spaced wells pumping at highly fluctuating rates over various periods of time. In short, the water level changes observed at the monitoring wells in this report occurred within complex and constantly fluctuating environments.

Methods

This study looks at groundwater level responses in selected BLM monitoring wells completed in sandstone intervals with the objectives of:

- Assessing maximum water level changes observed during CBM development in the PRB in relation to geographic location, proximity to developed coal seams, and depth of the completed interval
- Evaluating aquifer water level responses to decreased water production

WSGS obtained and reviewed manual and automated water level time series from the BLM for 58 sandstone monitoring wells. The complete dataset is available from the Wyoming Geographic Information Science Center's Wyoming GeoLibrary at http://wygl.wygisc.org /wygeolib/catalog/main/home.page. Selection criteria included a relatively complete record of more or less quarterly manual GWL measurements from inception of monitoring through 2015, the continuous presence of groundwater in the wellbore of sandstone monitoring wells, and an intact WOGCC water production history for CBNG wells within a 1 ½-mile radius during the monitoring period of record (POR).

After reviewing the available groundwater level data, WSGS decided to use only manual depth to groundwater (DGW) level measurements in this study. The use of pressure transducers and data loggers to monitor DGWs requires periodic inspection and calibration to ensure the acquisition of accurate data (Bear Draw Unit, MP2, and MP22). Even then, transducer malfunctions can result in spurious readings (Throne and Durham Ranch Section 6) and lost data. In some cases, automated monitoring was suspended while manual measurements continued (West Pine Tree and Palo). Lastly, automated monitoring equipment is usually calibrated to concurrent manual measurements.

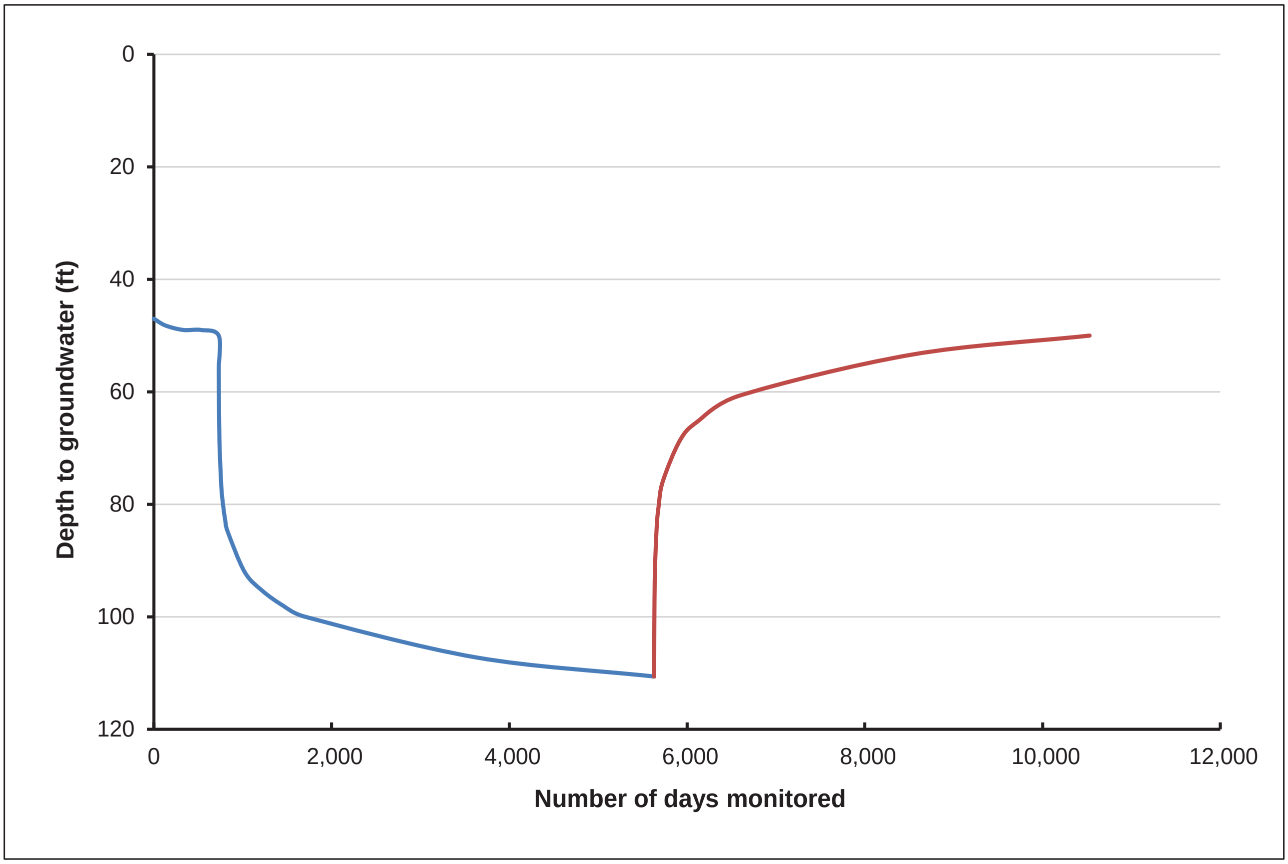

Figure 6. Idealized drawdown (blue) and recovery (red) curves for an observation well sited 1,000 ft from a single CBNG production well (Taboga and others, 2014).

WOGCC provided monthly water production rates for CBNG wells in the PRB. WSGS correlated water production volumes to specific coal zones, where possible. Water production from wells completed in several coal zones was assigned to "multiple" zone production. WSGS created an "unmonitored" classification for wells where the production zone was ambiguous or identified in the WOGCC database by formation (e.g. Fort Union) and not by coal seam.

WSGS previously generated maps of CBNG production zones (Stafford and Wittke, 2013; McLaughlin and others, 2012) within a 1 ½-mile radius of the BLM monitoring wells using ArcGIS® Geographical Information System (GIS) software by ESRI®. Once CBNG wells were identified within each zone, monthly water production data through 2015 were downloaded from the WOGCC website, http://wogcc.state.wy.us/, and monthly aggregated water production rates were calculated for each zone. Monitoring sites were determined to be in "producing" zones if CBNG well water production exceeded 1,000 bbls/month later than June 2015; monitoring well sites that did not meet this criteria were considered to be sited in "nonproducing" zones.

All data were downloaded, reviewed, and evaluated in Microsoft Excel®. Maximum water level changes were determined from manual DGW measurements for each sandstone monitoring well. Maximum changes in DGW were compared to the well's depth of completion and the vertical distance of the monitored sandstone from the nearest monitored coal seam. Rates of change (recovery or decline) in DGW were evaluated during calendar years 2013–2015 for well sites located in producing zones. DGW recovery or decline rates were calculated from the month that water production ceased for well sites in nonproducing zones.

RESULTS

WSGS evaluated water level data collected by the BLM at 58 sandstone wells and 41 associated coal seam wells located on 40 selected monitoring well sites (fig. 3). Several of the sites monitor multiple sandstone and coal strata through the use of nested wells, wellbore packers, or a combination of the two. Detailed information regarding well completion zones and depths, CBNG gas and water production rates, interburden thicknesses, and area CBNG wells can be found in Taboga and Stafford (2014). Well hydrographs (figs. A1-1 through A1-40) and tabular data (tables A1-1 through A1-3) for all well sites are included in the appendix of this report.

Monitoring the selected wells began as early as 1993 (MP2 and MP22) and as recently as 2009 (Rose Draw). Water level monitoring has continued at most wells into 2016, but was discontinued earlier in some wells at monitoring sites with multiple wells (All Night Creek, Beaver Creek, Bowers, and Buffalo SE). Manual DGW measurements were made more or less on three-month intervals in most wells but less frequently in others (Palo, Dilts, and West Pine Tree). Manual measurements were not made in cases where the field technician's safety was compromised by dangerous weather or high wellbore gas pressures, where access to the well was restricted by the landowner, or when obstructions in the wellbore prevented measurement.

Initial measurements obtained prior to the onset of water production within the associated 1 ½-mile radius buffer zone (Bear Draw, Big Cat, Hoe Creek, Juniper, Rose Draw, Sasquatch, Stuart Federal, and Wild Turkey) show relatively stable coal seam groundwater levels comparable in depth to water levels in associated sandstones. Coal seams at some well sites (Bar 76, Napier, Section 25, and Streeter) exhibit moderate water level declines prior to the onset of water production within the buffer zone likely due to CBNG development outside the buffer zone. Predevelopment water levels are unavailable at well sites where monitoring began after water production had started (Palo, Throne Ranch, and Williams Cedar Draw). At the Blackbird Coleman site, groundwater levels in the Wyodak coal seam rose briefly following the onset of CBNG development.

Table A1-1 summarizes changes in GWL and water production data for various times and periods of record at all 40 monitoring well sites. The table lists initial GWLs, maximum changes from initial levels, and final changes from initial levels observed during 2015. Volumes and dates of maximum water production are also shown for corresponding coal seams.

Maximum Groundwater Level Changes

Maximum groundwater level changes in sandstone wells over their respective PORs ranged from a 36-ft water level rise at West Pine Tree to a 538-ft decline at Cedar Draw (table A1-1). The average change for all sandstone wells is -82 ft (decline) with a median of -11.5 ft. The large difference between the average and median is driven by large drawdowns of 200 ft or more in 12 sandstone wells. When these high drawdown wells are removed, average (-14 ft) and median (-9 ft) water level changes compare more favorably. In comparison, maximum groundwater level changes in coal seam monitoring wells range from 16 to 1,446 ft of decline. For all coal seam monitoring wells, the average decline is 432 ft, and the median decline is 316 ft.

Maximum groundwater level changes vary widely across the Powder River Basin, apparently independent of monitoring site location (fig. 7). GWL responses may differ markedly by depth at well sites monitoring multiple sandstones (Juniper, MP22, Rose Draw, Stuart Sec 31, and Wormwood), although these variations do not exhibit consistent trends with increasing depth. For example, water level declines in the four sandstone wells at the Bowers site vary only slightly (from -12 to -30 ft) even though their depths of completion range from 73 to 558 ft. In contrast, maximum water level variations at the All Night Creek and Buffalo SE sites consist of both declines and rises with increasing depth (fig. 7).

WSGS examined the relationship between the maximum observed groundwater level change and the vertical separation between the monitored sandstone unit and nearest monitored coal seam (fig. 8). The largest variations (-538 to 11 ft) occur in sandstones separated from the nearest monitored coal seam by less than 200 vertical ft. All of the high decline (>-200 ft) wells fall within this minimum separation interval. Using many of the same wells as this study, Ross and Zoback (2008) attributed this relationship to vertical hydraulic communication between some narrowly separated sandstone and coal seam wells. GWL rises in three sandstone wells (All Night Creek #4, Buffalo SE #4, and Redstone), and moderate declines (<100 ft) in 13 other wells within this thin separation interval likely point to wide variations in the occurrence of interbedding between sandstones and shales in the Wasatch and Fort Union Formations. GWL changes in wells separated from a monitored coal seam by more than 200 ft range from -42 to 36 ft.

Maximum GWL changes varied by depth of the sandstone unit as well. The largest changes (-538 to 11 ft) are seen in wells completed at depths greater than ~600 ft below ground surface (bgs), including all wells with GWL declines of 200 ft or more (fig. 9). Thus non-CBNG wells completed at depths of 600 ft or more (about 20 percent of all non-CBNG wells; table 1) are at greatest risk of being significantly impacted. The greater impact to deep wells was predicted early by hydrogeologists and federal agencies during the CBNG development period (Bredehoeft, 2004; BLM, 2004). In shallower wells (mid-depths of completion less than ~600 ft bgs), GWL changes range from -84 to 36 ft.

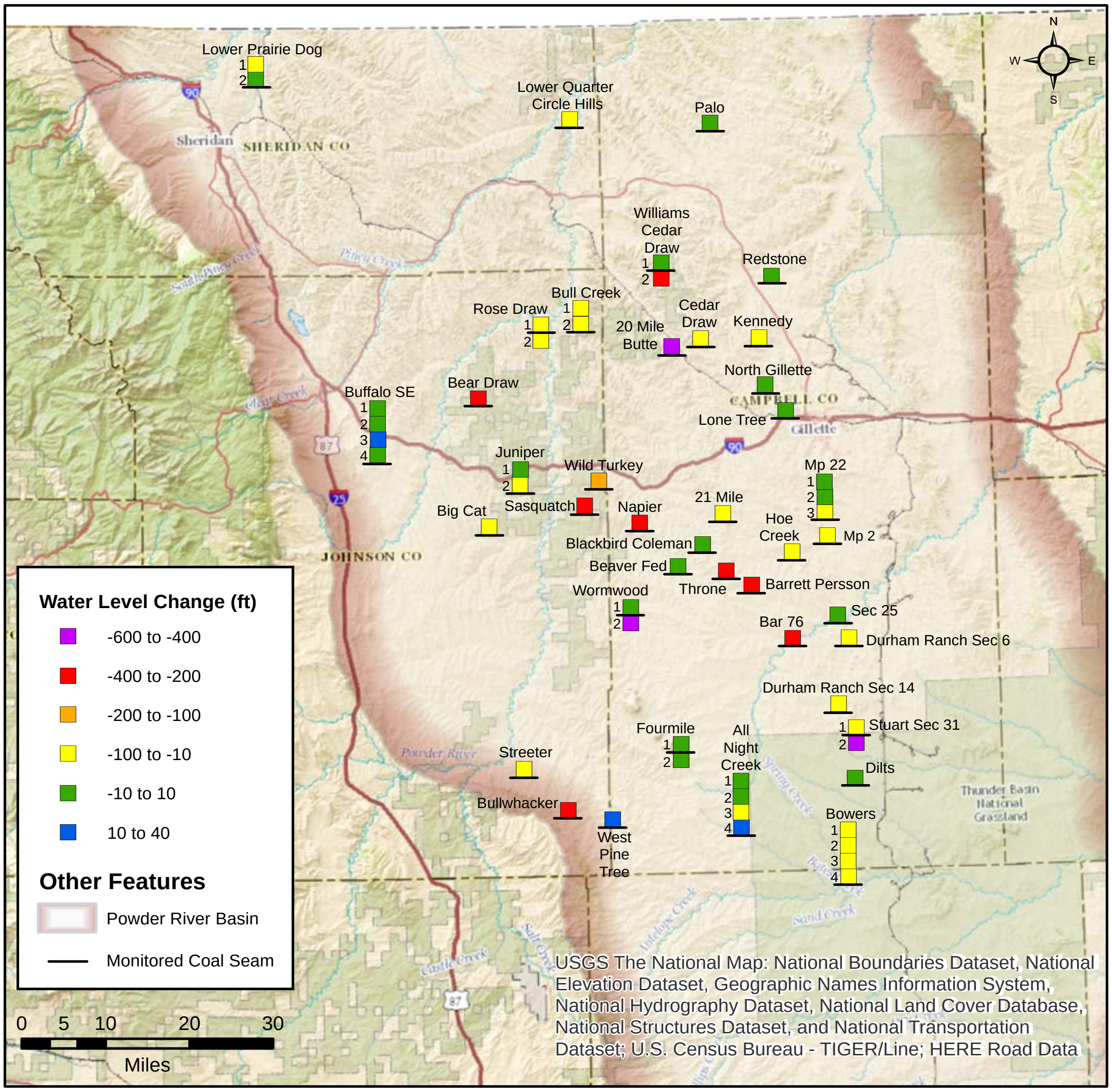

Figure 7. Maximum groundwater level changes observed at 40 BLM sandstone monitoring sites. Negative numbers represent GWL declines; positive numbers indicate rises in GWL. A stacked column indicates multiple sandstone wells are operating at the site (in order of depth, shallowest sandstone interval at top of column, and deepest interval at bottom). Black bar in each column indicates relative stratigraphic position of monitored coal seam(s).

The two factors, narrow separation interval and deep well completion, shown by the scatter plot analysis are predictive of impact to sandstone GWLs. Twelve of 18 wells that meet both criteria had GWL declines of 200 ft or greater. The remaining six wells (All Night Creek #4, Fourmile #2, Buffalo SE #4, Bull Creek #1, Durham Ranch 14 #1, and Rose Draw #2) showed GWL declines of less than 100 ft.

Rates of Groundwater Level Change

Annual rates of groundwater level change (fig. 10) are listed separately for producing (table A1-2) and nonproducing (table A1-3) sites. Rates of change were calculated during calendar years 2013–2015 for well sites located in producing zones and from the month that water production ceased for well sites in nonproducing zones. The largest variation in annual rate of change is observed in wells separated from a monitored coal seam by less than 200 ft. As expected, the highest rates of annual GWL decline occur in wells sited in producing zones (Bear Draw, Napier, and Wormwood). Some wells in nonproducing zones exhibit less than 10 ft/year (20 Mile Butte, Bull Creek, and Rose Draw).

The magnitude and shape of GWL responses observed at well sites in nonproducing zones provide a general predic-

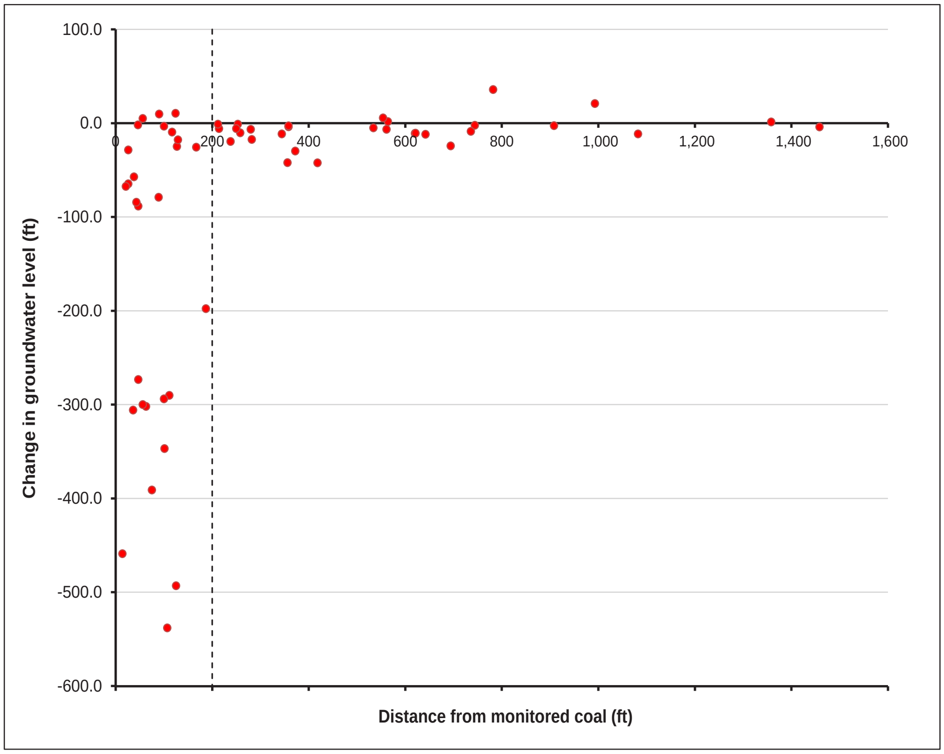

Figure 8. Scatter plot of change in GWL with time versus vertical separation (ft) between sandstone and coal. Negative numbers represent GWL declines; a positive number indicates rise in GWL. Dashed line represents 200 ft separation distance.

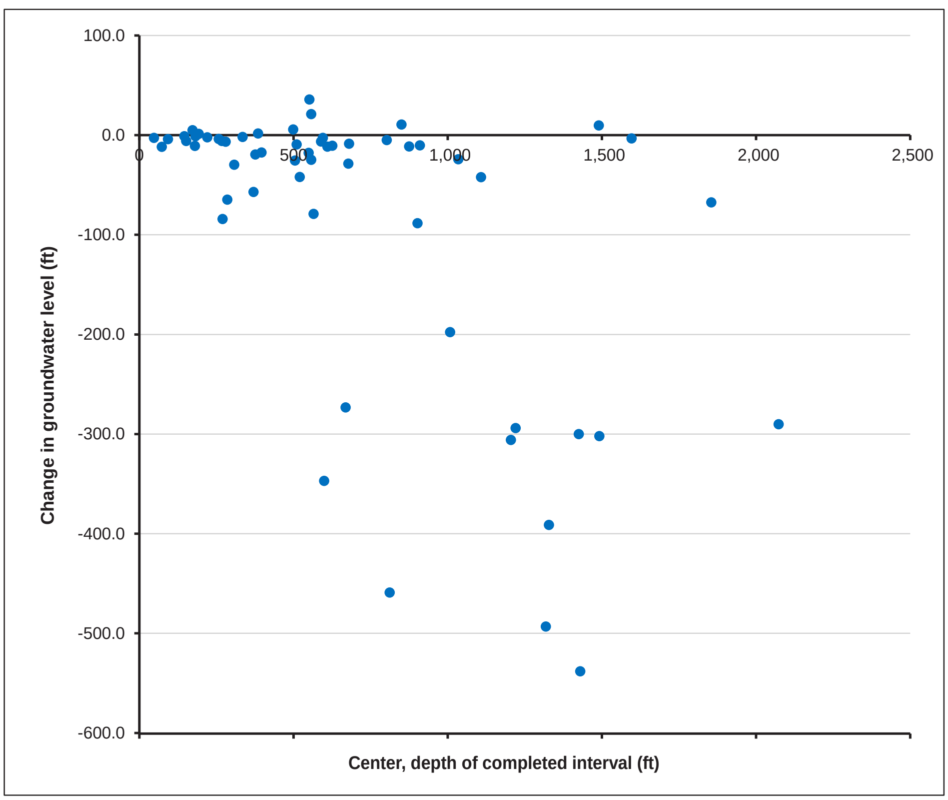

Figure 9. Scatter plot of change in GWL with time versus center of the depth of completed interval (ft) in sandstone monitoring wells. Negative numbers represent GWL declines; a positive number indicates rise in GWL.

