Groundwater Response in the Upper Wyodak Coal Zone, Powder River Basin, Wyoming

Karl G. Taboga, James E. Stafford, James R. Rodgers, and Chris J. Carroll

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Cover: Rochelle Hills, eastern Powder River Basin, Wyoming. This area is considered to be an important recharge area for the Upper Wyodak coal seam. Photo courtesy of James E. Stafford, WSGS, 2006.

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Abbreviations, acronyms, and symbols used in this report

Bbls	barrels (plural of oil barrel - 42 U.S. gallons)
BLM	U.S. Bureau of Land Management
Btu	British thermal units
CBNG	coalbed natural gas
DGW	depth to groundwater
Ft	feet
GIS	Geographical Information Systems
Lb	pound (weight)
MGD	million gallons per day
N/A	information not available or unknown
POR	period of record
PRB	Powder River Basin
R^2	coefficient of determination
SDGW	static depth to groundwater
µm	micro-meter
WOGCC	Wyoming Oil and Gas Conservation Commission
WSGS	Wyoming State Geological Survey

INTRODUCTION

In the past two decades, coalbed natural gas (CBNG) has developed into an important component of total U.S. natural gas production. During the decade of 2001-2010, CBNG production constituted, on average, 9.0 percent of all U.S. gas supplies (EIA, 2014). Additionally, the U.S Energy Information Administration (EIA) predicts that CBNG production will comprise about 5 percent of all U.S. gas production from 2015-2039. One of the nation's top producing CBNG areas in the lower 48 states is Wyoming's Powder River Basin (PRB). Cumulative CBNG production in the PRB through 2013 was 5.36 trillion cubic feet (WOGCC, 2014) which constitutes 16.7 percent of all CBNG produced during 1990-2013 in the United States.

CBNG production usually entails pumping large amounts of water from a targeted coal seam. As the dewatering process proceeds, water pressure decreases, desorption begins and natural gas bubbles form on the surfaces of pores and fractures within the coal. Both water and free CBNG are pumped to the surface where they are separated; the methane gas is transported to market through a series of compressor stations and pipelines. Depending on the water quality, the produced water may be released into evaporation/infiltration pits, discharged into streams, used for irrigation or livestock, or re-injected into deeper geologic formations.

Figure 1 (Kuuskraa and Brandenburg, 1989) shows production curves that generally typify the relative volumes of water and methane produced from a CBNG well over time. During the dewatering stage, 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 altogether, water levels in the targeted coal seam aquifer(s) will frequently rise, or recover in response.

Since the early 1990s, the Buffalo Wyoming Field Office of the Bureau of Land Management (BLM) has operated a network of groundwater monitoring well sites in the Wyoming portion of the PRB. This monitoring network, which currently includes 65 sites, has been designed to collect groundwater level data from the Wyodak Rider (Big George), Upper Wyodak, Lower Wyodak, Cook, and Wall coal zones. In prior years, the Wyoming State Geological Survey (WSGS) compiled the groundwater level data collected at the monitoring well sites and produced periodic reports for the BLM (Clarey and others, 2010; McLaughlin and others, 2012; Stafford and Wittke, 2013; Taboga and Stafford, 2014).

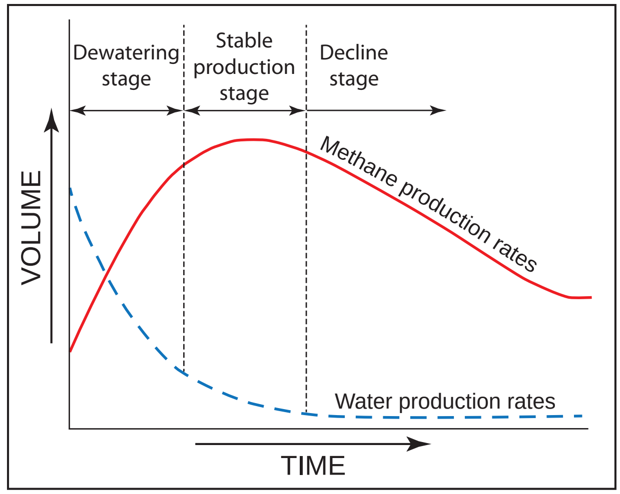


Figure 1. Typical production curves for a CBNG well depicting relative production rates of methane and water (modified from Kruuskraa and Brandenberg, 1989).

This report examines groundwater level responses to CBNG well production and recovery in the Upper Wyodak coal seam of the Powder River Basin by comparing groundwater level changes in 11 Upper Wyodak coal zone monitoring wells (fig. 2; table 1) to monthly water production from CBNG development within 1.5-mile radius buffer zones centered on each monitoring well site. Monitoring in these wells began as early as 1992 and has continued into 2014. Long term water level changes are also examined at 23 Upper Wyodak monitoring wells where initial measurements were taken prior to the onset of substantial CBNG development.

Special focus is placed on water level responses to water production declines observed as CBNG development has tapered off in recent years. Upper Wyodak water production data was obtained from the Wyoming Oil and Gas Conservation Commission (WOGCC) website at, http://wogcc.state.wy.us/.

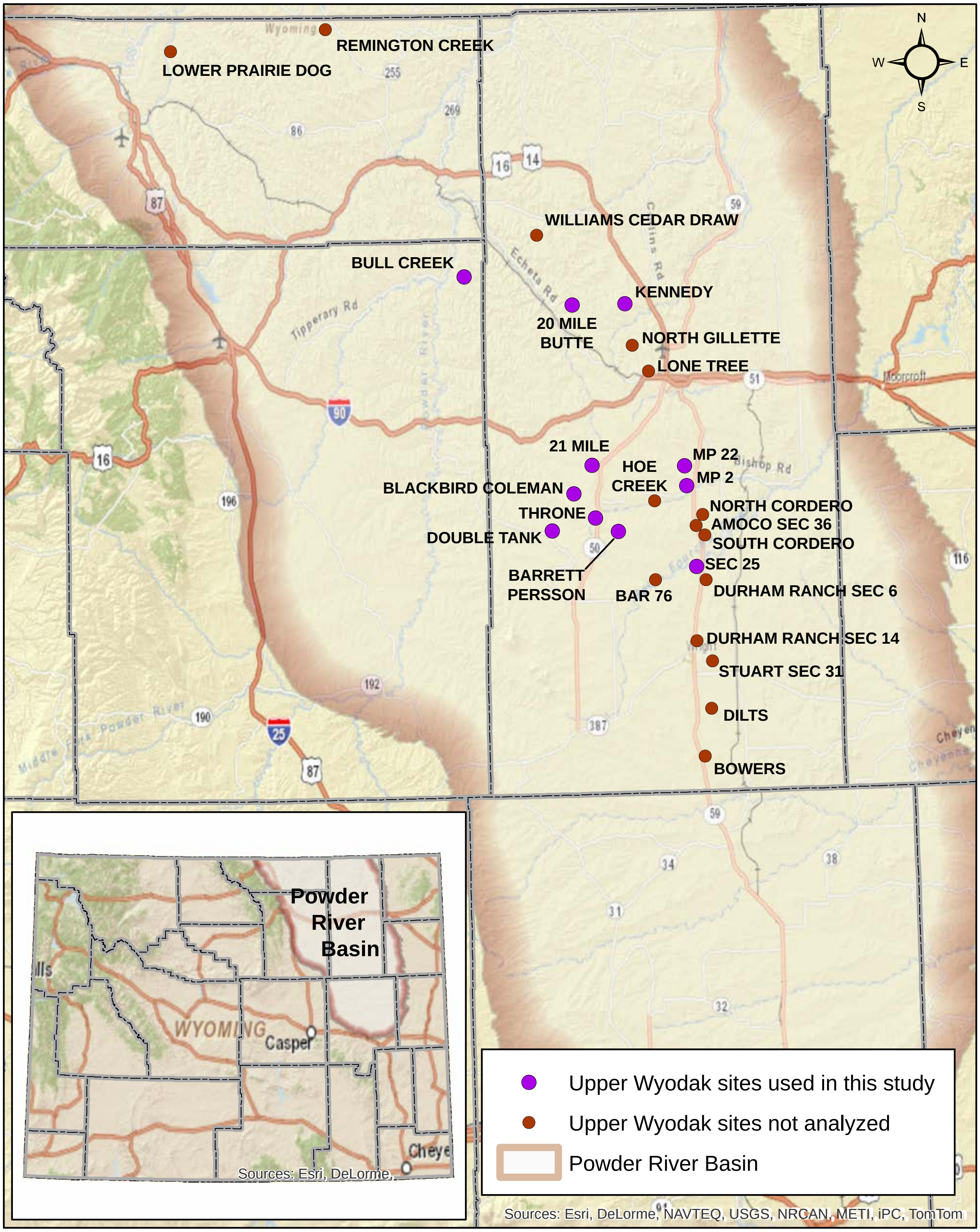


Figure 2. Location of BLM groundwater monitoring wells associated with CBNG production in the Powder River Basin, Wyoming (adapted from Stafford and Wittke, 2013).

Table 1. Selected BLM groundwater monitoring wells associated with CBNG production in the Upper Wyodak coal zone, Powder River Basin, Wyoming (modified from Stafford and Wittke, 2013).

County	Monitoring well site name	Location				Associated wells	Completed intervals	Approximate elevation (ft)	Start date
		Qtr/Qtr	Section	Township	Range				
Campbell	20 Mile Butte	SE SE	32	52 N	74 W	4	4	4557	01/28/04
	21 Mile	NE NE	22	48 N	74 W	3	3	5037	08/23/01
	Barrett Persson	SW SW	32	47 N	73 W	2	2	4945	12/06/00
	Blackbird Coleman	SW SE	5	47 N	74 W	2	2	4778	07/12/00
	Double Tank	NE SW	35	47 N	75 W	2	1	4783	12/19/02
	Kennedy	SE SE	33	52 N	73 W	2	2	4489	05/24/00
	MP 2	NW NW	2	47 N	72 W	2	2	4554	05/26/93
	MP 22	SE NE	22	48 N	72 W	4	4	4561	02/18/93
	Sec 25	SW SW	25	46 N	72 W	2	2	4659	11/09/96
	Throne	NW NW	26	47 N	74 W	2	2	5029	05/24/01
Johnson	Bull Creek	NW SE	12	52 N	77 W	3	3	3909	11/22/05

UPPER WYODAK COAL ZONE – ANDERSON COAL BED OF THE POWDER RIVER COAL FIELD, WYOMING

Geologic Setting

The Powder River Basin (PRB) is an elongate Laramide foreland basin that was in-filled through fluvial, deltaic, paludal, and lacustrine sedimentation. Mesozoic and Cenozoic sediments comprise the basin stratigraphy. Earliest formation of the structural basin was in the late Cretaceous. Rapid subsidence created a lake (Lake Lebo) which during the middle through late Paleocene was filled by fluvial-deltaic systems around the margins and deposited as sediments of 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).

Depositional Environments

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 floodplain facies (Flores, 1986). Peat accumulated in low-lying swamps and raised mires, in fluvial floodplains, abandoned channels, and interchannel environments (Flores and others, 1999).

Over time the anomalously thick PRB peats became coal deposits consisting of multiple coal beds, separated by channel-levee sandstones, and shales. Net-to-gross sandstone ratios from subsurface data indicate both north-south and east-west channel orientations, with overall sediment transport to the northeast into the early to middle Paleocene Cannonball Sea. The thickest peat deposits accumulated in raised mires well above drainage level and sustained by rainfall in a tropical climate. Generally, the coals are pod to lenticular in shape.

Mineable Coal

The Upper Wyodak coal zone lies in the Tongue River Member of the Fort Union Formation (fig. 3). It is more than 100 ft thick in the Eagle Butte coal mine area just north of Gillette, Wyoming (table 2). Where it splits, the upper bed is called the Anderson or Dietz 1 coal, and the lower bed is the Dietz 2 coal in Montana. The Wyodak coal zones are ‘early’ late Paleocene to latest Paleocene in age.

There are 12 active surface coal mines in the Wyoming part of the PRB. The Anderson coal bed ranges from 23 ft at Dry Fork Mine to 80 ft at the North Antelope Mine. It is often merged with the underlying Canyon coal of the Lower Wyodak coal zone and is mined at the Wyodak and Eagle Butte mines with a combined thickness of 85 to

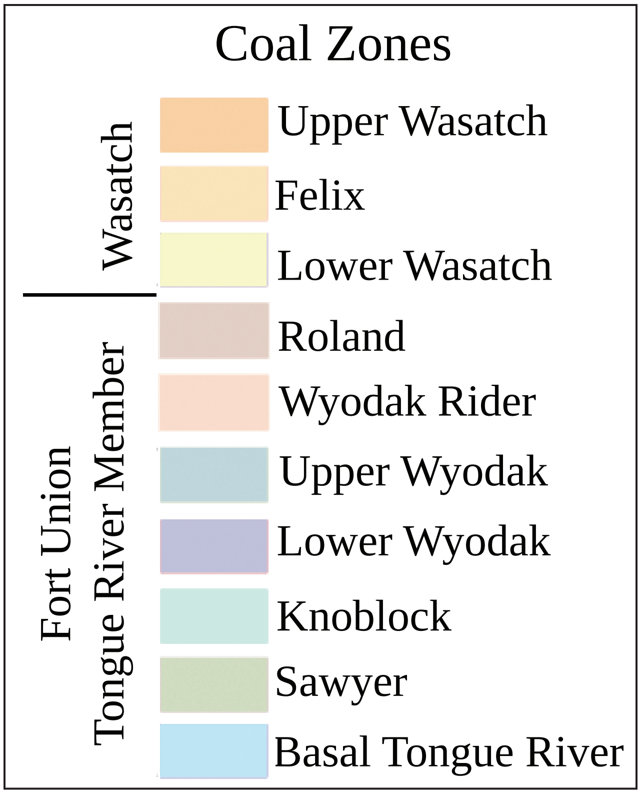


Figure 3. Coal zone nomenclature of the PRB (modified from Jones and Rodgers, 2007).

100 ft. Overburden to the Anderson coal bed ranges from 0-300 ft at these mines.

The coal rank of the Wyodak-Anderson is subbituminous with some lignite. The mineable coal has very low ash and sulfur, as well as low trace elements. Moisture is high, around 30 percent (Jones, 2010). Heat values range from 7,900 British thermal units per pound (Btu/lb) to 9,000 Btu/lb.

Stratigraphy

The Fort Union Formation in the PRB ranges from 2,300 to 6,000 ft thick. The thickest section is located in the western part of the basin, on the current basin center axis. It consists of conglomerate, sandstone, siltstone, mudstone, and lesser amounts of limestone, carbonaceous shale, and coal. The Wyodak Rider, Upper Wyodak, and Lower Wyodak coal zones contain as many as 11 coal beds. The coal beds within these coal zones were previously named, from top to bottom: Smith, Swartz, Badger, School, Sussex, Big George, Wyodak, upper and lower Wyodak, Anderson, Dietz, Canyon, and Werner (Flores and others, 1999).

A recent nomenclature change by the WSGS modifies these coal beds into basin-wide correlative coal zones (Jones, 2008). This is illustrated by WSGS cross-sections A-A' through F-F' (Appendix) by Nick Jones and James Rodgers (2007). Cross-section A-A', running 87 miles west northwest-east southeast in the northern part of the Wyoming PRB, shows that the Wyodak Rider coal zone contains the Smith and Lower Smith coal beds. The Lower Smith coal bed only occurs near the Montana border in the northwest side of the cross-section. The underlying Upper Wyodak coal zone contains the Anderson and Lower Anderson coal beds (also called the Wyodak-Anderson coal zone by Flores and others, 1999). The Wyodak-Anderson coal zone can be up to 900 ft thick. Beneath this coal zone the lower Wyodak coal zone contains the thick Canyon coal bed, and is very thick near Gillette on the east side of the cross-section. The Anderson and Canyon coal beds merge near Gillette at the Eagle Butte and Dry Fork mines. The Eagle Butte Mine has a 40 ft thick Anderson bed and a 60 ft Canyon bed with 2 ft of parting dipping about 4 degrees west. The Dry Fork Mine has a 23 ft thick Anderson bed, 4-12 ft of carbonaceous mudstone interburden, and a 60 ft thick Canyon bed below, with the same dip. The overburden on the Anderson coal bed at the Dry Fork Mine is 30-160 ft thick, and at the Eagle Butte Mine it is 50-300 ft thick. The Lower Canyon bed is thin near the Powder River, and then both beds thin northwest of the Powder River.

On cross-section B-B' which runs southwest to northeast across the northern part of the Wyoming part of the PRB, the Upper Wyodak coal zone contains a very thick Anderson coal bed from the eastern outcrop to the Powder River. Southwest of the river it splits into three coal beds, an unnamed upper bed, the Anderson (main bed), and the Lower Anderson coal bed.

Cross-section C-C' is parallel to B-B' but is 20 miles to the south. A very thick Anderson coal bed (top of the Upper Wyodak coal zone) underlies the Powder River. It thins to the northeast and splits into two moderately thick coal beds. The Dry Fork Mine has a 23 ft thick Anderson bed, 4-12 ft of carbonaceous mudstone interburden, and a 60 ft thick Canyon bed of the Lower Wyodak below. The overburden on the Anderson coal bed at the Dry Fork Mine is 30-160 ft thick, and at the Eagle Butte Mine it is 50-300 ft thick, dipping 4 degrees west.

In cross-section D-D', 10 miles south of Gillette, the Wyodak Rider coal zone contains the Smith/Big George coal beds. The underlying Upper Wyodak coal zone contains the Anderson and Lower Anderson coal beds. Cordero Rojo and Belle Ayr mines are at D' and both mine

Table 2. Active coal mine operations in the PRB of Wyoming, 2014 (modified from WSGS website, www.wsgs.wyo.gov/Research/Energy/Coal/Production-Mining.aspx).

Mine Names	Parent Company	PRB Coal Zone	Producing Beds	Seam Thickness	Bedding Dip in degrees	Overburden	BTU/lb from mine permit
Antelope Mine	Cloud Peak Energy Resources, LLC	Upper Wyodak	Anderson	A: 44 ft C: 36 ft	2 degrees west	N/A	8,880
Belle Ayr Mine	Alpha Natural Resources	Upper Wyodak	Anderson	70-75 ft	4 degrees west	240-285 ft	8,542
Black Thunder Mine	Arch Coal	Upper Wyodak	Anderson	70 ft	none	0-230 ft	9,011
Buckskin Mine	Peter Kiewit & Sons	Upper and Lower Wyodak	Anderson-Canyon (minor Smith bed in the Wyodak Rider zone)	A:30-40 ft C: 60-70 ft	3 degrees west	250 ft	8,297
Caballo Mine	Peabody Energy	Wyodak Rider and Upper Wyodak	Smith, Anderson	68 ft	3 degrees west	230 ft	8,501
Coal Creek Mine	Arch Coal	Upper Wyodak	Anderson	33 ft	1 degree west	N/A	8,400
Cordero Rojo Mine	Cloud Peak Energy Resources, LLC	Upper Wyodak	Anderson (Roland?)	55-70 ft	1 degree west	N/A	8,400
Dry Fork Mine	Western Fuels, Inc.	Upper and Lower Wyodak	Anderson-Canyon merged	A:23 ft 4-12 ft interburden carbonaceous mudstone; Canyon 60-65 ft	4 degrees west	30-160 ft	8,125
Eagle Butte Mine	Alpha Natural Resources	Upper and Lower Wyodak	Anderson-Canyon merged	A: 40 ft C: 60 ft, parting is 1-2 ft	4 degrees west	50-300 ft	8,434
North Antelope Rochelle Mines	Peabody Energy	Upper Wyodak	Anderson	72-80 ft	0-2 degrees northwest	70-300 ft	8,800
Rawhide Mine	Peabody Energy	Roland?	Upper Roland and Lower Smith?	UR: 30 ft; LS: 75 ft	3 degrees west	165 ft	8,300
Wyodak Mine	Black Hills Corp	Upper and Lower Wyodak	Anderson-Canyon merged	85 ft total	2 degrees northwest	0-100 ft	7,900

the very thick Anderson coal bed of the Wyodak coal zone. Belle Ayr reports a coal bed 70-75 ft thick (240-285 ft of overburden), while Cordero Rojo mines a 55-70 ft thick Anderson coal bed.

On cross-section E-E', 20 miles south of Gillette, the Upper Wyodak coal zone contains a very thick Anderson coal bed. The Black Thunder and School Creek mines both mine the Anderson coal bed at 70 ft thick, with a maximum overburden thickness of 230 ft and a westward dip of less than 1 degree.

On cross-section F-F' (120 miles long, north-northwest to south-southeast orientation) about 20 miles west of Gillette and closer to the center of the basin, the Wyodak Rider coal zone contains the very thick Smith/Big George coal beds, but only north of the Belle Fourche River. The underlying Upper Wyodak coal zone contains the very thick Anderson coal bed and the lower Anderson bed. These beds nearly merge near Gillette then split from there to the north. Beneath this coal zone the lower Wyodak coal zone contains the Canyon coal bed in the southern part of the cross section only. The Lower Canyon bed is thicker near the Powder River, but is not present north of Crazy Woman Creek.

COAL SEAM HYDROGEOLOGY

Introduction

Water saturated coal seams can act as aquifers. An aquifer is a geologic unit that contains adequate water-saturated and permeable materials to yield sufficient quantities of water to wells and springs (Lohman and others, 1972). Saturated coal seams serve as important sources of water in the Powder River Basin (PRB). In the eastern basin, domestic wells are frequently completed in coal seam aquifers where groundwater quality meets federal drinking water standards and livestock wells extract groundwater from coal aquifers throughout the basin.

Dual Porosity

Like other hydrogeologic units, coal aquifers possess both primary (intergranular, or matrix) and secondary (fracture) porosity (Li and others, 2012). Although both of these systems store and transport water and are hydrologically interconnected, there are wide differences in their hydraulic characteristics. Typically, primary porosity can store large amounts of groundwater, which is transported or conducted slowly. Fracture porosity, on the other hand, is generally characterized by low storage but high conductivity. These hydraulic properties largely influence the aquifer response to CBNG production.

Primary, or matrix, porosity in coals is composed of a hierarchy of pore systems ranked by size (Hodot, 1966): molecular scale micro-pores (less than 0.01 µm in diameter), transitional pores (0.01 – 0.1 µm dia.), meso-pores (0.1 – 1.0 µm dia.), and macro-pores (> 1.0 µm dia.). Matrix pores are generally saturated with water and adsorbed gases such as methane, carbon dioxide and. Matrix porosity is characterized by low permeabilities and high storage capacities.

Several types of fractures constitute the secondary, or fracture, porosity in coal seams. Fractures, traditionally designated by the mining industry as "cleats," have been extensively examined since the late 1800s. Early studies were conducted to improve the safety and efficiency of mining operations and generally provided broad descriptions of the occurrence, frequency, and orientation of fracturing. In the last 20 years, the growing importance of coalbed methane development has driven a renewed interest in the study of coal fracturing as geologists and engineers seek to understand how water and methane move through coal seams during CBNG production.

Most fractures in coals are assigned to one of two classes of cleats. Face cleats, which form first, are usually well defined, dominant, widely spaced and continuous. Butt cleats, formed secondarily, usually extend only between face cleats and are poorly defined. Face cleats and butt cleats are perpendicular or orthogonal to coal bedding planes and to each other (fig. 4). The distance between adjacent cleats can range from fractions of an inch to several feet and smaller fractures called microfractures are widespread. Although the origin of cleats is still under debate, cleat formation most likely results from compaction and contraction of the coal volume during coalification and from tectonic processes (Ting, 1977).

Groundwater Flow in Coal Seams

Weeks (2005) described the flow of groundwater in a coal seam aquifer during pumping. In the early stage, discharged water is produced predominately from fracture storage. As hydrostatic pressure declines in the fractures, interporosity flows are initiated and water flows slowly from the coal matrix into the cleat system at a variable rate. Finally, matric and fracture flows reach equilibrium and heads in both systems decline at the same rate.

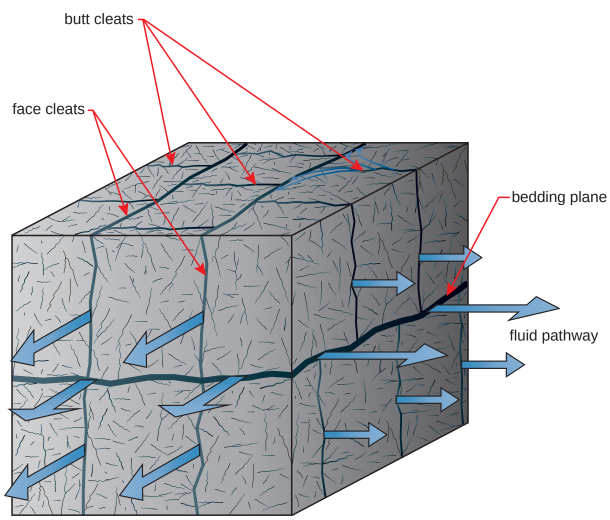


Figure 4. Cleat system and water flow. Graphic by James R. Rodgers,WSGS, 2014.

Coal seams exhibit horizontal hydraulic anisotropy because permeabilities are controlled by the type, orientation, frequency and aperture of the cleats. Typically, the directions of the maximum and minimum horizontal hydraulic conductivities correspond to the strike of the face and butt cleats, respectively (Stone and others, 1977; Pyrak-Nolte and others, 1993). However, other fracture sets that are independent of the cleat system, such as a fault damage zone, may control or influence the orientation of anisotropy (Weeks, 2005).

The fracture system is highly permeable but possesses low storage capacities. Fracture conductivities range from tenths of a foot to tens of feet per day but fracture porosity is usually less than 1 percent (Pyrak-Nolte and others, 1993).

