An evaluation of coalbed methane production trends in Wyoming's Powder River Basin:

a tool for resource management

Wyoming State Geological Survey
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Abstract

In this study, we evaluated production histories of the first ten years of coalbed methane (CBM) development in the Powder River Basin (PRB). We then used this evaluation to predict future gas and water production as CBM activity moves to the west in the PRB over the next decade. CBM wells more than two years old with water/gas ratios greater than 2 have produced 4.6% of the gas and 38% of the water in the PRB to date. Water/gas ratios for the first 10 years of CBM development in the PRB (22,111 wells two years old or older) averaged 1.83 barrels of water per thousand cubic feet (MCF) of gas produced. The predicted water/gas ratio for future CBM development in the Upper, Middle, and Little Powder River and Upper Tongue River drainages is less than 3 barrels/MCF. In stark contrast, the Clear Creek and Crazy Woman Creek drainages have projected water/gas ratios greater than 300 barrels/MCF. From now until 2020, CBM development in the Clear Creek and Crazy Woman Creek drainages is predicted to supply only 0.15% of the total gas extracted in the PRB, but will produce 20% of the water (130 billion gallons).

We recommend that all CBM wells with water/gas ratios greater than 3 after two years of production be reviewed. Barring extenuating circumstances, these wells should be regulated as water wells. Finally, the observations outlined in this study support a moratorium on CBM activity in the Clear Creek and Crazy Woman Creek drainages.

Introduction

This study was initiated to determine if there is information available that would further optimize the gas production and minimize water production in the CBM play in Wyoming's Powder River Basin (PRB). An improved understanding of production characteristics could make the CBM development more resource-responsible, particularly with respect to water management. Historically, water production has been the most contentious aspect of the CBM development in the PRB. In order to avoid further conflict, we make every effort in this report to maximize observation and minimize speculation. Now is an ideal time to examine CBM production characteristics because it is possible to retrieve ten years of production data from most of the drainage basins in the PRB.

General Observations

CBM well number 531860 exhibits an ideal water-gas production profile (**Figure 1**): the well produces substantial amounts of water in the first one to two years; gas production peaks in the first one to two years; and well life ends with a steep decline in both water and gas production lasting three years or more. The productive life of a typical CBM well is somewhere between five and ten years.

It is important to note that the described production scenario (**Figure 1**) applies to typical CBM wells, but many notable exceptions exist. For example, out of 22,211 CBM wells at

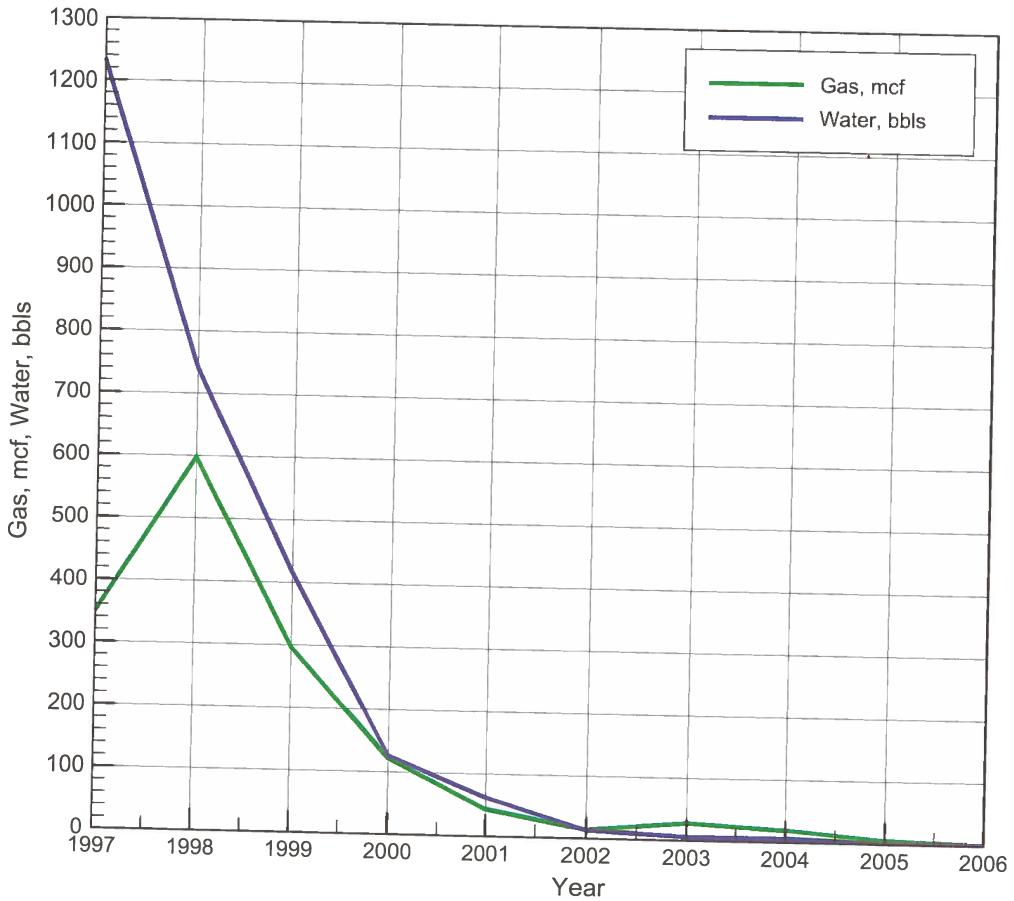

Figure 1. Annual gas and water production curves of the CBM well Thielen 20-41. Note that the well produces substantial amounts of water in the first two years, and gas production peaks in the second year.

least two years old in the PRB, 338 produced only gas (**Figure 2**). These wells are shown in red in **Figure 2** and occur in close proximity to the open pit coal mines along the eastern margin of the basin (shown in purple on **Figure 2**). Conversely, 851 wells produced only water after two or more years of "production"(**Figure 3**). Most of these water-rich wells appear to occur along NW-SE, or NE-SW linears (**Figure 3**). Between the gas-only and water-only wells shown in **Figure 2** and **Figure 3**, there is a wide variety of water-gas production profiles, with the ideal profile shown in Figure 1 somewhere near the middle of the production spectrum for CBM wells in the PRB.

Figure 4 presents a summary of the water/gas production histories of 22,211 CBM wells two years old or older in the PRB. As of March 2007, these wells produced approximately 2.3 trillion cubic feet (TCF) of gas, and approximately 4.2 billion barrels of water. The average

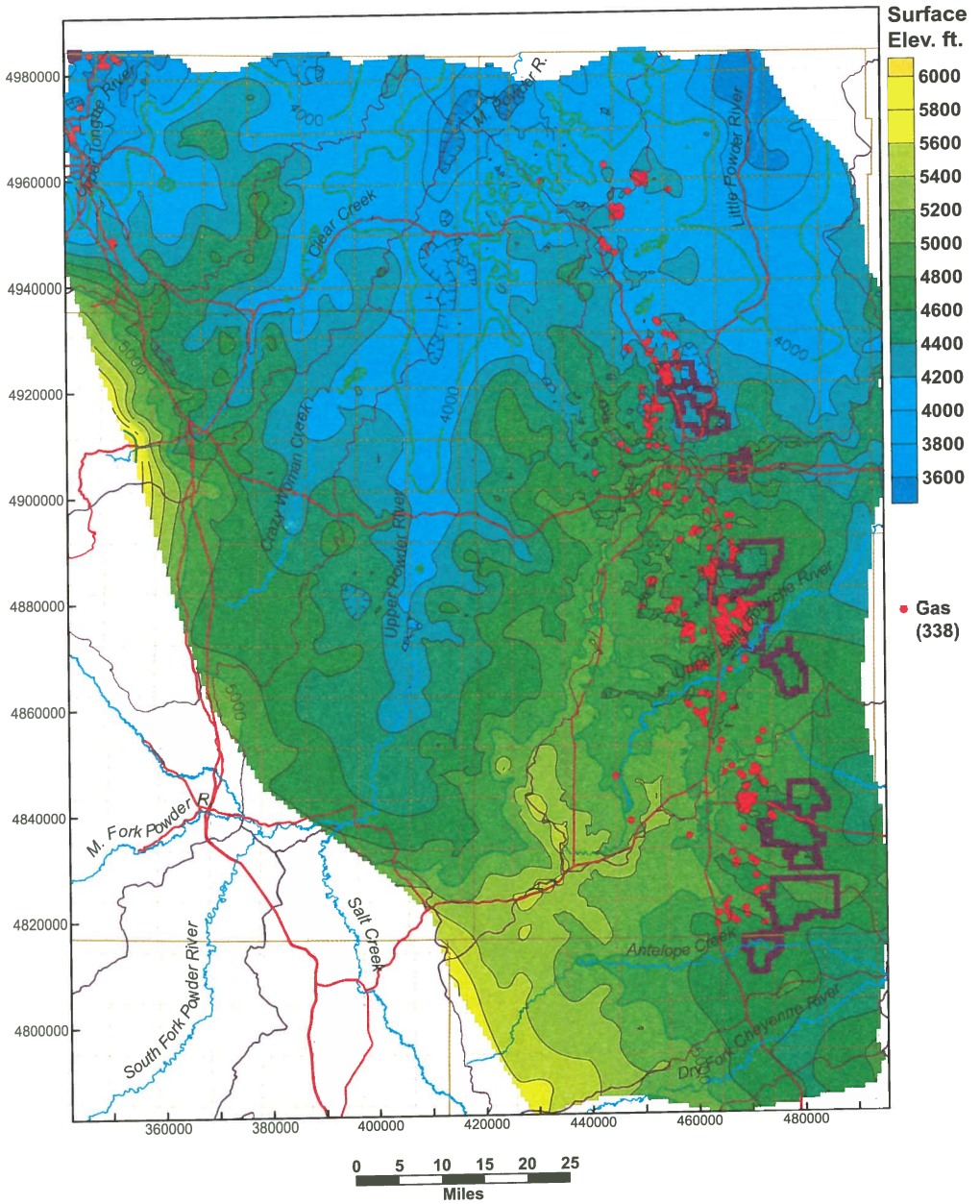

Figure 2. CBM wells more than two years old that have produced only gas (red dots). These wells are located near the open pit coal mines along the eastern margin of the basin (shown by the polygons outlined in purple).

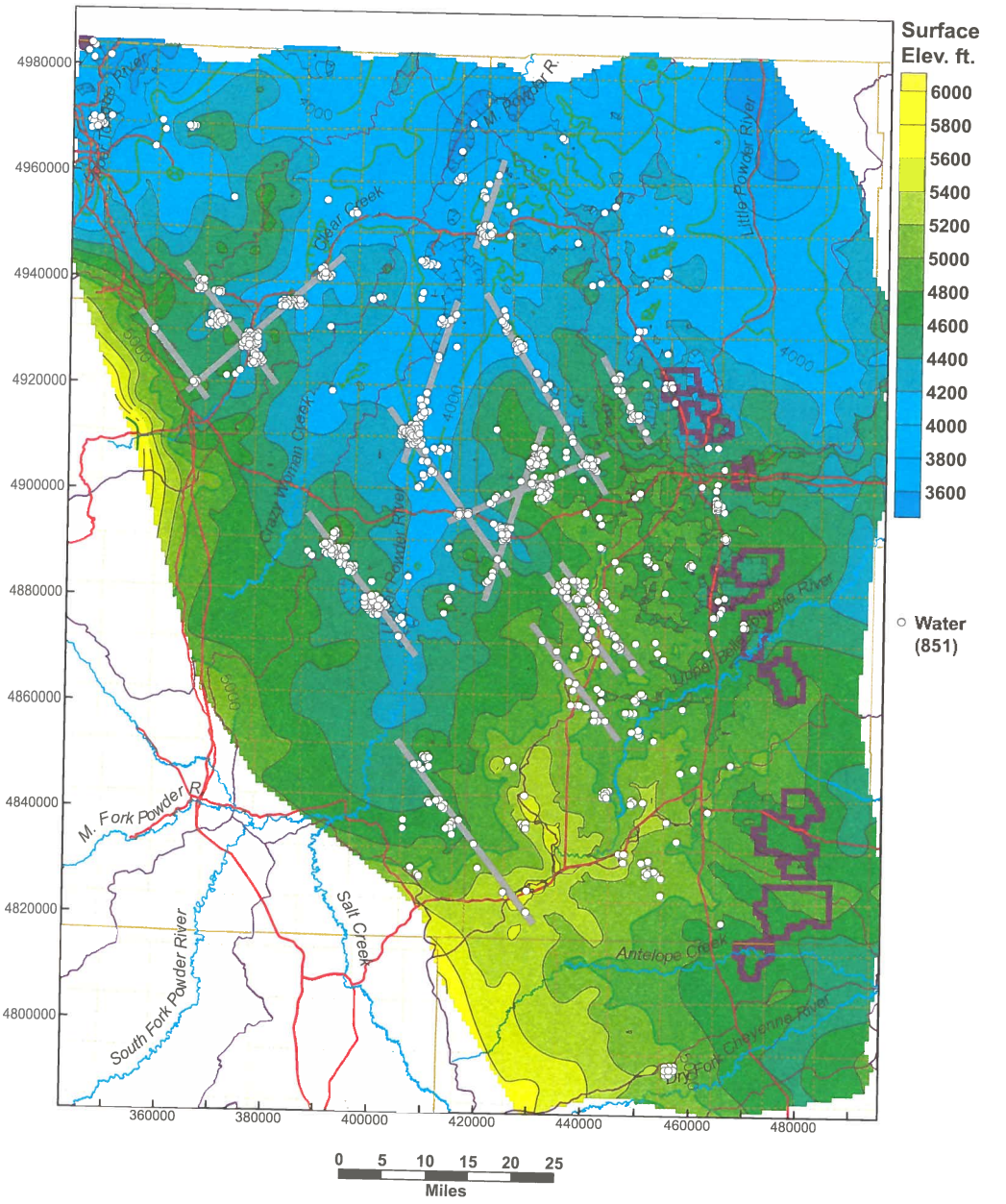

Figure 3. CBM wells more than two years old that have produced only water (white dots). Most of these wells appear to occur along NW-SE and NE-SW lineaments (i.e., faults or fracture zones shown in gray).