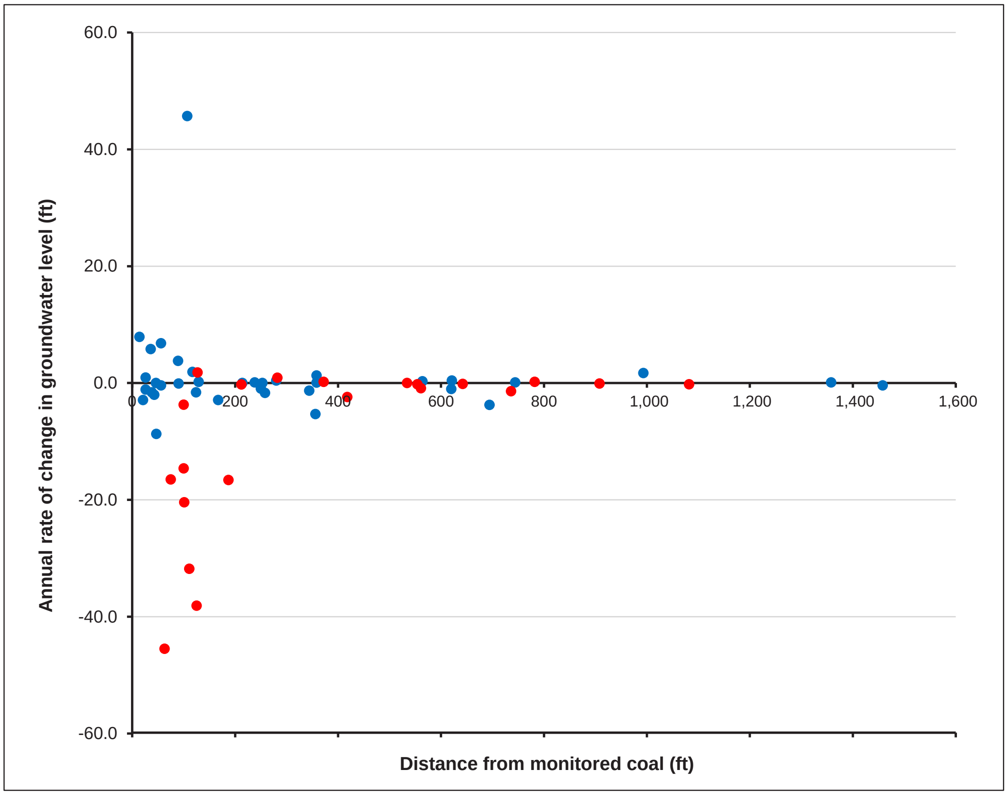

Figure 10. Scatter plot of annual rates of change in GWL (in ft) for monitored sandstone wells sited in producing (red) and nonproducing (blue) zones. Negative numbers represent GWL declines; a positive number indicates a rise in GWL.

tion of expected water level recovery in the PRB as CBNG production continues to decline. Mean rate of GWL recovery in all nonproducing zones is 1.2 ft/year. The highest rate of recovery (averaging 46 ft/year from 2013-2015) occurs at the Cedar Draw monitoring site. GWLs in the sandstone monitoring well there closely follow those in the coal seam (fig. A-8), suggesting a high degree of hydraulic communication. However, the rate of recovery at Cedar Draw is not linear but has slowed with time (fig. 7); recovery rates have dropped from 68 ft/year during 2013 to 25 ft/year in 2015. The sandstone well at Throne Ranch (fig. A1-36) exhibits a similar recovery curve. Other sandstone well sites in nonproducing zones exhibit linear recoveries (Stuart Section 31 and Barret Persson), continued linear declines (Bull Creek, MP22, All Night Creek #4, and Durham Ranch Section 6), or stable GWLs (Kennedy). Finally, excepting the Cedar Draw site, rates of GWL change at nonproducing well sites within the 200-ft separation interval range from -8.7 ft/year (Bull Creek) to 7.9 ft/year (Stuart Section 31); average rate of change in these wells is 0.4 ft/year.

CONCLUSION

The Wyoming State Geological Survey (WSGS) examined groundwater level time series from 58 selected sandstone monitoring wells obtained by the U.S. Bureau of Land Management (BLM) through manual measurements collected more or less every three months. For this report, the WSGS looked at groundwater level responses in the selected wells with the objectives of:

- Assessing maximum water level changes observed during CBM development in the PRB in relation to geographic location, proximity to developed coal seams, and depth of the completed interval
- Evaluating aquifer water level responses to decreased water production within a 1 ½-mile radius buffer zone of each BLM monitoring well

Maximum changes in GWL in the monitored wells ranged from a 538-ft decline to a 36-ft (rise); the average change for all sandstone wells was -82 ft (decline) with a median value of -11.5 ft. The large disparity between the mean and median values is driven by 12 sandstone wells with large GWL declines (-197 to -538 ft). Scatter plot analysis revealed these highly impacted wells are completed within 200 vertical ft of the nearest monitored coal seam at depths greater than 600 ft. Six other wells (All Night Creek #4, Fourmile #2, Buffalo SE #4, Bull Creek #1, Durham

Ranch 14 #1, and Rose Draw #2) meeting both completion criteria showed GWL declines of less than 100 ft.

Scatter plot analysis revealed annual rates of GWL decline are higher for monitoring well sites located in producing zones, as expected. The average rate of GWL recovery for sandstones in nonproducing zones is 1.2 ft/year. Average annual rates of change at nonproducing sites ranged from a decline of 8.7 ft/year at Bull Creek (during 2012–2015) to a 46 ft/year rise (during 2013–2015) at Cedar Draw since the cessation of water production.

The GWL data collected at the selected BLM sandstone monitoring well sites indicates:

1. Sandstone units located 600 ft bgs and within 200 ft of a producing coal seam were most likely to undergo large (>200 ft) GWL declines. In comparison, GWLs were relatively unaffected in sandstones positioned more than 200 ft from a producing coal seam.

2. GWL response is unpredictable once water production in a particular area has ceased. With the exception of the Cedar Draw site, GWLs exhibited modest recoveries of less than 10 ft/year or continued declines of similar magnitude for years following the end of water production.

DISCUSSION

As expected, groundwater levels in some of the study's monitoring wells are substantially impacted by water production from coalbed methane wells in the surrounding areas (figs. A-1 through A-40). Other sources and discharges of groundwater that may also impact monitoring well water levels should be considered, although a detailed analysis of these is beyond the scope of this report.

Recharge Variation

Variations in recharge rates likely affect groundwater level recovery rates at some monitoring sites. However, actual recharge contributions to coal seams and deep sandstones (figs. A-1 through A-40) are likely obscured by groundwater level changes resulting from variations in water production and sampling frequency of the monitoring wells. In contrast, water levels in the sandstone well at the 20 Mile site (fig. A1-1) apparently respond to seasonal recharge. Limited seasonal responses of one foot or less are observed in the shallowest sandstone wells at the MP 22 (fig. A1-26) and Redstone (fig. A1-26) sites when the hydrographs are viewed at small scale. All three sites are located along the eastern edge of the PRB in close proximity to recharge areas.

Furthermore, typical of semi-arid structural basins in Wyoming, the amount of recharge from precipitation is low in much of the PRB. Mathematical models by the USGS (Long and others, 2014) and WSGS (Taboga and Stafford, 2016) estimate average annual recharge in the PRB at about 0.2 inches, which would result in a groundwater level rise of one inch in a sandstone with a porosity of 20 percent. Finally, the recharge areas for the coal seams and the associated deep sandstone aquifers are of limited areal extent and located along the eastern PRB (Taboga and others, 2014, fig. 7), many miles from the monitoring wells. Upon infiltrating into an aquifer, the fixed amount of recharge is distributed within an increasingly large volume of aquifer matrix as it flows down gradient to the point that the resultant change in groundwater level at a distant well site may be undetectable.

Producing Water Wells

SEO records indicate that approximately 350 non-CBNG groundwater wells are sited within the buffer zones of the monitoring well sites examined in this report. Most wells provide water for livestock (159), domestic supplies (52), miscellaneous uses (62), irrigation (4), industry (7) or a combination of these uses (58). One Fort Union municipal well owned by the City of Gillette is located near the Lone Tree monitoring well site. The industrial wells and many of the miscellaneous use wells are owned by oil and gas production and coal mining companies.

It is unlikely that the small groundwater withdrawals for domestic and livestock uses would substantially impact water levels in the BLM monitoring wells. Per capita domestic water use in the PRB is estimated at 150–300 gallons per day (HKM, 2002), or 4–8 bpd. Thus, a household with a family of four would require 16–32 bpd. Groundwater withdrawals from livestock wells are difficult to quantify but are probably small as well. Withdrawals depend on the type of pump used (windmill or electric), the number of livestock served, the receiving unit (stock tank or reservoir), and seasonal watering duration. Furthermore, nearly 75 percent of the stock wells located near the monitoring well sites in this study were permitted before 1995 when substantial CBNG water production began.

On the other hand, the large withdrawals typical of irrigation, industrial, and miscellaneous wells may impact groundwater levels. Satellite imagery on Google Earth™ indicates that the four irrigation wells located near the monitoring sites were all permitted before 1969 and have been inactive since 1994 (Google Earth, 2017). In contrast, many of the miscellaneous use permits located near the monitoring well sites are for multiple coal dewatering wells with permitted yields of up to 1,500 gpm and may still be in use. Coal mine dewatering may account, in part, for the post-production water level declines observed in the Wyodak Coal monitoring wells at the MP 2 and MP 22 sites (Taboga and others, 2014).

Injection Wells

WOGCC records indicate that the Hoe Creek and Durham Ranch Sec. 14 monitoring well sites each have one active injection well located within their 1.5-mile buffer zones. Both wells are more than 11,000 ft deep and inject into the Paleozoic Minnelusa Formation, which is hydraulically isolated from the Wasatch/Fort Union aquifer system by approximately 4,000 ft of shales in the Upper Cretaceous confining unit (Thamke and others, 2014). Assuming that these wells are properly constructed, it is highly unlikely that injections of even very large volumes of produced water into the Minnelusa aquifer would have any impact on groundwater levels in the Wasatch/Fort Union sandstones.

Produced Water Discharges to Unlined Water Storage Pits and Stream Drainages

During CBNG development, one common method of produced water management was storage in unlined on-channel pits. Many of the storage pits were constructed by making improvements to existing on-channel stock water ponds; others were newly built along the channels of nearby ephemeral streams. Construction of these containment units was regulated by the SEO, while produced water discharges into them were regulated by the Wyoming Department of Environmental Quality. Substantial portions of these discharged waters infiltrated into shallow aquifers (Healy and others, 2008; Brinck and Frost, 2007).

A review of historic satellite imagery on Google Earth™ indicated that many of the buffer zones that encompass the monitoring wells examined in this study contained unlined water storage pits and on-channel livestock reservoirs. Infiltration from these types of storage units may account for groundwater level rises of several feet in shallow sand aquifers at the Section 25 and Bowers well sites, but similar sands at other monitoring sites (All Night Creek, Buffalo SE, L Quarter Circle Hills, MP 22) appear to be unaffected.

Water Quality

The BLM has not conducted water quality monitoring in any of the monitoring wells included in this report or in the agency's regional groundwater monitoring updates (Taboga and Stafford, 2014; Stafford and Wittke, 2013). However, the Gillette Area Groundwater Monitoring Organization has monitored groundwater levels and water quality in a large number of industry monitoring wells associated with coal mining in the eastern PRB. Also, the USGS conducted extensive water quality testing of selected SEO monitoring wells in the PRB during the early 2000s (Bartos and Ogle, 2002). Interested parties should contact these agencies and organizations directly.

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Appendix

Tables in Appendix

Table A1-1 summarizes depth to groundwater, monitoring dates, and water production information for each monitoring well site discussed in this report. Tables A1-2 and A1-3 list recent trends in groundwater levels observed at sites where CBNG production has been discontinued or is ongoing, respectively.

Table A1-1. Summarizes depth to groundwater, monitoring dates, and water production information for each monitoring well site discussed in this report.

				GWL change (ft)		Water production		
Monitoring well site name	Monitored unit	Depth to monitored unit (ft - bgs)	Period of record monitored	Initial depth to GW (ft)	Maximum during POR [date]	Period of recorded water production	Maximum water production (bbls/month) [date]	Average production during 2015 (bbls/month)
20 MILE BUTTE	Anderson Coal	896	Jan 2004 - Mar 2016	545	-161 [Nov 2013]	Apr 2001 - Feb 2015	57,681 [Nov 2001]	450
	Sandstone 1	500	Jan 2004 - Mar 2016	363	-42 [Jan 2006]	-------	-------	-------
21 MILE	Big George Coal	1278	Aug 2001 - Nov 2015	627	-270 [Nov 2015]	Apr 2002 - Aug 2015	60,017 [Oct 2006]	0
	Sandstone 1	799	Aug 2001 - Mar 2016	533	-10 [Nov 2015]	-------	-------	-------
ALL NIGHT CREEK	Big George Coal	984	Mar 2001 - Nov 2007	440	-620 [Nov 2007]	Sept 2000 - Dec 2015	472,319 [Dec 2002]	4
	Sandstone 1	200	Mar 2002 - Jan 2016	95	-2 [Nov 2010]	-------	-------	-------
	Sandstone 2	350	Mar 2002 - Jan 2016	201	2 [Apr 2011]	-------	-------	-------
	Sandstone 3	580	Mar 2002 - Jan 2016	252	-11 [Jan 2016]	-------	-------	-------
	Sandstone 4	840	Mar 2001 - Jan 2016	321	0 [Mar 2001]	-------	-------	-------
BAR 76	Wyodak Coal	726	Sept 1997 - Feb 2016	162	-616 [Feb 2008]	Oct 2001 - Nov 2013	284,679 [July 2002]	0
	Sandstone 1	659	Sept 1997 - Feb 2016	176	-273 [Oct 2015]	-------	-------	-------
BARRETT PERSSON	Wyodak Coal	1266	May 2001 - Feb 2016	826	-215 [Jun 2008]	Nov 1999 - Nov 2013	1,139,396 [Feb 2000]	0
	Sandstone 1	1180	May 2001 - Feb 2016	508	-306 [Feb 2011]	-------	-------	-------
BEAR DRAW	Big George Coal	2205	Mar 2006 - Mar 2016	499	-778 [Jun 2015]	May 2005 - Dec 2015	194,637 [May 2011]	47,262
	Sandstone 1	2052	Mar 2006 - Mar 2016	494	-290 [Mar_2016]	-------	-------	-------
BEAVER FED	Big George Coal	1186	Aug 2003 - May 2009	402	-433 [May 2009]	Jun 2006 - Dec 2015	141,699 [Jan 2007]	35,418
	Sandstone 1	552	Aug 2003 - Jan 2016	246	-7 [Jan 2016]	-------	-------	-------
BIG CAT	Big George Coal	1970	July 2003 - Mar 2016	200	-1424 [Mar 2016]	May 2004 - Dec 2015	446,647 [Jul 20040]	52,447
	Sandstone 1	862	July 2003 - Mar 2016	357	-11 [Nov 2008]	-------	-------	-------
BLACKBIRD COLEMAN	Wyodak Coal	1426	July 2000 - Mar 2016	371	-184 [Mar 2016]	Jul 2010 - Dec 2015	180,049 [Jul 2004]	898
	Sandstone 1	670	July 2000 - Mar 2016	251	-9 [Mar 2016]			

Table A1-1. Continued.

Monitoring well site name	Monitored unit	Depth to monitored unit (ft - bgs)	Period of record monitored	GWL change (ft) Initial depth to GW (ft)	Maximum during POR [date]	Water production Period of recorded water production	Maximum water production (bbls/month) [date]	Average production during 2015 (bbls/month)
BOWERS	Wyodak Coal	722	Jan `1998 - Jan 2005	420	-234 [Jan 2005]	Jul 1998 - Nov 2015	244,670 [Mar 2001]	24,421
	Sandstone 1	65	May 2002 - Feb 2016	60	-12 [Jan 2005]			
	Sandstone 2	265	May 2002 - Feb 2016	257	-30 [Dec 2005]			
	Sandstone 3	352	May 2002 - Feb 2016	301	-17 [May 2012]			
	Sandstone 4	520	Apr 2002 - Feb 2016	335	-25 [May 2012]			
BUFFALO SE	Smith Coal	1588	Oct 2001 - Mar 2016	281	-55 [May 2008]	Jun 2003 - Sept 2003	1,800 [Aug 2003]	0
	Sandstone 1	55	May 2002 - May 2007	48	-4 [Feb 2006]			
	Sandstone 2	155	Nov 2001 - Mar 2016	144	1 [Nov 2008]			
	Sandstone 3	520	Mar 2002 - Mar 2016	419	21 [Sept 2013]			
	Sandstone 4	1482	Aug 2001 - Mar 2016	338	10 [Jun 2006]			
BULL CREEK	Anderson Coal	974	Dec 2005 - Mar 2016	215	-177 [Aug 2012]	May 2004 - Dec 2011	20,155 [Sept 2006]	0
	Sandstone 1	480	Dec 2005 - Nov 2015	Artesian	-12 [Nov 2015]			
	Sandstone 2	876	Dec 2005 - Mar 2016	92	-88 [Mar 2016]			
BULLWHACKER	Big George Coal	1338	Apr 2002 - Dec 2009	93	-1071 [Dec 2009]	Aug 2001 - Dec 2015	368,412 [Jan 2003]	52,623
	Sandstone 1	1202	Apr 2002 - Jan 2016	25	-294 [Nov 2015]			
CEDAR DRAW	Wall Coal	1577	Feb 2004 - Mar 2016	231	-641 [Sept 2011]	June 2003 - Feb 2015	542823 [Nov 2006]	5,138
	Sandstone 1	1390	Feb 2004 - Mar 2016	227	-538 [Sept 2011]			
DILTS	Wyodak Coal	580	Apr 1999 - Sept 2015	341	-317 [Feb 2008]	Apr 2001 - Jun 2013	235,302 [Aug 2004]	0
	Sandstone 1	260	Apr 1999 - Feb 2016	120	-7 [Jan 2009]			
DURHAM RANCH SEC 14	Wyodak Coal	716	Jan 1998 - Mar 2016	268	-548 [Jan 2004]	May 1999 - May 2010	394,439 [Jul 2002]	0
	Sandstone 1	666	Jan 1998 - Mar 2016	25	-29 [Dec 2015]			
DURHAM RANCH SEC 6	Wyodak Coal	328	Nov 1997 - Mar 2016	118	-245 [Mar 2007]	Jul 1999 - Oct 2011	433,717 [Feb 2001]	0
	Sandstone 1	255	Nov 1997 - Mar 2016	96	-84 [Mar 2016]			

Table A1-1. Continued.

				GWL change (ft)		Water production		
Monitoring well site name	Monitored unit	Depth to monitored unit (ft - bgs)	Period of record monitored	Initial depth to GW (ft)	Maximum during POR [date]	Period of recorded water production	Maximum water production (bbls/month) [date]	Average production during 2015 (bbls/month)
FOURMILE	Big George Coal	1359	Nov 2007 - Jan 2016	867	-26 [Dec 2008]	Feb 2004 - Dec 2015	121,256	
	Sandstone 1	778	Nov 2007 - Jan 2016	427	-5 [Aug 2015]			
	Sandstone 2 (Underburden)	1546	Nov 2007 - Jan 2016	810	-3 [Aug 2015]			
HOE CREEK	Wyodak Coal	830	Jan 1998 - Mar 2016	231	-679 [Feb 2008]	Apr 1998 - Nov 2010	535378 [Jan 2000]	N/A (0) Last data 2012
	Sandstone 1	150	Jan 1998 - Nov 2015	101	-11 [Nov 2015]			
JUNIPER	Big George Coal	1548	Mar 2001 - Mar 2016	168	-1446 [June 2008]	July 2002 - Dec 2015	445,330 Sept 2004	15,917
	Sandstone 1	550	Mar 2002 - Sept 2015	429	-3 [Aug 2008]			
	Sandstone 2	1086	Jun 2001 - Mar 2016	342	-42 [Nov 2015]			
KENNEDY	Anderson Coal	707	Jul 2000 - Jan 2015	428	-222 [Sept 2008]	May 1999 - Jan 2010	146,083 [Jan 2001]	0
	Sandstone 1	520	Jul 2000 - Jan 2015	270	-18 [Aug 2009]			
LONE TREE	Wyodak-Anderson Coal	647	Feb 2000 - Jan2016	453	-207 Nov 2012	Mar 1992 - Mar 2010	223975 Sept 2006	N/A
	Sandstone 1	490	Feb 2000 - Jan2016	286	-9 Mar 2005			
LOWER PRAIRIE DOG	Anderson Coal	638	Aug 2000 - Mar 2016	168	-477 [Dec 2013]	Mar 2000 - June 2015	883,431 [Jan 2002]	30,675
	Sandstone 1	235	Jan 2002 - Mar 2016	193	-4 [May 2010]			
	Sandstone 2	352	Aug 2000 - Mar 2016	197	-20 [May 2010]			
LQC HILLS	Cook Coal	684	Apr 2005 - Feb 2016	23	-268 [Nov 2011]	Mar 2002 - June 2015	130,515 [Apr 2002]	18,516
	Sandstone 1	493	Apr 2005 - Feb 2016	41	-26 [Feb 2016]			
MP 2	Wyodak Coal	336	May 1993 - Feb 2016	163	-242 [May 2004]	July 2003 - Mar 2009	796,332 [Apr 2001]	0 Last data 2011
	Sandstone 1	260	May 1993 - Nov 2015	52	-65 [May 2015]			
MP 22	Wyodak Coal	438	Mar 1993 - Feb 2016	174	-316 [Jan 2002]	Mar 1993 - Mar 2008	624,794 [Mar 2000]	0 Last data 2012
	Sandstone 1	15	Apr 1998 - Feb 2016	20	-3 [Sept 2010]			
	Sandstone 2	107	Apr 1998 - Feb 2016	38	-1 [Feb 2016]			
	Sandstone 3	340	Feb 1993 - Feb 2016	84	-57 [Feb 2016]			
NAPIER	Big George Coal	1585	May 2001 - Aug 2012	432	-500 [Aug 2012]	Sept 2004 - Dec 2015	130,330 [Dec 2012]	77,671
	Sandstone 1	1462	May 2001 - Feb 2016	403	-302 [Feb 2016]			

Table A1-1. Continued.

Monitoring well site name	Monitored unit	Depth to monitored unit (ft - bgs)	Period of record monitored	GWL change (ft) Initial depth to GW (ft)	Maximum during POR [date]	Water production Period of recorded water production	Maximum water production (bbls/month) [date]	Average production during 2015 (bbls/month)
NORTH GILLETTE	Anderson Coal	534	Sept 2001 - Jan 2016	500	-75 [Feb 2003]	Aug 1999 - Jan 2011	635,349 May 2000	0 Last data 2014
	Sandstone 1	215	Sept 2001 - Jan 2016	122	-6 [Aug 2007]			
PALO	Canyon Coal	426	Feb 2001 - Jan 2016	299	-143 [Jan 2011]	Jan 2001 - Jun 2015	37,647 Mar 2001	619
	Sandstone 1	290	Feb 2001 - Feb 2014	246	-2 [Feb 2014]			
REDSTONE	Canyon Coal	241	Oct 1998 - Jan 2016	33	-225 [Mar 2002]	Jul 1999 - Jun 2012	445,936 [Jan 2000]	0 Last data 2014
	Sandstone 1	160	Oct 1998 - Jan 2016	25	5 [Apr 2001]			
ROSE DRAW	Wall Coal	1774	May 2009 - Feb 2016	51	-186 [Feb 2012]	Apr 2008 - Oct 2012	153402 [Apr 2010]	0
	Sandstone 1	989	May 2009 - Feb 2016	67	-24 [Dec 2015]			
	Sandstone 2 (Underburden)	1840	Sept 2009 - Feb 2016	13	-67 [Feb 2016]			
SASQUATCH	Big George Coal	1435	Jan 1998 - Mar 2016	230	-573 [Dec 2015]	Feb 2002 - Dec 2015	790079 [June 2005]	22,154
	Sandstone 1	1296	Jul 2001 - Mar 2016	225	-391 [Dec 2015]			
SEC 25	Wyodak Coal	420	Nov 1996 - Mar 2016	48	-405 [Feb 2005]	Oct 1999 - Jun 2012	536,697 [Mar 2007]	0
	Sandstone 1	134	Nov 1996 - Mar 2016	28	-6 [Dec 2015]			
STREETER	Big George Coal	1351	Aug 2004 - Jan 2016	159	-162 [Jan 2016]	Oct 2007 - Jan 2011	18,518 [Apr 2009]	0
	Sandstone 1	522	Aug 2004 - Jan 2016	214	-11 [May 2012]			
STUART SECTION 31	Wyodak Coal	664	Sept 1997 - Mar 2016	322	-458* [Jan 2004]	Mar 2000 - June 2011	1,455,235 [Apr 2000]	0 Last data 2013
	Sandstone 1	555	Oct 1997 - Mar 2016	253	-79 [Dec 2009]			
	Sandstone 2 (Underburden)	794	Oct 1997 - Mar 2016	129	-459 [Sept 2010]			
THRONE	Wyodak Coal	1506	May 2001 - Feb 2016	815	-308 [May 2006]	Aug 2000 - Dec 2015	248,161 [Jun 2003]	0
	Sandstone 1	1400	May 2001 - Feb 2016	601	-300 [Sept 2008]			
WEST PINE TREE	Big George Coal	1347	Sept 2007 - Jan 2016	272	-716 [Nov 2012]	Jul 2007 - Dec 2015	141,249 [Feb 2009]	27,627
	Sandstone 1	538	Sept 2007 - Jan 2016	272	36 [Nov 2010]			
WILD TURKEY	Big George Coal	1205	Nov 2004 - Mar 2016	268	-937 [Feb 2013]	Oct 2005 - Dec 2015	1,425,974 [Jul 2006]	70,875
	Sandstone 1	998	Nov 2004 - Mar 2016	128	-198 [Mar 2016]			

Table A1-1. Continued.

