Task 1B Report for the Powder River Basin Coal Review Current Water Resources Conditions

ENSR INTERNATIONAL

Prepared for

Bureau of Land Management
Casper Field Office and
Wyoming State Office

Submitted by

ENSR Corporation
Fort Collins, Colorado

September 2006

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EXECUTIVE SUMMARY

This Task 1B Report for the Powder River Basin (PRB) Coal Review describes the existing water resources conditions in the PRB study area. Existing conditions for air quality, social and economic conditions, and other environmental resources are presented in individual baseline (Task 1) reports. The description of current water resources conditions in this report is based on published and unpublished information; information obtained from local, state, and federal agencies and private companies; and a compilation of past and present actions in the Wyoming PRB developed for the Task 2 Report for the PRB Coal Review. The past and present actions summarized in the Task 2 report include surface coal mines (12 active mines and 1 temporarily inactive mine), power plants, railroads, coal technology facilities, major transmission lines, other mines, oil and gas development, major pipelines, reservoirs, and other industrial and non-industrial developments. Descriptions of the past and present activities identified in the Task 2 report were based on the most recent data available at the end of 2003.

For the purpose of this study, the Wyoming PRB study area comprises all of Campbell County, all of Sheridan and Johnson counties less the Bighorn National Forest lands to the west of the PRB, and the northern portion of Converse County. It includes all of the area administered by the Bureau of Land Management (BLM) Buffalo Field Office, a portion of the area administered by the BLM Casper Field Office, and a portion of the Thunder Basin National Grasslands, which is administered by the U.S. Forest Service. State and private lands also are included in the study area. For water resources, the existing conditions are presented for the Powder River Structural Basin (also referred to as the Powder River Physiographic Basin), which includes the Powder/Tongue River Basin and Northeast Wyoming River Basins planning areas. The detailed study area encompassed by the groundwater model domain places emphasis on the overlap between coal mine- and coal bed natural gas (CBNG)-related groundwater drawdown in the eastern PRB. The Task 3B Report for the PRB Coal Review is devoted to potential future impacts to water resources in the area of CBNG development and coal mine expansion in the eastern PRB. It includes a cumulative impact assessment of water quality and channel stability from surface discharge of groundwater from CBNG development.

ES.1 TECHNICAL APPROACH

Existing (2002) regional surface water and groundwater conditions in the Wyoming PRB study area were based on publicly available and accessible data and publications. The two principal studies used included the Powder/Tongue River Basin Study (HKM Engineering et al. 2002a) and the Northeast Wyoming River Basins Study (HKM Engineering et al. 2002b). Data on groundwater levels and groundwater quality primarily were obtained from various water resource and geological publications prepared by the U.S. Geological Survey (USGS). Additional data on groundwater levels came from BLM monitoring well files, the annual reports prepared by the Gillette Area Groundwater Monitoring Organization (GAGMO), the USGS waterdata website, and from the mine permit files of the Wyoming Department of Environmental Quality (WDEQ)/Land Quality Division (LQD). In addition, a numerical groundwater flow model was developed for this study to further analyze existing (2002) groundwater level impacts associated with coal mine dewatering and CBNG development in the eastern portion of the PRB study area.

ES.2 DESCRIPTION OF CURRENT REGIONAL CONDITIONS

Surface and groundwater are utilized extensively throughout the PRB for agricultural water supply, municipal water supply, and both domestic and industrial water supply. Surface water use is limited to major perennial drainages in agricultural areas within the basin found along these drainages. Municipal water supply comes from a combination of surface and groundwater. Domestic and industrial water supply primarily is from groundwater. The Powder/Tongue River Basin receives substantial surface water runoff from the Big Horn Mountains, leading to major agricultural development along drainages in the Tongue River and Powder River basins. Reservoirs are used throughout the basin for agricultural water supply and for municipal water supply in the Powder/Tongue River Basin. The discussion of water use in the Wyoming PRB is divided into the two major water planning areas of the basin, the Powder/Tongue River Basin and the Northeast Wyoming River Basins.

ES.2.1 Water Use

ES.2.1.1 Powder/Tongue River Basin

The main rivers in the Powder/Tongue River Basin are the Tongue River and the Powder River, which derive most of their flow from tributaries with headwaters in the Big Horn Mountains. Water use in the Powder/Tongue River Basin as of 2002 is summarized in **Table ES.2.1-1**.

Table ES.2.1-1
Water Use as of 2002 in the Powder/Tongue River Basin

Water Use	Dry Year		Normal Year		Wet Year	
	(acre-feet per year)					
	Surface Water	Groundwater	Surface Water	Groundwater	Surface Water	Groundwater
Agricultural	178,000	200	184,000	200	194,000	300
Municipal	2,700	500	2,700	500	2,700	500
Domestic	---	4,400	---	4,400	---	4,400
Industrial[1]	---	68,000	---	68,000	---	68,000
Recreation	Non-consumptive					
Environmental	Non-consumptive					
Evaporation	11,300	--	11,300	--	11,300	--
Total	**192,000**	**73,100**	**198,000**	**73,100**	**208,000**	**73,200**

[1]Includes conventional oil and gas production water and CBNG production water.

Source: HKM Engineering et al. 2002a.

As of January 1, 2002, approximately 161,160 acres of land were actively irrigated in the Powder/Tongue River Basin, and the vast majority of these lands were irrigated with surface water. Annual water depletions for surface water as a result of irrigation were approximately 194,000 acre-feet for wet years, 184,000 acre-feet for normal years, and 178,000 acre-feet for dry years (HKM Engineering et al. 2002a). These are estimated depletions and take into account irrigation return flow. The amount of groundwater used for irrigation was approximately

300 acre-feet per year for wet years and 200 acre-feet per year for normal and dry years. Most agricultural wells, especially stock wells, are screened in the Fort Union Formation. Agricultural water use in wet years is often greater than in dry years due to more land being in production.

There are 20 public water supply entities in the Powder/Tongue River Basin consisting of incorporated municipalities, water districts, and privately owned water systems. Two communities obtain water supply from outside the basin. Four of the entities obtain their water supply from surface water and consume approximately 2,700 acre-feet per year (HKM Engineering et al. 2002a). The remaining 16 entities consume approximately 500 acre-feet of groundwater per year. Domestic water use is satisfied by groundwater and totals approximately 2,400 to 4,400 acre-feet per year. Many of the municipal wells and most of the domestic wells are in the Fort Union Formation.

Conventional oil and gas production and CBNG development constitute the principal industrial water use in the Powder/Tongue River Basin. The total estimated groundwater consumption is approximately 68,000 acre-feet per year (HKM Engineering et al. 2002a). Approximately half of this groundwater comes from the Fort Union Formation and is consumed by the CBNG industry.

Recreational water use requires minimum flow releases from reservoirs, minimum water levels in reservoirs, or maintenance of instream flow water rights; however, it is non-consumptive.

Reservoir evaporation is a major source of water loss in the Powder/Tongue River Basin. Evaporation from the 14 key storage reservoirs in the basin totals approximately 11,300 acre-feet per year (HKM Engineering et al. 2002a). This primarily is a loss of surface water and exceeds the surface water and groundwater consumption by municipalities as well as the groundwater consumption by domestic wells. Only agricultural irrigation, conventional oil and gas operations, and CBNG development consume more water.

ES.2.1.2 Northeast Wyoming River Basins

The main rivers in the Northeast Wyoming River Basins are the Belle Fourche in Campbell and Crook counties and the Cheyenne River in Converse, Weston, and Niobrara counties. Water in these rivers and their tributaries comes from groundwater baseflow and from precipitation runoff, especially from heavy storms during the summer months.

Water use in the Northeast Wyoming River Basins as of 2002 is summarized in **Table ES.2.1-2**.

As of 2002, approximately 77,350 acres were irrigated in the Northeast Wyoming River Basins, of which approximately 13,000 acres were irrigated with groundwater. Surface water consumption by irrigation in 2002 totaled 71,000 acre-feet in wet years, 69,000 acre-feet in normal years, and 65,000 acre-feet in dry years (HKM Engineering et al. 2002b). Groundwater consumption for irrigation in 2002 totaled 17,000 acre-feet in wet years and normal years and approximately 11,000 acre-feet in dry years. Most of the groundwater consumption for irrigation was in the Niobrara River drainage, which is not part of the PRB structural basin. Agricultural water use can be higher in wet years than in dry years due to more land being in production.

Table ES.2.1-2
Water Use as of 2002 in the Northeast Wyoming River Basins

Water Use		Dry Year		Normal Year		Wet Year	
		(acre-feet per year)					
		Surface Water	**Groundwater**	**Surface Water**	**Groundwater**	**Surface Water**	**Groundwater**
Agricultural		65,000	11,000	69,000	17,000	71,000	17,000
Municipal		---	9,100	---	9,100	---	9,100
Domestic		---	3,600	---	3,600	---	3,600
Industrial	Oil and Gas[1]	---	46,000	---	46,000	---	46,000
	[2]	---	4,700	---	4,700	---	4,700
Recreation		Non-consumptive					
Environmental		Non-consumptive					
Evaporation	Key Reservoirs	14,000	---	14,000	---	14,000	---
	Stock Ponds	6,300	---	6,300	---	6,300	---
Total		**85,300**	**74,400**	**89,300**	**80,400**	**91,300**	**80,400**

[1]Includes conventional oil and gas production water and CBNG production water.
[2]Includes electricity generation, coal mining, and oil refining.
Other

Source: HKM Engineering et al. 2002b.

There are 33 public water supply entities in the Northeast Wyoming River Basins consisting of 9 incorporated municipalities, 19 water districts, and 5 privately owned water systems. Municipal and domestic water use is from groundwater only, and approximately 9,100 acre-feet of groundwater is consumed per year. Domestic groundwater demand is approximately 3,600 acre-feet per year (HKM Engineering et al. 2002b). Domestic water consumption primarily is from the Fort Union Formation. Municipal water consumption is from the Fort Union Formation and aquifers below the Fort Union.

Industrial water use in the Northeast Wyoming River Basins consists of conventional oil and gas production, CBNG development, coal mining, electric power generation, and oil refining. With one exception, groundwater is used exclusively by these industries, and the total use is approximately 50,700 acre-feet per year (HKM Engineering et al. 2002b). The groundwater comes primarily from the Fort Union Formation. Approximately 350 acre-feet per year of treated wastewater from the City of Gillette is used by the Wyodak Power Plant.

Recreational and environmental water uses are non-consumptive. They consist of maintaining minimum water levels in reservoirs and minimum flow releases for instream water rights and aquatic water needs. The largest reservoir in the Northeast Wyoming River Basins is the Keyhole Reservoir, which supports a variety of recreational activities and primarily is used for agricultural irrigation.

Evaporation from the six key storage reservoirs in the Northeast Wyoming River Basins is approximately 14,400 acre-feet of water annually (HKM Engineering et al. 2002b). There are approximately 16,600 stock ponds in the Northeast Wyoming River Basins and these evaporate approximately 6,300 acre-feet of water per year (HKM Engineering et al. 2002b). Thus, total evaporation loss in the Northeast Wyoming River Basins is approximately 20,000 acre-feet per year. Evaporation loss is greater than groundwater consumption by coal mining and greater than groundwater consumption by municipal and domestic water use combined. Only irrigation and CBNG development consume more water.

ES.2.2 Water Availability

ES.2.2.1 Surface Water

ES.2.2.1.1 Powder/Tongue River Basin

The Little Bighorn River, Tongue River, Powder River, Crazy Woman Creek, and Piney Creek carry the largest natural flows in the Powder/Tongue River Basin. Many of the other major drainages are affected by irrigation practices to the extent that their flows are not natural (HKM Engineering et al. 2002a). Water availability in the major subbasins of the Powder/Tongue River Basin is summarized in **Table ES.2.2-1**. This table presents the amount of surface water in acre-feet that is physically available above and beyond allocated surface water in these drainages. As a result of the Yellowstone River Compact, Wyoming must share some of the physically available surface water in the Powder/Tongue River Basin with Montana.

ES.2.2.1.2 Northeast Wyoming River Basins

The Belle Fourche and Cheyenne River basins carry most of the available surface water flow in the Northeast Wyoming River Basins. There are approximately 25 maintained gauging stations in these drainages. Many of these stations measure unnatural flow dominated by irrigation practices. In addition, most surface water flow in the Northeast Wyoming River Basins is intermittent to ephemeral. Total annual available flow for the Northeast Wyoming River Basins is summarized in **Table ES.2.2-2**.

Table ES.2.2-1
Surface Water Availability in the Powder/Tongue River Basin

Subbasin	Surface Water Availability (acre-feet)		
	Wet Years	**Normal Years**	**Dry Years**
Little Bighorn River	152,000	113,000	81,000
Tongue River	473,000	326,000	218,000
Clear Creek	213,000	124,000	80,000
Crazy Woman Creek	69,000	32,000	16,000
Powder River	547,000	324,000	16,000
Little Powder River	48,000	12,000	3,000
Total	**1,502,000**	**931,000**	**414,000**

Source: HKM Engineering et al. 2002a.

Table ES.2.2-2
Surface Water Availability in the Northeast Wyoming River Basins

Subbasin	Surface Water Availability (acre-feet)		
	Wet Years	**Normal Years**	**Dry Years**
Redwater Creek	34,000	26,000	17,000
Beaver Creek	30,000	20,000	14,000
Cheyenne River	103,000	31,000	5,000
Belle Fourche River	151,000	71,000	13,000
Total	**318,000**	**148,000**	**49,000**

Source: HKM Engineering et al. 2002b.

ES.2.2.2 Groundwater

An estimate of recoverable groundwater in the PRB is provided in **Table ES.2.2-3**.

ES.2.2.2.1 Powder/Tongue River Basin

There are five main aquifers in the Powder/Tongue River Basin that can be used for water supply as described below.

Madison Aquifer System. The Madison Aquifer is the deepest aquifer and lies within the Paleozoic Tensleep Sandstone, Amsden Formation, Madison Limestone, Bighorn Dolomite, and Flathead Sandstone. The Madison Limestone is the thickest unit and is approximately 200 to 1,100 feet thick with a transmissivity ranging from 500 to 90,000 gallons per day per foot (gpd/ft). Well yields from this aquifer have been as high as 4,000 gallons per minute (gpm). Water quality in the Madison Limestone mainly is dominated by calcium-magnesium bicarbonate with locally high concentrations of fluoride and radionuclides. Total dissolved solids (TDS) can range from 600 to 3,000 milligrams per liter (mg/L), with the high TDS water containing sulfates and chlorides. The water is of good quality, and the Madison Limestone is the most important high-yield aquifer in Wyoming for municipal, industrial, and irrigation water supply. Depths to the Madison in the Powder/Tongue River Basin range from approximately 6,000 feet east of Gillette, Wyoming, to as much as 16,000 feet in the southwestern part of the Powder/Tongue River Basin. Recharge to the Madison Limestone is approximately 75,000 acre-feet per year (HKM Engineering et al. 2002a). Other formations within the Madison Aquifer System can yield water; however, the quality of the water is not as good as that found in the Madison Limestone, and well yields are often much lower.

Table ES.2.2-3
Recoverable Groundwater in the PRB

Hydrogeologic Unit	Surface Area (acres)	Average Formation Thickness (feet)	Percentage of Sand/Coal	Average Sand/Coal Thickness (feet)	Specific Yield (percent)	Recoverable Groundwater (acre-feet)
Wasatch-Tongue River Aquifer Sandstones	5,615,609	2,035	50	1,018	13	743,121,790
Wasatch-Tongue River Aquifer Coals	4,988,873	2,035	6	126	0.40	2,516,519
Lebo Confining Layer Sandstones	6,992,929	1,009	33	250	13	227,137,339
Tullock Aquifer Sandstones	7,999,682	1,110	52	430	13	447,246,784

Source: BLM 2003a.

Dakota Aquifer System. The Dakota Aquifer consists of two main formations, the Cloverly Formation and the Newcastle Sandstone, which have a total thickness of approximately 200 feet. Yields from the Dakota Aquifer range from 1 to 40 gpm up to approximately 250 gpm (HKM Engineering et al. 2002a). The transmissivity of the main producing unit, the Cloverly Formation, is in the range of 7 to 230 gpd/ft. Water from the Dakota Aquifer is dominated by sodium bicarbonate with TDS ranging from 300 to 3,000 mg/L. With common well yields in the range of 5 to 20 gpm, the Dakota Aquifer is not a major source of water.

Fox Hills/Lance Aquifer System. The Fox Hills/Lance Aquifer System consists of the Lance Formation and the underlying Fox Hills Sandstone. The Lance Formation ranges from 600 to 3,000 feet in thickness and thickens to the south in the Powder/Tongue River Basin (HKM Engineering et al. 2002a). Well yields from the Lance Formation are approximately 15 gpm or less, and the transmissivity of the Lance Formation is 76 to 2,100 gpd/ft. The water quality in the Lance is dominated by sodium sulfate or calcium sulfate, and the TDS ranges up to 3,000 mg/L. The sodium absorption ratio (SAR) ranges from 1.9 to 39, and the water generally is not suitable for irrigation use, stock use, or domestic use. The Fox Hills Sandstone ranges in thickness up to 700 feet with a transmissivity in the range of 76 to 1,600 gpd/ft. Well yields generally are around 15 gpm but can range up to 50 gpm. The Gillette municipal public water supply has wells in the Fox Hills yielding 85 to 705 gpm (HKM Engineering et al. 2002a). The water quality is similar to that in the Lance Formation. Depths to the formation are on the order of 1,000 feet in most of the Powder/Tongue River Basin. The water quality of the Fox Hills Sandstone limits its usefulness for domestic or stock use. The fluoride content of the water on the east side of the Powder/Tongue River Basin can limit its use for municipal water supply.

Fort Union/Wasatch Aquifer System. Both the Wasatch and the Fort Union formations act as aquifers in the Powder/Tongue River Basin. The Wasatch is more of a local aquifer, while the Fort Union Formation is a regional aquifer. The Wasatch ranges in thickness from 500 to 2,000 feet and is a fine to coarse-grained lenticular sandstone with interbedded shale and coal. The transmissivity ranges from 520 to 2,200 gpd/ft, but well yields generally are less than 15 gpm. The TDS of the water ranges from 141 to 6,620 mg/L (HKM Engineering et al. 2002a), and the sulfate content can range up to 4,000 mg/L, with iron ranging up to 25 mg/L. The Wasatch is a local source of domestic and stock water supply, but it generally is not suitable for irrigation because of the high sodium content. The Fort Union Formation ranges from 1,200 to 3,900 feet in thickness in the Powder/Tongue River Basin and is a fine- to medium-grained siltstone with abundant coal and shale. Well yields from 1 to 60 gpm ranging up to 250 gpm are common, and the transmissivity ranges from 10 to 95 gpd/ft. The TDS content of the water ranges from 484 to 4,630 mg/L with high sulfate (up to 1,870 mg/L) and iron (up to 19 mg/L). The water generally is dominated by sodium bicarbonate and has a high SAR value (up to 32). The Fort Union is a major source of local water supply for domestic and stock water use. Major pumpage in the Fort Union is from CBNG wells, and the average pumping rate per well ranges from approximately 12 to 45 gpm, depending on the depth of the CBNG well.

Quaternary Alluvial Aquifer System. This aquifer system is local in nature and is found in alluvium and terrace deposits near the major drainages of the Powder/Tongue River Basin. The thickness of alluvium ranges up to approximately 100 feet. Well yields of 50 to 300 gpm are possible in local areas, and the transmissivity can range up to 20,300 gpd/ft. TDS for the water can range up to 4,000 mg/L and the chemical nature of the water varies considerably based on location. Water from the Quaternary Alluvial Aquifer has been used for municipal water supply, domestic water supply, and stock use. Quaternary alluvial aquifers that are in hydraulic connection with perennial streams are the main source of water supply in this aquifer system. These shallow alluvial aquifers can be recharged by groundwater flow from the underlying Wasatch Aquifer or from stream infiltration.

ES.2.2.2.2 Northeast Wyoming River Basins

There are six main aquifers underlying the Northeast Wyoming River Basins. One of these, the Arikaree Aquifer, is not within the PRB; the other five are described below.

Madison Aquifer System. The Madison Aquifer along the central and eastern flanks of the PRB consists of four water-bearing formations. From oldest to youngest these are the Whitewood Dolomite, Englewood Limestone, Pahasapa Limestone (equivalent to the Madison Limestone in the northern part of the PRB), and Minnelusa Formation. The Whitewood Dolomite is a massive bedded dolomite 50 to 60 feet thick that contains few wells and has a transmissivity of approximately

6,400 gpd/ft. This unit of the Madison Aquifer System is not used for water supply. The Englewood Limestone is 30 to 60 feet thick, also has very few wells, and is not used for water supply. The principal unit of the Madison Aquifer System that is used for water supply in the eastern PRB is the Pahasapa Limestone. This massive limestone has wells with yields up to 1,000 gpm and a transmissivity that typically ranges from 1,000 to 60,000 gpd/ft but locally can be as high as 300,000 gpd/ft. Water quality at the outcrop of the formation along the eastern flank of the PRB is calcium-magnesium bicarbonate water with a TDS of less than 600 mg/L. The TDS increases basinward to greater than 3,000 mg/L, and the water becomes dominated by sodium sulfate and sodium chloride with increasing concentrations of fluoride and radionuclides. This is the most important high-yield aquifer in Wyoming and is a source of water for municipal water supply as well as industrial, irrigation, and stock water use. The City of Gillette, Wyoming, uses this aquifer for water supply. The overlying Minnelusa Formation also is a major aquifer in the eastern PRB. This unit is 600 to 800 feet thick and consists of sandstone interbedded with limestone, dolomite, and shale. The upper part of the Minnelusa is an aquifer and yields 200 gpm to wells and has a transmissivity up to 900 gpd/ft. Water quality is good near the outcrop of the formation with TDS values below 600 mg/L. Basinward, the TDS increases to around 2,400 mg/L with an average of approximately 773 mg/L. The water quality changes from calcium bicarbonate water to water dominated by calcium sulfate and to sodium chloride waters in the deeper parts of the PRB. Fluoride enrichment and locally high values of radionuclides are a problem for municipal water use. The historical use of water from the Minnelusa has been for public water supply and domestic and stock use.

Dakota Aquifer System. The Dakota Aquifer System in the eastern PRB consists of three water-bearing units. From oldest to youngest, these are the Lakota Formation, Fall River Formation, and Newcastle Sandstone. The Lakota Formation ranges in thickness from 45 to 200 feet and is mainly a sandstone with interbedded conglomerates and shales. The unit generally is not used for water supply and yields 1 to 10 gpm to wells on average with a transmissivity of 220 to 810 gpm/ft. The Fall River Formation also is a sandstone with interbedded shale and siltstone and ranges in thickness from 35 to 150 feet. Well yield and transmissivity are similar to the Lakota Formation, and this unit also is not a source of water supply. The Newcastle Sandstone is the major aquifer of the Dakota Aquifer System in the eastern PRB and ranges in thickness up to 100 feet. As a result of a low transmissivity (up to 140 gpd/ft) and poor water quality within the PRB, this unit is used for water supply only near its exposures along the eastern rim of the PRB. The TDS of water in the basin can range up to 3,200 mg/L with the water dominated by calcium and sodium sulfate. Selenium and radionuclides can be issues of concern in some areas of this aquifer.

Fox Hills/Lance Aquifer System. This aquifer system consists of the Fox Hills Sandstone and the overlying Lance Formation. The Fox Hills Sandstone ranges from 150 to 700 feet in thickness and yields up to 700 gpm to wells. The transmissivity ranges from 70 to 1,600 gpd/ft, and the formation is used for municipal, industrial, domestic, and stock water supply. The water quality is similar to that in the overlying Lance Formation and consists of sodium bicarbonate to sodium sulfate water with a TDS ranging from 600 to 3,000 mg/L and locally high sodium and radionuclide contents. The locally high fluoride content can be a problem for domestic water supply. The Lance Formation ranges in thickness from 500 to 3,000 feet and yields up to 350 gpm to wells. The transmissivity ranges from 170 to 2,100 gpd/ft, and the water quality is similar to the Fox Hills Sandstone. The Lance Formation also is used for municipal, domestic, and stock water supply.

Fort Union/Wasatch Aquifer System. The Fort Union Formation in the eastern PRB ranges in thickness from 1,100 to 2,270 feet and is a coal-bearing sandstone with interbedded siltstone and shale. Flowing wells can have yields of up to 60 gpm from confined units in the Fort Union, and pumped wells produce up to 250 gpm with several hundred feet of drawddown. Transmissivity ranges up to 5,000 gpd/ft. The water quality can be quite variable with TDS ranging up to 8,000 mg/L and the water being dominated by sodium bicarbonate with SAR values ranging from 5.7 to 12.0. The Fort Union is used for municipal, domestic, and stock water supply. Approximately fourteen municipal and public water supply systems in the eastern PRB, including the City of Gillette and adjacent water districts, use the Fort Union for water supply (HKM Engineering et al. 2002b). The overlying Wasatch Formation is mainly sandstone with interbedded shale and coal that ranges up to 1,600 feet in thickness. Well yields are low and generally between 10 to 50 gpm, but can range up to 500 gpm in the southern part of the PRB. The transmissivity ranges up to 4,000 gpd/ft, but averages around 500 gpd/ft. Water quality generally is saline, with TDS values well above 1,000 mg/L and water quality varying from sodium bicarbonate to sodium sulfate. Locally, it is used for domestic and stock water supply and for public water supply for small communities. It is used most commonly for water supply in the southern part of the PRB.

Quaternary Alluvial Aquifer System. Quaternary alluvium can be found along major stream channels in terraces and as alluvial fill in the channels. The thickness ranges up to 100 feet, but is usually less than 50 feet in most areas. Coarse deposits with available water are found along the valleys of the Belle Fourche and Cheyenne rivers and their major tributaries. Well yields up to 1,000 gpm are possible. The transmissivity is highly variable, because of the clay content of the alluvium and can range from 15 to 64,000 gpd/ft. Water quality is highly variable and TDS ranges from approximately 100 to over 4,000 mg/L. The water generally is saline and suitable mostly for stock water and irrigation. The chemical makeup of the water can range from calcium bicarbonate water in areas of limestone bedrock to calcium sulfate water to sodium bicarbonate water in areas where groundwater from the Fort Union Formation discharges into the alluvium. Quaternary alluvial aquifers are often in hydraulic communication with the underlying bedrock (HKM Engineering et al. 2002b), and thus, the water quality can reflect bedrock water quality. Quaternary alluvial aquifers are used for domestic and municipal water supply as well as irrigation and stock water.

ES.2.3 CBNG Water Production and Discharge

In the PRB study area, CBNG development requires depressurization of the Fort Union coal bed aquifers through dewatering. The effect of this development on water resources is described below.

Most of the permitted CBNG wells in the PRB study area are located in the Upper Belle Fourche, Little Powder, and Upper Powder River drainages. Most of the water production by CBNG operations is found in the Upper Belle Fourche, Upper Cheyenne, Little Powder, Upper Tongue River, and Upper and Middle Powder River drainages (BLM 2003a). CBNG water production as of early 2002 was approximately 257 million barrels per year in the Northeast Wyoming River Basins (Upper Belle Fourche and Upper Cheyenne river basins) and approximately 312 million barrels per year in the Powder/Tongue River Basin (Upper and Middle Powder River, Little Powder River, and Upper Tongue River) (Wyoming Oil and Gas Conservation Commission 2005).

Groundwater produced by CBNG wells is often discharged directly to the surface in Wyoming without treatment. In the Powder/Tongue River Basin, this water generally is high in sodium bicarbonate, has TDS values well over 1,000 mg/L, and has a SAR greater than 8, making the water unsuitable for some agricultural uses in Wyoming. The water quality in the coal bed aquifers varies with location and depth in the Wyoming PRB. Groundwater quality in the northwestern part of the PRB is highly variable and generally high in TDS, sodium, calcium, sulfate, and bicarbonate. Groundwater pumped by CBNG wells in the eastern PRB, especially in the Belle Fourche and Cheyenne River basins, is generally low in TDS and low in sodium, allowing for direct discharge to ephemeral drainages (BLM 2003a).

As of early 2002, there were approximately 3,565 permitted CBNG outfalls for water discharge in the PRB. Approximately 43 percent of these outfalls are in the Upper Belle Fourche and Cheyenne River basins, approximately 21 percent are in the Upper Powder River drainage, and approximately 16 percent are in the Little Powder River drainage. This distribution places approximately half of the outfalls in the Powder/Tongue River Basin and approximately half in the Northeast Wyoming River Basins. Discharge at these outfalls ranges from 1 to approximately 25 gpm (BLM 2003a).

In the Belle Fourche and Cheyenne River basins, the discharge of CBNG-produced water directly to ephemeral and intermittent drainages is allowed. This water comes from shallow coal units and generally is low enough in TDS and SAR to be acceptable for direct surface discharge. Studies conducted by the BLM (2003a) have shown that conveyance losses for direct discharge to drainages are approximately 70 to 90 percent, depending on the time of year. Evaporation losses, which are a large component of conveyance losses, can be 80 percent during the summer months in Wyoming. Thus, most CBNG discharge water either infiltrates or evaporates within a few miles of the discharge outfall and generally is not recorded at USGS stream gauging stations. As a result, impacts to surface water flow and quality are limited to within a few miles of the discharge outfall and, as of 2002, have not been recorded by the network of USGS gauging stations.

In the northwestern part of the PRB, especially in the Powder/Tongue River Basin, discharge of CBNG water directly to drainages may not be permitted (BLM 2003a). Indirect discharge of CBNG-produced water involves impoundments similar to stock ponds. These impoundments are unlined and allow the CBNG discharge water to infiltrate into the shallow unsaturated alluvium. Impoundments can have in-channel or off-channel locations and WDEQ regulations differ depending on the location of the impoundment. Impoundments must have monitoring wells to evaluate impacts to alluvial groundwater if the initial groundwater investigation demonstrates that depth to groundwater is less than 150 feet (200 feet if the impoundment is greater than 50 acre-feet in size), and if the groundwater is Class III or better in quality (TDS less than 10,000 mg/L). These requirements apply to both in-channel and off-channel impoundments. Impoundments located within drainages (in-channel impoundments) may have discharge pipes to allow for some water to flow down the drainage in response to storm events. The Wyoming State Engineer's Office regulates the design of in-channel impoundments to ensure water rights are protected. The WDEQ regulates discharges into surface impoundments. Off-channel impoundments must be at least 500 feet from a drainage. The BLM is involved in regulating impoundments as a result of its permitting process for CBNG wells when federal land or federal mineral rights are involved. The WOGCC regulates the construction of impoundments on private and state lands.

Studies of the potential impacts to surface and groundwater quality from infiltration of CBNG water currently are underway by the BLM and private research groups funded by CBNG operators. The results to date are incomplete and very preliminary in nature. In the Bone Pile Creek area of the Upper Belle Fourche drainage, studies by the BLM (2003a) have shown that infiltration of CBNG water does not alter groundwater quality and that infiltration extends downward through the alluvium and into the Upper Wasatch Formation aquifer. At Burger Draw, which is in the Upper Powder River drainage, studies by the BLM (2003a) are ongoing. However, preliminary data suggest mounding of water in the unsaturated alluvium within approximately 15 to 25 feet of the impoundment and reaction between the CBNG water and minerals in the alluvium that increase TDS and other constituents. Infiltration extends to the Upper Wasatch Formation. At Brown Reservoir (Township 44 North, Range 76 West), similar studies found mounding within 15 feet of the impoundment and a water level rise of 10 feet, but no impacts to ephemeral drainages (BLM 2003a).

ES.2.4 Coal Mine Development Effects on Water Resources

Water pumped for dewatering of coal beds by the coal mines of the eastern PRB is: 1) used in the processing of coal; 2) used for dust control or reclamation; or 3) disposed of to ephemeral and intermittent drainages through Wyoming Pollution Discharge Elimination System permits issued by the WDEQ. The exact volume of water used by coal mines each year is not known for each mine, because mines often do not use their entire permitted water consumption volume each year. However, per existing permits in 2002, a total of 7,460 acre-feet of groundwater for consumptive use was allocated to the coal mines of the eastern PRB (Wyoming State Engineer's Office 2004). Most mines pumped between 300 and 920 acre-feet of groundwater in 2002. Groundwater use by the coal mines may be decreasing from a peak period from 1996 to 1998. This may be due to dewatering of the coal beds by CBNG wells, which increased substantially after 1995.

Water discharged by the coal mines to ephemeral and intermittent drainages is regulated by the WDEQ. Water cannot be discharged to a drainage if it substantially would alter the water quality of the drainage or produce flows that result in erosion to the banks and beds of the streams. Thus, discharge of excess water by the coal mines in accordance with permit criteria should have little or no measurable effect on drainages. Storm water runoff from the coal mines also is regulated and must be diverted to detention ponds to allow for settling of sediment. Storm water that does not infiltrate into the alluvial sands and clays while held in the detention ponds can be allowed to flow into the drainages once most of the sediment has settled.

When coal mines are reclaimed, the overburden is returned to the mined-out portion of the pit as spoils, and the mined area is reclaimed to conditions similar to original conditions for slope and drainage. In the Wyoming PRB, the spoils material gradually resaturates with water as groundwater from the Wasatch Aquifer and the Fort Union coal bed aquifers enters the spoils material. Spoils can take anywhere from 50 to 200 years to resaturate (GAGMO 2001). The water quality in the resaturated spoils usually is high in TDS, sulfate, sodium, and other metals and anions. Monitor wells in spoils from coal mines along the eastern PRB typically have a pH between 6.0 and 7.8, TDS in the range of 1,000 to 4,000 mg/L, bicarbonate values ranging from 500 to 1,300 mg/L, sodium in the range of 200 to 800 mg/L, high sulfate values ranging from 1,000 to 3,500 mg/L, and SAR values in the range of 2.0 to 7.0 (GAGMO 2001). Over time, the spoils are flushed by groundwater flowing through the reclaimed material and downgradient to the northwest in the Wasatch and Fort Union aquifers. Thus, the water quality in the spoils improves over time and becomes similar to that found in these aquifers near the coal mines. The time to flush spoils and improve the water quality varies considerably, based on the permeability of the spoils and groundwater flow rates in the aquifers. Based on an evaluation of coal mines near Gillette, Martin et al. (1988) estimated the time required to flush water from spoils can vary from a few tens to a few hundreds of years.

The coal mines in the study area often mine through ephemeral and intermittent drainages. Drainages as high as third- and fourth-order drainages can be removed by mining. During reclamation, the third-order and higher drainages must be restored. First- and second-order drainages are often not replaced (Martin et al. 1988). Studies summarized by the USGS showed that reclaimed coal mine areas have: 1) a lower infiltration rate for precipitation in the reclaimed areas compared to original natural areas, and 2) sediment loading to drainages during heavy storms that is considerably higher for reclaimed areas compared to the original natural areas. The USGS study found that the percentage of drainages disturbed by coal mining varied from 4 to 26 percent, the increase in runoff for reclaimed areas varied from 0.8 to 7.6 percent, and the increase in sediment erosion averaged approximately 436 percent. The decrease in infiltration rate was approximately 29 percent. The TDS increase in stream waters near reclaimed coal mines ranged from 1 to 7 percent higher than before reclamation (Martin et al. 1988). Thus, the potential impacts of coal mines to surface water features are dependent more on the changes in slope, infiltration capacity, and runoff characteristics of reclaimed areas than on the process of coal mining and disposal of water by coal mines. Over time, reclaimed areas become similar to the original natural areas in terms of soil properties, vegetation, and runoff characteristics; however, this may take a few centuries in the semiarid climate of the PRB.

Groundwater drawdown near the coal mines of the eastern PRB is the result of coal mine dewatering and CBNG depressurization of the coal beds. The drawdown effects for 2002 were modeled for this study as discussed in Section ES.3.

ES.3 GROUNDWATER MODELING

ES.3.1 Groundwater Modeling Protocol and Model Calibration

For purposes of this study, a numerical groundwater flow model was developed for the area of active coal mining in the eastern portion of the PRB study area. The area modeled extended from the coal mines north of Gillette, Wyoming, to the southern extent of coal mining near Wright, Wyoming. The purpose of the Coal Mine Groundwater Model (CMGM) was to provide a tool for estimating the combined impacts on groundwater as a result of coal mining and CBNG development in the eastern portion of the PRB.

As the CMGM is a submodel of the regional PRB model developed for the PRB Oil and Gas Environmental Impact Statement (EIS) (BLM 2003a), modifications to the regional model were required to narrow the focus of the model domain. The regional PRB model was modified in accordance with the CMGM protocol (ENSR and Environmental Solutions, Inc. 2005) which specifies the design and execution parameters. MODFLOW 2000 was chosen as the modeling code, and the modeling platform Groundwater Vistas was chosen for running the model. **Table ES.3.1-1** summarizes the stratigraphy and hydrostratigraphy of the eastern PRB that was used in the CMGM.

Table ES.3.1-1
Regional Model Layers[1]

PRB EIS Regional Model Layer	Geologic Formation	Coal Unit Designation	Geologic Unit	Predominant Lithologies	CMGM HSU
1	Wasatch Formation	--	Upper Wasatch Formation and alluvium	Sandstone, siltstone, claystone	1
2	Wasatch Formation	--	Shallow Wasatch sands	Sandstone, siltstone	1
3	Wasatch Formation	--	Confining unit within Wasatch Formation	Siltstone, claystone	2
4	Wasatch Formation	--	Intermediate Wasatch sands	Sandstone, siltstone	2
5	Wasatch Formation	--	Confining unit within Wasatch Formation	Siltstone, claystone	2
6	Wasatch Formation	--	Deep Wasatch sands	Sandstone, siltstone	3
7	Confining Layer	--	Confining unit at base of Wasatch Formation. Low-permeability clay layer separating Wasatch and Fort Union.	Siltstone, claystone, clay	4
8	Upper Fort Union	Wyodak-Anderson coal as defined by the USGS	Upper Fort Union coal (Unit 1) – Anderson Coal of Goolsby	Coal (minor sandstone, siltstone)	5
9	Upper Fort Union		Confining unit between coal units	Siltstone, claystone	5
10	Upper Fort Union	Wyodak-Anderson coal as defined by the USGS	Upper Fort Union coal (Unit 2) – Canyon Coal of Goolsby	Coal (minor sandstone, siltstone)	5
11	Upper Fort Union		Confining unit between coal units	Siltstone, claystone	5
12	Upper Fort Union	Wyodak-Anderson coal as defined by the USGS	Upper Fort Union coal (Unit 3) – Wall Coal of Goolsby	Coal (minor standstone, siltstone)	5
13	Upper Fort Union		Confining unit between coal units	Siltstone, claystone	5
14	Upper Fort Union	Wyodak-Anderson coal as defined by the USGS	Upper Fort Union coal (Unit 4) – Wyodak Coal of Goolsby	Coal (minor sandstone, siltstone)	5
15	Upper Fort Union	--	Confining unit at base of coal units	Siltstone, claystone	5
16	Lower Fort Union	--	Lebo Shale	Sandstone, siltstone, claystone	6
17	Fort Union Formation	--	Tullock Formation	Sandstone, siltstone	6

[1]PRB Oil and Gas EIS (BLM 2003a) groundwater model stratigraphy compared to CMGM stratigraphy.

The CMGM was first calibrated to steady-state conditions for 1975 and then for transient conditions from 1990 to 2002. The final calibration was to 2002 water level data from approximately 350 coal mine groundwater monitoring wells reported in GAGMO annual reports, from approximately 70 Wasatch Formation monitoring wells available in WDEQ/LQD mine permit files, and both USGS and BLM monitoring wells in the region. The calibration was checked by using the 2002 calibrated model for transient calibration to 2003 water levels in 18 selected well hydrographs for monitoring wells near the coal mines. The 2002 calibration statistics were within the requirements specified in the modeling protocol with the mean, absolute mean, and standard deviation all within 10 percent when these values are divided by the range in water levels for the model in 2002.

ES.3.2 Groundwater Modeling Results

The CMGM results for both the Wasatch and Upper Fort Union formations in the eastern PRB provide information on 1990 and 2002 groundwater elevations, coal mine-related groundwater drawdown for 2002, CBNG-related groundwater drawdown and mounding for 2002, and the combined effects of coal mine dewatering and CBNG development on groundwater levels in 2002. The model results are discussed below.

ES.3.2.1 Wasatch Formation

The Wasatch Formation is not a true aquifer. Groundwater in the Wasatch is found mainly in the thicker permeable sand units and does not form a continuous aquifer, because the sand units themselves are generally discontinuous and often not hydraulically interconnected. However, a groundwater model must treat the Wasatch as a continuous regional aquifer in order to calculate water levels and estimate drawdowns due to groundwater withdrawal. Consequently, a groundwater model of the Wasatch generates water levels and groundwater drawdown contours that are approximate only and not representative of water levels or aquifer behavior in any specific part of the Wasatch. Conversely, the Fort Union Formation is a true regional aquifer. Therefore, comparison of water levels and drawdowns in the Wasatch with those in the Fort Union must be made with caution.