Well Drawdown and Recovery

The timing and magnitude of groundwater responses to well pumping and recovery are difficult to predict and explain because numerous internal and external factors influence groundwater release, storage, and subsequent replenishment. Aquifers are complex subterranean environments where physical, spatial, and hydraulic characteristics are highly variable (anisotropic), site specific and in many cases must be inferred from indirect measurements. Intrinsically, the design and completion of the production well and the hydrogeologic properties of the target aquifer largely determine the rate of water production and groundwater level responses. However, external factors such as recharge, additional groundwater production from contiguous areas and the presence of adjacent hydrogeologic units, flow boundaries, geologic structures, and surface water bodies also influence groundwater responses.

Hydraulic Properties

Numerous studies have examined the hydraulic properties of the Upper Wyodak coal seam. Hydraulic properties vary widely between the matrix and cleat systems. Observed hydraulic conductivities, obtained during aquifer tests are dominated by the conductivities of the cleat systems. Rehm and others (1980) found that hydraulic conductivities ranged from 0.37 – 2.71 ft /day (geometric mean about 1 ft /day) in 193 samples of Fort Union coals from Wyoming, Montana, and North Dakota. Martin and others (1988) reported a geometric mean conductivity of 0.8 ft /day for 357 aquifer tests conducted by coal companies in the Eastern Powder River Basin. Peacock (1997) reported a geometric mean of 0.5 ft /day for 166 hydraulic conductivity tests in the central PRB. In contrast to these field conductivities, hydraulic conductivity in the matrix runs about 10^{-6} ft /day (McKee and others, 1988).

Wide variations exist also in both matrix storage coefficients and porosities when compared to those of the cleat system. Matrix porosities range from 4 percent to 23 percent while fracture porosity is usually less than 1 percent, (Pyrak-Nolte and others, 1993). Weeks (2005) reported combined (matrix and fracture) specific storage values of around 7 X 10^{-5}/ft compared to 2X10^{-5}/ft for the fractures alone.

Sources and Sinks

Aquifer inflows (sources), outflows (sinks) and storage volumes are frequently defined with a mass balance equation:

$$\textit{Outflows} - \textit{inflows} = \textit{change in storage.}$$

Typically, all three terms are expressed in units of mass, volume or flux (mass/time). In some cases, a mass balance model can determine the presence or magnitude of an unknown flow component if the volumes of other flows entering and leaving the aquifer are well quantified. Frequently, however, more than one flow volume is unknown and the mass balance equation is used to estimate a combination of multiple unknown flows. For example, if outflows are well quantified and changes in storage are known, then the volume of combined inflows from all sources can be determined. Even so, it may not be possible to break down an accurate estimation of total inflow, obtained from the application of a mass balance model, into individual inflow components such as annual recharge or leakage from an adjacent confining unit.

Outflows include volumes of water produced by wells within and outside of the area of interest, dewatering operations at nearby mines, discharges to water bodies, down-gradient groundwater flows from the target aquifer exiting the area of interest and leakage into adjacent hydrogeologic units. Inflows consist of direct or up-gradient recharge, leakage from adjacent hydrogeologic units and inputs from adjoining surface water bodies, injection wells and irrigation. Although the change in storage should be expressed in the same units as the two flow terms, in some practical applications, it may be discussed as the change in the depth to groundwater observed over the same time period as the two flow terms. For the monitored well fields in this study, the only flow term that has been quantified is the volume of CBNG co-produced water pumped from the Upper Wyodak coal zone during the monitoring period.

Water Level Responses to Pumping and Recovery

When a single well is pumped at a constant production rate in a homogeneous, isotropic aquifer, a radial cone of depression will form around the pumping well (fig. 5) in a manner consistent with one of the predictive analytical models developed by hydrogeologists over the last century. The term "homogeneous" means that the aquifer material is composed of a uniform material throughout its entirety. "Isotropic" indicates that the hydraulic properties of the aquifer are equal in all directions. Many factors such as the pumping rate of the well, the hydraulic properties and thickness of the aquifer, and the amount of water in storage can affect the size and shape of the cone of depression in a homogeneous, isotropic aquifer. When pumping ceases at the single production well, described above, the cone of depression becomes smaller in radius and depth and gradually the water level in the aquifer returns to its previous height. The period of time required for this depends on the size of the cone of depression, the magnitudes of aquifer inflows and outflows, and the aquifer's hydraulic properties.

An idealized plot of drawdown and recovery as a function of time for an observation well located 1,000 ft from a single pumping well in a confined homogeneous, isotropic aquifer is shown in figure 6. The drawdown and recovery plot was generated using the Theis non-equilibrium equation (Theis, 1935) and physical and hydraulic properties characteristic of PRB coal aquifers: hydraulic conductivity, K= 1 ft /day; aquifer thickness, b = 60 ft; storage coefficient, S=7 X 10 $^{-5}$; and a constant water pumping rate of 5,000 ft^3/day (~ 890 bbls/day). Further, the Theis equation makes the following assumptions:

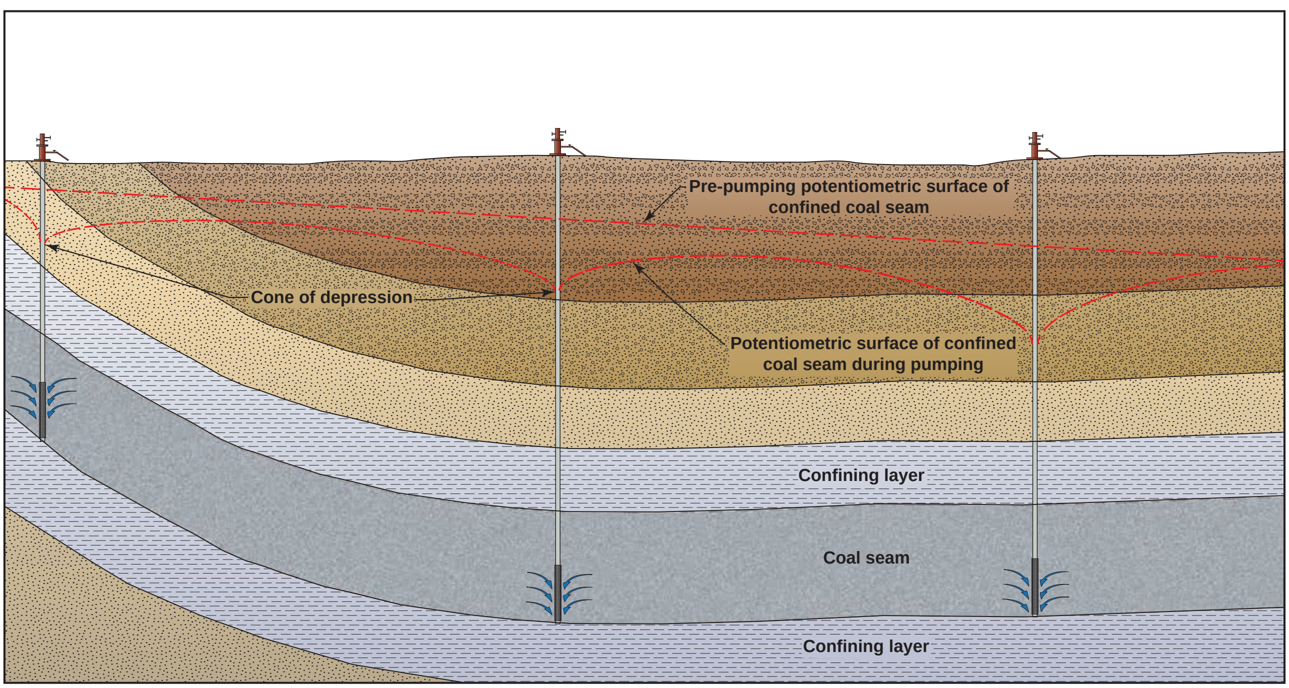


Figure 5. Cones of depression (red dashed lines) in potentiometric surface (groundwater level), in an over pressured coal, forming around pumping wells. Graphic by James R. Rodgers, WSGS, 2014.

- the aquifer is confined both top and bottom;
- there is no source of recharge to the aquifer;
- the aquifer is compressible and water is released instantaneously to the pumping well and;
- the well is pumped at a constant rate.

Although the general shape of these curves is readily apparent in several of the monitoring well hydrographs shown later in this report, in practice, producing CBNG wellfields operate within highly variable natural environments. Coal seam aquifers are neither homogeneous nor isotropic. 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 wellfield 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. Finally, an understanding of the quantity, timing, and variability of local and regional sources and sinks in the Upper Wyodak coal seam is far from complete. In short, the water level changes observed at the monitoring wells in this report occurred in complex and constantly fluctuating environments.

Furthermore, water level responses to the initiation or cessation of pumping do not occur immediately but depend on an aquifer's diffusivity which is considered to be a measure of the speed with which it reacts to changes in flow. Diffusivity is the ratio of conductivity to specific storage (K/Ss). Using the geometric mean conductivity of 1.0 ft/day (Rehm and others, 1980) and combined specific storage values of 7 X 10^{-5}/ft (Weeks, 2004), yields a hydraulic diffusivity of about 14,000 ft^2/day.

Recharge and Groundwater Movement in the PRB

The Upper Wyodak coal seam aquifer is part of the Upper Fort Union aquifer (Thamke and others, 2014), which in Wyoming includes the Tongue River Member of the Fort Union Formation and the Wasatch Formation. The Upper Fort Union aquifer extends northeasterly through the Powder River Basin of Wyoming and southeastern Montana into the Williston Basin of northeastern Montana, western North Dakota and southern Saskatchewan.

Recharge (fig. 7) likely enters the Upper Wyodak coal zone as direct precipitation and infiltrating streamflows at associated fractured clinker outcrops located along the eastern

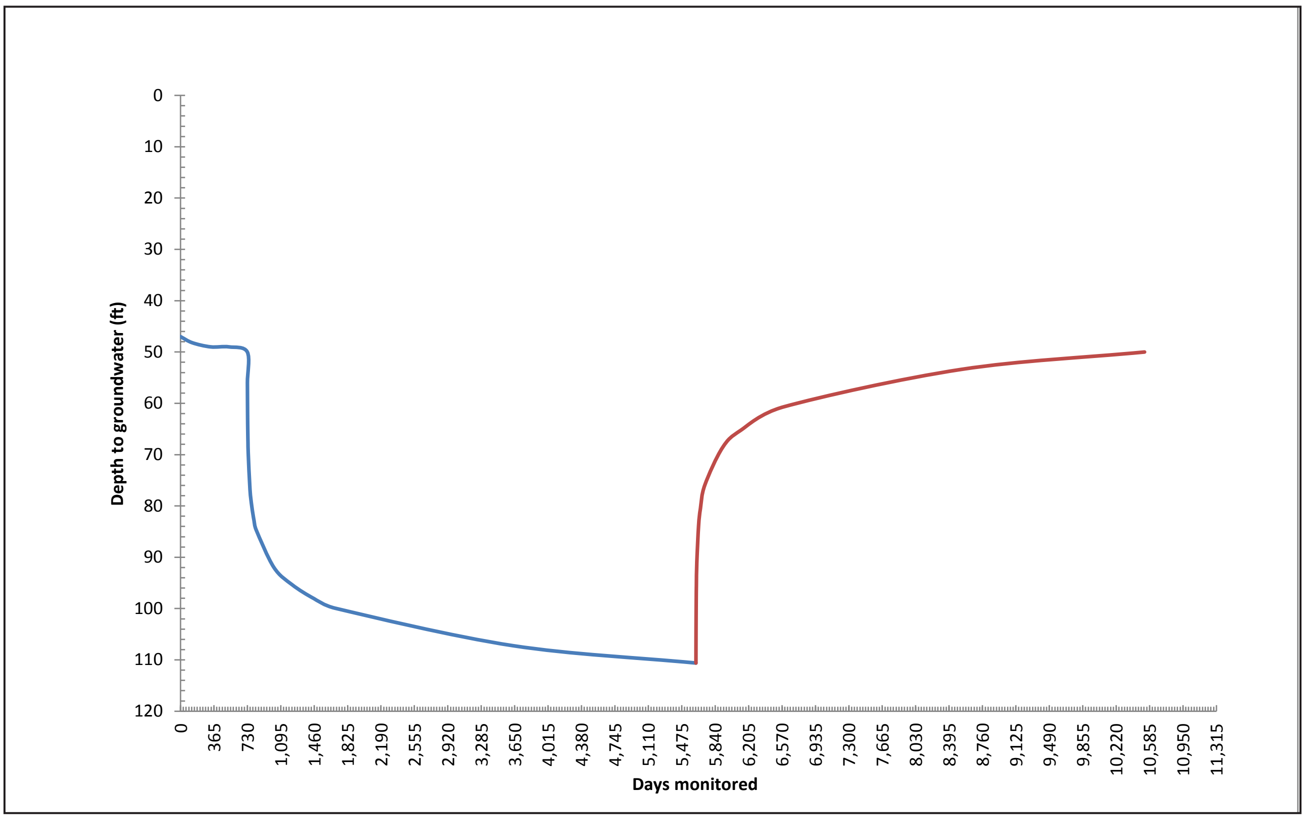


Figure 6. Drawdown and recovery curves in a isotropic confined aquifer.

margin of the PRB. Clinker is the vitrified residue that formed where coal outcrops were ignited by wildfires or lightning. These natural coal fires were extinguished when they reached depths where the available oxygen was not sufficient to support further combustion. Clinker deposits in the PRB are heavily fractured, highly permeable and widely distributed in close proximity to shallow deposits of Wyodak coals (Heffern and others, 2013). After infiltrating the clinker, recharge flows down dip through the coal seam under pressure. Regionally, groundwater in the Wyodak aquifer follows the topography of the PRB (Thamke and others, 2014) and flows to the north. Discharges occur at springs in drainages that incise shallow coal seam outcrops and to adjacent hydrogeologic units in areas where the Upper Wyodak is deeply buried.

METHODS

Water level changes during CBNG development

Groundwater level data were obtained from the Bureau of Land Management (BLM). The Wyoming Oil and Gas Conservation Commission (WOGCC) provided monthly water production rates for CBNG wells in the PRB. WSGS assigned water production values for each CBNG well to particular coal zones, when possible. Production from CBNG wells completed in undetermined and multiple coal seams is allocated to "unknown" and "multiple" zones, respectively. Also, WSGS created an "unmonitored" classification for production from coal zones that differs from the zone in which the groundwater monitoring well is completed. For instance, production from the Wyodak

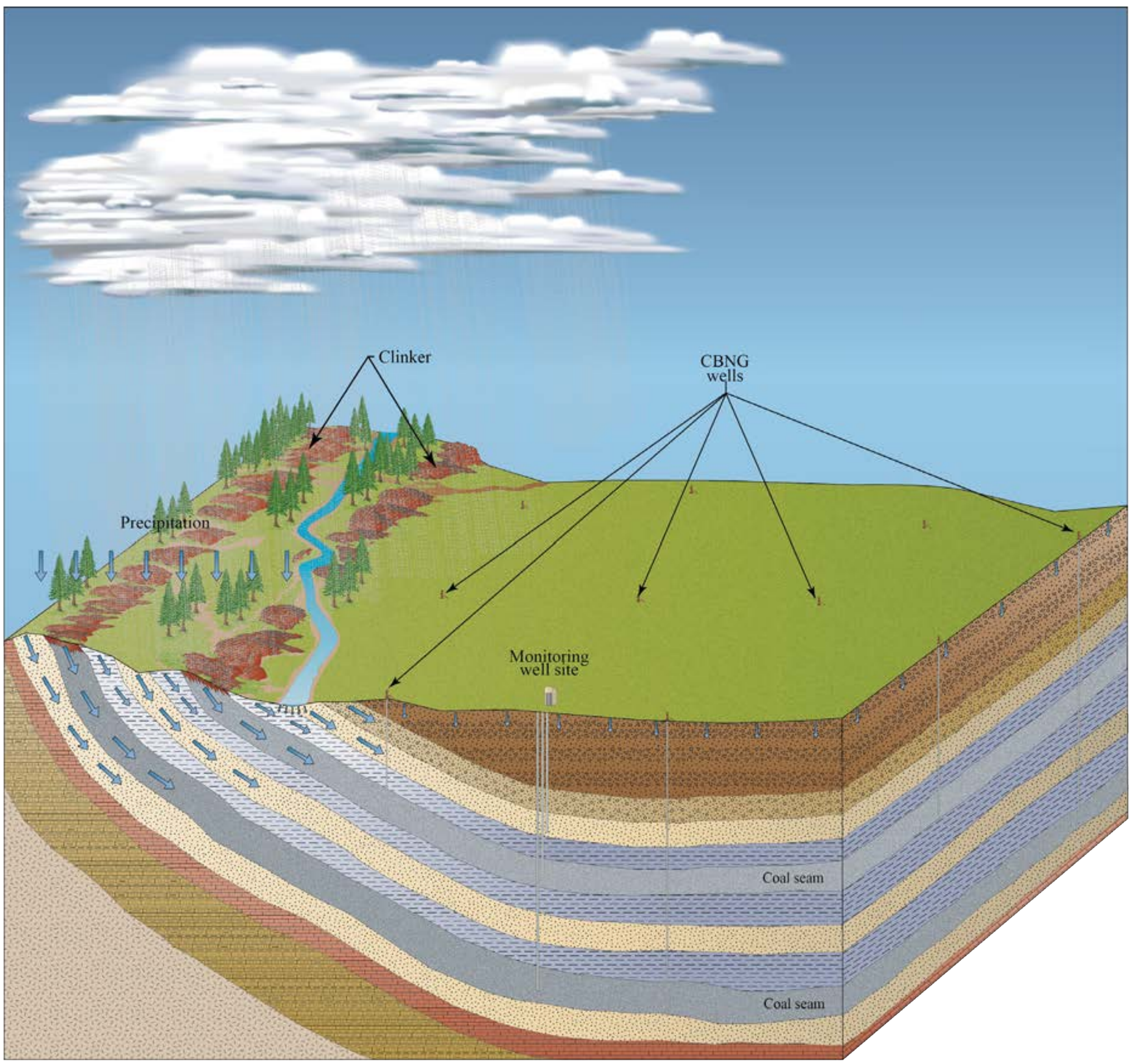


Figure 7. Sources of recharge to coal seams in Powder River Basin, Wyoming. Graphic by James R. Rodgers, WSGS, 2014.

Rider coal zone is assigned as "unmonitored" if the associated groundwater monitoring well is completed only in the Upper Wyodak.

The goal of this study is to examine groundwater level responses in selected BLM groundwater monitoring wells completed in the Upper Wyodak coal zone and to relate these to recent changes in production rates of co-produced water in proximal CBNG wells. WSGS obtained and reviewed manual and automated water level time series from the BLM (Taboga and Stafford, 2014) for 27 Upper Wyodak monitoring wells (available from the Wyoming Geographic Information Science Center's (WyGISC), Wyoming GeoLibrary at http://explorer.geospatialhub.org/geoportal/catalog/search/resource/details.page?uuid={0257C46F-A168-49B4-AF50-01D2B-FE2D4F8}portal/catalog/search/resource/details.page. Selection criteria included: a relatively complete record of quarterly manual static depth to groundwater (SDGW) measurements from inception of monitoring through 2013; the continuous presence of groundwater in the wellbore; and an intact WOGCC water production history for CBNG wells within a 1 ½ mile radius during the monitoring Period Of Record (POR). Only manual water level measurements were used because they generally exhibited greater consistency than corresponding transducer data. In some cases, monitoring wells with manual sampling gaps of more than one year's duration were included if concurrent transducer data was available or if the well hydrograph indicated the presence of a general trend in water level that remained consistent over several years. Monitoring wells completed in multiple coal zones, equipped with a packer or that went dry during the POR were disqualified. Based on these criteria WSGS selected 11 monitoring wells for hydrograph analysis (see fig. 2).

WSGS generated maps of CBNG production wells within a 1 ½ mile radius of the BLM monitoring wells using ArcGIS® 10.2 Geographical Information System (GIS) software by ESRI®. Once CBNG wells were identified within each zone, monthly water production data were downloaded from the WOGCC, http://wogcc.state.wy.us/, and monthly aggregated water production rates were calculated for each zone.

All data were transferred or downloaded, reviewed and evaluated in Microsoft Excel®. To compare monthly water production to quarterly (in some cases, intermittent) water level measurements, WSGS employed an Excel interpolation add-in by XonGrid®, available from http://sourceforge.net/projects/xongrid/. Daily water levels for the complete POR were generated by ordinary kriging using a beta value of 1.5 and the 10 nearest points. A dataset of monthly water levels was developed from both interpolated and measured groundwater levels.

WSGS identified the direction and duration of recent water level trends on the hydrographs generated from manual water level measurements and interpolated data for the 11 selected monitoring sites. Linear regression analyses were then performed on the original BLM manual water level measurements at each site to assess the statistical significance of the observed trends and estimate the current rate of recovery or decline. Coefficients of determination (R^2) were calculated for each analysis to evaluate how closely observed values fit the regression. P-values were used to determine statistical significance at the 0.01 level. Readers who are unfamiliar with these basic data analysis methods may benefit from explanations found online at: http://blog.minitab.com/blog/data-analysis-2.

WSGS generated cross sections G-G' and H-H' to determine Upper Wyodak coal zone depths along transects that include seven of the monitoring wells examined in this report (Sec 25, MP 2, MP 22, Kennedy, Barrett Persson, Throne, and Double Tank).

Water level changes in pre-development monitoring wells

CBNG production began prior to the onset of monitoring and likely impacted water levels at several of the BLM well sites considered in this report. To assess long term water level changes in the Upper Wyodak coal zone, WSGS obtained pre-development groundwater elevations, collected between 1975 – 2002, for 50 Upper Wyodak monitoring wells from a technical report prepared for the BLM by Applied Hydrology (2002 - table 2-2). Based on a comparison of well names and locations, WSGS confirmed that current water levels could be obtained or inferred for 20 of the pre-development monitoring wells, eleven of which are still actively monitored by the BLM or the Gillette Area Groundwater Monitoring Organization (GAGMO). In addition, WSGS included two BLM monitoring wells (Blackbird Coleman and Hoe Creek) after determining from hydrograph and production data (Taboga and Stafford, 2014) that initial water levels were measured prior to the onset of substantial CBNG development at those sites. Long term water level changes were calculated by comparing recent water level data to pre-development levels. Recent (2012 – 2013) water level data for the pre-development wells were compiled from direct measurements made by the BLM (Taboga and Stafford, 2014) and GAGMO (Hydro-Engineering, 2014) or inferred from area potentiometric surfaces constructed for GAGMO by Hydro-Engineering (2014).

WSGS conducted linear regression analyses to assess statistical relationships between recent (2013) water level changes and: 1) monitoring well proximity to recharge areas, 2) associated buffer zone well recovery times and, 3) maximum groundwater level drawdowns at seven BLM monitoring well sites where pre-development water level data was available. Monitoring well proximity to recharge areas was measured in a straight line from east to west using GIS software. Buffer zone well recovery times were determined from production data obtained from Taboga and Stafford (2014). Determining when significant water production has ceased is not straightforward because production in CBNG wellfields is frequently intermittent and continues at very low rates especially toward the end stages of wellfield production. In some cases, groundwater levels start to recover in response to reduced production. In this report, it was assumed that significant water production ceased when rates remained below 2% of peak production rates. Maximum groundwater level drawdowns were obtained from Taboga and Stafford (2014). Coefficients of determination (R^2) were calculated for each analysis to evaluate how closely observed values fit the regressions. P-values were used to determine statistical significance at the 0.01 level.

RESULTS

Monthly CBNG water production and corresponding groundwater level changes in the Upper Wyodak coal zone for each monitoring well site are shown in figures 8 to 29 and presented in tables 3 and 4. Additional data of interest is presented for the Bull Creek (fig. 17) and Double Tank (fig. 19) monitoring sites.

Table 3 summarizes changes in depth to groundwater (DGW) and water production data for various times and periods of record at all 11 monitoring well sites. The table lists initial and final 2013 DGW data with corresponding observation dates as well as volumes and dates of maximum water production and average monthly production levels for 2013. Initial water level monitoring for this group of wells began as early as 1993 (MP 2, MP 22) and as late as 2005 (Bull Creek). Initial water levels were first obtained in seven monitoring wells (20 Mile Butte, 21 Mile, Barrett Persson, Bull Creek, Double Tank, Kennedy and Throne) after CBNG/water production commenced within the associated 1.5-mile radius buffer zone. Initial DGW monitoring began prior to the onset of associated CBNG/water production at four sites: MP 2 (one month prior), MP 22 (two months), Blackbird Coleman (four months) and Sec 25 (32 months).

Maximum observed water level changes (declines) ranged from -160.5 ft at the 20 Mile Butte site to -519.1 ft at 21 Mile with an arithmetic average of -294.1 ft for all sites. During 2013, DGW changes varied from -22.8 ft (decline) at MP 2 to 42.6 ft (recovery) at Sec 25 and averaged 3.4 ft of recovery. Net water level changes for well POR's ending in 2013 average 186.7 ft of drawdown and range from 373.8 ft of drawdown at Double Tank to a 17.9 foot rise above initial levels at Bull Creek. It should be noted, however, that monitoring at Bull Creek began 21 months after the onset of methane/water production at associated CBNG wells and it is likely that groundwater levels were depressed prior to the onset of monitoring.

During 2013, monthly water production continued at only three sites: 20 Mile Butte, Barrett Persson and Blackbird Coleman. Water production at those sites ranged from 1,314 bbls/month at Blackbird Coleman to 3,882 bbls/month at 20 Mile Butte and averaged 2,573 bbls/month (85 bbls/day) for all three sites. Water level changes during 2013 at the three producing sites ranged from -9.6 ft at Blackbird Coleman (decline) to 9.4 ft at Barrett Persson (recovery) and averaged -0.8 ft. In contrast, water level changes for 2013 at the eight non-producing sites ranged from -22.8 ft at Double Tank to 42.6 ft at Sec 25 and averaged 5.0 ft (recovery).