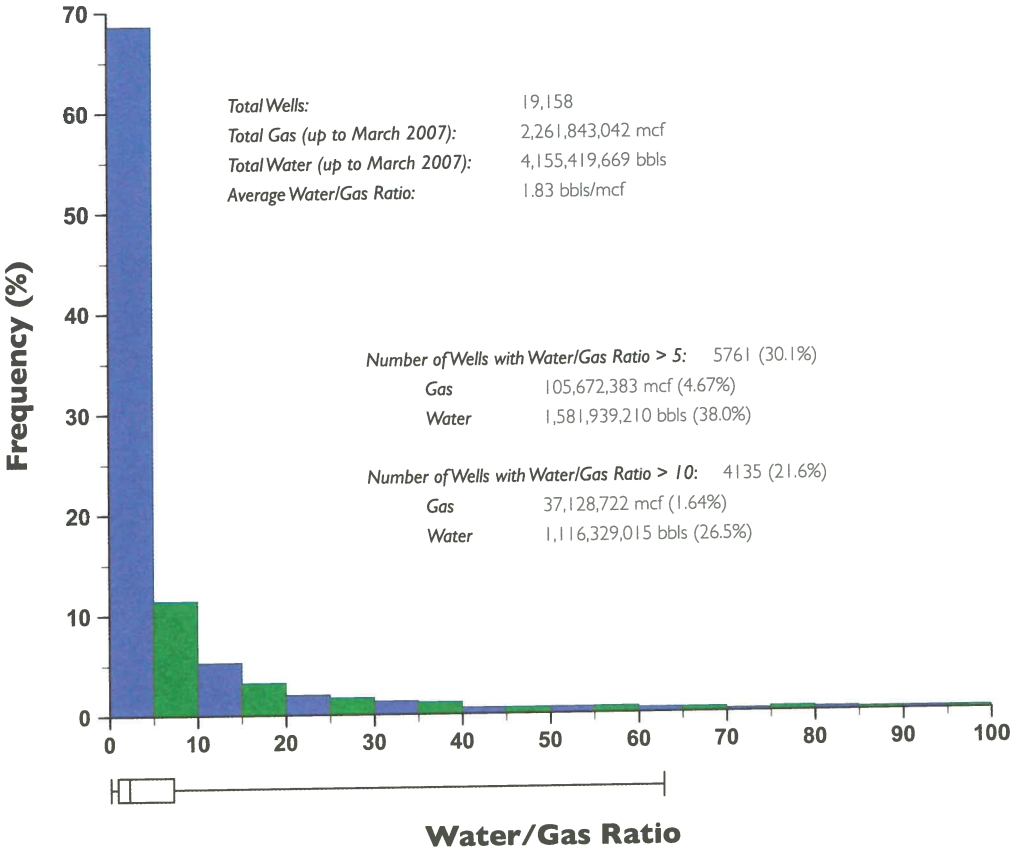

Figure 4. Histogram of the water/gas production ratios of 19,158 CBM wells in the Powder River Basin. The average water/gas ratio is 1.83 bbls/mcf. Note that there are 4,135 wells with a water/gas ratio greater than 10. These wells have produced only 3.7 billion cubic feet of gas (1.64% of total gas production), but more than 1.1 billion barrels of water (26.5% of total water production).

water/gas production ratio for the more than 22,000 CBM wells is 1.83 barrels (bbls) of water per thousand cubic feet (MCF) of produced gas. Other important observations that can be derived from **Figure 4** pertain to wells that have produced for more than two years with water/gas ratios greater than 10 (4,135 wells, or 18.6% of wells). These wells have produced 37.1 billion cubic feet (BCF) of gas (1.64% of total gas production), and more than 1.1 billion bbls of water (26.5% of total water produced). In addition, CBM wells with water/gas ratios greater than 5 (5,761 wells, or 25.9% of wells) have produced 105.6 BCF of gas (4.7% of total gas production) and more than 1.5 billion bbls of water (38.1% of total water produced), while CBM wells with water/gas ratios greater than 3 have produced slightly more than 233 BCF of gas (10.3% of total gas production) and slightly more than 2 billion bbls of water (49.8% of total water produced).

In summary, eliminating all wells with water/gas ratios greater than 10 would have saved 25% or more of the total water produced, while reducing total gas production by only 1.6%. If wells with water/gas ratios greater than 5 could have been avoided, it would have saved 38% of the total water produced, while eliminating just 4.7% of total gas production. Given this information, it should be possible to save significant amounts of produced water by eliminating CBM wells with high water/gas ratios and allowing development of the gas play to proceed more responsibly. Most importantly, this management action would substantially reduce animosity directed at the CBM play in the PRB.

Future Production

Most of the wells shown in **Figure 4** are located in the eastern part of the basin, and the CBM play in the PRB is currently moving into the western part of the basin. Specifically, the play is moving from the Dry Fork of the Cheyenne River, Antelope Creek, and Upper Belle Fourche River drainage west and north into the Little, Middle, and Upper Powder River drainages and the Upper Tongue River, Clear Creek, and Crazy Woman Creek drainages (**Figure 5**). Of the total number of CBM wells slated for the PRB, half have been drilled so far. Estimates of future drilling activity in the drainages shown in Figure 5 can be determined from approved and pending environmental documents, BLM permitting activity, Wyoming Oil and Gas Conservation Commission (WOGCC) records, and Wyoming Department of Environmental Quality (DEQ) and State Engineer's Office estimates. For three time periods, 2007-2010, 2011-2015, and 2016-2020, we assigned CBM wells to each of the drainage basins (**Figure 5**) in order to fill out the remaining wells to be drilled (approximately half of the total wells predicted for CBM development in the PRB). For 2007-2010, we assigned approximately 12,300 wells; for 2011-2015, we assigned approximately 16,400 wells; and for 2016-2020, we assigned approximately 13,000 wells.

Fortunately, in the Upper Tongue River; Clear Creek; Crazy Woman Creek; and Little, Middle, and Upper Powder River drainages, we have enough CBM activity and production history data to determine typical CBM well performance for each of the basins. For each drainage basin cited above, we determined cumulative gas and water production for CBM wells more than two years old. For each basin, we then divided total production by the number of wells two years old or older to calculate the average (typical) CBM well performance profile. Using the typical well performance in each basin and the number of CBM wells that will be drilled in each basin in the future, we can predict future gas and water production for each basin (**Table 1, Table 2, Tables 3a through 3j**, and **Tables 4a through 4j**). **Table 1** presents real data from 2006; **Table 2** shows the estimated number of new wells in each drainage basin; **Tables 3a through 3j** show predicted performance assuming a 5-year well life; and **Tables 4a through 4j** show predicted performance assuming a 10-year well life.

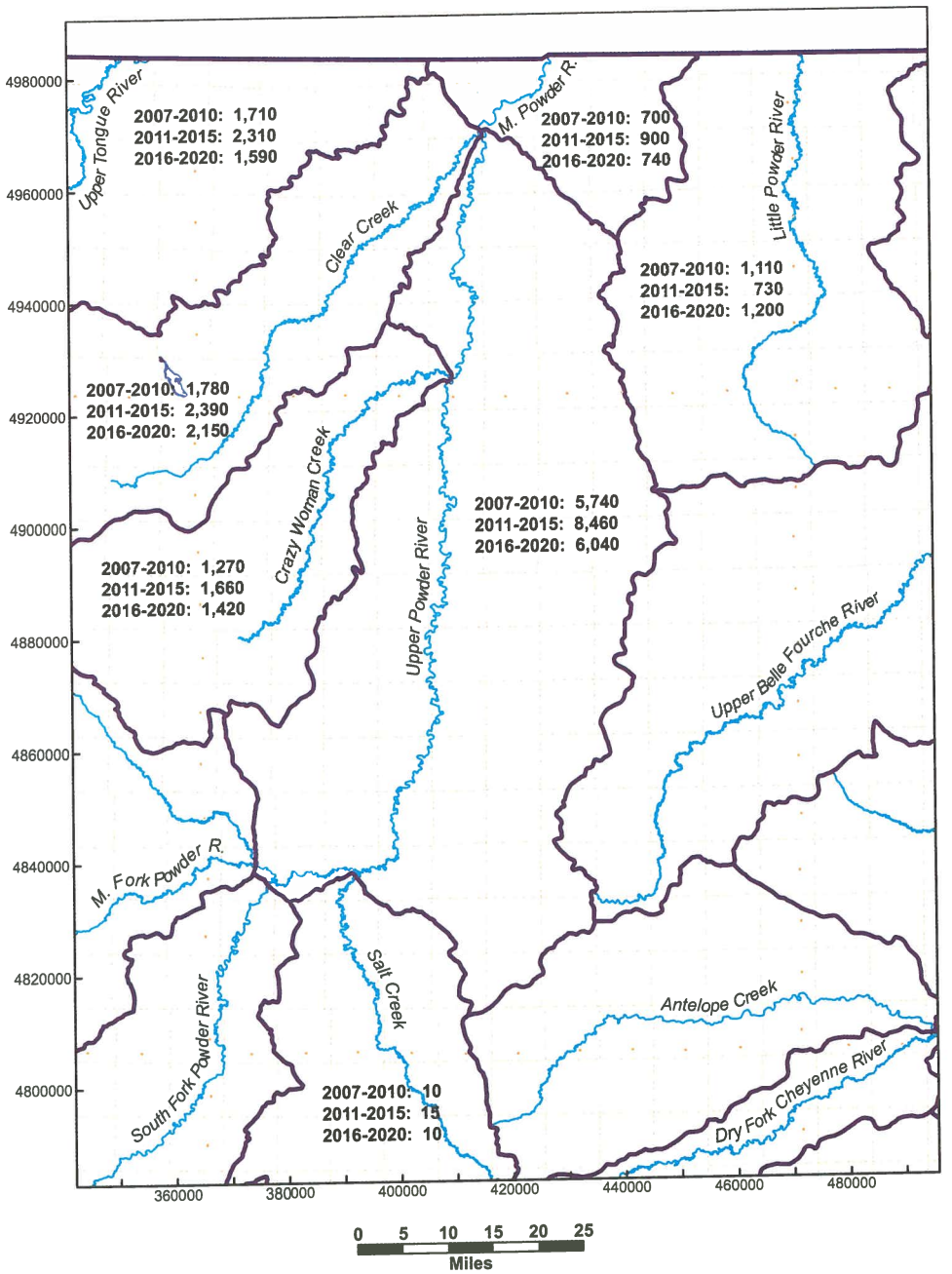

Figure 5. An estimated 41,900 wells will be drilled from 2007 to 2020. Predicted well numbers are: 6,320 wells in the Clear Creek drainage; 4,350 wells in the Crazy Woman Creek drainage; 3,040 wells in the Little Powder River drainage; 2,340 wells in the Middle Powder River drainage; 20,240 wells in the Upper Powder River drainage; and 5,610 wells in the Upper Tongue River drainage.

Table 1. Data reported for 2006.

Drainage	Producing wells	Gas rate (MCF/day)	Gas production (MCF)	Water rate (BBLS/day)	Water production (BBLS)
Clear Creek	392	1	120,007	67	5,914,600
Crazy Woman Creek	120	0	459	73	3,188,758
Little Powder River	2,756	25	24,923,454	65	64,133,193
Middle Powder River	1,324	41	22,045,429	88	47,266,610
Upper Powder River	7,103	56	159,305,798	111	318,025,559
Upper Tongue River	2,529	51	51,387,090	80	80,609,682
Total	14,224		257,782,237		519,138,402

Table 2. Estimated new wells in individual drainage basins (2007-2020).

Drainage	2006	2007-2010 (estimated new wells)	2011-2015 (estimated new wells)	2016-2020 (estimated new wells)	**Total**
Clear Creek	392	1,780	2,390	2,150	6,712
Crazy Woman Creek	120	1,270	1,660	1,420	4,470
Little Powder River	2,756	1,110	730	1,200	5,796
Middle Powder River	1,324	700	900	740	3,664
Upper Powder River	7,103	5,740	8,460	6,040	27,343
Upper Tongue River	2,529	1,710	2,310	1,590	8,139
Total	14,224	12,310	16,450	13,140	56,124

Table 3a. Predicted values for 2007-2008, assuming a 5-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	445	759	145,664	30,014,402	445	1,125	279,587	54,035,104
Crazy Woman Creek	318	414	152,110	18,870,325	318	707	165,031	44,705,059
Little Powder River	278	2,482	50,083,717	116,766,767	278	2,209	41,217,744	98,112,545
Middle Powder River	175	1,234	27,502,895	49,613,170	175	1,144	24,876,777	44,451,093
Upper Powder River	1,435	7,117	213,317,676	470,588,391	1,435	7,132	213,834,188	472,146,638
Upper Tongue River	428	2,451	52,191,659	96,667,851	428	2,372	49,622,061	91,540,339
Total	3,078	14,457	343,393,721	782,520,905	3,078	14,689	329,995,388	804,990,778

Table 3b. Predicted values for 2009-2010, assuming a 5-year well life.