Groundwater levels in the Wasatch Formation for 1990 reflect a period before the beginning of CBNG pumping and a period when the coal mines were beginning to increase dewatering of their mines to facilitate increased coal mining. Modeled groundwater elevations decrease from south to north across the model domain, with groundwater levels in the south near the southern group of coal mines (Subregion 3) around 4,700 to 4,850 feet above mean sea level (amsl) and groundwater elevations near the northern group of coal mines (Subregion 1) at approximately 4,200 to 4,350 feet amsl. The Belle Fourche River and Antelope Creek act as drains and remove water from the Wasatch Formation locally, as is evident in modeled groundwater level depressions near State Route (SR) 59 for the Belle Fourche and west of SR 59 for Antelope Creek. Groundwater drawdown in the Wasatch is evident around the southern group of mines (Subregion 3). There is a suggestion of a slight groundwater mound west of the central group of coal mines (Subregion 2). The northern group of coal mines (Subregion 1) also show a slight depression in groundwater levels within the mine boundaries.

The modeled groundwater levels for 2002 are similar to those for 1990. Groundwater flows from the southern end of the model domain to the northern end of the model domain, with groundwater levels in the south at approximately 4,700 to 4,850 feet amsl and those in the north around 4,200 to 4,350 feet amsl. As in 1990, the Belle Fourche River and Antelope Creek are removing groundwater from the Wasatch Formation. Groundwater drawdown is evident in the southern group of coal mines (Subregion 3), and to some extent in the central group of mines (Subregion 2) and the northern group of mines (Subregion 1). A groundwater mound west of the central group of mines (Subregion 2) is more pronounced, due mainly to CBNG discharge to the Wasatch.

Based on the modeled coal mine-related groundwater drawdown in the Wasatch Formation for 2002, groundwater drawdown in the southern group of mines (Subregion 3) is localized within or very near the coal mine boundaries and is in the range of 10 to 100 feet. For the central group of mines (Subregion 2), drawdown in the Wasatch also is localized near the mines and ranges from 10 to 50 feet. The 10-foot drawdown contour extends a maximum of approximately 3 to 4 miles to the west of the mines. For the northern group of mines (Subregion 1), the drawdown ranges from 10 to 110 feet, and the 10-foot drawdown contour extends west of the coal mines approximately 7 to 8 miles. Groundwater monitoring data in the northern group of mines is limited, and the extent of the 10-foot drawdown contour may be greater than what is actually present in the model results. Modeling suggests that dewatering of the Wasatch in the northern group of mines (Subregion 1) has impacts that extend beyond the mine boundaries; however, in the central and southern mine groups (Subregions 2 and 3, respectively), dewatering impacts to the Wasatch are localized in the vicinity of the mine boundaries.

Modeled groundwater impacts in the Wasatch Formation as a result of CBNG pumping and discharge show groundwater mounding (indicating a rise in groundwater levels since 1990) due to CBNG discharge. The mounding is most evident between Wright and the central group of coal mines (Subregion 2). Mounding is in the range of 10 to 20 feet, with locally high mounding up to 50 feet near the mine boundaries. West of the northern group of mines (Subregion 1), mounding in the Wasatch is in the range of 10 to 50 feet. Mounding in the Wasatch west of the southern group of mines (Subregion 3) is approximately 10 feet.

The modeled sum of groundwater impacts to the Wasatch due to CBNG pumping and discharge and coal mine dewatering shows a drawdown in the range of 10 to 70 feet for the southern group of mines (Subregion 3). For the central group of coal mines (Subregion 2), the total effect resulted in mounding of approximately 20 feet to the west of the coal mines in the CBNG fields and drawdown of 10 to 40 feet within the mine boundaries. For the northern group of mines (Subregion 1), the total effect primarily resulted in drawdown of 10 to 100 feet within or close to the mine boundaries. The Gillette area municipal wells also affect the Wasatch and, per the modeling results, create a drawdown of approximately 10 to 20 feet southeast of Gillette. Thus, for the Wasatch beyond the mine boundaries, the mounding associated with CBNG discharge offsets the drawdown associated with mine dewatering of the Wasatch. Within the mine boundaries, dewatering of the Wasatch by the mines has resulted in drawdown of water levels since 1990.

ES.3.2.2 Upper Fort Union Formation

Based on modeled groundwater elevations in the Upper Fort Union for 1990, groundwater generally flows from south to north across the model domain, with groundwater levels in the south at approximately 4,700 to 4,900 feet amsl and those in the north at approximately 4,100 to 4,250 feet amsl. For the southern group of coal mines (Subregion 3), there is a suggestion of groundwater mounding around and to the west of the mines, with groundwater drawdown within the mine boundaries. The mounding may be an artifact of the drawdown caused by dewatering within the mines. The same pattern, only on a more reduced scale, is found in the central group of mines (Subregion 2). For the northern group of mines (Subregion 1), there is minor groundwater drawdown within the mine boundaries. The drawdown estimates for the northern group of mines is affected by the lack of useable monitoring well data. Many monitoring wells are dry or affected by natural gas, and thus were not used in the modeling. As a result, drawdowns in the Upper Fort

Union for 2002 may be greater than estimated. West of SR 59 near the southern group of mines (Subregion 3), there is a westward bulge in the groundwater contours. This bulge is due to two monitoring wells that have water levels that are not consistent with other monitoring wells in the area. These monitoring wells may be screened differently than other wells, or be affected by a nearby pumping well. Along the southern boundary of the model domain, there is a steep groundwater gradient that is a result of boundary conditions preserved from the original PRB Oil and Gas EIS (BLM 2003) regional groundwater model. This steep groundwater gradient in the Upper Fort Union is an artifact of model design and not a true reflection of groundwater levels. It does not propagate through the model and affect model results.

Based on the modeled groundwater levels in the Upper Fort Union for 2002, there is a complex pattern of drawdown west of the southern group of mines (Subregion 3) that probably is due to the combined effect of coal mine dewatering and CBNG pumping. In the vicinity of the central group of mines (Subregion 2), groundwater drawdown west of the mines due to CBNG pumping is evident. The area near the northern group of mines (Subregion 1) does not show the effect of CBNG pumping in the 2002 groundwater levels. The sharp groundwater gradient in the Upper Fort Union along the southern model boundary is due to retention of model boundary conditions from the original PRB Oil and Gas EIS (BLM 2003) regional groundwater model, and not a reflection of true groundwater levels.

The modeled coal mine-related drawdown in the Upper Fort Union shows that drawdown due to coal mine dewatering primarily is limited to the mine boundaries. In the southern group of mines (Subregion 3), the drawdown ranges from 20 to 180 feet, with the 20-foot drawdown contour extending up to approximately 4 miles west of the mines. For the central and northern groups of mines (Subregions 2 and 1, respectively), drawdown in the Upper Fort Union is limited to the mine boundaries.

Modeled groundwater drawdown in the Upper Fort Union due to CBNG pumping is very pronounced, especially around Wright, Wyoming. For the area west and northwest of the southern group of coal mines (Subregion 3), CBNG-related drawdown is up to 300 feet. Near the central group of coal mines (Subregion 2), CBNG-related drawdown is in the range of 60 to 300 feet and is localized west of the coal mines. Near the northern group of mines (Subregion 1), CBNG-related drawdown is approximately 40 feet and is found in small localized areas to the west of the mines.

Based on the model results, the combined effect of CBNG pumping and coal mine dewatering on the Upper Fort Union is very similar to the effects of CBNG pumping alone, as CBNG pumping greatly dominates that of coal mine dewatering. West of the southern group of mines (Subregion 3), drawdowns of up to 400 feet are observed. Groundwater drawdown within mine boundaries is approximately 20 to 200 feet. For the central group of mines (Subregion 2), groundwater drawdown west of the coal mines is up to 400 feet in areas of CBNG pumping. Within the mine boundaries, groundwater drawdown is approximately 20 to 100 feet. Near the northern group of mines (Subregion 1), the drawdown is approximately 20 to 80 feet. Drawdown in the Upper Fort Union near the Gillette municipal well fields is approximately 20 to 40 feet.

ACRONYMS AND ABBREVIATIONS

°C	degrees centigrade
µg/L	micrograms per liter
µS/cm	microSiemens per centimeter
AHA	Applied Hydrology Consultants
amsl	above mean sea level
APD	Application for Permit to Drill
ASTM	American Society for Testing and Materials
BLM	Bureau of Land Management
CBNG	coal bed natural gas
cfs	cubic feet per second
CHD	Time-varying Specified Head Package
CHIA	Cumulative Hydrologic Impact Assessment
CMGM	Coal Mine Groundwater Model
EA	Environmental Assessment
EC	electrical conductivity
EIS	Environmental Impact Statement
ENSR	ENSR Corporation
ESI	Environmental Simulations, Inc.
FS	U.S. Forest Service
ft/day	feet per day
GAGMO	Gillette Area Groundwater Monitoring Organization
gpcpd	gallons per capita per day
gpd/ft	gallons per day per foot
gpd/ft^2	gallons per day per square foot
gpm	gallons per minute
gpm/ft	gallons per minute per foot
HSU	hydrostratigraphic unit
Kx	horizontal hydraulic conductivity
Ky	vertical hydraulic conductivity
LBA	lease by application
LQD	Land Quality Division
m/d	meters per day
mg/L	milligrams per liter
mmtons	million tons
MWH	Montgomery Watson Harza
NEPA	National Environmental Policy Act
PRB	Powder River Basin
PRRCT	Power River Regional Coal Team
SAR	Sodium adsorption ratio
TBNG	Thunder Basin National Grasslands
TDS	total dissolved solids
TMR	Telescopic Mesh Refinement
U.S.	United States
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WDEQ	Wyoming Department of Environmental Quality
WOGCC	Wyoming Oil and Gas Conservation Commission
WSEO	Wyoming State Engineer’s Office
WYPDES	Wyoming Pollution Discharge Elimination System

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1.0 INTRODUCTION

The Powder River Basin (PRB) of Wyoming is a major energy development area with diverse environmental values. The PRB is the largest coal-producing region in the United States (U.S.); PRB coal is used to generate electricity within and outside of the region. The PRB also has produced large amounts of oil and gas resources. Within the last decade, this region has experienced nationally significant development of natural gas from coal seams.

For the purpose of this study, the Wyoming PRB study area (**Figure 1-1**) comprises all of Campbell County, all of Sheridan and Johnson counties less the Bighorn National Forest lands to the west of the PRB, and the northern portion of Converse County. It includes all of the area administered by the Bureau of Land Management (BLM) Buffalo Field Office, a portion of the area administered by the BLM Casper Field Office, and a portion of the Thunder Basin National Grasslands (TBNG), which is administered by the U.S. Forest Service (FS) (**Figure 1-2**). State and private lands also are included in the study area. For water resources, the existing conditions are presented for the Powder River Structural Basin (also referred to as the Powder River Physiographic Basin), which includes the Powder/Tongue River Basin and Northeast Wyoming River Basins planning areas (**Figure 1-3**). The detailed study area encompasses the groundwater model domain (**Figure 1-1**), with emphasis placed on the overlap in the coal mine- and coal bed natural gas (CBNG)-related groundwater drawdown area.

During the 1970s and early 1980s, the PRB emerged as a major coal production region. Federal coal leasing was a high profile activity as over 90 percent of the PRB's coal is federally owned. Between 1974 and 1982, the BLM issued three and started a fourth separate regional coal environmental impact statement (EIS), all addressing federal coal leasing and development, as well as other regional development.

In 1982, the BLM temporarily halted further coal leasing. However, mining continued on existing leases. When leasing resumed in 1990, the existing mines were mature operations, and there was no need for regional leasing to open new mines. However, many of the mines were depleting their original reserves, so there was a need for maintenance leasing to provide reserves to enable existing mines to meet the expanding demand. The Powder River Regional Coal Team (PRRCT) decertified the region, allowing BLM to use the lease by application (LBA) process to meet this need. Each LBA required an EIS or environmental assessment (EA) as part of the leasing process.

Starting with the first LBAs, the BLM met the need for cumulative analysis in each EIS or EA with a discrete chapter addressing cumulative impacts. This approach served to highlight and focus cumulative impacts as distinct from site-specific impacts. With each subsequent EIS, the cumulative analysis was updated and new information added. In the mid-1990s, the BLM conducted a study called the PRB Coal Development Status Check to evaluate how actual development levels compared to the development levels predicted in the earlier regional EISs. The results of this study were presented to the PRRCT in 1996. Then, in the late 1990s, annual coal production and associated impacts drew closer to the maximum projections in the regional EISs. Furthermore, the large scale oil and gas development associated with coal bed natural gas (CBNG) development had not been foreseen in those EISs.

For the most recent LBAs, the BLM used the cumulative analysis from the Wyodak EIS (BLM 2000b) and PRB Oil and Gas EIS (BLM 2003a), particularly for air and water resources. Both EISs projected regional development including CBNG activity. They both used market demand projections to estimate future levels of coal development.

In early 2003, BLM completed a study of PRB coal demand through 2020 (Montgomery Watson Harza 2003). The study projected production to increase at a steady pace with current mines able to meet the demand as long as the existing mines continue to have access to additional coal reserves; therefore, the need for leasing using LBAs will continue into the foreseeable future. As part of processing these LBAs, BLM will need to maintain a current cumulative impact analysis. An initial step in that direction is this PRB Coal Review, which includes the identification of current conditions in the PRB.

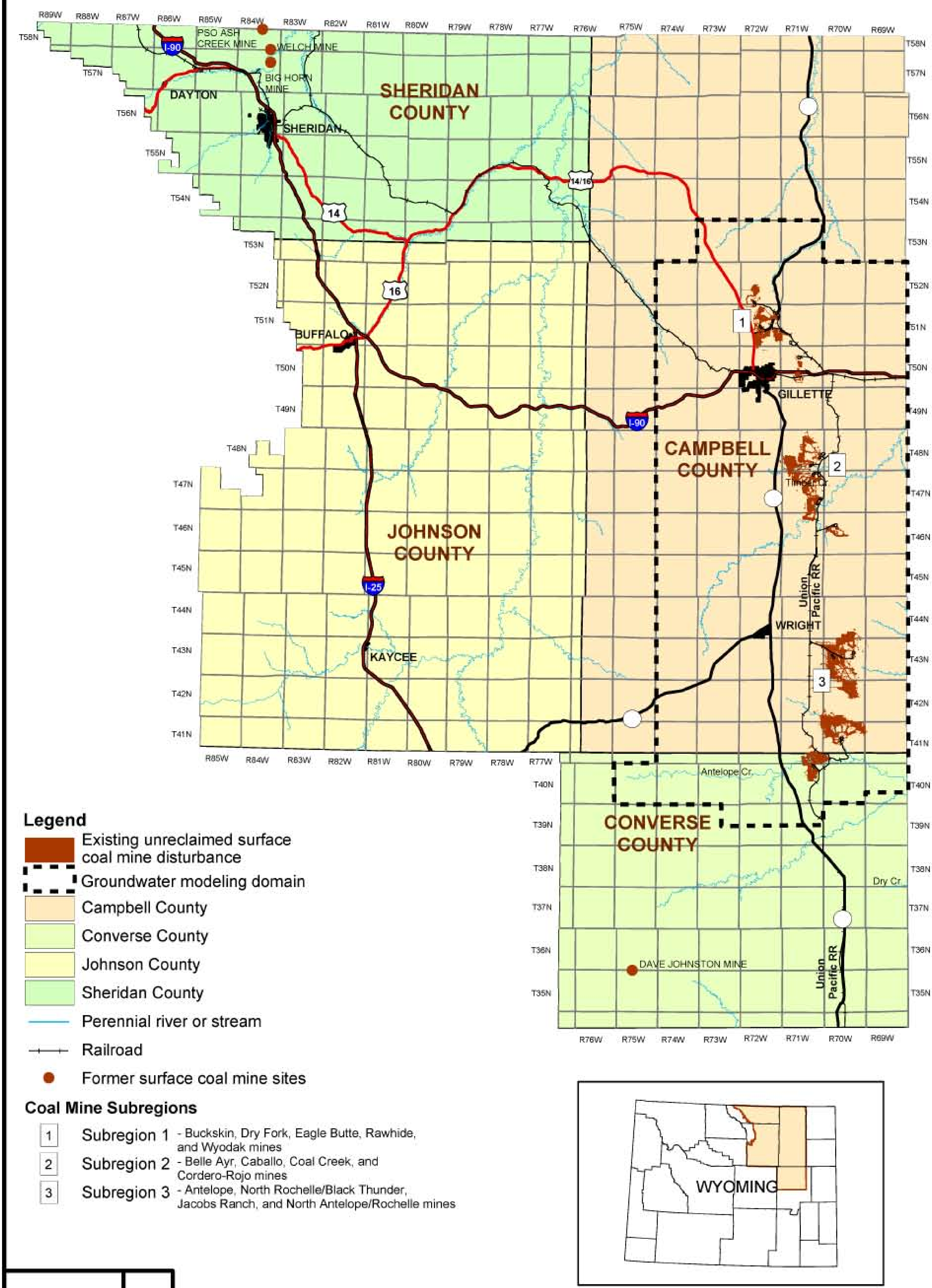
1.1 Objectives

This PRB Coal Review is a regional technical study to assess cumulative impacts associated with past, present, and reasonably foreseeable development in the PRB. The PRB Coal Review:

- Describes past and present (through 2002 for water) development activities in the PRB that have affected the environmental conditions in the study area;
- Describes the current (through 2002 for water, based on data availability) environmental conditions in the study area and compares these conditions to the conditions projected in the BLM's Coal Development Status Check (BLM 1996);
- Estimates reasonably foreseeable development in the study area through the year 2020, based on available information; and
- Estimates the environmental impacts associated with reasonably foreseeable future development through the year 2020.

The PRB Coal Review will provide data, models, and projections to facilitate cumulative analyses for future agency land use planning efforts and for future project-specific impact assessments for project development in compliance with the National Environmental Policy Act (NEPA). It should be noted that the PRB Coal Review itself is not a NEPA document. It is not a policy study, nor is it an analysis of regulatory actions or the impacts of project-specific development.

This report summarizes Task 1B of the PRB Coal Review, a description of the current (2002) water resource conditions associated with past and present coal development and other development in the PRB. The PRB Coal Review Task 1 descriptions for air quality, social and economic values, and other environmental resources are presented in separate stand-alone reports.



Powder River Basin Coal Review

Figure 1-1

Study Area

Source: BLM 2003a, 2004a; Thunder Basin Coal Company 2003.

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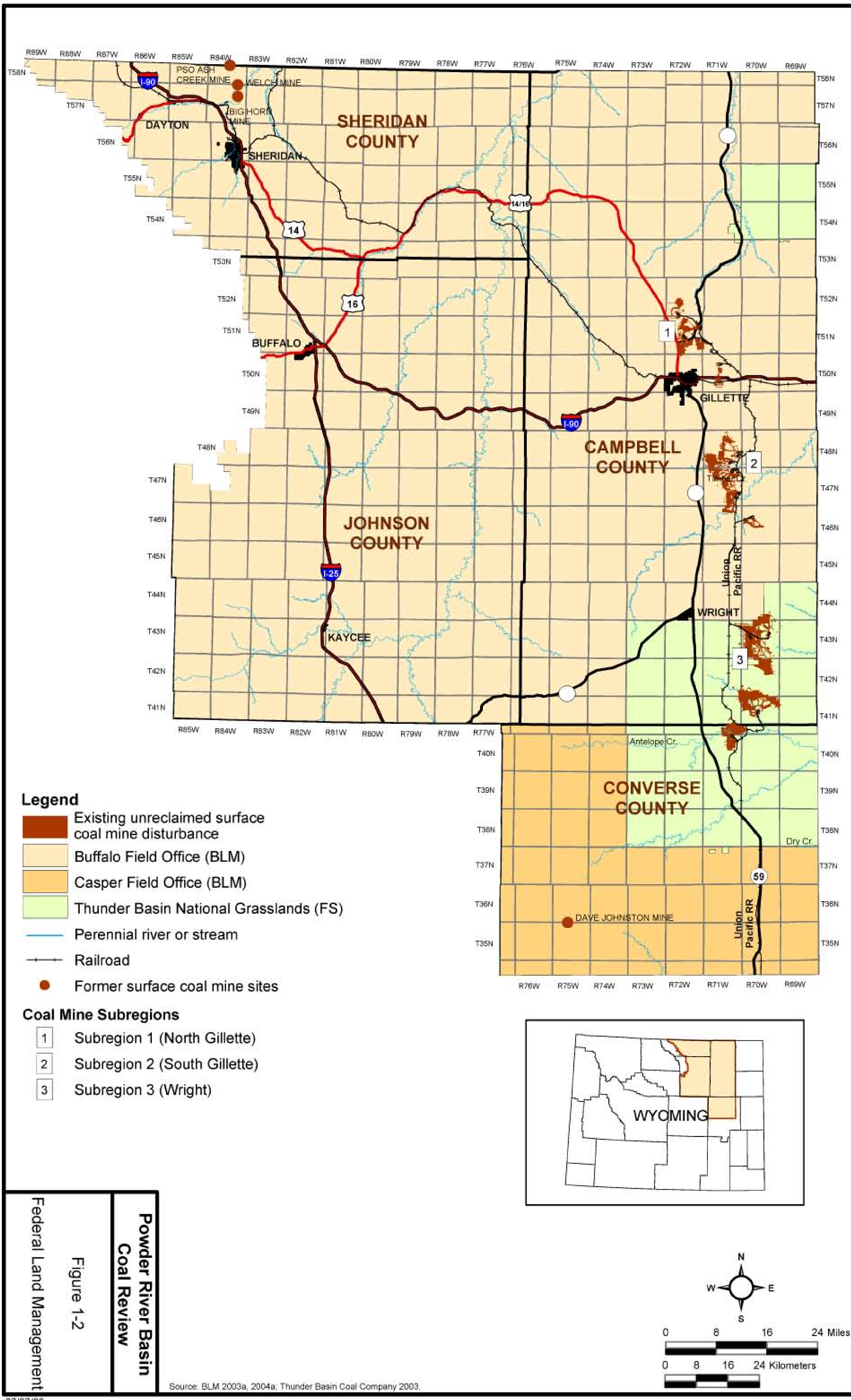

Powder River Basin Coal Review

Figure 1-2

Federal Land Management

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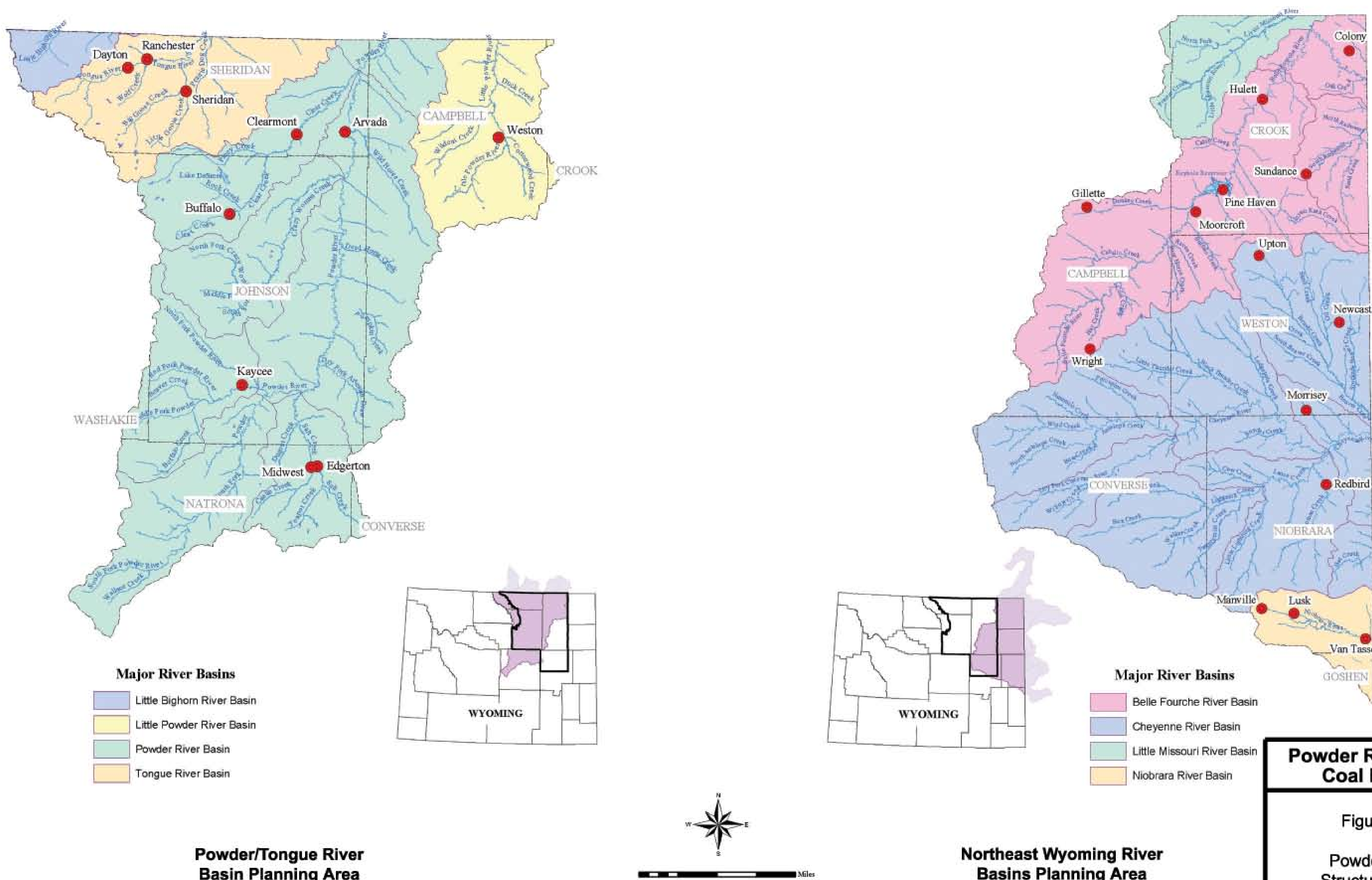


Source: HKM Engineering et al. 2002a,b.

Powder River Basin Coal Review

Figure 1-3

Powder River Structural Basin

07/27/05

1.2 Key Issues

The key issues related to water resources include:

- Potential impacts to groundwater levels in the Fort Union and Wasatch formations due to continued coal mine expansion and CBNG development.

- Potential impacts to surface water resources from coal mine- and CBNG-related water discharge.

1.3 Agency Outreach, Coordination, and Review

The BLM directed the preparation of this PRB Coal Review. In order to ensure the technical credibility of the data, projections, interpretations, and conclusions of the study and ensure the study's usefulness for other agencies' needs, the BLM initiated contact with other federal and state agencies early in the study. This contact included meetings, periodic briefings, and written communications.

The BLM conducted an agency outreach program to solicit input from other agencies relative to their:

- Interested role and level of involvement in the study;
- Available data for use in the study; and
- Technical areas in which the agency would like to participate or review deliverables.

As part of this agency outreach and technical oversight, the BLM organized technical advisory groups for air quality, water resources, and socioeconomics. These groups were composed of agency representatives with technical expertise in the applicable resource(s). The PRB Water Resources Advisory Team has been actively involved in review of data and the PRB Coal Mine Groundwater Model (CMGM) protocol, development, and calibration.

2.0 TECHNICAL APPROACH

The technical approach for surface and groundwater resources consisted of three main components:

- Obtaining current (year 2002) and past water data for the CBNG and coal mining operations in the Wyoming PRB study area
- Defining the existing (year 2002) surface water and groundwater resources conditions based on existing regional reports
- Developing a calibrated numerical groundwater flow model for the eastern PRB for use in defining existing (year 2002) conditions (Task 1B) and for the assessment of potential impacts through year 2020 (Task 3B)

2.1 Data Collection

Data collection for water resources relied on existing published compilations of data for the PRB that were readily available to the public. The PRB Oil and Gas EIS (BLM 2003a), publications by Wyoming state agencies, data provided by the BLM, and water resource publications by the U.S. Geological Survey (USGS) were used.

2.1.1 Groundwater

Data on groundwater levels and groundwater quality were obtained primarily from various water resources and geological publications prepared by the USGS. These publications are referenced in the appropriate sections of this report, where the data are presented. Additional data on groundwater levels came from the BLM monitoring well files and from the annual reports of the Gillette Area Groundwater Monitoring Organization (GAGMO), as well as Wyoming Department of Environmental Quality (WDEQ)/Land Quality Division (LQD) mine permit files for monitoring well data in the Wasatch Formation near the coal mines.

2.1.2 Surface Water

Surface water data primarily came from the detailed basin studies available from the Wyoming Water Development Commission. Two principal studies included the Powder/Tongue River Basin Study (HKM Engineering et al. 2002a) and the Northeast Wyoming River Basins Study (HKM Engineering et al. 2002b).

3.0 WATER RESOURCES OF THE WYOMING POWDER RIVER BASIN

3.1 Introduction

The Powder River structural basin of Wyoming, often referred to as the PRB, encompasses five major drainages. The drainages in the northern part of the basin include the Powder River, Tongue River, and Little Powder River. In the central and southern parts of the basin, the major drainages are the Belle Fourche and Cheyenne rivers. Surface water flows to the north into Montana in the northern part of the basin and to the east-northeast into South Dakota in the southern and central parts of the basin. Regional groundwater flow in Tertiary-age formations of the basin generally is to the north and into Montana. Thus, water in the Wyoming PRB, especially surface water, is shared to some degree with bordering states. Existing Wyoming water law and water compacts with adjacent states reflect this need to share surface water resources.

Water is one of the critical resources of the PRB. Agriculture in the basin depends primarily on surface water resources and to a lesser degree on groundwater resources, for irrigation. The stock industry in the basin depends on shallow groundwater wells in Tertiary formations and overlying alluvial formations for water. Municipal water is obtained from both surface water reservoirs and groundwater. Domestic water supply mainly comes from shallow groundwater found in Tertiary formations and to a lesser degree from overlying alluvial formations found along major rivers. Industrial use of water mainly is from groundwater. The coal industry of the eastern PRB must dewater the Tertiary coal units prior to removal of the coal. Surface strip mining of coal also requires the removal or realignment of drainages. The recently developed CBNG industry also must dewater Tertiary coal-bearing units in order to free the methane gas from the coal. Industrial use of groundwater in the basin thus competes with municipal, domestic, and to some degree with agricultural use of water resources. This competing demand for water in the basin has become a political issue for Wyoming over the past 10 years.

The discussion of water resources in the PRB focuses on two main issues: 1) current water use in the basin and 2) industrial use of water resources by the coal mine and CBNG industries. The discussion of water resources also serves to update the water resources section of the Coal Development Status Check (BLM 1996) by comparing current (year 2002) water use by the coal mine and CBNG industries to what was predicted in past BLM EAs and EISs and by the USGS cumulative assessment (Martin et al. 1988). The discussion of current water use was based on two recently completed state water plans: 1) the Powder/Tongue River Basin Plan (HKM Engineering et al. 2002a) and 2) the Northeast Wyoming River Basins Plan (HKM Engineering et al. 2002b). Water demand and impacts to water resources by the coal mine industry were based on annual hydrologic reports and Cumulative Hydrologic Impact Assessments (CHIAs) available from WDEQ/LQD and on the annual reports of the GAGMO. Current (2002) water consumption by the CBNG industry was based on production data supplied to the Wyoming Oil and Gas Conservation Commission (WOGCC) and on water quality data available in scientific reports by Wyoming state agencies and the USGS.

3.2 Basin Description

The PRB in Wyoming is a synclinal structural basin bounded on the west by the Big Horn Mountains, on the south by the Laramie Range and the Casper Arch, and on the east by uplifted and tilted beds of Tertiary stratigraphic units and the Black Hills. The basin is open on the north and continues into Montana. The basin is encompassed by two major river basin planning areas in northeastern Wyoming, the Powder/Tongue River Basin and the Northeast Wyoming River Basins. The water resources of the Wyoming PRB are discussed with reference to these two major river basin planning areas in order to be consistent with hydrologic studies and reports prepared by the State of Wyoming.

3.2.1 Powder/Tongue River Basin

The Powder/Tongue River Basin (**Figure 1-3**) covers the northern and northwestern portions of the PRB and includes the drainages of the Little Bighorn, Tongue, Powder, and Little Powder rivers. The Little Bighorn River is not part of the Powder River structural basin. This river basin encompasses all or part of Sheridan, Johnson, Campbell, Natrona, and Converse counties in north-central Wyoming. All of the rivers in the Powder/Tongue River Basin flow north into Montana and eventually into the Yellowstone River. The climate in this part of the basin is semi-arid, with average annual precipitation in the range of 13 to 15 inches. The topography is typical of the high plains with hilly to rugged uplands, wide valleys, and badlands. The Big Horn Mountains rise to approximately 10,000 feet above mean sea level (amsl) on the western side of the basin, and snowmelt in these mountains provides most of the surface water flow for the major drainages.

Significant water features in the Tongue River Basin include the Tongue River, Goose Creek, Big Goose Creek, Little Goose Creek, and Prairie Dog Creek (HKM Engineering et al. 2002a). Storage reservoirs in the Tongue River Basin include Twin Lakes, Big Goose Creek Reservoir, Bighorn Reservoir, and Dome Lake.

Significant streams in the PRB include the Powder River, Little Powder River, Clear Creek, and Crazy Woman Creek. Significant storage facilities include Lake DeSmet, Kearney Lake, Willow Park Reservoir, Cloud Peak Reservoir, and Tie Hack Reservoir in the Clear Creek watershed, Wallows Creek in the drainage of Crazy Woman Creek, Dull Knife Reservoir on the North Fork of the Powder River, and Lower Salt Reservoir on Salt Creek (HKM Engineering et al. 2002a).

Water development and use on the Tongue, Powder, and Little Powder rivers are governed by the Yellowstone River Compact of 1950 (HKM Engineering et al. 2002a). This compact divides the water of the tributaries of the Yellowstone River between Montana and Wyoming. Unappropriated or unused total divertible flow in these three tributaries of the Yellowstone River is allocated to Wyoming and Montana as follows:

- Tongue River: 40 percent to Wyoming, 60 percent to Montana
- Powder River and Little Powder River: 42 percent to Wyoming, 58 percent to Montana

In Wyoming, the constitution establishes water in the state to be the property of the state. Consequently, all development and management of water resources in Wyoming is governed by the state, and water use is administered by the State Engineer and the State Board of Control, which consists of the State Engineer and the Superintendent of each of the four water divisions of the state (HKM Engineering et al. 2002a).

3.2.2 Northeast Wyoming River Basins

The Northeast Wyoming River Basins (**Figure 1-3**) encompass the drainages of the central and southern part of the PRB that are found in the main coal-producing area of the eastern PRB from Gillette, Wyoming, south to the area around Wright, Wyoming. Drainages included in the Northeast Wyoming River Basins are the Little Missouri River, Belle Fourche River, Cheyenne River, and Upper Niobrara River. The Little Missouri and the Upper Niobrara are mostly outside of the Powder River structural basin and do not drain areas of active coal mining. The rivers of the Northeast Wyoming River Basins drain into South Dakota and Nebraska (Upper Niobrara).

The topography is much like that of the Powder/Tongue River Basin, except that the Big Horn Mountains are not present. The Laramie Range bounds the basin on the south, and precipitation typically ranges from 13 to 15 inches per year. The lack of a major mountain range like the Big Horn Mountains means that surface water flow is dependent on precipitation within the basin (HKM Engineering et al. 2002b). Topographic elevations range from 3,500 to 6,000 feet amsl in the plains and from 4,500 feet to 6,000 feet amsl in the Black Hills, which border the basin on the east.

The major drainages that are within the PRB are the Belle Fourche and Cheyenne rivers. Significant tributaries of these two rivers are listed below (HKM Engineering et al. 2002b):

- Belle Fourche River Tributaries: Redwater Creek, Beaver Creek, Caballo Creek, Blacktail Creek, Lytle Creek, Miller Creek, Inyan Kara Creek, Donkey Creek, and Arch Creek

- Cheyenne River Tributaries: Dry Fork Cheyenne River, Antelope Creek, Lightening Creek, Lance Creek, and Beaver Creek

The largest storage facility is the Keyhole Reservoir on the Belle Fourche River northeast of Moorcroft. Other reservoirs include the Gillette Reservoir on Donkey Creek, Stone #2 Reservoir on Bonepile Creek, Betty Reservoir on the South Fork of the Cheyenne River, Spencer Reservoir and M.W. Reservoir on Stockade Beaver Creek, Robbers Roost Reservoir on Robbers Roost Creek, Clark and Metzger Reservoir on Alum Creek, Klodt Reservoir on Mush Creek, and Tract 37 Reservoir on the North Fork of the Little Missouri River (HKM Engineering et al. 2002b). These reservoirs initially were built to support the stock industry that began after 1875 in Wyoming. Additional reservoirs were built for irrigation water supply, and in 1952 the U.S. Bureau of Reclamation constructed the Keyhole Reservoir to provide irrigation water for Wyoming and South Dakota (HKM Engineering et al. 2002b). Irrigation water supply is the main use of these reservoirs today.

Water development is regulated by the same laws and state agencies that regulate water use in the Powder/Tongue River Basin. Water compacts that govern surface water use in the Northeast Wyoming River Basins are the Belle Fourche River Compact of 1943 and the Upper Niobrara River Compact of 1962. The Belle Fourche River Compact recognizes all Wyoming rights existing at the time of the compact and permits Wyoming unlimited use of surface water for stock reservoirs not exceeding 20 acre-feet of capacity. In addition, Wyoming is allowed to use 10 percent of the available flow in the Belle Fourche River in excess of that needed to supply water rights existing at the time of the compact. However, no reservoir in Wyoming constructed after the compact can exceed 1,000 acre-feet of capacity. Reservoirs used for CBNG discharge water are excepted from this rule.

The Upper Niobrara River Compact between Wyoming and Nebraska restricts stock reservoirs to a maximum of 20 acre-feet of capacity. Diversion of surface water in the Upper Niobrara River is regulated. Groundwater development also is regulated by the compact. Compacts for the Cheyenne River and the Little Missouri River have not yet been ratified (HKM Engineering et al. 2002b).

The Belle Fourche River and the Cheyenne River are the major drainages of the eastern PRB coal area. Tributaries to these rivers are the drainages most affected by surface coal mining. North of Gillette, a few of the northern-most coal mines fall within the Little Powder River drainage. CBNG development south of Gillette falls within the Belle Fourche and Cheyenne river drainages. North of Gillette, CBNG development is within the Powder/Tongue River Basin.

3.3 Basin Water Use Profile

Surface and groundwater are utilized extensively throughout the PRB for agricultural water supply, municipal water supply, and both domestic and industrial water supply. Surface water use is limited to major perennial drainages and agricultural areas within the basin found mainly along these drainages. Municipal water supply comes from a combination of surface and groundwater. Domestic and industrial water supply primarily is from groundwater. The Powder/Tongue River Basin receives substantial surface water runoff from the Big Horn Mountains, leading to major agricultural development along drainages in the Tongue River and Powder River basins. Reservoirs are used throughout the basin for agricultural water supply and for municipal water supply in the Powder/Tongue River Basin. The discussion of water use in the PRB is divided into the two major water planning areas of the basin, the Powder/Tongue River Basin and the Northeast Wyoming River Basins. Much of the information that follows was taken from two water plans prepared for the Wyoming Water Development Commission (HKM Engineering et al. 2002a,b).

3.3.1 Powder/Tongue River Basin

The Powder/Tongue River Basin has ample surface water supply as a result of snowmelt and runoff from the Big Horn Mountains. Both the Tongue River and the Powder River derive most of their flow from tributaries that head in the Big Horns. Agricultural development in this area is dependent on surface water flow for irrigation water. Municipal water supply is derived from reservoirs near the Big Horns that trap surface runoff, and from groundwater. Domestic water supply is mainly from groundwater. The summary that follows was taken from a more detailed water plan developed by HKM Engineering et al. (2002a) for the Wyoming Water Development Commission. **Table 3.3-1** summarizes water use in the Powder/Tongue River Basin as of 2002.

3.3.1.1 Agricultural Water Use

Irrigated agricultural lands in the Powder/Tongue River Basin primarily are associated with forage production for the livestock industry. Primary crops are alfalfa, grass hay, and pasture grass. Lesser amounts of small grains and corn also are produced (HKM Engineering et al. 2002a). As of

January 1, 2002, approximately 161,160 acres of land were actively irrigated in the Powder/Tongue River Basin, and the vast majority of these lands were irrigated with surface water. Water depletions for surface water were approximately 194,000 acre-feet for wet years, 184,000 acre-feet for normal years, and 178,000 acre-feet for dry years (see **Table 3.3-2**) (HKM Engineering et al. 2002a). These are estimated depletions and take into account irrigation return flow. The amount of groundwater used for irrigation was approximately 279 acre-feet for wet years and 194 acre-feet for normal and dry years (see **Table 3.3-3**). Agricultural water use in wet years can be higher than in dry years due to more land being in production. The location of agricultural wells is shown in **Figure 3.3-1**. Most agricultural wells, especially stock wells, are screened in the Fort Union Formation.

Table 3.3-1
Water Use as of 2002 in the Powder/Tongue River Basin

	Dry Year		Normal Year		Wet Year	
	(approximate acre-feet per year)					
Water Use	**Surface Water**	**Groundwater**	**Surface Water**	**Groundwater**	**Surface Water**	**Groundwater**
Agricultural	178,000	200	184,000	200	194,000	300
Municipal	2,700	500	2,700	500	2,700	500
Domestic	---	4,400	---	4,400	---	4,400
Industrial[1]	---	68,000	---	68,000	---	68,000
Recreation	Non-consumptive					
Environmental	Non-consumptive					
Evaporation	11,300	---	11,300	---	11,300	---
Total	**192,000**	**73,100**	**198,000**	**73,100**	**208,000**	**73,200**

[1]Includes conventional oil and gas production water and CBNG production water.