				GWL change (ft)		Water production		
Monitoring well site name	Monitored unit	Depth to monitored unit (ft - bgs)	Period of record monitored	Initial depth to GW (ft)	Maximum during POR [date]	Period of recorded water production	Maximum water production (bbls/month) [date]	Average production during 2015 (bbls/month)
WILLIAMS CEDAR DRAW	Smith Coal	410	April 2007 - Feb 2016	169	-15 [Oct 2015]	Oct 2000 - Dec 2015	58,920 Jun 2009	12,678
	Sandstone 1	166	April 2007 - Feb 2016	116	3 [Jul 2012]			
	Anderson Coal	735	April 2007 - Feb 2016	244	-344 [Feb 2016]			
	Sandstone 2 (Underburden)	564	April 2007 - Feb 2016	260	-355 [Feb 2016]			
WORMWOOD	Wyodak Coal	1074	Dec 2006 - Feb 2016	262	-799 [Feb 2016]	Aug 2006 - Dec 2015	504,162 Mar 2007	
	Sandstone 1	478	Dec 2006 - Feb 2016	77	6 [Mar 2009]			
	Sandstone 2 (Underburden)	1287	Dec 2006 - Feb 2016	115	-493 [Nov 2015]			

Table A1-2. List of recent trends in groundwater levels observed at sites where CBNG production has been discontinued.

Site name/ water level status in associated coal seam	Monitored unit	Direction current observed trend	Trend interval [~36 months]	Annual rate of change [ft/year]
BEAR DRAW Big George Recovering	Sandstone 1	Declining	Dec 2012 - Nov 2015	-31.8
BEAVER FED Big George Insuf Data	Sandstone 1	Stable	Dec 2012 - Oct 2015	-0.9
BIG CAT Big George Insuf Data	Sandstone 1	Stable	Dec 2012 - Dec 2015	-0.2
BLACKBIRD COLEMAN Wyodak Declining	Sandstone 1	Stable	Dec 2012 - Nov 2015	-1.4
BOWERS Wyodak Insuf Data	Sandstone 1	Stable	Dec 2012 - Dec 2015	-0.2
	Sandstone 2	Stable	Dec 2012 - Dec 2015	0.2
	Sandstone 3	Stable	Dec 2012 - Dec 2015	0.9
	Sandstone 4	Recovering	Dec 2012 - Dec 2015	1.8
BULLWHACKER Big George Insuf Data	Sandstone 1	Declining	Nov 2012 - Nov 2015	-14.6
FOURMILE Big George Declining	Sandstone 1	Stable	Nov 2012 - Nov 2015	0.0
	Sandstone 2 (Underburden)	Declining	Nov 2012 - Nov 2015	-3.7
JUNIPER Big George Iwell Dry	Sandstone 1	Stable	Nov 2012 - Sept 2015	-0.1
	Sandstone 2	Declining	Nov 2012 - Nov 2015	-2.4
NAPIER Big George Insuf Data	Sandstone 1	Declining	Oct 2012 - Dec 2015	-45.5
SASQUATCH Big George Declining	Sandstone 1	Declining	Oct 2012 - Dec 2015	-16.5
WEST PINE TREE Big George Declining	Sandstone 1	Stable	Jul 2014 - Nov 2015	0.2
WILD TURKEY Big George Declining	Sandstone 1	Declining	Nov 2012 - Nov 2015	-16.6
WILLIAMS CEDAR DRAW Smith Declining	Sandstone 1	Stable	Oct 2012 - Oct 2015	-0.3
WILLIAMS CEDAR DRAW Wyodak Declining	Sandstone 2 (Underburden)	Declining	Oct 2012 - Oct 2015	-20.4
WORMWOOD Wyodak Declining	Sandstone 1	Stable	Nov 2012 - Nov 2015	-0.2
	Sandstone 2 (Underburden)	Declining	Nov 2012 - Nov 2015	-38.1

Table A1-3. List of recent trends in groundwater levels observed at sites where CBNG production is ongoing.

Site name/ water level status in associated coal seam	Monitored unit	Direction current observed trend	Trend interval [variable]	Annual rate of change [ft/year]	Notes
20 MILE BUTTE Recovering Anderson	Sandstone 1	Declining	Mar 2015 - Dec 2015	-5.3	Seasonal fluctuations
21 MILE Declining Big George	Sandstone 1	Stable	Sept 2011 - Nov 2015	-1.7	
ALL NIGHT CREEK Big George Insuf Data	Sandstone 1	Stable	Aug 2012 - Nov 2015	0.1	
	Sandstone 2	Stable	Aug 2012 - Nov 2015	0.3	
	Sandstone 3	Declining	Aug 2012 - Nov 2015	-1.3	
	Sandstone 4	Declining	Aug 2012 - Nov 2015	-1.6	
BAR 76 Wyodak Recovering	Sandstone 1	Insuff. Data	-------		
BARRETT PERSSON Wyodak Recovering	Sandstone 1	Recovering	Dec 2013 - Dec 2015	5.8	
BUFFALO SE Smith Stable	Sandstone 1	Stable	Sept 2003 - Mar 2007	-0.4	
	Sandstone 2	Stable	Sept 2003 - Dec 2015	0.1	
	Sandstone 3	Recovering	Sept 2003 - Dec 2015	1.7	
	Sandstone 4	Stable	Sept 2003 - Dec 2015	-0.1	
BULL CREEK Anderson Recovering	Sandstone 1	Artesian Insuff Data	Dec 2005 - Nov 2015		
	Sandstone 2	Declining	Mar 2012 - Nov 2015	-8.7	
CEDAR DRAW Wall Recovering	Sandstone 1	Recovering	Nov 2012 - Dec 2015	45.7	
DILTS Wyodak Well Dry	Sandstone 1	Stable	Aug 2013 - Dec 2015	0.4	
DURHAM RANCH SEC 14 Wyodak Recovering	Sandstone 1	Declining	Jun 2010 - Dec 2015	-1.1	
DURHAM RANCH SEC 6 Wyodak Insuf.Data	Sandstone 1	Declining	Dec 2011 - Dec 2015	-2.0	
HOE CREEK Wyodak Recovering	Sandstone 1	Declining	Dec 2010 - Nov 2015	-1.0	

Table A1-3. Continued.

Site name/ water level status in associated coal seam	Monitored unit	Direction current observed trend	Trend interval [variable]	Annual rate of change [ft/year]	Notes
KENNEDY Anderson Recovering	Sandstone 1	Stable	Mar 2010 - Nov 2015	0.2	
LONE TREE Wyodak Recovering	Sandstone 1	Recovering	Jul 2013 - Dec 2015	1.9	
LOWER PRAIRIE DOG Anderson Recovering	Sandstone 1	Recovering	Jul 2015 - Nov 2015	1.3	
	Sandstone 2	Stable	Jul 2015 - Nov 2015	0.1	
LQC HILLS Cook Insuf Data	Sandstone 1	Declining	Jul 2015 - Nov 2015	-2.9	
MP 2 Wyodak Fluctuating	Sandstone 1	Stable	Apr 2009 -Nov 2015	0.9	
MP 22 Wyodak Fluctuating	Sandstone 1	Stable	Feb 2008 - Nov 2015	0.1	
	Sandstone 2	Stable	Feb 2008 - Nov 2015	0.0	
	Sandstone 3	Declining	Feb 2008 - Feb 2016	-1.6	
NORTH GILLETTE Anderson Recovering	Sandstone 1	Stable	Mar 2010 - Dec 2015	0.0	
PALO Canyon Insuf Data	Sandstone 1	Insuff. Data	-------	-------	
REDSTONE Canyon Recovering	Sandstone 1	Stable	Aug 2012 - Nov 2015	-0.4	
ROSE DRAW Wall Recovering	Sandstone 1	Declining	Dec 2012 - Dec 2015	-3.8	
	Sandstone 2 (Underburden)	Declining	Dec 2012 - Dec 2015	-2.9	
SEC 25 Wyodak Recovering	Sandstone 1	Stable	Jul 2012 - Dec 2015	-0.9	
STREETER Big George Declining	Sandstone 1	Stable	Feb 2011 - Nov 2015	0.4	
STUART SEC 31 Wyodak Well Dry	Sandstone 1	Recovering	July 2011 - Dec 2015	3.8	
	Sandstone 2 (Underburden)	Recovering	July 2011 - Dec 2015	7.9	
THRONE Wyodak Recovering	Sandstone 1	Recovering	Sept 2010 - Nov 2015	6.8	

Explanation of Symbols Used in Appendix Figures

The hydrographs (figs. A1-1 through A1-40) contained in the appendix represent depth-to-groundwater measurements in coal seam and associated sandstone wells at 40 monitoring well sites scattered across the Powder River Basin. Most of the monitoring sites measure groundwater levels in one targeted coal seam and one associated sandstone layer. However, water levels are measured in two sandstones at seven sites (Fourmile, Stuart Section 31, Wormwood, Bull Creek, Juniper, Rose Draw, and Lower Prairie Dog), three sandstones at the MP 22 well site, and four sandstones at All Night Creek, Bowers, and Buffalo SE. Only one sandstone well hydrograph is shown for the Bull Creek site; there was insufficient data for the second well. Finally, two coal seams (Smith and Anderson) and two sandstones were monitored at the Williams Cedar Draw site.

In table A1-1, sandstones are numbered in increasing order of depth. For example, Sandstone 1 is the shallowest, Sandstone 2 is the next deepest, etc. This convention, used to differentiate sandstones at sites where multiple overlying sandstones are monitored (All Night Creek, Bowers, Buffalo SE, Juniper, Lower Prairie Dog, and MP 22) has been extended to the symbols contained in the hydrographs.

Manual measurements are represented by triangles and pressure transducer measurements by lines:

△, — Black for coal seams

△, — Orange for the closest overlying monitored sandstone

△, — Olive green for the closest underlying sandstone

Additional symbols are used at sites where multiple overlying sandstones are monitored (All Night Creek, Bowers, Buffalo SE, Juniper, Lower Prairie Dog, and MP 22).

△, — Brown for the shallowest overlying sandstone (Sandstone 1)

△, — Violet for Sandstone 2

△, — Red for Sandstone 3

At the Williams Cedar Draw site, the primary monitored coal seam (Anderson) and its associated sandstone are represented by triangles and the Smith coal seam and its associated sandstone by squares (□, □) using the colors specified above.

Black diamonds (◆) represent instances where manual measurement determined that the wellbore was dry to its total depth.

Total water production, as 1,000 barrels/month (mbbls/month), is shown for CBNG wells associated with each monitoring well site as a continuous blue line.

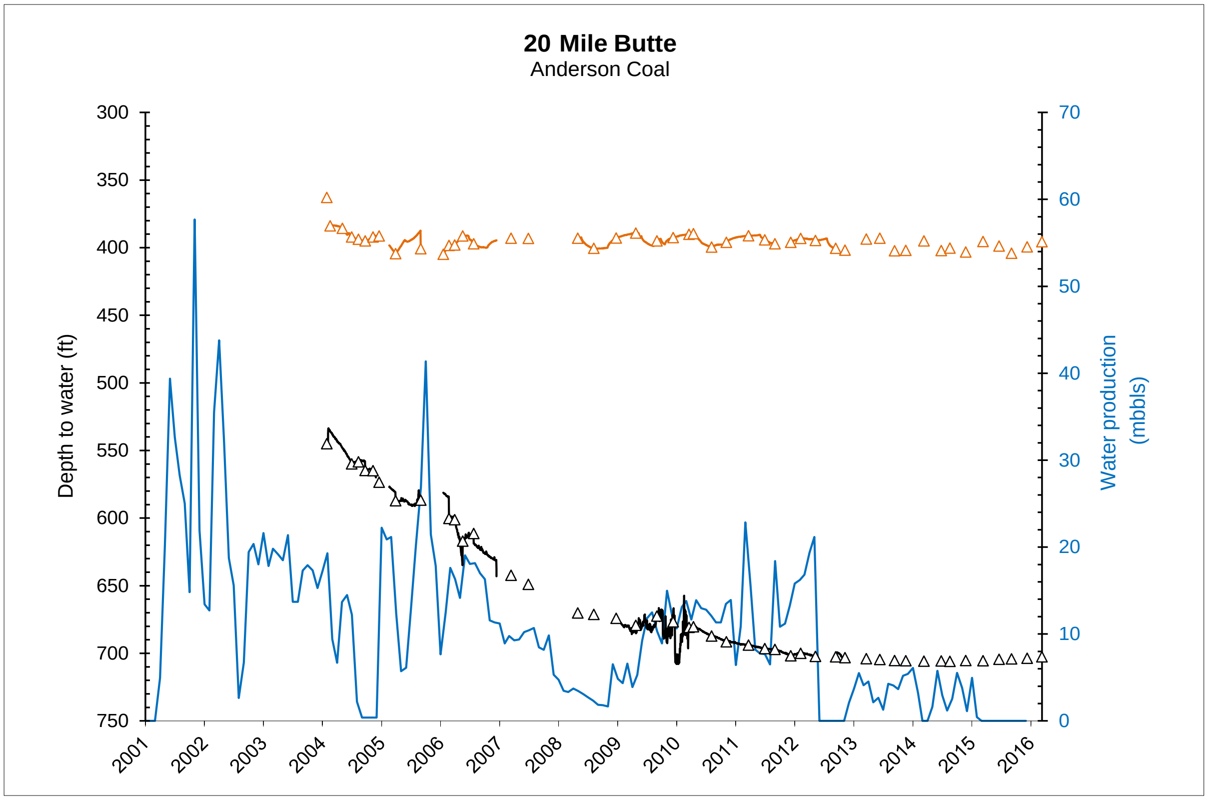

Figure A1-1. Depth to groundwater measurements in the Anderson coal seam and associated sandstone(s) at the 20 Mile monitoring site.

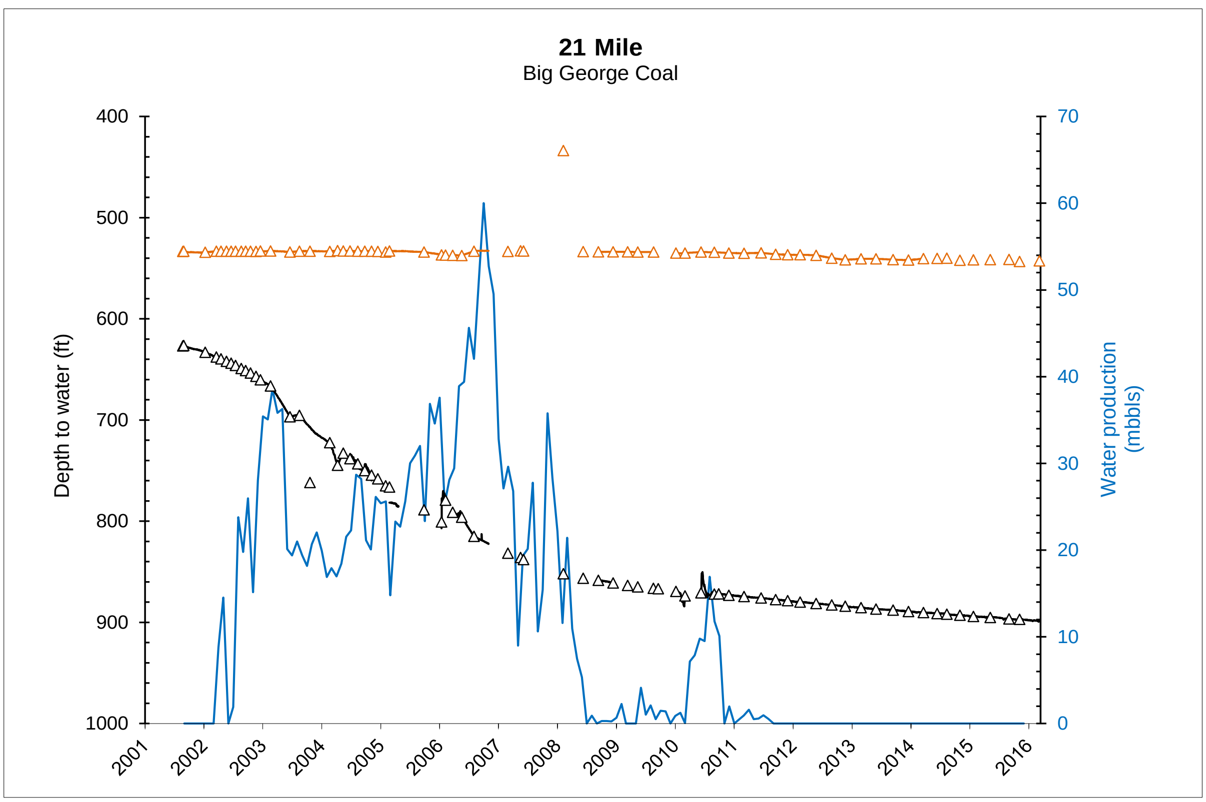

Figure A1-2. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the 21 Mile monitoring site.

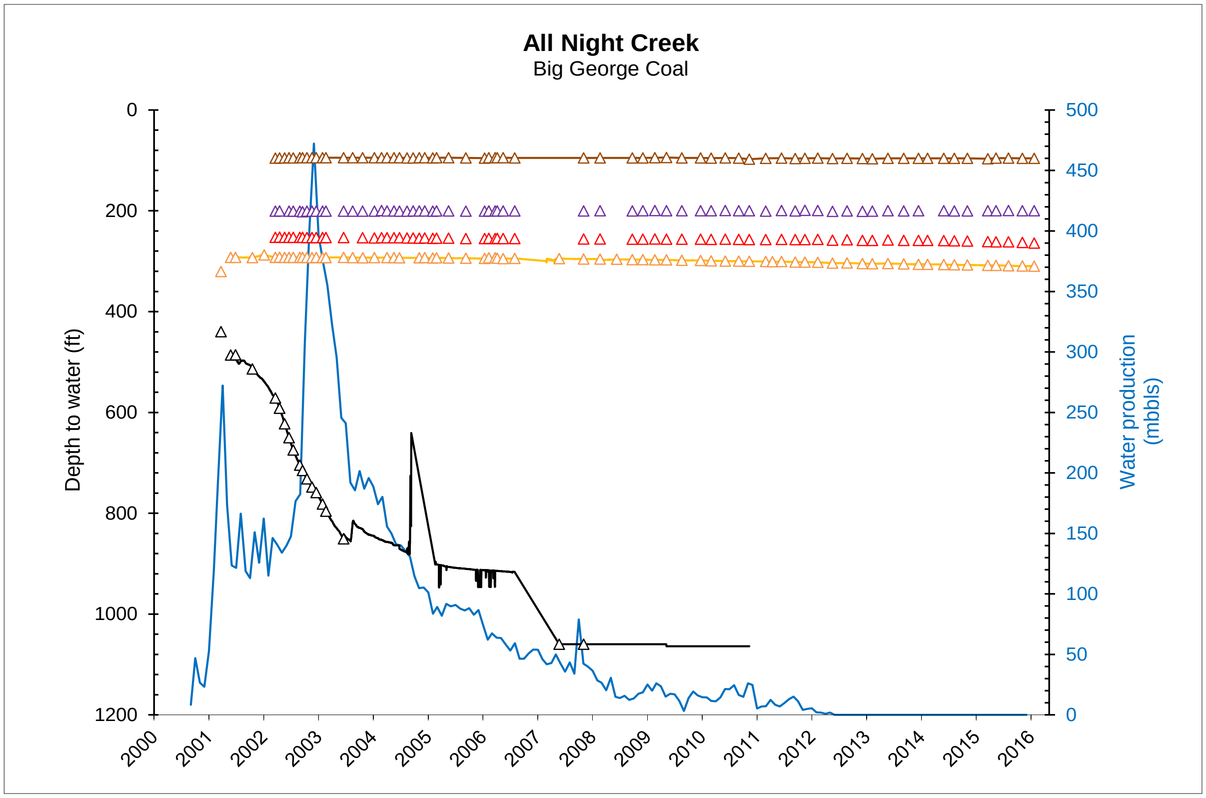

Figure A1-3. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the All Night Creek monitoring site.

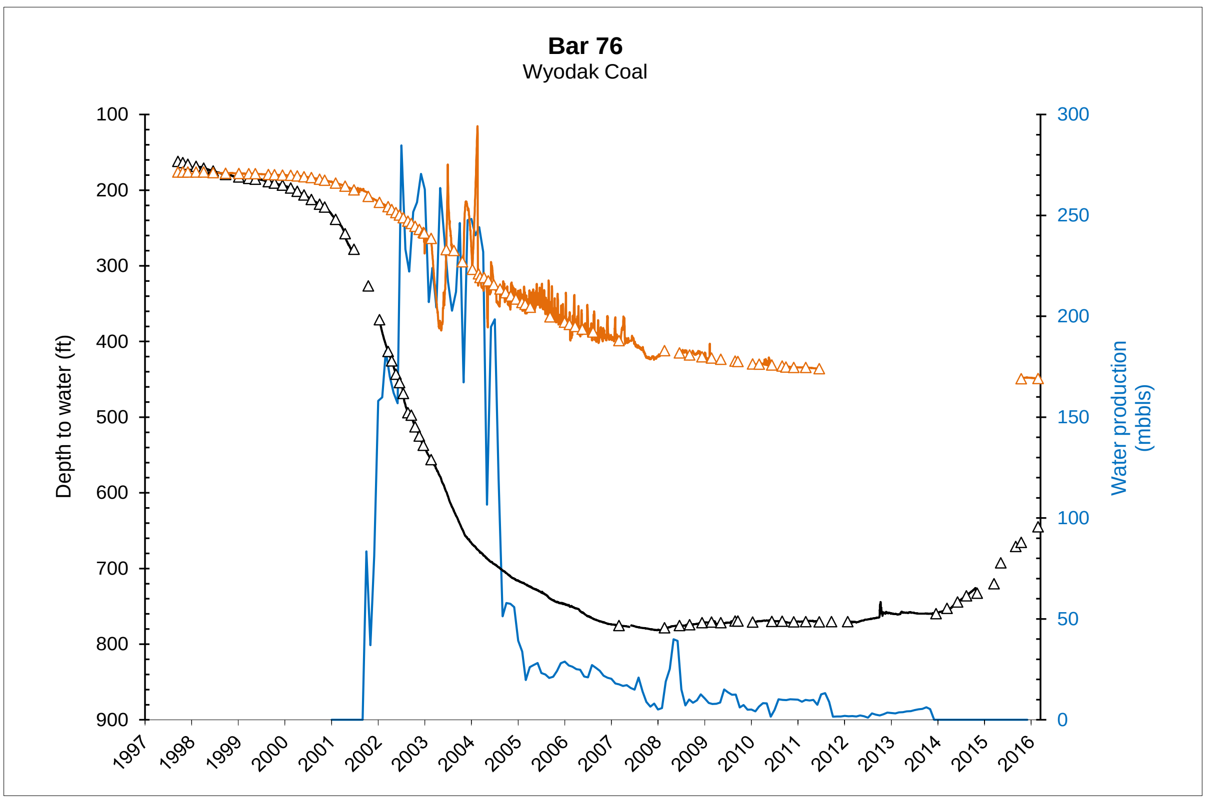

Figure A1-4. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Bar 76 monitoring site.