Drainage	2009				2010			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	445	1,492	356,722	77,010,847	445	1,858	373,865	99,406,294
Crazy Woman Creek	318	1,001	226,785	63,099,441	318	1,294	240,510	71,182,892
Little Powder River	278	1,935	34,766,097	85,527,850	278	1,661	30,370,689	74,989,882
Middle Powder River	175	1,055	22,245,888	40,479,061	175	965	20,297,290	37,414,100
Upper Powder River	1,435	7,146	214,436,762	473,237,127	1,435	7,161	214,908,429	473,933,909
Upper Tongue River	428	2,294	47,383,461	87,989,463	428	2,216	45,926,146	85,383,742
Total	3,078	14,922	319,415,716	827,343,788	3,078	15,155	312,116,929	842,310,818

Table 3c. Predicted values for 2011-2012, assuming a 5-year well life.

Drainage	2011				2012			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	2,258	386,858	118,137,869	478	2,291	398,913	120,300,125
Crazy Woman Creek	332	1,602	251,835	79,902,590	332	1,617	252,474	81,178,923
Little Powder River	146	1,256	25,312,071	59,061,839	146	1,125	21,052,388	50,099,361
Middle Powder River	180	800	18,798,746	34,978,603	180	885	18,944,966	35,266,024
Upper Powder River	1,692	7,432	219,236,453	490,408,565	1,692	7,689	228,454,757	518,218,942
Upper Tongue River	462	2,172	45,411,253	84,213,219	462	2,207	46,543,451	86,472,467
Total	3,290	15,600	309,397,217	866,702,685	3,290	15,813	315,646,950	891,535,843

Table 3d. Predicted values for 2013-2014, assuming a 5-year well life.

Drainage	2013				2014			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	2,324	405,857	120,300,125	478	2,357	407,400	124,384,275
Crazy Woman Creek	332	1,617	255,525	81,178,923	332	1,646	256,203	82,487,027
Little Powder River	146	1,125	17,952,674	50,099,361	146	862	15,840,887	38,990,007
Middle Powder River	180	885	19,091,452	35,266,024	180	895	19,199,949	35,657,839
Upper Powder River	1,692	7,689	239,209,038	518,218,942	1,692	8,203	247,626,991	550,116,772
Upper Tongue River	462	2,207	47,529,808	86,472,467	462	2,276	48,171,920	89,185,144
Total	3,290	15,846	324,444,354	891,535,843	3,290	16,238	331,503,349	920,821,064

Table 3e. Predicted values for 2015-2016, assuming a 5-year well life.

Drainage	2015				2016			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	2,390	407,931	125,994,667	430	2,342	397,620	124,770,554
Crazy Woman Creek	332	1,660	256,436	82,886,380	284	1,612	234,591	80,780,180
Little Powder River	146	730	14,389,988	34,107,648	240	824	15,847,354	38,229,390
Middle Powder River	180	900	19,286,081	35,802,922	148	868	18,976,389	34,713,601
Upper Powder River	1,692	8,460	253,805,441	559,427,808	1,208	7,976	246,306,572	529,384,124
Upper Tongue River	462	2,310	48,594,933	90,079,863	318	2,166	46,736,863	86,489,884
Total	3,290	16,450	336,740,811	928,299,288	2,628	15,788	328,499,388	894,367,733

Table 3f. Predicted values for 2017-2018, assuming a 5-year well life.

Drainage	2017				2018			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	430	2,294	380,085	121,625,454	430	2,246	369,985	118,617,173
Crazy Woman Creek	284	1,564	232,478	76,555,078	284	1,516	222,379	73,546,798
Little Powder River	240	918	18,892,299	44,636,029	240	1,012	21,108,064	48,958,138
Middle Powder River	148	836	18,040,579	32,874,108	148	804	17,103,068	31,458,685
Upper Powder River	1,208	7,492	228,946,030	477,009,716	1,208	7,008	208,692,831	440,357,171
Upper Tongue River	318	2,022	42,011,165	77,059,977	318	1,878	37,894,199	70,529,631
Total	2,628	15,126	308,502,635	829,760,362	2,628	14,464	285,390,525	783,467,596

Table 3g. Predicted values for 2019-2020, assuming a 5-year well life.

Drainage	2019				2020			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	430	2,198	367,741	115,684,872	430	2,150	366,968	113,342,483
Crazy Woman Creek	284	1,468	220,134	72,224,802	284	1,420	219,361	70,902,807
Little Powder River	240	1,106	22,617,630	52,577,316	240	1,200	23,654,775	56,067,367
Middle Powder River	148	772	16,408,690	30,366,494	148	740	15,857,444	29,437,958
Upper Powder River	1,208	6,524	192,839,567	416,937,539	1,208	6,040	181,203,885	399,402,359
Upper Tongue River	318	1,734	35,214,080	65,737,500	318	1,590	33,448,460	62,003,022
Total	2,628	13,802	267,667,842	753,528,524	2,628	13,140	254,750,893	731,155,997

Table 3h. Average gas production rate (MCF/ day) for a well with a 5-year life.

Drainage	First year	Second year	Third year	Fourth Year	Fifth year
Clear Creek	0.651	1.107	0.6376	0.1417	0.0488
Crazy Woman Creek	1.3791	0.1334	0.6376	0.1417	0.0488
Little Powder River	46.9815	98.1607	71.4302	48.6643	33.4347
Middle Powder River	29.3269	88.6184	88.7794	65.7555	52.2013
Upper Powder River	46.9501	108.6936	126.8044	99.2566	72.8505
Upper Tongue River	39.1008	99.4465	86.6365	56.3998	37.1553
Numbers based on 330 production days per year					

Table 3i. Average water production rate (BBLS/day) for a well with a 5-year life.

Drainage	First year	Second year	Third year	Fourth Year	Fifth year
Clear Creek	77.2799	198.5543	189.9167	185.12	147.8781
Crazy Woman Creek	132.9672	266.7362	189.9167	83.4593	83.4593
Little Powder River	132.8737	206.5325	139.333	116.6724	112.5097
Middle Powder River	103.1554	174.1944	134.0363	103.4272	87.9295
Upper Powder River	188.1022	327.9139	229.48	146.6293	109.787
Upper Tongue River	75.5467	198.4408	137.4231	100.8445	78.5875
Numbers based on 330 production days per year					

Table 3j. Predicted cumulative gas and water production (2006-2020).

Drainage	Average Rate (MCF/ day/well)	Average Rate (bbls/ day/well)	2006-2020		Percentage of total production	
			Cumulative gas (MCF)	Cumulative water (bbls)	% Gas	% Water
Clear Creek	0.51722	159.7498	5,165,203	1,469,538,843	0.11	11.98
Crazy Woman Creek	0.46812	151.30774	3,186,311	982,689,983	0.07	8.01
Little Powder River	59.73428	141.58426	378,029,832	912,356,693	8.17	7.44
Middle Powder River	64.9363	120.54856	298,675,645	555,046,292	6.46	4.52
Upper Powder River	90.91104	200.38248	3,262,124,417	7,107,413,562	70.53	57.94
Upper Tongue River	63.74778	118.16852	678,066,548	1,240,434,252	14.66	10.11
Total			4,625,247,955	12,267,479,625	100	100

Table 4a. Predicted values for 2007-2008, assuming a 10-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	445	798	123,788	26,912,947	445	1,204	272,031	53,502,147
Crazy Woman Creek	318	426	149,269	18,053,476	318	731	162,718	44,944,486
Little Powder River	278	2,758	40,021,403	130,437,088	278	2,760	40,082,950	130,566,584
Middle Powder River	175	1,367	21,976,958	44,558,486	175	1,409	23,222,755	47,007,311
Upper Powder River	1,435	7,828	170,539,436	395,298,237	1,435	8,552	196,533,619	473,719,174
Upper Tongue River	428	2,704	39,994,611	80,507,346	428	2,878	45,724,519	91,941,108
Total	3,078	15,879	272,805,465	695,767,579	3,078	17,534	305,998,592	841,680,809

Table 4b. Predicted values for 2009-2010, assuming 10-year well life.

Drainage	2009				2010			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	445	1,609	357,415	78,934,652	445	2,015	376,390	103,724,812
Crazy Woman Creek	318	1,037	226,997	64,090,938	318	1,342	241,283	72,504,887
Little Powder River	278	2,762	40,127,736	130,653,946	278	2,764	40,158,249	130,727,100
Middle Powder River	175	1,452	24,470,816	48,891,593	175	1,494	25,395,207	50,345,573
Upper Powder River	1,435	9,277	226,859,018	528,599,545	1,435	10,002	250,596,333	563,666,089
Upper Tongue River	428	3,053	50,716,341	99,859,152	428	3,227	53,965,985	105,669,610
Total	3,078	19,189	342,758,324	951,029,826	3,078	20,844	370,733,447	1,026,638,071

Table 4c. Predicted values for 2011-2012, assuming a 10-year well life.

Drainage	2011				2012			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	2,452	389,585	124,318,333	478	2,889	407,445	146,152,492
Crazy Woman Creek	332	1,662	252,802	81,555,084	332	1,982	258,360	91,245,367
Little Powder River	146	2,634	38,140,450	125,031,589	146	2,504	33,898,273	116,128,849
Middle Powder River	180	1,542	26,177,442	51,751,892	180	1,590	26,904,961	53,092,047
Upper Powder River	1,692	10,984	272,000,441	605,874,707	1,692	11,965	296,282,556	653,146,285
Upper Tongue River	462	3,437	56,551,961	111,057,764	462	3,646	59,250,741	117,516,086
Total	3,290	22,710	393,512,682	1,099,589,370	3,290	24,576	417,002,336	1,177,281,125

Table 4d. Predicted values for 2013-2014, assuming a 10-year well life.

Drainage	2013				2014			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	3,326	420,502	159,222,638	478	3,762	428,487	171,262,225
Crazy Woman Creek	332	2,302	266,330	100,058,669	332	2,622	271,928	109,050,871
Little Powder River	146	2,375	30,815,351	111,138,719	146	2,245	28,718,888	82,629,654
Middle Powder River	180	1,637	27,480,614	54,217,461	180	1,685	28,196,521	52,724,399
Upper Powder River	1,692	12,947	316,288,107	681,931,809	1,692	13,929	337,902,196	691,569,075
Upper Tongue River	462	3,855	61,633,551	122,809,429	462	4,064	63,633,540	124,312,872
Total	3,290	26,441	436,904,455	1,229,378,725	3,290	28,307	459,151,561	1,231,549,097

Table 4e. Data for 2015-2016, assuming a 10-year well life.

Drainage	2015				2016			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	4,199	435,521	185,031,016	430	4,590	432,673	196,547,069
Crazy Woman Creek	332	2,942	277,081	118,194,671	284	3,214	260,390	124,901,773
Little Powder River	146	2,116	27,284,956	100,376,874	240	2,080	27,552,550	100,519,455
Middle Powder River	180	1,732	28,902,583	57,112,070	148	1,748	28,797,425	57,007,294
Upper Powder River	1,692	14,910	356,617,134	761,047,883	1,208	15,408	358,246,311	769,558,785
Upper Tongue River	462	4,273	65,602,461	132,818,005	318	4,338	65,878,569	132,697,387
Total	3,290	30,172	479,119,737	1,354,580,519	2,628	31,378	481,167,917	1,381,231,763

Table 4f. Predicted values for 2017-2018, assuming a 10-year well life.

Drainage	2017				2018			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	430	4,575	416,368	182,130,805	430	4,560	407,188	192,357,656
Crazy Woman Creek	284	3,181	258,510	124,587,574	284	3,147	248,644	118,467,097
Little Powder River	240	2,043	29,435,355	105,152,741	240	2,005	30,590,485	101,548,786
Middle Powder River	148	1,721	27,911,986	57,351,481	148	1,694	27,045,768	53,977,315
Upper Powder River	1,208	15,181	344,166,542	667,948,906	1,208	14,954	328,593,083	693,847,841
Upper Tongue River	318	4,229	61,428,802	139,318,198	318	4,119	57,580,145	118,299,616
Total	2,628	30,929	463,617,564	1,276,489,706	2,628	30,479	444,465,314	1,278,498,312

Table 4g. Predicted values for 2019-2020, assuming a 10-year well life.

Drainage	2019				2020			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	430	4,545	405,537	190,401,323	430	4,530	405,295	189,010,322
Crazy Woman Creek	284	3,114	246,633	117,544,454	284	3,080	246,094	116,621,812
Little Powder River	240	1,968	30,925,805	98,274,981	240	1,930	30,450,651	91,015,058
Middle Powder River	148	1,667	26,424,152	53,069,004	148	1,640	25,888,905	52,241,523
Upper Powder River	1,208	14,727	317,185,627	680,763,410	1,208	14,500	306,892,564	674,453,343
Upper Tongue River	318	4,010	55,205,490	114,255,777	318	3,900	53,800,407	111,042,879
Total	2,628	30,030	430,393,243	1,254,308,950	2,628	29,580	417,683,914	1,234,384,937

Table 4h. Average gas production rate (MCF/ day.well) for a well with a 10-year life.