Source: HKM Engineering et al. 2002a.

3.3.1.2 Municipal and Domestic Water Use

There are 20 public water supply entities in the Powder/Tongue River Basin consisting of incorporated municipalities, water districts, and privately owned water systems. Two communities obtain water supply from outside the basin. Four of the entities obtain their water supply from surface water and consume approximately 2,700 acre-feet per year (HKM Engineering et al. 2002a). The remaining 16 entities consume approximately 500 acre-feet of groundwater per year. Domestic water use is satisfied by groundwater and totals approximately 2,400 to 4,400 acre-feet per year. **Table 3.3-4** summarizes municipal water use in the Powder/Tongue River Basin. **Figure 3.3-2** shows the location of municipal wells, and **Figure 3.3-3** shows the location of domestic wells. Many of the municipal wells and most of the domestic wells are in the Fort Union Formation.

3.3.1.3 Industrial Water Use

Conventional oil and gas production and CBNG development constitute the industrial water use in the Powder/Tongue River Basin. Both of these industries consume groundwater. The total estimated groundwater consumption is approximately 68,000 acre-feet per year (see **Table 3.3-1**) (HKM Engineering et al. 2002a). Approximately half of this groundwater comes from the Fort Union Formation and is consumed by the CBNG industry. Conventional oil and gas wells consume

Table 3.3-2
Agricultural Surface Water Depletions in the Powder/Tongue River Basin

Source of Water Supply	Climate Stations[1]	Active Irrigation (acres)	Hydrologic Condition	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
				(acre-feet)												
Little Bighorn Basin	Sheridan	1,781	Wet	0	0	0	0	56	370	731	618	206	0	0	0	1,981
			Normal	0	0	0	6	126	421	654	640	216	0	0	0	2,063
			Dry	0	0	0	29	342	402	539	369	162	0	0	0	1,843
Tongue River Basin	Sheridan	62,760	Wet	0	0	0	27	1,994	12,268	24,914	20,365	9,461	2	0	0	69,031
			Normal	0	0	0	189	4,614	15,398	22,463	21,741	6,960	3	0	0	71,368
			Dry	0	0	0	1,049	11,422	14,764	21,219	14,108	5,458	8	0	0	68,028
Upper Clear Creek	Buffalo	39,176	Wet	0	0	0	18	1,606	8,482	15,170	13,276	6,295	4	0	0	44,851
			Normal	0	0	0	148	4,023	11,228	13,811	13,489	5,201	5	0	0	47,905
			Dry	0	0	0	825	6,202	11,096	13,418	9,207	3,755	8	0	0	44,511
Lower Clear Creek	Buffalo and Weston	7,174	Wet	0	0	0	27	329	1,491	2,915	2,443	1,202	3	0	0	8,410
			Normal	0	0	0	56	735	2,065	2,528	2,431	991	4	0	0	8,810
			Dry	0	0	0	203	1,325	1,924	2,488	1,656	713	6	0	0	8,315
Upper Crazy Woman Creek	Buffalo	12,324	Wet	0	0	0	6	506	2,678	4,774	4,160	1,975	1	0	0	14,100
			Normal	0	0	0	47	1,265	3,541	4,346	4,228	1,631	2	0	0	15,060
			Dry	0	0	0	259	1,949	3,498	4,222	2,885	1,178	3	0	0	13,994
Lower Crazy Woman Creek	Buffalo and Weston	1,418	Wet	0	0	0	54	130	278	498	447	213	5	0	0	1,625
			Normal	0	0	0	66	173	326	423	394	173	6	0	0	1,561
			Dry	0	0	0	96	184	302	403	305	138	9	0	0	1,437
Upper Powder River	Kaycee	18,107	Wet	0	0	0	210	2,288	5,307	9,336	8,568	4,331	20	0	0	30,060
			Normal	0	0	0	207	1,085	3,879	5,715	5,910	1,827	27	0	0	18,650
			Dry	0	0	0	551	1,214	4,558	8,036	5,462	2,393	38	0	0	22,252
South Fork Powder River	Kaycee and Midwest	2,103	Wet	0	0	0	5	304	725	1,157	1,028	548	1	0	0	3,768
			Normal	0	0	0	4	25	251	425	567	64	1	0	0	1,337
			Dry	0	0	0	6	7	218	684	457	176	1	0	0	1,549
Lower Powder River	Buffalo and Weston	6,440	Wet	0	0	0	322	779	1,324	2,253	2,045	947	32	0	0	7,702
			Normal	0	0	0	378	747	1,222	1,653	1,527	626	36	0	0	6,189
			Dry	0	0	0	494	548	1,115	1,662	1,298	588	55	0	0	5,760
Little Powder River Basin	Weston	9,873	Wet	0	0	0	655	939	2,339	3,435	3,183	1,611	24	0	0	12,186
			Normal	0	0	0	591	1,119	2,142	3,039	2,763	1,325	21	0	0	11,000
			Dry	0	0	0	580	1,678	1,982	2,814	2,048	825	17	0	0	9,944
Total		**161,156**	**Wet**	**0**	**0**	**0**	**1,324**	**8,930**	**35,261**	**65,181**	**56,131**	**26,790**	**91**	**0**	**0**	**193,708**
			Normal	**0**	**0**	**0**	**1,691**	**13,914**	**40,475**	**55,057**	**53,690**	**18,915**	**105**	**0**	**0**	**183,847**
			Dry	**0**	**0**	**0**	**4,091**	**24,870**	**39,862**	**55,485**	**37,795**	**15,386**	**145**	**0**	**0**	**177,634**

[1]Where more than one climate station is listed, the stations were weighted 50-50.

Source: HKM Engineering et al. 2002a.

Table 3.3-3
Agricultural Groundwater Depletions in the Powder/Tongue River Basin

Source of Water Supply	Climate Stations[1]	Active Irrigation (acres)	Hydrologic Condition	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
				(acre-feet)												
Upper Clear Creek	Buffalo	20	Wet	0	0	0	0	1	4	8	7	3	0	0	0	23
			Normal	0	0	0	0	2	6	7	7	3	0	0	0	25
			Dry	0	0	0	0	3	6	7	5	2	0	0	0	23
Upper Crazy Woman Creek	Buffalo	97	Wet	0	0	0	0	4	20	37	34	16	0	0	0	112
			Normal	0	0	0	0	10	27	34	35	13	0	0	0	119
			Dry	0	0	0	2	15	27	33	24	10	0	0	0	110
Upper Powder River	Kaycee	58	Wet	0	0	0	0	8	17	31	28	14	0	0	0	98
			Normal	0	0	0	0	0	6	11	15	1	0	0	0	34
			Dry	0	0	0	0	0	6	19	12	4	0	0	0	41
Lower Powder River	Buffalo and	28	Wet	0	0	0	0	4	8	15	14	6	0	0	0	46
			Normal	0	0	0	0	0	3	5	7	1	0	0	0	16
			Dry	0	0	0	0	0	2	9	6	2	0	0	0	19
Total		**203**	**Wet**	**0**	**0**	**0**	**0**	**17**	**49**	**91**	**83**	**39**	**0**	**0**	**0**	**279**
			Normal	**0**	**0**	**0**	**0**	**13**	**42**	**58**	**64**	**18**	**0**	**0**	**0**	**194**
			Dry	**0**	**0**	**0**	**3**	**18**	**40**	**68**	**47**	**18**	**0**	**0**	**0**	**194**

[1]Where more than one climate station is listed, the stations were weighted 50-50.

Source: HKM Engineering et al. 2002a.

Weston

groundwater to stimulate production. For the year 2000, approximately 2,343 wells produced approximately 44,000 acre-feet of water, and 1,593 injection wells consumed approximately 38,000 acre-feet of water (HKM Engineering et al. 2002a). Most of the water produced by oil and gas wells was reused for injection and came from units below the Fort Union Formation. As of January 1, 2002, there were approximately 9,390 CBNG wells of record in the Powder/Tongue River Basin. Most of these wells were in the Powder River, Little Powder River, and Tongue River drainages (Figure 3.3-5). These wells consumed approximately 36,900 acre-feet of groundwater per year from the Fort Union Formation (HKM Engineering et al. 2002a). This amounts to approximately 3.9 acre-feet per well per year. As of 2002, a total of 50,500 acre-feet of groundwater had been pumped by CBNG wells since the 1970s in the Powder/Tongue River Basin (HKM Engineering et al. 2002a). The location of industrial wells is shown in **Figure 3.3-4**, and the location of CBNG wells is shown in **Figure 3.3-5**. No water currently is being used for the electric power industry, although Lake DeSmet has been developed as a surface water reservoir for future electric power generation (HKM Engineering et al. 2002a).

Table 3.3-4
Municipal Water Use in the Powder/Tongue River Basin

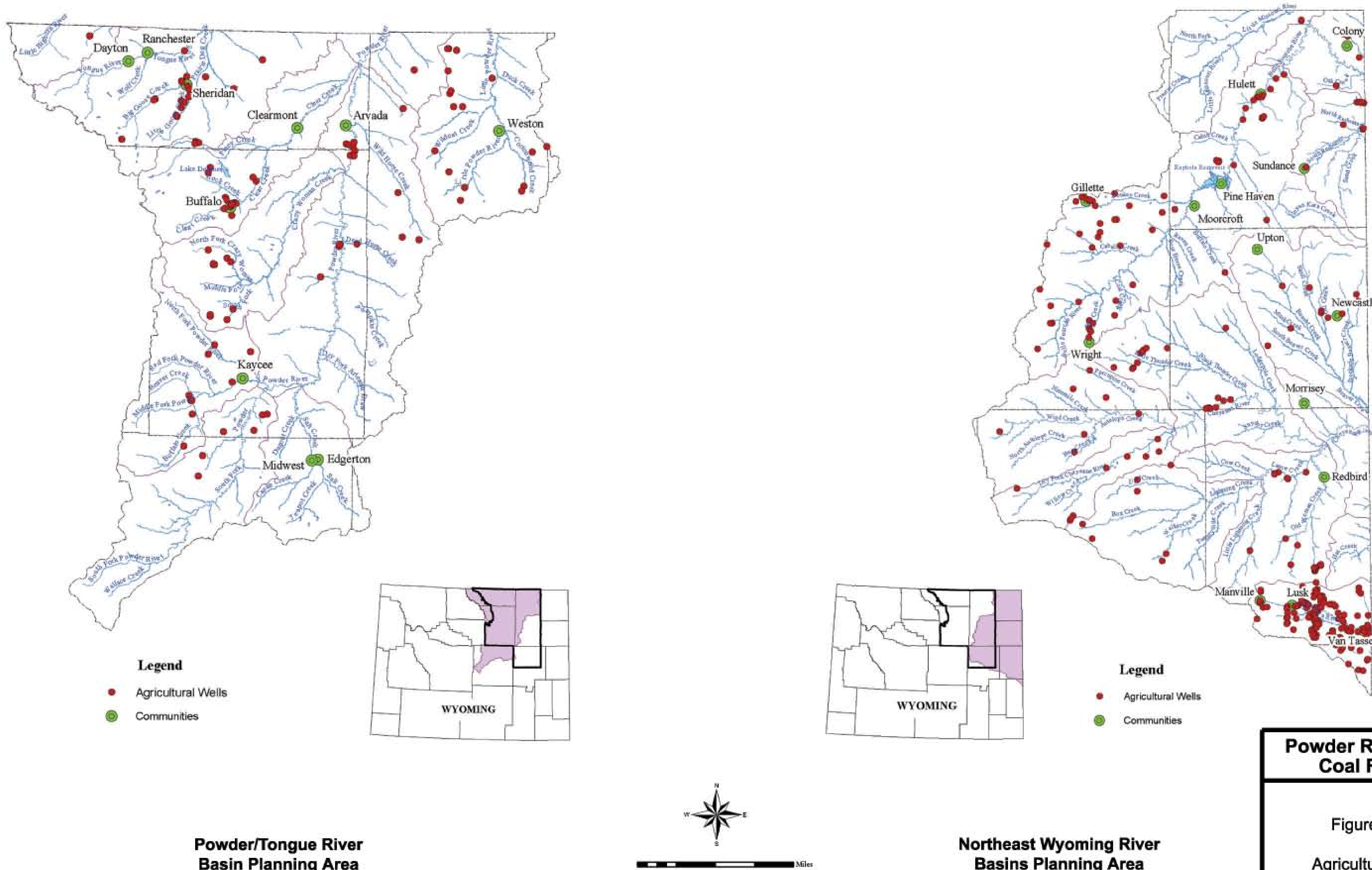
Municipality	Population[1]	Gpcpd[2]	Annual Use (million gallons)
Anderson I&SD	Supplied by City of Gillette		
Arvada WD	Individual wells, no central system		
Town of Clearmont	125	220	10.0
Cook Road WD	225	N/A	--
Countryside WUA	250	N/A	--
Eight-mile Subdivision	90	140	4.6
Green Valley Estates I&SD	72	N/A	--
Heritage Village W&SD	700	81	20.7
Town of Kaycee	300	210	23.0
Linch Utility	20	N/A	--
Means W&SD	300	600	65.7
Pine Butte I&DS	100	N/A	--
Prairie View/Champion I&SD	Individual wells, no central system		

Source: HKM Engineering et al. 2002a.

[1]Based on the 2000 census.
[2]Gallons per capita per day.

3.3.1.4 Recreational and Environmental Water Use

Lake DeSmet is the largest body of recreational water in the Powder/Tongue River basin. Recreational water use requires minimum flow releases from reservoirs, minimum water levels in reservoirs, or maintenance of instream flow water rights. However, recreational water use is non-consumptive.



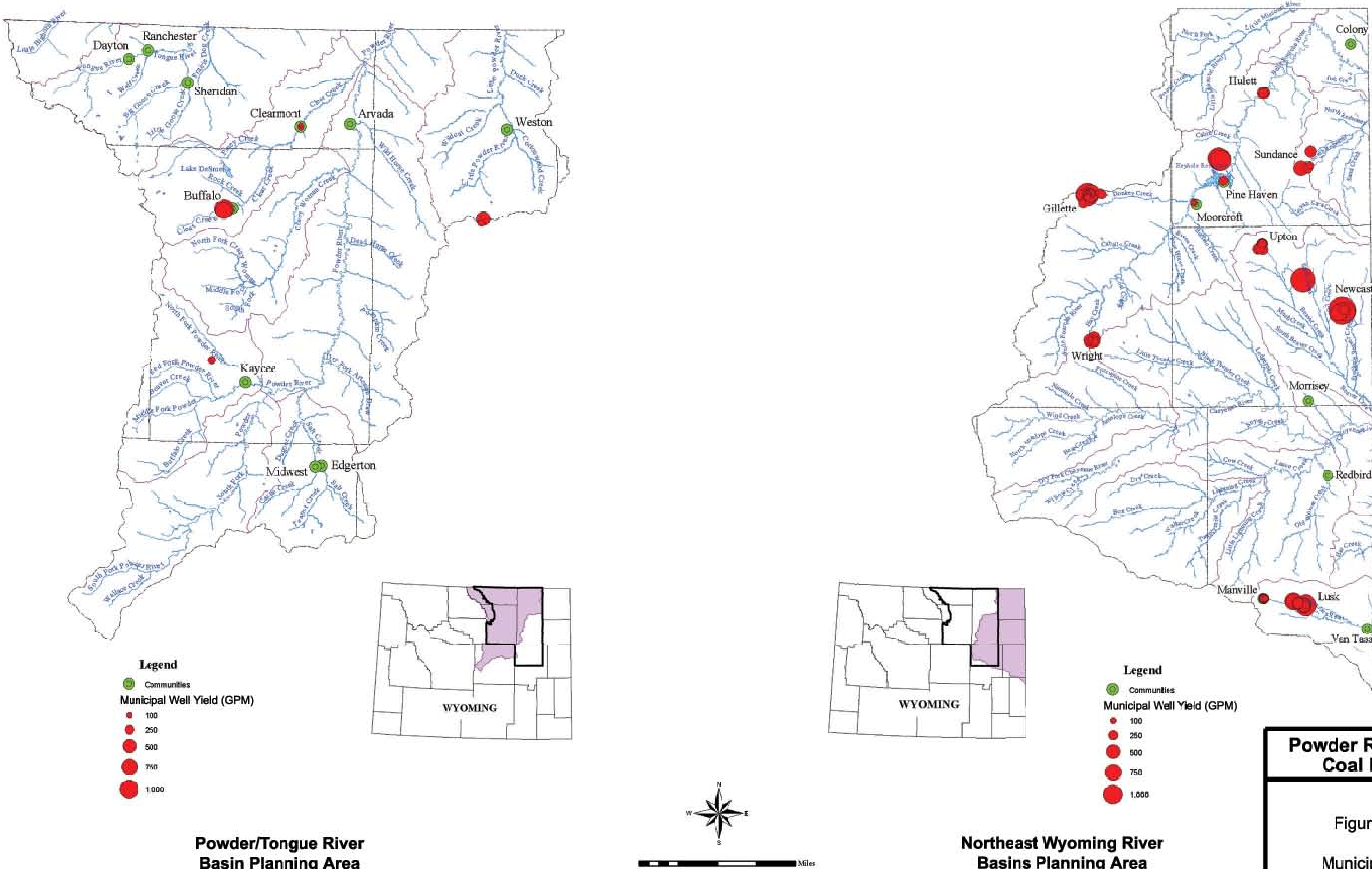
Powder River Basin Coal Review

Figure 3.3-1

Agricultural Wells

Source: HKM Engineering et al. 2002a,b.

07/27/06



Powder/Tongue River Basin Planning Area

Northeast Wyoming River Basins Planning Area

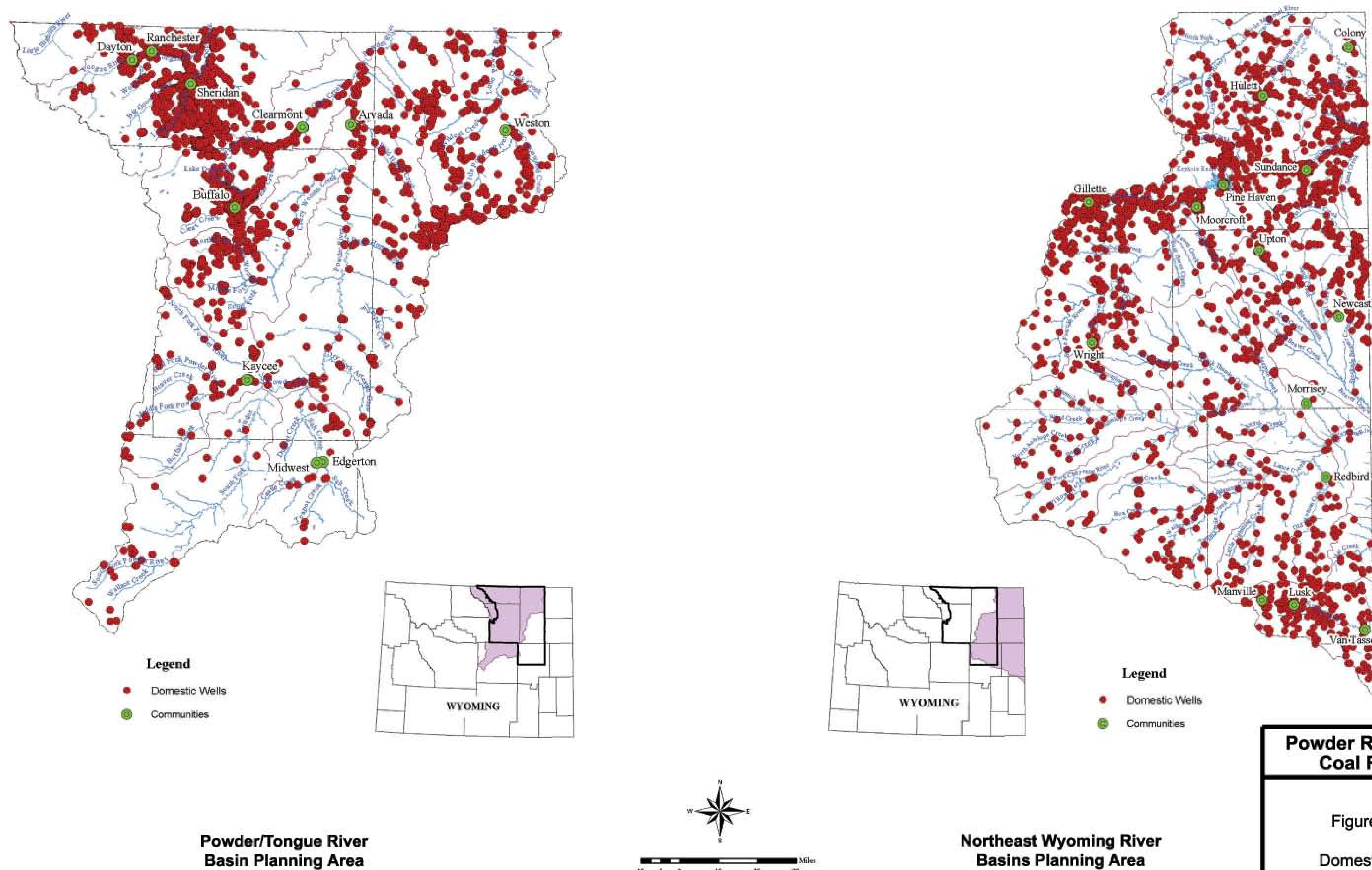
Source: HKM Engineering et al. 2002a,b.

Powder River Basin Coal Review

Figure 3.3-2

Municipal Wells

07/27/06



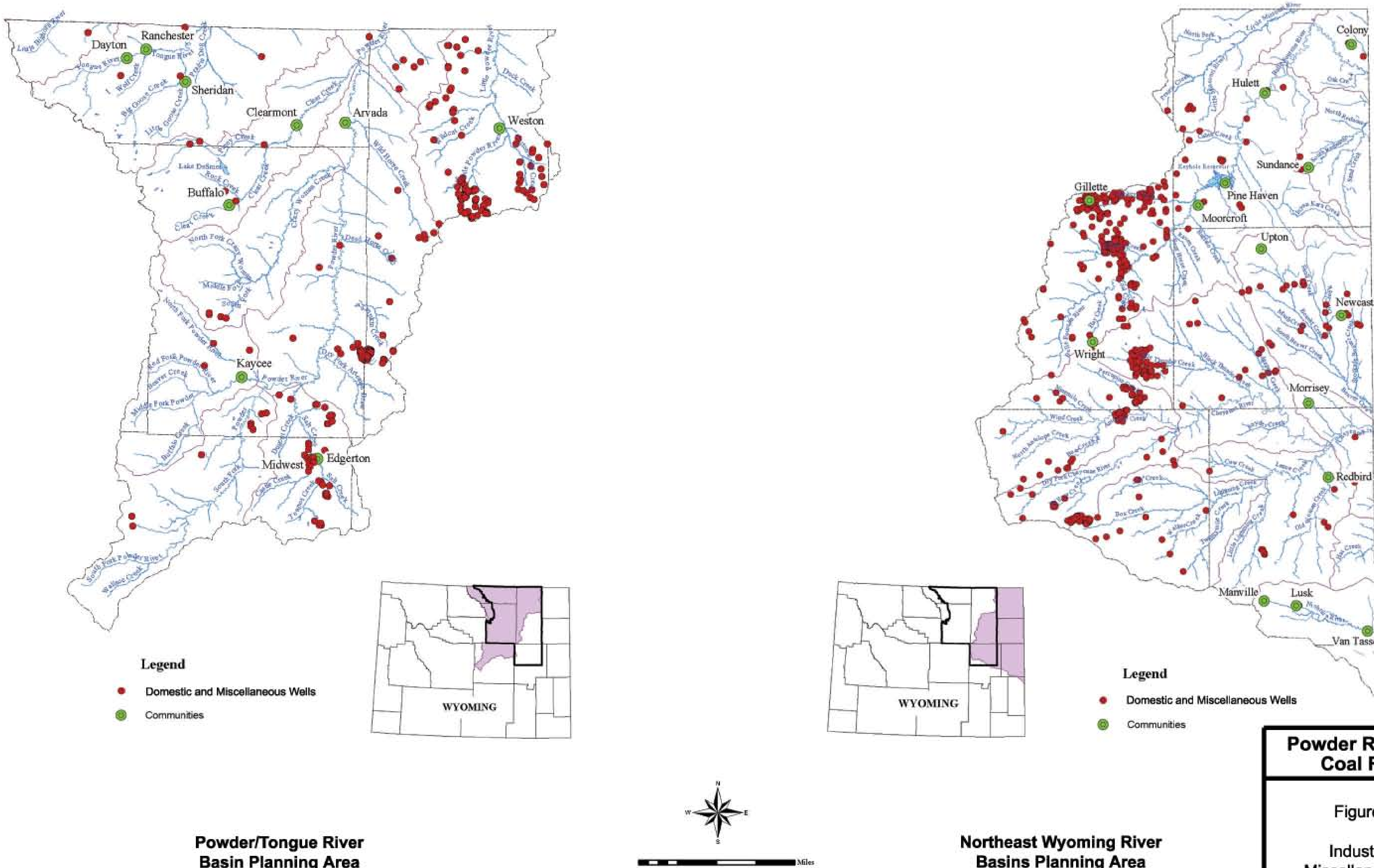
Source: HKM Engineering et al. 2002a,b.

Powder River Basin Coal Review

Figure 3.3-3

Domestic Wells

07/27/06



Powder/Tongue River Basin Planning Area

Northeast Wyoming River Basins Planning Area

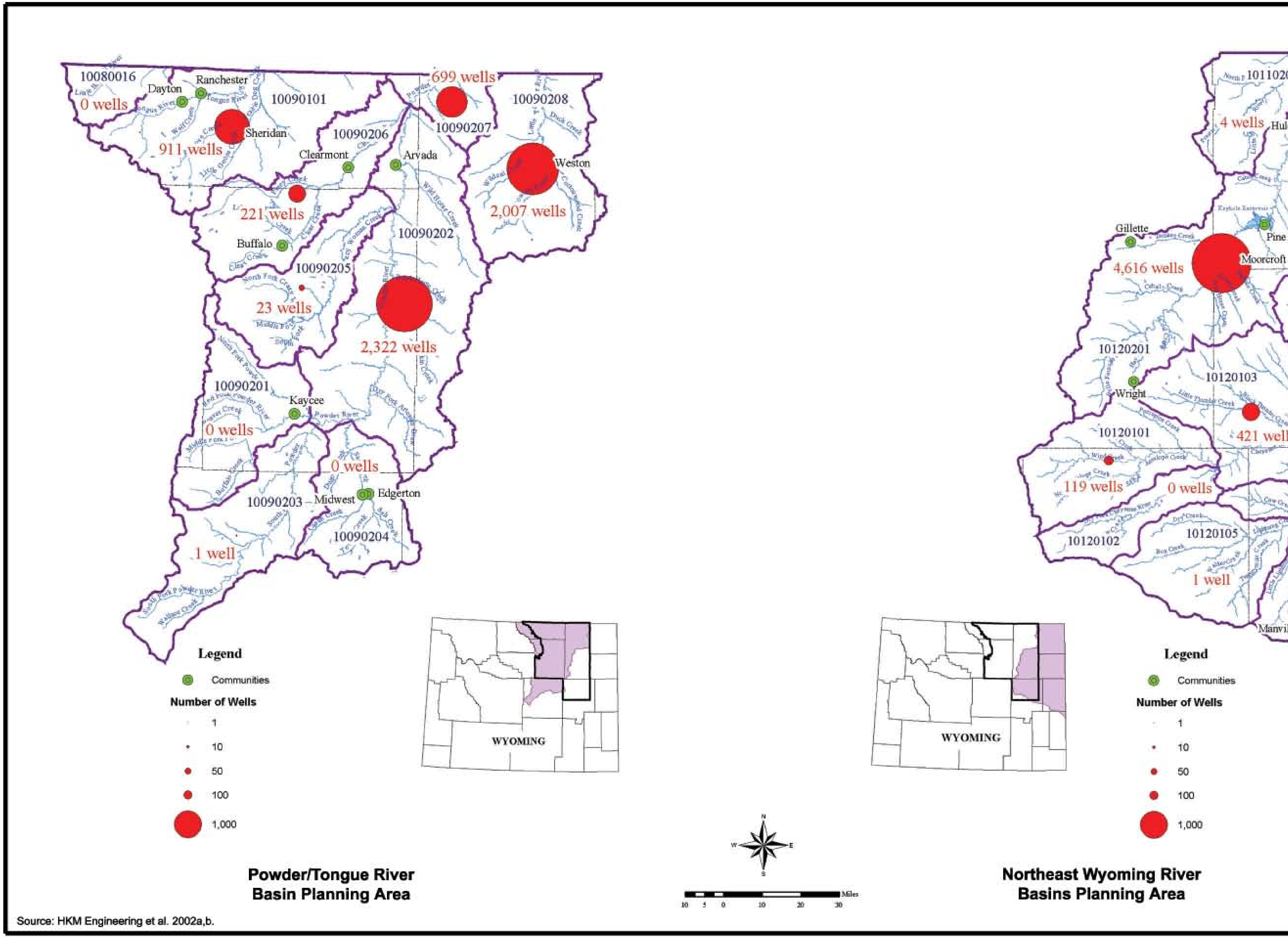
Source: HKM Engineering et al. 2002a,b.

Powder River Basin Coal Review

Figure 3.3-4

Industrial and Miscellaneous Wells

07/27/06



Source: HKM Engineering et al. 2002a,b.

Powder River Basin Coal Review

Figure 3.3-5

CBNG Wells

07/27/06

3.3.1.5 Reservoir Evaporation

Reservoir evaporation is a major source of water loss in the Powder/Tongue River Basin. Evaporation from the 14 key storage reservoirs in the basin totals approximately 11,300 acre-feet per year (see **Figure 3.3-6** and **Table 3.3-1**) (HKM Engineering et al. 2002a). This is primarily a loss of surface water and exceeds the surface water and groundwater consumption by municipalities as well as the groundwater consumption by domestic wells. Only agricultural irrigation, conventional oil and gas operations, and CBNG development consume more water. **Table 3.3-5** summarizes reservoir evaporation from key storage reservoirs.

Table 3.3-5
Reservoir Evaporation in the Powder/Tongue River Basin

Key Storage Reservoirs	Active Capacity (acre-feet)	Dam Height (feet)	Surface Area (acres)	Annual Net Evaporation Loss (acre-feet)
Big Goose Park	10,362	85	318	557
Big Horn	4,624	45	179	296
Cross Creek	798	30	51	278
Cloud Peak	3,570	36	174	85
Dome Lake No. 1	1,506	30	96	8,372
Dull Knife	4,345	80	130	170
Healy	5,140	50	246	205
Kearney Lake	6,324	67	193	556
Lake Desmet	111,827	80	2,653	291
Muddy Guard No. 2	1,934	57	48	113
Sawmill	1,275	38	75	136
Tie Hack	2,435	110	63	148
Twin Lakes	1,317	54	52	112
Willow Park	4,457	56	213	N/A

Source: HKM Engineering et al. 2002a.

3.3.2 Northeast Wyoming River Basins

The Northeast Wyoming River Basins are those that lie to the northeast, east, and southeast of Gillette, Wyoming, in Crook, southeastern Campbell, Weston, northern Converse, and northern Niobrara counties. The main rivers are the Belle Fourche in Campbell and Crook counties and the Cheyenne River in Converse, Weston, and Niobrara counties. The Little Missouri River lies in northern Crook County and is not part of the Powder River structural basin; however, it does border the coal mines north of Gillette, Wyoming. The Niobrara River is not part of the Powder River structural basin and is not near the coal mines of the eastern PRB. Important tributaries to the Belle Fourche River that are near coal mines are Caballo Creek and Hay Creek; important tributaries to the Cheyenne River that are near coal mines are North Antelope Creek, Porcupine Creek, Little Thunder Creek, Black Thunder Creek, and Willow Creek. Except for the Niobrara River, the Northeast Wyoming River Basins drain into South Dakota. Water in the rivers comes from groundwater baseflow and from precipitation, especially from heavy storms during the summer months. Over the past 10 years, discharge of groundwater from CBNG wells has contributed locally to flow in these drainages. The topography is typical of the High Plains – rolling topography with elevated tablelands and numerous incised drainages. There are no large mountains in the Northeast Wyoming River Basins.

3.3.2.1 Agricultural Water Use

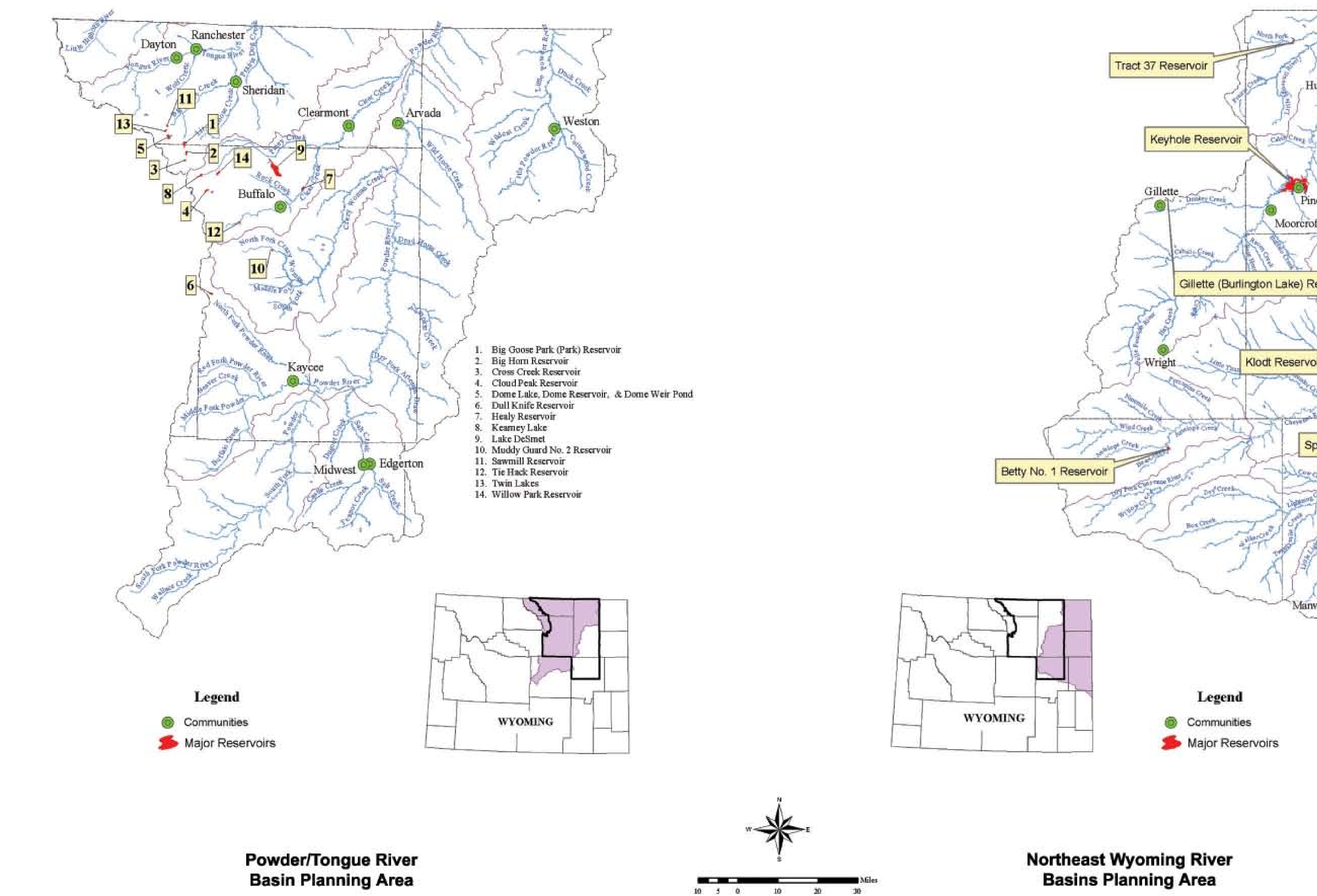
Irrigated agricultural lands in the Northeast Wyoming River Basins are associated with forage production for the livestock industry. Crops are mainly alfalfa, grass hay, and pasture grass. Approximately 77,350 acres are irrigated in the Northeast Wyoming River Basins, with approximately 13,000 of these acres being irrigated by groundwater. Surface water consumption by irrigation in 2002 totaled 71,000 acre-feet in wet years, 69,000 acre-feet in normal years, and 65,000 acre-feet in dry years (see **Table 3.3-6**) (HKM Engineering et al. 2002b). Groundwater consumption for irrigation in 2002 totaled 17,000 acre-feet in wet years and normal years and approximately 11,000 acre-feet in dry years. Water use in wet years can exceed that in dry years due to more land being in production. Agricultural irrigation wells are shown in **Figure 3.3-1**. As shown in **Table 3.3-7**, most of the groundwater consumption for irrigation was in the Niobrara River drainage. **Tables 3.3-8** and **3.3-9** show the relative surface and groundwater depletion, respectively, in the Northeast Wyoming River Basins.

3.3.2.2 Municipal and Domestic Water Use

There are 33 public water supply entities in the Northeast Wyoming River Basins consisting of 9 incorporated municipalities, 19 water districts, and 5 privately owned water systems (**Table 3.3-10**). Municipal and domestic water use is from groundwater only, and approximately 9,100 acre-feet of groundwater is consumed per year. Domestic groundwater demand is approximately 3,600 acre-feet per year (see **Table 3.3-6**) (HKM Engineering et al. 2002b). **Figure 3.3-2** shows the location of municipal wells, and **Figure 3.3-3** shows the location of domestic wells. Domestic water consumption is mainly from the Fort Union Formation. Municipal water consumption is from the Fort Union Formation and aquifers below the Fort Union.

3.3.2.3 Industrial Water Use

Industrial water use in the Northeast Wyoming River Basins consists of conventional oil and gas production, CBNG development, coal mining, electric power generation, and oil refining. Groundwater is used exclusively by these industries, and the total use is approximately 50,700 acre-feet per year (see **Table 3.3-6**) (HKM Engineering et al. 2002b). The groundwater comes mainly from the Fort Union Formation. **Figure 3.3-4** shows the location of industrial wells other than CBNG wells. Electric power generation comes from two power plants, the Wyodak Power Plant and the Osage Power Plant. The Wyodak Power Plant is near Gillette and consumes approximately 700 acre-feet of water per year. Half of this water comes from treated wastewater from the City of Gillette. The Osage Power Plant uses 870 acre-feet of groundwater per year. Coal mine water use is based on data from five mines, which use a combined total of 2,700 acre-feet of groundwater per year (HKM Engineering et al. 2002b). Permitted coal mine water use for 2002 totaled approximately 7,500 acre-feet for all operating coal mines in the eastern PRB of Wyoming (Wyoming State Engineer's Office [WSEO] 2004). CBNG wells in the Northeast Wyoming River Basins totaled approximately 5,161 wells by the end of 2001; the wells consumed approximately 35,600 acre-feet of water per year. A total of 99,700 acre-feet of groundwater has been pumped and discharged by CBNG wells since the 1970s (HKM Engineering et al. 2002b). Most of the CBNG



Source: HKM Engineering et al. 2002a,b.

Powder River Basin Coal Review

Figure 3.3-6

Reservoirs

07/27/06

Table 3.3-6
Water Use as of 2002 in the Northeast Wyoming River Basins

Water Use		Dry Year		Normal Year		Wet Year	
		(approximate acre-feet per year)					
		Surface Water	**Groundwater**	**Surface Water**	**Groundwater**	**Surface Water**	**Groundwater**
Agricultural		65,000	11,000	69,000	17,000	71,000	17,000
Municipal		---	9,100	---	9,100	---	9,100
Domestic		---	3,600	---	3,600	---	3,600
Industrial	Oil and Gas[1]	---	46,000	---	46,000	---	46,000
	Other[2]	---	4,700	---	4,700	---	4,700
Recreation		Non-consumptive					
Environmental		Non-consumptive					
Evaporation	Key Reservoirs	14,000	---	14,000	---	14,000	---
	Stock Ponds	6,300	---	6,300	---	6,300	---
Total		**85,300**	**74,400**	**89,300**	**80,400**	**91,300**	**80,400**

[1]Includes conventional oil and gas production water and CBNG production water.
[2]Includes electricity generation, coal mining, and oil refining.

Source: HKM Engineering et al. 2002b.

Table 3.3-7
Irrigated Lands in the Northeast Wyoming River Basins by Source of Water

Subbasin Name	Hydrologic Unit Code	Primary Source of Agricultural Water Supply (acre-feet)		
		Groundwater	Surface Water	Total
Upper Little Missouri	10110201	0	10,140	10,140
Upper Belle Fourche	10120201	930	13,138	14,068
Lower Belle Fourche	10120202	186	5,714	5,900
Redwater Creek	10120203	164	2,213	2,377
Upper Cheyenne	10120103	127	7,145	7,272
Antelope Creek	10120101	0	1,250	1,250
Beaver Creek	10120107	273	11,276	11,549
Hat Creek	10120108	0	1,941	1,941
Lance Creek	10120104	667	7,395	8,062
Lightning Creek	10120105	469	2,385	2,854
Dry Fork Cheyenne	10120102	32	1,436	1,468
Angostura Reservoir	10120106	0	4,204	4,204
Niobrara Headwaters	10150002	14,950	847	15,797
Total		**17,798**	**69,084**	**86,882**

Source: HKM Engineering et al. 2002b.