Table 4 summarizes recent trends (three years or less) and associated properties of recovery or decline in groundwater levels observed at each site. Six sites (21 Mile, Barrett Persson, Bull Creek, Kennedy, Sec 25, and Throne) exhibited recoveries through 2013; all but two (Bull Creek and Sec 25) of these recoveries have continued for more than 36 months. Coefficients of determination (R^2) for the regression analyses of the seven recovering sites varied from 0.78 to greater than 0.99; all recovering trends exhibit p-values less than 0.01, indicating that the observed trends are statistically significant. Calculated annual rates of recovery vary from 2.5 (Barrett Persson) to 45.1 (Sec 25) ft /year.

Groundwater levels at the remaining five sites (20 Mile Butte, Blackbird Coleman, Double Tank, MP 2 and MP 22) exhibited statistically significant declines through 2013. Periods of decline range from 21 months (MP 22) to more than 36 months (20 Mile Butte, Blackbird Coleman, Double Tank). Coefficients of determination for the regression analyses of the five declining sites vary from 0.89 to greater than 0.99; all trends exhibit p-values less than 0.01, indicating that the observed trends are statistically significant. Calculated annual rates of decline vary from 4.4 (20 Mile Butte) to 21.6 (MP 2) ft /year.

Table 3. Summary statistics for groundwater level changes in selected Upper Wyodak coal seam monitoring wells, PRB of Wyoming, 2014.

Monitoring well site name	Initial depth to GW (ft) [Start date]	Maximum GW level change (ft) [Date]	Final 2013 depth to GW (ft)	Water level change during 2013 (ft)	Net water level change for POR ending 2013 (ft)	Maximum water production (bbls/month) [Date]	Average monthly water production 2013 (bbls/month)
20 MILE BUTTE	545.0 [1/28/2004]	-160.5 [11/18/2013]	705.5	-2.3	-160.5	57,681 [Nov. 2001]	3,882
21 MILE	629.9 [8/19/2001]	-519.1 [8/25/2001]	932.1	4.7	-302.2	198,250 [Aug. 2002]	0
BARRETT PERSSON	826.3 [12/6/2000]	-215.4 [6/24/2008]	1002.0	9.4	-175.7	1,174,196 [Feb. 2000]	2,523
BLACKBIRD COLEMAN	370.9 [7/12/2002]	-166.6 [12/27/2013]	537.4	-9.6	-166.5	180,049 [July. 2004]	1,314
BULL CREEK	215.0 [11/22/2005]	-175.9 [8/7/2012]	197.1	6.6	17.9	27,099 [Sep. 2006]	0
DOUBLE TANK	148.9 [12/19/2002]	-373.7 [12/16/2013]	522.6	-18.4	-373.7	22,849 [Nov. 2002]	0
KENNEDY	405.2 [5/24/2000]	-244.8 [10/26/2008]	537.4	15.8	-132.2	117,968 [Jan. 2001]	0
MP 2	163.1 [5/26/1993]	-242.4 [5/28/2007]	333.1	-22.8	-170.0	305,922 [Nov. 2000]	0
MP 22	173.8 [2/18/1993]	-316.2 [1/21/2002]	325.7	-13.5	-151.9	367,887 [Mar. 2000]	0
SEC 25	48.3 [11/9/1996]	-512.3 [1/12/2007]	366.3	42.6	-317.9	536,697 [Mar. 2007]	0
THRONE	815.2 [5/24/2001]	-307.8 [5/16/2006]	936.2	25.1	-120.9	255,181 [Jun. 2003]	0

Table 4. Linear regression statistics for groundwater level changes in selected Upper Wyodak coal seam monitoring wells, PRB of Wyoming, 2014.

Monitoring well site name	Direction current observed trend	Duration observed trend (months)	Number of observations	Significant (Y_N)	Coefficient of determination	p-value	Regressed annual rate of change
20 MILE BUTTE	Decline	>36	13	Y	0.89	1.29E-6	-4.4
21 MILE	Recovering	>36	13	Y	0.97	1.14E-9	5.0
BARRETT PERSSON	Recovering	>36	12	Y	0.78	1.30E-4	2.5
BLACKBIRD COLEMAN	Decline	>36	13	Y	>0.99	2.61E-15	-10.4
BULL CREEK	Recovering	14	5	Y	0.97	2.23E-3	4.7
DOUBLE TANK	Decline	>36	13	Y	>0.99	3.00E-18	-20.3
KENNEDY	Recovering	>36	13	Y	0.99	7.47E-13	15.6
MP 2	Decline	25	9	Y	0.94	1.64E-5	-21.6
MP 22	Decline	21	8	Y	0.89	4.20E-4	-11.4
SEC 25	Recovering	21	8	Y	0.99	1.53E-7	45.1
THRONE	Recovering	>36	13	Y	0.95	1.46E-8	14.0

Results from Individual Monitoring Well Sites

20 Mile Butte Monitoring Site

The 20 Mile Butte monitoring site (fig. 8) is located west-northwest of Gillette. Groundwater level monitoring at the 20 Mile Butte site began January 28, 2004, 34 months after the onset of water production (April 2001) from the Upper Wyodak coal zone (fig. 9). As a result, the timing and magnitudes of early groundwater level declines are unknown. Water production from the Wyodak coal zone dropped off to zero in late 2012 but resumed at low levels (average 3,882 barrels per month (bbls/month)) in 2013. With the exception of several sporadic, low magnitude recoveries of short duration, groundwater levels at the site have dropped continuously during the 2004 -2013 POR. The rate of decline has decreased since 2012, coincident with the drop in water production. Measured water levels at the site dropped 2.3 ft during 2013; in comparison, the trend analysis projected a water level decline rate of 4.4 ft/year over the last three years.

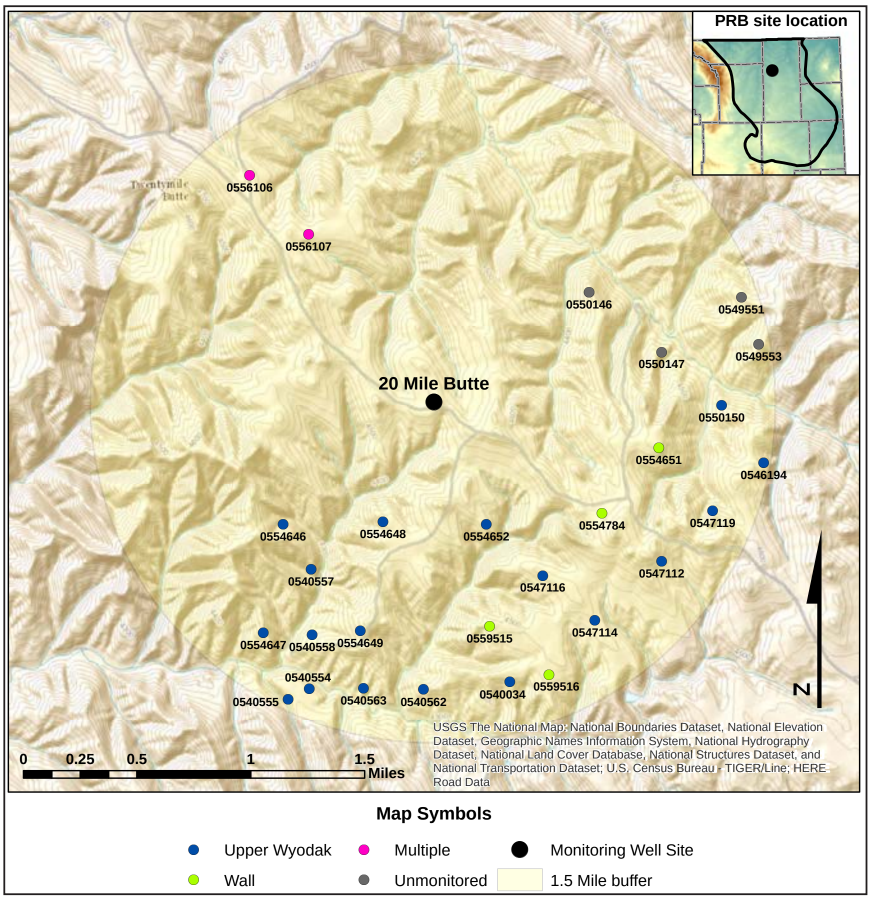
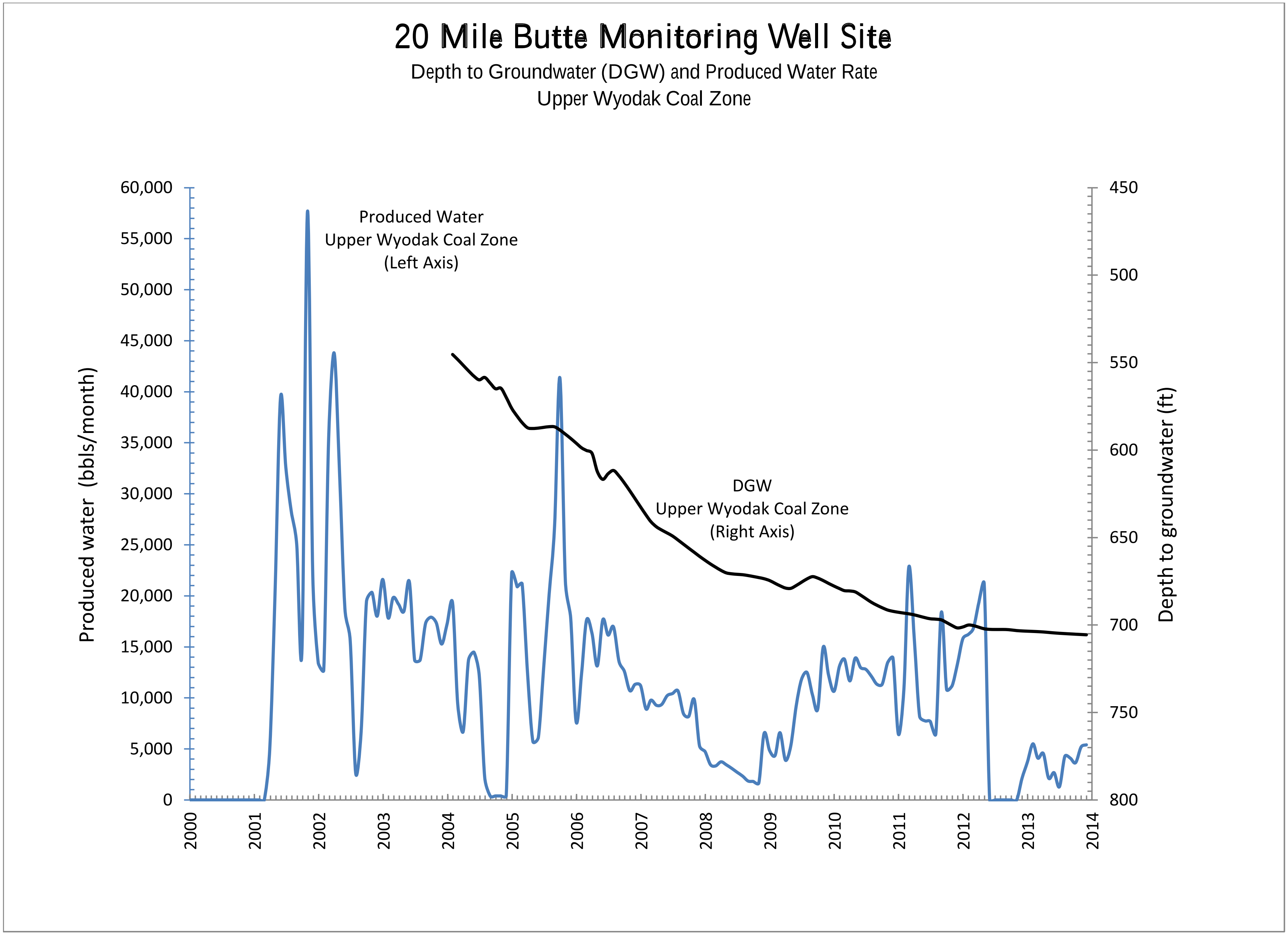


Figure 8. Location of associated CBNG wells within a 1.5 mile radius of the 20 Mile Butte monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 9. Water production and depth to groundwater at 20 Mile Butte monitoring site.



21 Mile Monitoring Site

The 21 Mile monitoring site (fig. 10) is located south of Gillette on the western edge of the area where CBNG wells are commonly completed in the Upper Wyodak coal zone. Although, small amounts (~2,300 bbls/month) of water were produced from area CBNG wells during a four month period in late 1999, substantial water production did not begin until April 2001 (fig. 11). Water level monitoring started five months later in September 2001. Groundwater levels steadily declined from 2001 through 2003, and then generally stabilized through 2007. Groundwater levels began to recover in mid-2007 in response to a sharp drop in water production starting in late 2006. Water production in the 21-mile buffer zone ceased altogether in August 2012. Measured water levels recovered 4.7 ft during 2013 which shows close agreement with the recovery rate (5.0 ft/year) modeled by the trend analysis.

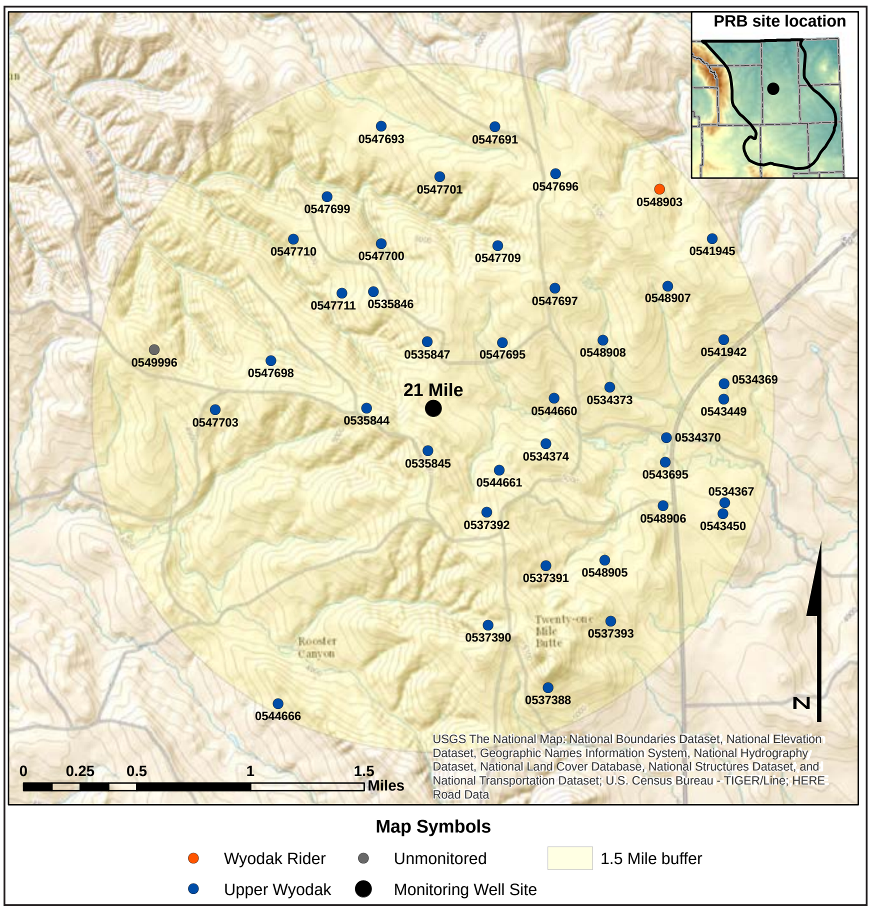
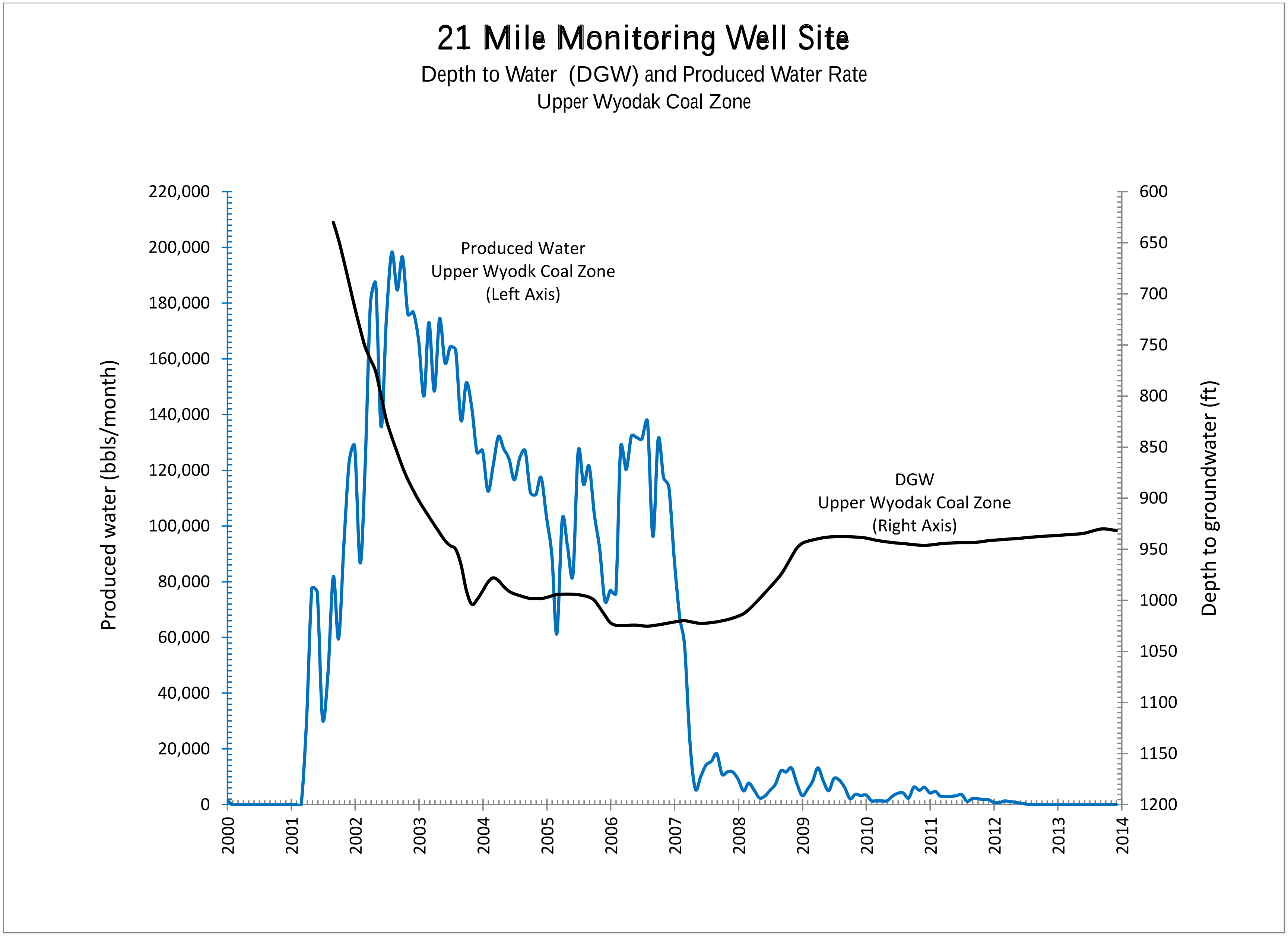


Figure 10. Location of associated CBNG wells within a 1.5 mile radius of the 21 Mile monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 11. Water production and depth to groundwater at 21 Mile monitoring site.



Barrett Persson Monitoring Site

Water production began around the Barrett Persson monitoring site (fig. 12), located south of Gillette, in November 1999 and rapidly peaked three months later (February 2000) at 1,174,196 bbls/month. Water level monitoring started over a year later in January 2001. From 2001 – 2009, water production dropped from an average 181,000 bbls/month to 73,500 bbls/month (fig. 13). Groundwater levels, which had declined over 215 ft since 2000, began a protracted recovery in August 2008 that continued through 2013. The rate of actual water level recovery increased in 2013 in comparison to the previous two years. This accounts, in part, for the lack of agreement between modeled (2.5 ft) and actual (9.4 ft) recovery rates in 2013.

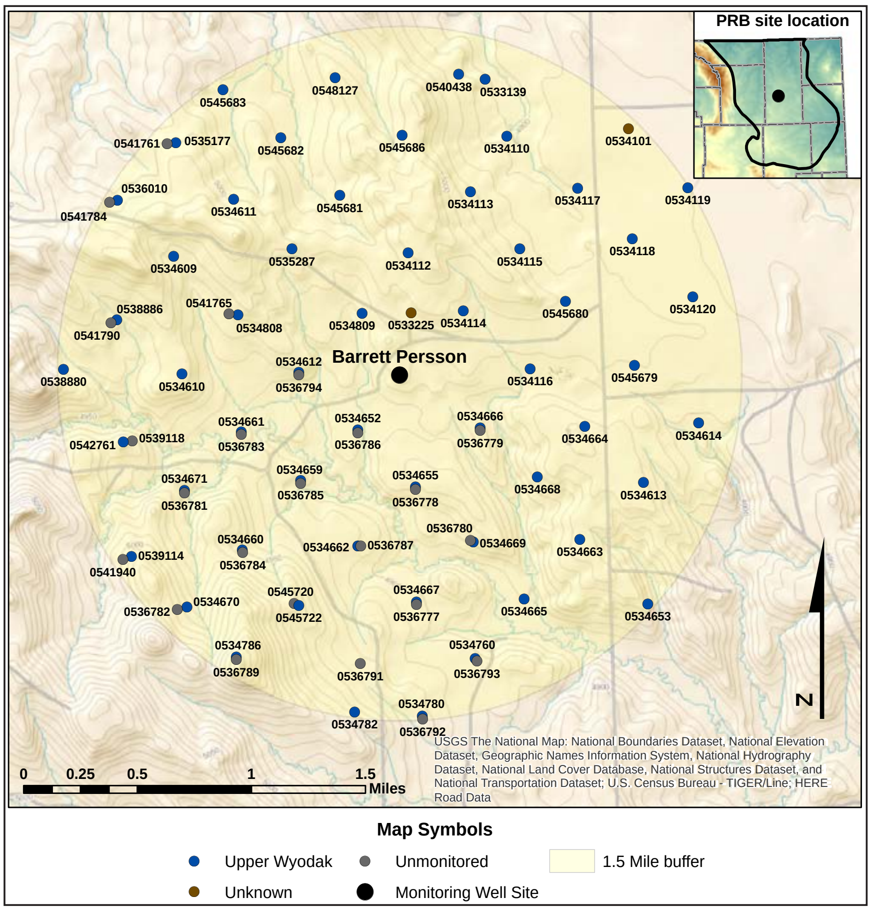
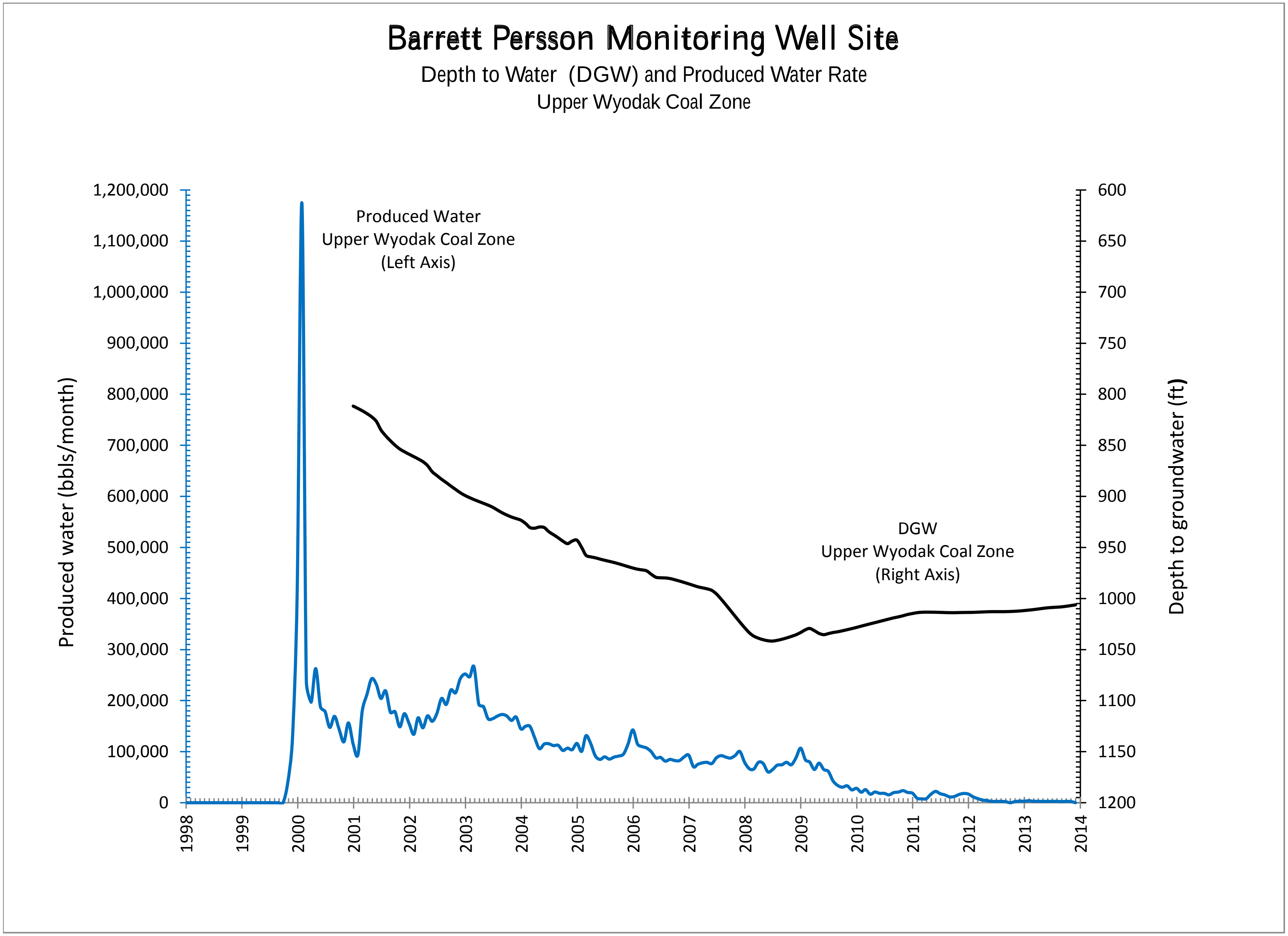


Figure 12. Location of associated CBNG wells within a 1.5 mile radius of the Barrett Persson monitoring site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 13. Water production and depth to groundwater at Barrett Persson monitoring site.