Drainage	First year	Second year	Third year	Fourth Year	Fifth year	Sixth year	Seventh Year	Eighth year	Ninth Year	Tenth year
Clear Creek	0.651	1.107	0.6376	0.1417	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488
Crazy Woman Creek	1.3791	0.1334	0.6376	0.1417	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488
Little Powder River	46.9815	98.1607	71.4302	48.6643	33.4347	27.9208	26.7805	24.4414	27.0595	34.8496
Middle Powder River	29.3269	88.6184	88.7794	65.7555	52.2013	41.35	30.5283	43.2075	44.098	9.696
Upper Powder River	46.9501	108.6936	126.8044	99.2566	72.8505	62.9887	38.6838	55.1791	52.4208	15.8309
Upper Tongue River	39.1008	99.4465	86.6365	56.3998	37.1553	27.1891	24.2364	23.5669	26.8303	31.6677
Numbers based on 330 production days per year										

Table 4i. Average water production rate (Bbls/day.well) for a well with a 10-year life.

Drainage	First year	Second year	Third year	Fourth Year	Fifth year	Sixth year	Seventh Year	Eighth year	Ninth Year	Tenth year
Clear Creek	77.2799	198.5543	189.9167	185.12	147.8781	147.8781	83.4593	83.4593	83.4593	83.4593
Crazy Woman Creek	132.9672	266.7362	189.9167	83.4593	83.4593	83.4593	83.4593	83.4593	83.4593	83.4593
Little Powder River	132.8737	206.5325	139.333	116.6724	112.5097	95.2756	116.2186	107.296	158.8428	247.7238
Middle Powder River	103.1554	174.1944	134.0363	103.4272	87.9295	74.8851	67.9157	68.4097	111.4427	61.2452
Upper Powder River	188.1022	327.9139	229.48	146.6293	109.787	81.3762	68.3664	88.6435	121.863	132.356
Upper Tongue River	75.5467	198.4408	137.4231	100.8445	78.5875	72.8778	71.9433	65.2971	65.7261	45.8129
Numbers based on 330 production days per year										

Table 4j. Predicted cumulative gas and water production (2006-2020).

Drainage	Average Rate (MCF/ day/well)	Average Rate (bbls/ day/well)	2006-2020		Percentage of total production	
			Cumulative gas (MCF)	Cumulative water (bbls)	% Gas	% Water
Clear Creek	0.28301	128.0464	5,398,231	2,005,423,037	0.09	12.12
Crazy Woman Creek	0.25846	117.38352	3,367,498	1,305,009,915	0.06	7.88
Little Powder River	43.97232	143.32781	493,126,556	1,618,334,618	8.26	9.78
Middle Powder River	49.35613	98.66412	390,841,523	780,614,061	6.54	4.72
Upper Powder River	67.96585	149.45175	4,238,008,765	9,159,450,648	70.95	55.34
Upper Tongue River	45.22293	91.24998	842,354,212	1,682,714,911	14.10	10.17
Total			5,973,096,786	16,551,547,190	100	100

Future CBM Production Scenarios

A difficult task in constructing the future gas and water production scenarios shown in **Table 1a** and **Table 1b** was determining how to build production scenarios for existing wells into the equation. To do this, we started the tables in 2006 with reported production figures. **Table 1a** represents predicted production scenarios for CBM activities in the noted drainage basins for 2006 through 2020, assuming that a typical well will have a 5-year production life. **Table 1b** represents predicted production scenarios for CBM activities in the noted drainage basins for 2006 through 2020, assuming that a typical well will have a 10-year production life.

Figure 6 assumes a 5-year production life for CBM wells and shows that the greatest gas production will occur in the Upper Powder River drainage (3×10^8 MCF/year). The Upper Tongue River, Little Powder River, and Middle Powder River drainages will produce 2×10^7 to 4×10^7 MCF/year, while the Clear Creek and Crazy Woman Creek drainages will produce only 3×10^5 MCF/year. In other words, from 2006 to 2020, the Clear Creek and Crazy Woman Creek drainages will produce three orders of magnitude less gas than the Upper Powder River drainage. If wells produce for 10 years instead of 5, the gas production versus time curves for the period 2006-2020 change only slightly (**Figure 7**).

Figure 8 shows predicted water production scenarios for six of the PRB drainage basins from 2006 to 2020, based on a 5-year CBM well life expectancy. The Upper Powder River drainage basin will produce between 4 and 5 billion barrels of water from 2006 to 2020. The Upper Tongue River, Middle Powder River, and Little Powder River drainages will each produce approximately 40 to 80 million barrels of water each year; the Clear Creek drainage will average 150 million barrels of water per year; and the Crazy Woman Creek drainage will produce 100 million barrels of water per year (**Table 8**). Extending CBM well life expectancy to ten years changes the water production scenarios for each drainage basin only slightly.

With the data shown in **Figures 6-9**, we can predict the water/gas ratio for each of the western and northern drainages in the PRB. The water/gas ratio is one of the most important parameters to consider when designing management strategies that maximize gas production while minimizing water production. For wells in the Upper, Middle and Little Powder River drainages from 2006-2020 (the second half of the PRB CBM play), the water/gas ratio will be less than 3. In stark contrast, the water/gas ratio for the Crazy Woman Creek and Clear Creek drainages will be 300 or greater, two orders of magnitude higher than the ratios for the other drainages (**Figure 10**).

Current CBM well estimates for the years 2007-2020 (**Figure 5**) indicate that approximately 11,000 wells (25% of all new wells) will be drilled in the Crazy Woman Creek and Clear Creek drainages. These wells will produce approximately 9,000,000 MCF of gas (0.15% of total gas produced from 2007-2020), and approximately 3.3 billion barrels of water (20% of the water CBM development will produce from 2007-2020). **Figure 11** shows water/gas ra-

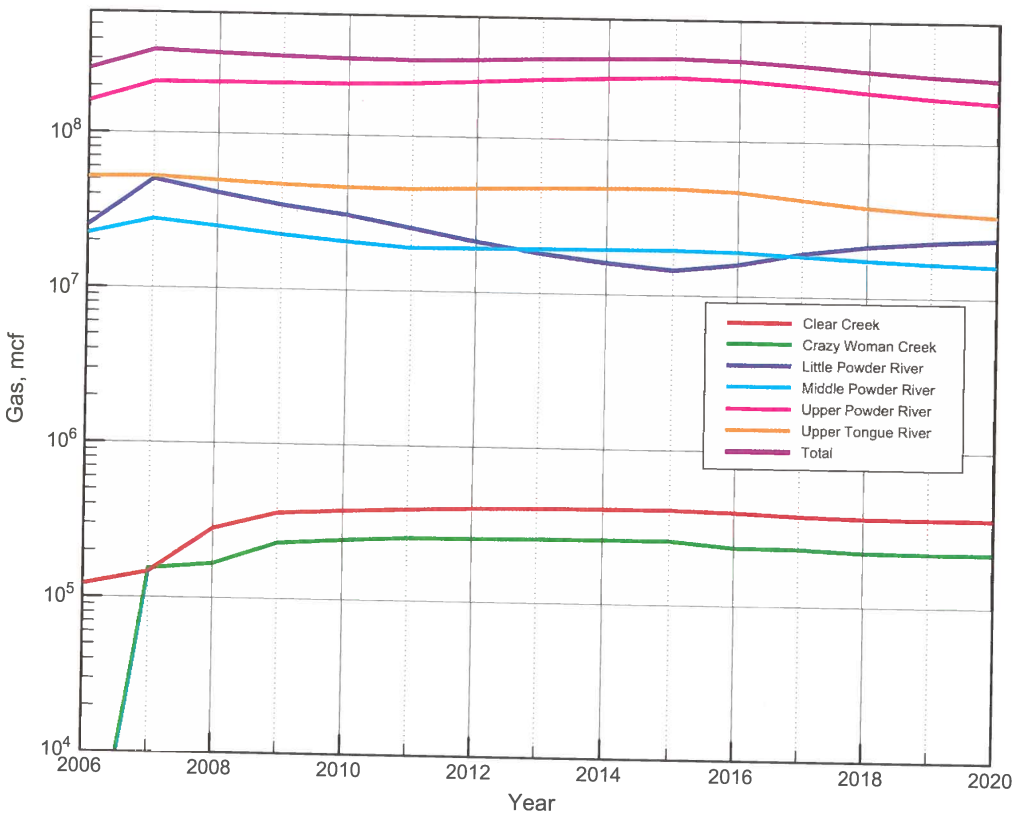

Figure 6. Plot of the estimated yearly gas production for each drainage. Well life is assumed to be 5 years. Note that the yearly gas production from the Upper Powder River drainage is three orders of magnitude higher than the yearly gas production from the Clear Creek and Crazy Woman Creek drainages. The yearly gas productions of the Upper Tongue River, Middle Powder River, and Little Powder River drainages are two orders of magnitude higher than the yearly gas productions of the Clear Creek and Crazy Woman Creek drainages.

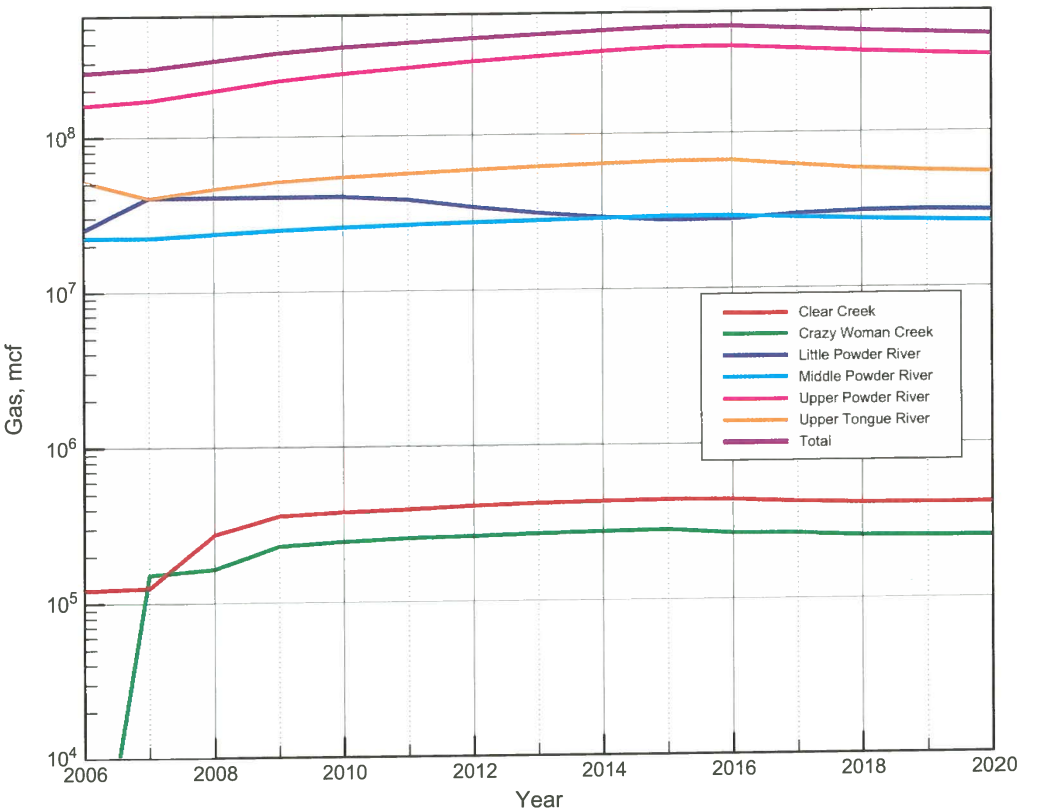

Figure 7. Plot of the estimated yearly gas production for each drainage. Well life is assumed to be 10 years. Note that the yearly gas production from the Upper Powder River drainage is three orders of magnitude higher than the yearly gas productions of the Clear Creek and Crazy Woman Creek. The yearly gas production of the Upper Tongue River, Middle Powder River, and Little Powder River drainages is two orders magnitude higher than the yearly gas production of the Clear Creek and Crazy Woman Creek drainages.