Table 3.3-8
Agricultural Surface Water Depletions in the Northeast Wyoming River Basins

Source of Water Supply	Climate Stations	Active Irrigation (acres)	Hydrologic Condition	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
										(acre-feet)						
Little Missouri River	Colony, Weston	9,799	Wet	0	0	0	614	1,047	1,828	3,427	3,082	1,577	72	0	0	11,648
			Normal	0	0	0	532	1,138	2,000	2,912	2,514	1,276	83	0	0	10,455
			Dry	0	0	0	775	1,451	1,813	2,640	2,005	972	103	0	0	9,759
Upper Belle Fourche River	Gillette	3,312	Wet	0	0	0	57	281	698	1,229	1,118	529	4	0	0	3,915
			Normal	0	0	0	79	344	671	1,003	942	416	10	0	0	3,465
			Dry	0	0	0	173	413	683	898	669	309	8	0	0	3,152
Middle Belle Fourche River	Moorcroft	9,011	Wet	0	0	0	103	562	1,573	2,990	2,942	1,546	17	0	0	9,734
			Normal	0	0	0	109	745	1,941	2,620	2,708	1,264	19	0	0	9,406
			Dry	0	0	0	216	1,382	1,908	2,290	1,961	858	16	0	0	8,630
Lower Belle Fourche River	Colony	5,584	Wet	0	0	0	99	348	997	2,261	1,867	1,065	23	0	0	6,661
			Normal	0	0	0	100	530	1,325	2,001	1,787	886	29	0	0	6,656
			Dry	0	0	0	206	1,309	1,241	1,789	1,226	567	37	0	0	6,374
Redwater Creek	Sundance	2,213	Wet	0	0	0	6	84	342	776	608	298	0	0	0	2,115
			Normal	0	0	0	12	138	481	756	696	267	1	0	0	2,350
			Dry	0	0	0	21	303	394	627	400	190	1	0	0	1,937
Upper Beaver Creek	Upton	669	Wet	0	0	0	2	38	147	256	203	144	1	0	0	791
			Normal	0	0	0	3	47	147	199	212	124	1	0	0	733
			Dry	0	0	0	9	142	137	202	128	80	1	0	0	698
Middle Beaver Creek	Newcastle, Upton	6,000	Wet	0	0	0	12	331	1,439	2,360	1,714	1,327	5	0	0	7,188
			Normal	0	0	0	27	435	1,475	1,914	1,930	1,155	3	0	0	6,938
			Dry	0	0	0	92	1,292	1,337	1,894	1,156	723	3	0	0	6,496
Lower Beaver Creek	Morrisey, Newcastle	3,561	Wet	0	0	0	54	201	682	1,005	768	558	22	0	0	3,291
			Normal	0	0	0	59	244	828	1,065	1,114	636	22	0	0	3,969
			Dry	0	0	0	79	604	713	875	574	378	20	0	0	3,242
Northern Tributaries To Cheyenne	Morrisey	7,958	Wet	0	0	0	209	362	1,685	2,025	2,105	886	228	0	0	7,501
			Normal	0	0	0	196	747	1,474	1,762	1,900	923	112	0	0	7,113
			Dry	0	0	0	322	1,296	1,848	1,845	1,178	938	148	0	0	7,577
Southern Tributaries To Cheyenne	Redbird	12,736	Wet	0	0	0	323	1,151	3,086	4,186	4,096	2,065	11	0	0	14,919
			Normal	0	0	0	612	1,287	3,282	4,093	3,669	2,040	5	0	0	14,988
			Dry	0	0	0	730	2,633	3,464	3,721	2,589	1,195	39	0	0	14,371
Lower Cheyenne River	Morrisey, Redbird	2,602	Wet	0	0	0	58	109	556	680	697	295	63	0	0	2,458
			Normal	0	0	0	55	238	502	594	644	308	31	0	0	2,372
			Dry	0	0	0	95	453	630	625	391	307	41	0	0	2,542
Niobrara River	Lusk	847	Wet	0	0	0	1	67	250	303	323	113	0	0	0	1,057
			Normal	0	0	0	7	73	255	259	262	151	0	0	0	1,007
			Dry	0	0	0	20	40	144	222	160	58	1	0	0	646
Total		**64,292**	**Wet**	**0**	**0**	**0**	**1,539**	**4,582**	**13,282**	**21,499**	**19,524**	**10,405**	**446**	**0**	**0**	**71,277**
			Normal	**0**	**0**	**0**	**1,790**	**5,965**	**14,381**	**19,177**	**18,377**	**9,446**	**315**	**0**	**0**	**69,451**
			Dry	**0**	**0**	**0**	**2,738**	**11,318**	**14,313**	**17,627**	**12,436**	**6,574**	**417**	**0**	**0**	**65,424**

[1]Where more than one climate station is listed, the stations were weighted 50-50.

Source: HKM Engineering et al. 2002b.

Table 3.3-9
Agricultural Groundwater Depletions in the Northeast Wyoming River Basins

Source of Water Supply	Climate Stations[1]	Active Irrigation (acres)	Hydrologic Condition	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
				(acre-feet)												
Little Missouri River	Colony, Weston	0	Wet	0	0	0	0	0	0	0	0	0	0	0	0	0
			Normal	0	0	0	0	0	0	0	0	0	0	0	0	0
			Dry	0	0	0	0	0	0	0	0	0	0	0	0	0
Upper Belle Fourche River	Gillette	352	Wet	0	0	0	0	0	25	146	177	89	0	0	0	437
			Normal	0	0	0	0	0	32	121	171	72	0	0	0	396
			Dry	0	0	0	0	0	37	112	108	49	0	0	0	306
Middle Belle Fourche River	Moorcroft	112	Wet	0	0	0	0	0	5	38	51	28	0	0	0	123
			Normal	0	0	0	0	0	10	33	50	23	0	0	0	117
			Dry	0	0	0	0	2	11	30	34	15	0	0	0	91
Lower Belle Fourche River	Colony	186	Wet	0	0	0	0	5	28	81	75	44	0	0	0	233
			Normal	0	0	0	0	12	40	72	76	37	0	0	0	237
			Dry	0	0	0	3	37	38	66	49	22	0	0	0	215
Redwater Creek	Sundance	163	Wet	0	0	0	0	0	3	53	63	40	0	0	0	159
			Normal	0	0	0	0	0	11	49	66	33	0	0	0	159
			Dry	0	0	0	0	0	10	42	45	24	0	0	0	120
Upper Beaver Creek	Upton	0	Wet	0	0	0	0	0	0	0	0	0	0	0	0	0
			Normal	0	0	0	0	0	0	0	0	0	0	0	0	0
			Dry	0	0	0	0	0	0	0	0	0	0	0	0	0
Middle Beaver Creek	Newcastle, Upton	143	Wet	0	0	0	0	0	14	54	58	43	0	0	0	168
			Normal	0	0	0	0	0	14	44	64	37	0	0	0	159
			Dry	0	0	0	0	1	13	43	39	24	0	0	0	120
Lower Beaver Creek	Morrisey, Newcastel	0	Wet	0	0	0	0	0	0	0	0	0	0	0	0	0
			Normal	0	0	0	0	0	0	0	0	0	0	0	0	0
			Dry	0	0	0	0	0	0	0	0	0	0	0	0	0
Northern Tributaries to Cheyenne	Morrisey	127	Wet	0	0	0	0	0	12	33	46	20	0	0	0	112
			Normal	0	0	0	0	1	11	29	44	21	0	0	0	105
			Dry	0	0	0	0	1	16	31	27	20	0	0	0	95
Southern Tributaries to Cheyenne	Redbird	387	Wet	0	0	0	0	11	72	146	161	84	0	0	0	474
			Normal	0	0	0	1	21	93	145	161	83	0	0	0	505
			Dry	0	0	0	6	69	102	135	102	46	0	0	0	461
Lower Cheyenne River	Morrisey, Redbird	0	Wet	0	0	0	0	0	0	0	0	0	0	0	0	0
			Normal	0	0	0	0	0	0	0	0	0	0	0	0	0
			Dry	0	0	0	0	0	0	0	0	0	0	0	0	0
Niobrara River	Lusk	11,566	Wet	0	0	0	1	387	3,397	4,528	5,105	1,797	0	0	0	15,515
			Normal	0	0	0	29	948	3,650	3,880	4,271	2,407	1	0	0	15,185
			Dry	0	0	0	207	615	2,064	3,351	2,527	898	1	0	0	9,663
Total		**13,036**	**Wet**	**0**	**0**	**0**	**1**	**704**	**3,557**	**5,078**	**5,736**	**2,145**	**0**	**0**	**0**	**17,222**
			Normal	**0**	**0**	**0**	**31**	**982**	**3,861**	**4,373**	**4,903**	**2,713**	**1**	**0**	**0**	**16,864**
			Dry	**0**	**0**	**0**	**216**	**726**	**2,292**	**3,809**	**2,930**	**1,098**	**1**	**0**	**0**	**11,072**

[1]Where more than one climate station is listed, the stations were weighted 50-50.

Source: HKM Engineering et al. 2002b.

Table 3.3-10
Municipal Water Use in the Northeast Wyoming River Basins

Municipality	Population[1]	Gpcpd[2]	Annual Use (million gallons)
American Road W&SD	210	104	8.0
Antelope Valley	800	N/A	N/A
Cambria I&SD	110	140	5.6
Cedar Hills	250	40	3.7
Central Campbell Co. I&SD	1,500	60	32.9
Collins Heights I&SD	250	N/A	N/A
Crestview WD	490	150	26.8
Force Road JPB	250	360	32.9
Fox Park I&SD	843	N/A	N/A
Freedom Hills Subdivision	400	N/A	N/A
City of Gillette	22,000	200	1,606.0
Town of Hulett	450	100	16.4
Lance Creek W&SD	40	525	250
Lost Springs	N/A	N/A	N/A
City of Lusk	1,600	160	93.4
Town of Manville	100	700	25.6
Town of Moorcroft	770	130	36.5
City of Newcastle	3,300	225	271.0
Newton Industrial Park I&SD	25	160	1.5
Osage WD	216	230	18.1
Peoples I&SD	80	N/A	N/A
Town of Pine Haven	222	220	17.8
Salt Creek WD	500	150	27.4
Southfork Estates I&SD	115	80	3.4
Sunburst W&SD	Water supplied by City of Gillette		
City of Sundance	1,250	150	68.4
Town of Upton	950	225	78.0
Van Tassell	N/A	N/A	N/A
Vista West I&SD	250	100	9.1
Wessex I&SD	21	150	1.1
West End WD	300	50	5.5
Westridge WUA	260	240	22.8
Wright W&SD	1,500	219	119.9

[1]2000 Census.
[2]Gallons per capita per day.

Source: HKM Engineering et al. 2002b.

activity has been in the Belle Fourche drainage (**Figure 3.3-5**). Conventional oil and gas wells totaled approximately 2,878 wells by the end of 2001; they produced approximately 10,200 acre-feet of water. An estimated 1,127 injection wells consumed approximately 10,400 acre-feet of water (HKM Engineering et al. 2002b). **Figure 3.3-5** shows the general locations of CBNG wells as of January 1, 2002.

3.3.2.4 Recreational and Environmental Water Use

Recreational and environmental water uses are non-consumptive. They consist of maintaining minimum water levels in reservoirs and minimum flow releases for instream water rights and aquatic water needs. The largest reservoir in the Northeast Wyoming River Basins is the Keyhole Reservoir (**Figure 3.3-6**), which supports a variety of recreational activities and primarily is used for agricultural irrigation.

3.3.2.5 Reservoir Evaporation

There are six key storage reservoirs in the Northeast Wyoming River Basins (see **Figure 3.3-6**). Evaporation from these six reservoirs is approximately 14,400 acre-feet of water annually (see **Table 3.3-11**) (HKM Engineering et al. 2002b). The largest of the reservoirs is the Keyhole Reservoir with an active capacity of approximately 186,000 acre-feet (HKM Engineering et al. 2002b). This reservoir is near Moorecroft and Pine Haven on the Belle Fourche River drainage. There are approximately 16,600 stock ponds in the Northeast Wyoming River Basins and these evaporate approximately 6,300 acre-feet of water per year (HKM Engineering et al. 2002b). Thus, total evaporation loss in the Northeast Wyoming River Basins is approximately 20,700 acre-feet per year. Evaporation loss is greater than groundwater consumption by coal mining and greater than groundwater consumption by municipal and domestic water use combined. Only irrigation and CBNG development consume more water.

Table 3.3-11
Reservoir Evaporation in the Northeast Wyoming River Basins

Key Storage Reservoirs	Active Capacity (acre-feet)	Dam Height (feet)	Surface Area (acres)	Annual Net Evaporation Loss (acre-feet)
Betty No. 1	1,345	32	171	355
Gillette	2,080	10	145	N/A
Keyhole	185,800	115	13,686	12,915
Klodt	980	26	124	317
Spencer	2,162	45	126	224
Tract 37	2,454	31	302	560

Source: HKM Engineering et al. 2002b.

3.4 Basin Water Availability

Water availability in the PRB is an issue of concern, especially for the future. Industrial use of groundwater by the CBNG industry and the increasing demands on surface water for irrigation and general water supply are presenting potential problems for long-term use of water in the basin. This section summarizes data on surface and groundwater availability. Impacts to groundwater resources associated with the coal mining industry and CBNG development are discussed in later sections. Most of the data on surface and groundwater availability presented in this section come from the Powder/Tongue River Basin Water Plan (HKM Engineering et al. 2002a) and the Northeast

Wyoming River Basins Water Plan (HKM Engineering et al. 2002b) prepared for the Wyoming Water Development Commission.

3.4.1 Surface Water Availability

Surface water availability is mainly a function of precipitation runoff with some groundwater baseflow additions during the summer and fall months. Surface water availability is defined as the water physically available above and beyond surface water resources already allocated for use (HKM Engineering et al. 2002a). Stream flow at gauging stations and estimates of stream flow for ungauged drainages are a measure of surface water flow. Surface water availability is that flow minus allocated water currently in use. The Powder/Tongue River Basin Water Plan (HKM Engineering et al. 2002a) and the Northeast Wyoming River Basins Water Plan (HKM Engineering et al. 2002b) both describe how surface water flows were determined and how surface water availability was calculated. This section summarizes the pertinent results from these two water plans.

3.4.1.1 Powder/Tongue River Basin

There are approximately 114 stream gauging stations in the Powder/Tongue River Basin. Most of these are maintained by the USGS or WSEO. Flow at these gauging stations has to take into account surface water diversions, irrigation return flow, and storage in reservoirs before the "natural flow" can be estimated. Some gauges measure mostly "unnatural flow" in that they measure surface water flow dictated mainly by irrigation practices. For ungauged drainages, flow can be estimated in Wyoming using the regression equations developed by the USGS and summarized by Miller (2003). The results of these calculations are presented in the Powder/Tongue River Basin Water Plan (HKM Engineering et al. 2002a).

Table 3.4-1 shows that rivers such as the Little Bighorn River, Tongue River, Powder River, Crazy Woman Creek, and Piney Creek carry the largest natural flows. Many of the other major drainages in the Powder/Tongue River Basin are affected by irrigation practices to the extent that their flows are not natural (HKM Engineering et al. 2002a). **Table 3.4-2** presents the estimates for ungauged natural flows. Water availability in the major subbasins of the Powder/Tongue River Basin is summarized in **Table 3.4-3**. This table presents the amount of surface water in acre-feet that is physically available above and beyond allocated surface water in these drainages. As a result of the Yellowstone River Compact, Wyoming must share some of the physically available surface water in the Powder/Tongue River Basin with Montana (see Section 3.2.1, Powder/Tongue River Basin). During normal years, for example, there remains about 931,000 acre-feet of surface water available for additional allocation in Wyoming in the Powder/Tongue River Basin. Appendix A presents a summary of surface water quality data from selected USGS gauging stations in the Powder/Tongue River Basin. **Table 3.4-4** summarizes electrical conductivity (EC) and sodium adsorption ratio (SAR) values for key rivers in the PRB. EC is a measure of total salinity, while SAR can be used to determine the potential use of the water for agriculture. SAR values greater than 8 are unsuitable for some agricultural uses.

Table 3.4-1
Summary of Normal Year Stream Flows (1970 to 1999) at Natural Flow Stations in the Powder/Tongue River Basin

Basin	Station Number	Station Name	Average Stream Flow for 1970-1999 (acre-feet)												
			Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Little Bighorn	06288600	Little Bighorn River Below Dayton Gulch Near Burgess Junction, Wyoming	422	303	267	237	196	220	361	3,862	6,199	1,629	778	463	14,937
	06288700	Dry Fork Little Bighorn River Below Lick Creek Near Burgess Junction, Wyoming	1,854	1,591	1,477	1,379	1,227	1,329	1,722	6,442	9,677	4,367	2,630	2,024	35,720
	06288960	Little Bighorn River near Parkman, Wyoming	4,002	3,337	3,079	2,837	2,458	2,766	3,732	17,480	27,873	10,893	6,005	4,414	88,877
	06288975	Elkhorn Creek Above Fuller Ranch Ditch Near Parkman, Wyoming	116	101	92	86	75	88	139	470	602	186	136	123	2,213
	06288990	West Fork Little Bighorn River Near Parkman, Wyoming	932	790	731	671	589	675	901	3,871	5,812	2,315	1,355	1,037	19,677
	06289000	Little Bighorn River at State Line Near Wyola, Montana	5,412	4,543	4,226	3,927	3,465	3,879	5,112	21,438	33,132	13,750	7,872	5,948	112,704
	06289100	Red Canyon Creek Near Parkman, Wyoming	35	31	25	27	23	42	214	545	241	64	31	27	1,304
	06289800	East Pass Creek Near Parkman, Wyoming	474	391	365	339	303	331	552	1,928	2,318	1,057	644	510	9,211
	06291200	Lodge Grass Creek at State Line Near Wyola, Montana	466	351	310	282	238	273	581	3,838	5,310	1,658	784	529	14,620
Tongue	06297000	South Fork Tongue River Near Dayton, Wyoming	1,462	1,069	976	816	655	749	1,756	14,632	20,914	5,932	2,554	1,700	53,216
	06297480	Tongue River at Tongue Canyon Campground Near Dayton, Wyoming	5,140	3,987	3,650	3,349	2,827	3,124	5,922	31,052	40,989	14,721	7,889	5,768	128,419
	06298000	Tongue River Near Dayton, Wyoming	5,232	4,031	3,687	3,369	2,853	3,163	6,003	31,944	41,798	15,382	8,019	5,825	131,306
	06298480	Little Tongue River at Steamboat Point Near Dayton, Wyoming	137	96	85	74	59	71	239	2,024	2,889	689	280	176	6,819
	06298490	Little Tongue River Above South Fork Little Tongue River Near Dayton, Wyoming	102	70	60	52	40	47	133	1,615	2,453	532	202	121	5,427
	06298500	Little Tongue River Near Dayton, Wyoming	228	162	140	127	111	124	392	3,153	4,156	1,074	427	278	10,372
	06299480	Wolf Creek Below Alden Creek Near Wolf, Wyoming	481	347	306	269	221	261	757	5,691	8,097	2,060	859	561	19,909
	06299490	Wolf Creek Above Red Canyon Creek Near Wolf, Wyoming	537	404	362	330	272	308	753	5,442	7,717	2,019	857	564	19,565
	06299500	Wolf Creek at Wolf, Wyoming	543	405	355	321	281	301	827	5,443	7,591	2,118	934	627	19,746
	06300500	East Fork Big Goose Creek Near Big Horn, Wyoming	434	279	208	210	153	169	516	4,890	10,683	3,453	1,208	777	22,980

Table 3.4-1 (Continued)

Basin	Station Number	Station Name	Average Stream Flow for 1970-1999 (acre-feet)												
			Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
	06301480	Coney Creek Above Twin Lakes Near Big Horn, Wyoming	31	19	13	10	7	9	46	1,069	1,782	423	84	55	3,548
Powder	06309200	Middle Fork Powder River Near Barnum, Wyoming	458	392	362	328	296	434	2,192	9,883	4,450	1,052	528	430	20,805
	06309260	Buffalo Creek Above North Fork Buffalo Creek Near Arminto, Wyoming	31	26	23	20	18	29	229	1,337	562	91	37	28	2,429
	06309270	North Fork Buffalo Creek Near Arminto, Wyoming	87	74	68	61	55	81	383	1,674	775	195	102	83	3,639
	06309280	Buffalo Creek Below North Fork Buffalo Creek Near Arminto, Wyoming	0	0	0	0	0	0	51	1,904	700	41	3	1	2,700
	06309450	Beaver Creek Below Bayer Creek Near Barnum, Wyoming	183	160	144	127	117	163	545	1,824	1,026	395	238	186	5,106
	06309460	Beaver Creek Above White Panther Ditch Near Barnum, Wyoming	603	555	539	513	479	566	1,040	2,191	1,524	876	673	595	10,154
	06311000	North Fork Powder River Near Hazelton, Wyoming	305	230	190	148	127	143	546	3,946	3,634	1,076	481	347	11,173
	06313950	North Fork Crazy Woman Creek Below Pole Creek Near Buffalo, Wyoming	670	487	403	316	261	305	1,062	5,365	5,452	1,909	946	698	17,873
	06314000	North Fork Crazy Woman Creek Near Buffalo, Wyoming	681	494	412	327	273	313	1,079	5,238	5,249	1,878	934	700	17,577
	06314500	North Fork Crazy Woman Creek Below Spring Draw Near Buffalo, Wyoming	581	430	358	268	229	273	1,081	7,809	7,212	2,176	946	671	22,032
	06315480	Poison Creek Below Tetley Spring Near Mayoworth, Wyoming	224	179	155	129	114	128	321	1,133	1,112	490	290	233	4,508
	06315490	Poison Creek Near Mayoworth, Wyoming	256	207	181	153	134	152	362	1,195	1,174	541	331	268	4,954
	06315500	Middle Fork Crazy Woman Creek Near Greub, Wyoming	728	568	492	398	350	426	1,222	5,982	5,545	2,015	1,045	796	19,565
	06317300	Sourdough Creek Near Buffalo, Wyoming	73	56	47	36	30	33	96	822	847	265	115	84	2,504
	06317340	Little Sourdough Creek Near Buffalo, Wyoming	34	20	7	3	2	5	188	201	133	35	16	25	668
	06319470	South Rock Creek at Forest Boundary Near Buffalo, Wyoming	461	353	296	234	199	220	818	5,550	5,256	1,631	730	520	16,268
	06319480	South Rock Creek Above Red Canyon Near Buffalo, Wyoming	439	336	278	216	186	208	790	5,473	5,219	1,595	706	502	15,949
	06321500	North Piney Creek Near Story, Wyoming	829	650	535	441	374	472	1,688	10,668	9,908	2,619	1,137	897	30,217

Source: HKM Engineering et al. 2002a.

Table 3.4-2
Summary of Estimated Stream Flows at Ungauged Natural Flow Nodes in the Powder/Tongue River Basin

Basin	Station Name	Estimated Average Stream Flow for 1970-1999 (acre-feet)												
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Tongue	Rapid Creek Just Below Little Rapid Creek in Section 32, T55N, R85W	98	73	65	58	49	54	156	1,050	1,453	407	169	110	3,742
	Beaver Creek at Bottom of Section 26, T55N, R85W	27	20	18	16	14	15	43	290	402	113	47	30	1,034
	Soldier Creek at Right Edge of Section 28, T56N, R85W	60	44	39	35	30	33	95	640	886	248	103	67	2,281
	Prairie Dog Creek Just Above Dutch Creek in Section 34, T57N, R83W	487	1,314	3,453	2,229	3,493	2,296	1,963	1,560	1,253	886	725	673	20,332[1]
Powder	Red Fork Powder River Just Below North & South Forks Red Fork Powder River in Section 29, T44N, R84W	2,706	2,511	2,415	2,290	2,104	2,477	4,405	9,771	7,396	4,024	3,071	2,695	45,866
	Kelly Creek at Top of Section 21, T49N, R82W	73	55	45	36	30	35	132	629	646	228	106	75	2,092
	Little North Fork Crazy Woman Creek Just Below Grossett Canyon in Section 14, T49N, R83W	166	125	103	82	69	80	299	1,425	1,463	516	240	170	4,737
	Muddy Creek at Diversion Near East Side of Section 35, T49N, R83W	153	115	94	75	63	73	275	1,309	1,344	474	220	156	4,351
	Billy Creek at Diversion to O'Malley Draw in Section 13, T48N, R83W	96	79	69	59	52	59	151	481	477	212	125	98	1,957
	Little Piney Creek Just Below Bear Gulch in324 Section 28, T53N, R83W	324	421	625	676	1,295	1,250	811	544	470	309	338	273	7,336[1]
	North & South Forks Shell Creek (Combined), at Confluence of Little North Fork Shell Creek and North Fork Shell Creek in Section 11, and Confluence of Unnamed Tributary & South Fork Shell Creek in Section 14; all in T52N, R83W	56	42	35	28	23	27	114	701	745	219	90	62	2,141
	Johnson Creek at Top of Section 22, T51N, R83W	53	41	33	27	22	26	109	672	714	210	86	59	2,052
	French Creek at Penrose Ditch Diversion in Section 27, T51N, R83W	128	98	80	64	53	62	262	1,614	1,715	504	207	142	4,928

Note: The monthly and annual flows for Prairie Dog Creek and Little Piney Creek are the average of the dry, normal, and wet year monthly and annual flows.

Source: HKM Engineering et al. 2002a.

Table 3.4-3
Surface Water Availability in the Powder/Tongue River Basin

Subbasin	Surface Water Availability (acre-feet per year)		
	Wet Years	Normal Years	Dry Years
Little Bighorn River	152,000	113,000	81,000
Tongue River	473,000	326,000	218,000
Clear Creek	213,000	124,000	80,000
Crazy Woman Creek	69,000	32,000	16,000
Powder River	547,000	324,000	16,000
Little Powder River	48,000	12,000	3,000
Total	**1,502,000**	**931,000**	**414,000**

Source: HKM Engineering et al. 2002a.

3.4.1.2 Northeast Wyoming River Basins

Stream flow in the major drainages of the Northeast Wyoming River Basins is much less than in the Powder/Tongue River Basin due to the absence of a major mountain range to provide snowmelt runoff. Surface water availability in the Northeast Wyoming River Basins is presented in detail in the Northeast Wyoming River Basins Water Plan (HKM Engineering et al. 2002b), and pertinent data are summarized in this section.

A summary of average monthly and annual flows at gauging stations is presented in **Table 3.4-5**. There are approximately 25 maintained gauging stations in the Cheyenne and Belle Fourche drainages. Many of these stations measure unnatural flow dominated by irrigation practices. As most surface water flow in the Northeast Wyoming River Basins is intermittent to ephemeral, there are many ungauged drainages. Thus, surface water flow estimates and ultimately surface water availability in the Northeast Wyoming River Basins is based on estimates from regression equations developed by the USGS (Miller 2003). **Table 3.4-6** summarizes estimates of flow in ungauged ephemeral and intermittent drainages. Total annual available flow for the Northeast Wyoming River Basins is summarized in **Table 3.4-7**. The Belle Fourche and Cheyenne river basins carry most of the available surface water flow in the Northeast Wyoming River Basins. Appendix A contains surface water quality data for selected drainages in the Northeast Wyoming River Basins; **Table 3.4-4** presents EC and SAR values for drainages in the PRB.

3.4.2 Groundwater Availability

Groundwater availability is determined more by interference caused by groundwater drawdown on permitted municipal and domestic water users than on the amount of available water. Because many stratigraphic formations contain a considerable supply of water in storage relative to probable demands for water, groundwater supply is an issue of aquifer drawdown and aquifer water quality and impacts to water supply wells from continued drawdown in an aquifer. An estimate of recoverable groundwater in the PRB is provided in **Table 3.4-8**. This section summarizes the major water supply aquifers of the PRB and their hydraulic characteristics that ultimately determine drawdown from wells.

Table 3.4-4
Stream Electrical Conductivity and Sodium Absorption Ratio Values for the PRB

Subwatershed	Drainage Area (square mile)	Station Location	Station ID #	EC (µS/cm)[1]			SAR			Water Quality Period of Record
				7Q10[2]	Low Monthly Flow	Maximum Monthly Flow	7Q10	Low Monthly Flow	Maximum Monthly Flow	
Upper Tongue River	1,477	Tongue River at state line near Decker, Montana	06306300	1,179	731	318	1.29	0.86	0.36	1981-2001
Upper Powder River	6,050	Powder River at Arvada, Wyoming	06317000	NA	3,400	1,797	NA	7.83	4.76	1981-2001
Salt Creek	769	Salt Creek near Sussex, Wyoming	06313400	6,741	5,668	5,204	25.1	23.6	18.9	1981-2001
Crazy Woman Creek	945	Crazy Woman Creek at Upper Station near Arvada, Wyoming	06316400	NA	1,937	1,066	NA	2.26	1.29	1972-1990; 2001
Clear Creek	1,110	Clear Creek near Arvada, Wyoming	06324000	3,879	1,276	883	3.96	1.46	1.07	1987-1989; 2001
Middle Powder River	8,088	Powder River at Moorhead, Montana	06324500	4,400	2,154	1,421	6.15	4.62	3.92	1930-1972; 1975-2001
Little Powder River	1,235	Little Powder River above Dry Creek near Weston, Wyoming	06324970	NA	3,300	1,785	NA	6.94	4.44	1981-2001
Antelope Creek	959	Antelope Creek near Teckla, Wyoming	06364700	NA	2,354	1,800	NA	2.6	2.82	1978-1981; 2001
Upper Cheyenne River	5,270	Cheyenne River near Riverview, Wyoming	06386500	NA	4,127	2,271	NA	8.66	5.63	1969-1970 1975-1980
Upper Belle Fourche River	1,690	Belle Fourche River below Moorcroft, Wyoming	06426500	NA	2,755	1,532	NA	6.77	3.81	1981-1993; 2000-2001

[1]µS/cm = micoSiemens per centimeter

[2]7Q10 = The average low flow for 7 consecutive days that occurs once every 10 years or has a 10 percent chance of occurrence in any given year.

Source: BLM 2003a.

Table 3.4-5
Summary of Stream Flows at Gauging Stations in the Northeast Wyoming River Basins

Basin	Station Number	Station Name	Natural Flow	Average Stream Flow for 1970-1999 (acre-feet)												
				Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Cheyenne	06364700	Antelope Creek near Teckla, Wyoming	NO	97	64	18	22	159	545	291	1,520	1,005	361	148	93	4,323
	06365300	Dry Fork Cheyenne River near Bill, Wyoming	NO	3	6	5	3	17	44	20	194	37	30	8	1	366
	06365900	Cheyenne River near Dull Center, Wyoming	NO	176	101	26	36	407	798	633	3,475	2,247	854	425	66	9,244
	06375600	Little Thunder Creek near Hampshire, Wyoming	NO	3	4	5	5	48	86	11	824	131	135	100	2	1,354
	06376300	Black Thunder Creek near Hampshire, Wyoming	NO	307	16	0	51	272	846	308	1,788	671	549	405	498	5,710
	06378300	Lodgepole Creek near Hampshire, Wyoming	NO	1	2	1	1	2	45	33	223	91	32	34	1	464
	06386000	Lance Creek near Riverview, Wyoming	NO	133	111	83	333	870	1,205	902	5,594	2,717	2,993	2,078	694	17,713
	06386500	Cheyenne River near Spencer, Wyoming	NO	275	233	71	1,023	1,487	866	2,040	20,050	9,286	2,103	535	3,453	41,423
	06392900[1]	Beaver Creek at Mallo Camp near Four Corners, Wyoming	YES	112	102	100	97	98	127	138	136	144	131	120	112	1,415
	06392950[2]	Stockade Beaver Creek near Newcastle, Wyoming	NO	786	763	785	769	721	877	785	654	675	699	730	751	8,996
	06394000[3]	Beaver Creek near Newcastle, Wyoming	NO	876	804	796	881	2,381	5,716	2,353	3,250	2,339	1,106	797	497	21,796
	06395000	Cheyenne River at Edgemont, South Dakota	NO	1,910	1,416	684	800	3,106	8,847	4,275	14,156	10,524	4,720	3,269	1,700	55,407

Table 3.4-5 (Continued)

Basin	Station Number	Station Name	Natural Flow	Average Stream Flow for 1970-1999 (acre-feet)												
				Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Belle Fourche	06425720	Belle Fourche River below Rattlesnake Creek near Piney, Wyoming	NO	6	6	12	24	79	212	66	685	236	101	149	20	1,596
	06425780	Belle Fourche River above Dry Creek near Piney, Wyoming	NO	21	6	14	45	190	611	131	1,097	282	239	179	70	2,887
	06425900	Caballo Creek at Mouth near Piney, Wyoming	NO	13	10	1	10	27	221	30	788	76	99	45	18	1,339
	06425950	Raven Creek near Moorcroft, Wyoming	YES	6	0		2	54	169	3	78	2		13	0	333
	06426400	Donkey Creek near Moorcroft, Wyoming	NO	34	180	33	20	37	1,707	145	2,309	1047	17	5	4	4,434
	06426500	Belle Fourche River below Moorcroft, Wyoming	NO	682	203	149	420	1,761	4,664	2,268	5,169	2,134	997	515	281	19,243
	USBR Gage	Belle Fourche River - total Keyhole Reservoir Discharge	NO	114	320	0	1	0	881	784	2,149	2,402	4,821	4,526	761	16,759
	06427500	Belle Fourche River below Keyhole Reservoir	NO	257	260	103	104	96	1,015	760	2,194	2,362	4,833	4,600	833	17,417
	06428200	Belle Fourche River near Alva, Wyoming	NO	1,826	1,648	1,063	1,375	2,419	7,705	7,511	10,171	7,526	4,925	4,981	1,998	53,148
	06428500	Belle Fourche River at Wyoming - South Dakota State Line	NO	2,307	2,082	1,272	1,741	3,233	10,987	10,552	15,575	12,134	6,507	5,402	2,336	74,127
	06429905	Sand Creek near Ranch A near Beulah, Wyoming	YES	1,312	1,307	1,285	1,237	1,092	1,231	1,288	1,881	1,776	1,499	1,480	1,334	16,722
	06430500	Redwater Creek at Wyoming-South Dakota State Line	NO	2,108	2,077	2,043	2,006	1,928	2,240	2,367	3,697	3,135	2,190	2,245	2,119	28,155
Niobrara	06454000[4]	Niobrara River at Wyoming-Nebraska State Line	NO	150	151	159	179	207	316	297	249	208	143	151	118	2,328

[1]Study Period: 1975-1982, 1992-1997
[2]Study Period: 1975-1982, 1992-1997
[3]Study Period: 1975-1982, 1992-1997
[4]Study Period: 1970-1994

Source: HKM Engineering et al. 2002b.

Table 3.4-6
Summary of Estimated Stream Flow at Ungauged Flow Nodes in the Northeast Wyoming River Basins

Basin	Station Name/Location	Estimated Average Stream Flow for 1970-1999 (acre-feet)												
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Cheyenne	Willow Creek at mouth in Section 28, T38N, R72W	9	0	0	3	76	238	4	109	3	10	18	0	470
	Woody Creek at mouth in Section 5, T39N, R69W	1	0	0	0	10	31	0	14	0	1	2	0	59
	Lake Creek at mouth in Section 30, T40N, R68W	3	0	0	1	23	72	1	33	1	3	5	0	142
	Sheep Creek at mouth in Section 7, T40N, R67W	1	0	0	0	7	23	0	11	0	1	2	0	45
	Wagonhound Creek at mouth in Section 31, T41N, R67W	2	0	0	1	15	48	1	22	1	2	4	0	96
	Snyder Creek at mouth in Section 23, T40N, R64W	8	0	0	3	71	223	3	103	3	10	17	0	441
	Boggy Creek at mouth in Section 32, T40N, R63W	2	0	0	1	20	61	1	28	1	3	5	0	122
	Sevenmile Creek at mouth in Section 34, T40N, R63W	1	0	0	0	10	30	0	14	0	1	2	0	58
	Mule Creek at mouth in Section 6, T39N, R61W	4	0	0	1	31	96	1	44	1	4	7	0	189
	Robbers' Roost Creek at mouth in Section 23, T40N, R61W	5	0	0	2	43	136	2	63	2	6	10	0	269
	Beaver Creek just below Mush Creek in Section 32, T44N, R62W	33	0	0	10	292	1,187	15	546	16	51	77	0	2,227
	Oil Creek at mouth in Section 26, T43N, R62W	346	0	0	61	3,958	6,405	377	2,930	87	275	2,425	0	16,864
	Blacktail Creek at mouth in Section 2, T41N, R61W	200	195	193	186	163	188	191	293	262	240	215	198	2,524
	Dry Beaver Creek just above Beaver Creek in Section 4, T47N, R60W	107	99	97	92	95	111	133	136	141	130	118	107	1,366
Belle Fourche	Dry Creek at mouth in Section 29, T47N, R70W	2	0	0	1	14	43	1	20	1	2	3	0	87
	Yellow Hammer Creek at mouth in Section 10, T47N, R70W	1	0	0	0	5	16	0	7	0	1	1	0	31
	Whitetail Creek at mouth in Section 32, T48N, R69W	1	0	0	0	8	24	0	11	0	1	2	0	47
	Four Horse Creek at mouth in Section 11, T48N, R69W	8	0	0	3	73	228	4	105	3	10	17	0	451
	Timber Creek at mouth in Section 2, T48N, R69W	2	0	0	1	19	60	1	27	1	3	5	0	119
	Buffalo Creek at mouth in Section 14, T49N, R68W	11	0	0	3	93	290	4	133	4	12	22	0	572
	Donkey Creek just upstream of gauge in Section 30, T50N, R68W	0	0	0	413	1,135	3,278	1,555	4,005	946	0	0	0	11,332
	Trail Creek at mouth in Section 24, T50N, R68W	1	0	0	0	10	32	0	15	0	1	2	0	61
	Dry Creek at mouth in Section 24, T50N, R68W	2	0	0	1	14	45	1	21	1	2	3	0	90
	Robinson Creek at mouth in Section 18, T50N, R67W	1	0	0	0	4	14	0	6	0	1	1	0	27
	Duck Creek at mouth in Section 8, T50N, R67W	5	0	0	4	59	115	4	53	2	5	24	0	271
	Miller Creek at mouth in Section 9, T50N, R67W	58	0	0	41	672	1,314	44	604	18	57	271	0	3,079
	Smoke Creek at mouth in Section 9, T50N, R67W	1	0	0	1	17	34	1	16	0	1	7	0	78

Table 3.4-6 (Continued)

Basin	Station Name/Location	Estimated Average Stream Flow for 1970-1999 (acre-feet)												
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
	Berger Creek at mouth in Section 12, T50N, R67W	2	0	0	2	28	56	2	26	1	2	11	0	130
Belle Fourche (conti.)	Lone Tree Creek at mouth in Section 26, T51N, R67W	5	0	0	4	62	121	4	55	2	5	25	0	283
	Wind Creek at mouth in Section 13, T50N, R67W	133	0	0	93	1,539	3,008	101	1,382	41	129	620	0	7,046
	Deer Creek at mouth in Section 23, T51N, R67W	28	0	0	20	325	635	21	292	9	27	131	0	1,488
	Eggie Creek at mouth in Section 21, T51N, R66W	4	0	0	3	45	88	3	40	1	4	18	0	206
	Mule Creek at mouth in Section 15, T50N, R66W	17	0	0	12	197	385	13	177	5	17	79	0	902
	Cottonwood Creek at mouth in Section 35, T51N, R66W	5	0	0	3	52	102	3	47	1	4	21	0	238
	Arch Creek at mouth in Section 11, T51N, R66W	7	0	0	2	62	195	3	90	3	8	15	0	385
	Inyan Kara Creek at mouth in Section 25, T52N, R66W	1,154	1,142	1,122	1,083	1,028	1,311	1,128	1,750	1,553	1,319	1,310	1,165	15,065
	Cabin Creek at mouth in Section 14, T52N, R66W	5	0	0	2	47	148	2	68	2	6	11	0	291
	Miller Creek at mouth in Section 12, T52N, R66W	5	0	0	1	39	122	2	56	2	5	9	0	241
	Lytle Creek at mouth in Section 8, T53N, R65W	3	0	0	1	27	84	1	39	1	4	6	0	166
	Whitetail Creek at mouth in Section 14, T54N, R65W	83	82	81	78	69	77	81	118	112	94	93	84	1,052
	Blacktail Creek at mouth in Section 12, T54N, R65W	210	209	205	198	175	197	206	301	284	240	237	213	2,675
	Beaver Creek at mouth in Section 1, T55N, R64W	459	457	449	433	382	431	451	658	621	524	518	467	5,850
	East Creek at mouth in Section 32, T55N, R63W	48	48	47	45	40	45	47	68	65	55	54	49	611
	Arnold Creek at mouth in Section 28, T55N, R63W	22	22	22	21	18	21	22	32	30	25	25	23	283
	Horse Creek at mouth in Section 19, T56N, R61W	76	75	74	71	63	71	74	108	102	86	85	77	962
	Pine Creek at mouth in Section 33, T56N, R61W	172	171	168	162	143	161	169	247	233	197	194	175	2,192
	Kilpatrick Creek at mouth in Section 3, T55N, R61W	69	69	68	65	58	65	68	99	94	79	78	70	882
	Kruger Creek at mouth in Section 11, T55N, R61W	34	34	33	32	28	32	33	48	46	39	38	34	431
	Oak Creek at mouth in Section 20, T55N, R60W	216	215	211	203	179	202	212	309	292	247	243	219	2,748
	South Redwater Creek just above Sand Creek in Section 31, T53N, R60W	565	563	553	533	470	530	555	810	765	646	637	575	7,202
	Redwater Creek just above South Redwater Creek in Section 31, T53N, R60W	287	286	281	271	239	269	282	411	388	328	324	292	3,658

Note: Monthly and annual flows are averaged from the wet, dry, and normal estimated flows.