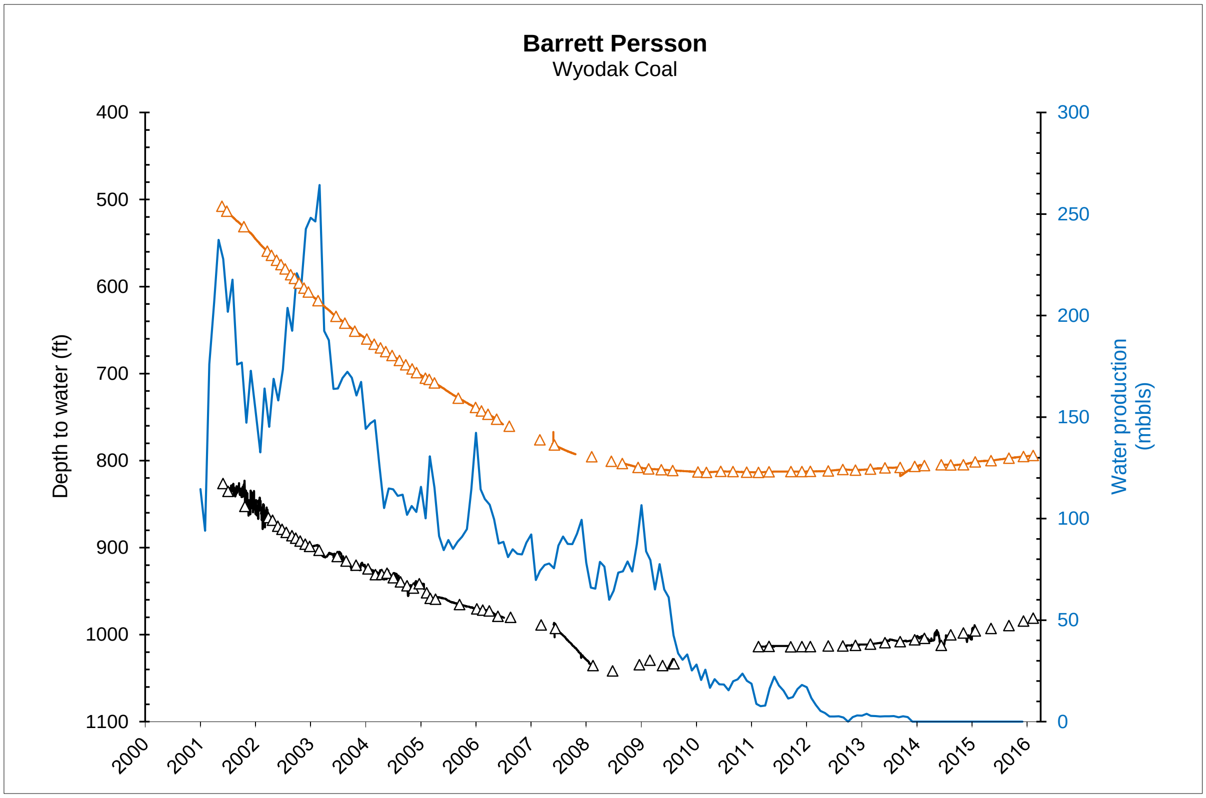

Figure A1-5. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Barrett Persson monitoring site.

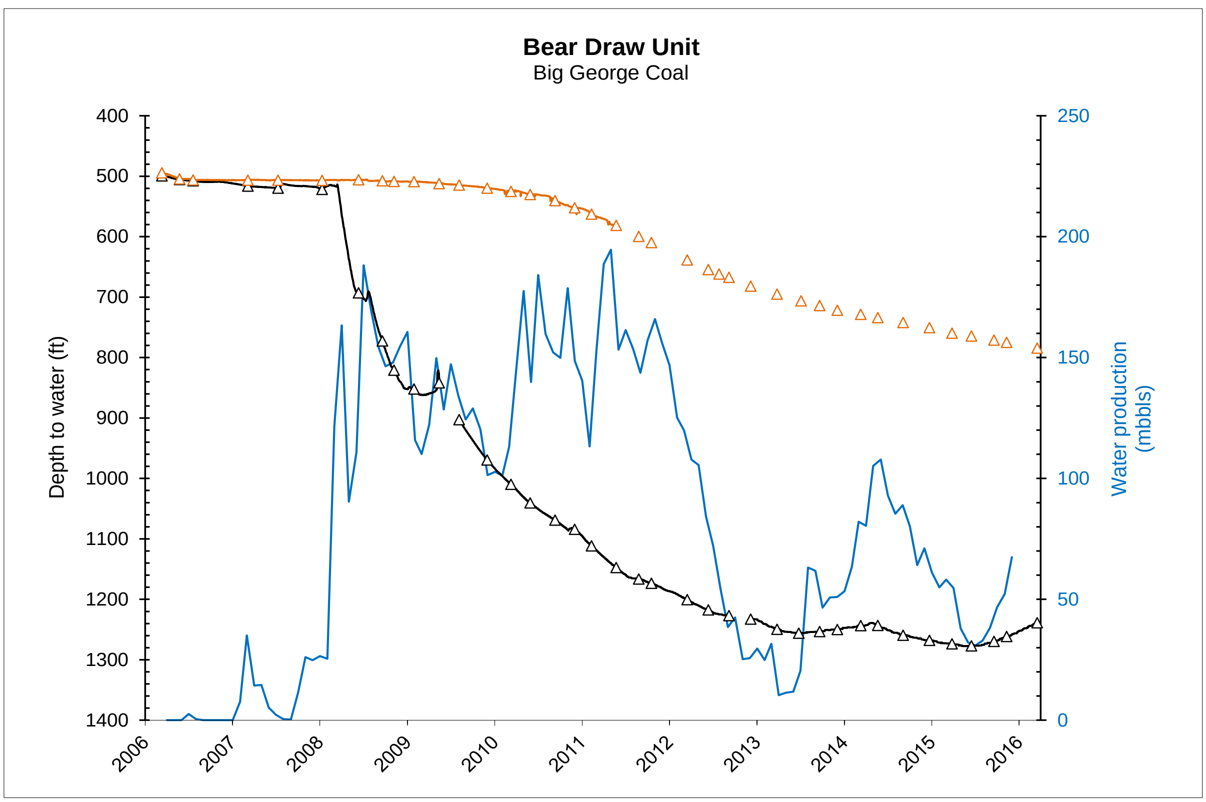

Figure A1-6. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Bear Draw Unit monitoring site.

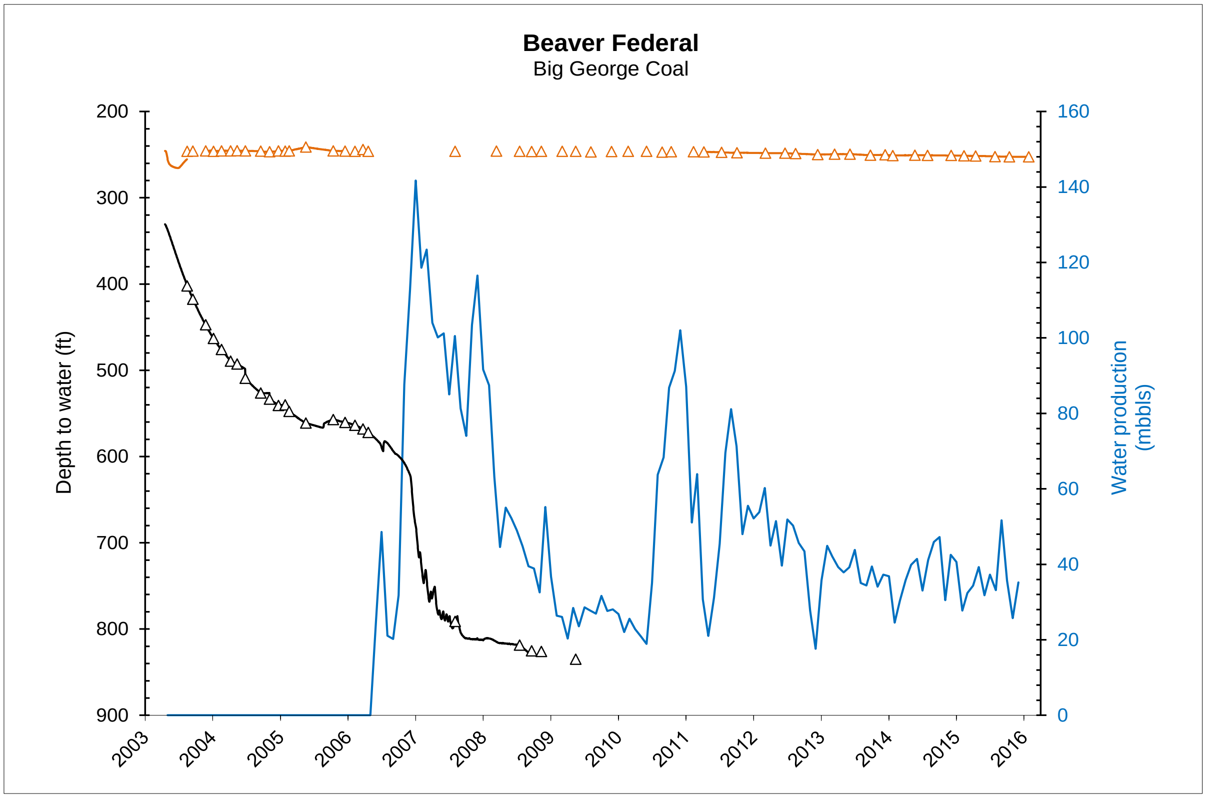

Figure A1-7. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Beaver Federal monitoring site.

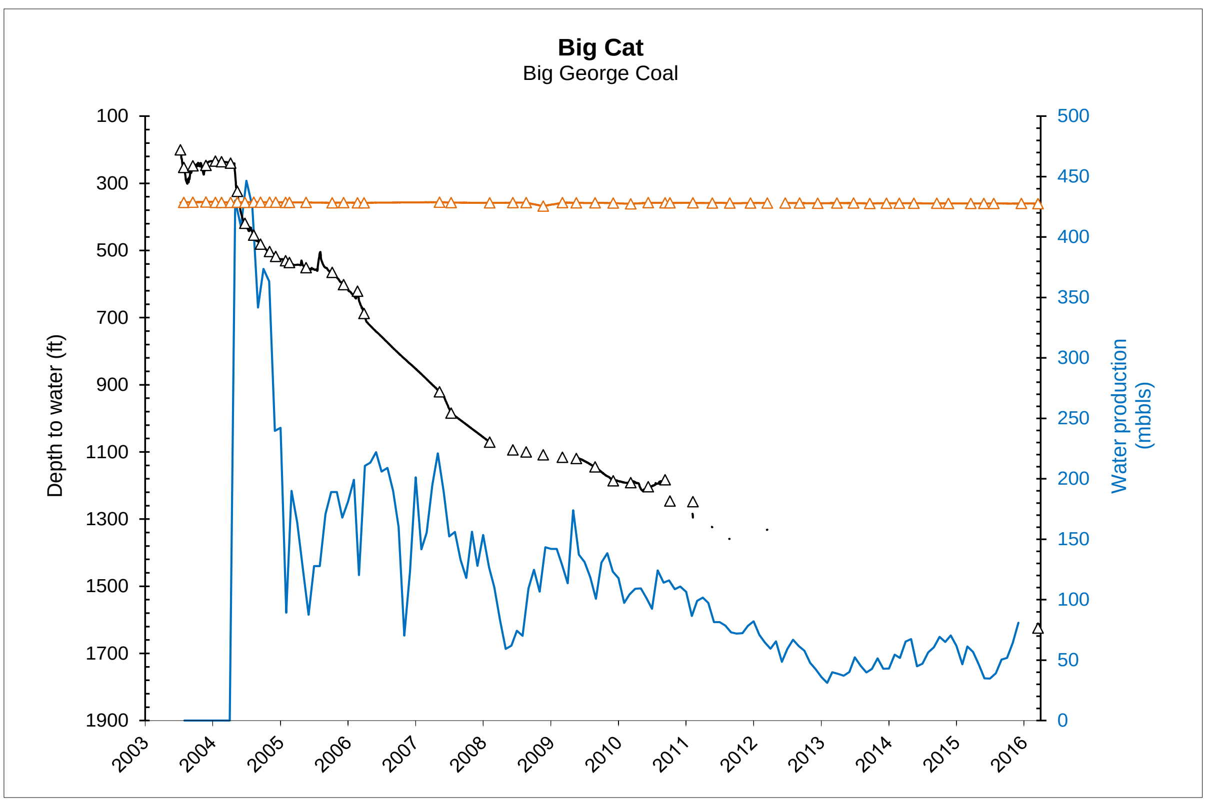

Figure A1-8. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Big Cat monitoring site.

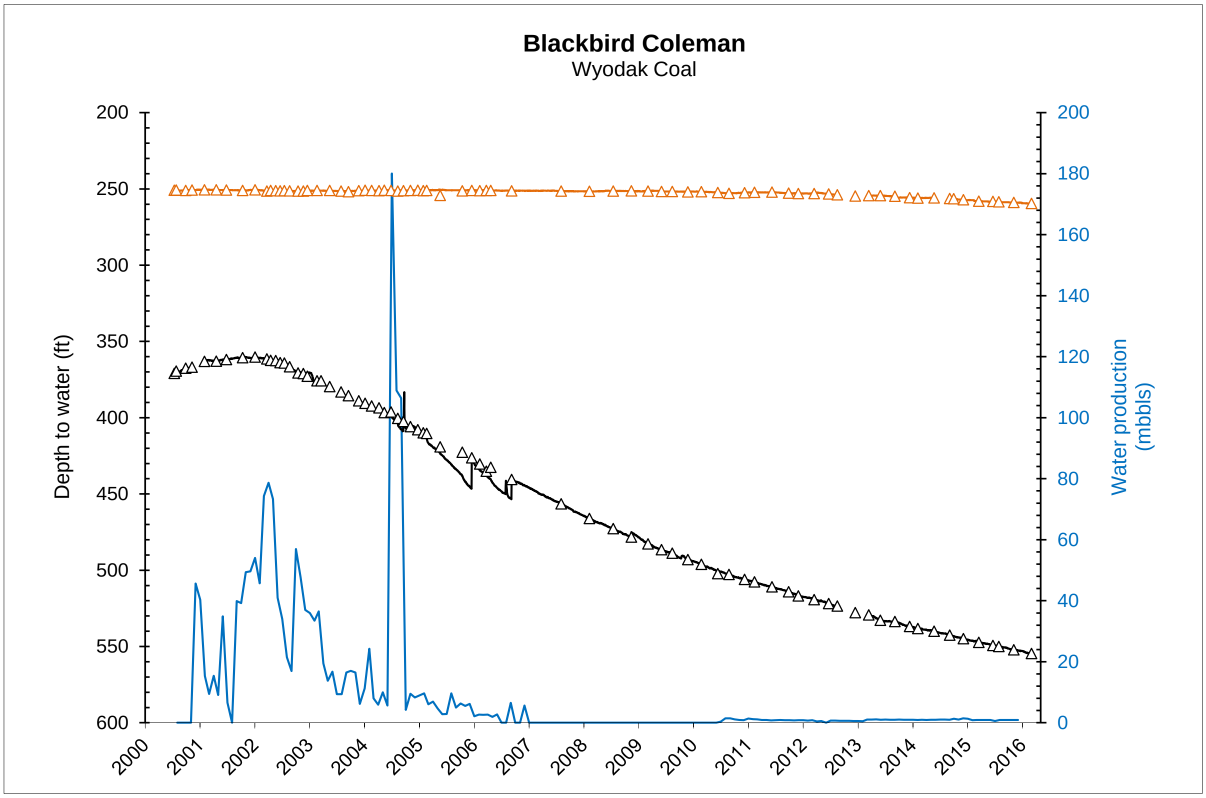

Figure A1-9. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Blackbird Coleman monitoring site.

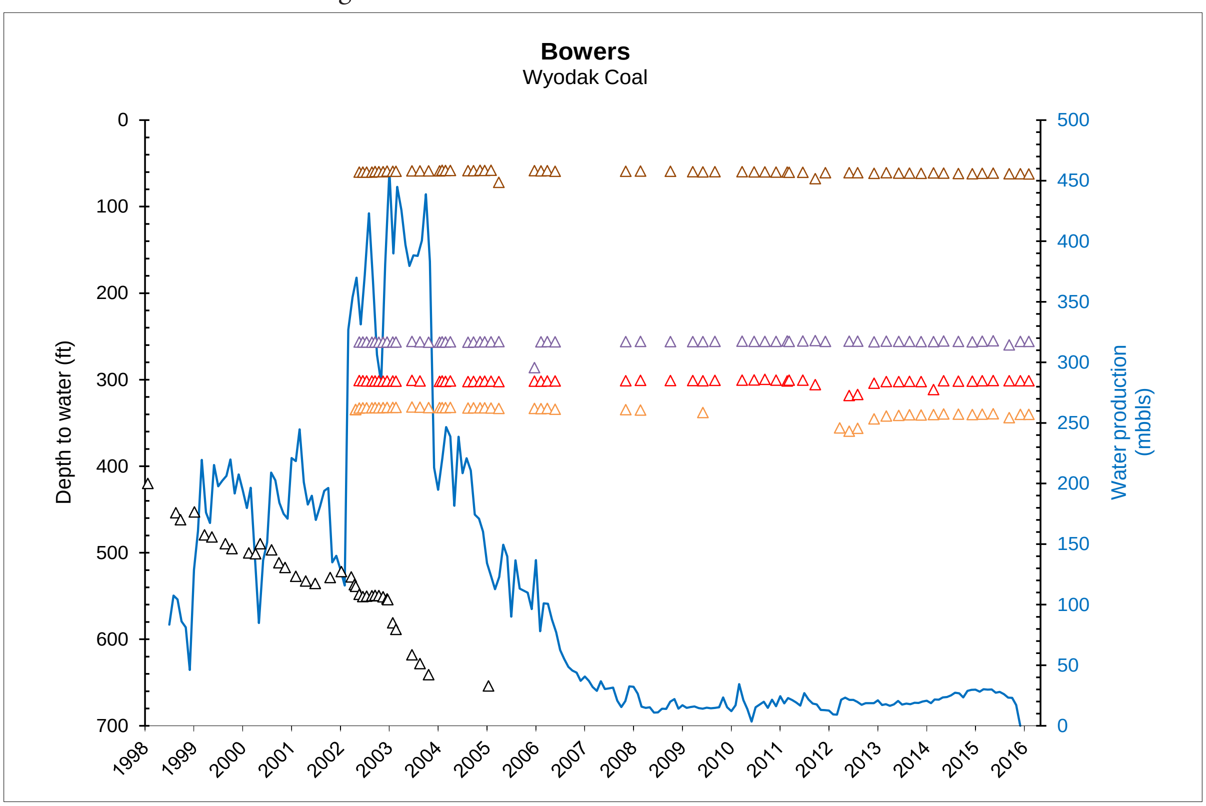

Figure A1-10. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Bowers monitoring site.

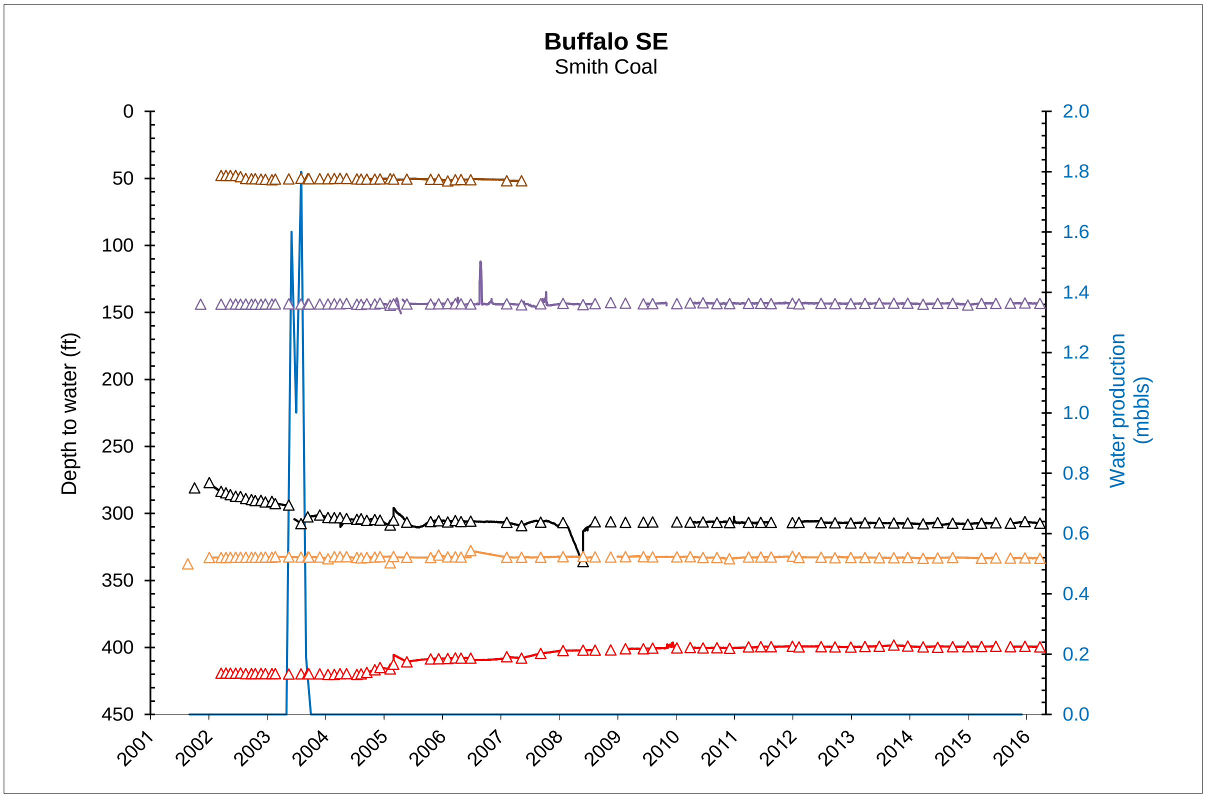

Figure A1-11. Depth to groundwater measurements in the Smith coal seam and associated sandstone(s) at the Buffalo SE monitoring site.