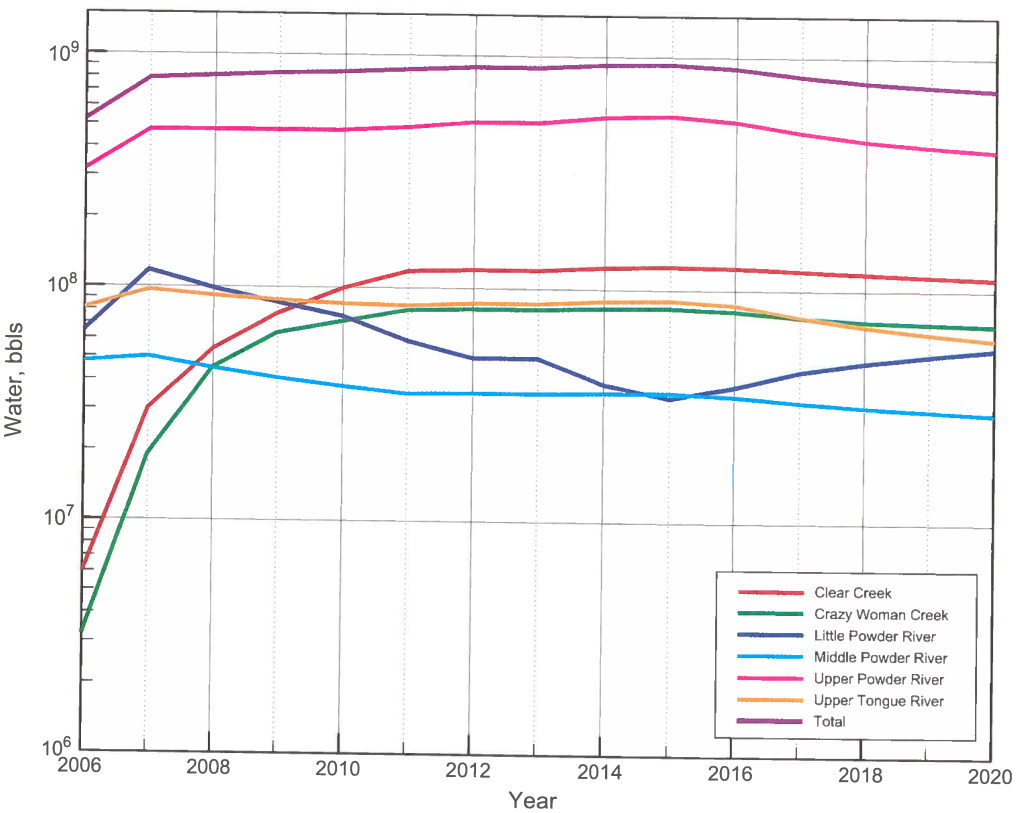

Figure 8. Plot of estimated yearly water production for each drainage. Well life is assumed to be 5 years. Clear Creek and Crazy Woman Creek drainages are predicted to produce more water than the Little and Middle Powder River drainages, but two orders of magnitude less gas (Figure 6).

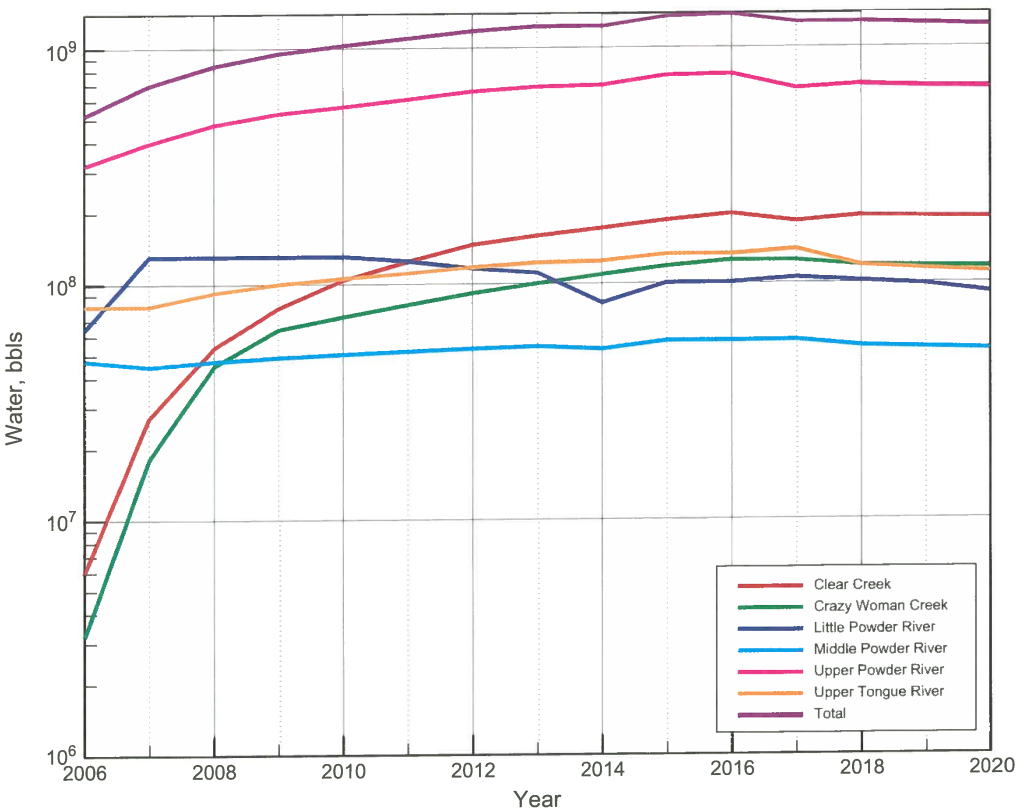

Figure 9. Plot of the estimated yearly water production for each drainage. Well life is assumed to be 10 years. Clear Creek and Crazy Woman Creek drainages are predicted to produce more water than the Little and Middle Powder River drainages, but two orders of magnitude less gas (Figure 7).

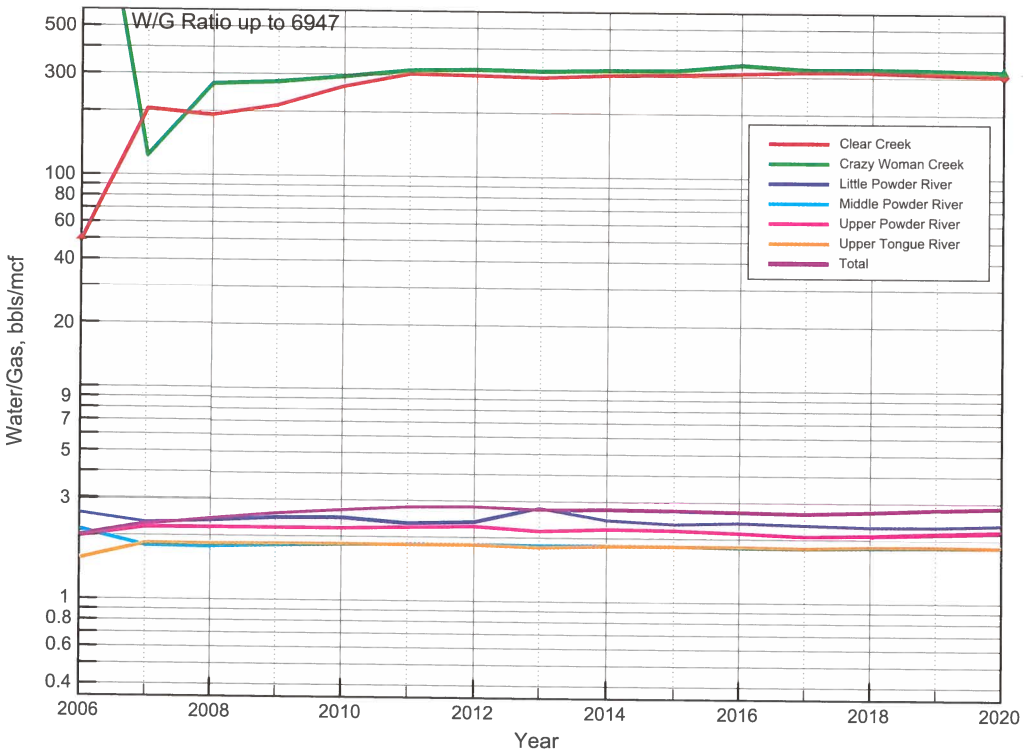

Figure 10. Plot of the estimated water production/gas production ratios for each drainage in the Powder River Basin. Well life is assumed to be 5 years. The average water/gas ratio is approximately 2.8. The water/gas ratios in the Little, Middle, and Upper Powder River and Upper Tongue River drainages are close to this average. The water/gas ratios in the Clear Creek and Crazy Woman Creek drainages are 100 times higher than the average water/gas ratio.

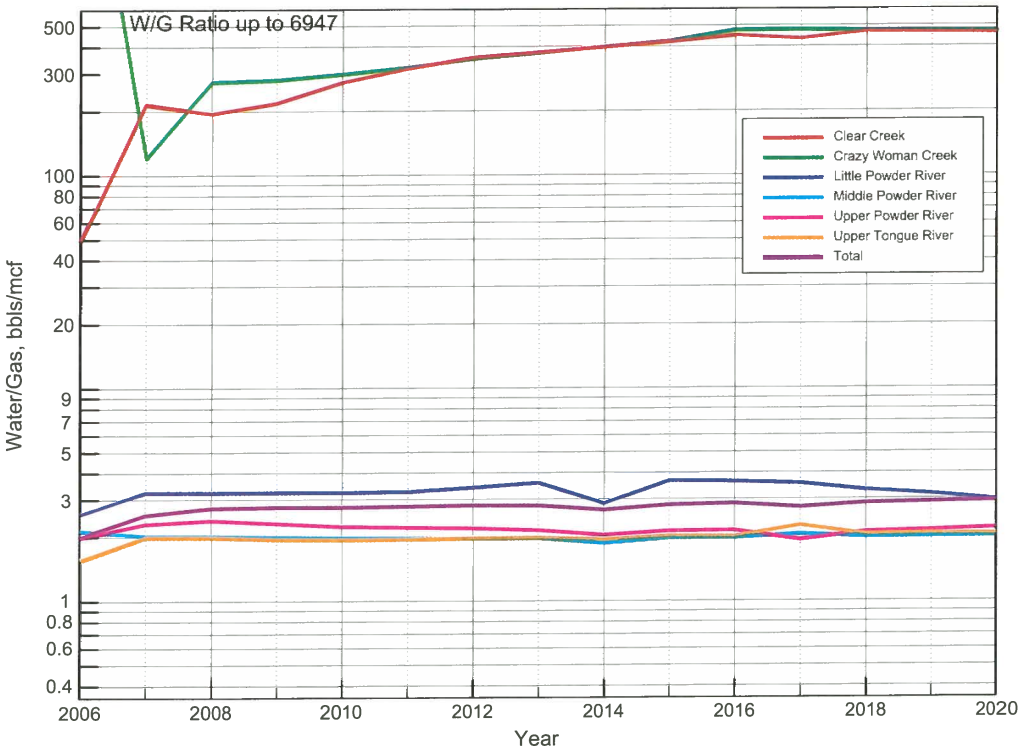

Figure 11. Plot of the estimated water production/gas production ratios for each drainage in the Powder River Basin. Well life is assumed to be 10 years. The average water/gas ratio is approximately 2.8. The water/gas ratios in the Little, Middle, and Upper Powder River and Upper Tongue River drainages are close to this average. The water/gas ratios in the Clear Creek and Crazy Woman Creek drainages are 100 times higher than the average water/gas ratio.

tio versus time for a well life expectancy of 10 years. The only substantial difference between **Figure 10** and **Figure 11** is that a 10-year well life results in a water/gas ratio greater than 300 for the Crazy Woman Creek and Clear Creek drainages, a water/gas ratio greater than three but less than 4 for the Little Powder River drainage, and water/gas ratios near 2 for the other drainages (**Figure 11**).

A number of rock/fluid characteristics differ between the Clear Creek and Crazy Woman Creek drainages, and the Upper, Middle, and Little Powder River and Upper Tongue River drainages. First, the Clear Creek and Crazy Woman Creek drainages cross that part of the PRB where the gas-producing coal beds are buried most deeply (**Figure 12**).

Next, the potentially productive coal beds in the Clear Creek and Crazy Woman Creek drainages are thinner than those in the other, more productive basins (**Figure 13**), and the targeted stratigraphic section is more sandstone-rich. For purposes of illustration, compare the cross section through the "Big George" area (**Figure 14**) with the coal bed distribution in the Clear Creek and Crazy Woman Creek drainages (**Figure 13**).

Also, a preliminary map of the groundwater table (elevation) based on wells 300 to 2,000 feet deep (approximately15,326 wells) demonstrates that: 1) the Clear Creek and Crazy Woman Creek drainages are spatially associated with very high groundwater recharge rates (**Figure 15**); and 2) CBM activity has already lowered the water table substantially in these two drainages (**Figure 16**).

Finally, the distribution of CBM wells more than two years old that have produced water and no commercial quantities of gas appears to be strongly influenced by linear elements in the PRB. These wells typically occur along NW-SE and NE-SW linear trends, perhaps suggesting a relationship between regional fracture systems (i.e., NW-SE and NE-SW faults) and high rates of groundwater flow.

All of the geologic factors discussed above help explain why existing wells, and probably future wells, in the Clear Creek and Crazy Woman drainages have such consistently high water/gas ratios.