Source: HKM Engineering et al. 2002b.

Table 3.4-7
Surface Water Availability in the Northeast Wyoming River Basins

Subbasin	Surface Water Availability (acre-feet per year) Wet Years	Normal Years	Dry Years
Redwater Creek	34,000	26,000	17,000
Beaver Creek	30,000	20,000	14,000
Cheyenne River	103,000	31,000	5,000
Belle Fourche River	151,000	71,000	13,000
Total	**318,000**	**148,000**	**49,000**

Source: HKM Engineering et al. 2002b.

Table 3.4-8
Recoverable Groundwater in the PRB

Hydrogeologic Unit	Surface Area (acres)	Average Formation Thickness (feet)	Percentage of Sand/Coal	Average Sand/Coal Thickness (feet)	Specific Yield (percent)	Recoverable Groundwater (acre-feet)
Wasatch-Tongue River Aquifer Sandstones	5,615,609	2,035	50	1,018	13	743,121,790
Wasatch-Tongue River Aquifer Coals	4,988,873	2,035	6.2	126	0.40	2,516,519
Lebo Confining Layer Sandstones	6,992,929	1,009	33	250	13	227,137,339
Tullock Aquifer Sandstones	7,999,682	1,110	52	430	13	447,246,784

Source: BLM 2003a.

3.4.2.1 Powder/Tongue River Basin

There are five main aquifers in the Powder/Tongue River Basin that can be used for water supply. These aquifers are listed below in order from oldest to youngest. **Table 3.4-9** summarizes the hydrologic properties of the major aquifers.

- Madison Aquifer System
- Dakota Aquifer System
- Fox Hills/Lance Aquifer System
- Fort Union/Wasatch Aquifer System
- Quaternary Alluvial Aquifer System

Madison Aquifer System: The Madison Aquifer is the deepest aquifer and lies within the Paleozoic Tensleep Sandstone, Amsden Formation, Madison Limestone, Bighorn Dolomite, and Flathead Sandstone. The Madison Limestone is the thickest unit and is approximately 200 to 1,100 feet thick with a transmissivity ranging from 500 to 90,000 gpd/ft. Well yields from this aquifer have been as

Table 3.4-9
Summary of Groundwater Availability/Development Potential of Major Aquifer Systems, Powder/Tongue River Basin Plan Area

Major Aquifer System	Geologic Unit	Thickness (feet)	Lithologic Character	Hydrological Character[1,2,3]	General Water Quality[3]	Availability/Development Potential[3.4]	Remarks[3]
Quaternary Alluvial Aquifer System	Alluvium and Terrace Deposits	0-100+	Silt, sand, and gravel; unconsolidated and interbedded; present along most streams.	Yield of 50 to 300 gpm may be possible, often through induced recharge. Terraces topographically high and often drained. Specific capacity 0.3-7 gpm/ft; permeability, 380 and 1,100 gpd/ft^2, and transmissivity, 9,700 and 20,300 gpd/ft from two tests in Sheridan County (Lowry and Cummings 1966). Coarser deposits have better aquifer properties.	TDS content generally ranges from about 100 to >4,000 mg/L. Chemical characteristics of water differ geographically. Chemical type and mineralization of the water can be expected to vary depending on underlying rock types and the nature and degree of interconnection with surface water. Alluvial deposits in the western part of the planning area generally contain water of better quality than alluvial deposits in the eastern part. Suitability for municipal/public, domestic, irrigation, and stock use is variable and dependent on location and above factors.	Historical source for municipal/public, domestic, and stock use. Production has ranged up to 250 gpm with induced infiltration of surface water. Groundwater development potential generally better in coarse-grained deposits and poorer in fine-grained materials. Moderate to high yields might be possible to optimally located and properly designed wells if induced infiltration from surface water can be tolerated in the upper reaches of the Powder River and Piney, Clear, and Crazy Woman creeks. Moderate supplies may be able to be developed in thicker deposits of coarse material in the alluvuim of Prairie Dog Creek as well as the alluvium of the Tongue River and Dutch Creek (Lowry and Cummings 1966; Whitcomb et al. 1966).	Quaternary alluvial aquifers generally in hydraulic connection with all bedrock aquifers in outcrop areas and also with surface waters. Alluvial aquifers in larger valleys provide hydraulic interconnection between otherwise hydraulically isolated bedrock aquifers (Whitcomb 1965). Alluvial aquifers also serve as interchange point and storage for groundwater in the hydrologic cycle (Davis and Rechard 1977; Davis 1976); induced recharge from surface waters is probable in areas of extensive development.
Fort Union/Wasatch Aquifer System	Wasatch formation	500 to 2,000±	Fine- to coarse-grained lenticular sandstones interbedded with shale and coal. Yields water from, lenticular sandstone and to a lesser extent from jointed coal and clinker beds (Hodson, Pearl, and Druse 1977). Divided into two conglomeratic members (Kingsbury and Moncrief members) near the Bighorn Mountains (Lowry and Cummings 1966).	Yields generally <15 gpm. Specific capacity of Wasatch wells and those completed in the coarse-grained facies of the Wasatch Formation in Sheridan County averaged 0.33 and 1.0 gpm/ft respectivley; permeability 6.5 gpd/ft^2 (one test - coal, Sheridan County); transmissivity 520 gpd/ft (one test - coal, Sheridan County) and 2,200 gpd/ft (one test - sandstone, Sheridan County) (Lowry and Cummings 1966).	TDS content of waters is variable and ranges from 141 to 6,620 mg/L (Larson 1984). Sulfate and iron content range from 0.6 – 4,080 mg/L and 0 - 25 mg/L, respectively, and water varies from soft to very hard. Dominant cations generally are sodium, calcium and magnesium, sodium and calcium, or sodium and magnesium. (Lowry and Cummings 1966; Whitcomb et al. 1966)	Important local source for domestic and stock water supply. Yields from fine-grained facies generally small and barely adequate for stock and domestic use and generally can be expected to be <15 gpm. Wells completed in the Kingsbury Conglomerate and Moncrief Members may have potential for higher production. Water quality generally suitable for domestic supplies although undesireable constituents may make other water sources more attractive, if available. Water quality suitability for stock ranges from poor to good. Generally unsuitable for irrigation due to high salinity and sodium content.	Kingsbury Conglomerate and Moncrief Members located at the base of the mountains in Sheridan Counties.

Table 3.4-9 (Continued)

Major Aquifer System	Geologic Unit	Thickness (feet)	Lithologic Character	Hydrological Character[1,2,3]	General Water Quality[3]	Availability/Development Potential[3,4]	Remarks[3]
Fort Union/Wasatch Aquifer System (continued)	Fort Union Formation	1,200-3,900	Sandstone, fine- to medium-grained, lenticular, interbedded with siltstone, coal, and shale. "Clinker" associated with coal outcrops.	Flowing yields of 1-60 gpm reported where confined. Pumped yields up to 250 gpm with several hundred feet of drawdown (eastern Campbell County, east of planning area). Specific capacity for 85 wells in Sheridan County averaged 0.42 gpm/ft; permeability 2.5 and 7.9 gpd/ft^2 transmissivity 10 and 95 gpd/ft, and storage coefficient 9.0 X 10^{-5} and 3.5 X 10^{-4} for tests performed on two wells in Sheridan County (Lowry and Cummings 1966). Coal and clinker generally better aquifer properties than sandstones. Locally, clinker transmissivity up to 3,000,000 gpd/ft; anisotropy and leaky confining layers are common.	TDS content of waters is variable and ranges from 484-4,630 mg/L (Larson 1984). Sulfate and iron content range from 0.3-1,870 mg/L and 0.06-19 mg/L, respectively. Water varies from soft to very hard and is generally a sodium bicarbonate type (Lowry and Cummings 1966; Whitcomb et al. 1966). Water co-produced with CBNG is predominantly sodium bicarbonate type with TDS content and SAR (15 samples) of 540-2,010 mg/L (mean of 1,309 mg/L) and 7.7-32 (mean of 19.82), respectively in planning area (Rice et al. 2000). BLM Wyodak EIS assumed average TDS concentration of 764 mg/L (BLM 1999a,b).	Important, extensively used relatively shallow (<1,000 feet in depth) local source for domestic and stock supply. Low yields, generally less than 25 gpm, can be expected. Four of the 12 municipal/public supply wells in service for the City of Gillette (east of planning area) as of 1994 had been tested at pumping rates ranging from 50 to 130 gpm (Wester-Wetstein and Associates, Inc. 1994).	Total of 6,820 CBNG wells permitted with WSEO in planning area as of 12/31/00. Maximum, minimum, and mean depths and range of actual yields listed on permits were 92-4,100 (mean 637) feet below ground surface, and 1-60 (mean 49) gpm, respectively. Range of depths to main water bearing zone listed on WSEO permits were 58-3,816 (mean 580) feet below ground surface. BLM Exxon Pistol Point EA assumed average water production for each CBNG well to average between 30 and 45 gpm (BLM 1992). BLM Lower Prairie Dog Creek EA assumed average water production for each CBNG well to be 15 gpm (BLM 1999). BLM Wyodak EIS assumed average expected water production to be 12 gpm over the estimated 12-year life of each CBNG well (BLM 1999a,b). BLM Wyodak Drainage EA assumed average water production for each CBNG well to be 11.1 gpm (BLM 2000).
Fox Hills/Lance Aquifer System	Lance Formation	600-1,900 (north) 1,950-3,000 (south)	Sandstone, fine- to medium-grained, lenticular, interbedded with sandy siltstone, claystone, and shale.	Generally yields less than 15 gpm with specific capacities 0.03-0.16 gpm/ft in planning area. Limited development due to uneconomical drilling depths. In eastern area of Powder River structural basin, yields up to 350 gpm but with large drawdowns and long well completion intervals; permeability 34 gpd/ft^2; transmissivity 76-2100 gpd/ft for wells also completed in Fox Hills Sandstone.	TDS content in waters generally range from <500-3,060 mg/L. Composition variable, mainly sodium sulfate or calcium sulfate. Variable iron (0-6.03 mg/L) and sulfate (<100-1,780 mg/L) content, SAR 1.9-39. Generally undesireable for domestic water source due to possible high iron, manganese, and sulfate content. Generally fair to poor for stock use. Unsuitable for irrigation due to high salinity and/or high SAR.	Historical source for domestic and stock supply. Generally yields less than 15 gpm in planning area. Development limited due to uneconomical drilling depths. Water quality generally suitable for domestic supplies although undesireable constituents may make other water sources more attractive, if available. Water quality suitability for stock ranges from poor to good. Generally unsuitable for irrigation due to high salinity and/or sodium content.	--

Table 3.4-9 (Continued)

Major Aquifer System	Geologic Unit	Thickness (feet)	Lithologic Character	Hydrological Character[1,2,3]	General Water Quality[3]	Availability/Development Potential[3,4]	Remarks[3]
Fox Hills/Lance Aquifer System (continued)	Fox Hills Sandstone	0-700	Sandstone, fine- to medium-grained, interbedded with shale and siltstone.	Generally yields less than 15 gpm with specific capacities, 0.03-0.37 gpm/ft in planning area. Transmissivity, 76-1,600 gpd/ft for wells also completed in Lance Formation. Limited development due to uneconomical drilling depths.	Similar to Lance Formation. Water suitable for domestic use, usually present only near outcrop. Water suitable for stock use generally found at depths of up to 1,000 feet, away from outcrop. The quality of water may be unsatisfactory for domestic and stock use where the the aquifer is deeper than 1,000 feet (Crist and Lowry 1972).	Historical source for municipal/public, domestic, and stock supply. Generally yields less than 15 gpm in planning area. No more than 50 gpm can be expected from wells completed in wells in the planning area (Natrona County). Well for Town of Edgerton produced 25 gpm with a specific capacity of 0.037 gpm/ft (Crist and Lowry 1972). Development limited due to uneconomical drilling depths. Tested yields of Gillette municipal/public supply wells (east of planning area) have ranged from 85 to 705 gpm (Wester-Wetstein and Associates, Inc. 1994).	High fluoride content may be of concern in eastern part of planning area. Has been used as municipal/public water supply source for Town of Edgerton. Has been used for oil well water flooding operations in eastern Powder River structural basin.
Dakota Aquifer System	Muddy Sandstone (New Castle Sandstone)	0-40±	Light gray, fine-grained, lenticular sandstone and siltstone often termed a member of Thermopolis Shale.	Minor unit of Dakota Aquifer System. Oil field data (Powder River structural basin): porosity 5-20 percent; permeability <7 gpd/ft^2 ; transmissivity <150 gpd/ft.	No data in planning area.	No data in planning area. Groundwater possibilities in planning area generally not known. Probably capable of yielding small quantities of no more than 10 gpm water to wells. Deep drilling depths probably would preclude consideration other than at outcrops. Dakota Aquifer System historical source for domestic and stock use in eastern Powder River structural basin.	--
	Cloverly Formation	140-150	Interbedded dark shale and brown siltstone with 15-45 feet of basal, fine- to coarse-grained well sorted sandstone.	Flowing yields of 1-40 gpm, up to 250 gpm reported for pumped wells (south of planning area); specific capacity 0.12-0.2 gpm/ft. Oil field data: porosity 15-18 percent, and permeability 0.4-4 gpd/ft^2, and transmissivity 7-230 gpd/ft.	Water from Cloverly and Morrison formations in Natrona County predominantly sodium bicarbonate type. Other types include calcium bicarbonate, calcium sulfate, sodium sulfate, and calcium sulfate. TDS content ranges between 300 and 3,000 mg/L.	Generally deeply buried in planning area except at outcrops. Yields small supplies to springs at outcrops. Well yields of 5 to 20 gpm may be expected. Yields of greater than 100 gpm may be possible from complete section of rocks.	--
Madison Aquifer System	Tensleep Sandstone	50-250 (Northwestern Basin) <500 (Southwestern Basin)	Fine- to medium-grained, massive, crossbedded sandstone with occasional thin dolomite beds.	Unit of Madison Aquifer System. Flowing yields up to 400 gpm; specific capacity 1 gpm/ft. Oil field data: porosity 0-24 percent, permeability 0-21 gpd/ft^2, and transmissivity 0-1900 gpd/ft.	Water type is variable (magnesium carbonate, calcium magnesium sulfate, sodium sulfate, calcium sodium sulfate, calcium sulfate) and concentration of TDS varies directly to distance from the outcrop and generally ranges from <300-3,240 mg/L. Generally very hard but suitable for domestic, stock, and irrigation use at or near outcrop. (Crist and Lowry 1972; Whitcomb et al. 1966) TDS content 204-2,930 mg/L in six samples in Natrona County (Larson 1984).	Sandstone generally well cemented, but primary permeability is sufficient at most locations to permit yields of 50 gpm to wells. There is potential for higher yields where secondary permeability is high. Yield of 600 gpm reported for an irrigation well at the foot of the Bighorn Mountains in Johnson County. Development may be limited economically due to deep drilling depths in Johnson County in outcrop area or in narrow belt generally less than about 1 mile paralleling the east margin of the outcrop (Whitcomb et al. 1966; Crist and Lowry 1972).	--

Table 3.4-9 (Continued)

Major Aquifer System	Geologic Unit	Thickness (feet)	Lithologic Character	Hydrological Character[1,2,3]	General Water Quality[3]	Availability/Development Potential[3,4]	Remarks[3]
Madison Aquifer System (continued)	Amsden Formation	150-300 (Northwestern Basin) 0-200 (Southwestern Basin)	Red and purple shale with some sandstone, cherty dolomite, and limestone.	Aquitard unless fractured.	--	Generally deeply buried in planning area except at outcrops. Groundwater possibility generally not known.	--
	Madison Limestone	1,100± (Northwestern Basin) 200-400 (Southwestern Basin)	Limestone, dolomitic limestone, and dolomite, sandy at base.	Principal unit of Madison Aquifer System. Flowing yields over 4,000 gpm but highly variable, specific capacity <1 to 50 but is flow-dependent, transmissivity 500-90,000 gpd/ft or higher and highly variable.	Waters at outcrop: TDS <600mg/L, predominantly calcium and magnesium bicarbonate type water. TDS increases basinward to > 3,000 mg/L, sodium sufate chloride predominating. Fluoride enrichment characteristic of Madison System waters throughout the Powder River structural basin. Concentrations of radionuclides could be of concern in some areas.	Probably most important high yield aquifer in Wyoming. Historical source for municipal/public water supply, industrial, irrigation, and stock use in Powder River structural basin. Several fish hatcheries use Pahasapa/Madison aquifer as water source in northeastern part of Powder River structural basin. Yields variable geographically and dependent on secondary permeability. Drilling depths may inhibit development.	Total estimated recharge to the Madison Limestone in the Powder River structural basin in 1973 was approximately 75,000 acre-feet/year (WSEO 1976).
	Bighorn Dolomite	400-500 (Northwestern Basin) absent (Southwestern Basin)	Massive dolomite, becoming thin-bedded at top and sandy at base.	Generally deeply buried except in outcrop areas. Groundwater possibilities generally not known.	--	Groundwater possibilities generally not known. Probably would yield water to wells depending on secondary permeability.	--
	Flathead Sandstone	345± (Northwestern Basin) 90 (Southwestern Basin)	Tan to reddish sandstone, locally conglomeratic, interbedded with green shale and siltstone.	Minor unit of Madison Aquifer System. Not exploited due to deep burial; however, a few wells yield water near outcrops.	--	Groundwater possibilities generally not known. Probably would yield water to wells depending on secondary permeability. Generally deeply buried except in outcrop areas. Yields small quantities of water to springs from sandstone and conglomerate in the Bighorn Mountains (McCullough 1966; Crist and Lowry 1972)	--

[1]Reported yields may reflect development needs rather than aquifer capability; higher yields can sometimes be expected, with corresponding drawdown increases. Reported water well transmissivities or permeabilities may be for wells completed in two aquifers or screened in only part of a single aquifer. Reported ranges include varying amounts of data (Featers et al. 1981).
[2]Oilfield (and USGS test) data are variously derived resulting in internal inconsistencies in this compilation. Permeabilities are measured on cores or derived from other data, and transmissivities are from drill stem tests or calculated from permeability. Test data are usually for limited horizons of high anticipated yields and, therefore, are not representative of the formation as a whole (Feathers et al. 1981).
[3]gpm = gallons per minute
gpm/ft = gallons per minute per foot
gpd/ft = gallons per day per foot
gpd/ft^2 = gallons per day per cubic foot
TDS = total dissolved solids
mg/L = milligrams per liter
[4]Actual development potential would require site-specific office and field investigations to define aquifer capability and constraints unique to each project and site.

Taken from: Feathers, Libra, Stephenson, and Eisen, 1981, *Occurrence and Characteristics of Groundwater in the Powder River Basin, Wyoming*

Source: HKM Engineering et al. 2002a.

high as 4,000 gpm. Water quality in the Madison Limestone is mainly dominated by calcium-magnesium carbonate with locally high concentrations of fluoride and radionuclides. TDS can range from 600 to 3,000 mg/L, with the high TDS water containing sulfates and chlorides. The water is of good quality, and the Madison Limestone is the most important high-yield aquifer in Wyoming for municipal, industrial, and irrigation water supply. Depths to the Madison in the Powder/Tongue River Basin range from approximately 6,000 feet east of Gillette, Wyoming, to as much as 16,000 feet in the southwestern part of the Powder/Tongue River Basin. Recharge to the Madison Limestone is approximately 75,000 acre-feet per year (HKM Engineering et al. 2002a). The other formations within the Madison Aquifer System can yield water; however, the quality of the water is not as good as that found in the Madison Limestone, and well yields are often much lower.

The Dakota Aquifer System: The Dakota Aquifer consists of two main formations, the Cloverly Formation and the Newcastle Sandstone, which have a total thickness of approximately 200 feet. Yields from the Dakota Aquifer range from 1 to 40 gpm up to approximately 250 gpm (HKM Engineering et al. 2002a). The transmissivity of the main producing unit, the Cloverly Formation, is in the range of 7 to 230 gpd/ft. Water from the Dakota Aquifer is dominated by sodium bicarbonate with TDS ranging from 300 to 3,000 mg/L. With common well yields in the range of 5 to 20 gpm, the Dakota Aquifer is not a major source of water.

Fox Hills/Lance Aquifer System: The Fox Hills/Lance Aquifer System consists of the Lance Formation and the underlying Fox Hills Sandstone. The Lance Formation ranges from 600 to 3,000 feet in thickness and thickens to the south in the Powder/Tongue River Basin (HKM Engineering et al. 2002a). Well yields are on the order of 15 gpm or less, and the transmissivity of the Lance Formation is 76 to 2,100 gpd/ft. The water quality in the Lance Formation is dominated by sodium sulfate or calcium sulfate, and the TDS ranges up to 3,000 mg/L. The SAR ranges from 1.9 to 39, and the water generally is not suitable for irrigation use, stock use, or domestic use. The Fox Hills Sandstone ranges in thickness up to 700 feet, with a transmissivity in the range of 76 to 1,600 gpd/ft. Well yields generally are around 15 gpm but can range up to 50 gpm. The Gillette municipal public water supply has wells in the Fox Hills yielding 85 to 705 gpm (HKM Engineering et al. 2002a). The water quality is similar to that in the Lance Formation. Depths to the formation are on the order of 1,000 feet in most of the Powder/Tongue River Basin. The water quality of the Fox Hills Sandstone limits its usefulness for domestic or stock use. The fluoride content of the water on the east side of the Powder/Tongue River Basin can limit its use for municipal water supply.

Fort Union/Wasatch Aquifer System: Both the Wasatch and the Fort Union formations act as aquifers in the Powder/Tongue River Basin. The Wasatch is more of a local aquifer, while the Fort Union Formation is a regional aquifer. The Wasatch ranges in thickness from 500 to 2,000 feet and is a fine to coarse-grained lenticular sandstone with interbedded shale and coal. The transmissivity ranges from 520 to 2,200 gpd/ft, but well yields generally are less than 15 gpm. The TDS of the water ranges from 141 to 6,620 mg/L (HKM Engineering et al. 2002a), and the sulfate content can range up to 4,000 mg/L, with iron ranging up to 25 mg/L. The Wasatch is a local source of domestic and stock water supply, but it generally is not suitable for irrigation because of the high sodium content. The Fort Union Formation ranges from 1,200 to 3,900 feet in thickness in the Powder/Tongue River Basin and is a fine- to medium-grained siltstone with abundant coal and shale. Well yields from 1 to 60 gpm ranging up to 250 gpm are common, and the transmissivity ranges from 10 to 95 gpd/ft. The TDS content of the water ranges from 484 to 4,630 mg/L with high sulfate (up to 1,870 mg/L) and iron (up to 19 mg/L). The water generally is dominated by sodium bicarbonate and has a high SAR value (up to 32). The Fort Union is a major source of local water supply for domestic and stock water use. Major pumpage in the Fort Union is from CBNG wells, and the average pumping rate per well ranges from approximately 12 to 45 gpm, depending on the depth of the CBNG well.

Quaternary Alluvial Aquifer System: This aquifer system is local in nature and is found in alluvium and terrace deposits near the major drainages of the Powder/Tongue River Basin. The thickness of alluvium ranges up to approximately 100 feet. Well yields of 50 to 300 gpm are possible in local areas, and the transmissivity can range up to 20,300 gpd/ft. TDS for the water can range up to 4,000 mg/L and the chemical nature of the water varies considerably based on location. Water from the Quaternary Alluvial Aquifer has been used for municipal water supply, domestic water supply, and stock use. Quaternary alluvial aquifers that are in hydraulic connection with perennial streams are the main source of water supply in this aquifer system. These shallow alluvial aquifers can be recharged by groundwater flow from the underlying Wasatch Aquifer or from stream infiltration.

Water quality data for the Fort Union, Wasatch, and Quaternary Alluvial aquifers are presented in Appendix B. These data were compiled from studies conducted by the USGS. **Figure 3.4-1** displays groundwater quality in the PRB as selected Stiff diagrams (diagrams showing the relative percent of major ions to depict water quality) to illustrate the distribution of sodium, sulfate, bicarbonate, and calcium. **Figure 3.4-2** summarizes groundwater quality in the PRB using Piper diagrams (trilinear diagrams that provide a visual comparison of several water types). These diagrams illustrate the regional variation in water quality for the Fort Union, Wasatch, and Quaternary Alluvial aquifers. As the diagrams show, the Fort Union is elevated in sodium and bicarbonate, especially in the central or deeper parts of the basin. The Wasatch Formation tends to have locally elevated sulfate. Water quality in the alluvium is quite variable.

3.4.2.2 Northeast Wyoming River Basins

There are six main aquifers underlying the river basins of northeastern Wyoming. These are listed below in order from oldest to youngest. **Table 3.4-10** summarizes the hydrologic properties of stratigraphic units in the Northeast Wyoming River Basins. The Arikaree Aquifer is not within the PRB, but it is discussed briefly below for completeness.

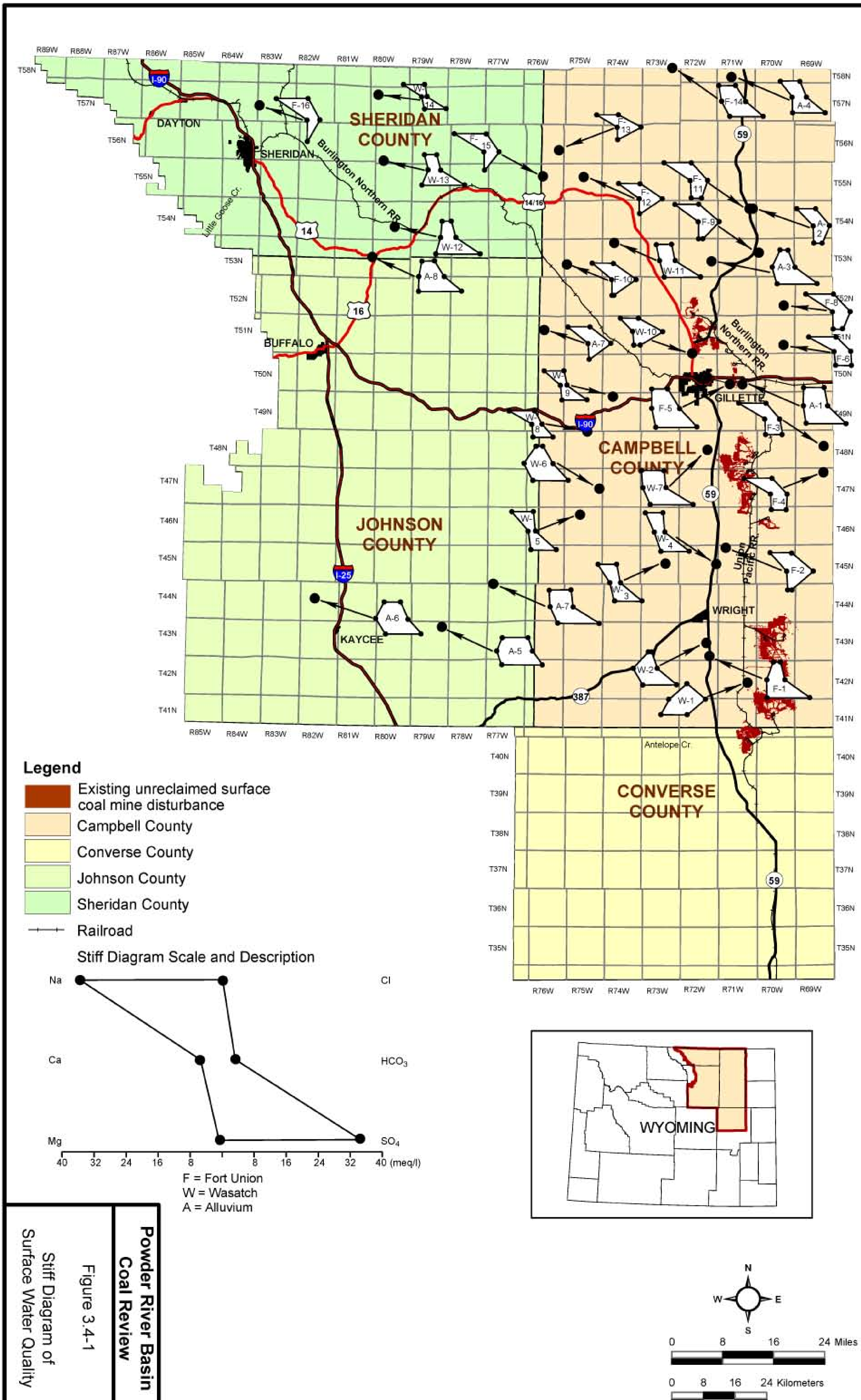
- Madison Aquifer System
- Dakota Aquifer System
- Fox Hills/Lance Aquifer System
- Fort Union/Wasatch Aquifer System
- Tertiary Arikaree Aquifer (Niobrara Basin)
- Quaternary Alluvial Aquifer System

Madison Aquifer System: The Madison Aquifer along the central and eastern flanks of the PRB consists of four water-bearing formations. From oldest to youngest these are the Whitewood Dolomite, Englewood Limestone, Pahasapa Limestone (equivalent to the Madison Limestone in the northern part of the PRB), and Minnelusa Formation. The Whitewood Dolomite is a massive bedded dolomite 50 to 60 feet thick that contains few wells and has a transmissivity of approximately 6,400 gpd/ft. This unit of the Madison Aquifer System is not used for water supply. The Englewood Limestone is 30 to 60 feet thick, also has very few wells, and is not used for water supply. The principal unit of the Madison Aquifer System that is used for water supply in the eastern PRB is the Pahasapa Limestone. This massive limestone has wells with yields up to 1,000 gpm and a transmissivity that typically ranges from 1,000 to 60,000 gpd/ft but locally can be as high as 300,000 gpd/ft. Water quality at the outcrop of the formation along the eastern flank of the PRB is calcium-magnesium bicarbonate water with a TDS of less than 600 mg/L. The TDS increases basinward to greater than 3,000 mg/L, and the water becomes dominated by sodium sulfate and sodium chloride with increasing concentrations of fluoride and radionuclides. This is the most important high-yield aquifer in Wyoming and is a source of water for municipal water supply as well as industrial, irrigation, and stock water use. The City of Gillette, Wyoming, uses this aquifer for water supply. The overlying Minnelusa Formation also is a major aquifer in the eastern PRB. This unit is 600 to 800 feet thick and consists of sandstone interbedded with limestone, dolomite, and shale. The upper part of the Minnelusa is an aquifer and yields 200 gpm to wells and has a transmissivity up to 900 gpd/ft. Water quality is good near the outcrop of the formation with TDS values below 600 mg/L. Basinward, the TDS increases to around 2,400 mg/L, with an average of about 773 mg/L. The water quality changes from calcium bicarbonate water to water dominated by calcium sulfate and to sodium chloride waters in the deeper parts of the PRB. Fluoride enrichment and locally high values of radionuclides are a problem for municipal water use. The historical use of water from the Minnelusa has been for public water supply and domestic and stock use.

Dakota Aquifer System: The Dakota Aquifer System in the eastern PRB consists of three water-bearing units. From oldest to youngest, these are the Lakota Formation, Fall River Formation, and Newcastle Sandstone. The Lakota Formation ranges in thickness from 45 to 200 feet and is mainly a sandstone with interbedded conglomerates and shales. The unit generally is not used for water supply and yields 1 to 10 gpm to wells on average with a transmissivity of 220 to 810 gpm/ft. The Fall River Formation also is a sandstone with interbedded shale and siltstone and ranges in thickness from 35 to 150 feet. Well yield and transmissivity are similar to the Lakota Formation, and this unit also is not a source of water supply. The Newcastle Sandstone is the major aquifer of the Dakota Aquifer System in the eastern PRB and ranges in thickness up to 100 feet. As a result of a low transmissivity (up to 140 gpd/ft) and poor water quality within the PRB, this unit is used for water supply only near its exposures along the eastern rim of the PRB. The TDS of water in the basin can range up to 3,200 mg/L with the water dominated by calcium and sodium sulfate. Selenium and radionuclides can be issues of concern in some areas of this aquifer.

Fox Hills/Lance Aquifer System: This aquifer system consists of the Fox Hills Sandstone and the overlying Lance Formation. The Fox Hills Sandstone ranges from 150 to 700 feet in thickness and yields up to 700 gpm to wells. The transmissivity ranges from 70 to 1,600 gpd/ft, and the formation is used for municipal, industrial, domestic, and stock water supply. The water quality is similar to that in the overlying Lance Formation and consists of sodium bicarbonate to sodium sulfate water with a TDS ranging from 600 to 3,000 mg/L and locally high sodium and radionuclide contents. The locally high fluoride content can be a problem for domestic water supply. The Lance Formation ranges in thickness from 500 to 3,000 feet and yields up to 350 gpm to wells. The transmissivity ranges from 170 to 2,100 gpd/ft, and the water quality is similar to the Fox Hills Sandstone. The Lance Formation also is used for municipal, domestic, and stock water supply.

Fort Union/Wasatch Aquifer System: The Fort Union Formation in the eastern PRB ranges in thickness from 1,100 to 2,270 feet and is a coal-bearing sandstone with interbedded siltstone and shale. Flowing wells can have yields of up to 60 gpm from confined units in the Fort Union, and pumped wells produce up to 250 gpm with several hundred feet of drawddown. Transmissivity

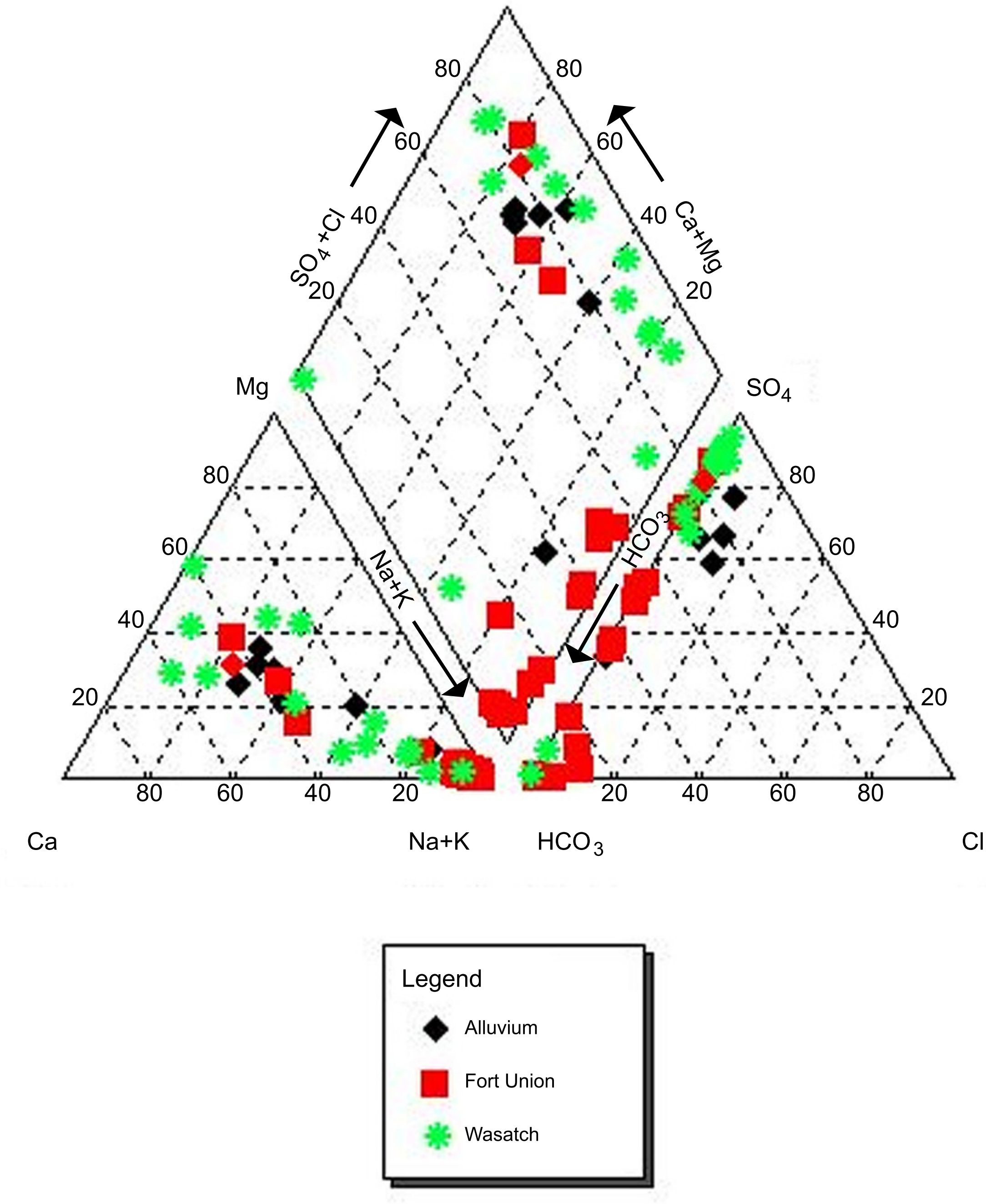


Powder River Basin Coal Review

Figure 3.4-1

Stiff Diagram of Surface Water Quality

07/27/06



Powder River Basin Coal Review

Figure 3.4-2

Piper Diagrams for Selected Wells in the PRB

Table 3.4-10
Summary of Groundwater Availability/Development Potential of Major Aquifer Systems, Wyoming River Basins Plant Area

Major Aquifer System	Geologic Unit	Thickness (Feet)	Lithologic Character	Hydrological Character[1,2]	General Water Quality	Availability/Development Potential[3]	Remarks
Quaternary Alluvial Aquifer System	Alluvium and Terrace Deposits	0-100+	Clay rich sandy silt, silt, sand and gravel; unconsolidated and interbedded; present along most streams. Thickness generally less than 50 feet but may be thicker. Coarser deposits in valleys of the Belle Fourche and the Cheyenne rivers. Alluvium overlying formations of Tertiary-age generally is fine- to medium-grained in central part of basin (Hodson et al. 1971).	Yield of 1,000 gpm possible, often through induced recharge. Terraces topographically high and often drained. Specific capacity 0.3-18 gpm/ft; porosity 28-45 percent; permeability 0.1-1,100 gpd/ft^2; transmissivity 15-64,000 gpd/ft; specific yield 2-39 percent. Coarser deposits have better aquifer properties.	TDS content generally ranges from approximately 100 to >4,000 mg/L, and chemical characteristics of water differ geographically. Chemical type and mineralization of the water can be expected to vary depending on underlying rock types and the nature and degree of interconnection with underlying bedrock aquifers as well as surface water. Moderate to high mineralization tolerable for stock and domestic use. Suitability for irrigation generally limited to salt-tolerant crops. Water in the alluvium in Black Hills generally is better quality than central part of basin (Hodson et al. 1971).	Historical source for domestic and stock use. Production has ranged from 1 to 900 gpm. Groundwater development potential generally better in coarse-grained deposits and poorer in fine-grained materials. Yields in the high end of the above range might be possible for optimally located and properly designed wells if induced infiltration from surface water can be tolerated (Belle Fourche, Cheyenne, and Niobrara river basins). Potential source for irrigation, municipal/public, and industrial sources where more than 40 feet of saturated well-sorted sand and gravel are present.	Quaternary alluvial aquifers generally in hydraulic connection with all bedrock aquifers in outcrop areas and also with surface waters. Alluvial aquifers in larger valleys provide hydraulic interconnection between otherwise hydraulically-isolated bedrock aquifers (Whitcomb 1965). Alluvial aquifers also serve as interchange point and storage for groundwater in the hydrologic cycle (Davis and Rechard 1977; Davis 1976). Induced recharge from surface waters is probable in areas of extensive development.
Middle Tertiary Aquifer	Arikaree Formation	0-500 (Southeast only)	Tuffaceous sandstone, fine-grained with silty zones, coarse sand lenses, and concretionary zones.	Yields up to 1,000 gpm; specific capacity up to 232 gpm/ft; porosity 5-24 percent; permeability <1-300 gpd/ft^2; transmissivity up to 77,000 gpd/ft.	TDS content of water ranges from 261 to 535 mg/L. Composition mainly calcium bicarbonate (Whitcomb 1965). Median TDS content in samples from 12 wells in Niobrara County 321 mg/L (Larson 1984).	Historical source for municipal/public, industrial, domestic, stock, and irrigation supply with tested production ranging as high as 195 to 730 gpm (Whitcomb 1965). Yields of 1,000 gpm might be possible for optimally located and properly-designed wells.	Water level data available from two observation wells located east and south east of Lusk in Niobrara County (32-62-05-baa01 and 32-62-32-bbb01). Water levels have shown approximately 6 to 13 feet decline in water levels in the aquifer since the 1970s with possibly some stabilization and slight recovery since early to mid 1990s (USGS 2001).
Fort Union/Wasatch Aquifer System	Wasatch Formation	up to 1,600	Fine- to coarse-grained lenticular sandstones interbedded with shale and coal, coarser in south.	Yields generally <15 gpm, locally flowing wells exist. Yields historically could be expected to range from 10 to 50 gpm in the north part of the basin with the possibility of higher yields up to 500 gpm in the south part of the basin (Hodson et al. 1973). Specific capacity 0.10-14 gpm/ft (Hodson et al. 1973); porosity 28-30 percent; permeability 0.01-65 gpd/ft^2; transmissivity average 500 gpd/ft and range 1-4,000 gpd/ft.	TDS content of waters is variable and ranges from <200 to >8,000 mg/L (Hodson et al. 1973). Sodium sulfate and sodium bicarbonate are general dominate water types. Major ion composition varies with depth and shows more sodium and bicarbonate content with depth. Radium 226 + 228 may be of concern near uranium deposits.	Historical source for municipal/public, domestic, and stock supply. Yields ranging from 10 to 50 gpm in the north part of the basin can be expected with the possibility of higher yields up to 500 gpm in the south part of the basin (Hodson et al. 1973).	Water level data available from two observation wells located in Campbell County (50-72-21-aba01 and 42-71-35-aaa01) and one observation well in Converse County (37-70-10-cbb01). Water levels in the aquifer have shown approximately a 40-foot rise between 1983 and 2000 in Gillette and approximately 40 to 50 feet of decline southeast of Wright in Campbell County. Water levels in the aquifer in northwest Converse County have shown a rise of approximately 7 feet between 1988 and 1999 after a decline of approximately 6 feet between 1986 and 1988 (USGS 2001).