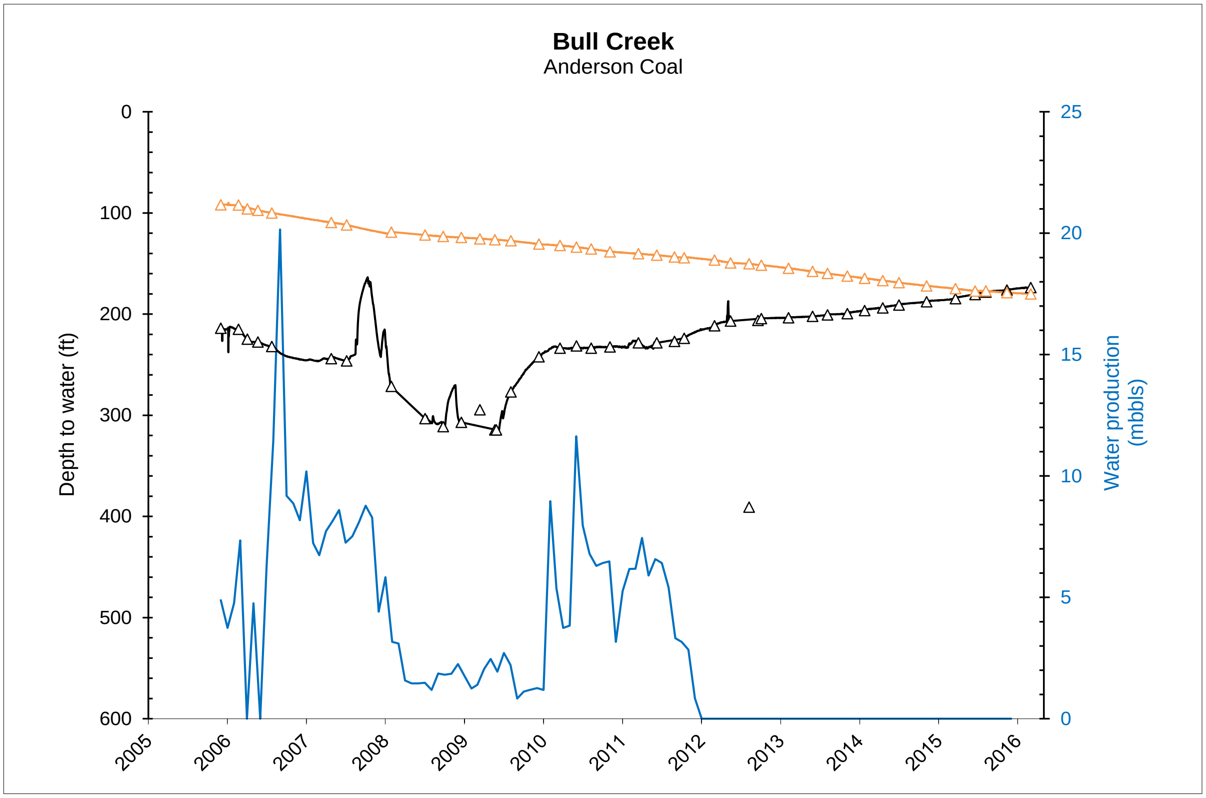

Figure A1-12. Depth to groundwater measurements in the Anderson coal seam and associated sandstone(s) at the Bull Creek monitoring site.

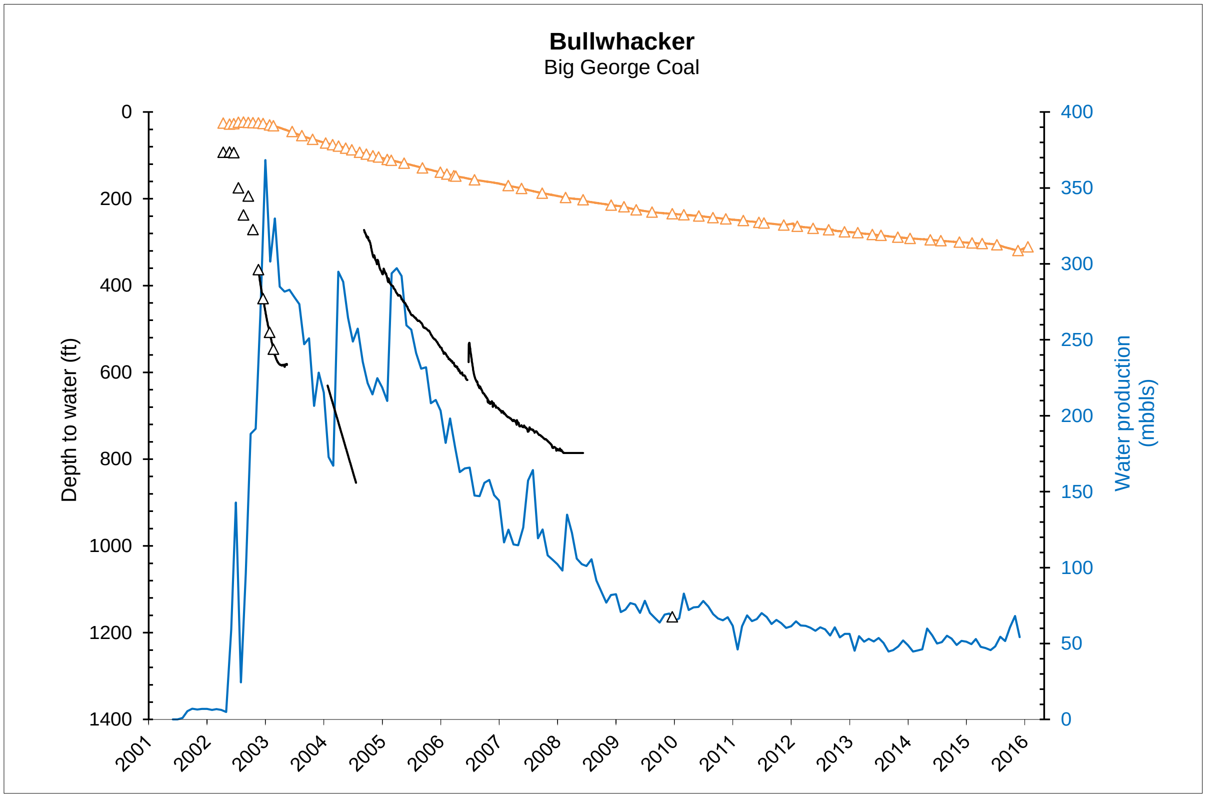

Figure A1-13. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Bullwhacker monitoring site.

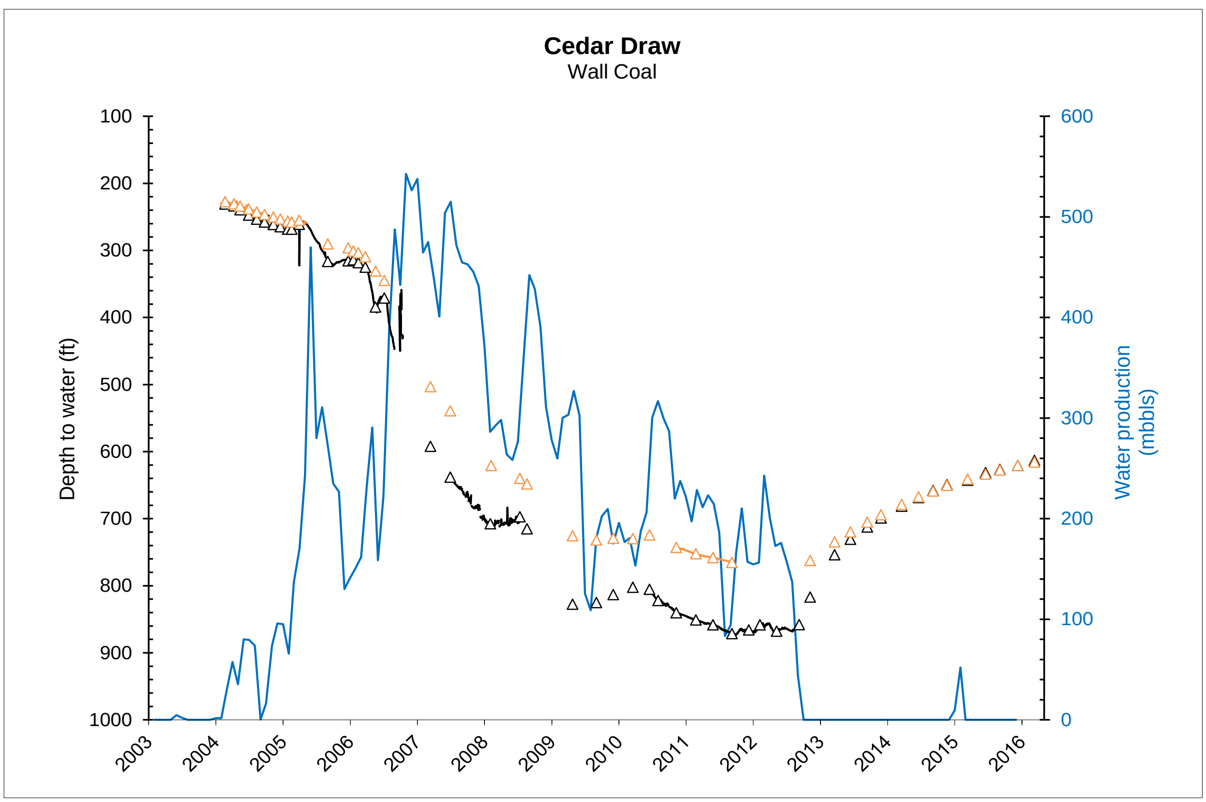

Figure A1-14. Depth to groundwater measurements in the Wall coal seam and associated sandstone(s) at the Cedar Draw monitoring site.

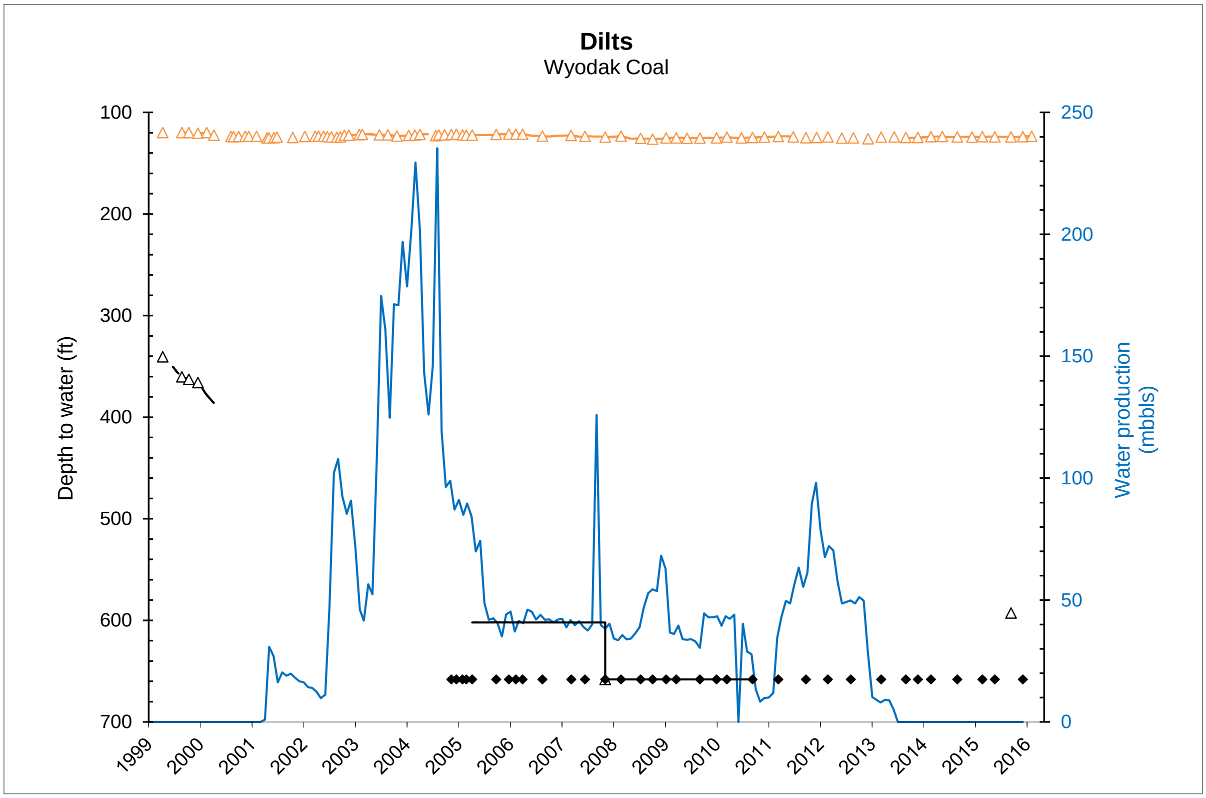

Figure A1-15. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Dilts monitoring site.

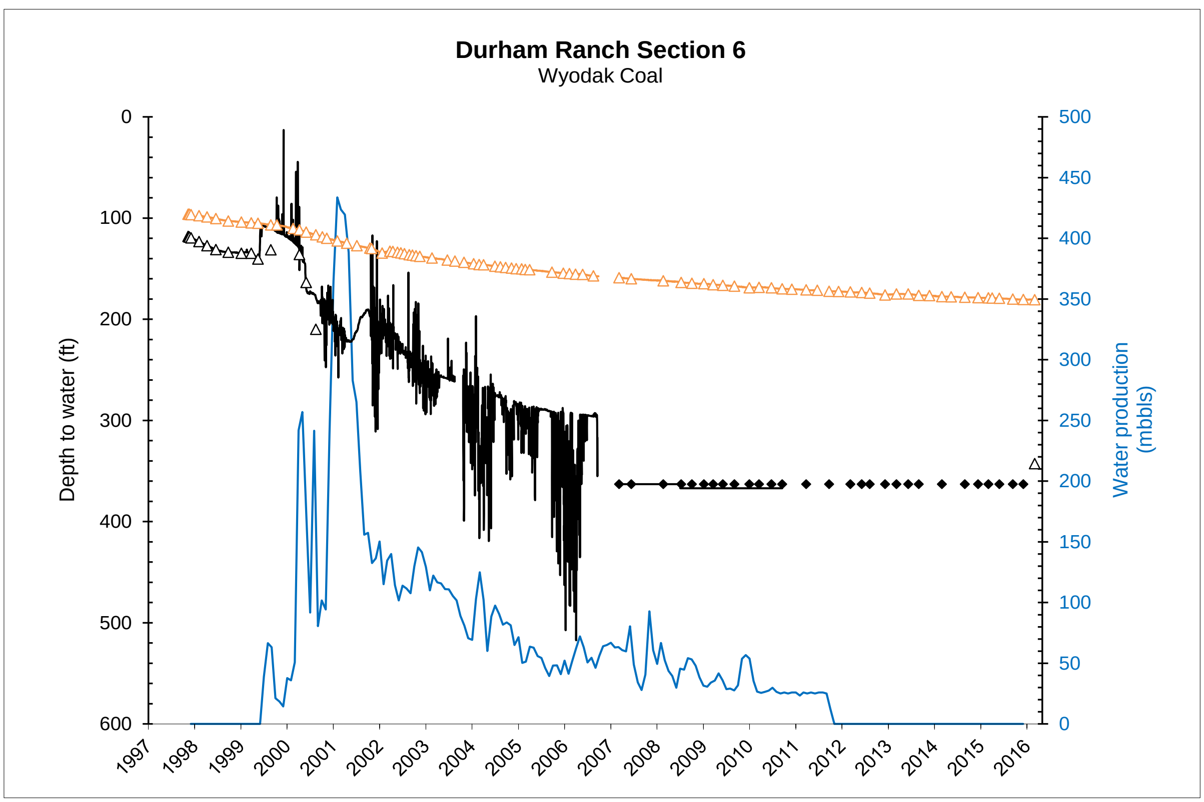

Figure A1-16. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Durham Ranch Section 6 monitoring site.

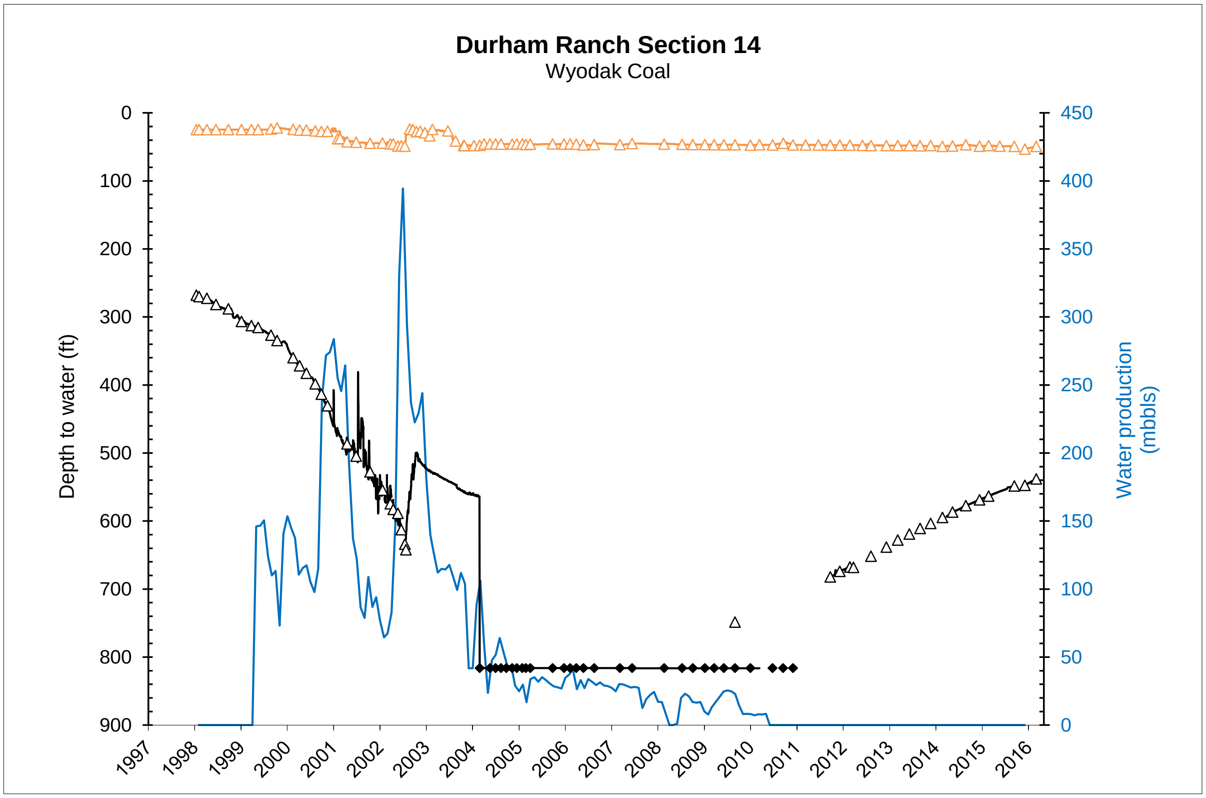

Figure A1-17. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Durham Ranch Section 14 monitoring site.

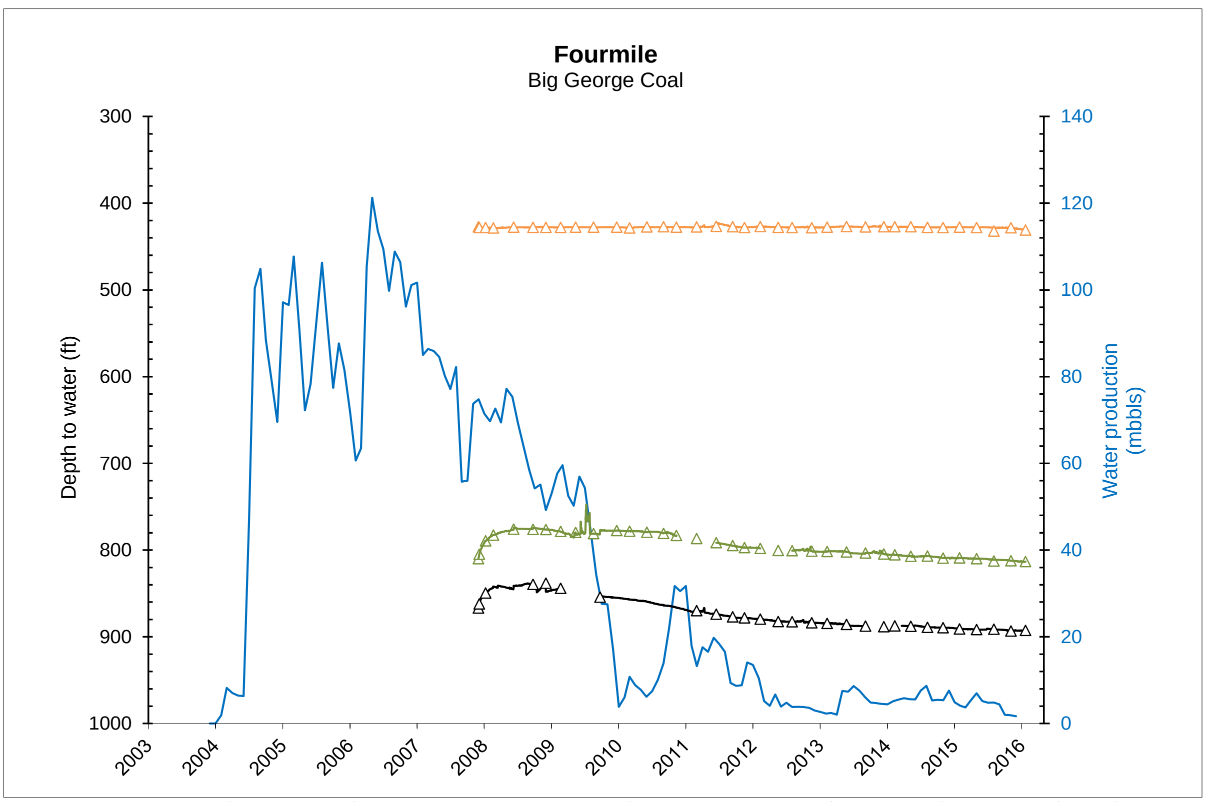

Figure A1-18. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Fourmile monitoring site.