Other Important Observations

Groundwater quality research in the targeted coal-rich stratigraphic interval of the PRB clearly shows that the salinity, or total dissolved solids (TDS), of produced water increases as you move west across the basin (**Figure 18**). The sodium absorption ratio (SAR) of the groundwater also increases to the west. It is apparent that groundwater quality consistently declines from east to west in the PRB (**Figure 18**, **Figure 19**). Lastly, no significant relationship appears to exist between the depth of a CBM well and the elevation of the water table (**Figure 20**). This observation suggests that the groundwater system associated with the coal-rich stratigraphic interval of the PRB should be considered a regional hydrologic system with

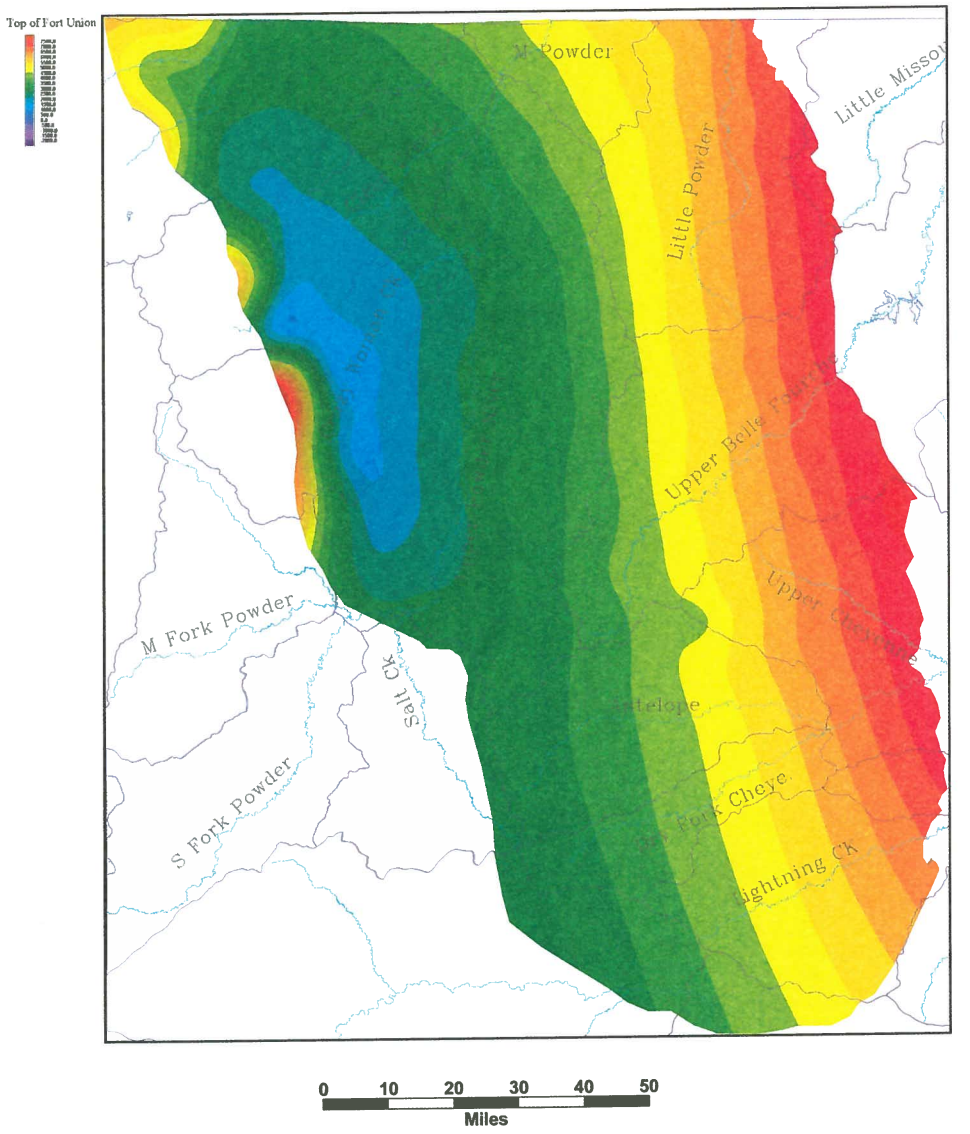

Figure 12. Structure contour map of the top of the Fort Union Formation, Powder River Basin. Note that the deepest portion of this asymmetric basin is located within the Clear Creek and Crazy Woman Creek drainages.

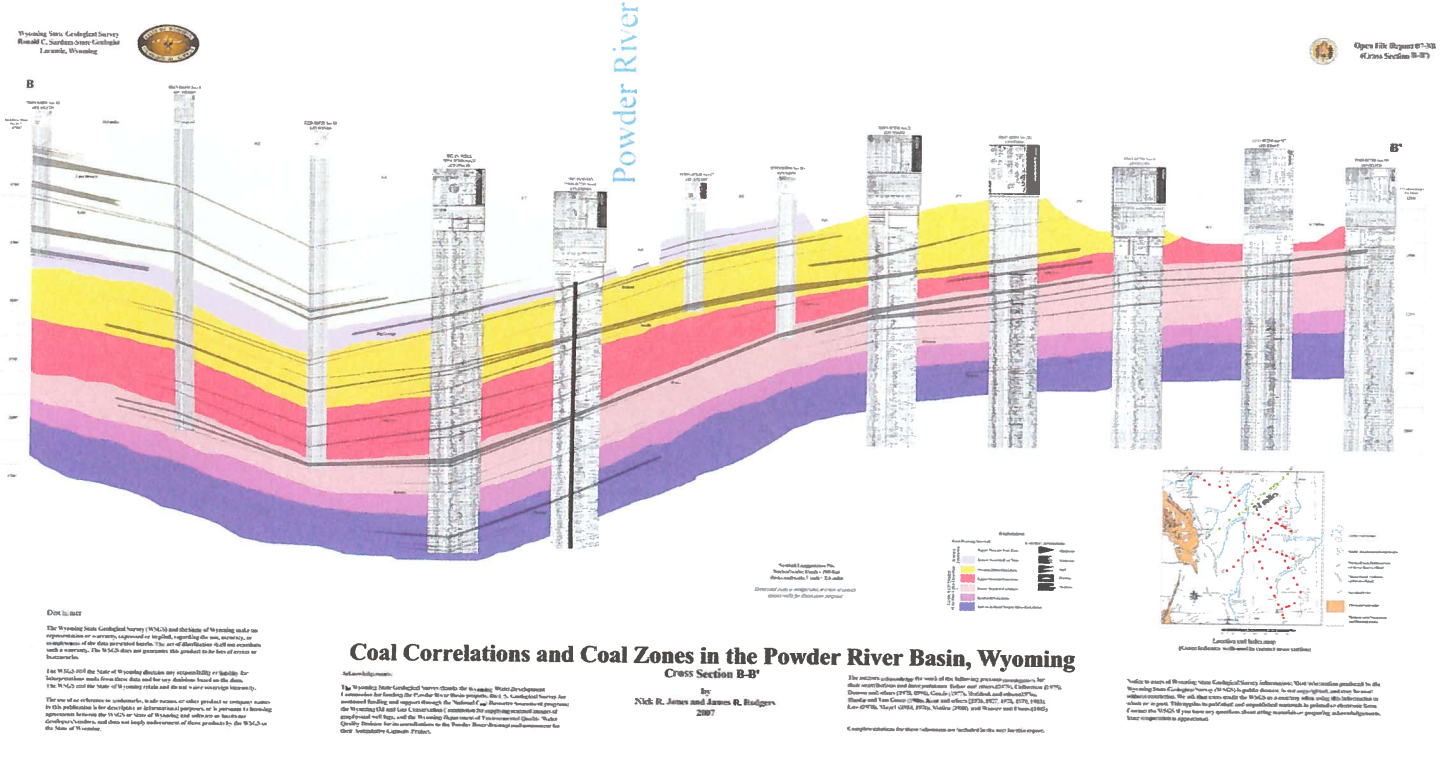

Figure 13. NE-SW structural cross section of Tertiary coal seams in the Powder River Basin.

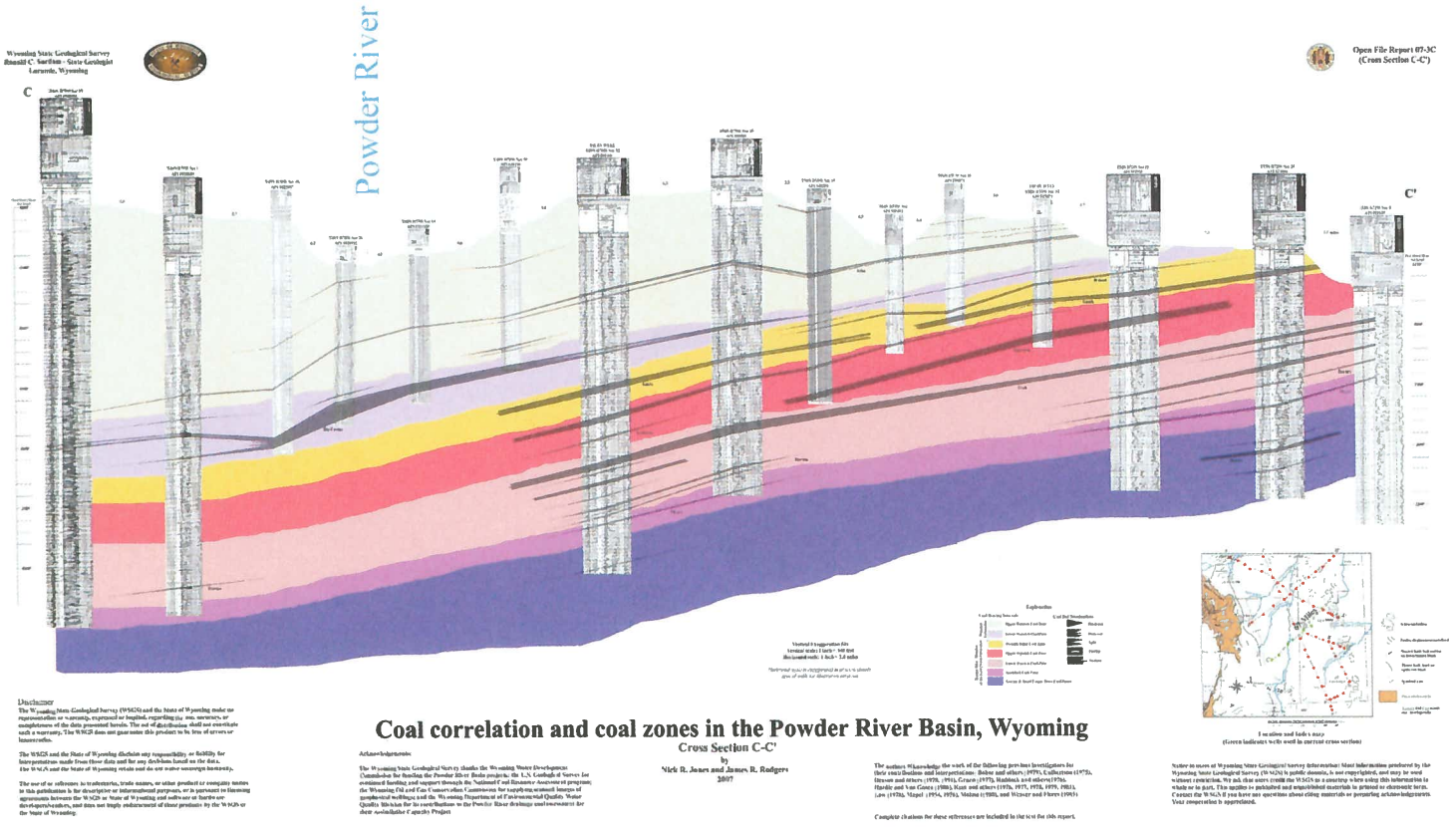

Figure 14. NE-SW structural cross section of Tertiary coal seams in the Powder River Basin.

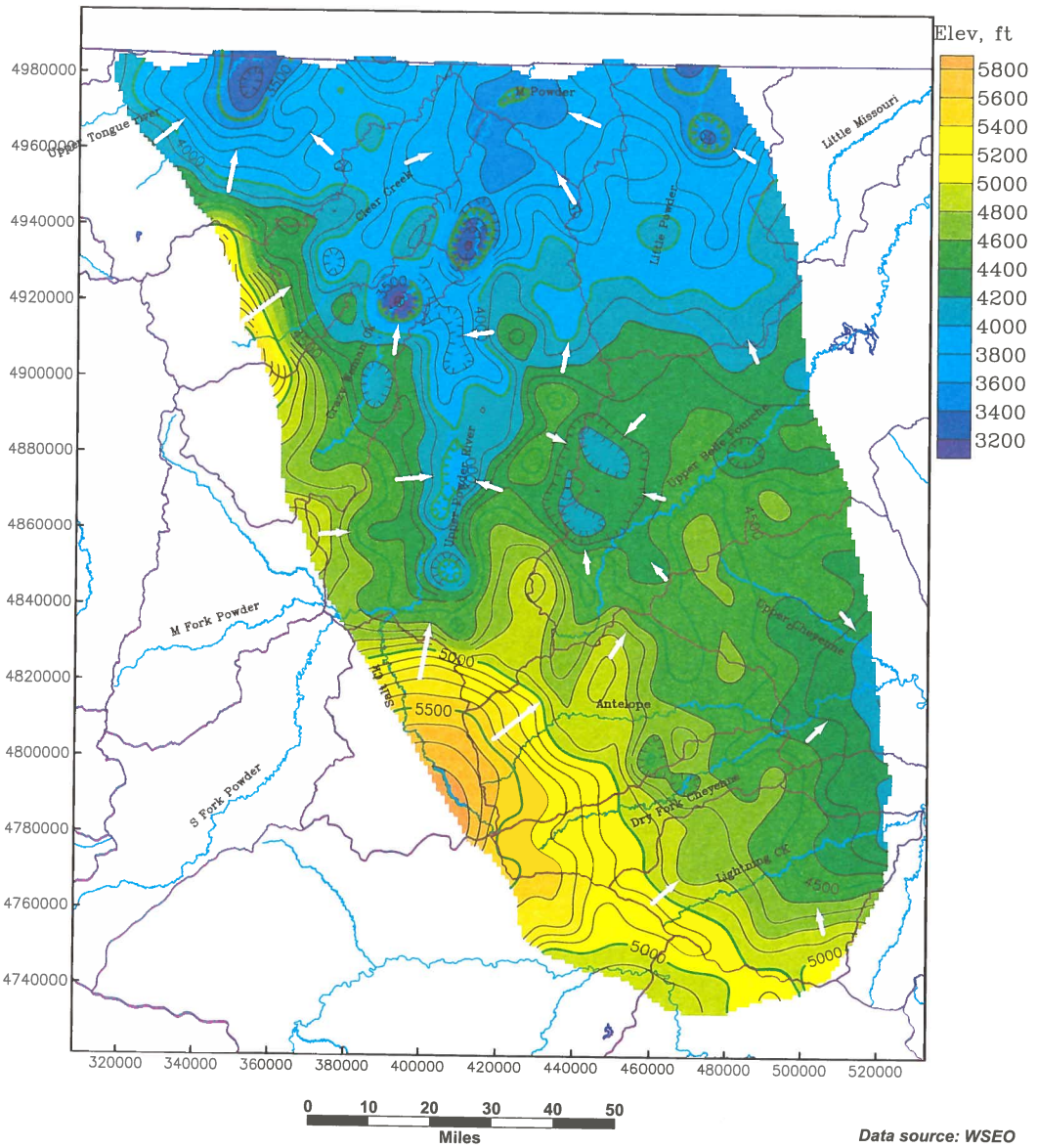

Figure 15. Contour map of the groundwater table (elevation) based on wells 300 to 2,000 feet deep (approximately 15,326 wells) shows the directions of groundwater flow (white arrows) and relative flow rate (length of the arrows).