Table 3.4-10 (Continued)

Major Aquifer System	Geologic Unit	Thickness (Feet)	Lithologic Character	Hydrological Character[1,2]	General Water Quality	Availability/Development Potential[3]	Remarks
Fort Union/Wasatch Aquifer System (continued)	Fort Union Formation	1100-2270	Sandstone, fine- to medium-grained, lenticular, interbedded with siltstone, coal, and shale. Middle part may be shalier in north, upper part siltier in south. "Clinker" associated with coal outcrops.	Flowing yields of 1-60 gpm where confined. Yields up to 250 gpm with several hundred feet of drawdown. Specific capacity 0.1-2 gpm/ft; permeability 0.01-100 gpd/ft^2; transmissivity 1-5,000 gpd/ft. Coal and clinker generally have better aquifer properties than sandstones. Locally, clinker transmissivity up to 3,000,000 gpd/ft; anisotropy and leaky confining layers are common.	TDS content and major ion composition of Fort Union Formation Waters as above. Water co-produced with CBNG is predominantly sodium bicarbonate type with TDS content and SAR (32 samples) of 270-1170 mg/L (mean of 653 mg/L) and 5.7-12 (mean of 7.85), respectively (Rice et al. 2000). BLM Wyodak EIS assumed average TDS concentration of 764 mg/L (BLM 1999a,b). High radionuclide content of concern in areas near uranium ore zones.	Historical source for municipal/public, domestic, and stock supply. Maximum expected yields of approximately 130 to 150 gpm (Hodson et al. 1973; Wester-Wetstein and Associates, Inc. 1994). Exploration and development of new Fort Union well field including conjunctive use/recharge of CBNG production water under consideration for the City of Gillette.	Source for approximately 14 municipal and public water supply systems including the City of Gillette and adjacent districts, joint powers boards and privately owned water systems, and water users associations in Campbell County. City of Gillette mixes Fort Union Formation water with that from the Madison and Fox Hills/Lance system for municipal/public water supply. Total of 5,285 CBNG wells permitted with WSEO in planning area as of 12/31/00. Maximum, minimum, and mean depths and range of actual yields listed on permits were 138-5,507 (mean 772) feet below ground surface, and 1-120 (mean 27) gpm, respectively. Range of depths to main water bearing zone listed on WSEO permits were 124-1558 (mean 124) feet below ground surface. BLM Wyodak EIS assumed average expected water production to be 12 gpm over the estimated 12 year life of each CBNG well (BLM 1999a,b). BLM Wyodak Drainage EA assumed average water production for each CBMG well to be 11.1 gpm (BLM 2000).
Fox Hills/Lance Aquifer System	Lance Formation	500-1000 (North) 1600-3000 (South)	Sandstone, fine- to medium-grained, lenticular, interbedded with sandy siltstone and claystone.	Yields up to 350 gpm but with large drawdowns and long well completion intervals. Locally flowing wells exist. Specific capacity 0.05-2 gpm/ft; permeability 6-35 gpd/ft^2; transmissivity 170-2100 gpd/ft.	TDS content in waters at Foxhills/Lance System outcrops north of Niobrara County range from 600-1,500 mg/L, and in Niobrara County range from 1,000-3,300 mg/L. Composition mainly sodium, bicarbonate, and sulfate. Fluoride enrichment is characteristic of Fox Hills/Lance Formation waters. Possible high sodium and radionuclide content could be of concern in some areas.	Lance Formation historical source for municipal/public, domestic, and stock supply. Generally yields less than 20 gpm, but yields of several hundred gallons per minute may be possible from complete section 5 of the formation (Hodson et al. 1973).	High fluoride content is of concern for development as source for municipal/public water systems.
	Fox Hills Sandstone	150-200 (North) 400-700 (South)	Sandstone, fine-to medium-grained, interbedded with shale and siltstone.	Yields up to 705 gpm but with large drawdowns and long well completion intervals. Locally flowing wells exist. Specific capacity 0.05-2 gpm/ft; permeability 34 gpd/ft^2; transmissivity 76-1,600 gpd/ft for wells also completed in Lance.	Similar to Lance Formation.	Historical source for municipal/public, industrial, domestic, and stock supply. Tested yields of Gillette municipal/public supply wells have ranged from 85 to 705 gpm (Wester-Wetstein and Associates, Inc. 1994).	High fluoride content is of concern for development as source for municipal/public water systems. Has been used for oil well water flooding operations. Water level data available from one observation well completed in the aquifer southeast of Gillette in Campbell County (49-70-31bbb01) has shown approximately 50 feet of decline since 1983 (USGS 2001).

Table 3.4-10 (Continued)

Major Aquifer System	Geologic Unit	Thickness (Feet)	Lithologic Character	Hydrological Character[1,2]	General Water Quality	Availability/Development Potential[3]	Remarks
Dakota Aquifer System	Newcastle Sandstone	0-60 (Northeastern Basin) 0-100 (Southeastern Basin)	Sandstone, fine- to medium-grained, locally conglomeratic, lenticular, with interbedded siltstone, shale, and claystone.	Minor unit of Dakota Aquifer System exploited near outcrop only; often excessive pumping lift. Oil field data: porosity 5-27 percent; permeability <11 gpd/ft^2; transmissivity 0-140 gpd/ft.	Waters at Dakota System outcrop generally contain over 1,000 mg/L TDS. TDS content 180-3,200 mg/L in 17 samples in Weston County (Larson 1984). Composition changes basinward from calcium, magnesium, and sulfate at outcrop to sodium and sulfate, to sodium and bicarbonate. Deep Basin waters >10,000 mg/L TDS and are enriched to sodium and chloride. Possible high fluoride, selenium, and radionuclide content could be of concern in some areas.	Dakota Aquifer System historical source for domestic and stock use.	Few reported wells in northern Black Hills (1958) due to excessive drilling depths except in outcrop areas. Yields typically adequate for stock and domestic purposes. Historically, wells typically have been completed in both the Lakota and Fall River formations to obtain maximum production (Whitcomb et al. 1958). Water level data available from one observation well completed in the aquifer (Lakota Formation) northeast of Lusk in Niobrara County (36-62-28ab02) has shown approximately 23 feet of decline between 1974 and 2000 (USGS 2001).
	Fall River Formation	95-150 (Northeastern Basin) 35-85 (Southeastern Basin)	Sandstone, fine- to coarse-grained with interbedded shale and siltstone.	Flowing yield 1-10 gpm; wells often also completed in Lakota Formation. Specific capacity <0.5 gpm/ft. Oil field data: porosity 11-23 percent; permeability 0-36 gpd/ft^2 ; transmissivity 1-900 gpd/ft.	--	--	--
	Lakota Formation	45-300 (Northeastern Basin) 115-200 (Southeastern Basin)	Sandstone, fine- to coarse-grained, in places conglomeratic, very lenticular, irregularly interbedded with shale which becomes dominant at top (Fuson Shale).	Flowing yield 1-10 gpm, up to 150 gpm. Water well data: specific capacity 0.01-1.4 gpm/ft; permeability 2-14 gpd/ft^2 transmissivity 220-810 gpd/ft for two wells also in Fall River.	--	--	--
Madison Aquifer System	Minnelusa Formation (Hartville Formation)[4]	600-800 (Northeastern Basin) 1,000± (Southeastern Basin)	Sandstone, fine- to coarse-grained, interbedded with limestone, dolomite, and shale, locally gypsiferous, especially at top.	Upper part has historically been considered part of Madison Aquifer System, middle is aquitard, lower is minor aquifer in hydraulic connection with Madison. Flowing yields of over 200 gpm possible; specific capacity 1-5 gpm/ft. Oil field data: porosity 6-25 percent; permeability <0.1-18 gpd/ft^2; transmissivity 2-900 gpd/ft.	Similar to Madison Formation waters at outcrop (TDS < 600mg/L, predominantly calcium, magnesium, and bicarbonate type water). TDS content 230 – 2,450 mg/L from 26 samples in Crook County with median and mean of 520 and 773 mg/L, respectively (Larson 1984). Some east basin waters near outcrops show TDS up to 3,000 mg/L (calcium and sulfate enrichment). Deep basin waters TDS > 10,000 mg/L (mainly sodium and chloride type water). Fluoride enrichment characteristic of Madison System waters throughout the basin. Concentrations of radionuclides could be of concern in some areas.	Historical source for municipal/public water supply, domestic, and stock use.	Large quantities of water produced from flowing wells at Huelett (1958). Generally deeply buried (> 600 - 700 feet minimum) in area (northern Black Hills - 1958) (Whitcomb et al. 1958). Subject of USGS investigation with Pahasapa/Madison Limestone (Ogle 2001). Water level data available from one observation well located in Crook (44-62-36-cbb02) and one in Niobrara (36-62-28-bbd01) counties. Water levels have risen approximately 2 feet (since 1998) and 15 feet (since 1995), respectively, in the two observation wells (USGS 2001).

Table 3.4-10 (Continued)

Major Aquifer System	Geologic Unit	Thickness (Feet)	Lithologic Character	Hydrological Character[1,2]	General Water Quality	Availability/Development Potential[3]	Remarks
Madison Aquifer System (continud)	Pahasapa Limestone (Madison Limestone)[4]	550-990 (Northeastern Basin) 250± (Southeastern Basin)	Massive fine-grained limestone and dolomitic limestone, locally cherty or cavernous.	Principal unit of Madison Aquifer System. Flowing or pumped yields up to 1,000 gpm; specific capacity 0.5-50+ gpm/ft, flow-dependent; transmissivity 1,000-60,000 gpd/ft locally to 300,000 gpd/ft+.	Waters at outcrop (TDS < 600mg/L, predominantly calcium, magnesium, and bicarbonate type water). TDS increase basinward to >3,000 mg/L, sodium, sulfate, and chloride predominating. Fluoride enrichment characteristic of Madison System waters throughout the basin. Concentrations of radionuclides could be of concern in some areas.	Probably the most important high-yield aquifer in Wyoming. Historical source for municipal/public water supply, industrial, irrigation, and stock use. Several fish hatcheries use Pahasapa/Madison aquifer as a water source. Base flow and spring discharge from the Pahasapa/Madison aquifer form part of the surface run-off in the Black Hills area (Ogle 2001). Tested pumping rate of seven City of Gillette Pahasapa/Madison aquifer wells ranged from 535 to 900 gpm (Wester-Wetstein and Associates, Inc. 1994).	Subject of USGS investigation with the Minnelusa Formation (Ogle 2001). Water level data available from nine observation wells located in Crook (56-67-28-aab01), (56-67-28-aab02), (53-65-18bbd02), (52-63-25-dcd01), (49-62-36-cbb01); Weston (48-65-35ccb01), (46-66-25dbb01), (44-63-26cac01); and Niobrara (36-62-28-ab01) counties. Water levels generally have risen from 13 to 40 feet in some of the observation wells since 1995 (USGS 2001). Total estimated recharge to the Madison Limestone in the PRB in 1973 was approximately 75,000 acre feet per year (WSEO 1976).
	Englewood Limestone (Gurnsey Formation, part)[4]	30-60 (Northeastern Basin) 0-50± (Southeastern Basin)	Thin-bedded limestone, locally shaley.	Minor unit of Madison Aquifer System; USGS test: porosity 15-18 percent; permeability <0.1 gpd/ft^2.	--	--	Generally no groundwater development in area (Northern Black Hills - 1958). Formations may contain some water in permeable zones, but generally are considered to be too deeply buried to be considered important aquifers (Whitcomb et al. 1958).
	Whitewood Dolomite	50-60 (Northeastern Basin) absent (Southeastern Basin)	Massive bedded dolomite, locally cherty.	Minor unit of Madison Aquifer System; the few existing wells also produce from the Madison aquifer. USGS test: porosity 10-25 percent; specific capacity 15 gpm/ft; permeability <0.1-11 gpd/ft^2; transmissivity 6400 gpd/ft.	--	--	--

[1] Reported yields may reflect development needs rather than aquifer capability; higher yields can sometimes be expected, with corresponding drawdown increases. Reported water well transmissivities or permeabilities may be for wells completed in two aquifers.
[2] Oilfield (and USGS test) data are variously derived resulting in internal inconsistencies in this compilation. Permeabilities are measured on cores or derived from other data and transmissivities are from drill stem tests or calculated from permeability.
[3] Actual development potential would require site-specific office and field investigations to define aquifer capability and constraints unique to each project and site.
[4] Nomenclature for equivalent strata exposed in the Hartville uplift on the southeastern basin flank (Feathers et al. 1981).

Taken from: Feathers, Libra, Stephenson, and Eisen, 1981, *Occurrence and Characteristics of Groundwater in the Powder River Basin, Wyoming*

Source: HKM Engineering et al. 2002b.

ranges up to 5,000 gpd/ft. The water quality can be quite variable with TDS ranging up to 8,000 mg/L and the water being dominated by sodium bicarbonate with SAR values ranging from 5.7 to 12.0. The Fort Union is used for municipal, domestic, and stock water supply. Approximately 14 municipal and public water supply systems in the eastern PRB, including the City of Gillette and adjacent water districts, use the Fort Union for water supply (HKM Engineering et al. 2002b). The overlying Wasatch Formation is mainly sandstone with interbedded shale and coal that ranges up to 1,600 feet in thickness. Well yields are low and generally between 10 to 50 gpm, but can range up to 500 gpm in the southern part of the PRB. The transmissivity ranges up to 4,000 gpd/ft, but it averages around 500 gpd/ft. Water quality generally is saline, with TDS values well above 1,000 mg/L and water quality varying from sodium bicarbonate to sodium sulfate. Locally, it is used for domestic and stock water supply and for public water supply for small communities. It is used most commonly for water supply in the southern part of the PRB.

Middle Tertiary Arikaree Aquifer: The Arikaree Formation generally is found south and southeast of the Powder River structural basin, mainly in Niobrara County, and is thus not a water supply aquifer within the PRB itself (HKM Engineering et al 2002b). This unit is a tuffaceous sandstone up to 500 feet in thickness that can yield up to 1,000 gpm to wells. The transmissivity of the aquifer ranges up to 77,000 gpd/ft. The TDS of the water ranges from 260 to about 535 mg/L and the water is mainly calcium bicarbonate. The water is used in Niobrara County for municipal and public water supply, industrial water supply, irrigation, and stock water.

Quaternary Alluvial Aquifer System: Quaternary alluvium can be found along major stream channels in terraces and as alluvial fill in the channels. The thickness ranges up to 100 feet, but is usually less than 50 feet in most areas. Coarse deposits with available water are found along the valleys of the Belle Fourche and Cheyenne rivers and their major tributaries. Well yields up to 1,000 gpm are possible. The transmissivity is highly variable, because of the clay content of the alluvium and can range from 15 to 64,000 gpd/ft. Water quality is highly variable and TDS ranges from approximately 100 to over 4,000 mg/L. The water generally is saline and suitable mostly for stock water and irrigation. The chemical makeup of the water can range from calcium bicarbonate water in areas of limestone bedrock to calcium sulfate water to sodium bicarbonate water in areas where groundwater from the Fort Union Formation discharges into the alluvium. Quaternary alluvial aquifers are often in hydraulic communication with the underlying bedrock (HKM Engineering et al. 2002b), and thus, the water quality can reflect bedrock water quality. Quaternary alluvial aquifers are used for domestic and municipal water supply as well as irrigation and stock water.

Water quality data for selected wells screened in the Fort Union, Wasatch, and Quaternary Alluvial aquifers are presented in **Tables B-1** through **B-4** Appendix B. These data were compiled from studies conducted by the USGS. These aquifers are the main aquifers used for water supply in the Northeast Wyoming River Basins and the aquifers most affected by coal mining and CBNG development. **Figures 3.4-1** and **3.4-2** summarize groundwater quality in the PRB, including the Northeast Wyoming River Basins, using Stiff and Piper diagrams. For reference, surface and groundwater quality standards for Wyoming are available on the WDEQ website (WDEQ 2004).

3.5 Coal Bed Natural Gas Water Use

3.5.1 Introduction

CBNG development began in earnest around 1990 in the southern part of the Wyoming PRB to the west of the operating coal mines. Natural gas trapped in the coal units of the Fort Union Formation was developed by depressurizing the coal bed aquifers of the formation to facilitate the release of the gas. Shallow coal units to the west of the operating coal mines were exploited early in the 1990s in the drainages of the Belle Fourche and Cheyenne rivers. Beginning in approximately 1995, CBNG development expanded to the west and to the northwest in the PRB to access the natural gas in deeper stratigraphic members of the Fort Union Formation.

CBNG development requires depressurization of the Fort Union Formation coal bed aquifers through dewatering of those aquifers to a level that will allow for the release of gas from the coal. CBNG wells are regulated both by the WOGCC as oil and gas wells and by the WSEO as water production wells. Discharge of water by these wells is regulated by the WDEQ for both quantity and quality of water discharged either to surface drainages or to surface impoundments. WDEQ regulates discharges into both in-channel and off-channel impoundments. WSEO regulates the design of in-channel impoundments due to the potential effect on water rights. On public lands administered by the BLM, CBNG development also is regulated by the BLM through permit requirements associated with applications for permit to drill (APD's) and the NEPA analyses. The BLM also regulates CBNG wells and water discharge where public minerals are involved beneath private lands. The WOGCC regulates impoundments constructed on private and state lands. The WDEQ requires that all impoundments must have monitoring wells to evaluate the impacts of water stored in the impoundments on alluvial groundwater if the depth to groundwater is less than 150 feet (200 feet if the impoundment is greater than 50 acre-feet in size) and if the groundwater present beneath the impoundment is Class III or better water quality (TDS less than 10,000 mg/L).

3.5.2 CBNG Water Production

As of late 2001 and early 2002, there were approximately 14,550 CBNG wells permitted in the Wyoming PRB (HKM Engineering et al. 2002a,b). Approximately 9,390 of these wells are in the northwestern part of the basin in the Powder/Tongue River Basin, and approximately 5,160 of the wells are in the area west of the coal mines of the eastern PRB, in the Northeast Wyoming River Basins. Most of the CBNG wells west of the coal mines are in the drainages and subdrainages of the Belle Fourche and Cheyenne rivers. The general location of the CBNG wells is shown in **Figure 3.3-5**. Data from the files of the WOGCC presented in **Table 3.5-1** has approximately 12,000 permitted CBNG wells in the Wyoming PRB prior to January of 2002.

Most of the permitted CBNG wells are located in the upper Belle Fourche, Little Powder, and Upper Powder River drainages. Most of the water production by CBNG operations is found in the Upper Belle Fourche, Upper Cheyenne, Little Powder, Upper Tongue River, and Upper and Middle Powder River drainages (BLM 2003a). CBNG water production as of early 2002 was approximately 297 million barrels per year in the Northeast Wyoming River Basins (Upper Belle Fourche and Upper Cheyenne River basins) and approximately 216 million barrels per year in the Powder/Tongue River Basin (Upper and Middle Powder River, Little Powder River, and Upper Tongue River) as shown in **Table 3.5-1**. During 2002, CBNG water production in the Northeast

Wyoming River Basins was approximately 258 million barrels, mostly in the upper Belle Fourche River watershed; CBNG water production in the Powder/Tongue River Basin in 2002 was approximately 310 million barrels. Average CBNG water production per well increased steadily from approximately 50 to 400 barrels per day from 1990 to 1996 and then remained at that peak level until approximately 2000. By early 2002, production per well was declining and was around 300 barrels per day per well (BLM 2003a). CBNG wells have an average life expectancy of approximately 7 years, with the majority of water production coming in the first few years to get the coal bed aquifer depressurized. Once methane production is underway, dewatering of the coal bed aquifer is at a reduced and usually steady rate in the range of 1 to 5 gpm. Over time, the water production from an individual CBNG well declines and eventually reaches a level of approximately 1 to 2 gpm. Water quality from CBNG wells in the Fort Union Formation is summarized in **Table 3.5-2**.

Table 3.5-1
Water Production by CBNG Wells in the PRB

Subwatershed	Number of Pre-2002 CBNG Wells[1]	2000 Water Production (barrels)[2]	2001 Water Production (barrels)[2]	Number of Wells in 2002	2002 Water Production (barrels)[3]
Upper Tongue River	819	6,290,722	26,984,948	1,258	67,158,341
Upper Powder River	2,808	42,736,739	90,426,440	2,210	122,389,945
Crazy Woman Creek	150	28,706	9,862	5	30,821
Clear Creek	389	43,877	301,126	171	6,611,551
Middle Powder River	727	7,563,589	19,034,451	670	30,431,564
Little Powder River	1,814	66,667,649	79,325,493	1,817	84,610,410
Antelope Creek	251	1,769,502	7,209,092	189	20,475,248
Upper Cheyenne River	401	48,491,981	46,919,356	344	33,824,899
Upper Belle Fourche River	4,659	200,409,537	242,735,454	4,032	203,251,653
Middle North Platte River	6	0	524	6	64,873
Total	**12,024**	**374,302,302**	**512,946,746**	**10,702**	**568,848,805**

[1]Pre-2002 wells include all wells drilled or authorized and projected for completion by 2002. Water production shown for 2000 and 2001 comes from these wells. Not all pre-2002 wells produced during 2000 or 2001.
[2]Data were compiled from WOGCC 2001, 2002.
[3]2002 data compiled from WOGCC 2005.

Note: One barrel equals 42 gallons.

Source: BLM 2003a; WOGCC 2005.

3.5.3 CBNG Water Discharge

Groundwater produced by CBNG wells primarily is discharged directly to the surface in Wyoming, generally without treatment. The water in the northwestern part of the PRB usually is high in sodium bicarbonate, has TDS values well over 1,000 mg/L, and has a SAR greater than 8, making the water unsuitable for some agricultural uses. The water quality in the coal bed aquifers varies with location and depth in the Wyoming PRB. Thus, groundwater quality in the PRB is highly variable and generally elevated to some degree in TDS, sodium, calcium, sulfate, and bicarbonate. In the eastern part of the PRB, however, groundwater discharged by the CBNG wells is generally low in TDS and sodium and often of better quality than surface water. The key issues for regulation of CBNG water discharge are TDS and SAR levels. TDS is often expressed in terms of electrical

Table 3.5-2
Average Water Quality Data for CBNG-produced Water from the Fort Union Formation

Parameter (units)	MRL	Minimum	Maximum	Median	Detection Ratio (detections/total samples)	DWS
Temperature (˚C)	--	12	29	19	--	--
pH (standard units)	--	6.8	8	7.3	--	6.5-8.5
TDS (mg/L)	--	270	2,720	838	--	500
Calcium (mg/L)	--	1.8	68.9	26.3	--	--
Magnesium (mg/L)	--	1.6	45.7	14	--	--
Sodium (mg/L)	--	109	1,000	270	--	--
Potassium (mg/L)	--	3.1	48	7.3	--	--
Bicarbonate (mg/L)	--	289	3,134	952	--	--
Sulfate (mg/L)	--	<0.3	16.7	X	--	250
Chloride (mg/L)	--	5.1	64.6	10.6	--	250
Fluoride (mg/L)	--	0.4	4.13	1.1	--	2
Iron (mg/L)	--	0.02	4.9	0.38	--	0.3
Manganese (mg/L)	--	0.0014	0.0914	0.0136	--	0.05
Barium (mg/L)	--	0.14	1.6	0.6	--	2
Sodium adsorption ratio	--	5	68.7	8.8	--	--
Aluminum (µg/L)	<50	--	<50	--	0/70	50 to 200
Silver (µg/L)	<1	--	<1	--	0/70	100
Arsenic (µg/L)	<0.2	--	2.6	--	38/70	50
Boron (µg/L)	<0.1	--	390	--	24/70	--
Beryllium (µg/L)	<0.1	--	<0.1	--	0/70	--
Bismuth (µg/L)	<20	--	46	--	30/70	--
Cadmium (µg/L)	<0.1	--	<0.1	--	0/70	5
Cerium (µg/L)	<0.1	--	14	--	2/70	--
Cobalt (µg/L)	<0.1	--	0.24	--	19/70	--
Chromium (µg/L)	<1	--	1.8	--	10/70	--
Cesium (µg/L)	<0.1	--	0.78	--	30/70	--
Copper (µg/L)	<0.1	--	29	--	70/70	1,000
Mercury (µg/L)	<0.1	--	0.25	--	1/70	2
Lanthanum (µg/L)	<10	--	<10	--	0/70	--
Lithium (µg/L)	<10	--	208	--	70/70	--
Molybdenum (µg/L)	<0.2	--	4.1	--	32/70	--
Nickel (µg/L)	<0.5	--	35	--	66/70	100
Lead (µg/L)	<0.1	--	0.43	--	5/70	--
Rubidium (µg/L)	<0.1	--	38	--	70/70	--
Antimony (µg/L)	<2	--	<2	--	0/70	6
Scandium (µg/L)	<0.1	--	3	--	66/70	--
Selenium (µg/L)	<2	--	<2	--	0/70	50
Tin (µg/L)	<0.1	--	5.5	--	7/70	--
Strontium (µg/L)	<0.1	--	1,900	--	70/70	--
Thorium (µg/L)	<20	--	<20	--	0/70	--
Thallium (µg/L)	<0.2	--	0.34	--	1/70	--
Uranium (µg/L)	<0.1	--	<0.1	--	0/70	--
Vanadium (µg/L)	<0.2	--	1.1	--	1/70	--
Tungsten (µg/L)	<20	--	51	--	4/70	--
Yttrium (µg/L)	<20	--	<20	--	0/70	--
Zinc (µg/L)	<1	--	80	--	39/70	5000
Zirconium (µg/L)	<50	--	<50	--	0/70	--

Note: --- = no recommended value
˚C = degrees centigrade
DWS = drinking water standard (primary or secondary maximum contaminant level)
µg/L = micrograms per liter
mg/L = milligrams per liter
MRL = minimum reporting limit
X = less than minimum reporting

Source: BLM 2003a.

conductivity (EC) measured directly in the field. **Figure 3.5-1** shows the distribution of EC and SAR in CBNG waters in the PRB.

As of early 2002, there were approximately 3,565 permitted CBNG outfalls for water discharge in the PRB (see **Figure 3.5-2**). These outfalls are summarized in **Table 3.5-3**. Approximately 43 percent of these outfalls are in the Upper Belle Fourche and Cheyenne River basins, approximately 21 percent are in the Upper Powder River drainage, and approximately 16 percent are in the Little Powder River drainage. This distribution places approximately half of the outfalls in the Powder/Tongue River Basin and approximately half in the Northeast Wyoming River Basins.

Discharge at these outfalls ranges from 1 to approximately 25 gpm. Many outfalls are linked to approximatley 5 to 7 CBNG wells. The discharge water comes not only from the coal bed aquifer being dewatered, but also from interbedded and overlying sand units in the coal-bearing sections of the Fort Union Formation. Multiple outfalls can be covered by one discharge permit. Thus, the number of discharge permits does not correspond to the number of outfalls in **Table 3.5-3**.

Table 3.5-3
Permitted CBNG Outfalls in the PRB

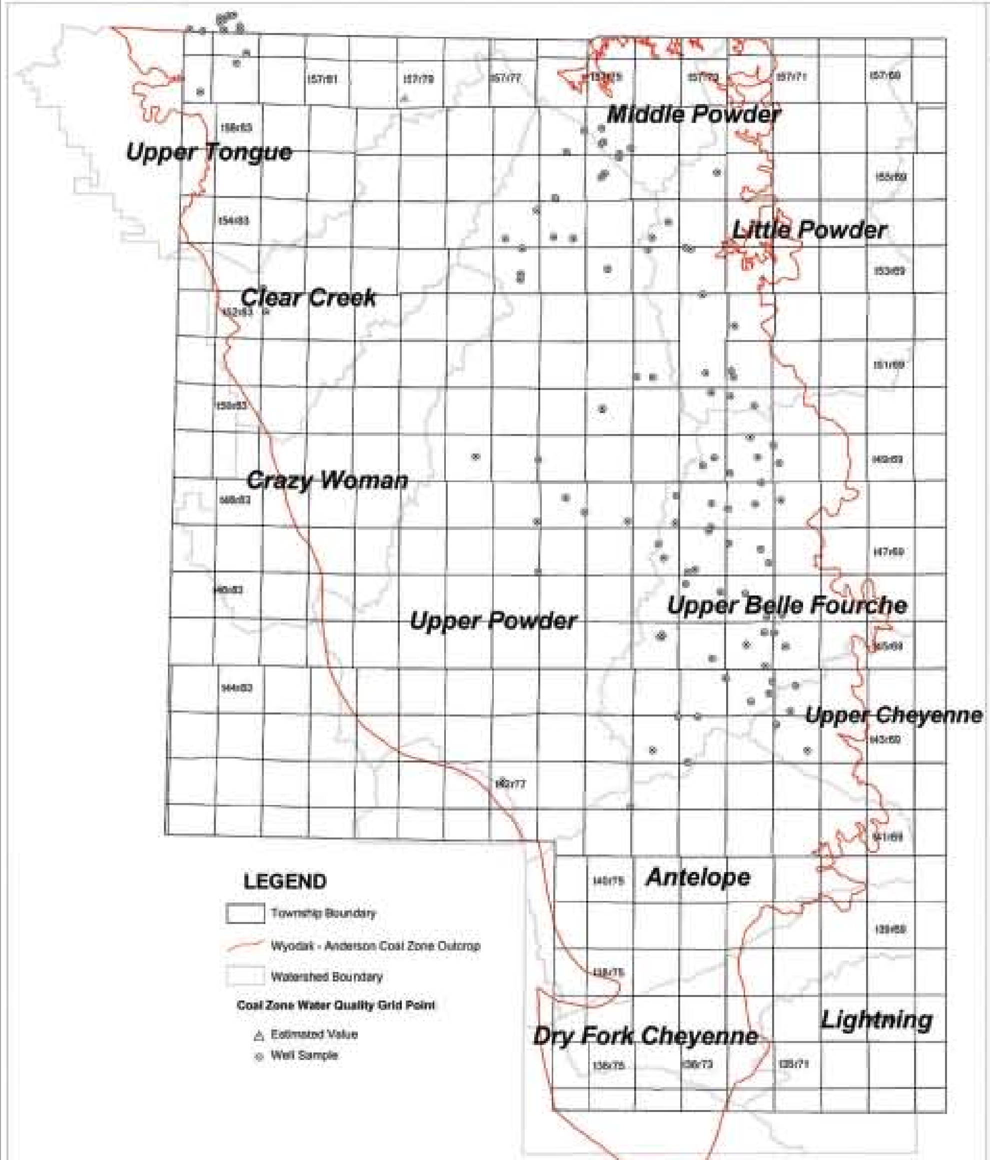
Subwateshed	Number of Existing CBNG Discharge Permits	Number of Existing CBNG Discharge Outfalls	Year 2001 CBNG Dischages (cfs)[1]	Estimated Discharge per Outfall (cfs)[1]
Upper Tongue River	22	105	4.8	0.05
Upper Powder River	160	760	16.1	0.02
Clear Creek	18	67	0.05	0.0007
Crazy Woman Creek	4	10	0.002	0.00022
Middle Powder River	38	184	3.4	0.02
Little Powder River	118	561	14.1	0.002
Antelope Creek	59	223	1.3	0.006
Upper Cheyenne River	37	125	8.4	0.07
Upper Belle Fourche River	290	1,530	43.2	0.03
Total	**746**	**3,565**	**--**	**--**

[1]cfs = cubic feet per second.

Source: BLM 2003a.

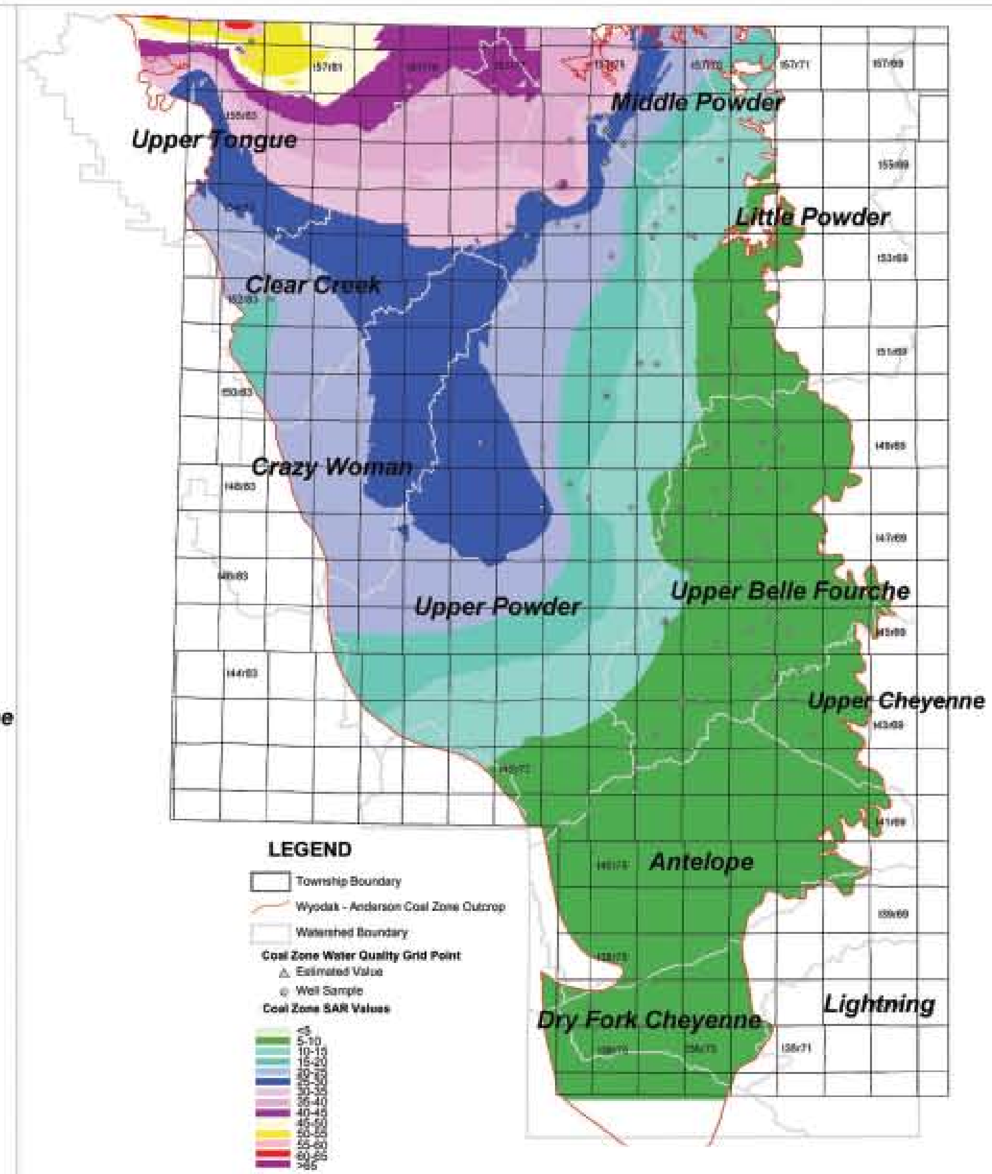
In the Belle Fourche and Cheyenne River basins, the discharge of CBNG-produced water directly to ephemeral and intermittent drainages is allowed. This water comes from shallow coal units and generally is low enough in TDS and SAR to be acceptable for direct surface discharge. Studies conducted by the BLM (2003a) have shown that conveyance losses for direct discharge to drainages are approximately 70 to 90 percent, depending on the time of year. Evaporation losses, which are a large component of conveyance losses, can be 80 percent during the summer months in Wyoming. Thus, most CBNG discharge water either infiltrates or evaporates within a few miles of the discharge outfall and generally is not recorded at USGS stream gauging stations. Impacts to surface water flow and quality are thus limited to within a few miles of the discharge outfall and, as of 2002, have not been recorded by the network of USGS gauging stations.