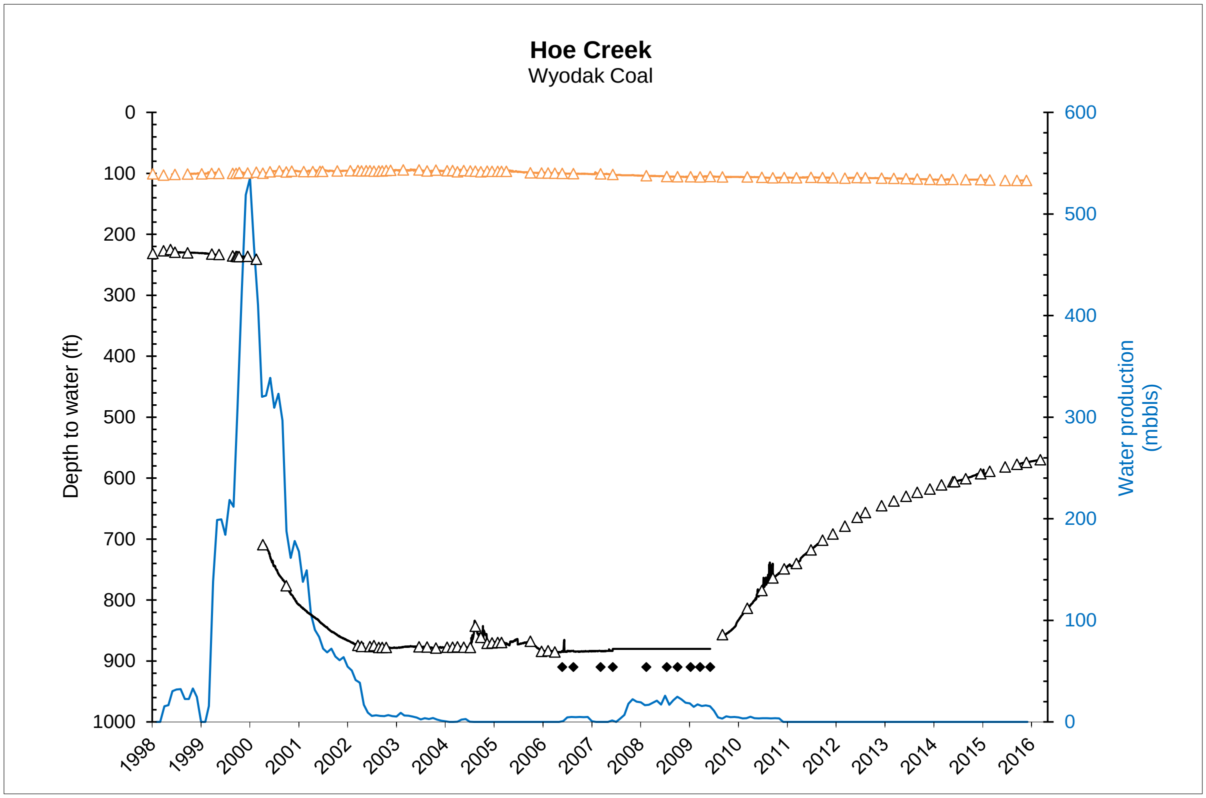

Figure A1-19. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Hoe Creek monitoring site.

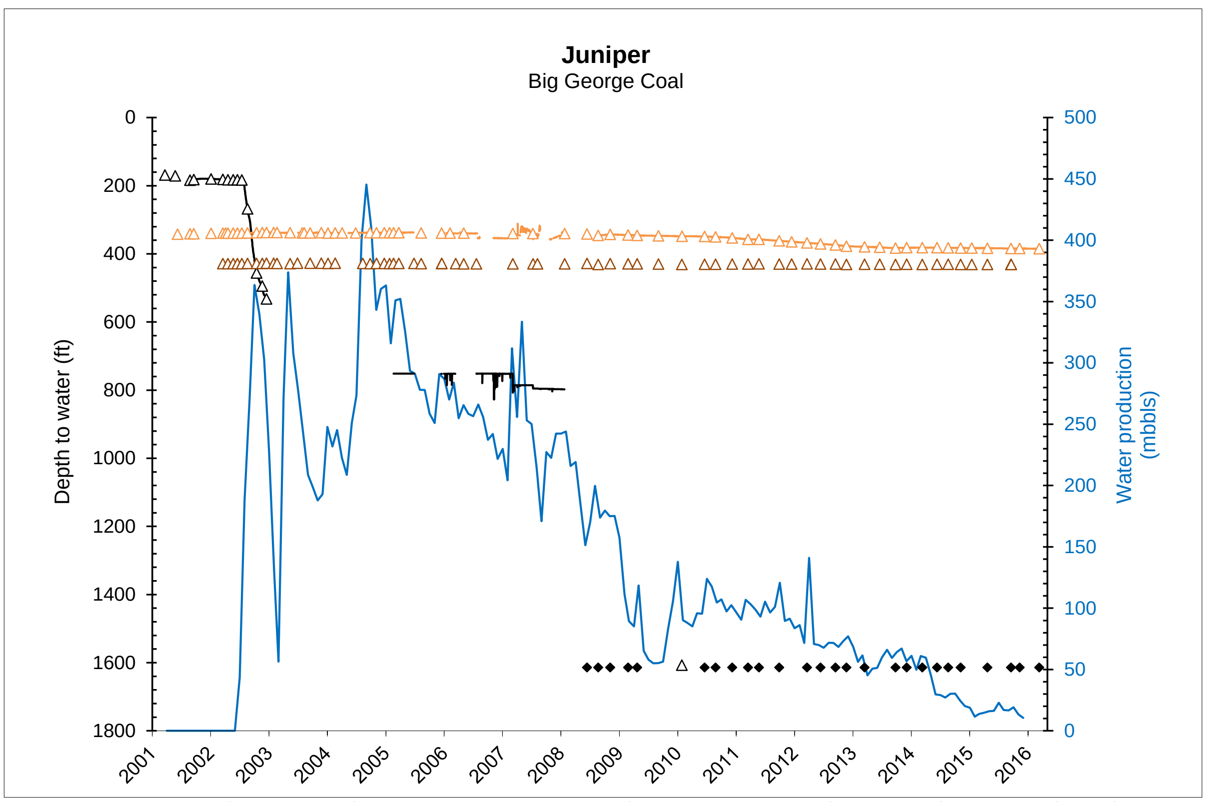

Figure A1-20. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Juniper monitoring site.

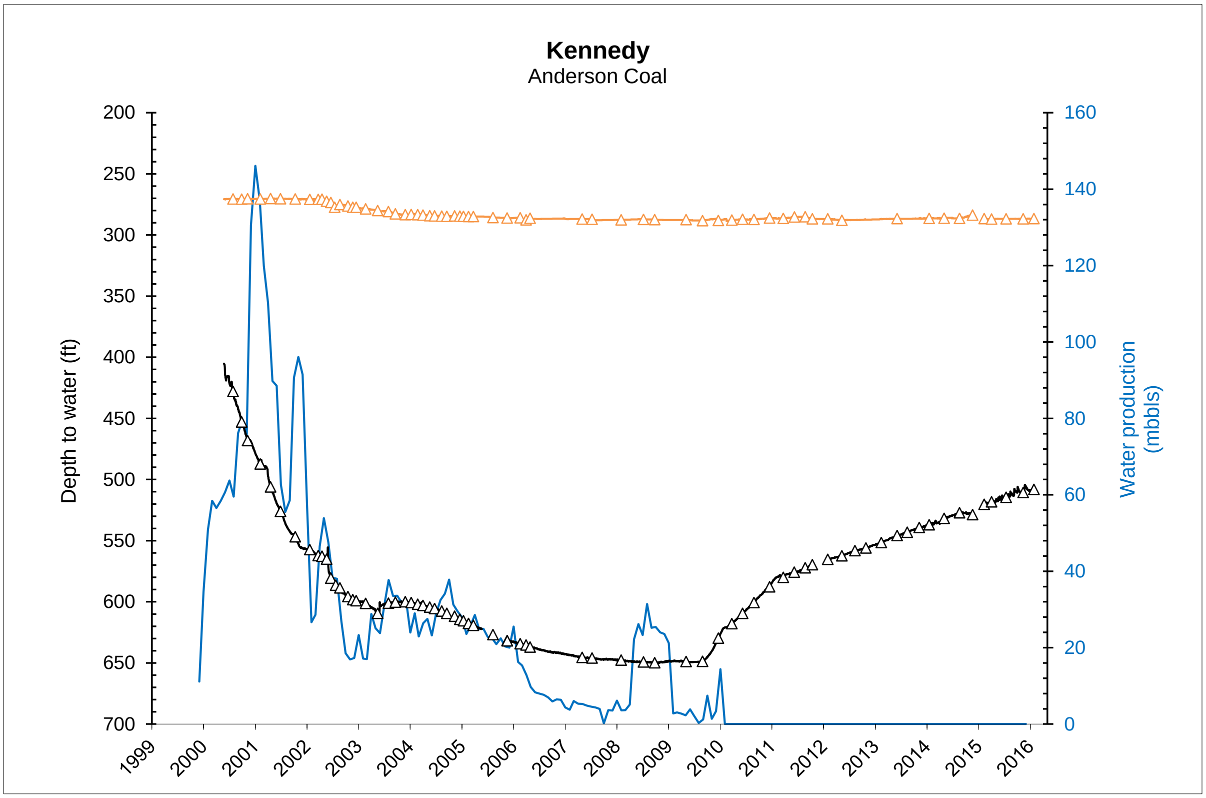

Figure A1-21. Depth to groundwater measurements in the Anderson coal seam and associated sandstone(s) at the Kennedy monitoring site.

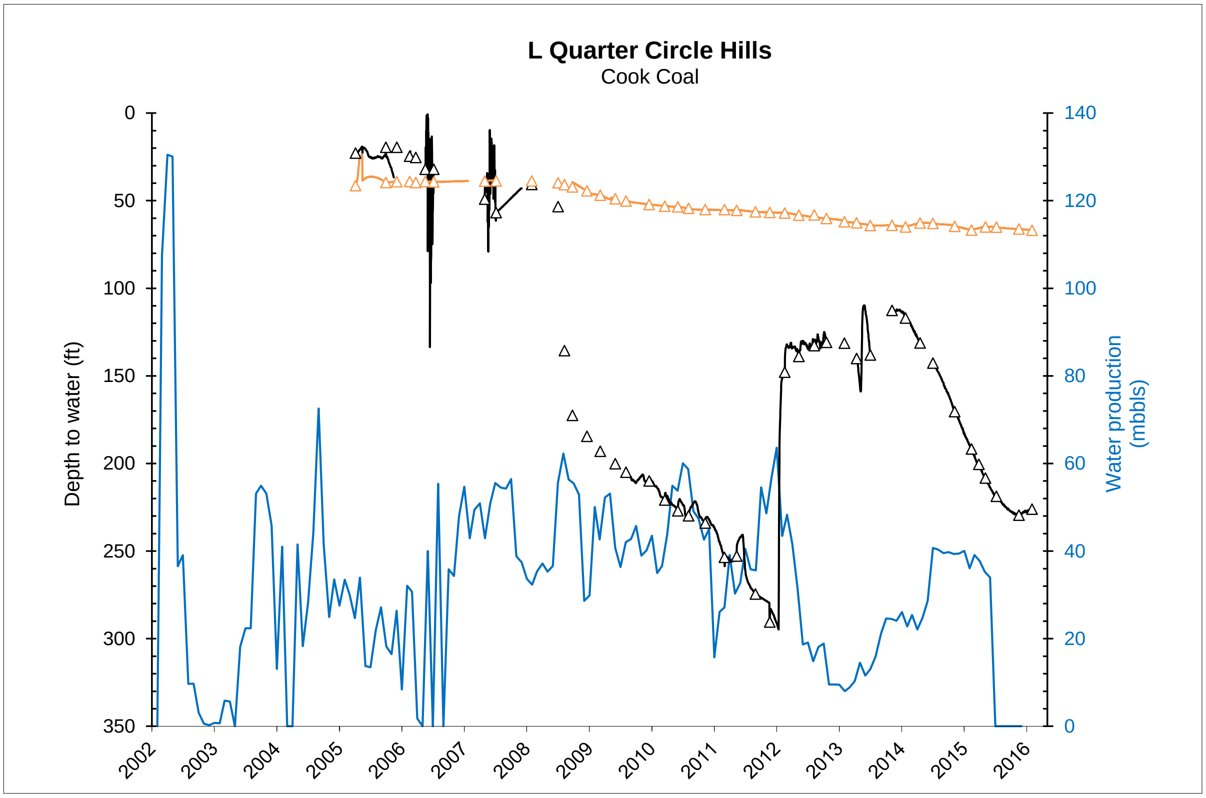

Figure A1-22. Depth to groundwater measurements in the Crook coal seam and associated sandstone(s) at the L Quarter Circle Hills monitoring site.

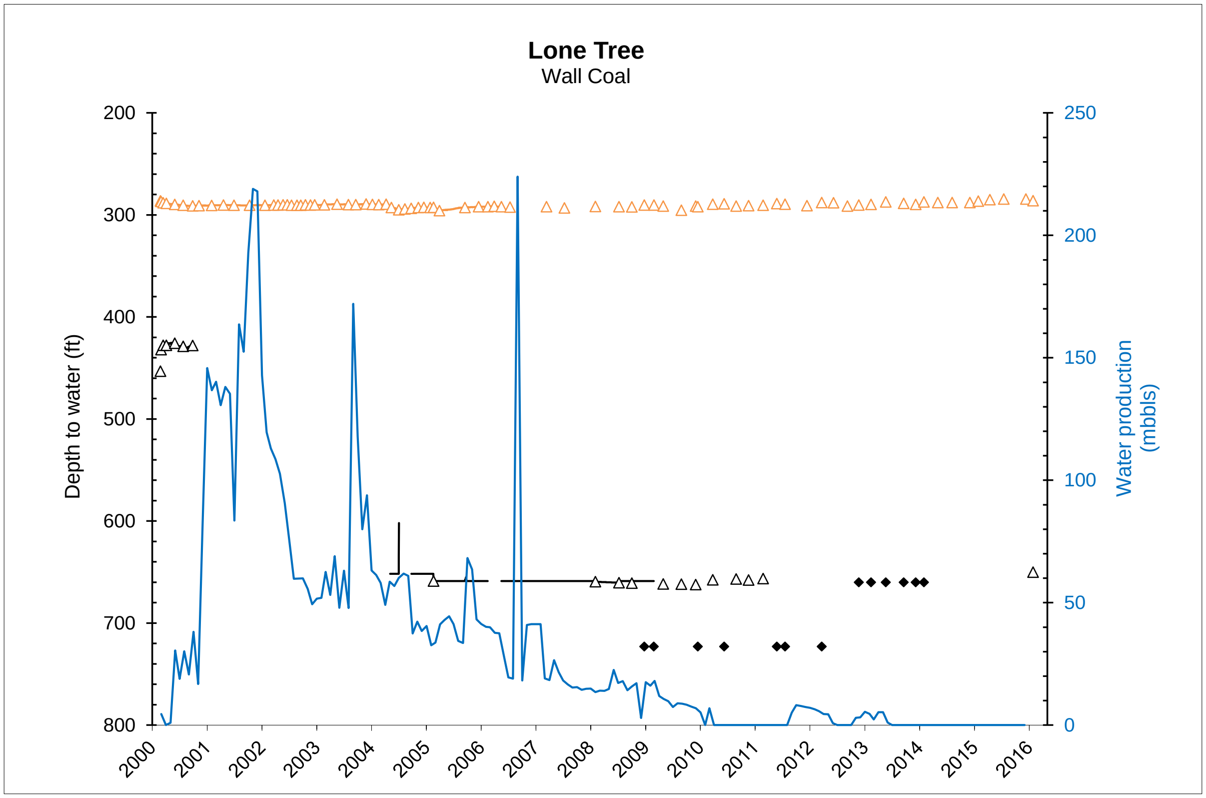

Figure A1-23. Depth to groundwater measurements in the Wall coal seam and associated sandstone(s) at the Lone Tree monitoring site.

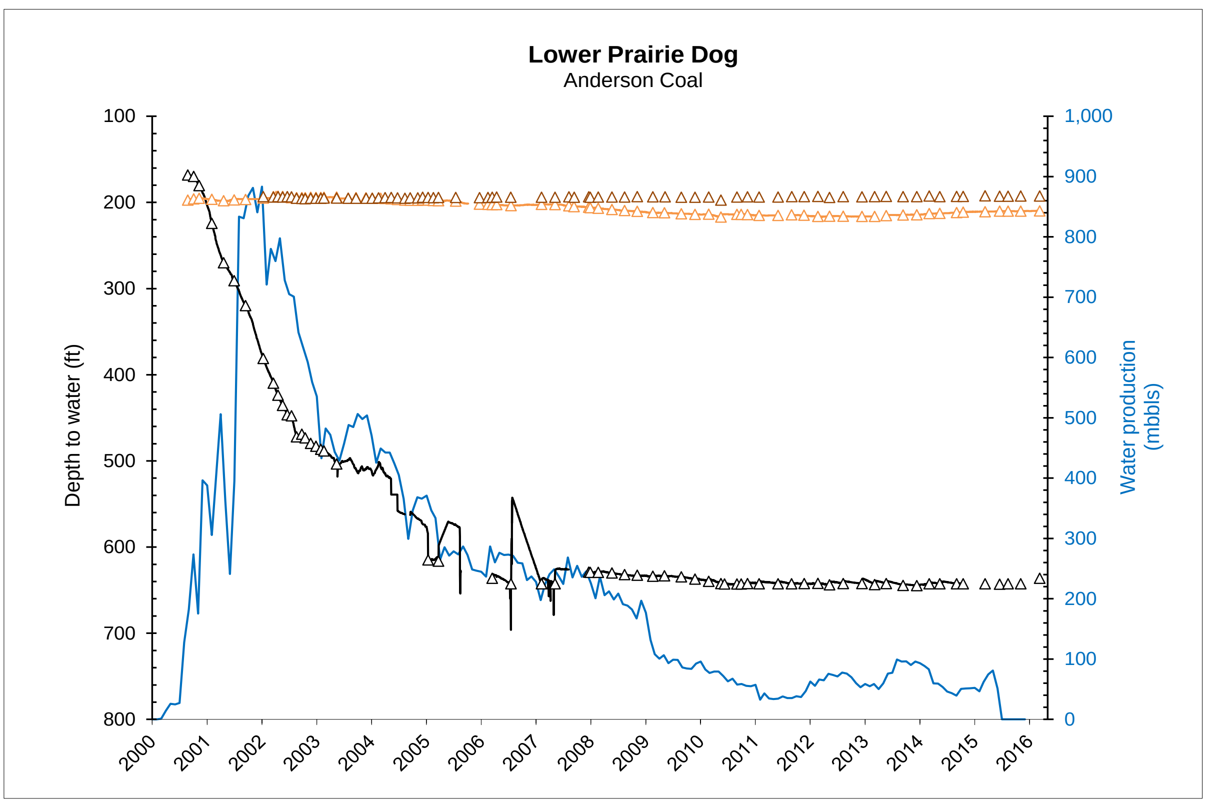

Figure A1-24. Depth to groundwater measurements in the Anderson coal seam and associated sandstone(s) at the Lower Prairie Dog monitoring site.

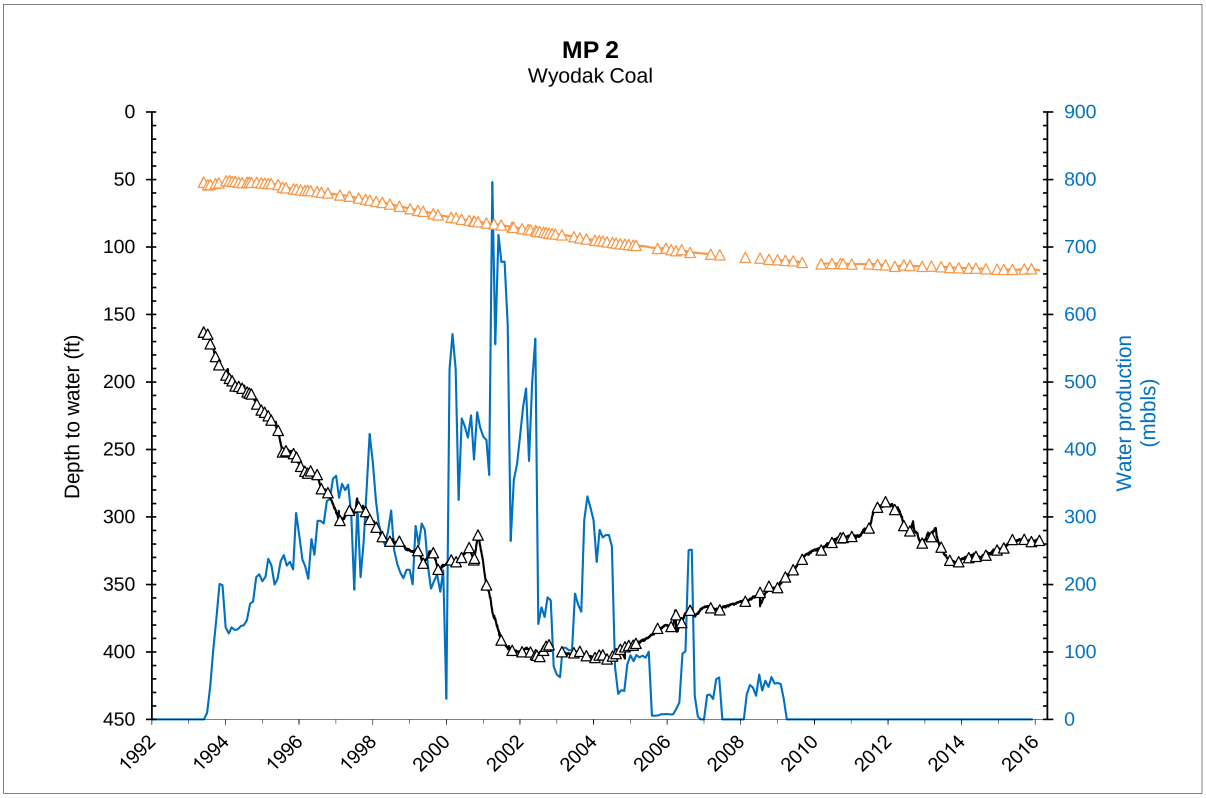

Figure A1-25. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the MP 2 monitoring site.