Blackbird Coleman Monitoring Site

Groundwater level monitoring at the Blackbird Coleman site (fig. 14) began in August 2000, five months before the onset of water production in the associated buffer zone. By the end of 2001, groundwater in the monitoring well had risen nearly 9.0 ft above initial levels despite an average monthly water production of over 25,700 bbls in 2001 (fig. 15). In 2002, average production exceeded 48,100 bbls/month and water levels began a long decline that continued through 2013. Water production from the Upper Wyodak ceased from January 2007 – June 2010 and then resumed at low levels (average 1,346 bbls/month) through 2013. Groundwater levels have continued a decline that started in 2002. The linear drop in groundwater head may be related to continued water production from area CBNG wells completed in multiple coal zones and from coal zones where water levels are not monitored (Taboga and Stafford, 2014). In 2013, observed groundwater levels fell 9.6 ft in close agreement with the modeled 10.4 ft decline.

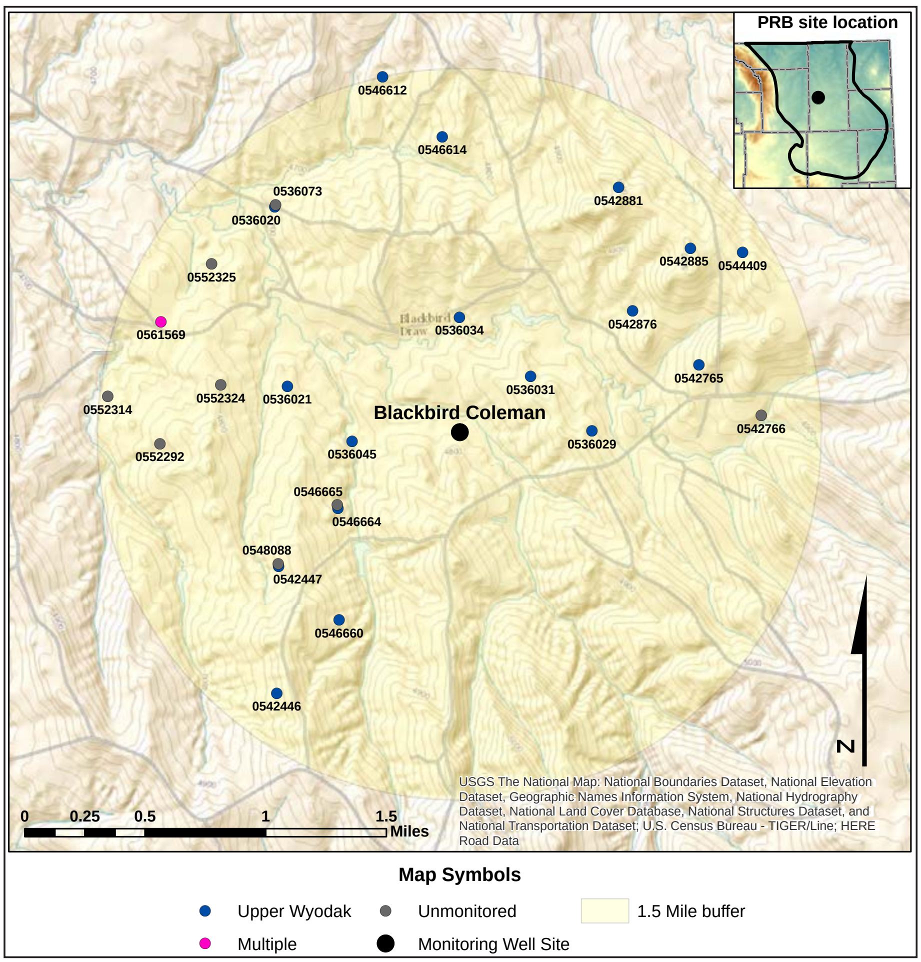
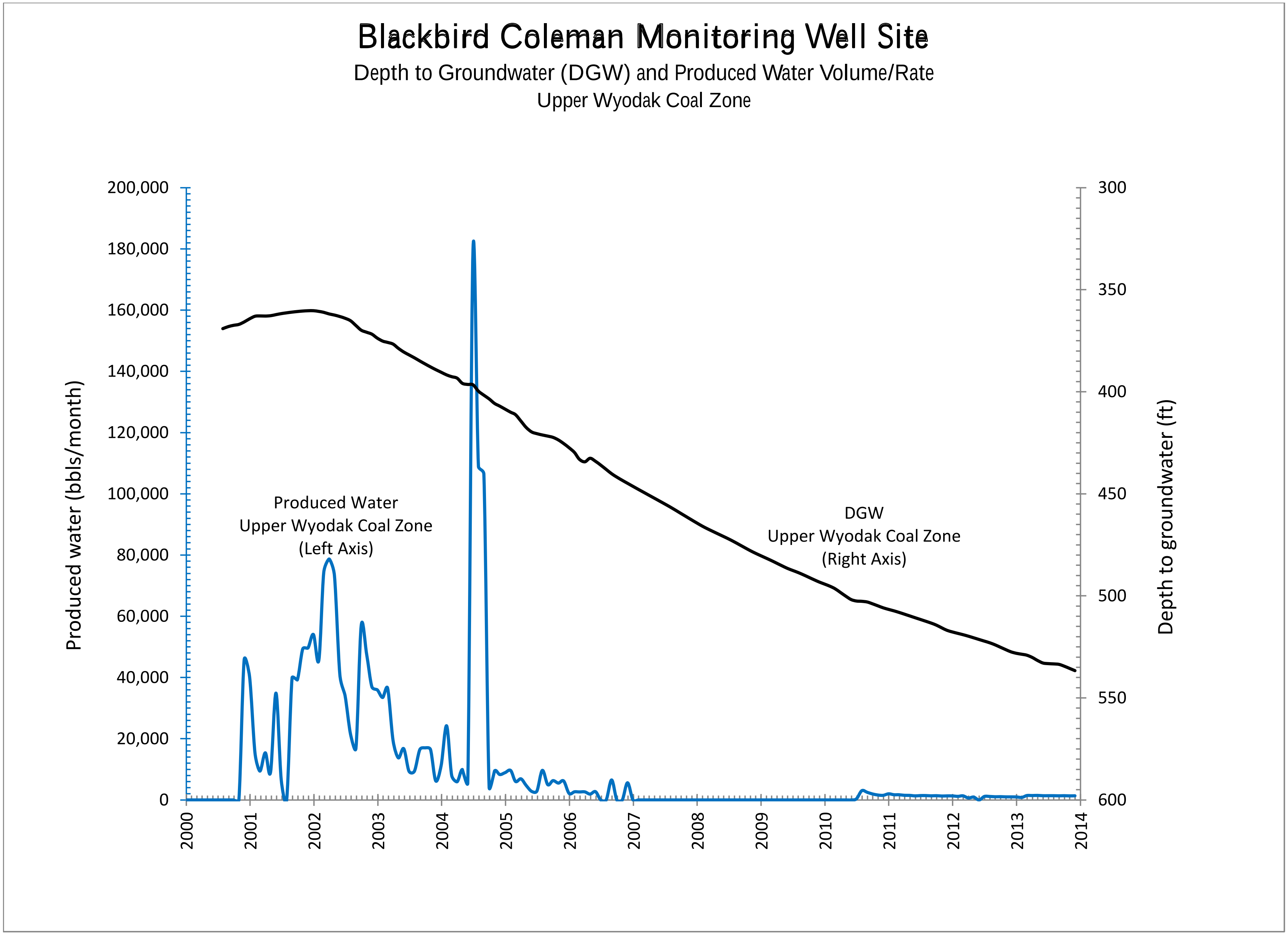


Figure 14. Location of associated CBNG wells within a 1.5 mile radius of the Blackbird Coleman monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 15. Water production and depth to groundwater at Blackbird Coleman monitoring site.



Bull Creek Monitoring Site

The Bull Creek monitoring site (fig. 16) is located west-northwest of Gillette near the Powder River. Groundwater level monitoring began in December 2005, 21 months after the onset of water production from the Upper Wyodak coal zone (fig. 17). As a result, the pre-development groundwater level and the magnitude of early groundwater level declines are unknown. The shallow groundwater levels (~200 ft) indicate the artesian nature of the Bull Creek monitoring well, which is completed at a depth of 980 – 1,013 ft.

Water production rates from the area's four Upper Wyodak CBNG wells ranged from 0 to 27,099 bbls/month and averaged 7,349 bbls/month during the period from March 2004 until January 2012 (fig. 17). Additionally, brief periods of high production from dual completed CBNG wells pumping from both the Upper Wyodak and Wall coal zones occurred during August 2008 – July 2009 and October 11 – May 2012. Figure 17 illustrates the complexities involved in comparing water production to monitoring well water level changes; presently there is no way to determine individual water production rates from specific coal zones in multiple completed wells.

Water levels declined from the onset of monitoring until November 2008, then briefly recovered and declined again in the first half of 2009. The cessation of pumping from the multiple completed well (# 1925392 in fig. 16) closest to the monitoring well probably accounts for the rapid water level recovery seen from July 2009 until January 2010. Subsequently, the rate of recovery slowed and continued into 2013. The nearly 200 ft drop in groundwater levels that occurred in early 2012 may be a measurement error in that it is based on one measurement taken August 7, 2012 and it far exceeds any previously observed decline. Groundwater levels recovered 6.6 ft in 2013, higher than the 4.7 ft recovery projected by the regression model.

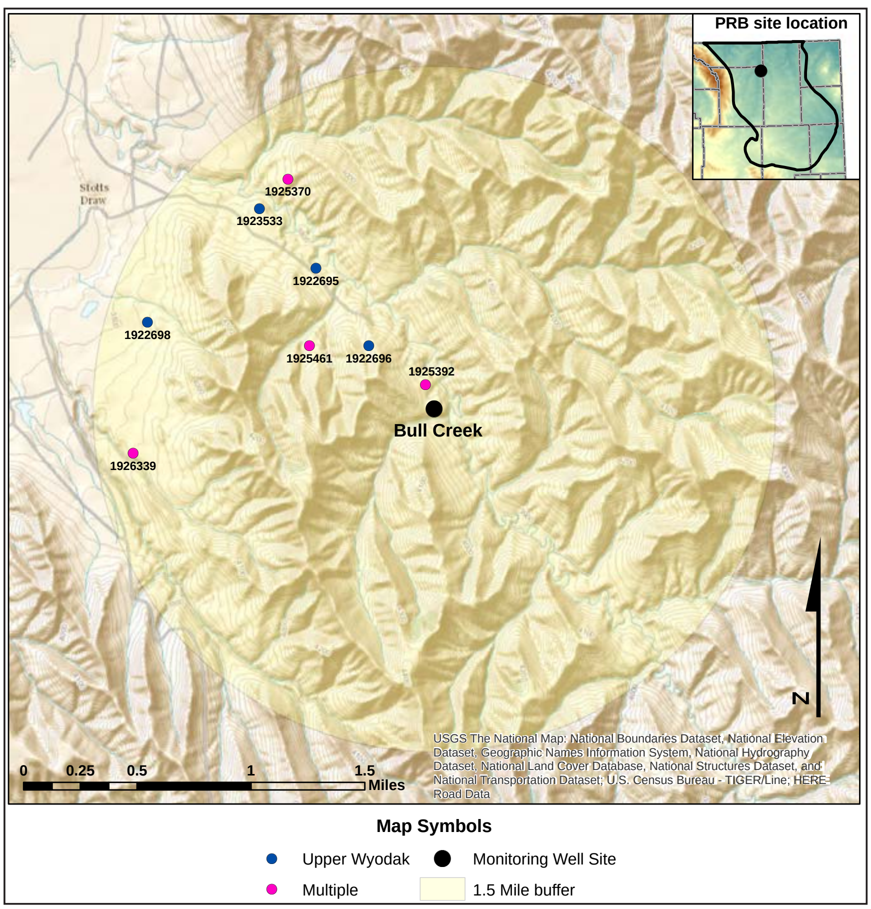
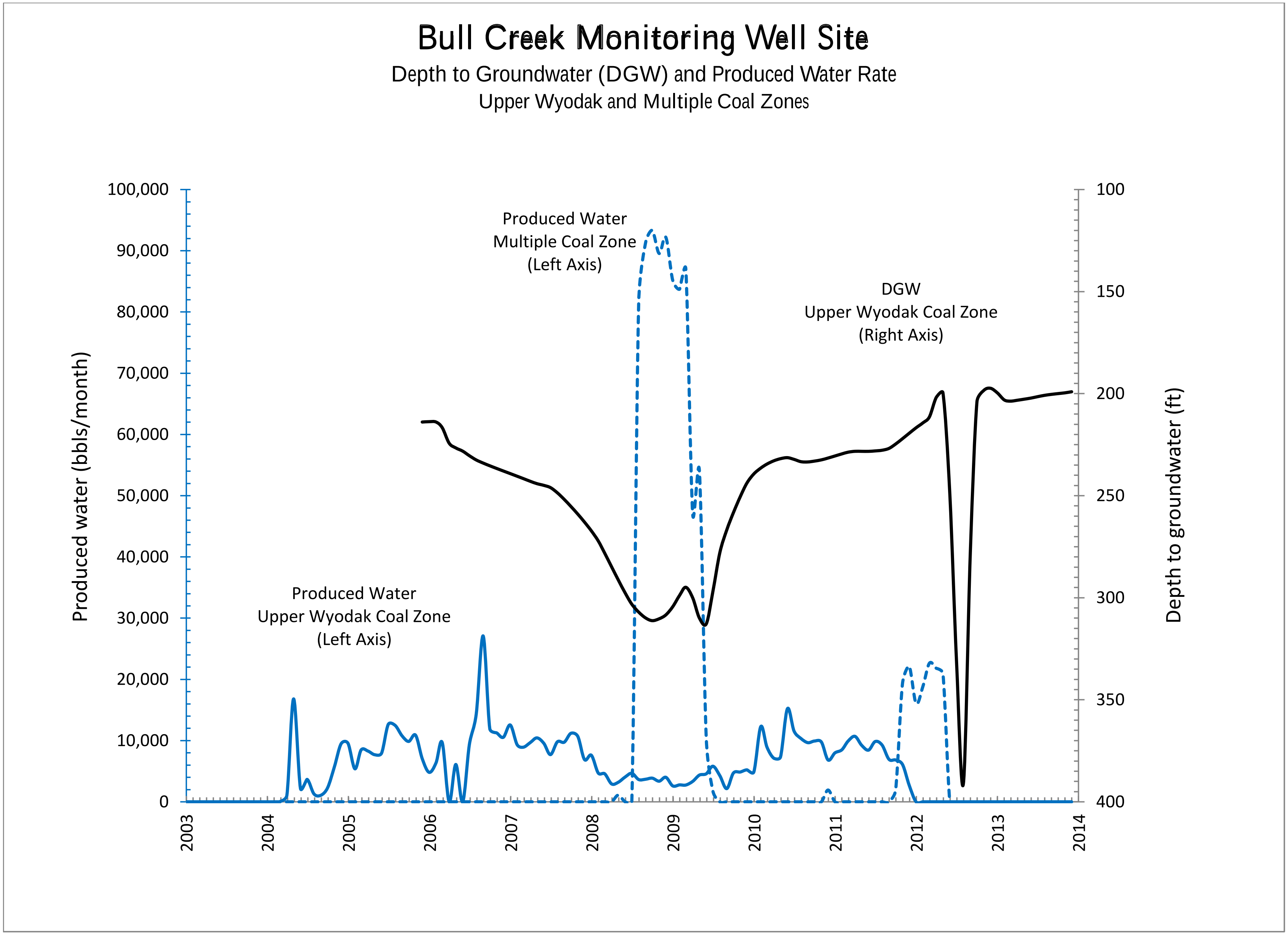


Figure 16. Location of associated CBNG wells within a 1.5 mile radius of the Bull Creek monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 17. Water production and depth to groundwater at Bull Creek monitoring site.



Double Tank Monitoring Site

The Double Tank monitoring site (fig. 18) is located south of Gillette and consists of two monitoring wells; one is completed in the Upper Wyodak coal zone and the other is completed in the Wyodak Rider coal zone. Monitoring at both wells started in January 2003, two months after the onset of water production from both the Upper Wyodak and Wyodak Rider coal zones (fig. 19). Water production from the Wyodak Rider increased rapidly from initial levels reaching a maximum rate of 488,410 bbls eight months after production began. In comparison, water production from the Upper Wyodak has been trivial; maximum production (22,849 bbls) occurred in November 2002, two months before water level monitoring started, then ceased altogether in October 2006.

Groundwater levels in the Upper Wyodak coal zone show a strong response to pumping in the overlying Wyodak Rider coal zone even though the two zones are separated by over 200 ft of inter-burden at the Double Tank site. The timing and magnitude of the slopes of the precipitous initial water level declines observed in both zones in late 2002 and the more gradual decline that took place after suggest the existence of vertical hydraulic communication between the two coal zones. Linear regressions of the late time drawdown curves give slopes of -0.068 (R^2=0.877) for the Wyodak Rider and -0.050 (R^2=0.999) for the Upper Wyodak. Initial head in the Upper Wyodak was 107 ft higher than in the Wyodak Rider. This difference increased to 442 ft by the end of 2013. Measured water levels declined 18.4 ft during 2013, close to the modeled decline of 20.3 ft.

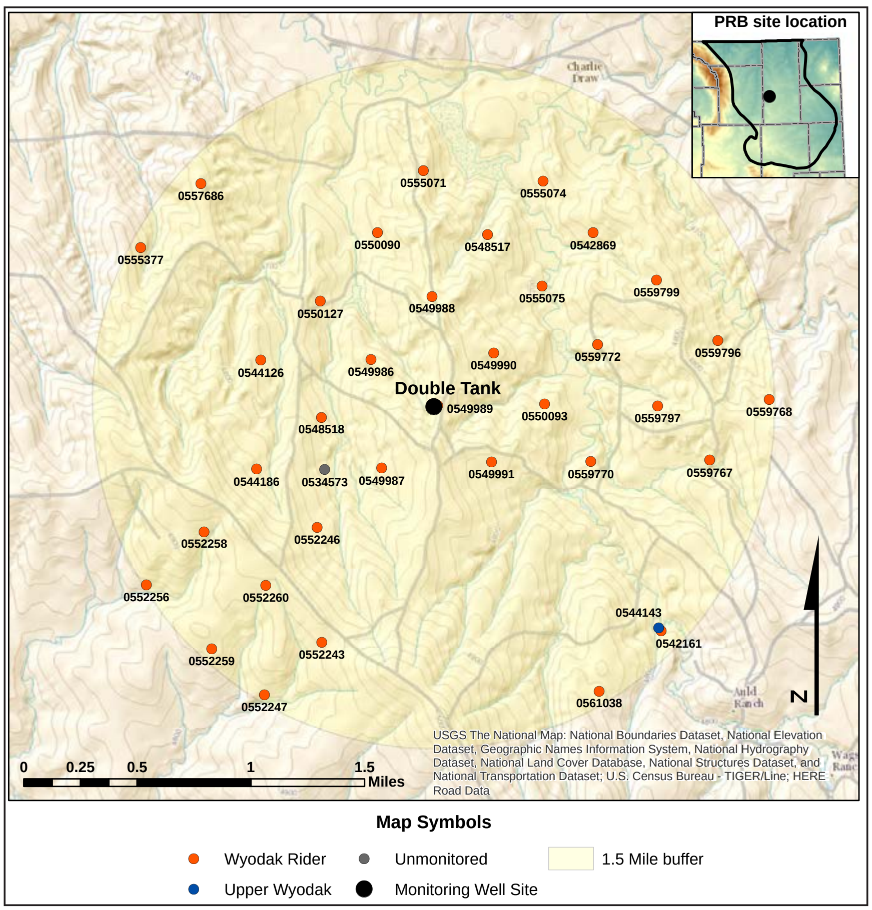
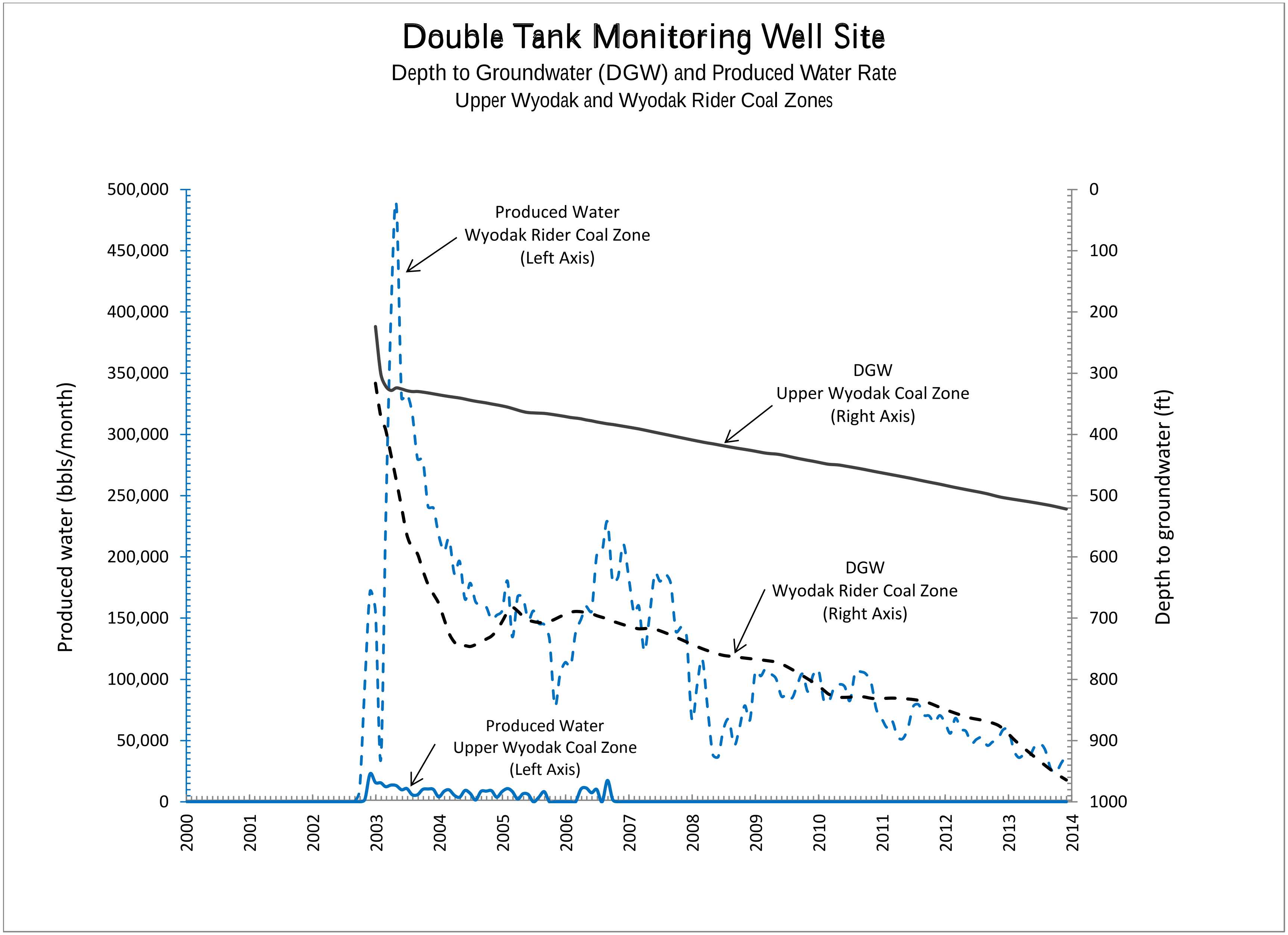


Figure 18. Location of associated CBNG wells within a 1.5 mile radius of the Double Tank monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 19. Water production and depth to groundwater at Double Tank monitoring site.



Kennedy Monitoring Site

The Kennedy monitoring site (fig. 20) is located northwest of Gillette. Groundwater level monitoring at the site began in June 2000, six months after the onset of water production (December 1999) from the Upper Wyodak coal zone (fig. 21). As a result, the magnitudes of early groundwater level declines are unknown. There has been no water production from the Upper Wyodak coal zone since January 2010. With the exception of a brief, low magnitude recovery in 2003, groundwater levels at the site dropped continuously from 2004 until August 2009. Since then, water levels have recovered over 90 ft. The annual rate of recovery was 15.8 ft in 2013.