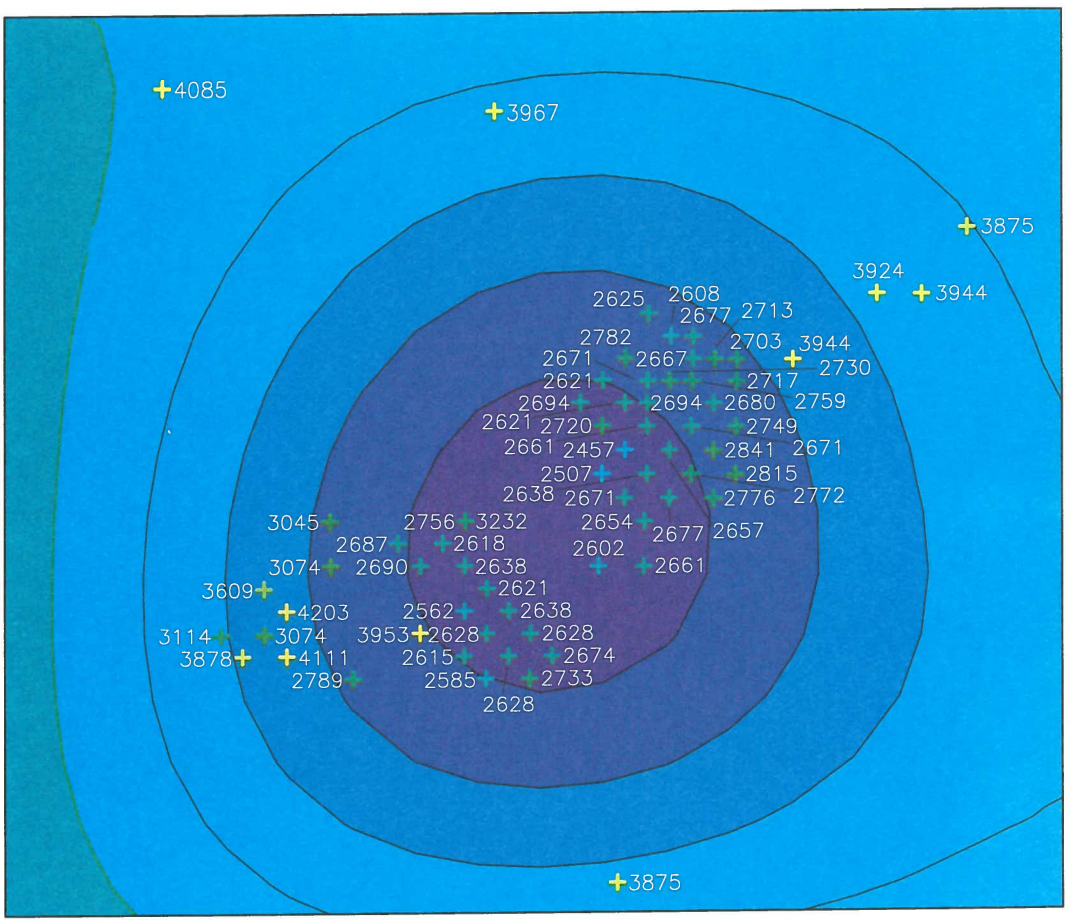

Figure 16. Contour map of the groundwater table (elevation) based on 67 wells within the Crazy Woman Creek drainage shows that CBM activity has already lowered the groundwater table significantly. Numbers indicate the elevation of the water table in feet.

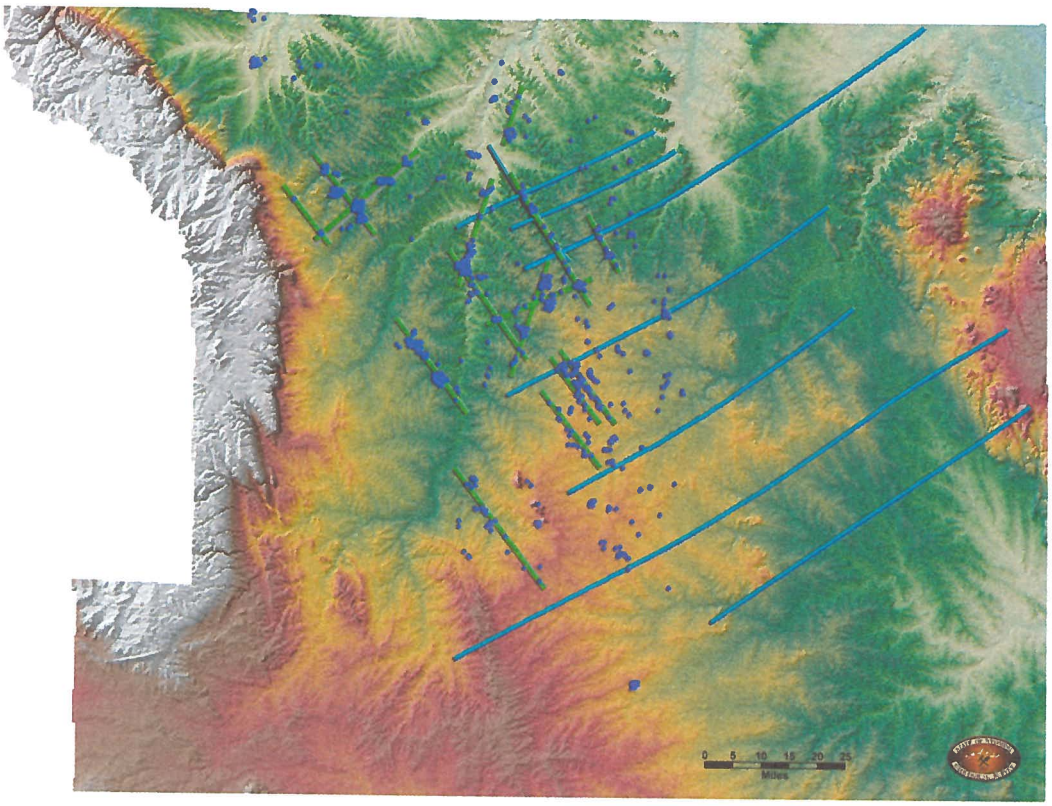

Figure 17. The distribution of CBM wells more than 2 years old that have produced significant amounts of water but no commercial quantities of gas appear to be strongly influenced by regional faults or fracture zones (blue and green lines) in the Powder River Basin.

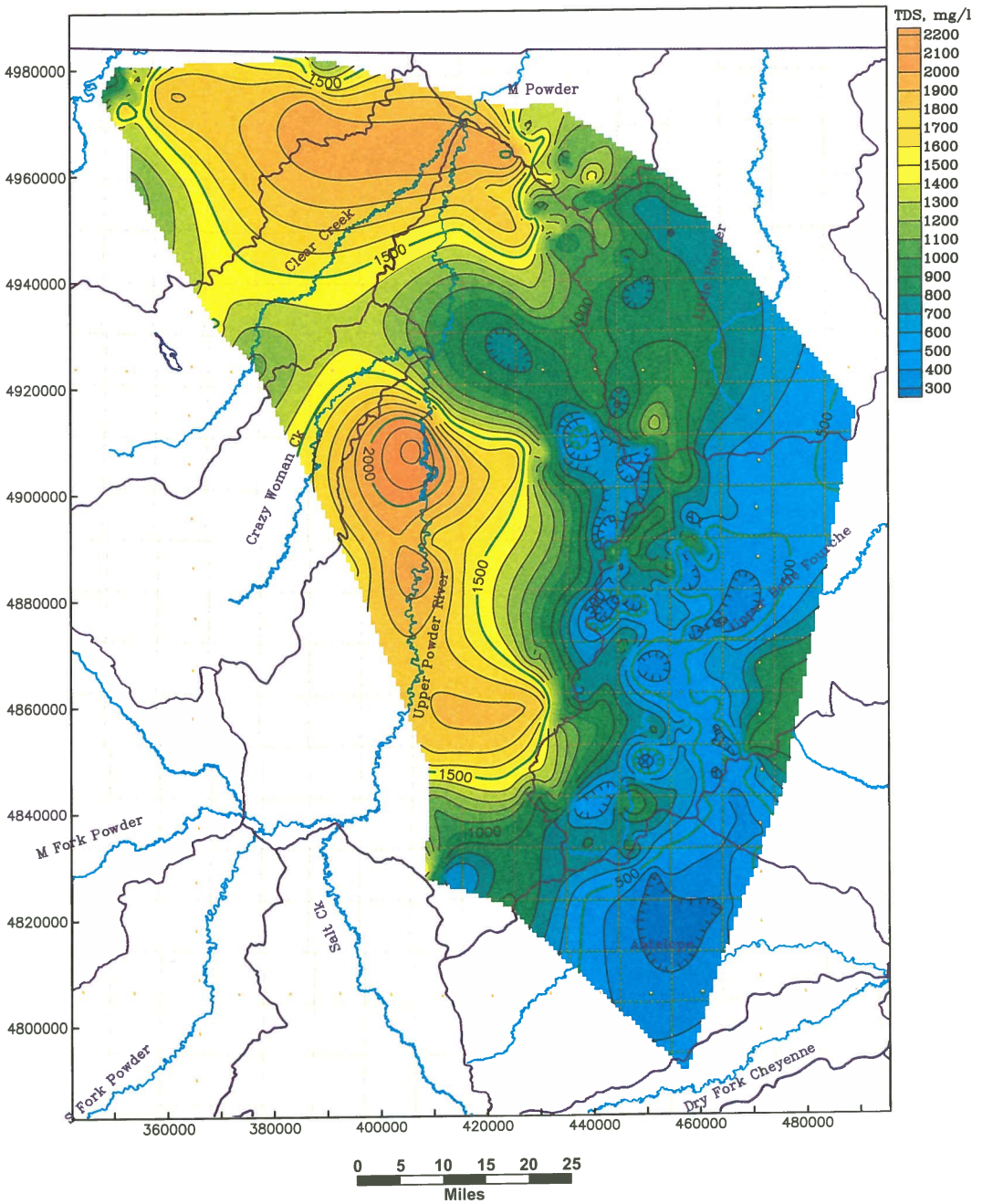

Figure 18. Salinity contour map of the CBM water from the Powder River Basin shows that the salinity, or total dissolved solids, of the CBM produced water increases significantly in the west and northwest parts of the Powder River Basin, namely in the Upper Powder River, Crazy Woman Creek, Clear Creek, and Upper Tongue River drainages.