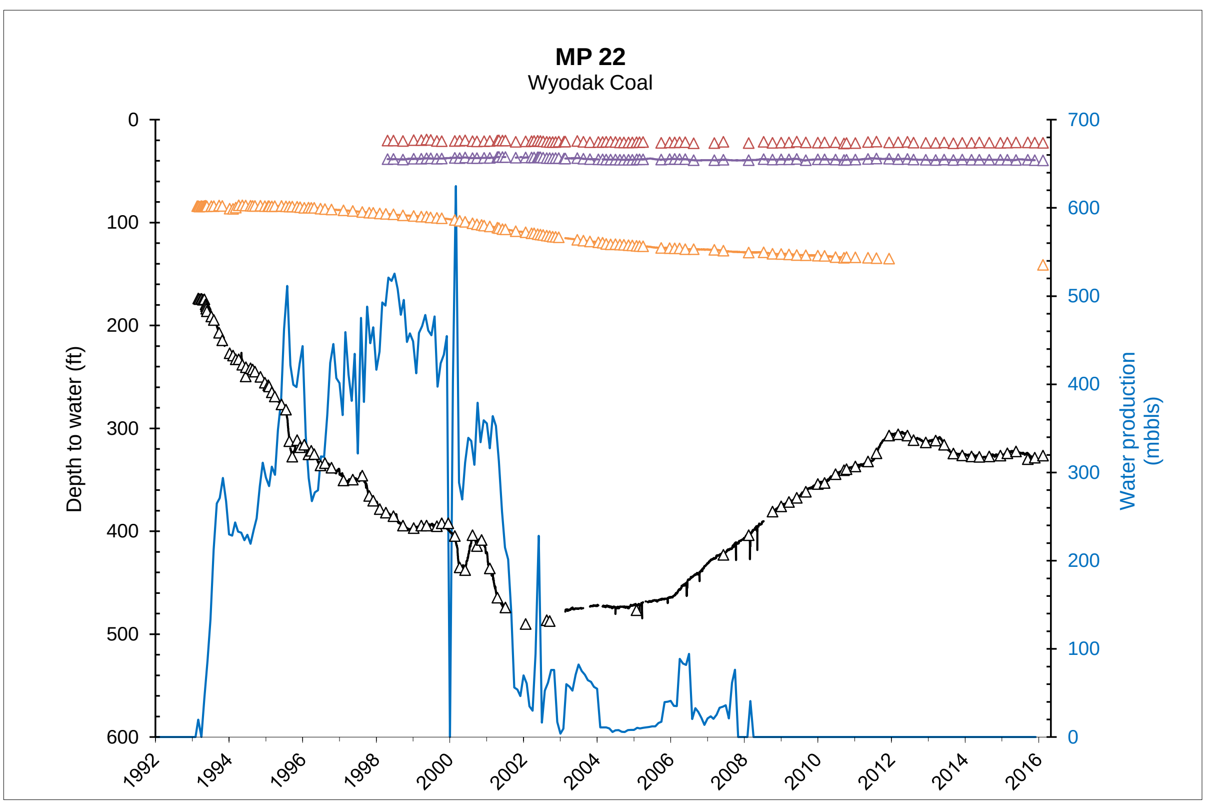

Figure A1-26. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the MP 22 monitoring site.

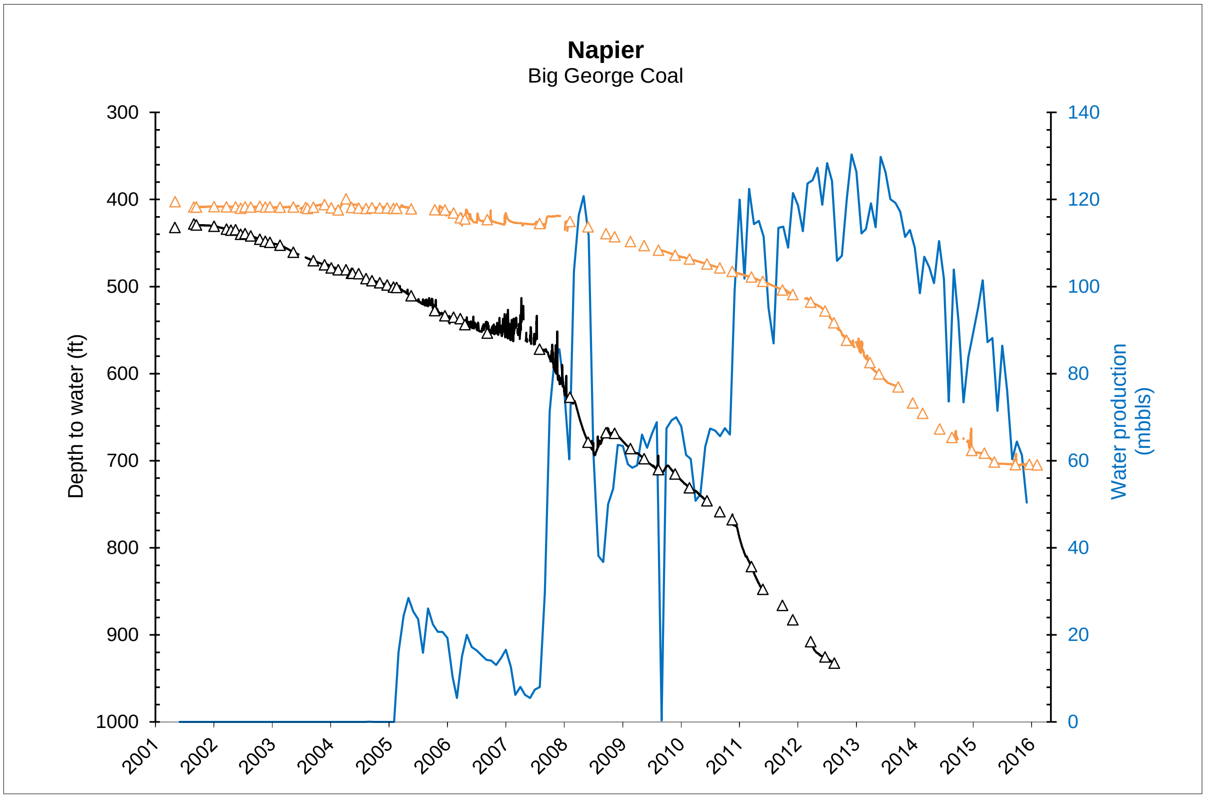

Figure A1-27. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Napier monitoring site.

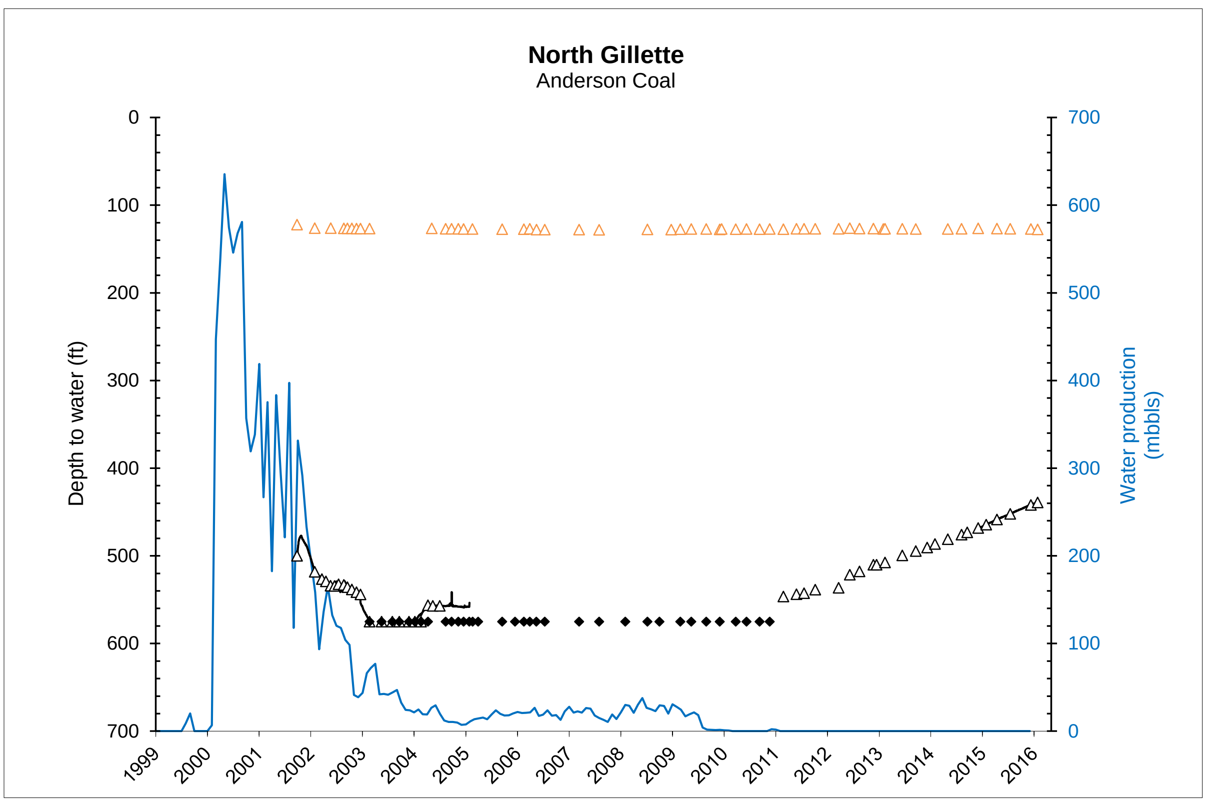

Figure A1-28. Depth to groundwater measurements in the Anderson coal seam and associated sandstone(s) at the North Gillette monitoring site.

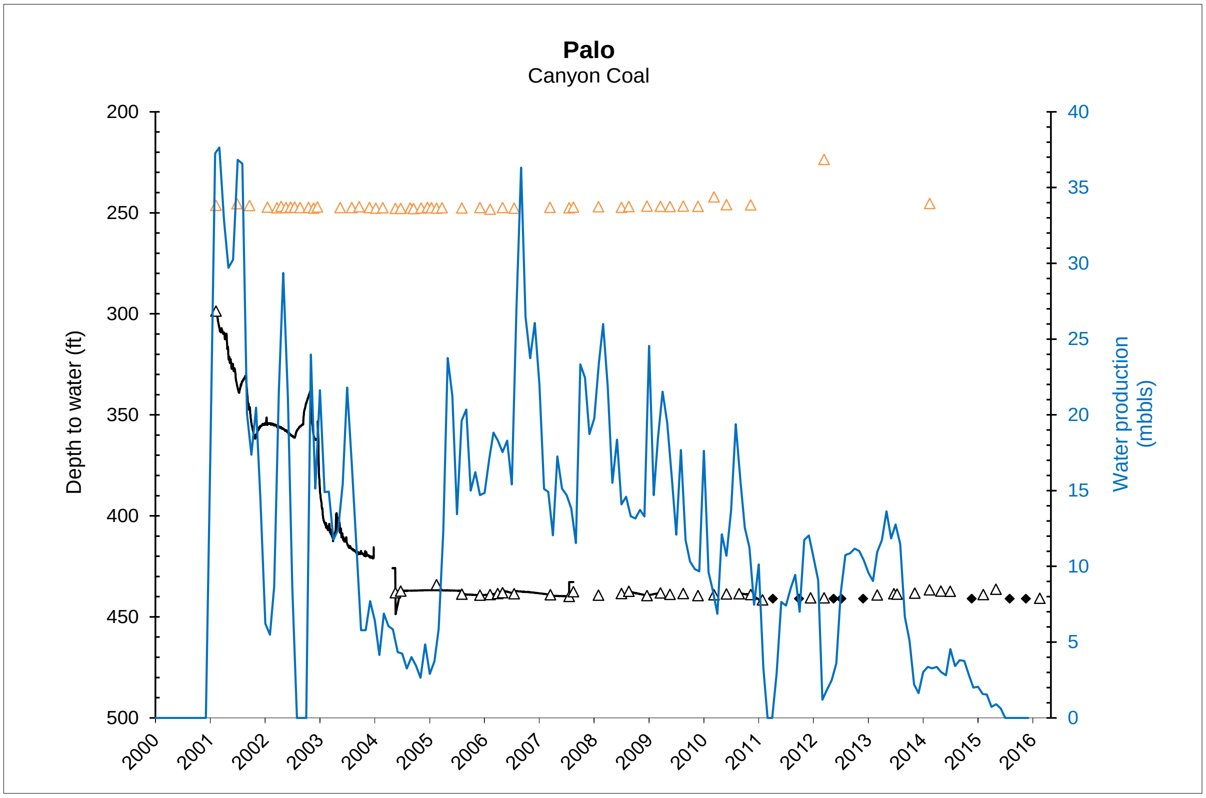

Figure A1-29. Depth to groundwater measurements in the Canyon coal seam and associated sandstone(s) at the Palo monitoring site.

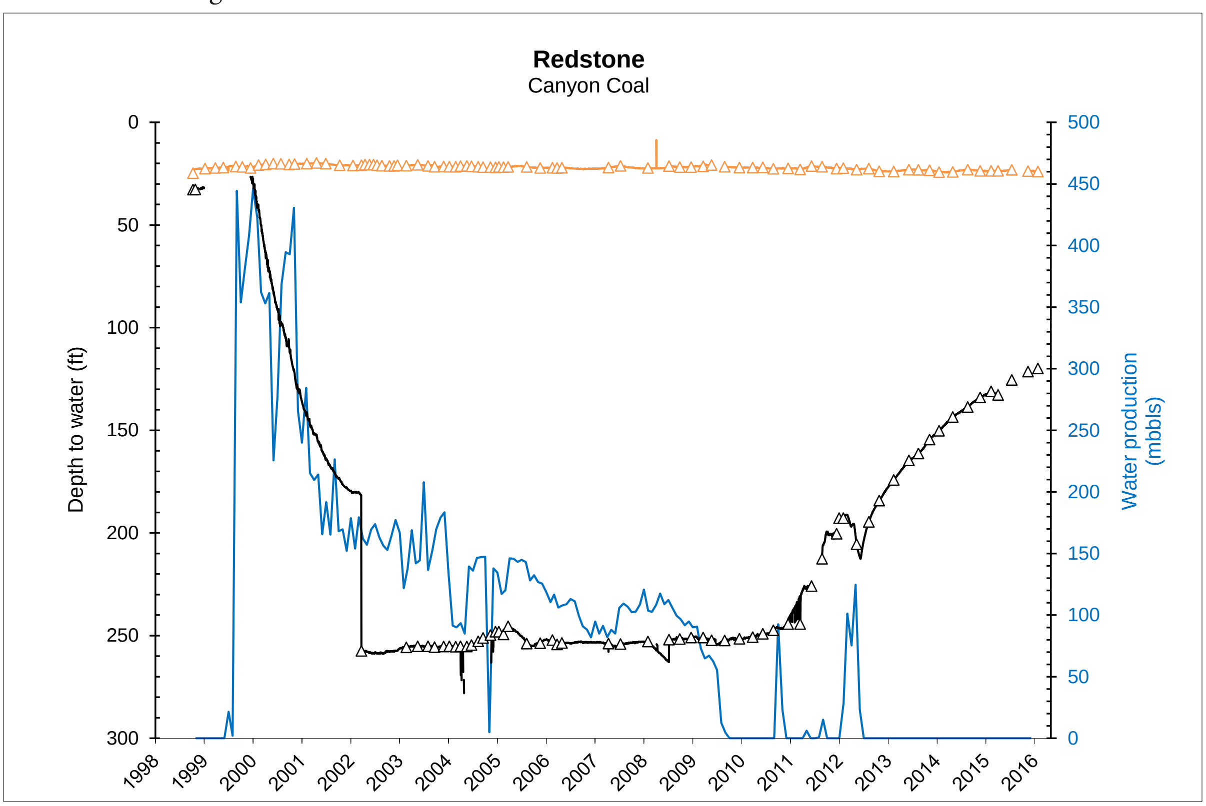

Figure A1-30. Depth to groundwater measurements in the Canyon coal seam and associated sandstone(s) at the Redstone monitoring site.

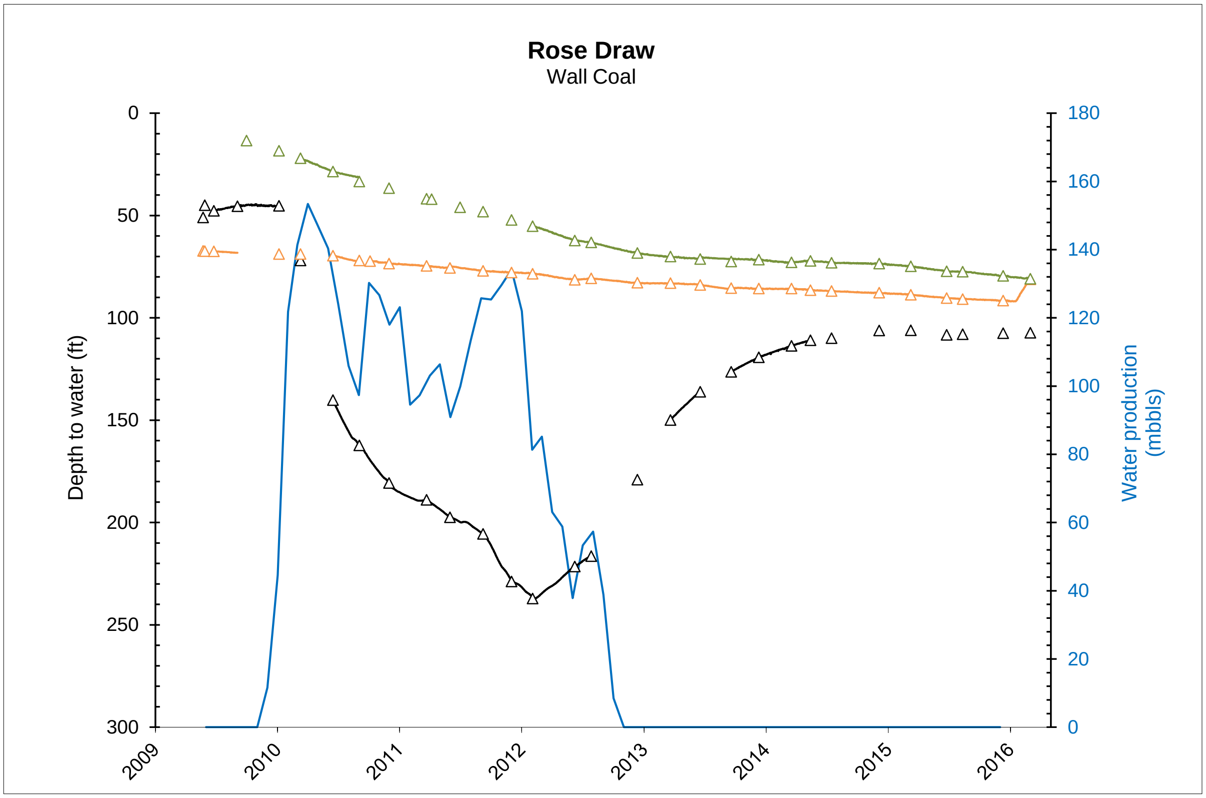

Figure A1-31. Depth to groundwater measurements in the Wall coal seam and associated sandstone(s) at the Rose Draw monitoring site.

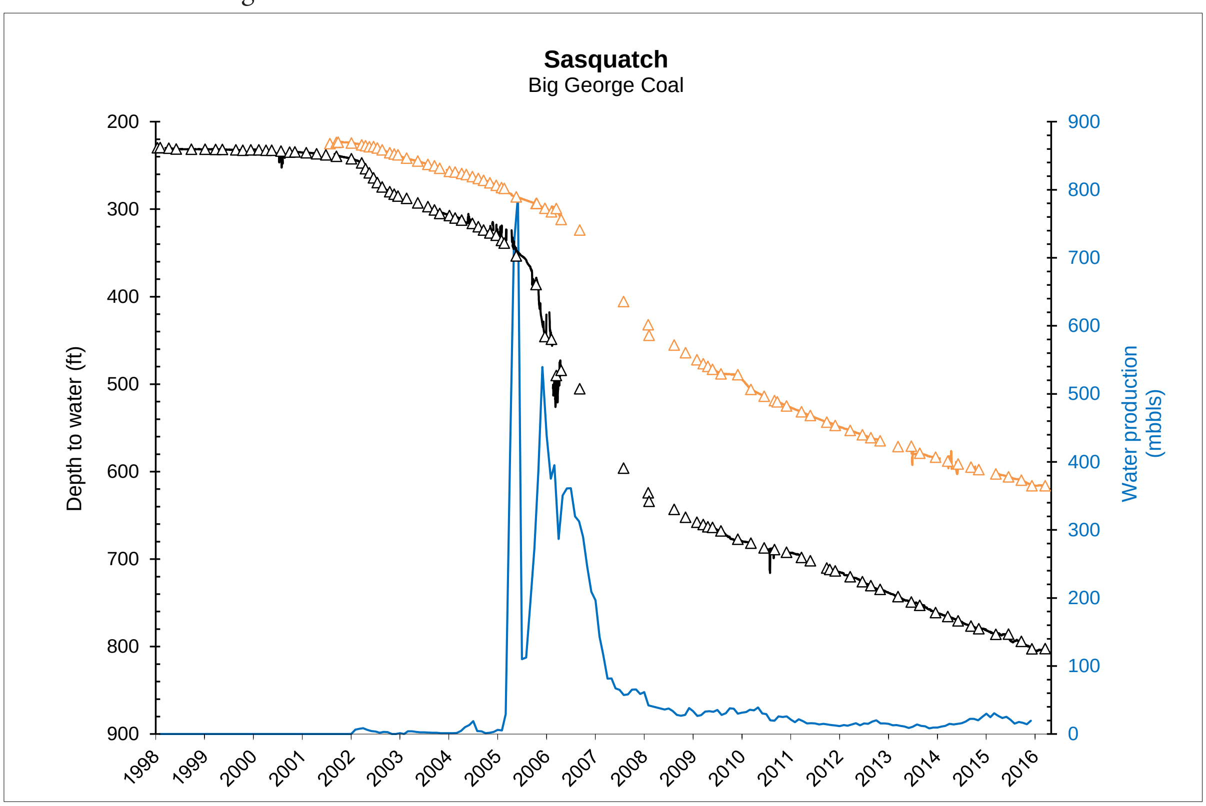

Figure A1-32. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Sasquatch monitoring site.

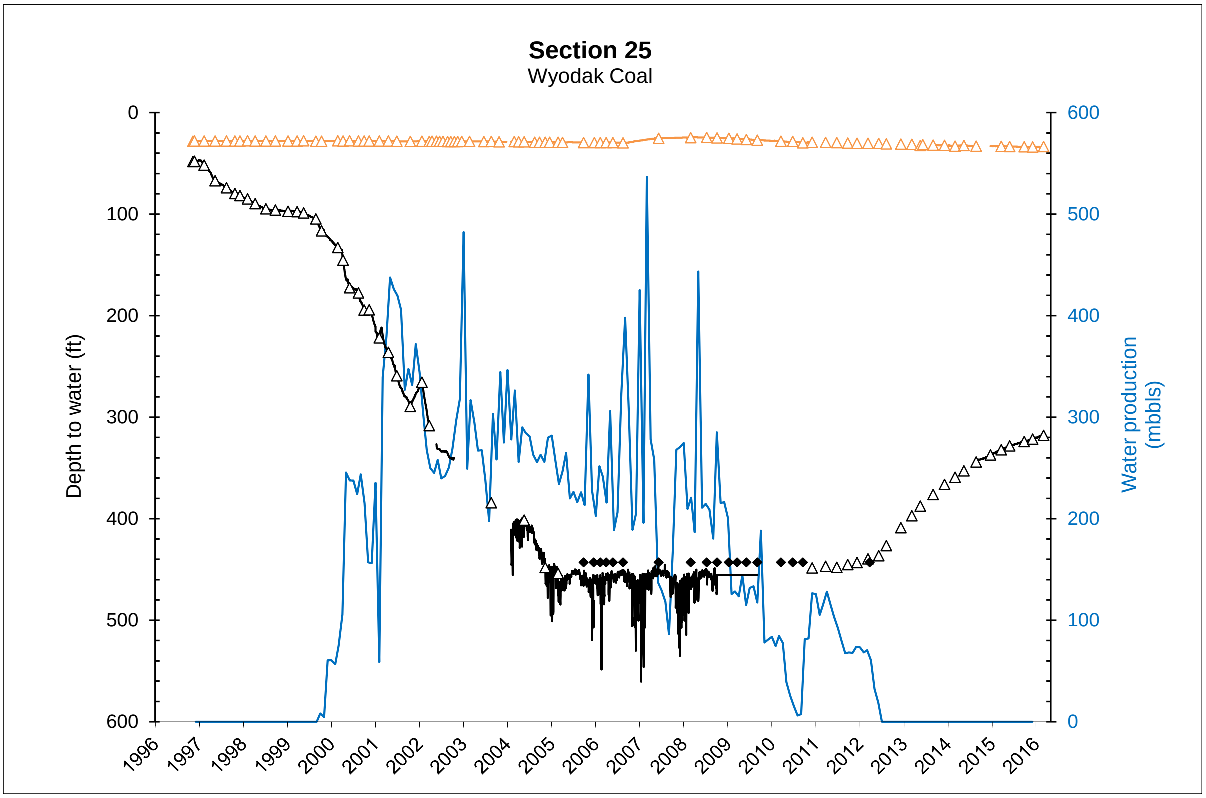

Figure A1-33. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Section 25 monitoring site.