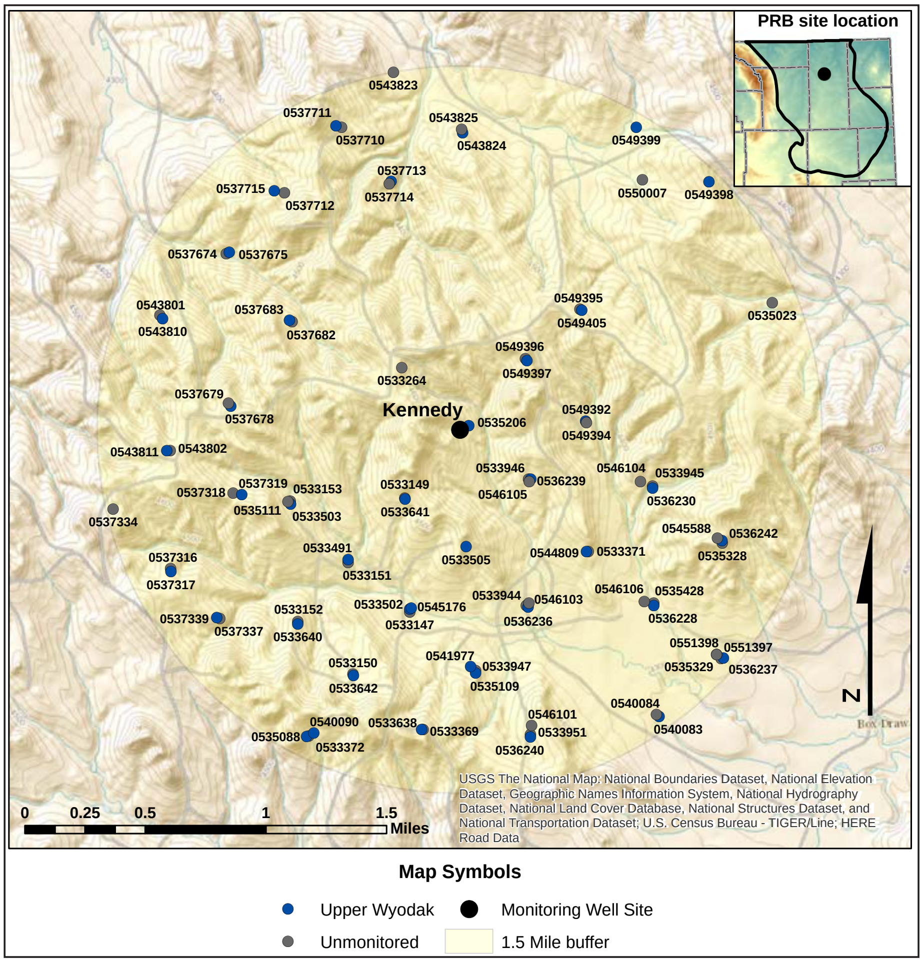
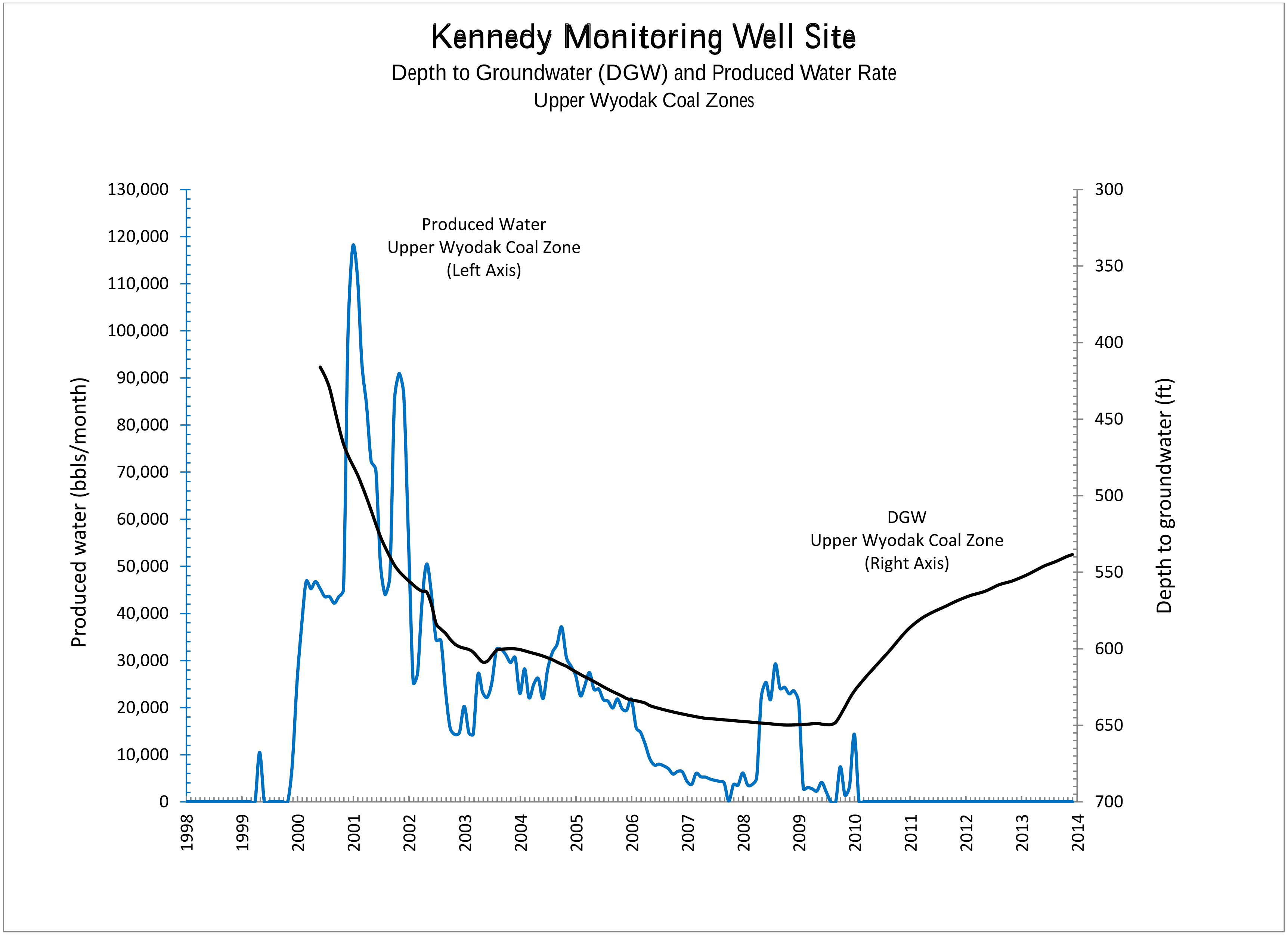


Figure 20. Location of associated CBNG wells within a 1.5 mile radius of the Kennedy monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 21. Water production and depth to groundwater at the Kennedy monitoring site.



MP 2 Monitoring Site

The MP 2 monitoring site (fig. 22) is located south-south-east of Gillette approximately 1 mile west (downgradient) of the Belle Ayr surface coal mine. Water level monitoring at the site began in June 1993, one month before water production from the Upper Wyodak coal zone began in the associated buffer zone (fig. 23). Water production continued until July 2005, dropped to zero until June 2006, and then resumed at low levels for a five month period (July – October 2006). Since then, no water has been produced from the Upper Wyodak zone in the associated buffer zone.

Groundwater levels steadily declined from the onset of monitoring through into late 1999, recovered briefly, and then declined steeply into late 2001. Levels stabilized from 2002 through 2004 and then began a prolonged recovery that lasted through 2011. Groundwater levels have declined by nearly 44 ft since early 2012 even though there has been no water production from the Upper Wyodak since October 2006. In 2013 alone, water levels declined 22.8 ft at the MP 2 site. The recent decline may be due to dewatering operations at the nearby Belle Ayr surface mine. Figure 22 shows the proximity of the current coal permit boundary to the MP 2 site. It should be noted that the two wells within the permit boundary (0530401 and 0530603) were plugged and abandoned by the end of 2009.

Monthly discharges from a Wyoming Pollutant Discharge Elimination System (WYPDES) permitted outfall (Permit # WY0003514) at the Belle Ayr mine averaged 0.06 million gallons per day (MGD), or 1429 bbls/day, from 2001 – 2010. In contrast, average monthly discharges increased over tenfold to 0.70 MGD (16,667 bbls/day) during 2011 – 2013. According to the WYPDES permit (WDEQ, 2014) the authorized outfalls may discharge groundwater "which accumulates in the mine pits, storm water runoff from surrounding areas, plant process water, and/or water from dewatering wells." Although the outfall data do not specify the origin of the monthly discharges, the fact that the decline in groundwater levels at the MP 2 site closely follows the substantial increases in outfall discharges from the up gradient surface mine must be considered.

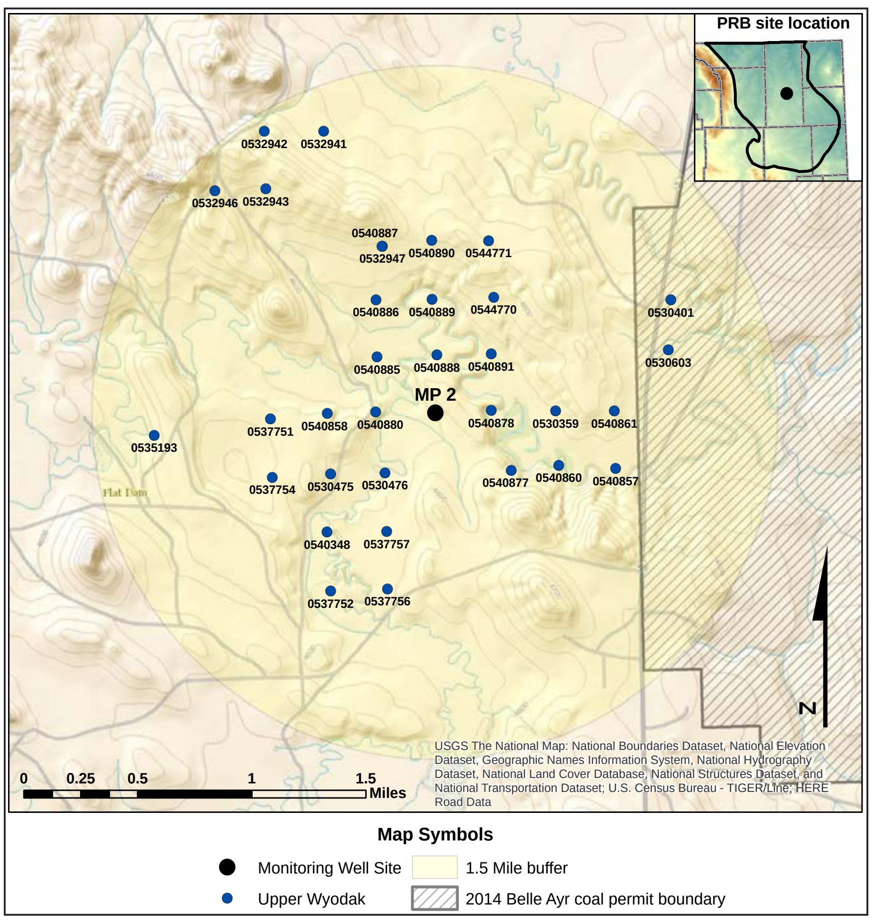
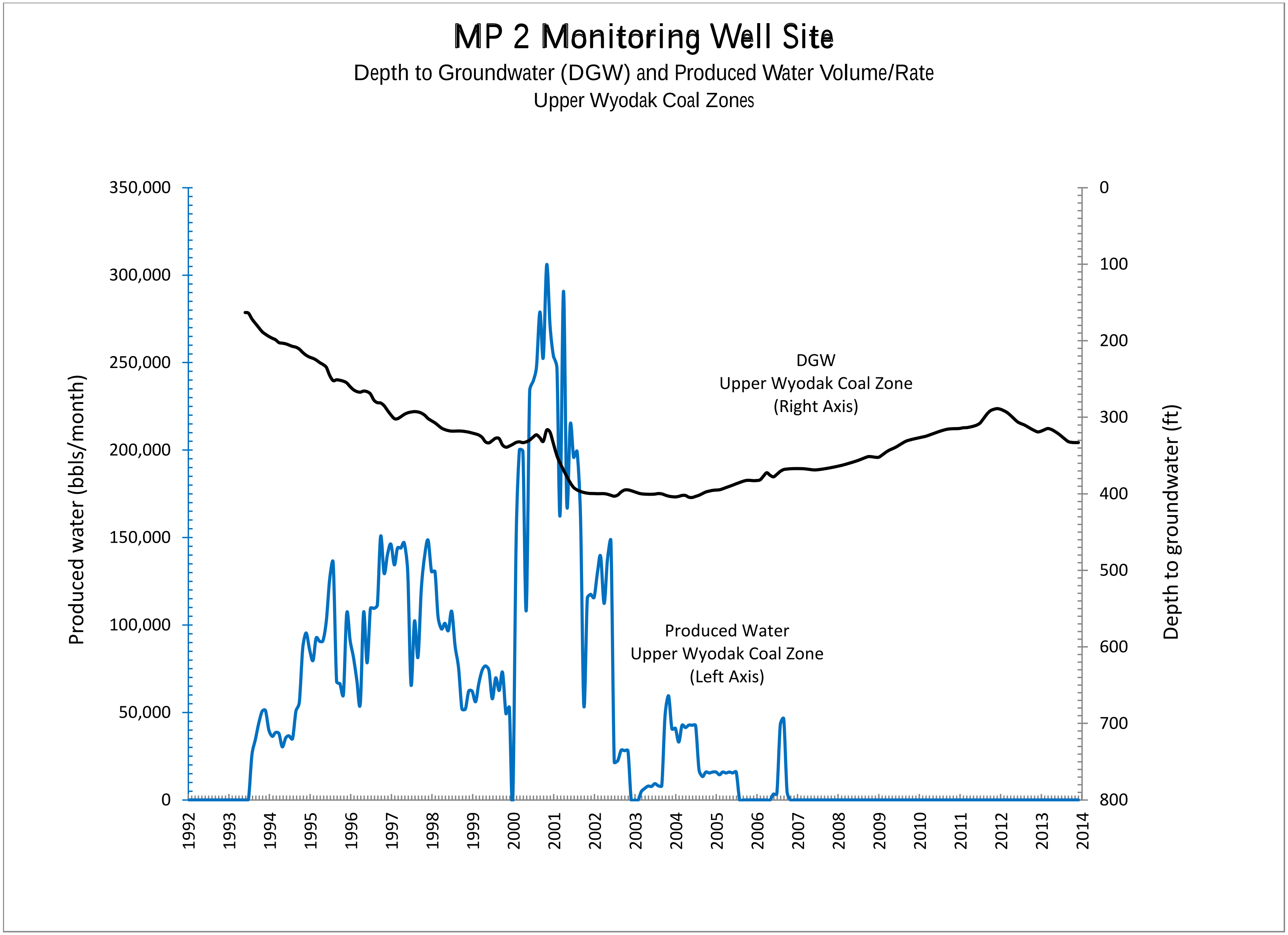


Figure 22. Location of associated CBNG wells within a 1.5 mile radius of the MP 2 monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 23. Water production and depth to groundwater at the MP 2 monitoring site.



MP 22 Monitoring Site

The MP 22 monitoring site (fig. 24) is located south of Gillette; approximately 2.5 miles northwest of the MP 2 site and within 1.5 miles of the Belle Ayr surface coal mine. The timing and magnitude of water production and groundwater level changes at the MP 22 site closely parallels those observed at the MP 2 site. Water level monitoring began two months before the onset of water production from the Upper Wyodak coal zone (fig. 25). Average monthly water production from mid-1993 through 1999 was 63,800 bbls. Production dropped to zero during January 2000, then resumed the following month and continued at higher rates (average 116,300 bbls/month) through 2001. Water production was scaled back until early 2008 and then ceased thereafter.

Groundwater levels showed a general overall decline from the onset of monitoring through 2001, stabilized through 2004 and then entered a period of prolonged recovery until mid-2012. Since then water levels have dropped over 17 ft and continue to decline. As with MP 2, the recent decline may be due to dewatering operations at the nearby surface mine.

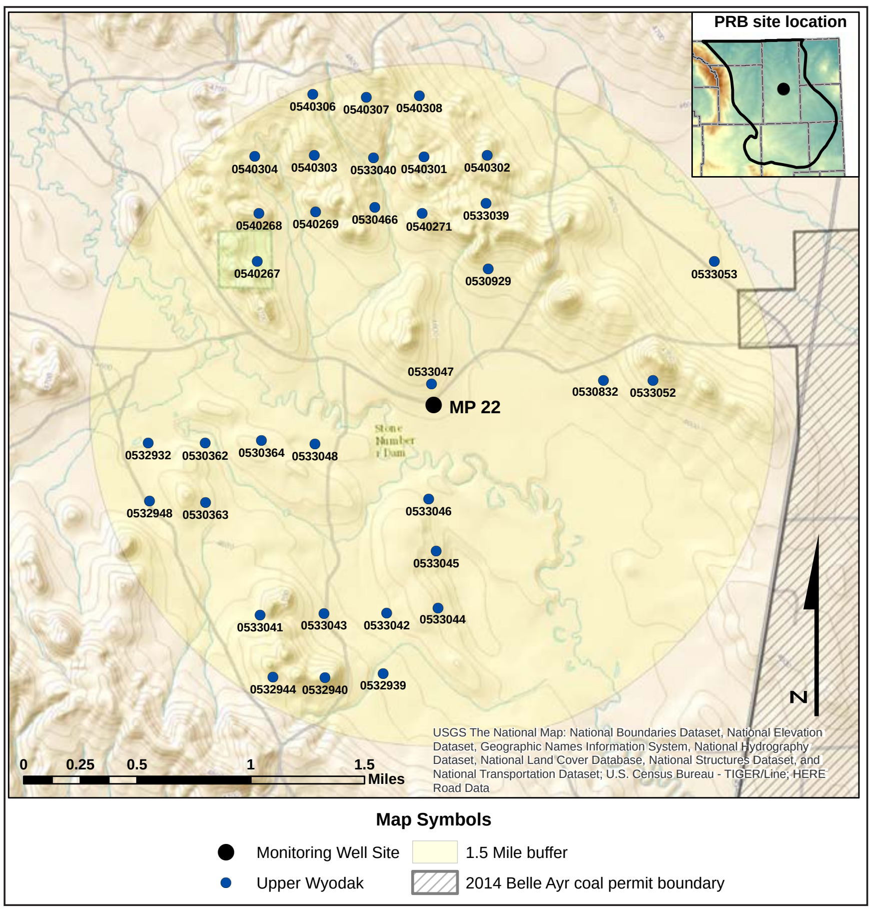
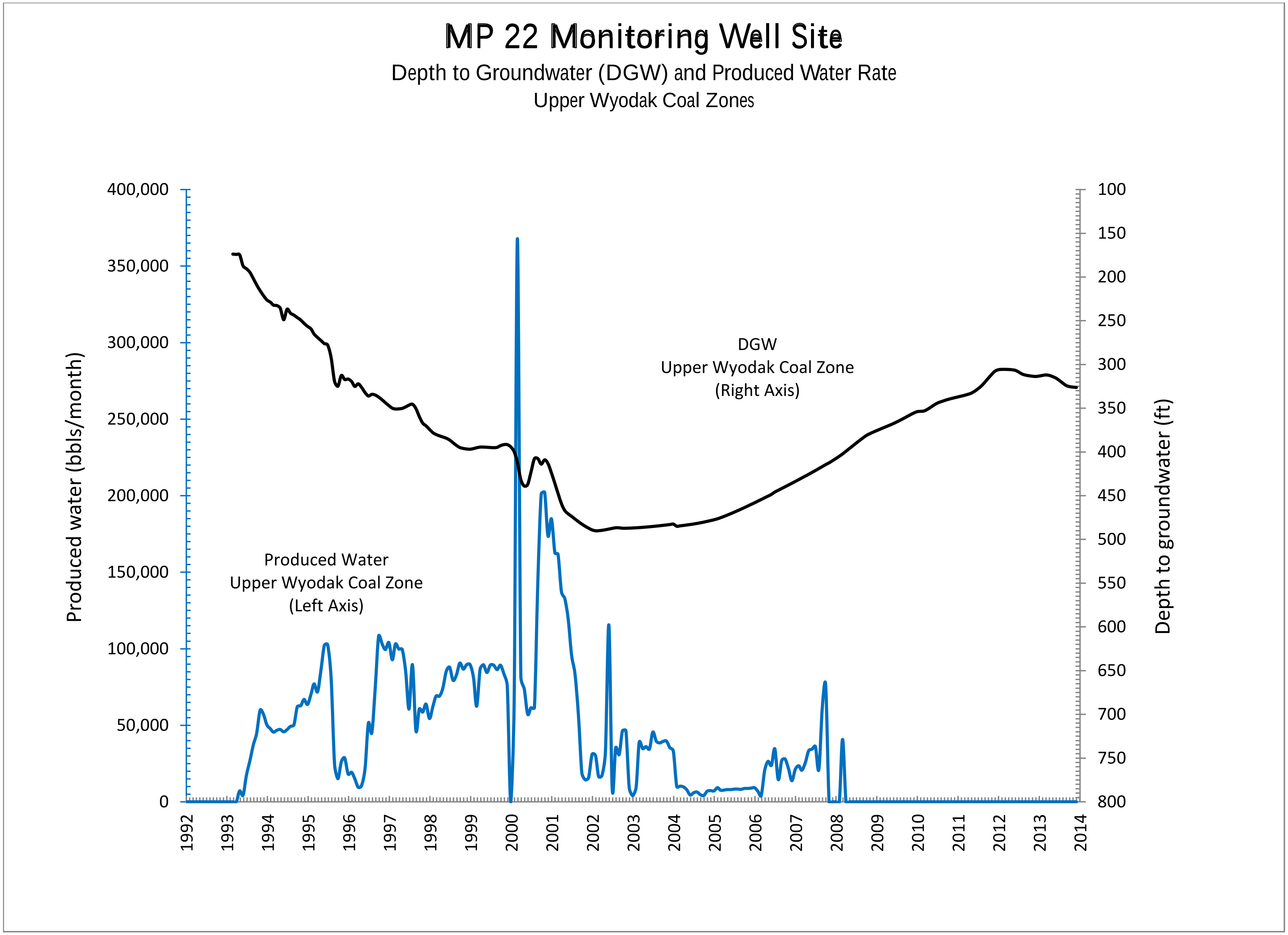


Figure 24. Location of associated CBNG wells within a 1.5 mile radius of the MP 22 monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 25. Water production and depth to groundwater at the MP 22 monitoring site.



Sec 25 Monitoring Site

The Sec 25 monitoring site (fig. 26) is located south of Gillette. Groundwater level monitoring began in December 1996, 32 months (August 1999) before the onset of Upper Wyodak water production from the associated buffer zone (fig. 27). The 12 month average water production rate reached around 300,000 bbls/month by 2002 and remained near that level until 2007. Water production rapidly dropped off and ceased in mid-2012.

Groundwater levels showed a general decline from the onset of monitoring until late 2004, remained stable into late 2012 and then recovered through 2013. The annual rate of recovery in 2013 was over 42 ft.

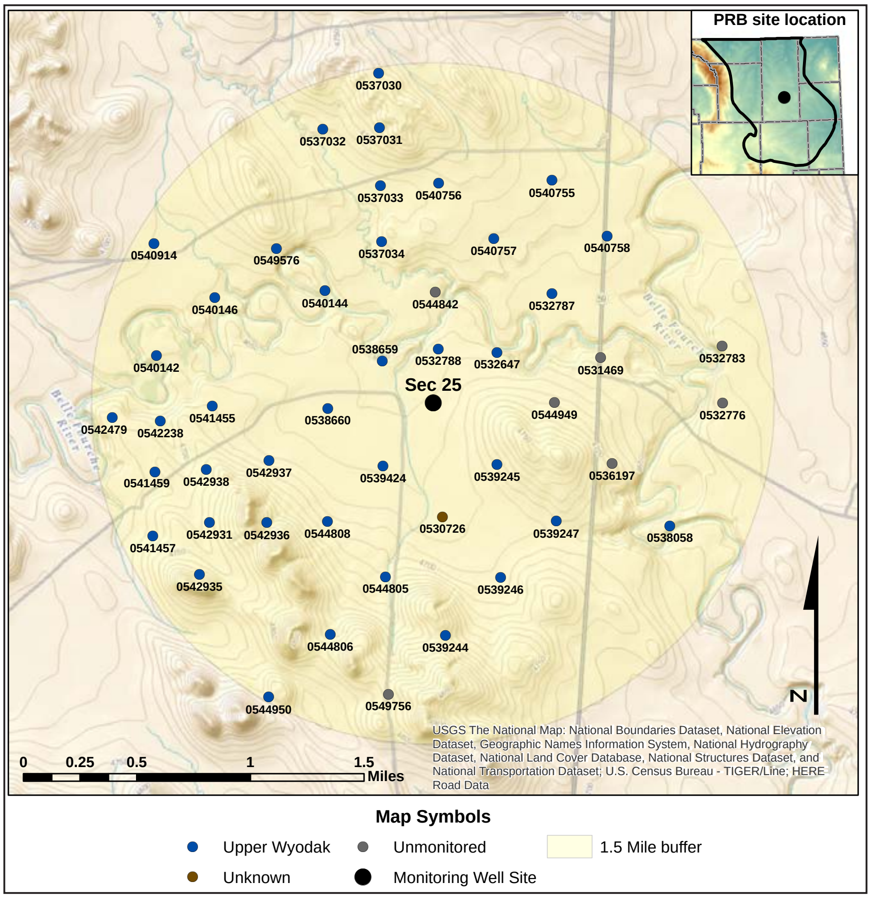
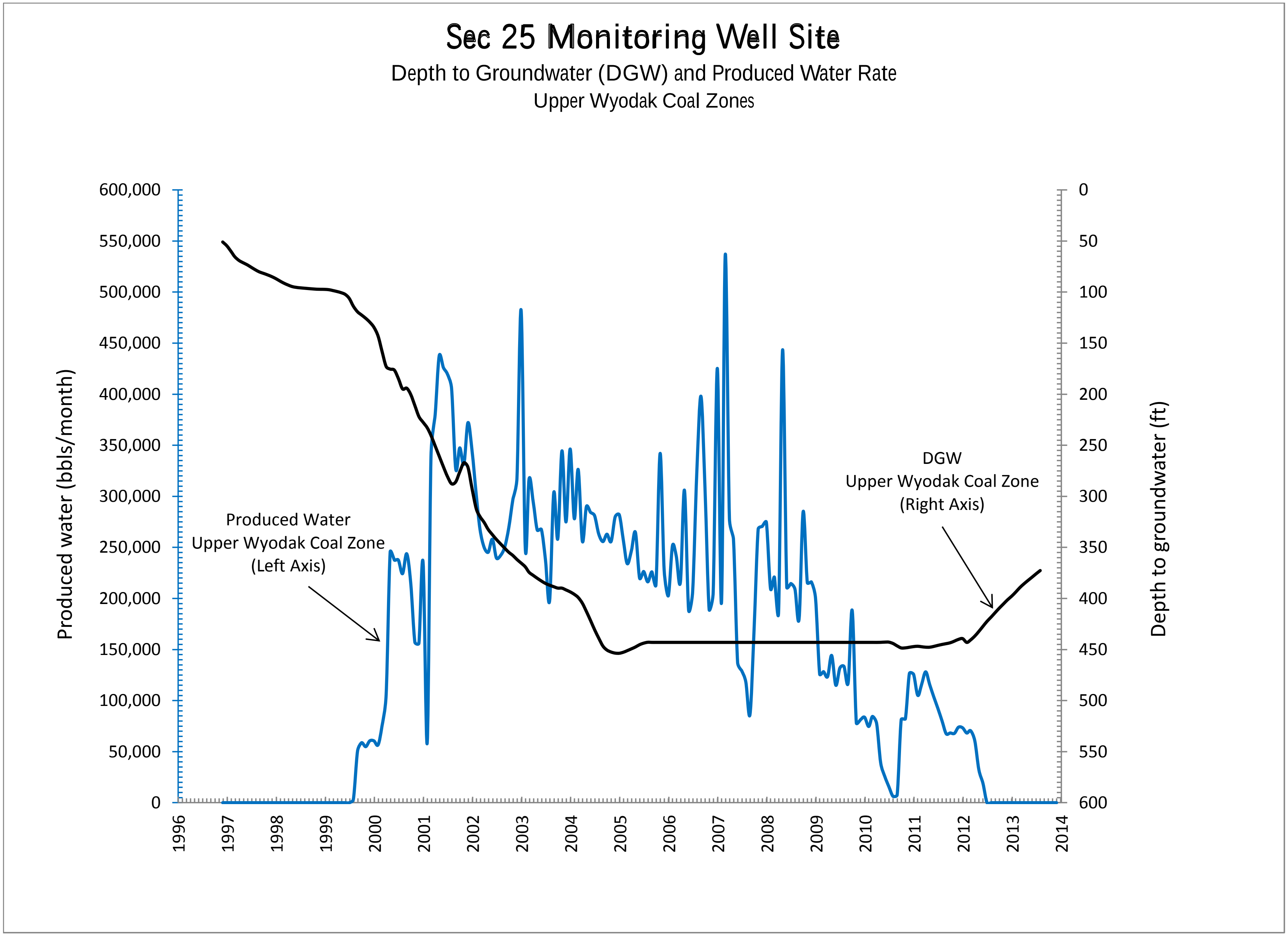


Figure 26. Location of associated CBNG wells within a 1.5 mile radius of the Sec 25 monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 27. Water production and depth to groundwater at the Sec 25 monitoring site.