LOCATIONS OF WELLS SAMPLED



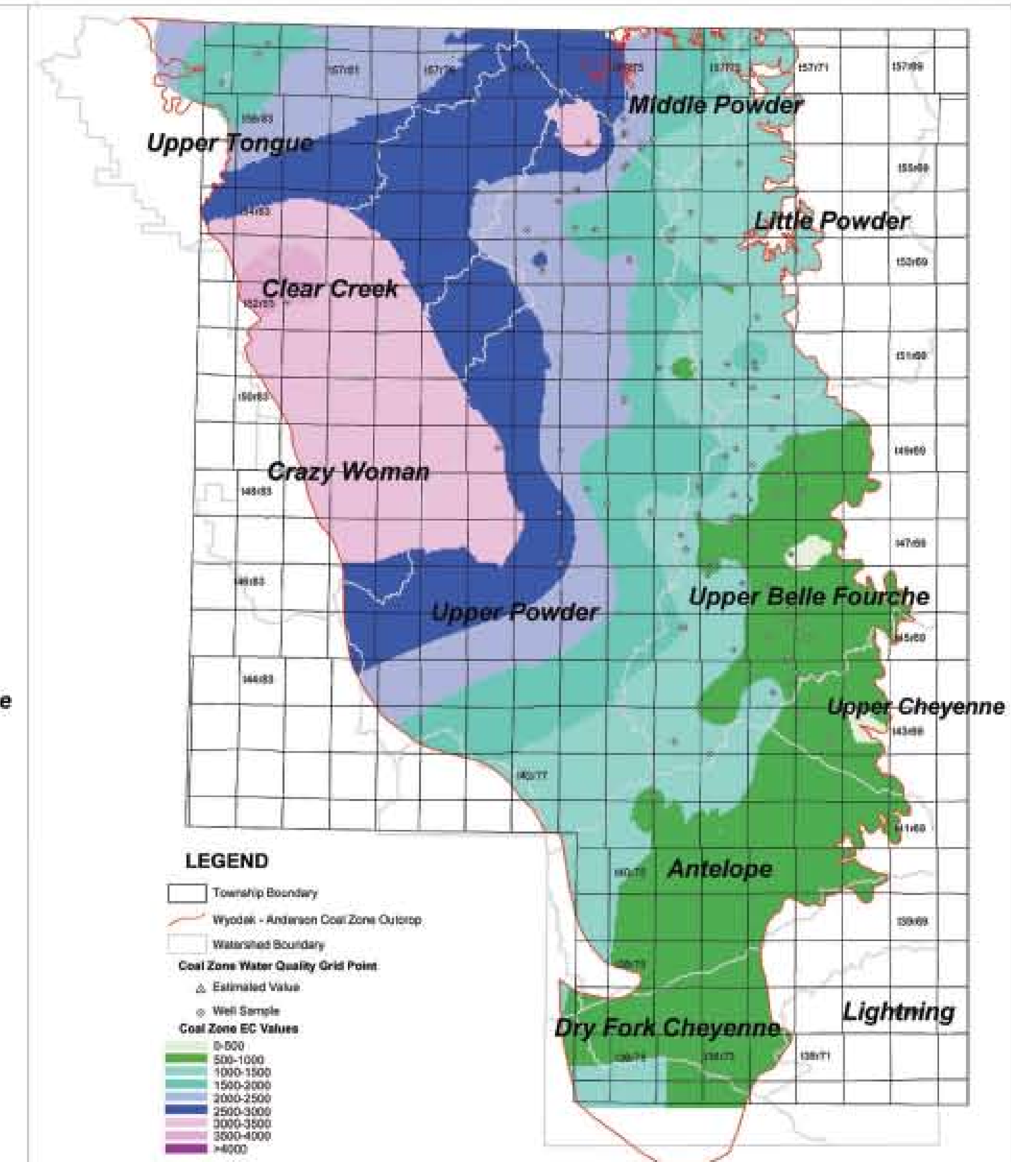
Wyodak - Anderson Coal Zone Produced Water Values Based on Confidential Data

PRODUCED WATER SAR VALUES



Wyodak - Anderson Coal Zone Produced Water SAR Values Based on Confidential Data

PRODUCED WATER EC VALUES



Wyodak - Anderson Coal Zone Produced Water EC Values Based on Confidential Data

SAR and EC Values by Subwatershed

	Little Powder		Upper Belle Fourche		Upper Cheyenne		Dry Fork Cheyenne		Antelope Creek		Upper Tongue		Clear Creek		Crazy Woman Creek		Middle Powder River		Upper Powder River		Salt Creek	
	SAR	EC	SAR	EC	SAR	EC	SAR	EC	SAR	EC	SAR	EC	SAR	EC	SAR	EC	SAR	EC	SAR	EC	SAR	EC
Maximum	23.0	1807	13.4	1828	8.1	1104	7.6	1067	9.0	1230	64.7	3712	42.3	3891	29.8	3455	41.9	3042	43.3	3408	13.1	1883
Minimum	7.7	930	6.1	397	5.6	448	5.5	600	5.8	506	22.6	1413	19.0	2334	19.7	2430	13.2	1182	7.7	785	6.2	974
Mean	11.1	1271	8.2	970	6.4	599	6.7	872	7.1	905	38.7	2406	29.2	3022	24.8	3129	27.8	2077	19.5	2163	9.7	1415
Median	10.3	1230	8.0	977	6.3	558	6.9	877	7.0	921	40.0	2424	28.8	2968	25.2	3169	26.1	1984	19.4	2142	9.5	1388

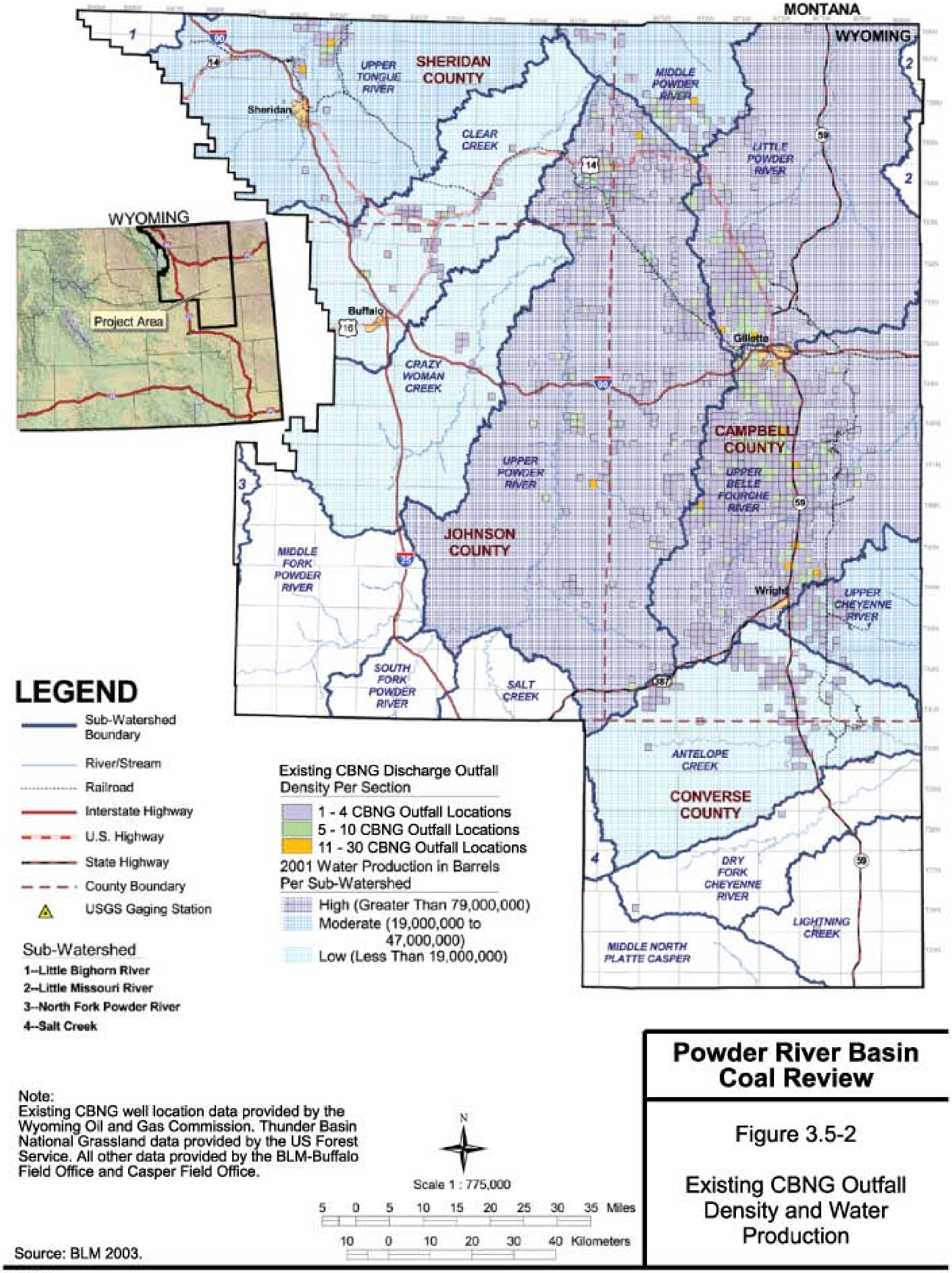
Source: BLM 2003a.

Powder River Basin Coal Review

Figure 3.5-1

SAR and EC Values for CBNG Produced Water by Subwatershed

07/27/06



Note:
Existing CBNG well location data provided by the Wyoming Oil and Gas Commission. Thunder Basin National Grassland data provided by the US Forest Service. All other data provided by the BLM-Buffalo Field Office and Casper Field Office.

Source: BLM 2003.

Powder River Basin Coal Review

Figure 3.5-2

Existing CBNG Outfall Density and Water Production

07/27/06

In the northwestern part of the PRB, especially in the Powder/Tongue River Basin, discharge of CBNG water directly to drainages may not be permitted (BLM 2003a). Indirect discharge of CBNG-produced water involves impoundments similar to stock ponds that are regulated by the WOGCC, WDEQ, BLM, and WSEO (in-stream impoundments). These impoundments are unlined and allow the CBNG discharge water to infiltrate into the shallow unsaturated alluvium. Impoundments can have in-channel or off-channel locations and WDEQ regulations relative to water quality differ depending on the location of the impoundment. Impoundments must have monitoring wells to evaluated impacts to alluvial groundwater if the initial groundwater investigation demonstrates that the depth to groundwater is less than 150 feet (200 feet if the impoundment is greater than 50 acre-feet in size), and if the groundwater present is Class III or better in quality (TDS less than 10,000 mg/L). These requirements apply regardless of the location or type of impoundment. Impoundments located within drainages (in-channel impoundments) may have discharge pipes to allow for some water to flow down the drainage in response to storm events. The WSEO regulates the design of in-channel impoundments to ensure water rights are protected. Off-channel impoundments must be at least 500 feet from a drainage. The WDEQ regulates discharges into both off-channel and in-channel impoundments. In addition, BLM review and approval of impoundment design is part of the APD and NEPA process for permitting of CBNG wells. The WOGCC regulates CBNG wells as oil and gas wells and thus also plays a role in regulating impoundments on private and state lands.

Studies of the potential impacts to surface and groundwater quality from infiltration of CBNG water currently are underway by the BLM, USGS, and private research groups funded by the CBNG operators. The results to date are incomplete and very preliminary in nature. In the Bone Pile Creek area of the Upper Belle Fourche drainage, studies by the BLM (2003a) have shown that infiltration of CBNG water does not alter groundwater quality and that infiltration extends downward through the alluvium and into the Upper Wasatch Formation aquifer. At Burger Draw, which is in the upper Powder River drainage, studies by the BLM (2003a) are ongoing. However, preliminary data suggest mounding of water in the unsaturated alluvium within approximately 15 to 25 feet of the impoundment and reaction between the CBNG water and minerals in the alluvium that increase TDS and other constituents. Infiltration extends to the Upper Wasatch Formation. At Brown Reservoir (T44N, R76W), similar studies found mounding within 15 feet of the impoundment and a water level rise of 10 feet, but no impacts to ephemeral drainages (BLM 2003a).

Thus, as of early 2002, discharge of CBNG water to ephemeral drainages and to impoundments had not produced any measurable impacts to surface water flow or quality beyond a few miles from the discharge outfall, due to high conveyance losses. In addition, discharge to impoundments had not appeared to affect groundwater or surface water beyond approximately 25 feet from the unlined impoundments. The PRB Oil and Gas Final EIS (BLM 2003a) specifies in the Record of Decision the type of discharge allowed in each of the drainages of the Wyoming PRB. Except for the Belle Fourche and Cheyenne River drainages, most discharge must be to impoundments, to reinjection wells, or to water treatment facilities. In the Belle Fourche and Cheyene River drainages, CBNG wells can discharge produced water directly to ephemeral drainages (BLM 2003a).

3.6 Coal Mine Water Use

3.6.1 Introduction

Coal mining has been a major part of the economy of the PRB since the early 1970s. Coal in the Fort Union Formation is exposed along the eastern side of the PRB from Gillette, Wyoming, south to near Wright, Wyoming. Many of the coal bed outcrops burned due to ignition of methane gas thousands of years ago. These burned areas are now clinker zones that allow for recharge to the coal bed aquifers due to the high permeability of the fractured clinker.

The coal mines in the eastern PRB of Wyoming are shown in **Figure 1-1**. These coal mines are strip mines that remove low sulfur coal from coal beds in the Tongue River member of the Fort Union Formation. Many of the coal areas are overlain by the Wasatch Formation. This formation in the eastern PRB is a local aquifer, containing water in the more sandy and permeable beds. This stratigraphic unit is removed by the mines before mining of the coal can begin. In addition, dewatering of the coal bed aquifers in the Fort Union Formation is required to facilitate mining. The coal beds of the Fort Union Formation dip to the northwest, requiring the coal mines to move progressively to the northwest and to mine deeper as they expand their mines to follow the PRB coal beds. CBNG development in the eastern PRB extracts natural gas from the same coal beds mined by the coal companies. As a result, the CBNG wells located near the lease boundaries of the current coal mines would be mined through as the coal mines expand to the northwest over the next 20 years.

3.6.2 Coal Mine Water Production

Coal mine water use currently is determined by three main factors: 1) the tons of coal mined per year; 2) the depth of the coal; and 3) the permeability of the Wasatch and Fort Union members mined through during coal removal. Coal mine dewatering and disposal of pumped water is regulated by the: 1) WSEO for the permitting of dewatering wells and 2) WDEQ for water disposal via Wyoming Pollution Discharge Elimination (WYPDES) permits. The WDEQ/LQD division regulates coal mining in general, and the BLM regulates coal mining through its leasing of federally-owned coal beneath private and public lands in Wyoming.

Water pumped for dewatering of coal beds by the coal mines of the eastern PRB is: 1) used in the processing of coal; 2) used for dust control or reclamation; or 3) released to ephemeral and intermittent drainages through WYPDES permits. The exact volume of water used by coal mines each year is not known for each mine, because mines often do not use their entire permitted water consumption volume each year. However, per existing permits in 2002, a total of 7,460 acre-feet of groundwater for consumptive use was allocated to the coal mines of the eastern PRB (WSEO 2004) (**Table 3.6-1**). Most mines pumped between 300 and 920 acre-feet of groundwater in 2002. The North Antelope Mine pumped 1,228 acre-feet of water, while a few mines were dry and had no groundwater pumpage (WSEO 2004). As shown in **Table 3.6-1**, groundwater use by the coal mines may be decreasing from a peak period from 1996 to 1998. This may be due to dewatering of the coal beds by CBNG wells, which increased substantially after 1995.

Table 3.6-1
Permitted Groundwater Use for Wyoming PRB Coal Mines

Coal Mine Subregion	Year (acre-feet)									
	1976	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**
Subregion 1	6.14	0	92.1	276.3	61.4	6.14	92.1	184.2	153.5	307
Subregion 2	61.4	61.4	18.42	0.03	0.012	0.921	92.1	122.8	144.29	178.06
Subregion 3	61.4	9.21	6.14	9.21	3.07	1.535	92.1	184.2	24.56	276.3
Total	**128.9**	**70.6**	**116.7**	**285.5**	**64.5**	**8.6**	**276.3**	**491.2**	**322.4**	**761.4**

Coal Mine Subregion	Year (acre-feet)									
	1986	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
Subregion 1	614	61.4	61.4	184.2	1,075	1,228.2	1,781	1,151.3	890.3	921
Subregion 2	73.68	184.26	184.2	245.6	862.7	693.82	1,627	1,096	1,261.8	626.28
Subregion 3	214.9	307	245.6	307	629.4	1,320.1	1,873	1,565.7	2,456	1,228
Total	**902.6**	**552.7**	**491.2**	**736.8**	**2,567**	**3,242.2**	**5,280**	**3,812.9**	**4,608.1**	**2,775.3**

Coal Mine Subregion	Year (acre-feet)						
	1996	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Subregion 1	2,977.9	3,991	2,456	1,842	1,535	951.7	1,504
Subregion 2	2,149	896.44	1,964.8	709.17	2,213	1,749.9	1,965
Subregion 3	3,684	3,499.8	4,881.3	4,850.6	3,684	2,824.4	3,991
Total	**8,810.9**	**8,387.2**	**9,302.1**	**7,401.8**	**7,433**	**5,526**	**7,460**

Source: WSEO 2004.

Water discharged by the coal mines to ephemeral and intermittent drainages is regulated by the WDEQ. Water cannot be discharged to a drainage if it substantially would alter the water quality of the drainage or produce flows that would result in erosion to the banks and beds of the streams. Thus, discharge of excess water by the coal mines in accordance with permit criteria should have little or no measurable effect on drainages. Storm water runoff from the coal mines also is regulated and is conveyed to detention ponds to allow for settling of sediment. Storm water that does not infiltrate into the alluvial sands and clays while held in the detention ponds can be allowed to flow into the drainages once most of the sediment has settled.

3.6.3 Coal Mine Spoils Water

When coal mines are reclaimed, the overburden is returned to the mined-out portion of the pit as spoils, and the mined area is reclaimed to conditions similar to original conditions for slope and drainage. In the Wyoming PRB, the spoils material gradually resaturates with water as groundwater from the Wasatch Aquifer and the Fort Union coal bed aquifers enters the spoils material. Spoils can take anywhere from 50 to 200 years to resaturate (GAGMO 2001). The water quality in the resaturated spoils usually is high in TDS, sulfate, sodium, and other metals and anions. Monitor wells in spoils from coal mines along the eastern PRB typically have a pH between 6.0 and 7.8, TDS in the range of 1,000 to 4,000 mg/L, bicarbonate values ranging from 500 to 1,300 mg/L, sodium in the range of 200 to 800 mg/L, high sulfate values ranging from 1,000 to 3,500 mg/L, and SAR values in the range of 2.0 to 7.0 (GAGMO 2001). Over time, the spoils are flushed by groundwater flowing through the reclaimed material and downgradient to the northwest in the Wasatch and Fort Union aquifers. Thus, the water quality in the spoils improves over time and becomes similar to that found in these aquifers near the coal mines. The time to flush spoils and improve the water quality varies considerably, based on the permeability of the spoils and groundwater flow rates in the aquifers. The time required to flush water from spoils can vary from a few tens to a few hundreds of years (Martin et al. 1988). This estimate was based on an evaluation of coal mines in the vicinity of Gillette, Wyoming.

3.6.4 Surface Drainages Near Coal Mines

Coal mines often mine through ephemeral and intermittent drainages. Drainages as high as third- and fourth-order drainages can be removed by mining. During reclamation, the third-order and higher drainages must be restored. First- and second-order drainages often are not replaced (Martin et al. 1988). Studies of coal mines near Gillette, Wyoming, summarized by the USGS showed that reclaimed coal mine areas have: 1) a lower infiltration rate for precipitation in the reclaimed areas compared to original natural areas, and 2) sediment loading to drainages during heavy storms that is considerably higher for reclaimed areas compared to the original natural areas. The USGS study found that the percentage of drainages disturbed by coal mining varied from 4 to 26 percent, the increase in runoff for reclaimed areas varied from 0.8 to 7.6 percent, and the increase in sediment erosion averaged approximately 436 percent. The decrease in infiltration rate was approximately 29 percent. The TDS increase in stream waters near reclaimed coal mines ranged from 1 to 7 percent higher than before reclamation (Martin et al. 1988). Thus, the potential impacts of coal mines to surface water features are dependent more on the changes in slope, infiltration capacity, and runoff characteristics of reclaimed areas than on the process of coal mining and disposal of water by coal mines. Over time, reclaimed areas become similar to the original natural areas in terms of soil properties, vegetation, and runoff characteristics; however, this may take a few centuries in the semiarid climate of the PRB.

3.6.5 Groundwater Levels Near Coal Mines

Groundwater drawdown near the coal mines of the eastern PRB is the result of coal mine dewatering and CBNG depressurization of the coal beds. It is often difficult to separate the effects of coal mine dewatering from that of nearby CBNG dewatering in the Fort Union Formation. Coal mine dewatering has resulted in groundwater level declines in the Wasatch of 20 to 100 feet within and up to a distance of approximately 1 to 3 miles from the mine boundaries. In the Fort Union Aquifer, combined CBNG and coal mine dewatering drawdowns of 40 feet or greater usually occur within approximately 3 to 5 miles of the coal mines, and drawdowns of up to 5 feet can occur at a distance of up to 11 miles from the coal mines (GAGMO 2001). Section 4.3, Groundwater Modeling Results for Current Conditions, of this report presents a discussion of the relative effects of CBNG pumping and coal mine dewatering on the Fort Union and Wasatch formations.

Groundwater level declines in the Fort Union Aquifer within and near the coal mines of the eastern PRB are available in the GAGMO (2001) 20-year report that summarizes groundwater data for these coal mines from 1980 to 2000. Data and maps presented by GAGMO (2001) show that for most mines, groundwater level declines in the mine area over the same 20-year period were in the range of 20 to 60 feet. A maximum drawdown of 120 feet was observed near the Buckskin Mine, and the Belle Ayr and the North Antelope/Rochelle mines had maximum water level declines of 100 feet within 1 mile or less of their permit boundaries (**Table 3.6-2**). CBNG fields near these coal mines have been active since approximately 1995, and groundwater level declines in the Fort Union Aquifer in these fields have been in the range of 100 to 240 feet. Many of these CBNG fields are within 2 miles or less of the coal mine permit boundaries. Thus, the current groundwater levels near the coal mines are a combined effect of CBNG development and coal mine dewatering, with groundwater level declines beyond approximately 2 miles from the coal mines being substantially influenced by CBNG development. The GAGMO (2001) data and interpretative contours are based on water level declines in individual monitor wells, not average water level declines over broad areas such as a square mile. As such, these declines and interpretative contours would be expected to differ from water level declines modeled with a numerical groundwater flow model. The results of numerical modeling conducted for this study are presented in Section 4.3, Groundwater Modeling Results for Current Conditions.

Table 3.6-2
Eastern PRB Estimated and Actual Groundwater Level Drawdowns in the Fort Union Aquifer

Coal Mine	Mine Area Water Level Decline 1980 – 2000[1] (feet)	CBNG Field Water Level Decline[1] (feet)	Distance to CBNG Field[1] (feet)	USGS 1988 Estimated Distance to 5-foot Drawdown Contour[2] (feet)	Measured Distance to 5-foot Drawdown Contour[1] (feet)	Comments
Subregion 1-North Of Gillette						
Buckskin	20 to 120	180 to 240	3,000-6,000	50,000	Up to 2,000	Affected by CBNG drawdown
Rawhide	40 to 60	100 to 200	6,000	60,000	Up to 10,000	Affected by CBNG drawdown
Eagle Butte	10 to 40	60 to 200	2,000	64,000	CBNG	CBNG obscures drawdown
Dry Fork	40	No CBNG field	--	Not used	Not used	--
Wyodak	40 to 60	No CBNG field	--	60,000	Up to 3,000	No CBNG influence
Subregion 2-South Of Gillette						
Caballo	20 to 40	100 to 240	10,000	50,000	Up to 3,000	5-foot drawdown measured east of mine near clinker.
Belle Ayr	80 to 100	100 to 240	1,000	40,000	Up to 5,000	5-foot drawdown measured east of mine near clinker.
Cordero-Rojo	20 to 60	160 to 240	15,000	Not used	Not used	--
Cordero	20 to 40	100 to 180	6,000	50,000	Up to 3,000	5-foot drawdown measured east of mine near clinker.
Coal Creek	10 to 60	60	8,000	60,000	Up to 5,000	5-foot drawdown measured east of mine near clinker.
Subregion 3-Wright						
Jacobs Ranch	20 to 40	80 to 100	2,000	28,000	Up to 12,000	5-foot drawdown measured east of mine near clinker.
Black Thunder	60	100 to 200	6,000	30,000	Up to 10,000	5-foot drawdown measured east of mine near clinker.
North Rochelle	20 to 40	No CBNG	--	50,000	Up to 2,000	5-foot drawdown measured east of mine near clinker.
North Antelope/Rochelle	60 to 100	No CBNG	--	40,000	Up to 15,000	5-foot drawdown measured east of mine near clinker.
Antelope	5 in Anderson; 40 Canyon	No CBNG	--	40,000	Up to 3,000	5-foot drawdown measured east of mine near clinker.

[1]GAGMO 2001.
[2]Based on Martin et al. 1988.

Note: 5-foot drawdown contour measured to east of mines where it is obscured to west by CBNG field drawdown. Measurement approximate and maximum distance given in table.
Measurements made on GAGMO (2001) maps and are estimates resulting from averages in different directions from mines.
Measurements made from mine lease boundary.

4.0 MODELING

4.1 Groundwater Modeling Protocol

For purposes of this study, a numerical groundwater flow model was developed for the area of active coal mining in the eastern portion of the PRB study area. The area modeled extended from the coal mines north of Gillette, Wyoming, to the southern extent of coal mining near Wright, Wyoming. The purpose of the CMGM was to provide the BLM with a tool for defining existing conditions (Task 1) and for assessing the combined impact of coal mining and CBNG development in the eastern portion of the PRB through year 2020 (Task 3).

The existing regional PRB groundwater model, developed for the PRB Oil and Gas EIS (BLM 2003a) was modified in two respects: 1) the model was telescoped to include only the overlap zone of coal mine dewatering and CBNG development in the eastern PRB of Wyoming, and 2) the model incorporated enhancements to the existing regional PRB groundwater model. These enhancements included: 1) a tighter grid spacing of 0.25 mile near the coal mines to better assess groundwater drawdown impacts near the mines, and a uniform grid spacing of 0.5 mile for the remainder of the model domain; 2) replacement of constant heads for perennial streams with the MODFLOW River Package; 3) replacement of drains used for CBNG wells with the MODFLOW Well Package; 4) simplification of the model layering from 17 layers to 6 hydrostratigraphic units (HSUs); and 5) modeling of the coal mine spoils and resaturation of the coal mine spoils following cessation of coal mining. In addition, approximately 350 GAGMO (GAGMO 2001, 2003) monitoring wells were used in the model calibration for the Fort Union Formation aquifer, coal stratigraphic data obtained from the BLM (Braz 2005) were incorporated into the model around the coal mines, and approximately 70 monitoring wells in the Wasatch Formation obtained from WDEQ/LQD mine permit files were used to calibrate the Wasatch Formation aquifer. These enhancements were intended to enable the CMGM to better represent the hydrologic interactions between aquifer units, streams, and groundwater pumpage in the zone of overlap between coal mining and CBNG activity in the eastern portion of the PRB study area. A summary of the modifications made to the original PRB Oil and Gas EIS (BLM 2003a) regional groundwater model during the development of the CMGM is presented in Appendix C.

4.1.1 Groundwater Flow System

As the CMGM is a submodel of the regional PRB groundwater model developed for the PRB Oil and Gas EIS (BLM 2003a), the groundwater flow system in the CMGM is the same as in the regional PRB groundwater model. The groundwater flow system and the conceptual model for the regional PRB groundwater model are presented in Chapter 2 of the *Technical Report PRB Oil and Gas EIS: Groundwater Modeling of Impacts Associated with Mining and Coal Bed Methane Development in the Powder River Basin* (Applied Hydrology Associates [AHA] 2002). Important components of the groundwater flow system that pertain to the eastern PRB and the CMGM are summarized below.

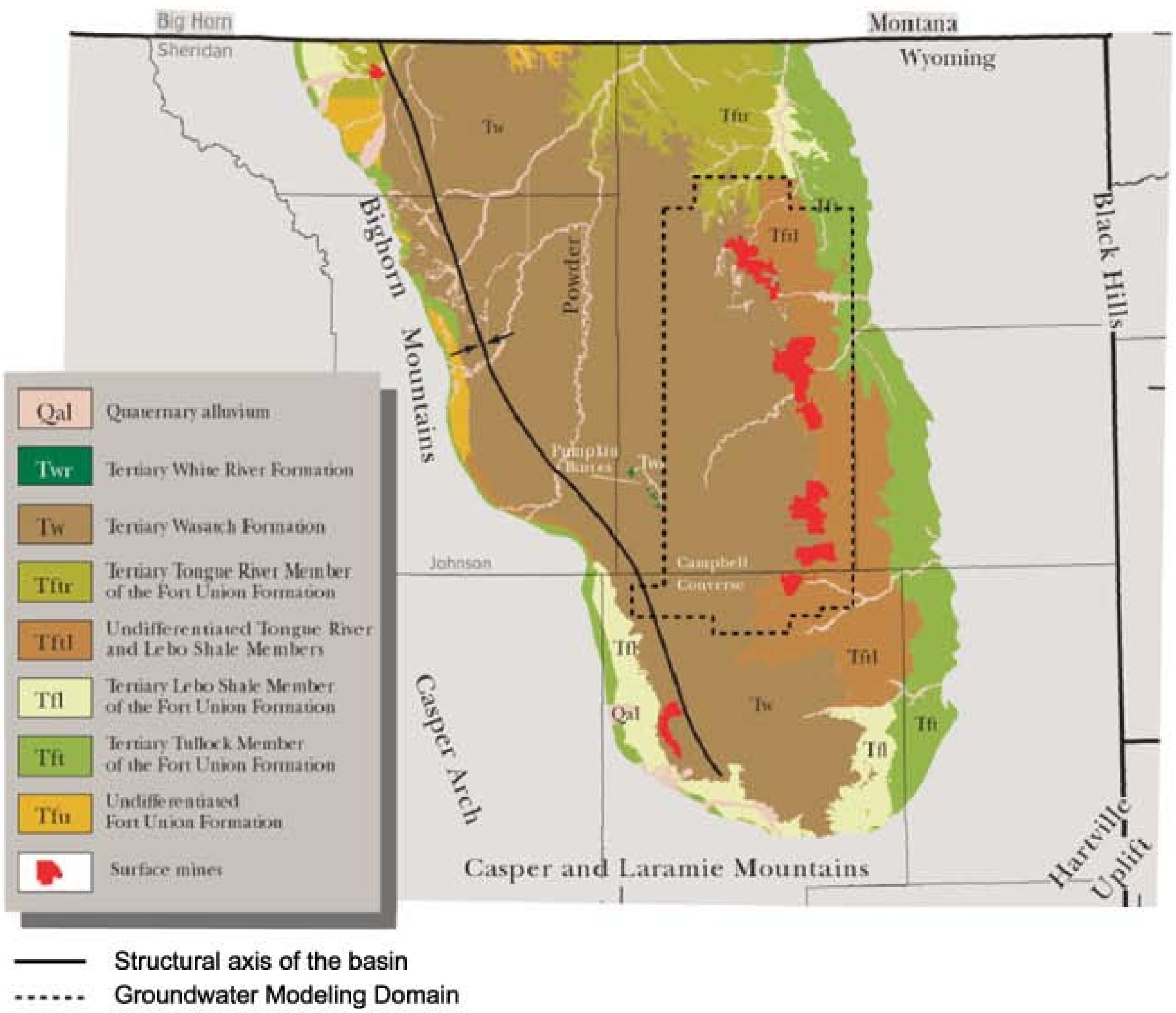
4.1.1.1 Hydrogeologic Framework of the Eastern PRB

Stratigraphic units in the eastern PRB affected by coal mining and CBNG development include Quaternary alluvium along major streams and the Tertiary-age Wasatch and Fort Union formations (BLM 2003a). The geology of the PRB is shown in **Figure 4.1-1**, and geologic cross-sections are shown in **Figure 4.1-2** with the location of the cross-sections given in **Figure 4.1-3**.The Quaternary alluvium consists mainly of unconsolidated silt, sand, and gravel along the major drainages of the Belle Fourche and Cheyenne River systems (Hodson et al. 1973). Local ephemeral streams often have a thin veneer of alluvium along and within their stream banks. The alluvium along major stream channels can be up to 50 feet in thickness, but is usually in the range of 10 to 30 feet (Ringen and Daddow 1990). Water yield from the alluvium is quite variable and is a function of the saturated thickness and grain-size distribution. Major streams can have bank storage in the alluvium, but most drainages have water in the alluvium only on a seasonal basis. Recharge to the alluvium results from surface precipitation or discharge from wells. Discharge from the alluvium is to local streams (AHA 2002). The Quaternary alluvium does not constitute an aquifer, even on a local scale, in the eastern PRB.

Tertiary stratigraphic units include the Wasatch and Fort Union formations. The Wasatch Formation is exposed at the surface over most of the PRB and overlies the Fort Union Formation (AHA 2002). The Wasatch Formation is not a regional aquifer within the PRB, but rather forms local aquifers in areas where the Wasatch has a high sand content. The Wasatch Formation consists of fine- to medium-grained sandstones, claystones, and coals. The thickness of the formation increases across the eastern PRB and reaches a thickness of approximately 3,000 feet near the center of the PRB. Sandstones constitute approximately one third of the formation (Seeland 1992); the sandstones are lenticular and generally discontinuous. Sand channels can yield up to 500 gpm in the eastern PRB near the coal mines (Martin et al. 1988). Coal units within the Wasatch can form aquifer units, mostly on the western side of the PRB. Low-permeability claystones generally inhibit vertical movement in the Wasatch.

The Fort Union Formation is the main coal-bearing Tertiary unit in the PRB and forms a regional aquifer throughout the basin. The Fort Union consists of coal seams, sandstones, siltstones, and claystones. The Fort Union can be divided into the Tongue River member, the lower Tongue River/Lebo Shale member, and the Tullock member. In the groundwater model for the eastern PRB, the Tongue River member is referred to as the Upper Fort Union, and the Tullock and Lebo members are in the Lower Fort Union (**Table 4.1-1**).

The Tongue River member (Upper Fort Union) contains the coal seams and is the principal unit mined for coal in the eastern PRB. There are seven to nine major coal seams in the Tongue River member (Wyoming State Geological Survey 1996) and many discontinuous, lenticular sandstone layers. The coals show a considerable variation in thickness and continuity and often split and reform across the basin (AHA 2002; BLM 2003a). For this reason, the coal seams are treated as part of a hydrogeological unit in the regional PRB groundwater model, rather than as individual aquifers. Correlation of coal seams is difficult and controversial within the PRB. In the eastern part of the PRB, the coal seams of the Tongue River member merge into one major coal unit called the Wyodak-Anderson Coal (Flores et al. 1999). In the regional PRB groundwater model, the Tongue River member has been called the Upper Fort Union, and the coal seams have been grouped into four separate coal units (**Table 4.1-1**). The upper three coal units merge into one unit in the eastern PRB. The coal stratigraphy used in the regional PRB groundwater model is that of Goolsby, Finely,



Powder River Basin Coal Review

Figure 4.1-1

Geologic Map

Source: Flores et al. 2001.

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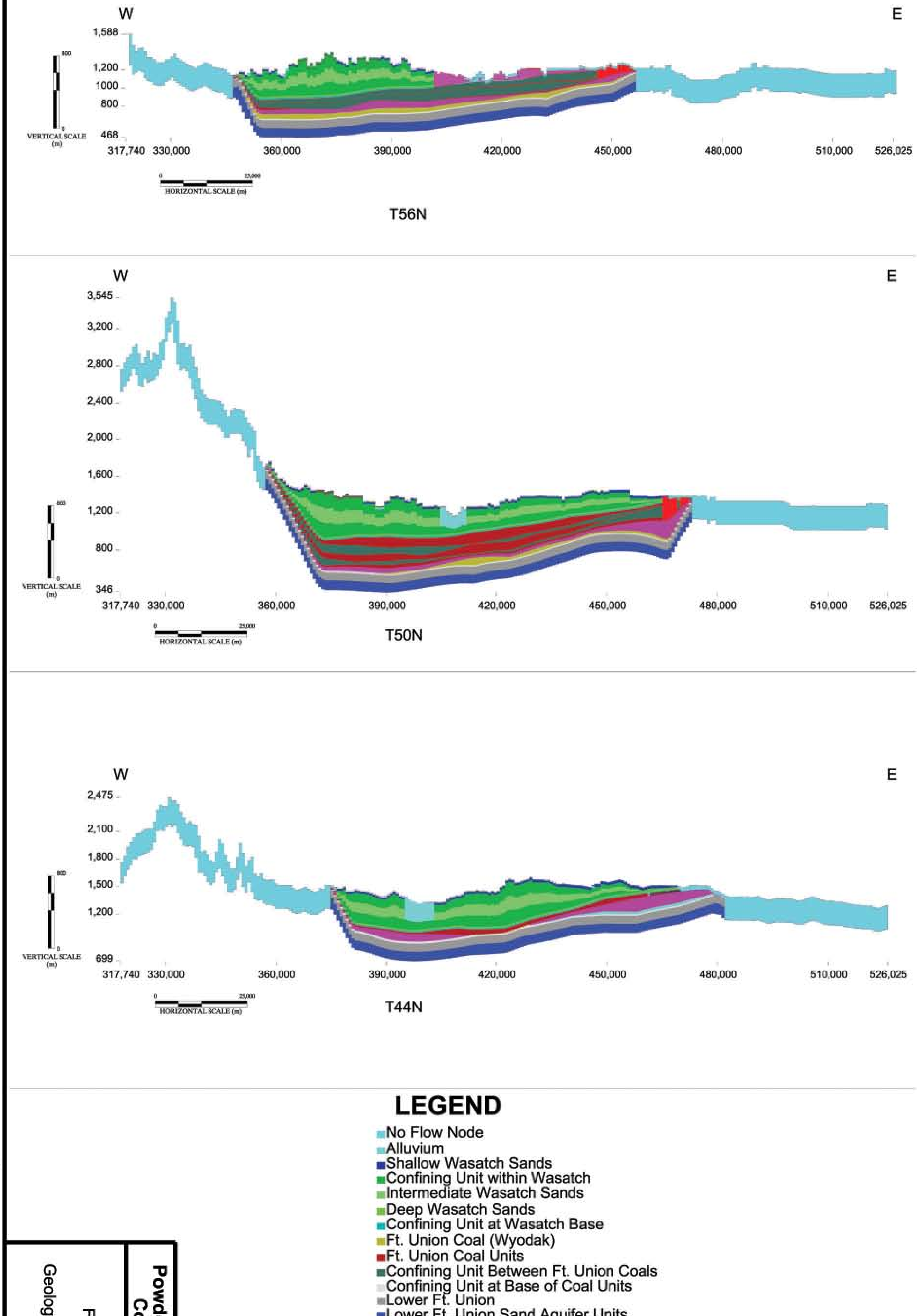
Table 4.1-1
Regional Model Layers[1]

PRB Oil and Gas EIS Regional Model Layer	Geologic Formation	Coal Unit Designation	Geologic Unit	Predominant Lithologies	CMGM HSU
1	Wasatch Formation	--	Upper Wasatch Formation and alluvium	Sandstone, siltstone, claystone	1
2	Wasatch Formation	--	Shallow Wasatch sands	Sandstone, siltstone	1
3	Wasatch Formation	--	Confining unit within Wasatch Formation	Siltstone, claystone	2
4	Wasatch Formation	--	Intermediate Wasatch sands	Sandstone, siltstone	2
5	Wasatch Formation	--	Confining unit within Wasatch Formation	Siltstone, claystone	2
6	Wasatch Formation	--	Deep Wasatch sands	Sandstone, siltstone	3
7	Confining Unit between Wasatch and Fort Union	--	Low permeability unit at base of Wasatch Formation-separating Wasatch and Fort Union formations plus non-coal bearing claystone units at the top of the Fort Union	Siltstone, claystone, local sandstone and clay units	4
8	Upper Fort Union	Wyodak-Anderson Coal as defined by USGS	Upper Fort Union coal (Unit 1) – Anderson Coal of Goolsby	Coal (minor sandstone, siltstone)	5
9	Upper Fort Union		Confining unit between coal units	Siltstone, claystone	5
10	Upper Fort Union	Wyodak-Anderson Coal as defined by USGS	Upper Fort Union coal (Unit 2) – Canyon Coal of Goolsby	Coal (minor sandstone, siltstone)	5
11	Upper Fort Union		Confining unit between coal units	Siltstone, claystone	5
12	Upper Fort Union	Wyodak-Anderson Coal as defined by USGS	Upper Fort Union coal (Unit 3) – Wall Coal of Goolsby	Coal (minor standstone, siltstone)	5
13	Upper Fort Union		Confining unit between coal units	Siltstone, claystone	5
14	Upper Fort Union	Wyodak-Anderson Coal as defined by USGS	Upper Fort Union coal (Unit 4) – Wyodak Coal of Goolsby	Coal (minor sandstone, siltstone)	5
15	Upper Fort Union	--	Confining unit at base of coal units	Siltstone, claystone	5
16	Lower Fort Union	--	Lebo Shale	Sandstone, siltstone, claystone	6
17	Fort Union Formation	--	Tullock Formation	Sandstone, siltstone	6

[1]PRB Oil and Gas EIS (BLM 2003a) groundwater model stratigraphy compared to CMGM stratigraphy.

and Associates (2001). This coal stratigraphy has been preserved in the CMGM, because the CMGM is a submodel of the regional PRB groundwater model. In the CMGM, the Upper Fort Union has been represented by a single HSU (HSU-5). HSU-5 represents the Wyodak-Anderson coal in the eastern PRB and includes all the major coal seams found in and near the operating coal mines of the eastern PRB. In addition, the coal stratigraphy near and within the coal mines available from the BLM (Braz 2005) has been incorporated into the CMGM and merged with the stratigraphy of Goolsby, Finely, and Associates (2001) west of the coal mines. This was done by combining the data from the BLM (Braz 2005) with the data of Goolsby, Finely, and Associates (2001) and contouring the combined data set to form a single merged data set with a consistent pattern of



Note: Coordinate System: NAD 27 UTM Zone 13 Meters
colors within cross sections represent different values
hydraulic conductivity

Powder River Basin Coal Review

Figure 4.1-2

Geologic Cross-sections

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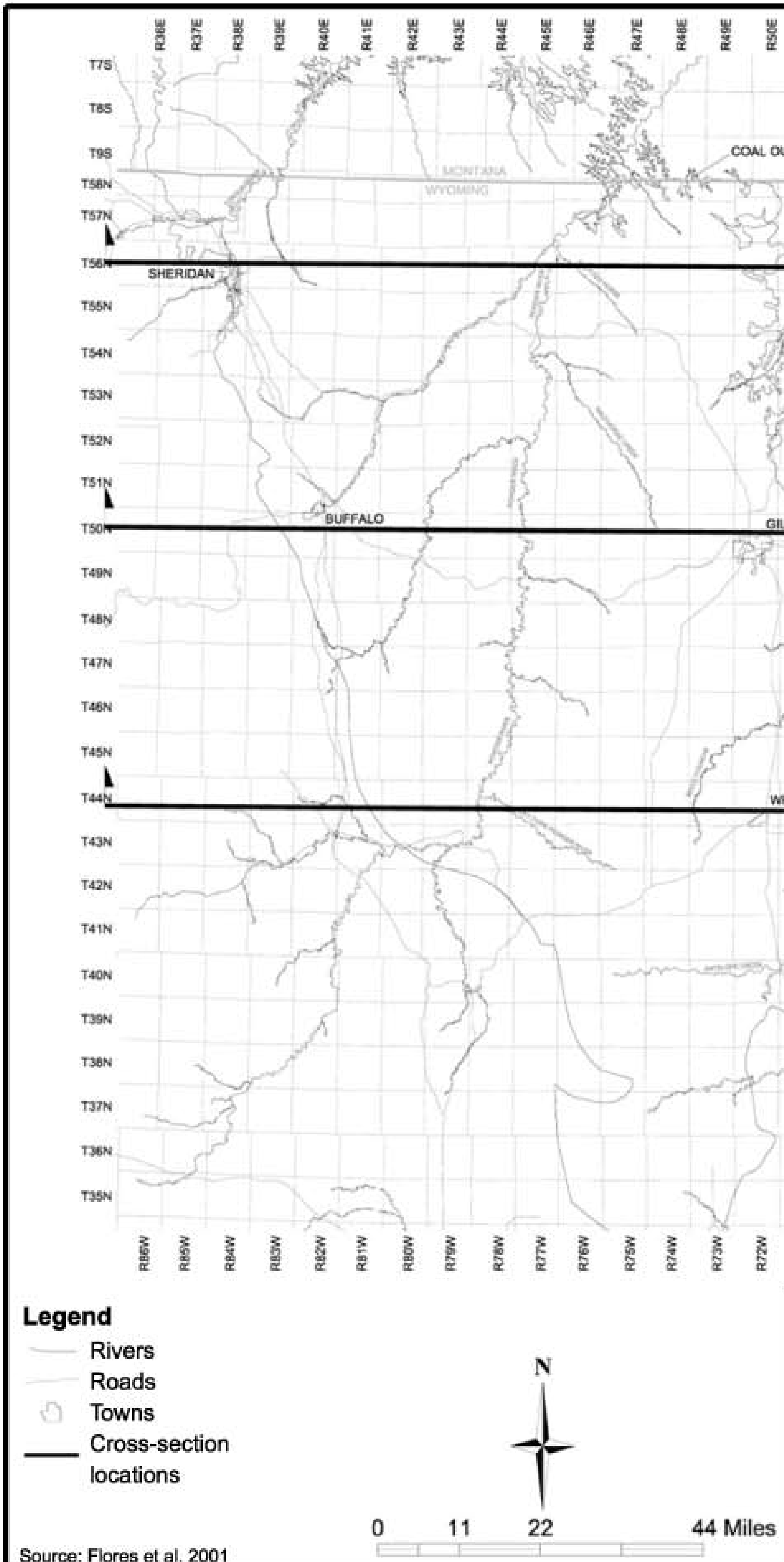

Powder River Basin Coal Review

Figure 4.1-3

Locations of Cross-sections

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elevations for the different coal units. Thus, the CMGM represents the detailed coal mine stratigraphy found within and near the operating coal mines.