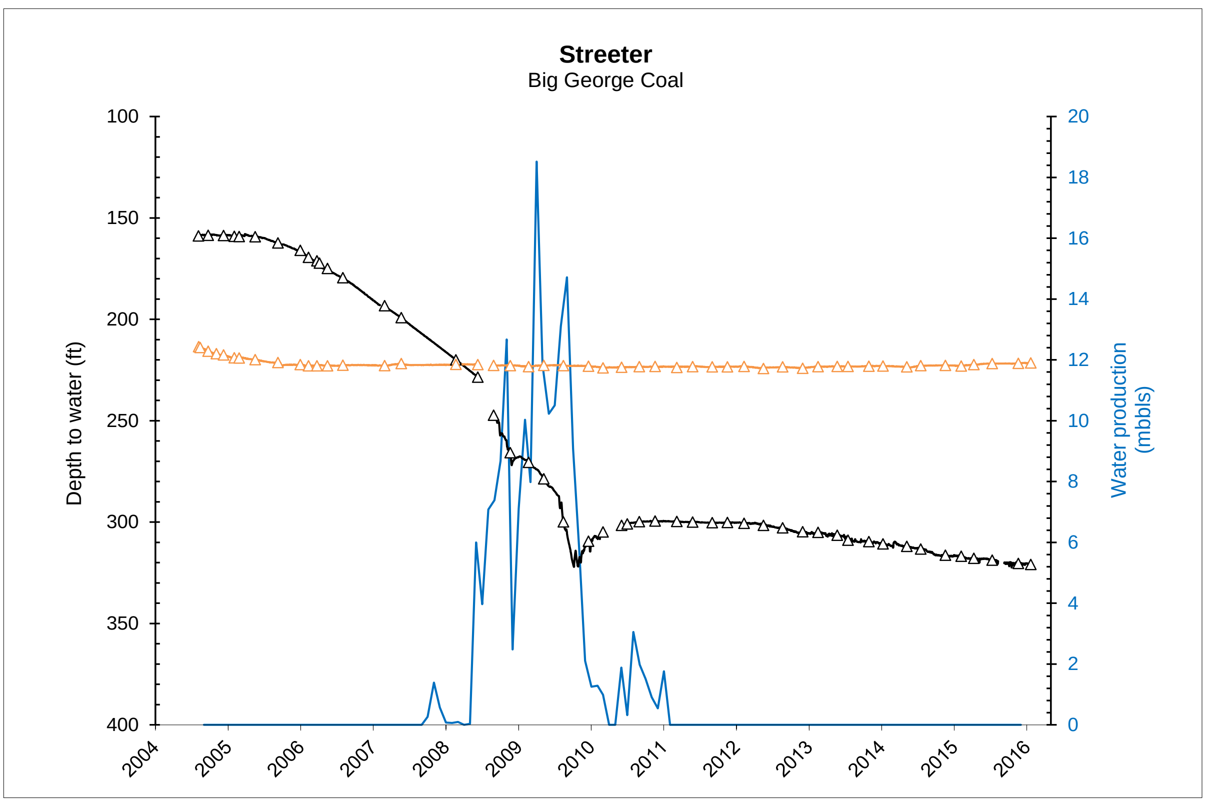

Figure A1-34. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Streeter monitoring site.

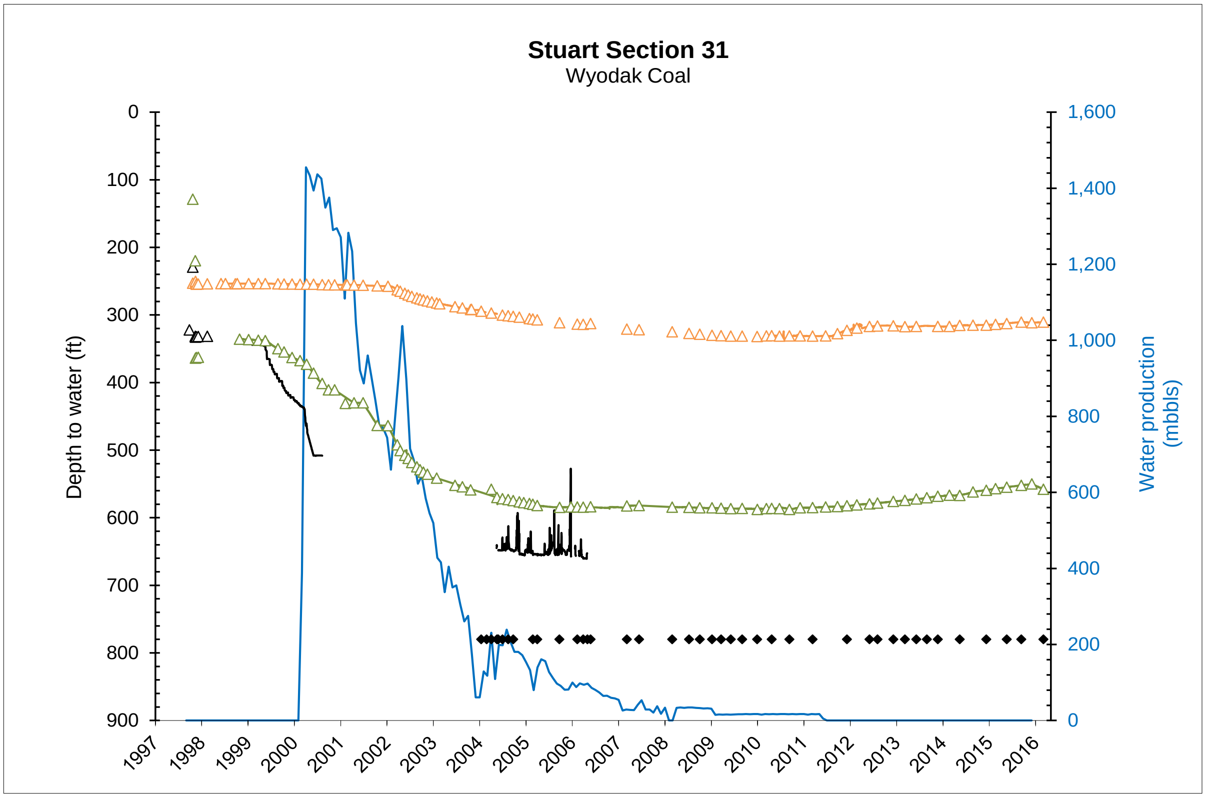

Figure A1-35. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Stuart Section 31 monitoring site.

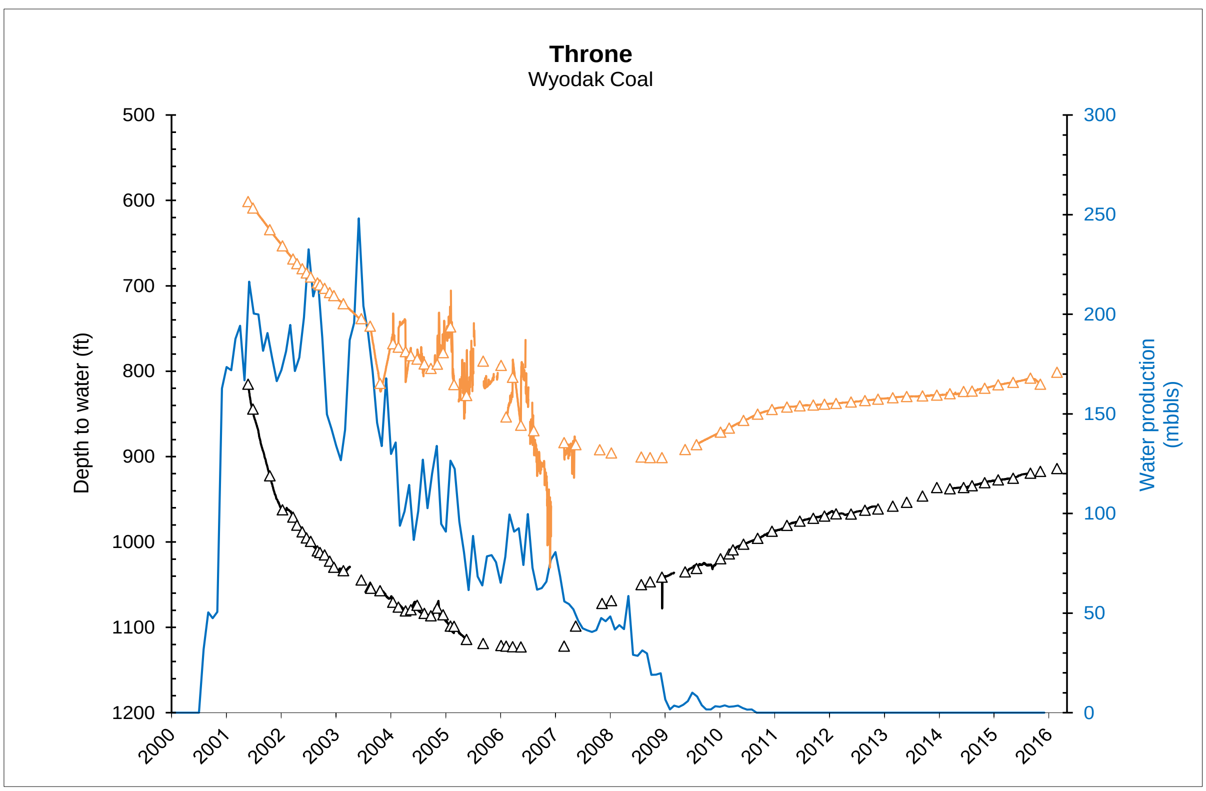

Figure A1-36. Depth to groundwater measurements in the Wyodak coal seam and associated sandstone(s) at the Throne monitoring site.

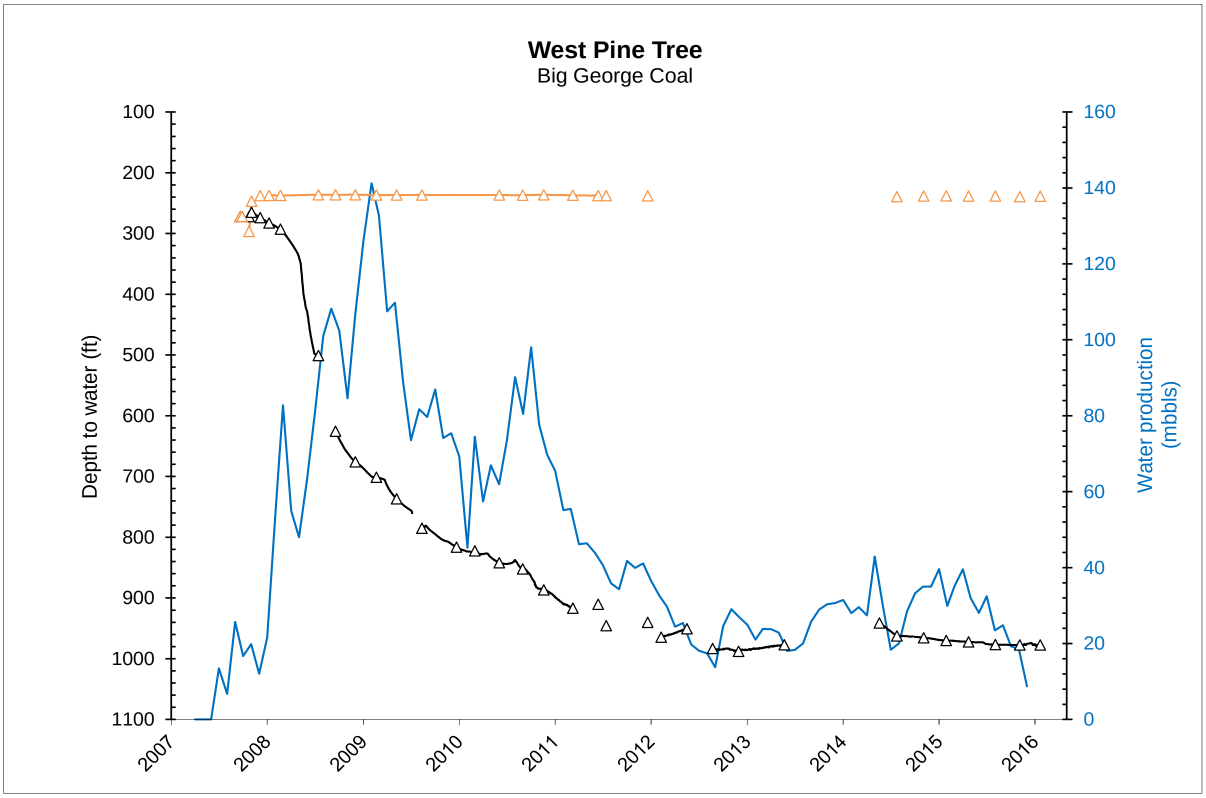

Figure A1-37. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the West Pine Tree monitoring site.

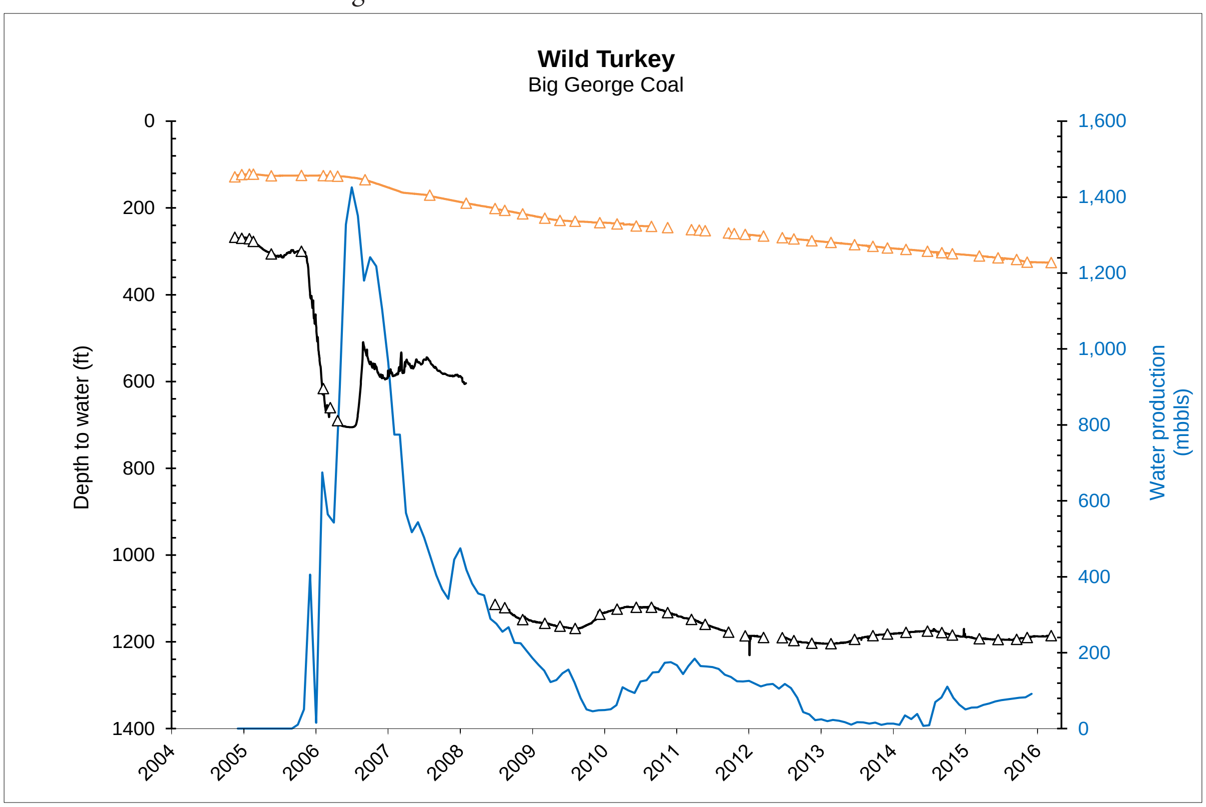

Figure A1-38. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Wild Turkey monitoring site.

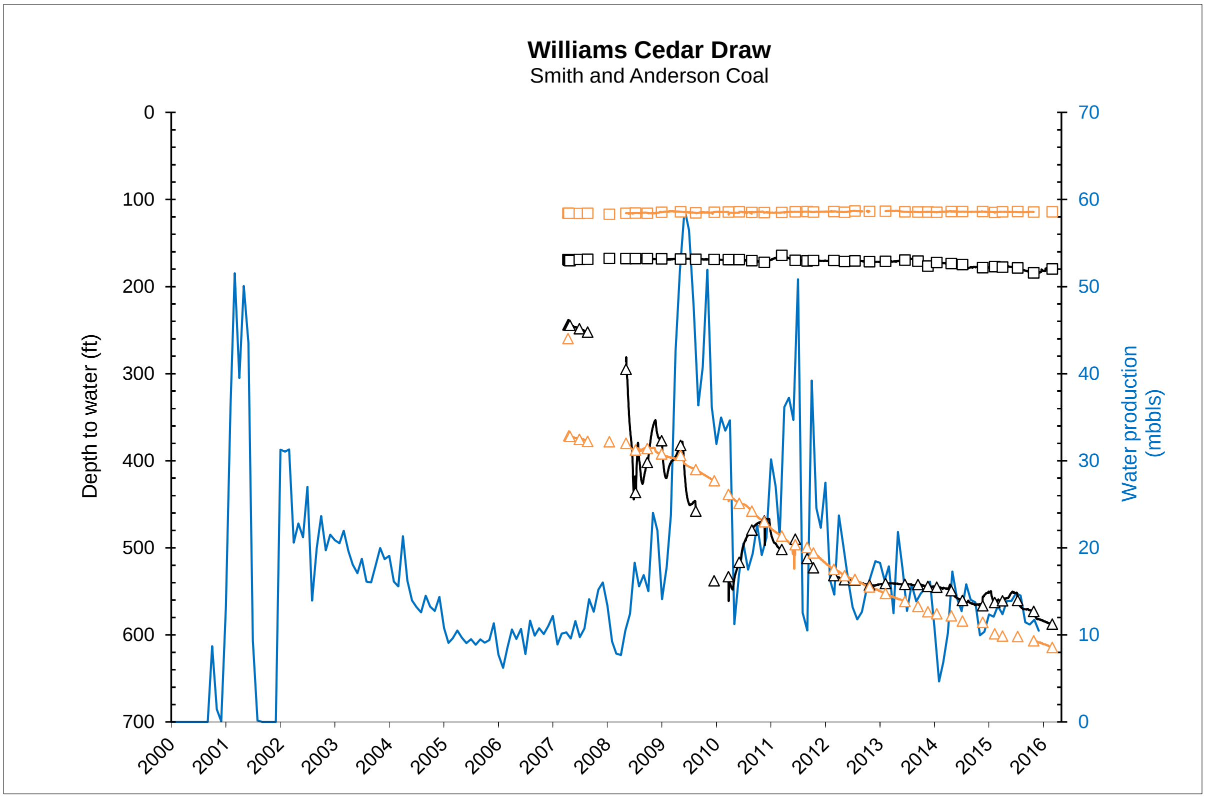

Figure A1-39. Depth to groundwater measurements in the Smith and Anderson coal seam and associated sandstone(s) at the Williams Cedar Draw monitoring site.

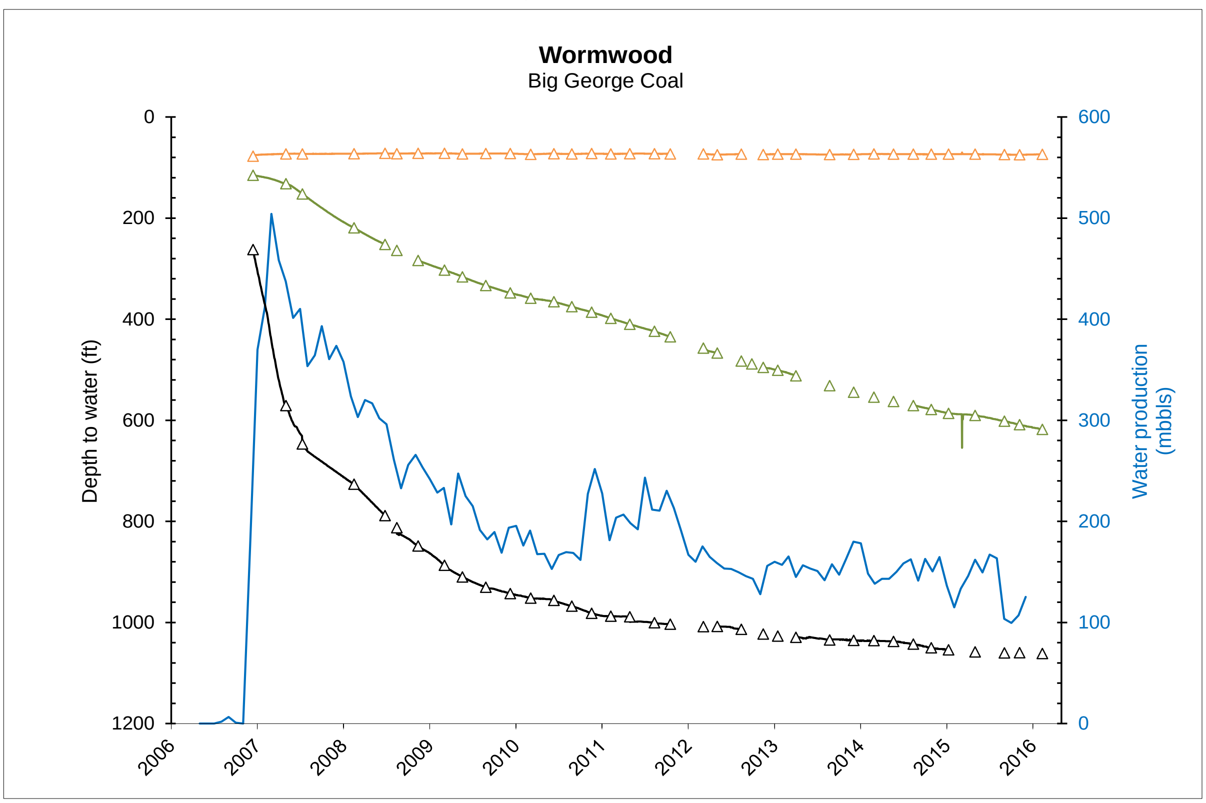

Figure A1-40. Depth to groundwater measurements in the Big George coal seam and associated sandstone(s) at the Wormwood monitoring site.

Interpreting the past, providing for the future

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