Throne Monitoring Site

The Throne monitoring site (fig. 28) is located south of Gillette. Groundwater level monitoring at the site began in July 2001, 12 months after the onset of water production (July 2000) from the Upper Wyodak coal zone (fig. 29). As a result, the magnitudes of early groundwater level declines are unknown. The 12 month average water production rate rapidly reached nearly 200,000 bbls/month by the end of 2001 and remained near that level through 2003. Water production dropped off sharply after that and ceased in September 2010. With the exception of several brief, low magnitude recoveries, groundwater levels at the site dropped continuously from the onset of monitoring through 2006. Since then, water levels have recovered over 180 ft but still show a net decline of 121 ft from initial levels. The rate of recovery was 25.1 ft in 2013.

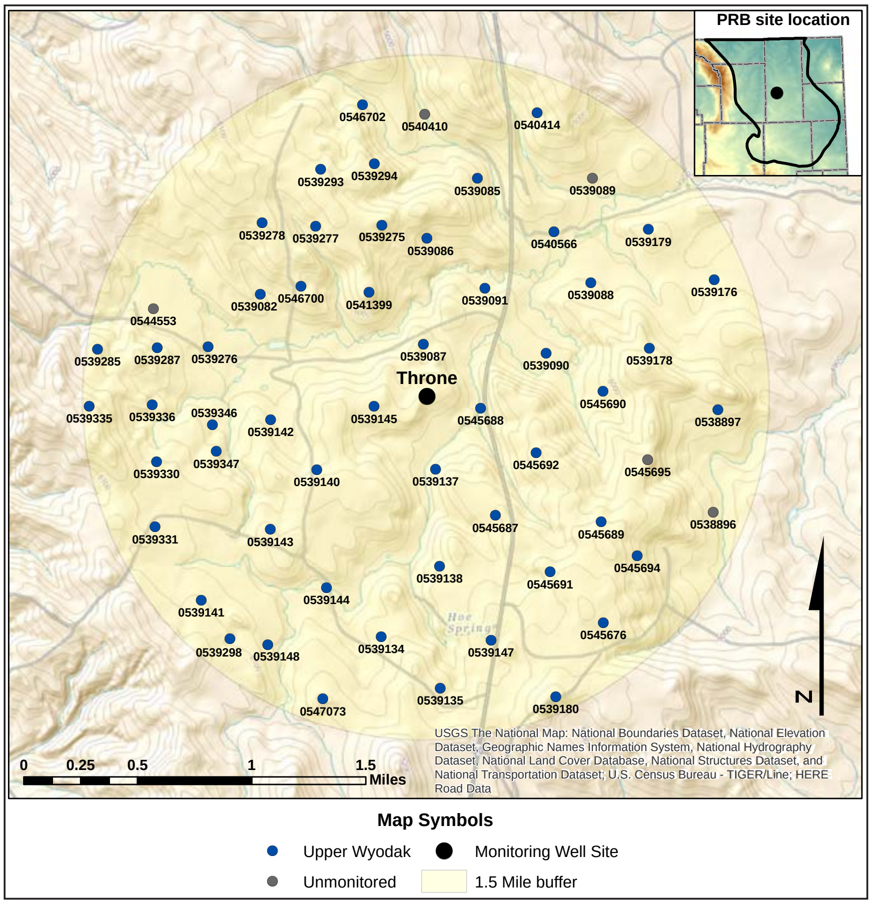
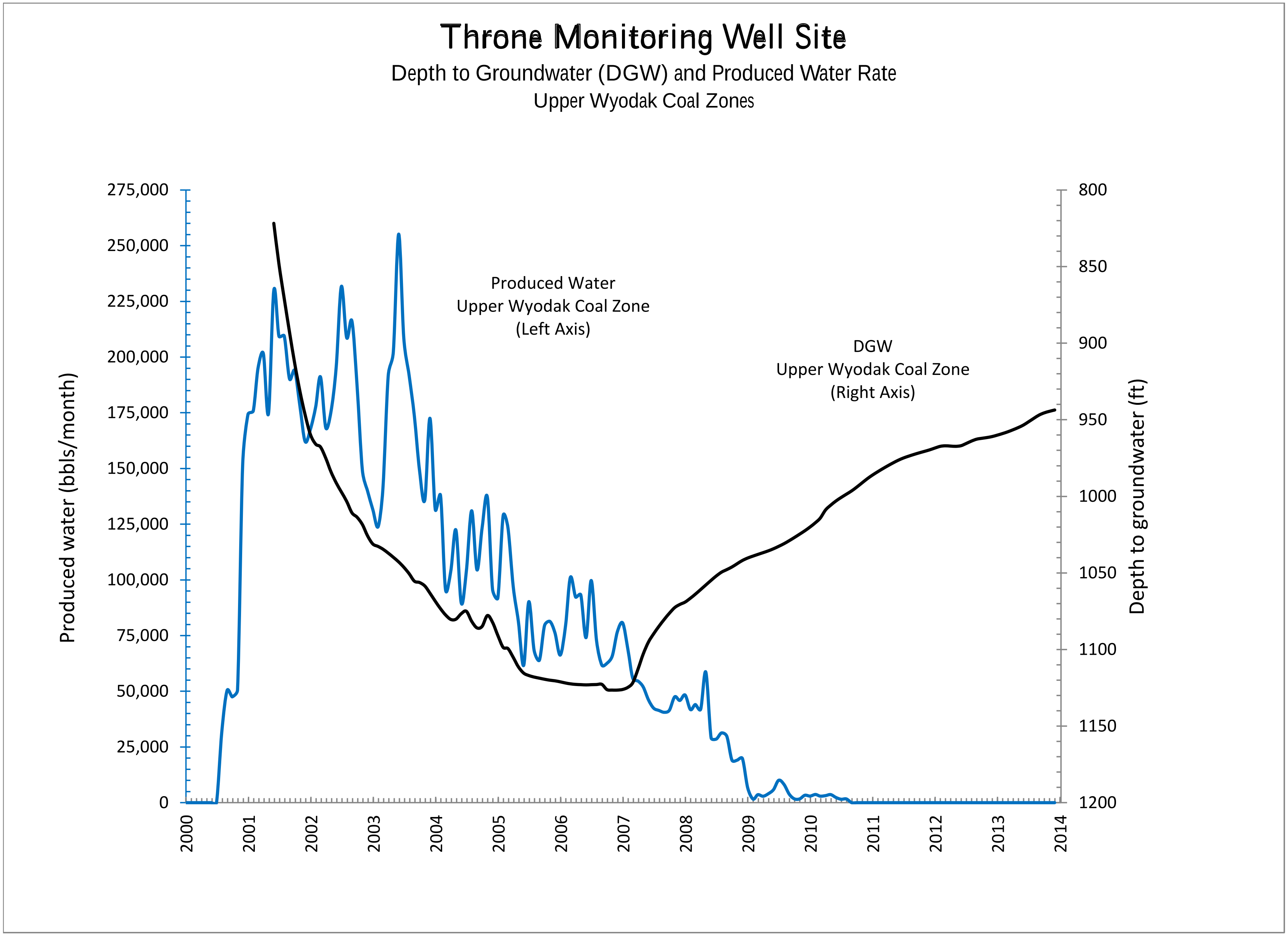


Figure 28. Location of associated CBNG wells within a 1.5 mile radius of the Throne monitoring well site. The seven digit number corresponds to the American Petroleum Institute (API) well number.

Figure 29. Water production and depth to groundwater at the Throne monitoring site.



Historic Water Levels Changes in the Upper Wyodak Coal Zone

Table 5 lists groundwater level changes observed in the Upper Wyodak coal seam over the last four decades; that is, from “pre-development” (prior to extensive coal mining or CBNG development) to the present. Table 5 also shows maximum water level changes for five BLM monitoring wells included in the original technical report prepared by Applied Hydrology (2002 - table 2-2), and for two additional BLM wells (Blackbird Coleman and Hoe Creek) where initial measurements were made prior to substantial CBNG development. Drawdowns were recorded in all five monitoring wells. Figure 30 shows that groundwater levels have generally declined throughout the upper Wyodak coal zone with the magnitude of decline generally increasing from east to west. In contrast, water levels increased slightly in monitoring well GW42R15 and an unnamed well east of Gillette.

The geospatial distribution of the historical water level changes shown in Figure 30 is related to the structural geometry of the eastern PRB. Cross-sections G-G’ and H-H’ show depths to the top of the Upper Wyodak along transects that include seven of the water level monitoring wells examined in this report. The gentle westward dip of the Upper Wyodak coal zone (less than 1 degree) along cross-section G-G’ agrees with the regional dip of the PRB observed in cross-section E-E’. In contrast, local structures account for the minor variations in depth (<400 feet) along H-H’ (Jones, 2008). When viewed together, Figure 30 and cross-sections G-G’ and H-H’ suggest that the magnitude of current groundwater changes is influenced by hydrogeologic factors related to basin geometry, such as: 1) the distance between a monitoring well and its associated recharge area, 2) well recovery time and 3) the geospatial distribution of Upper Wyodak hydrostatic pressures.

Proximity to recharge areas influences groundwater level recovery in that, areas located closer to recharge areas should recover earlier than distant well fields. Bartos and Ogle, (2002) noted that Upper Wyodak coals were likely recharged along an extensive band of Upper Wyodak clinker and coal outcrops (Heffern and others, 2013; Jones and others, 2011) that extends from north to south along the eastern edge of the PRB. Figure 30 shows that the historic monitoring wells exhibiting the lowest net water level declines (with the exception of the Blackbird Coleman site) are located close to these outcrops and, in fact the two eastern wells where groundwater levels have risen slightly are sited in close proximity to very large clinker outcrops. In comparison, water level declines are larger in wells located farther to the west.

Recovery time, or the length of time since water production in an associated buffer zone was significantly reduced or ceased, also affects the magnitude of water level change. During recovery, water levels rise rapidly at first and then slow as the system approaches equilibrium (figs. 6, 21, 27, 28). Recovery times in the PRB have a geospatial component because CBNG development began earliest in those areas of the eastern PRB where thick Upper Wyodak coal seams are buried at relatively shallow depths, and then later continued westward where the Upper Wyodak is more deeply buried. Consequently, water production typically ended earlier in the eastern CBNG fields where recovery periods have been longer than those to the west. Comparisons of several monitoring wells shown in Figure 30 and examined in the 2013 BLM Groundwater Monitoring Report (Taboga and others, 2014) reveal that water production usually ceased by early 2008 in production areas exhibiting water level declines of less than 250 feet (Amoco, MP 2, MP 22 and Blackbird Coleman). Conversely, water production continued beyond early 2008 in areas where net declines of more than 300 feet are observed (Hoe Creek, Federal 1-14-2025 and Durham Ranch Sec 14).

Hydrostatic pressures in the Upper Wyodak coal zone increase as the PRB dips westward (cross-section G-G’). Efficient CBNG extraction entails lowering hydraulic pressures in the targeted coal seam to the point that desorption begins and natural gas bubbles form on the surfaces of pores and fractures within the coal. Additional water must be pumped from more deeply buried coals to further reduce groundwater levels, and corresponding water pressures, so that sufficient quantities of CBNG can be produced economically. Subsequently, if coal seam hydraulic properties are similar, groundwater level recovery should take longer in fields with larger maximum drawdowns.

Table 6 shows the results of regression analyses relating current groundwater level changes in seven BLM wells (Table 5) related to the 1) proximity to recharge area, 2) well recovery time and 3) maximum groundwater level drawdown. Coefficients of determination (R^2) for the regression analyses of the seven well sites varied from 0.005 to 0.859; p-values ranged from 0.885 to 0.003.

The regression analyses indicate that current groundwater levels in the selected monitoring wells have the strongest statistical relationship to the maximum observed drawdown ($R^2 = 0.859$) and is statistically significant (P value = 0.003) when evaluated at the 0.01 significance level. The relationship with recovery time showed an R^2 value of 0.564 and P-value of 0.052. The distance from the recharge area displayed the weakest statistical relationship to current groundwater level changes with an R^2 value of 0.005 and P-value of 0.885

CONCLUSION

The WSGS examined groundwater level time series from eleven selected Upper Wyodak coal zone 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 compared the groundwater response time series to concurrent monthly water production data (WOGCC, 2014) for Upper Wyodak CBNG wells located within a one and one half mile radius buffer zone of each BLM monitoring well. During 2013, CBNG water was produced at low levels (< 4,000 bbls/month) from the buffer zones of only the 20 Mile Butte, Barrett Persson and Blackbird Coleman monitoring well sites; there was no water production associated with the eight remaining monitoring wells.

During 2013, groundwater levels declined in five monitoring wells (range 2.3 - 22.8 ft) and rose in six wells (4.7 - 42.6 ft). Still, current water levels remain below initial observed levels in all but one well, Bull Creek (refer to fig. 2). Water level monitoring did not begin at the Bull Creek site, however, until 21 months after the onset of water production from the Upper Wyodak coal zone, so it is likely that groundwater levels were somewhat depressed before initial measurements were made.

In well sites associated with current CBNG water production, during 2013, groundwater levels declined at the 20 Mile (-2.3 ft) and Blackbird Coleman (-9.6 ft) sites but rose 9.4 ft at Barrett Persson. In comparison, four monitoring wells in non-producing buffer zones showed groundwater declines and four wells showed recoveries in 2013.

Long term changes in Upper Wyodak coal zone groundwater levels are related to the location of monitoring wells. Generally, minor to moderate declines occur in the eastern PRB with declines becoming more pronounced in western areas. A regression analysis indicates that this geospatial distribution of current net groundwater decline is most likely due to the maximum drawdown observed in a monitoring well.

Linear regression analyses of groundwater levels in all wells indicate that recent short term trends (13 to 36 months) are moderately to highly linear (R^2 values from 0.78 – 0.99) and statistically significant at the 0.01 level: all p-values were less than 0.0022. Slopes of the linear regressions indicate that annual rates of change range from -21.6 ft/yr (groundwater level decline) to 45.1 ft/yr (groundwater level recovery). It is unknown if groundwater levels will continue to recover/decline at current rates or in a linear manner in the future; WSGS encourages BLM to continue their current groundwater monitoring program.

Table 5. Historic groundwater level changes in selected Upper Wyodak coal seam monitoring wells, PRB, Wyoming (adapted from Applied Hydrology Associates, Inc., 2002).

Well ID#	Observation Well Name	PLSS Location	Surface Elevation (ft)	Pre-development GW Elevation[a] (ft)	Date	Current GW Elevation (ft)	Max. Change GW[b] Elevation (ft)	Most Recent Net Change GW Elevation (ft)
P54733.0W	NA-38A	NWNW-S5-T41N-R70W	---	4595	1980	4423 [c]	----	-172
P41368.0W	SOW-109	SWSW-S20-T41N-R70W	4766	4581	1980	4580 [d]	----	-1
P27385.0W	CCR-17	SWNE-S19-T46N-R70W	4597	4586	1980	4530 [d]	----	-56
P27405.0W	CCR-2A	SENW-S4-T45N-R70W	4697	4717	1980	4697 [d]	----	-20
---	MC-2-1-P	S2-T46N-R71W	---	4491	1980	4460 [c]	----	-31
P55243.0W	GW42R15	SWSE-S1-T41N-R70W	---	4731	1980	4740 [c]	----	9
---	ECH-8	S35-T42N-R71W	---	4596	1980	4412 [c]	----	-184
P38086.0W	BTR-28	NWNW-S18-T43N-R70W	4745	4608	1980	4467 [d]	----	-141
P90658.0W	MP 22	SENE-S22-T48N-R72W	4561	4387	1993	4234 [b]	-316	-154
---	MP 2	NWNW-S2-T47N-R72W	4554	4391	1993	4221 [b]	-242	-170
P72107.0W	Amoco	NWSE-S36-T47N-R72W	4682	4438	1995	4199 [b]	-251	-239
49-005-07139	Federal 1-14-2025 (Sec 25)	SWSW-S25-T46N-R72W	4659	4611	1996	4293 [b]	-512	-318
P72100.0W	Lin-W2	SESE-S16-T46N-R72W	---	4468	1996	4126 [c]	----	-342
---	American	S36-T46N-R72W	---	4465	1996	4138 [c]	----	-327
P107525.0W	Bar 76	NESE-S1-T45N-R73W	4768	4606	1997	4008 [b]	----	-598
P106973.0W	Durham Ranch Sec 14	SENE-S14-T44N-R72W	4861	4593	1998	4266 [b]	-548	-327
P32080.0W	GN-6	NWNW-S21-T51N-R72W	4291	4268	1977	4260 [d]	----	-8
---	Unnamed	S21-T50N-R71W	---	4387	1977	4400 [c]	----	13
---	HWY	S31-T49N-R71W	---	4466	1977	4270 [c]	----	-196
---	WRRI-10A	S31-T48N-R71W	---	4457	1977	4300 [c]	----	-157
P26427.0W	BTR-20	NESE-S3-T42N-R70W	---	4652	pre-2002	4600 [c]	----	-52
---	Hoe Creek	SWSW-S7-T47N-R72W	4734	4503 b	1998	4116 [b]	-679	-387
49-005-36025	Blackbird Coleman	SWSE-S5-T47N-R74W	4778	4407 b	2000	4241 [b]	-167	-166

[a] From Applied Hydrology Consultants, unless otherwise noted.

[b] From **WSGS,** Taboga and Stafford (2014).

[c] From **GAGMO,** Interpolated from potentiometric surface, Gillette Area Groundwater Monitoring Organization - Hydro-Engineering (2014).

[d] From **GAGMO,** GAGMO monitoring well, Hydro-Engineering (2014).

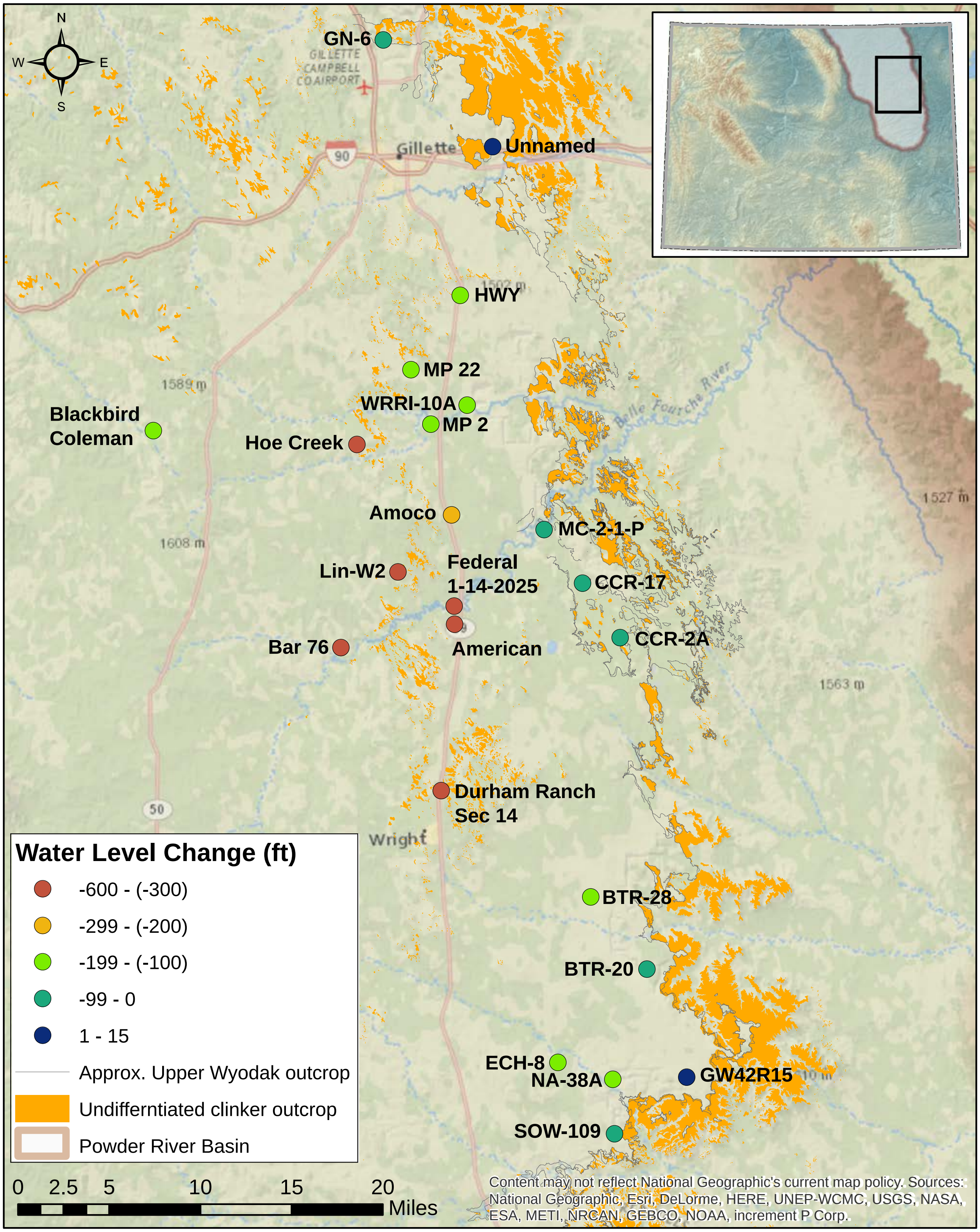


Figure 30. Historic groundwater level changes in selected Upper Wyodak coal zone monitoring wells, Upper Wyodak coal zone outcrops and undifferentiated clinker outcrops, Powder River Basin, Wyoming.

Table 6. Linear regression statistics for groundwater level changes in historic monitoring wells as related to selected geologic and energy development factors, PRB of Wyoming, 2014.