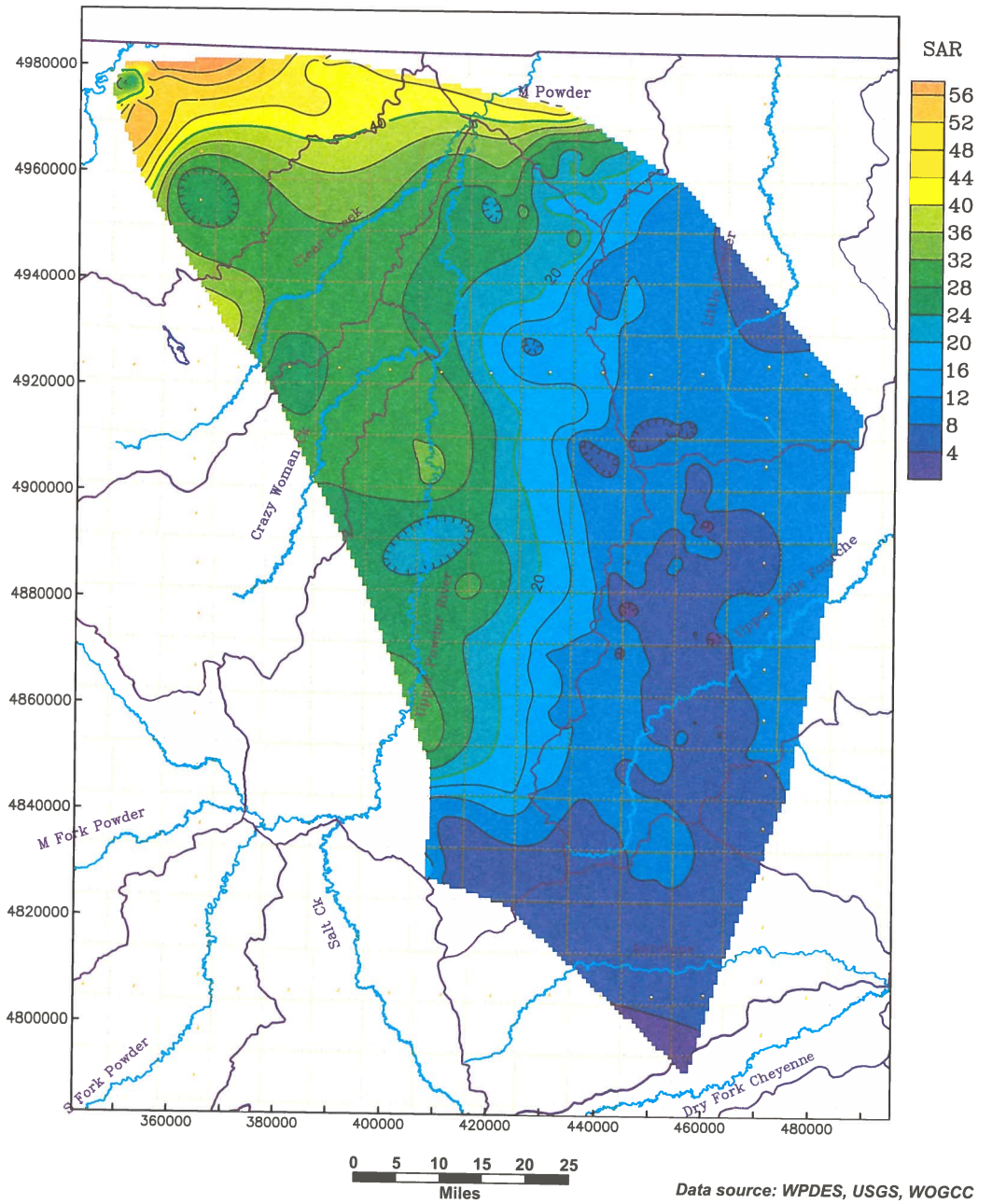

Figure 19. Sodium absorption ratio (SAR) contour map of the CBM produced water from the Powder River Basin. The sodium absorption ratio of the CBM produced water increases from southeast to northwest across the basin.

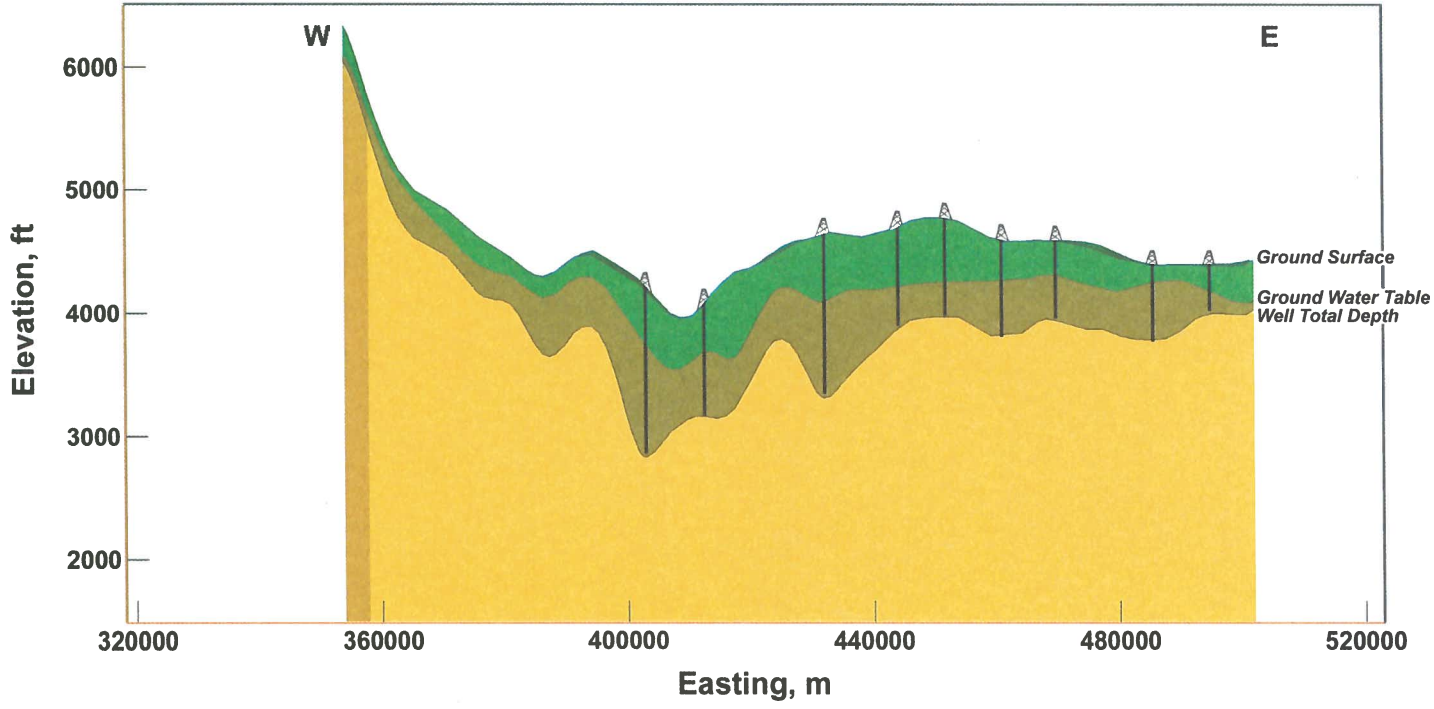

Figure 20. An east-west cross section of the ground surface elevation, groundwater table, and total well depth through the northern Powder River Basin shows that there is no significant relationship between the depth of the CBM wells and the elevation of the groundwater table.

substantial connectivity. A different classification of the hydrologic system (i.e., as a series of discontinuous perched water tables) would require additional observations and substantial evidence.

Conclusions

The following observations should be considered in future management strategies for CBM development in the PRB.

1. The vast majority of commercial CBM wells in the PRB produce substantial amounts of gas within two years of well completion (Figure 1).

2. A significant number of CBM wells (851) in the PRB have existed for more than two years and have produced no reportable gas.

3. CBM wells more than 2 years old with water/gas ratios greater than 10 have produced 1.64% of the gas and 26.5% of the water in the PRB to date. CBM wells more than 2 years old with water/gas ratios greater than 5 have produced 4.67% of the gas and 38% of the water in the PRB to date.

4. Water/gas ratios for the first half of CBM development in the PRB (22,211 wells more than two years old) averaged 1.83 barrels of water for every MCF of gas produced.

5. Based on the first 10 years (1997-2007) of CBM development in the PRB, we can evaluate future CBM production trends.

6. Future CBM development in the Upper, Middle, and Little Powder River and Upper Tongue River drainages has a predicted water/gas ratio of less than 3.

7. Conversely, the Clear Creek and Crazy Woman Creek drainages have projected water/gas ratios greater than 300.

8. During the second half of CBM development in the PRB, 25% of the new wells will probably be drilled in the Clear Creek and Crazy Woman Creek drainages; these areas will contribute only 0.15% of gas produced during this period, but will account for 20% of the water produced.

9. As the CBM play moves from east to west in the PRB, most of the targeted coal-rich section will lie in the lowest/deepest structural part of the basin.

10. The targeted Fort Union Formation coals are relatively thick in the Upper Powder River drainage (the "Big George" coal), whereas the stratigraphic interval targeted in

the Clear Creek and Crazy Woman Creek drainages contains thinner coals and more sandstones.

11. Groundwater flow rates are highest along the western margin of the PRB.

12. Already, CBM activity in the Upper Tongue River, Upper Powder River, Crazy Woman Creek, and Clear Creek drainages has measurably lowered the elevation of the water table.

13. Regional linears and associated fracture patterns appear to significantly affect groundwater flow patterns in the PRB.

14. Groundwater quality (based on TDS and SAR) declines from east to west in the PRB.

15. Preliminary research suggests that the best model for the groundwater associated with the Fort Union coal beds is a regional groundwater system characterized by substantial hydrologic connectivity.

Recommendations

The data and information in this report strongly support Wyoming State Engineer Patrick Tyrrel's recommendation to the Coalbed Methane Task Force concerning the regulation of CBM wells, after a reasonable amount of time, based on water/gas ratios. The observations outlined in this study suggest that the Wyoming State Engineer's Office should review every CBM well drilled in the PRB with a water/gas ratio greater than 3 after two years of production. These CBM wells should be discouraged unless the operator can do all of the following: 1) document special circumstances that have prevented the well from producing commercial quantities of gas; 2) quantify any decrease in water elevation in the well as a result of 2 or more years of water production (document any decrease in water table elevation); and 3) demonstrate that there are commercial quantities of gas in the perforated and completed coal intervals in the well. If the operator cannot do all of the above, we suggest the well be regulated as a water well rather than a CBM well.

This report strongly supports a moratorium on all CBM activity in the Clear Creek and Crazy Woman Creek drainages. Historically, these areas have very little commercial gas, yet have produced immense quantities of water. Predicted production trends based on projected CBM wells indicate that these areas will contribute only 0.15% of gas produced in the future, yet will account for 20% of future produced water. A moratorium on future CBM activity in these two drainages would save 3.3 billion barrels of water (130 billion gallons).

Implementing these changes would be a positive step in developing a strategy to minimize both produced water and animosity toward future CBM development, and would place regulation of CBM activity in the PRB on a sound, scientifically-supported path.

Acknowledgements

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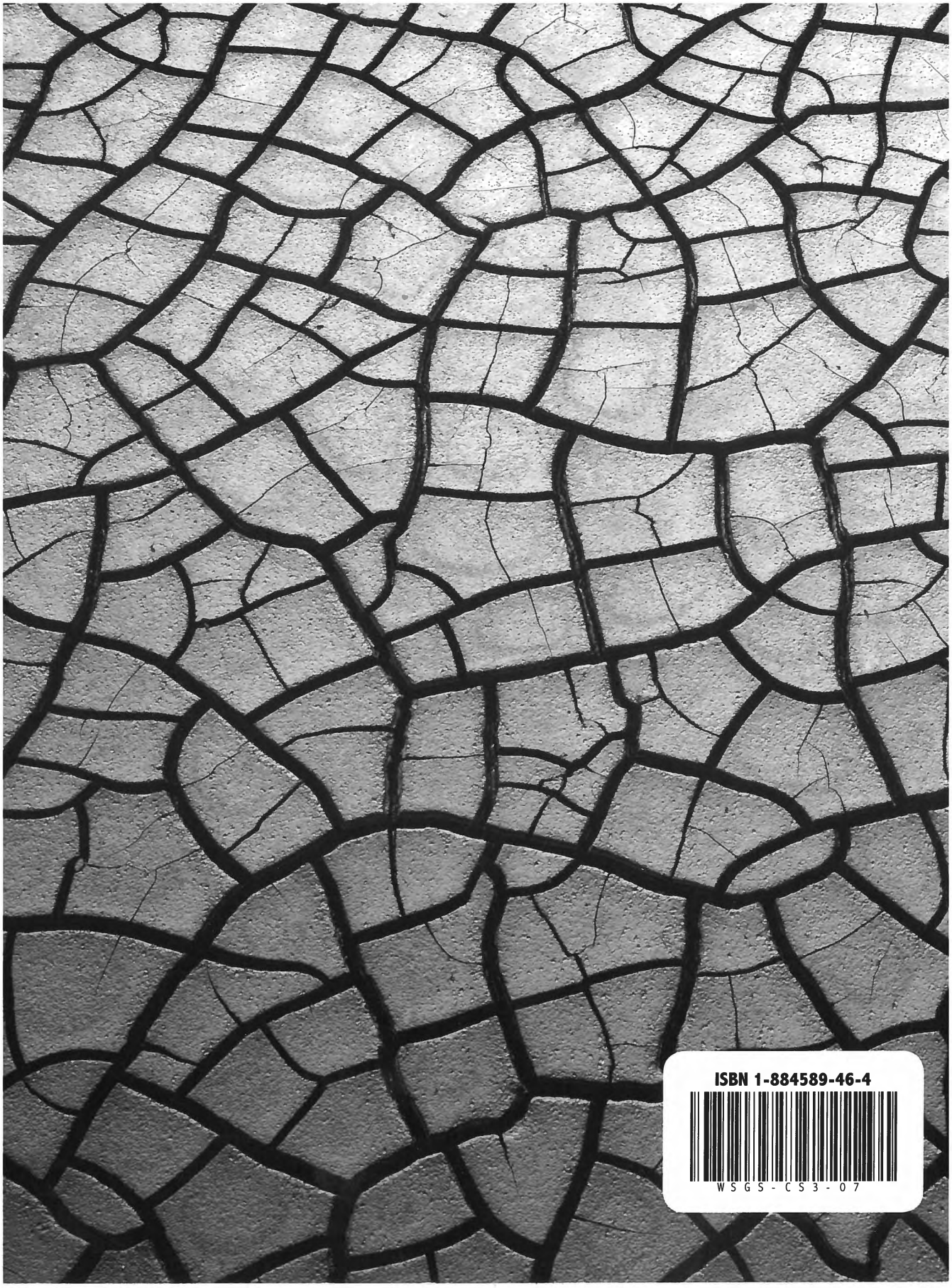

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