Observation Well Name	Current Change GW Elevation (ft)	Distance from recharge area (mi)	Recovery time (days)	Maximum Observed Drawdown (ft)
MP 22	-153.5	7.3	2508	-316
MP 2	-170.0	5.7	3056	-242
Amoco	-239.0	5.1	2568	-251
Federal 1-14-2025 (Sec 25)	-317.9	6.4	956	-512
Durham Ranch Sec 14	-326.6	11.1	1717	-548
Hoe Creek	-386.5	11.6	2021	-679
Blackbird Coleman	-166.1	21.1	2964	-167
R^2 =	----	0.005	0.564	0.859
p value =	----	0.885	0.052	0.003

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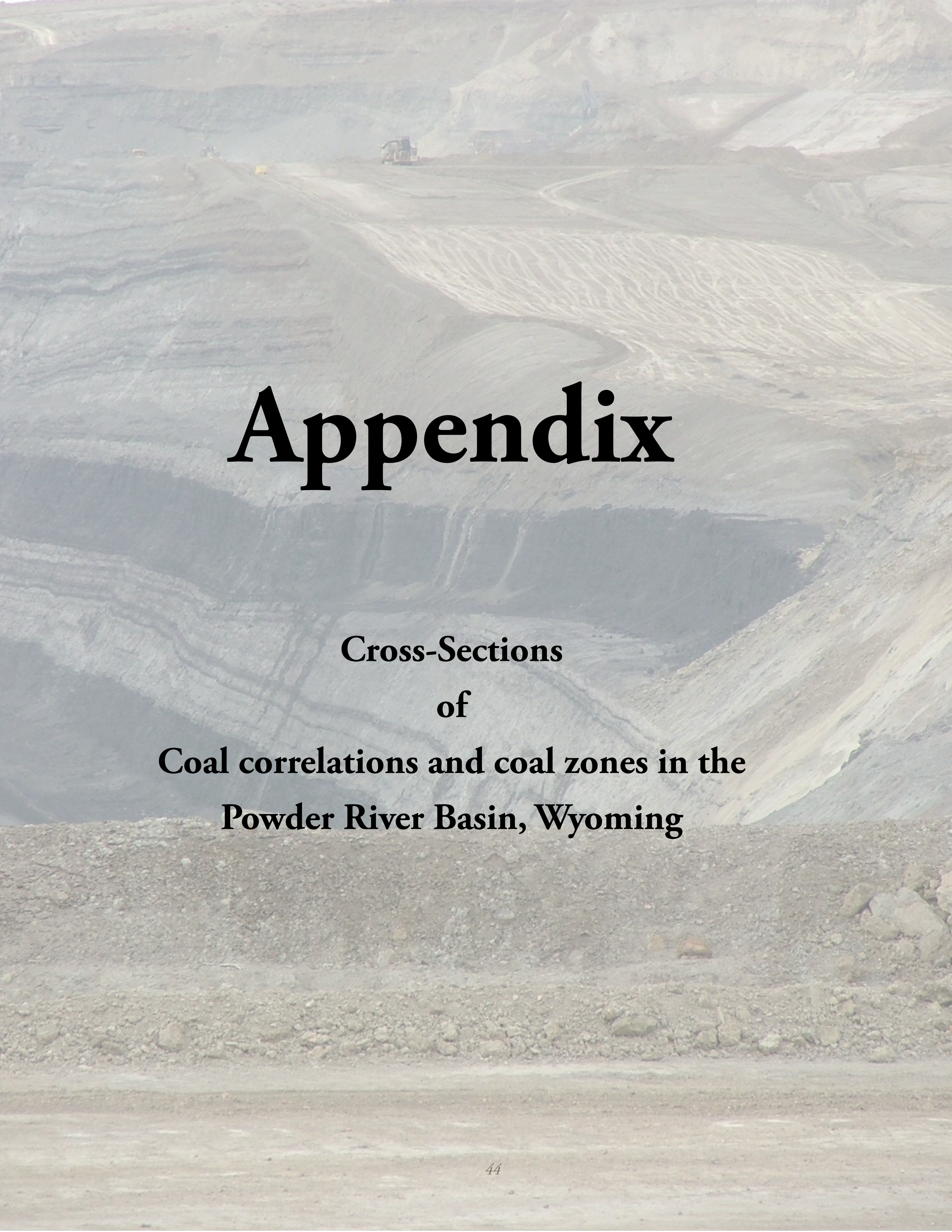


Appendix

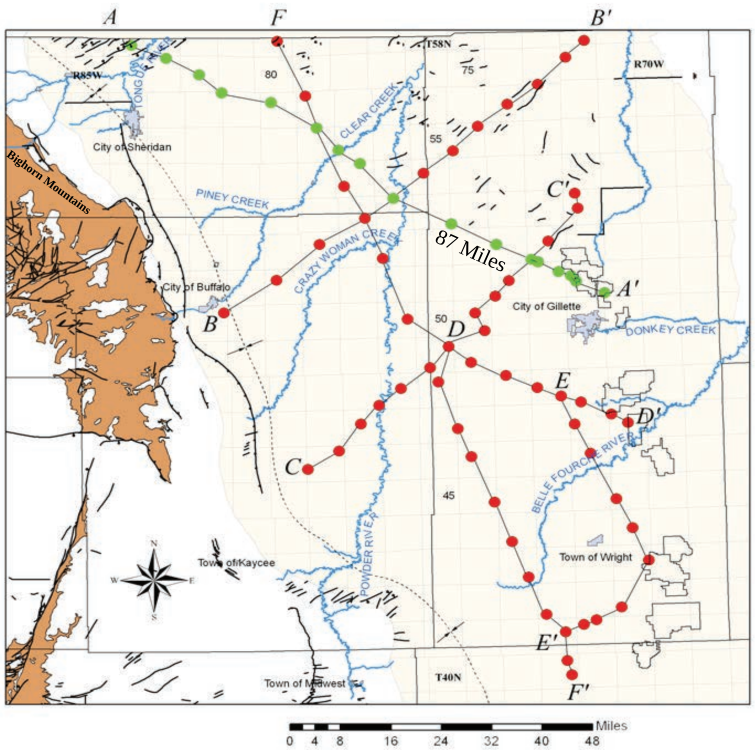
Cross-Sections
of
Coal correlations and coal zones in the Powder River Basin, Wyoming

Cross Section A-A’

Vertical Exaggeration 50x

Horizontal scale is exaggerated in areas of closely spaced wells

Modified from Jones, N. R., and Rodgers, J.R., (2007)



Location and Index map
(Green indicates wells used in current cross section)

Explanation of Location and Index map and accompanying cross section.

Active coal mines

Faults, displacement undefined

Normal fault, ball and bar on down thrown block

Thrust fault, teeth on upthrown block

Synclinal axis

Precambrian rocks

Tertiary and Cretaceous coal bearing rocks

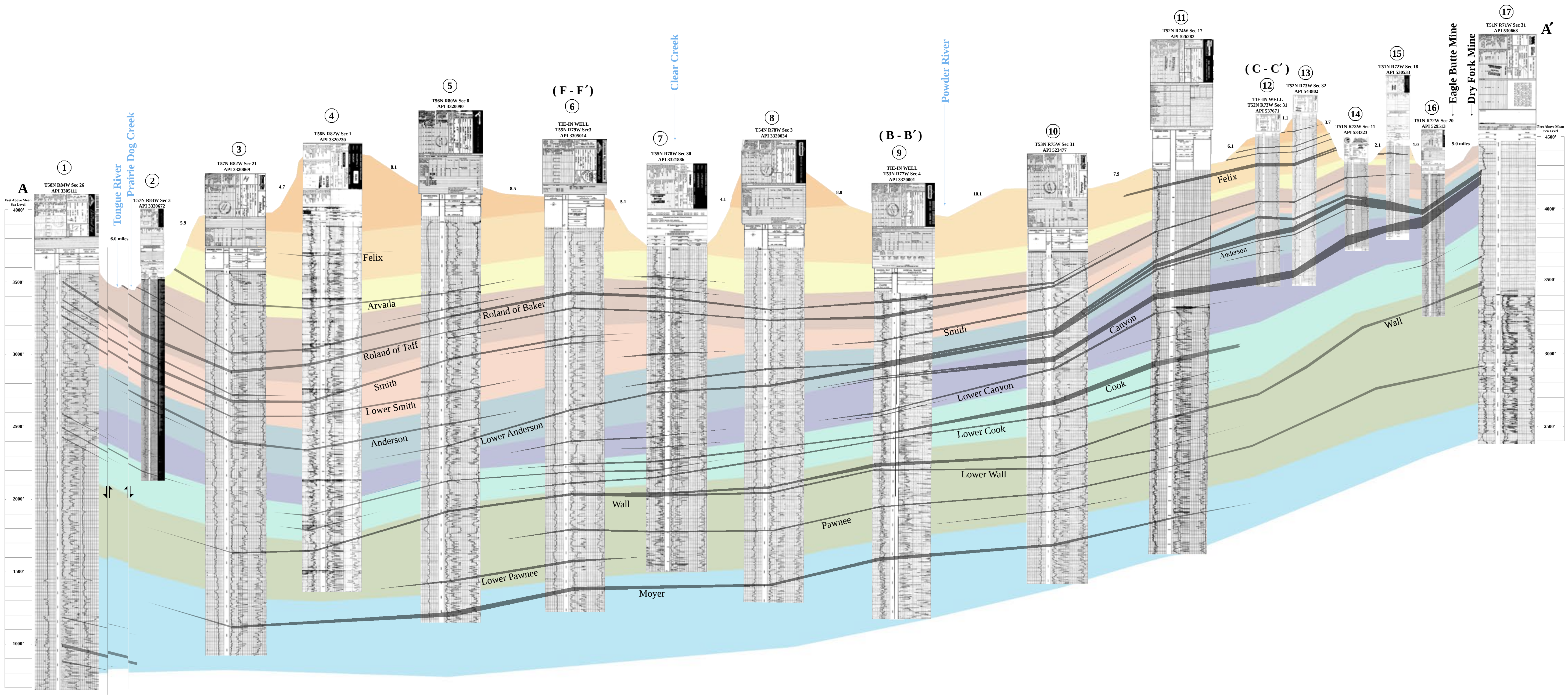
Coal Zones

Wasatch:
- Upper Wasatch
- Felix
- Lower Wasatch

Fort Union Tongue River Member:
- Roland
- Wyodak Rider
- Upper Wyodak
- Lower Wyodak
- Knoblock
- Sawyer
- Basal Tongue River

Coal Bed Terminations

- Pinch Out
- Shale Out
- Split
- Parting
- No Data



Coal correlations and coal zones in the Powder River Basin, Wyoming

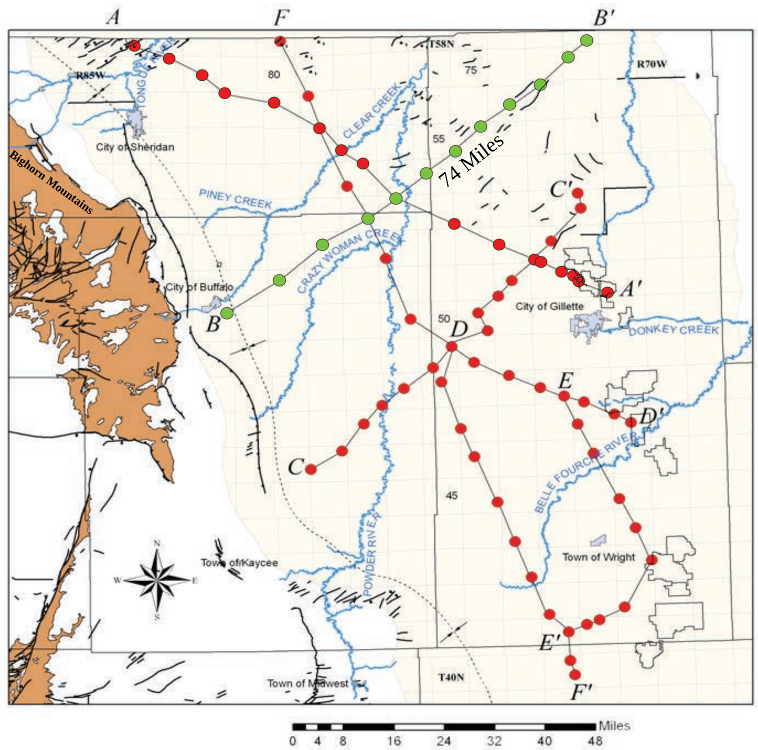
Cross Section A-A'

Cross Section B-B’

Vertical Exaggeration 50x

Horizontal scale is exaggerated in areas of closely spaced wells

Modified from Jones, N. R., and Rodgers, J.R., (2007)



Location and Index map
(Green indicates wells used in current cross section)

Explanation of Location and Index map and accompanying cross section.

Active coal mines

Faults, displacement undefined

Normal fault, ball and bar on down thrown block

Thrust fault, teeth on upthrown block

Synclinal axis

Precambrian rocks

Tertiary and Cretaceous coal bearing rocks

Coal Zones

Wasatch

Upper Wasatch

Felix

Lower Wasatch

Fort Union Tongue River Member

Roland

Wyodak Rider

Upper Wyodak

Lower Wyodak

Knoblock

Sawyer

Basal Tongue River

Coal Bed Terminations

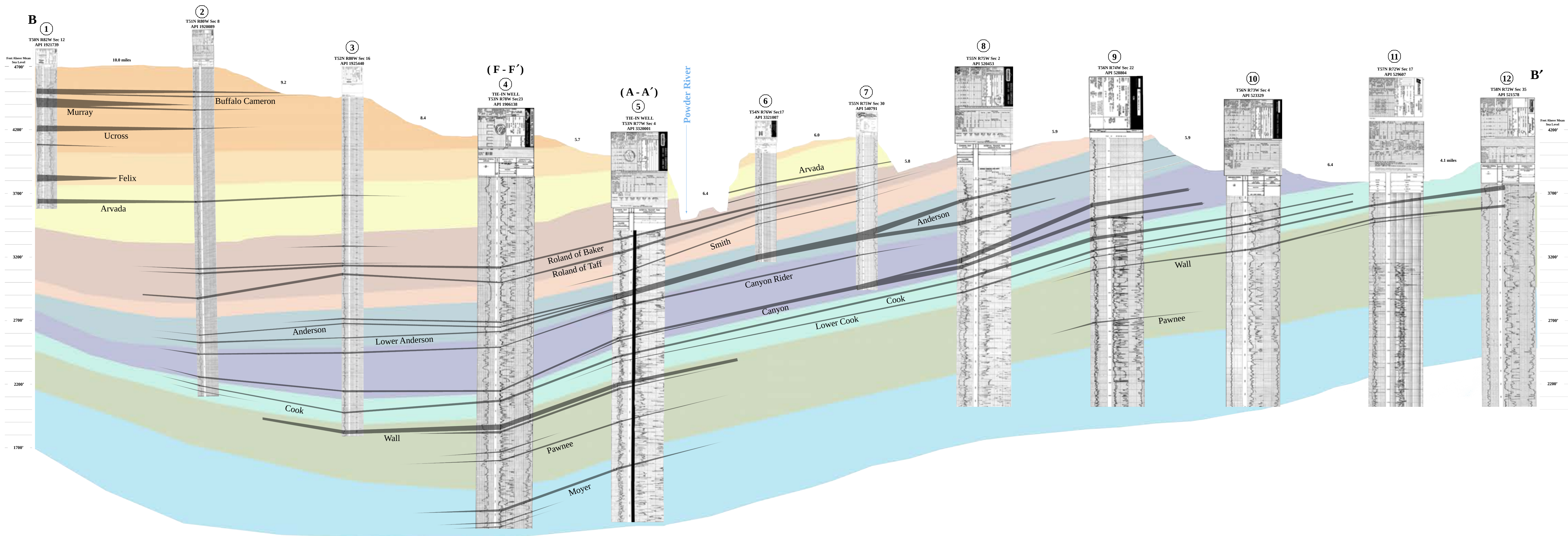
Pinch Out

Shale Out

Split

Parting

No Data



Coal correlations and coal zones in the Powder River Basin, Wyoming

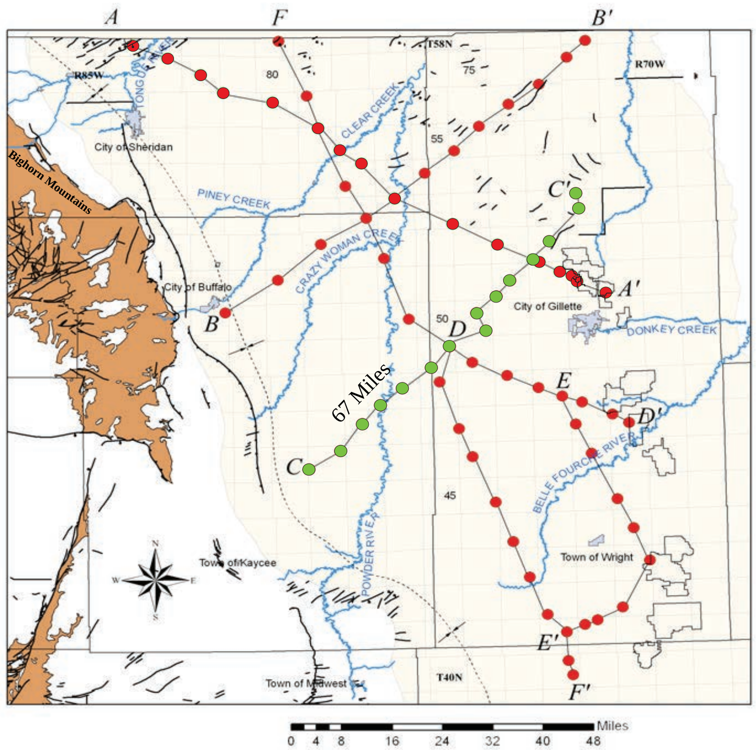
Cross Section B-B’

Cross Section C-C’

Vertical Exaggeration 50x

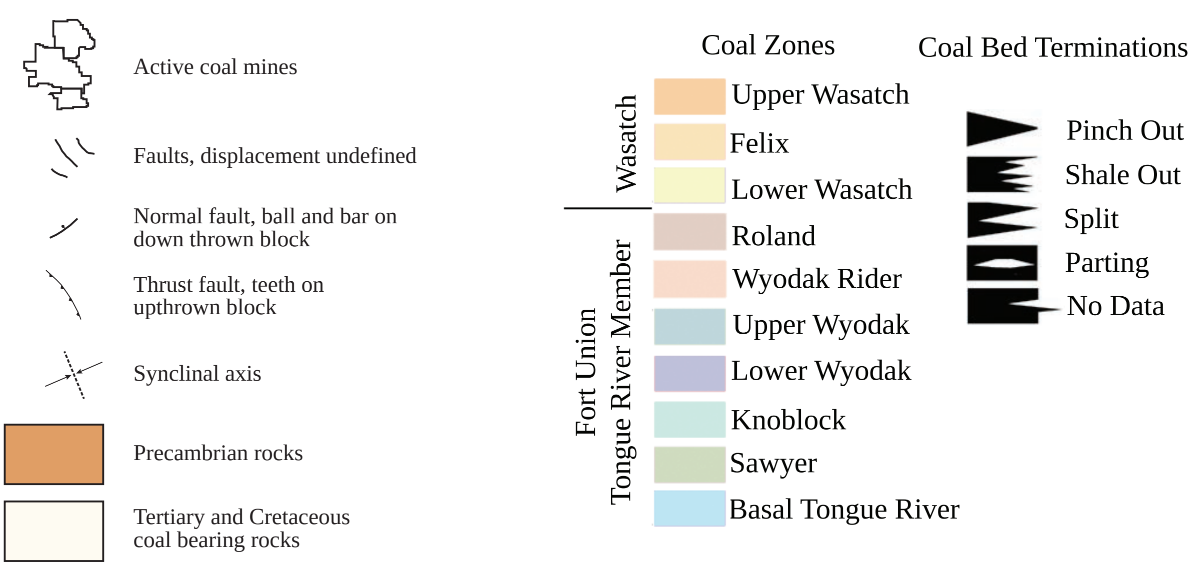
Horizontal scale is exaggerated in areas of closely spaced wells

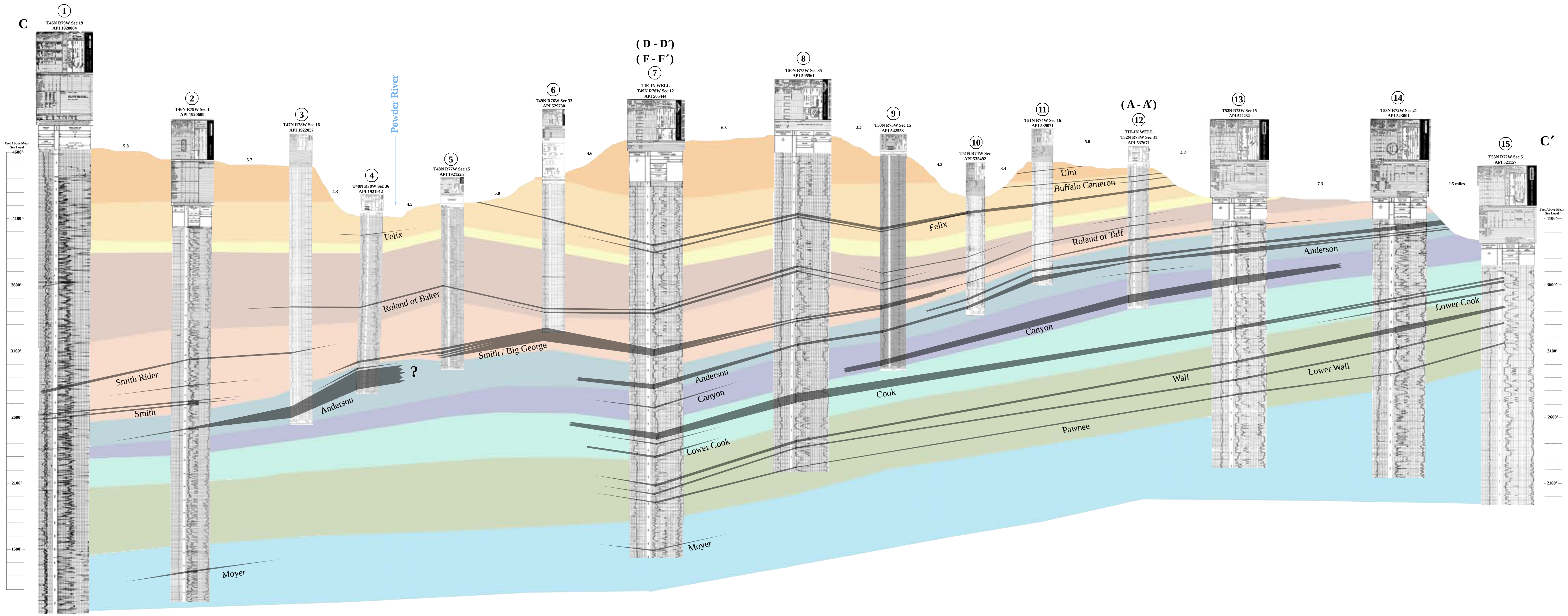
Modified from Jones, N. R., and Rodgers, J.R., (2007)



Location and Index map
(Green indicates wells used in current cross section)

Explanation of Location and Index map and accompanying cross section.





Coal correlations and coal zones in the Powder River Basin, Wyoming

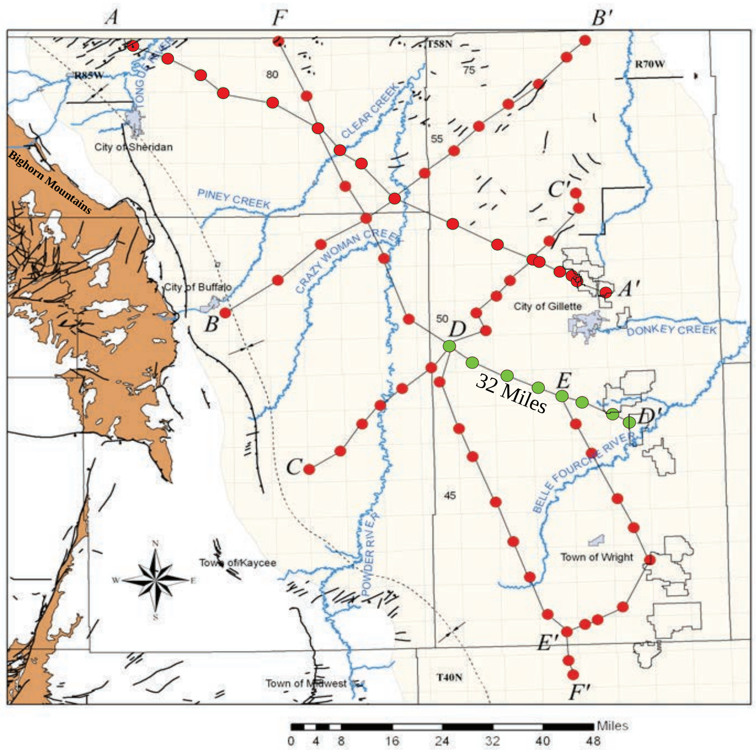
Cross Section C-C'

Cross Section D-D’

Vertical Exaggeration 50x

Horizontal scale is exaggerated in areas of closely spaced wells

Modified from Jones, N. R., and Rodgers, J.R., (2007)



Location and Index map
(Green indicates wells used in current cross section)

Explanation of Location and Index map and accompanying cross section.

Active coal mines

Faults, displacement undefined

Normal fault, ball and bar on down thrown block

Thrust fault, teeth on upthrown block

Synclinal axis

Precambrian rocks

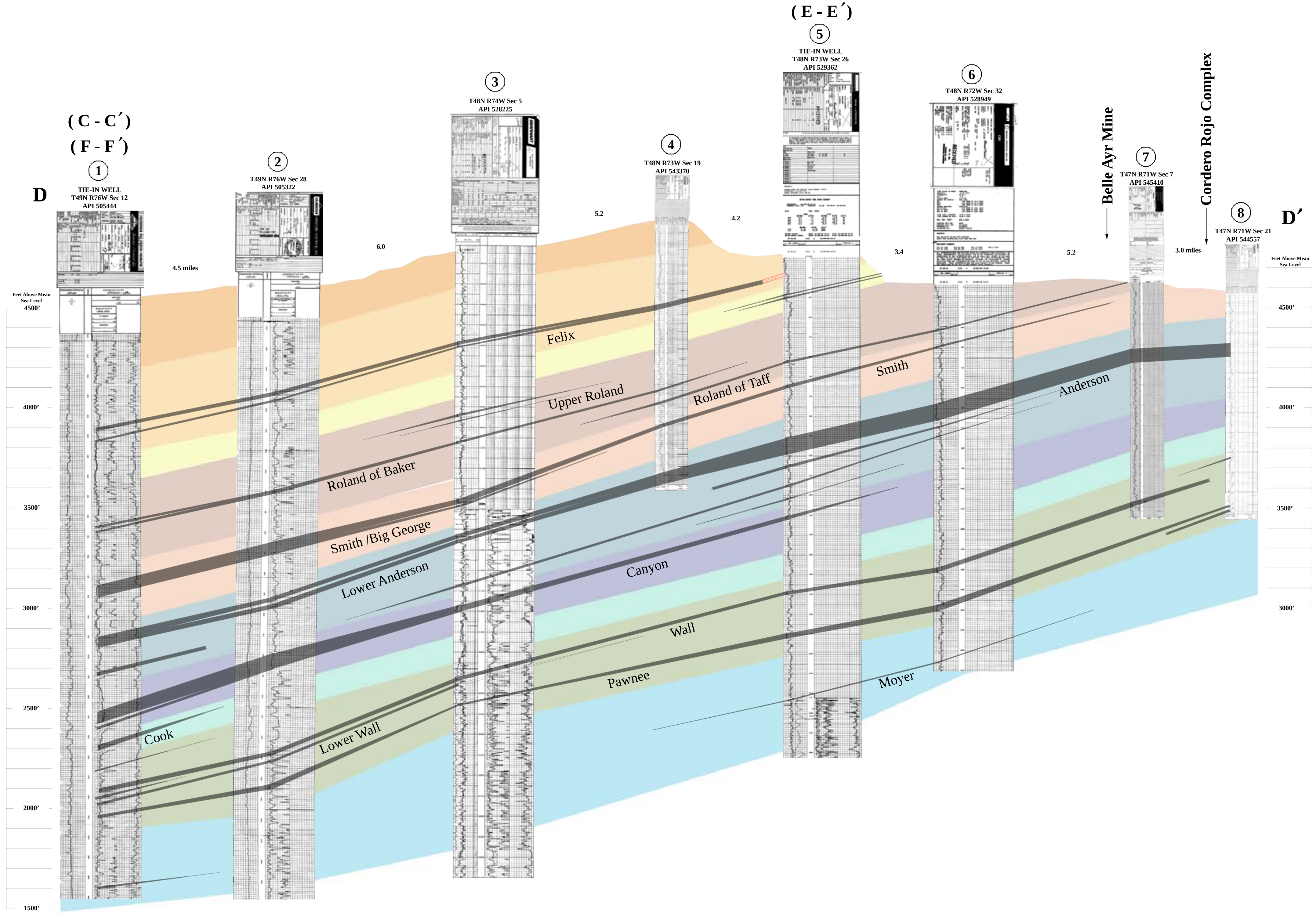
Tertiary and Cretaceous coal bearing rocks

Coal Zones

Wasatch
- Upper Wasatch
- Felix
- Lower Wasatch

Fort Union Tongue River Member
- Roland
- Wyodak Rider
- Upper Wyodak
- Lower Wyodak
- Knoblock
- Sawyer
- Basal Tongue River

Coal Bed Terminations
- Pinch Out
- Shale Out
- Split
- Parting
- No Data



Coal correlations and coal zones in the Powder River Basin, Wyoming

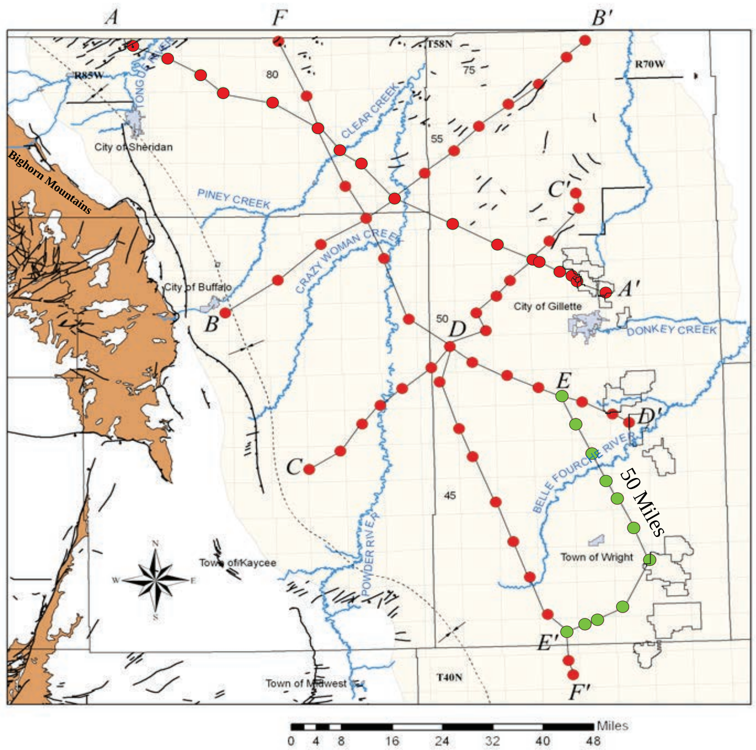
Cross Section D-D'

Cross Section E-E’

Vertical Exaggeration 50x

Horizontal scale is exaggerated in areas of closely spaced wells

Modified from Jones, N. R., and Rodgers, J.R., (2007)



Location and Index map
(Green indicates wells used in current cross section)

Explanation of Location and Index map and accompanying cross section.

Active coal mines

Faults, displacement undefined

Normal fault, ball and bar on down thrown block

Thrust fault, teeth on upthrown block

Synclinal axis

Precambrian rocks

Tertiary and Cretaceous coal bearing rocks

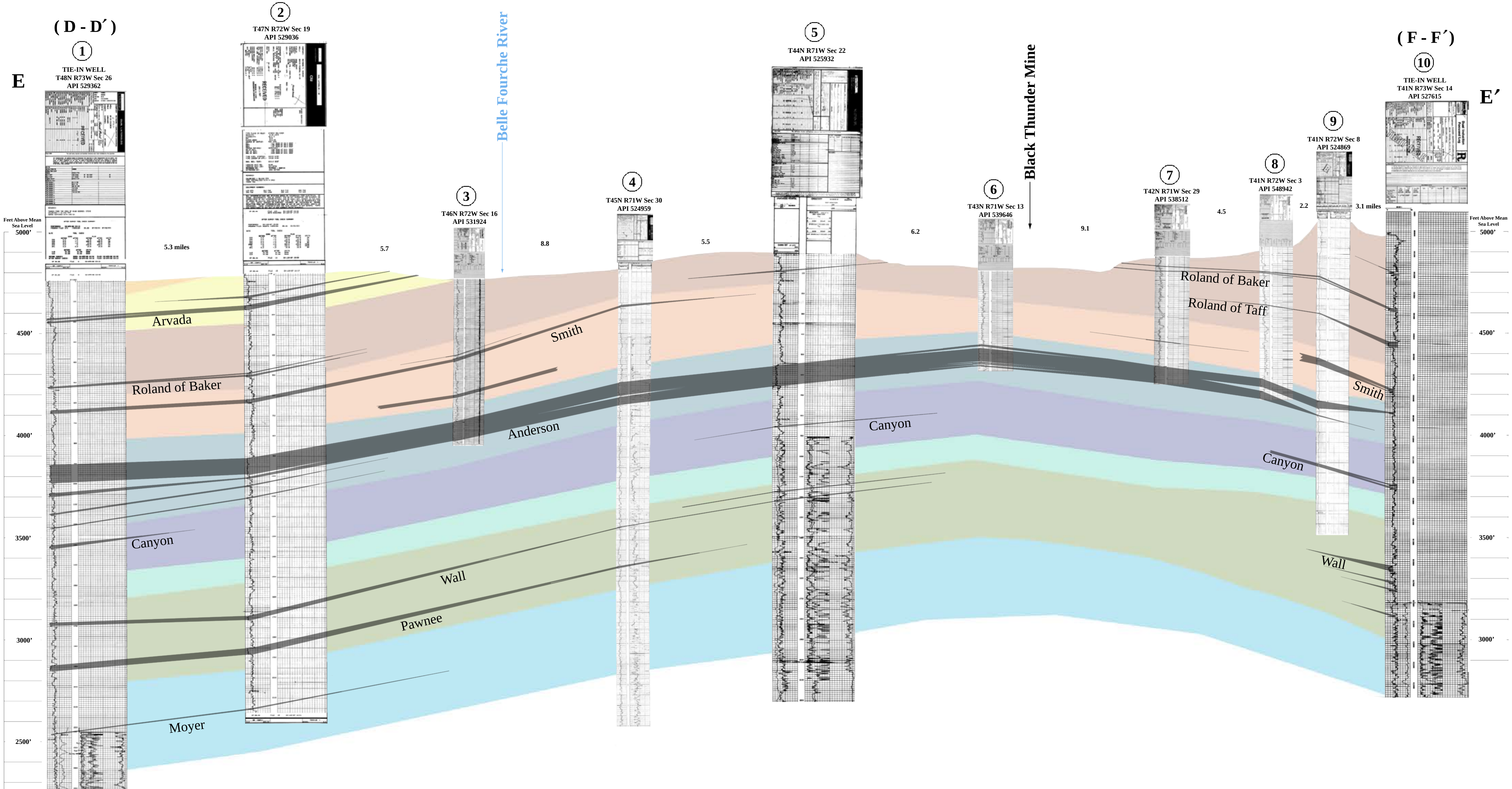
Coal Zones

Wasatch
- Upper Wasatch
- Felix
- Lower Wasatch

Fort Union Tongue River Member
- Roland
- Wyodak Rider
- Upper Wyodak
- Lower Wyodak
- Knoblock
- Sawyer
- Basal Tongue River

Coal Bed Terminations

- Pinch Out
- Shale Out
- Split
- Parting
- No Data



Coal correlations and coal zones in the Powder River Basin, Wyoming

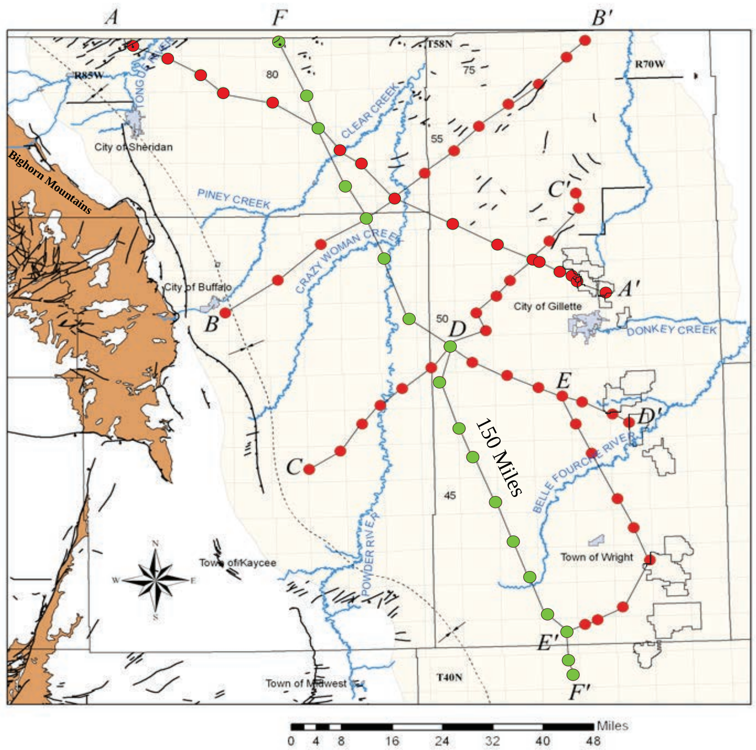
Cross Section E-E'

Cross Section F-F’

Vertical Exaggeration 50x

Horizontal scale is exaggerated in areas of closely spaced wells

Modified from Jones, N. R., and Rodgers, J.R., (2007)



Location and Index map
(Green indicates wells used in current cross section)

Explanation of Location and Index map and accompanying cross section.

Active coal mines

Faults, displacement undefined

Normal fault, ball and bar on down thrown block

Thrust fault, teeth on upthrown block

Synclinal axis

Precambrian rocks

Tertiary and Cretaceous coal bearing rocks

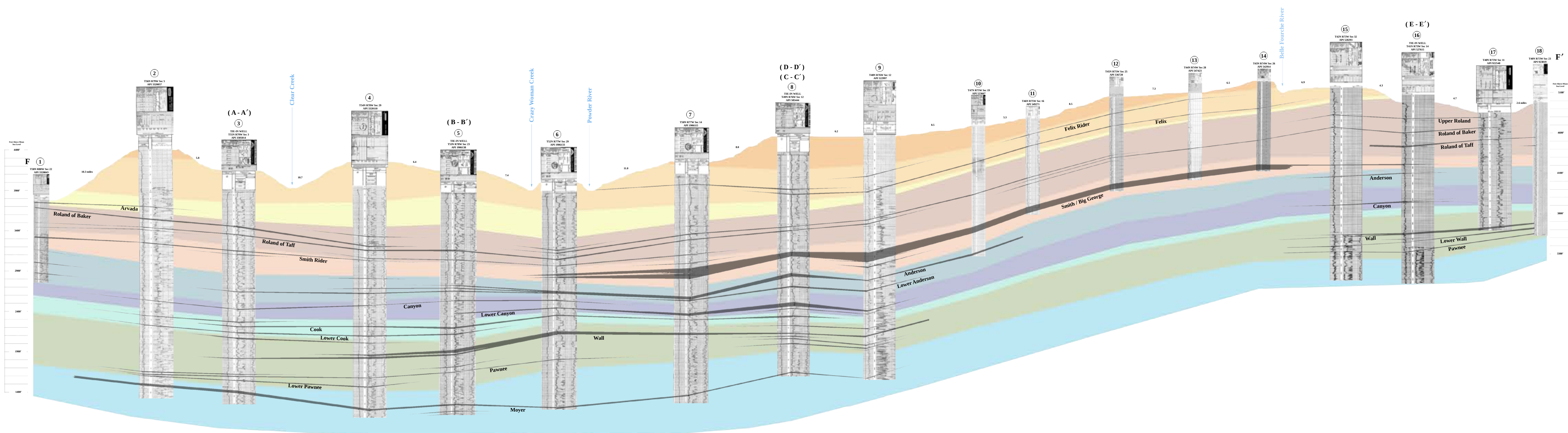
Coal Zones

Wasatch
- Upper Wasatch
- Felix
- Lower Wasatch

Fort Union Tongue River Member
- Roland
- Wyodak Rider
- Upper Wyodak
- Lower Wyodak
- Knoblock
- Sawyer
- Basal Tongue River

Coal Bed Terminations

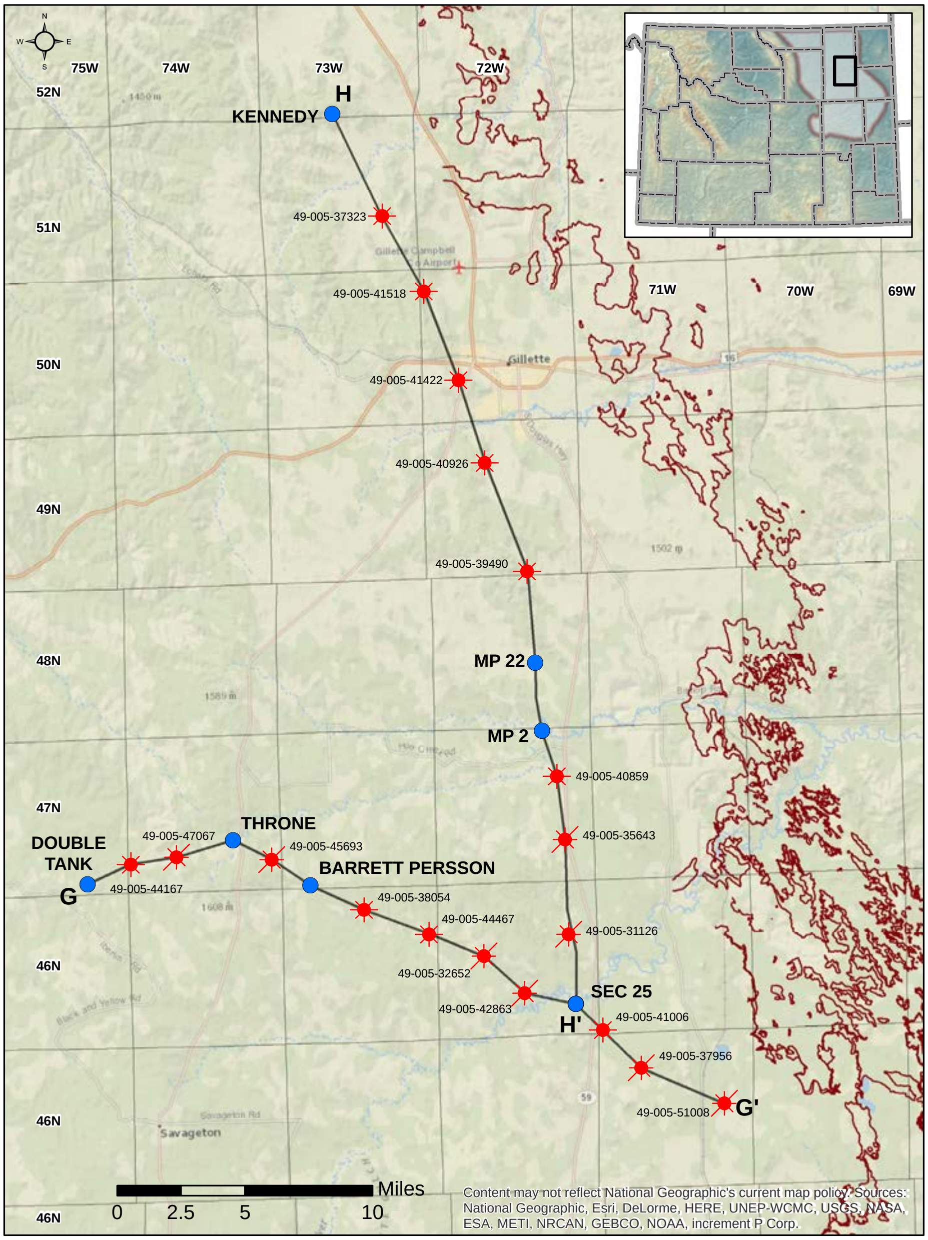
- Pinch Out
- Shale Out
- Split
- Parting
- No Data



Coal correlations and coal zones in the Powder River Basin, Wyoming

Cross Section E-E’

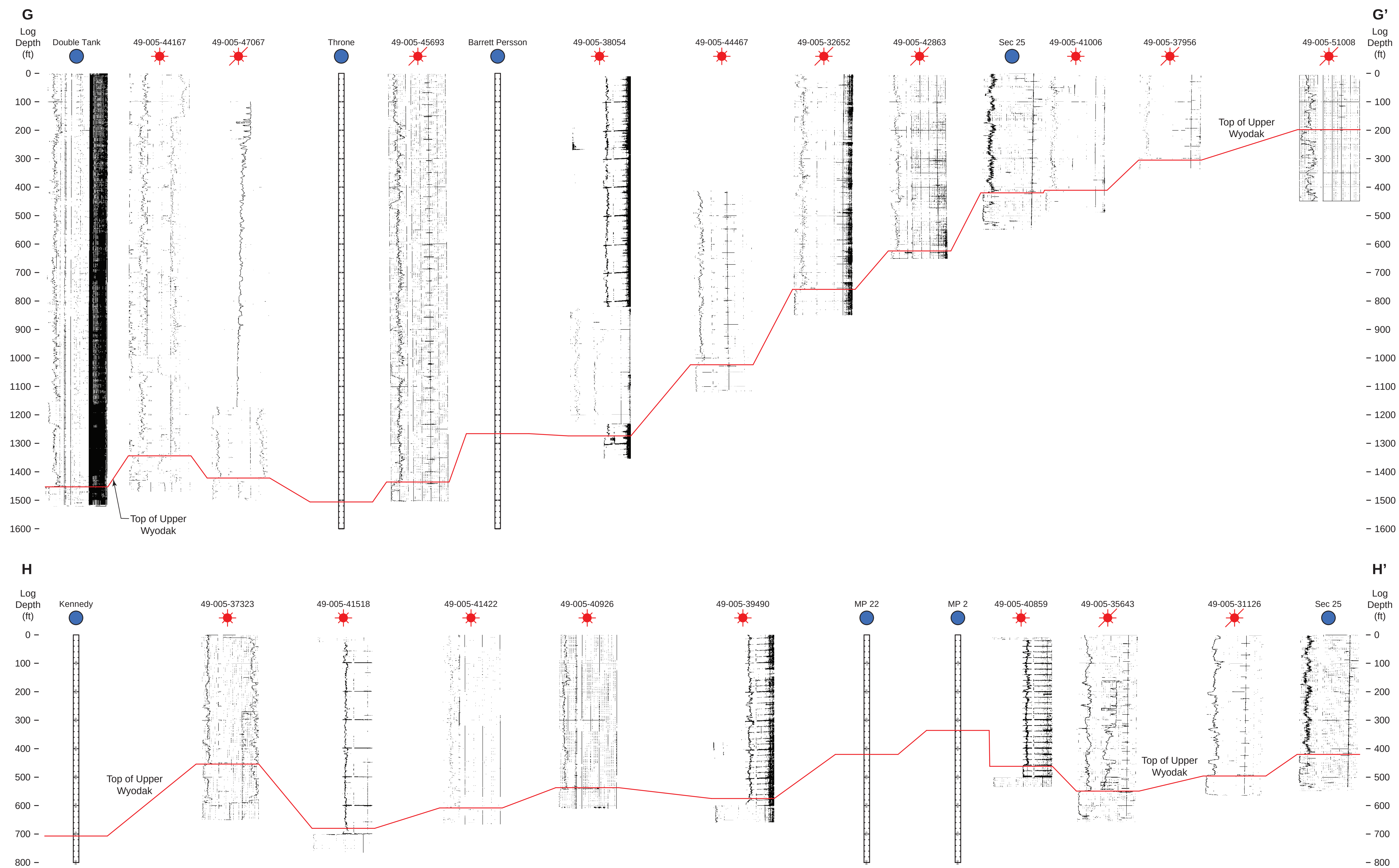
Cross Section G-G’ & Cross Section H-H’



Location and Index map

Explanation of Location and Index map and accompanying cross sections.

- Upper Wyodak monitoring wells
- Gas well
- Plugged gas well
- Cross section lines
- Approx. Upper Wyodak outcrop



Cross sections showing Upper Wyodak coal zone depths in the Powder River Basin, Wyoming

Cross Sections G-G' and H-H'

GLOSSARY

Anastomosed stream – A brook, creek or river that, along its course, divides into several branches, which reconnect further downstream.

Braided stream – A stream that consists of several small channels separated by small islands and sand and gravel bars. Commonly found in rivers with high channel slopes and sediment loads.

Buffer zone – A designated geographical area of a distinct size wherein a particular effect is considered to be significant.

Butt cleats – Short, poorly defined coal seam fractures that extend between longer parallel fractures called face cleats.

Cleats – Fractures observed in coal seams.

Clinker – The vitrified residue that forms where coal outcrops burned after being ignited by wildfires or lightning. Often, clinker has similar material properties to manmade brick.

Coal zone – A layer or stratum of one or more coal seams. A coal zone is distinguishable from adjacent coal strata by some particular property such as the geologic time of formation or depositional environment.

Coalbed natural gas – A mixture of hydrocarbon gases, consisting primarily of methane, generated by chemical and biological processes during the formation of coal seams.

Cone of depression – A volume of lower water pressure that forms around a well that is actively pumping groundwater.

Discharge – The production of liquids and/or gases from a well.

Flows – The movement of liquids, gases or unconsolidated solids from one space to another.

Fluvial-deltaic system – An environmental system associated with rivers and river deltas.

Groundwater – Water that occurs in geologic material below ground surface.

Groundwater decline – A lowering of the water table or potentiometric surface over time.

Groundwater level recovery – A rise in the water table or potentiometric surface over time.

Homogeneous – A geological material that possesses uniform physical properties everywhere.

Hydraulic – Pertaining to the physical properties of a geologic material as it affects the flow and transport of water.

Hydraulic anisotropy – A condition where an aquifer's hydraulic properties vary with the direction of groundwater flow. For example, a porous sandstone block with an open fracture exhibits hydraulic anisotropy because water would flow at a greater velocity along the fracture than across it.

Hydrograph – A graph that depicts flow rate, water pressure or water level over some time interval.

Interporosity flows – The flow of water from one porosity system to another such as from matrix pores to a fracture, cavity or pipe, or vice versa.

Isotropic – A condition where an aquifer's hydraulic properties do not vary with the direction of groundwater flow.

Lacustrine – The physical properties and environment associated with lakes; pertaining to an object, material or process formed in or associated with a lacustrine environment.

Meandering stream – A stream that follows a sinuous rather than a straight channel.

Monitoring well – A well that has been constructed or converted for the primary purposes of measuring water levels and/or collecting water samples for chemical analysis.

Nomenclature – A system of names used to denote and classify objects and conditions in a particular science.

Overburden – Geologic material that overlies a mineral deposit.

Permeability – The capacity of a geologic material to transmit fluids

Plugged and abandoned well – An unproductive well that has been decommissioned. The well head is removed, the casing is cut off several feet below ground level and the remaining casing is filled with cement.

Potentiometric surface – A surface that represents the level to which groundwater would rise in tightly cased wells (Fetter, 2001). The potentiometric surface is usually shown as a contour map of equal water level elevations.

Produced water – Water that is pumped from a coal seam in order to produce methane. Also called co-produced water.

Transducer – A wellbore instrument placed at a known depth below the water surface in a well that measures the water pressure of the overlying water column. Water pressure measurements are converted to groundwater elevations by the instrument's software.

Well completion – The final processes involved in well construction. Modern well completion includes installing the well screen in the desired stratum, sealing off the bottom of the well bore with cement, installing the well production tubing and stimulating the well as needed. Completed wells are ready to start production.

Up-gradient recharge – Recharge that flows through an aquifer into a particular area. Up-gradient recharge enters the aquifer as direct recharge elsewhere, usually at an outcrop, and then flows through the aquifer into the area in question.

Interpreting the past , providing for the future