The coals of the Tongue River member (Upper Fort Union) generally are separated from the sandstones of the overlying Wasatch Formation by continuous, low-permeability claystone and siltstone units of variable thickness. This confining unit between the Wasatch and Upper Fort Union varies in thickness from 11 to 363 feet and is generally at least 30 feet thick (AHA 2002). This low-permeability layer between the Wasatch and Fort Union formations has been grouped along with the shale and claystone units above the coal in the Fort Union into HSU-4.

Groundwater in the Upper Fort Union downdip of the outcrop of the Fort Union generally is confined by this zone of low-permeability claystones and siltstones that separates the Wasatch and the Fort Union (Martin et al. 1988). The coal seams of the Upper Fort Union range in thickness from a few feet to more than 200 feet and tend to decrease in thickness toward the southeastern part of the basin (AHA 2002). In the eastern PRB and in the regional PRB groundwater model, the Lower Tongue River member of the Fort Union Formation and the Lebo Shale member are grouped with the Lower Fort Union (HSU-6).

Groundwater flow in the coal seams is highly variable. Permeability in the coals depends on fracturing and faulting (secondary permeability), and groundwater flow in the Upper Fort Union in general is predominately in the sandstone units and in the highly fractured coal seams. Groundwater yields to wells in the Upper Fort Union are in the range of 10 to 50 gpm and can range up to 100 gpm for highly fractured areas (Hadley and Keefer 1975). Recharge to the Upper Fort Union comes from precipitation along the outcrop areas of the eastern PRB and from downward groundwater flow from the overlying Wasatch Formation. Discharge occurs in walls and floors of the coal mine pits, at locations where streams intercept the Upper Fort Union, and especially at the CBNG wells that predominate in the eastern PRB.

The base of the Upper Fort Union coals is a claystone that acts as a confining layer separating the Upper Fort Union from the underlying sandstones and shales of the Lebo Shale member. The Lower Fort Union Formation in the regional PRB groundwater model and in the CMGM (**Table 4.1-1**) is represented by the Tullock and Lebo Shale members of the Fort Union Formation. These are fine- to medium-grained sandstones with thin interbedded coal seams, siltstones, and carbonaceous shales (Martin et al. 1988). The sandstones are more massive than those in the Upper Fort Union and tend to account for 21 to 88 percent of the formation (AHA 2002). The Tullock member is a regional aquifer that can yield 200 to 300 gpm to water supply wells (BLM 2003a). The Lower Fort Union in the CMGM is modeled with HSU-6.

4.1.1.2 Groundwater Flow Systems in the Eastern PRB

There are two main groundwater flow systems in the eastern PRB: 1) a shallow local groundwater flow system in the Wasatch Formation that is controlled by drainage divides and streams, and 2) a regional groundwater flow system in the Fort Union Formation that flows from southeast to northwest across the PRB and eventually into the Montana portion of the basin. Recharge to the shallow groundwater flow system in the Wasatch Formation comes from precipitation, from well and mine discharge, and from leakage through streams and rivers. Recharge to the regional groundwater flow system in the Fort Union comes from precipitation recharge along the outcrop of the Fort Union in the eastern PRB and from downward groundwater flow from the Wasatch to the

Upper Fort Union. Discharge from the flow systems in the Wasatch Formation is mainly to streams and wells and to some extent to plants through evapotranspiration. Discharge from the Fort Union groundwater system is mainly to wells and to some extent to major rivers such as the Powder River. In the eastern PRB, discharge from the Fort Union system is mainly to wells, especially CBNG wells.

Recharge to the Wasatch Formation groundwater system is mainly from infiltration of surface water, surface water discharge, and runoff in streams during storm events. This recharge is very difficult to quantify (AHA 2002). Recharge in the southern part of the PRB from stream infiltration can be in the range of 0.43 to 1.44 acre-feet per mile following storm events (Lenfest 1987). Values can range as high as 3.56 to 26.5 acre-feet per mile. Studies of conveyance losses from CBNG discharge to streams during dry weather indicate that conveyance losses can range from 64 to 100 percent over a distance of approximately 2 miles or less from the discharge point (AHA 2001; Meyer 2000). Evapotranspiration can account for approximately 18 percent of conveyance loss associated with CBNG discharge (Hydrologic Consultants, Inc. 2001). Thus, recharge to the upper Wasatch flow system can be as high as 80 percent of discharge at the outfall location or can be as low as 40 to 50 percent.

Recharge to the Fort Union flow system along the outcrop zone in the eastern PRB is unknown but has been estimated to be in the range of 0.1 to 0.6 inch per year (AHA 2002). Recharge to the Fort Union flow system from downward leakage from the Wasatch Formation also is unknown. Limited studies by the BLM in the Marquiss field (BLM 2003a) have shown that a 40-foot claystone lens separating the sands of the Wasatch Formation from the coals of the Upper Fort Union can provide a significant hydraulic barrier to downward flow, but still allow for some vertical leakage from the Wasatch to the Upper Fort Union (BLM 2002). The Marquiss study suggests a vertical hydraulic conductivity for the claystone aquitard between the Wasatch and the Upper Fort Union (HSU-4) in the range of 6.0×10^{-11} feet/second (AHA 2002, Chapter 8).

Groundwater flow in the Wasatch and the Fort Union formations is not well understood, and current conceptual models for groundwater flow in the PRB are often in disagreement. A summary of current published conceptual models for groundwater flow in the PRB is available in the groundwater modeling technical report that accompanies the PRB Oil and Gas EIS (AHA 2002). These conceptual models were developed for the PRB generally without consideration for coal mine dewatering and CBNG depressurization of the Upper Fort Union. The basic concept common to all of these published models is that there are two flow systems in the PRB, as discussed earlier. The upper flow system is in the Wasatch Formation and is a local groundwater flow system driven by recharge from precipitation and from stream infiltration and controlled by drainage divides and discharge to ephemeral streams. These local flow systems are very poorly understood and have not been studied in any detail. The second flow system is the regional flow system in the Fort Union Formation that “naturally” flows from southeast to northwest across the PRB and is driven by recharge in the outcrop zone of the Upper Fort Union (the “clinker zone”) and by discharge to major streams such as the Powder River and eventually subsurface flow into Montana.

Groundwater flow in the eastern PRB today is affected by discharge of CBNG water to the Wasatch and removal of groundwater from the Fort Union by CBNG pumping. In the Wasatch Formation, mounding of groundwater in the Wasatch of 10 to 20 feet is evident west of the coal mines located south of Gillette, Wyoming. Also, major drainages such as the Belle Fourche and Antelope Creek locally control the regional flow of groundwater in the Wasatch Formation. For the Fort Union

Formation, groundwater flow in the eastern PRB is still from southeast to northwest even with all the CBNG pumping. Within approximately 5 to 8 miles of the coal mines, however, groundwater flow in the Fort Union is controlled by the pumping in the CBNG wells that lie just to the west of the coal mines. Beyond approximately 10 to 12 miles west of the coal mines and generally for the area of the eastern PRB west of State Highway 59, groundwater flow in the Upper Fort Union is from southeast to northwest, with water levels in the southeast being approximately 4,800 feet amsl and those in the northeast being approximately 4,200 feet amsl for the area west of the coal mines north of Gillette, Wyoming. Section 4.3, Groundwater Modeling Results for Current Conditions, presents a more detailed discussion of groundwater flow in the eastern PRB for the base year (2002).

In the eastern PRB, recharge to the Upper Fort Union from precipitation is somewhat reduced due to coal mining and the interception of clinker recharge by the mine pits. Recharge to the Upper Fort Union from the Wasatch also is probably low, but higher than in the past due to CBNG discharge to the Wasatch. Discharge from the Upper Fort Union is mainly to CBNG wells. Recharge to the upper Wasatch Formation is from CBNG discharge, precipitation, and storm runoff infiltration. Discharge from the Wasatch is to private wells, coal mines, ephemeral streams, and plant evapotranspiration. Plant evapotranspiration has been estimated to range from 8.3 to 14.9 inches per year, with an average value for the PRB of approximately 12.7 inches per year (Lenfest 1987). Regional recharge to the Wasatch from precipitation is probably in the range of 0.03 inch per year, but can range from 0.01 to 0.06 inch per year (AHA 2002).

Aquifer hydraulic properties for the Wasatch Formation, the Upper Fort Union, and the alluvium mainly are available from aquifer tests conducted by the coal mines in the eastern PRB. These tests thus apply to areas within a few miles of the coal mines. These data are summarized in Appendix B of the groundwater modeling technical report that accompanies the PRB Oil and Gas EIS (AHA 2002). For the alluvium, the hydraulic conductivity ranges from 0.01 to 349.7 feet per day (ft/day) with a median value of 33.5 ft/day. The specific storage ranges from 7.9 x 10^{-5} to 2.3 x 10^{-1} per foot with a median value of 1.3 x 10^{-2}. Specific yield ranges from 0.001 to 0.23 with a median value of 0.018. For the Fort Union coals, the hydraulic conductivity ranges from 0.04 to 74.27 ft/day with a median value of 1.99 ft/day. The specific storage ranges from 2.1 x 10^{-7} to 1.1 x 10^{-1} per foot with a median value of 3.0 x 10^{-4}. The specific yield ranges from 4.1 x 10^{-5} to 1.1 x 10^{-1} with a median value of 3.1 x 10^{-4}. Wasatch Formation sands have a hydraulic conductivity that ranges up to 20.2 ft/day with a median value of 5.1 ft/day. The specific storage ranges from 2.3 x 10^{-6} to 1.0 x 10^{-1} per foot with a median value of 1.4 x 10^{-4}. The specific yield ranges up to 0.19 with a median value of 0.00011. Wasatch clay confining units have a horizontal hydraulic conductivity in the range of 2.4 x 10^{-5} to 3.1 x 10^{-2} ft/day with a median value of 6.6x 10^{-5} ft/day. The specific storage ranges from 5.3 x 10^{-5} to 6.2 x 10^{-5} per foot with a median value of 2.1 x 10^{-5} based on eight aquifer tests. Pit backfill material in the reclaimed coal mines has a horizontal hydraulic conductivity in the range of 0.07 to 2.0 feet/day (Martin et al. 1988). These hydraulic data are in the regional PRB groundwater model and were used as starting values in the CMGM.

4.1.2 Hydrologic Issues

Groundwater models are constructed to resolve particular hydrologic issues that cannot be addressed with simple analytical calculations. The hydrologic issues for the area of overlap between CBNG development and coal mining in the eastern PRB are discussed below.

4.1.2.1 Hydrostratigraphy of the Wasatch and Fort Union Formations

The Wasatch and Fort Union formations are the two stratigraphic units most affected by coal mining and CBNG development. Both of these units have a complex lithology and, therefore, a complex hydrology. The Wasatch Formation is not a true regional aquifer, but rather contains local aquifers in the thicker and more continuous sand units. The Fort Union Formation contains numerous coal seams and sand units that act locally as aquifers. The Fort Union is considered to be a regional aquifer in eastern Wyoming and can be subdivided into lithostratigraphic (formations correlated by similar rock type) members based primarily on the correlation of coal units. The issue is which lithostratigraphic members of the Fort Union act as aquifers and can be treated as aquifers in a numerical model. Also, there is some difference of opinion as to how the coal units of the Fort Union should be correlated.

For a numerical groundwater model, the correlation and naming of the coal units is not a key issue. The key is which lithostratigraphic members of the Fort Union act as regional aquifers. This is because groundwater models only recognize layer thickness and layer aquifer properties, not lithology or rock correlations. For the purpose of the CMGM, the lithostratigraphic members of the Fort Union Formation and also the Wasatch Formation have been grouped into HSUs based on: 1) available aquifer property data in the existing regional groundwater model for the PRB; 2) correlations of lithostratigrahic members of both formations presented in the groundwater modeling technical report that accompanies the PRB Oil and Gas EIS (AHA 2002); and 3) the overall purpose of the CMGM, which is to model groundwater impacts due to pumping in the Upper Fort Union by CBNG depressurization and coal mine dewatering and discharge of CBNG water to the upper Wasatch Formation. The use of HSUs allowed the numerical model to run more efficiently than the existing parent model, which has 17 layers that attempt to replicate the geology of the PRB.

4.1.2.2 Stream/Aquifer Interaction

Most drainages in the eastern PRB are ephemeral. Major perennial drainages are the Belle Fourche and Cheyenne rivers. However, these drainages are not perennial over their entire lengths, nor are they necessarily perennial over any given stretch throughout the entire year. Water discharged to ephemeral drainages by CBNG development or coal mine dewatering infiltrates into the alluvium along the drainages and ultimately into the upper Wasatch Formation. Alluvium along drainages can range in thickness from a few feet to approximately 40 to 60 feet. Studies by the BLM presented in the PRB Oil and Gas EIS (BLM 2003a) and the administrative record that accompanies that EIS (BLM 2003b) have shown that the conveyance loss for CBNG discharge is approximately 70 percent, on average, and that this loss occurs within 2 to 3 miles of the CBNG discharge outfall. Approximately 80 percent of the conveyance loss is due to infiltration of the water into the alluvium and into the Wasatch Formation, although this varies seasonally.

4.1.2.3 Groundwater Pumping by CBNG Wells

CBNG wells have a life cycle of approximately 7 years (BLM 2003a). During the first year, groundwater in the Upper Fort Union coal seams is pumped at a high rate to depressurize the coal aquifer and release the methane gas from the cleats in the coal. Once methane gas production begins, pumping levels off at a lower rate to maintain the hydrostatic head on the coal. Over time, the pumping rate of the well declines to a few gallons per minute as methane production from the well declines. The depth of a CBNG well determines the pumping rates required for methane gas production. Thus, the location of a well determines the pumping rates, and these rates change over the approximately 7-year life of the well.

CBNG development near the coal mines of the eastern PRB is in a mature stage of development. Many of the CBNG wells can be expected to decrease water production over the next 5 years, and only a few new wells are expected to be developed. Pumping rates permitted by the WOGCC are available on the WOGCC web site for permitted CBNG wells. Actual pumping rates usually are less than permitted. However, only the permitted pumping rates are known or available in public records. Thus, pumping rates used in a numerical model have to be based on permitted pumping rates, and the scaling down of pumping rates over the 7-year life cycle of a pod of CBNG wells is approximate and arbitrary, leading to only approximate pumping rates for wells beyond the calibration time period of the model. Thus, pumping rates for CBNG wells beyond 2002 are approximate and based on the estimates of future CBNG development as defined in the Task 2 Report for the PRB Coal Review, Past and Present and Reasonably Foreseeable Development Activities *(*ENSR 2005).

4.1.2.4 Groundwater Discharge by CBNG Wells

Discharge of groundwater from CBNG wells is through outfalls permitted by the WDEQ. Pods of CBNG wells, often 7 to 10 wells, discharge from the same outfall. The location of the outfalls available from the WDEQ, and outfalls of record as of 2002 (the calibration period for the CMGM), are in the existing regional PRB groundwater model (AHA 2002). A critical issue for recharge to the upper Wasatch Formation is the rate of discharge of CBNG water at outfalls. Discharge rates are not known for most outfalls, but they generally are less than the sum of the permitted pumping rates for the individual wells in an outfall pod. Discharge rates at outfalls in the numerical model, therefore, are the sum of the pumping rates of the wells near the outfall. As a result, outfall discharge rates were based on the permitted pumping rates in the existing regional PRB groundwater model for year 2002 (Task 1), with future outfall discharges rates from 2002 to 2020 (Task 3) based on the assumed pumping rates for CBNG wells in that time period (Task 2).

4.1.2.5 Groundwater Pumping and Discharge by Coal Mines

Coal mines dewater the Wasatch and Fort Union formations, as needed, to mine the coal in their open pit mines. Dewatering can be conducted using wells or sumps in the pits themselves. Permitted dewatering rates are available from the WSEO for most, but not all, of the coal mines. Actual dewatering rates are somewhat less than permitted rates, but they generally are close to permitted rates. The produced groundwater is used for dust control, as process water, and for reclamation at mine sites. Water not used can be discharged to holding ponds and then eventually to ephemeral drainages. The amount of water discharged to drainages varies considerably from mine to mine and seasonally. Groundwater discharge to drainages by coal mines is minimal compared to CBNG water discharge and is anticipated to have minimal effect on recharge to the upper Wasatch Formation. Groundwater use by coal mines between the calibration period of 2002 and year 2020 (for Task 3) is based on the expected pit configurations provided by the mine operators to the BLM. Current and projected groundwater consumption rates are summarized in the Task 2 report. For the purpose of modeling, it was assumed that all of the water pumped by a coal mine was or would be consumed by operations.

4.1.2.6 Vertical Groundwater Flow

Groundwater in the Wasatch and Fort Union formations has a vertical flow component. In many areas, especially areas of recharge from CBNG water discharge, the vertical flow component is downward. Also, in areas where the coal seams of the Fort Union Formation have been depressurized by CBNG development, groundwater flow presently is downward from the Wasatch to the Fort Union and possibly upward from the underlying Tullock member of the Fort Union Formation to the Upper Fort Union. Only a few areas in the eastern PRB have nested monitor wells that demonstrate the vertical flow component, and the nature of vertical groundwater flow in the PRB has not been evaluated. Vertical groundwater flow in the CMGM was based on calibration of the model because of the lack of aquifer data on vertical flow and because of the rather incomplete understanding of groundwater flow in the PRB due to the lack of long-term aquifer studies.

4.1.2.7 Coal Clinker Zones

The outcrop areas of the coal seams of the Fort Union Formation are zones of burned coal referred to as clinker. These are zones of high secondary permeability and are the main recharge zones for the Fort Union Formation. The high secondary permeability of the clinker zones ends abruptly at the interface between the burned coal and the unburned coal. This transition in permeability for the coal outcrop areas of the Fort Union Formation affects the recharge to the Fort Union. Thus, recharge to the Upper Fort Union along these clinker outcrop zones is not well known. The final recharge values used in the CMGM were based on calibration. The initial starting values were set at 10 percent of precipitation.

4.1.2.8 Coal Mine Spoils

When coal mines are reclaimed, the overburden removed to access the coal is returned to the mined out portion of the mine pit as mine spoils during the reclamation process. These mine spoils resaturate with groundwater over time and become shallow mine-spoil aquifers with unique hydraulic properties and water chemistry. Over time, groundwater flowing from the clinker recharge zones in the Fort Union Formation and the outcrop areas of the Wasatch Formation will move the water in the mine spoils downgradient into the Wasatch and Fort Union formations west of the coal mines. Eventually, over a period of a few tens to a few hundred years (Martin et al. 1988), the mine-spoil aquifers will become part of the Wasatch and Fort Union aquifers. Modeling of these mine spoil aquifers following cessation of coal mining and reclamation of the mines required modification of the hydraulic properties of the Wasatch and Fort Union formations as a function of time to accommodate progressive reclamation of individual coal mining areas. This was done based on estimated dates of mine closure and reclamation provided by the BLM.

4.1.2.9 Precipitation Recharge

The eastern PRB is a rather dry area that receives precipitation from summer storms, spring rains, and snowmelt. Most of the drainages are ephemeral and flow in response to snow melt and rain storms. Recharge from precipitation is thus seasonal and not uniform over the area. Most precipitation that falls on the rolling plains of the eastern PRB evaporates or is transpired by vegetation. Therefore, recharge to the upper hydrostratigraphic unit, which is usually the Wasatch Formation, from precipitation was modeled using a regional average annual recharge rate. The starting value for precipitation recharge used in the CMGM was 5 percent of precipitation, equivalent to approximately 0.00014 ft/day.

4.1.3 Groundwater Model Design

The CMGM was used to address the hydrologic issues discussed above such as boundary conditions, grid spacing, convergence criteria, and calibration following the guidelines established by the American Society for Testing and Materials (ASTM) (1993) for groundwater model design and calibration to address these hydrologic issues. Specific aspects of the groundwater model design are presented below. The groundwater model did not consider agricultural wells, private domestic wells, or stock ponds in the water budget due to the lack of reliable and consistent data on these wells and ponds. Recharge from precipitation was modified to account in a general way for additional recharge from stock ponds. Although pumpage from agricultural and private domestic wells was not considered in the model, it is anticipated it would fall within the range of error in the data on pumpage by CBNG wells.

4.1.3.1 Model Code

The numerical code used in the CMGM is MODFLOW 2000 running inside the Groundwater Vistas modeling platform. The regional PRB groundwater model (AHA 2002) used MODFLOW 96, because that was the current version of MODFLOW available at the time. The regional PRB groundwater model has been translated into Groundwater Vistas from Visual MODFLOW. Groundwater Vistas was selected as the modeling platform because of its superior modeling capabilities, such as advanced solvers, telescoping mesh refinement (TMR), and the ability to change model parameters easily and quickly.

4.1.3.2 Model Boundaries and Telescoping Mesh Refinement

The boundaries for the CMGM were developed by taking a subarea from the existing PRB groundwater model using the TMR feature of Groundwater Vistas. The CMGM boundaries extend approximately 20 to 25 miles west of the coal mines of the eastern PRB, approximately 5 to 10 miles north and south of the northernmost and southernmost coal mines, and encompass the clinker recharge area to the east of the coal mines. The western and northern boundaries were chosen based on a reasonable estimate of the expected extent of the 10-foot drawdown in the Wasatch and Fort Union formations due to coal mine dewatering. Where possible, hydrologic divides in the upper Wasatch Formation were used for model boundaries. The CMGM domain does not cross the drainage divide separating the Powder River from the Belle Fourche and Cheyenne River drainages. This is because groundwater flow in the upper Wasatch Formation does not cross these divides. Thus, the CMGM only encompasses the Belle Fourche and Cheyenne River basins in the area between Gillette and Wright, Wyoming. The model boundaries for the CMGM are shown in **Figure 1-1**.

The process of using TMR in Groundwater Vistas can be summarized as follows. TMR is the process of creating a more refined submodel within a portion of a larger regional model. The submodel created with TMR is not linked to the larger original model, but rather constitutes a separate model that preserves all of the properties of the original model for the area within the boundaries of the TMR. Once the refined separate model is created with TMR, it can be saved and then read back into the modeling platform (e.g., Groundwater Vistas) and treated as a new model. The boundary conditions, input parameters, and other features of the TMR model can be changed to create a new model. In Groundwater Vistas, the modeler can use the larger regional model to compute and set the boundary conditions around the submodel generated with TMR. The input and output files from Groundwater Vistas generally are compatible with other modeling platforms following a simple translation procedure that can be found in the manuals for other modeling platforms.

4.1.3.3 Model Grid

The CMGM grid spacing is 0.25 mile by 0.25 mile throughout the entire model. The regional PRB groundwater model (AHA 2002) has a uniform grid spacing of 0.5 mile throughout the model. The original model spacing was tightened near the coal mines to more accurately model drawdown in the Upper Fort Union near the coal mines and to provide for more accurate calibration to coal mine monitor wells.

4.1.3.4 Model Predictive Scenario Periods

The CMGM was calibrated to 2002 water levels, the timeframe for which relatively complete water level data were available (see Section 4.1.4, Groundwater Model Calibration and Goals). Future predictive scenarios (Task 3) will be developed for the years 2010, 2015, and 2020. Time steps within each of the predictive scenario periods will be set during modeling.

4.1.3.5 Hydrostratigraphic Units

The concept of the HSU can be summarized as follows. Geologic mapping is based on the definition of lithologic units and correlation of these lithologic units to form a stratigraphic framework for interpreting the geology of an area, such as a basin, in three dimensions. These lithologic units are often not distinct hydraulically. That is, several lithologic units can behave as a single aquifer unit. For this reason, hydrogeologists and especially groundwater modelers prefer to define HSUs for the purpose of modeling groundwater flow. The concept of the HSU was introduced by Maxey (1964) and incorporated into a standard text on groundwater modeling by Anderson and Woessner (1992). Defining model layers as HSUs becomes useful in larger models because of the lack of hydraulic properties and even water level data for most of the lithologic units, and because simplifying the lithostratigraphy of the model with HSUs makes the model run more efficiently.

The regional PRB groundwater model utilized 17 layers in an attempt to replicate the geology of the PRB. However, because there are little or no aquifer data for most of these layers, and because many of these layers are not regional aquifers, the layers of the regional PRB groundwater model were grouped into six HSUs in the CMGM. **Table 4.1-1** illustrates how the 17 layers were combined into 6 HSUs. The six HSUs in **Table 4.1-1** were based on the following:

HSU-1: This encompasses the alluvium of the stream valleys and the upper Wasatch Formation sands. The bottom of this unit was set at 200 feet below the topographic surface of the model. This unit receives most of the recharge. Layers 1 and 2 of the regional PRB groundwater model are encompassed by this unit.

HSU-2: This unit encompasses the intermediate Wasatch sands and layers 3 through 5 of the regional PRB groundwater model. In the regional model, the thickness of these layers was calculated based on the difference between the bottom of layer 2 and the top of layer 6. This difference was divided equally among layers 3 through 5 in the regional PRB groundwater model. In the CMGM, this HSU has a thickness determined by the difference between the bottom of HSU-1 and the top of HSU-3.

HSU-3: This unit encompasses the deep Wasatch Sands. The top of this HSU is the top of layer 6 in the regional PRB groundwater model, which was set in the regional PRB groundwater model at 100 feet above the top of layer 8. In the CMGM, the top of HSU-3 is 100 feet above the top of HSU-4.

HSU-4 This unit is a confining layer between the Wasatch and Fort Union formations. This low permeability layer in the CMGM consists of layer 7 in the regional PRB groundwater model plus the shale and claystone units that lie above the coals in the Fort Union Formation. The properties of this layer were taken from the regional PRB model and adjusted during calibration. The thickness of this layer varies over the model, but is approximately the same as the thickness of layer 7 in the regional PRB model. In the area of the coal mines, this layer ranges from 60 to 240 feet in thickness.

HSU-5: This unit encompasses the Upper Fort Union coals (coals 1 through 4 in **Table 4.1-1**) and encompasses layers 8 through 15 of the regional PRB groundwater model. The top of this HSU is the top of layer 8 in the regional model. Coals 1 through 4 merge into a single large coal bed in the eastern PRB in the regional PRB groundwater model. As a result, a single HSU includes all these coal units in the CMGM. These are the coal units referred to as the Wyodak-Anderson coal in the eastern PRB (Flores et al. 1999).

HSU-6: This unit represents the permeable sands of the Tullock member of the Lower Fort Union and the Lebo Shale. It encompasses layers 16 and 17 of the regional PRB groundwater model. The top of this HSU includes the bottom of layer 15 of the regional model. This unit represents the Lower Fort Union Formation.

4.1.3.6 Model Aquifer Properties

The aquifer properties in the regional PRB groundwater model were used as starting values for calibration of the CMGM. These included hydraulic conductivity, specific storage, specific yield, and porosity. These properties were based on Appendix B of the groundwater technical report (AHA 2002) that accompanied the PRB Oil and Gas EIS (BLM 2002) and were the best available data for the PRB. Most of the data in Appendix B was taken from coal mine aquifer test results reported to the WDEQ/LQD in required annual reports (BLM 2002).

4.1.3.7 Groundwater Pumping by Coal Mines

The position of mine pits as a function of time from 1990 to 2020 (BLM 2005b) was used for placement of the drain cells that were used to represent pumpage of groundwater by the coal mines in both the CMGM calibration and the predictive scenarios for 2010, 2015, and 2020 (Task 3). The locations of coal mine pits over time were taken from information compiled for the Task 2 report;

locations were based on the projected future reserves and mining by the active coal mines in the eastern PRB. Past locations of mine pits were obtained from the BLM (BLM 2005b).

4.1.3.8 CBNG Well Groundwater Pumping

The locations of CBNG wells within the model domain were based on the locations of CBNG wells in the regional PRB groundwater model. These CBNG well locations are current as of 2002. These wells and their 2002 pumping rates were checked against a table of wells compiled from data on the WOGCC web site for wells that fall within the model domain. Well locations and pumping rates were adjusted, as needed. Pumping rates for 2002 were the permitted pumping rates. Future locations of CBNG wells (for Task 3) in the model domain were taken from the Task 2 report for the PRB Coal Review. Pumping rates for CBNG wells from 2002 to 2020 also were based on the Task 2 report. In the regional PRB groundwater model, CBNG wells were modeled as drains. In the CMGM, the CBNG drains of the regional model were converted to wells using the MODFLOW Well Package, with the appropriate permitted pumping rate included for each well. Because all CBNG wells could be represented in the CMGM, just as they were not represented in the regional PRB groundwater model, one well in a model grid space was used to represent all CBNG wells that fall within that grid space.

4.1.3.9 CBNG Well Discharge to Drainages

CBNG outfalls in the regional PRB groundwater model that fall within the CMGM domain were used. These outfalls were represented as recharge cells to allow for infiltration of the CBNG water into HSU-1 as recharge. The recharge assigned to a recharge cell(s) was set at 60 percent of the outfall discharge rate used in the regional PRB groundwater model. This discharge rate was checked to ensure it conformed to the permitted pumping rates of CBNG wells in the same model grid space. As the actual discharge at outfalls is not known with any certainty, the outfall discharge rate used in the model was the permitted discharge rate. The recharge rate of 60 percent was based on the approximate estimates of a conveyance loss of 70 to 80 percent for CBNG discharge and the approximate estimate that approximately 80 percent of the conveyance loss would be due to infiltration, as discussed in Section 4.1.1.2, Groundwater Flow Systems in the Eastern PRB.

4.1.3.10 Stream/Aquifer Interaction

In the model, ephemeral streams receiving recharge from CBNG well outfalls have recharge cells for the area of discharge to the ephemeral stream, as discussed above. The rest of the ephemeral stream was modeled with drain cells to allow for the ephemeral stream to interact with groundwater in HSU-1, if recharge should raise the groundwater level above the bottom of the stream. Perennial streams were modeled with the MODFLOW River Package.

4.1.3.11 Vertical Flow Between Hydrostratigraphic Units

Vertical conductance values between HSUs in the CMGM were set during calibration. Initial starting values were based on the vertical conductivity for confining layers already in the existing regional PRB groundwater model.

4.1.3.12 Clinker Recharge

Recharge to the clinker outcrop areas was initially set at 10 percent of precipitation and adjusted, as needed, during calibration.

4.1.3.13 Mine Spoils

In the model, the area of mine pits for each of the operating coal mines was converted to a mine spoils aquifer in the time step during which the mine reclaims that portion of the mine pit. The hydraulic properties of the spoils were based on data available in Martin et al. (1988). For mines with reclaimed areas in the calibration year of 2002 (Task 1), the reclaimed areas have a spoils zone with appropriate hydraulic properties and water levels from GAGMO reports. From 2002 to 2020 (Task 3), conversion of mine pits to spoils aquifers was done only for the predictive periods of 2010, 2015, and 2020.

4.1.3.14 Summary of Model Design

Table 4.1-2 presents a summary of the model design parameters discussed above and includes model design parameters derived directly from the regional PRB groundwater model but not discussed in detail in this section. The model design presented in this section is intended to represent the initial starting conditions for the CMGM. During the process of calibration, some of the design parameters may have been varied by the modeler, as needed, to enhance the calibration and/or make the model run more efficiently.

4.1.4 Groundwater Model Calibration and Goals

The CMGM was calibrated in accordance with ASTM (1993, 1994a,b) standards. The calibration wells used included the following: 1) BLM and USGS wells within the regional PRB groundwater model domain; 2) BLM and USGS wells within the CMGM subdomain; 3) GAGMO (2001, 2003) wells within the CMGM domain for the Fort Union; and 4) Wasatch monitor wells around the coal mines available from WDEQ/LQD files. Calibration consisted of two stages: 1) recalibration of the regional PRB groundwater model with six HSU units using BLM and USGS wells, as well as GAGMO (2001, 2003) wells in the Fort Union and Wasatch monitor wells from WDEQ/LQD files; and 2) calibration of the CMGM subdomain using USGS and BLM wells within the model subdomain, monitor wells from the GAGMO (2001, 2003) report, and Wasatch monitor wells from WDEQ/LQD files. CBNG well locations in the regional PRB model are correct for 2002. During recalibration of the regional groundwater model, the CBNG pumping rates were changed to reflect available WOGCC data for time periods from 1990 to 2002. In addition, the CBNG wells previously represented by MODFLOW drain cells in the regional model were converted to the MODFLOW Well Package to facilitate the change in pumping rates. In the CMGM model, all CBNG wells were represented by the MODFLOW well package to provide for better control on the pumping rates as a function of time. For all monitoring wells used in the calibrations, data on water levels from 1990 to 2002 were used where available.

Table 4.1-2
Summary of Coal Mine Groundwater Model Design and Assumptions

Parameters	Design and Assumptions
Area	Eastern portion of the PRB focusing on the coal mine areas
Code	MODFLOW 2000 with Groundwater Vistas Version 4.1
Calibration Period	Steady-state to 1975; transient from 1990 to 2002 with emphasis on 2002 time period
Dimensions	See **Figure 1-1**
X Coordinates	Established during model construction
Y Coordinates	Established during model construction
Coordinates	NAD27 Universe Transverse Mercator Zone 13, meters
Grid Spacing	0.25 to 0.25 mile per cell
Layers (HSUs)	Six based on HSUs; Quasi-3D; low permeability layer between Wasatch and Fort Union treated as separate HSU.
Surfaces	Based on regional PRB Oil and Gas EIS (BLM 2003a) model
Geology	Based on regional PRB Oil and Gas EIS (BLM 2003a) model and Braz (2005)
No-flow Boundaries	The no-flow boundary of each layer is different and is determined by the formation the layer represents
Boundaries	Time-varying Specified Head Package (CHD) along boundaries within regional PRB Oil and Gas EIS (BLM 2003a) model. Ephemeral streams as drains. Lateral no-flow boundaries based on original EIS model. Perennial streams as river cells.
Groundwater Recharge	Basin-wide infiltration: 5% of precipitation = 0.00014 ft/day Clinker infiltration: 10% precipitation = 0.00028 ft/day Infiltration from each subwatershed fluctuates depending on how much water is produced by the CBNG wells and the prevailing water management practices
Perennial Rivers Ephemeral Streams	Perennial Rivers: Set as MODFLOW River boundary condition trending linearly downstream between two topographic elevations. Ephemeral Streams: Set as MODFLOW Drain boundary condition with elevations trending linearly downstream between two topographic elevations.
Coal Mines	Mine plans from BLM. Future mine locations based on the Task 2 Report for the PRB Coal Review. GAGMO (2001, 2003) data for Fort Union coal mine monitor wells. WDEQ/LQD for coal mine Wasatch monitor wells.
CBNG Wells	Modeled with MODFLOW Well package. Locations based on regional PRB groundwater model. Pumping rates for 2002 from WOGCC database. Future pumping rates from Task 2 Report for PRB Coal Review. Past pumping rates from WOGCC database.
Solver	PCG2 Solver
Rewetting	Set to rewet from sides and below. Rewetting interval is 15, threshold is 5 meter, and increment is 0.1 meter

The BLM and USGS wells used for calibration consist of the BLM monitor wells in the PRB (provided by the BLM) (BLM 2005a; Meyer 2004) and USGS monitor wells with 2002 or newer water level data that were available on the USGS water data web site (USGS 2004). These wells were compiled into a single spreadsheet and used in the model for recalibration of the regional PRB groundwater model after that model had been streamlined to 6 HSUs from the original 17 layers.

The GAGMO (2001, 2003) wells are monitor wells near the coal mines and are maintained by the coal mines. These wells number approximately 350 and monitor water levels in all formations, including the Tullock Formation, on a quarterly basis. Most of the GAGMO (2001, 2003) wells are screened in the Fort Union Formation. Water level data from 1990 to 2002 were used for calibration of the CMGM. The Wasatch monitor wells are also monitoring wells near the coal mines maintained by the coal mines.

Calibration goals enable all involved parties (BLM, modeler, reviewers) to determine and understand what constitutes an acceptable calibration. Some of these goals are qualitative and some are quantitative. Quantitative goals are based on statistical analysis of errors (residuals) at target locations (USGS, BLM, and GAGMO wells). While there is agreement in the modeling community that calibration goals are helpful, no specific goals have been proposed in the literature or by ASTM. The following goals were used for this analysis and have been used by Environmental Simulations, Inc. (ESI) across the country; these goals have undergone peer review by the U.S. Environmental Protection Agency (USEPA) and other agencies.

- The residual standard deviation divided by the range in head at targets should be less than 10 percent.
- The absolute residual mean divided by the range in head at all targets should be less than 10 percent.
- The residual mean will be less than 5 percent of the range in head at target locations.
- There will be limited spatial bias in the distribution of residuals.
- Flow directions will be close to those observed in the field.

The first two goals relate the range in errors at targets to the range in heads at the site. Achieving these goals helps to guarantee that the overall hydraulic gradients in the model are correct. Achieving the third goal (residual mean) assures that the head values are close to reality, because negative and positive errors cancel out producing a mean error close to zero. The last two goals are qualitative and are used to make sure that the model is not over- or under-predicting heads in large portions of the model.

4.1.5 Groundwater Model Predictive Simulations

Predictive simulations using the CMGM (for Task 3) were used to estimate the cumulative impact on groundwater and surface water resources in the model domain due to CBNG development, coal mining, and other reasonably foreseeable development for years 2010, 2015, and 2020. The predictive periods 2010, 2015, and 2020 were requested by the BLM. It is expected that by year 2020, most, if not all, CBNG development in the eastern PRB would have been completed and that groundwater production by CBNG wells would have decreased substantially.

Resaturation of coal mine spoils during the above timeframes was simulated based on data provided by the coal mines regarding what areas would be reclaimed during each of the intervals simulated. A separate predictive scenario was run for a time period beyond year 2020 (to year

2040) that represents the hypothetical end of coal mining in the eastern PRB. After year 2040, it was assumed that all coal mining in the eastern PRB would cease and groundwater levels would rebound based on no coal mining and no CBNG pumping. This hypothetical predictive run was used to determine the final rebound of water levels in the Wasatch and Fort Union aquifers and the changes to the hydrology of these aquifers due to the presence of mine spoils in areas previously mined for coal. This post-mining predictive scenario was used to estimate the post-mining and post-CBNG water levels in the eastern PRB.

4.2 Groundwater Model Calibration

Calibration of the groundwater model was accomplished in two steps. In the first step, the original regional PRB model (AHA 2002) was recalibrated based on the specifications contained in the model protocol and using six HSUs along with GAGMO (2001, 2003) and Wasatch monitoring wells. A low-permeability layer was placed between the Wasatch and the Upper Fort Union to simulate the thick clay zone that separates these two stratigraphic units, as discussed above in Section 4.1.3.5, Hydrostratigraphic Units. The recalibration of the regional model was necessary because some of the underlying assumptions in the original regional model were changed in the protocol for the CMGM. After the regional PRB model was recalibrated, a technique known as TMR was used to create a more local model around the coal mines in the eastern PRB. The calibration of the CMGM was then revised, where necessary, to meet the calibration goals established in the protocol. A summary of the calibration report (Environmental Simulations, Inc. [ESI] 2006) is presented below.

4.2.1 Calibration Concepts

Many of the terms used in model calibration come from the statistical literature and some are unique to groundwater modeling. Calibration is the process of adjusting parameters in the model so the model-computed water levels match water levels measured in wells. Calibrating a groundwater model is difficult, because relatively little information is available on subsurface conditions. Most of the parameters in a model, such as hydraulic conductivity, are only known at a few points where measurements have been taken. Even at those known points, the measurement of subsurface properties is an inexact science. The initial estimates of aquifer properties, entered when the model is first created, are changed so that the model computes more realistic water level elevations.

During the calibration, the model-computed water levels are compared to water levels measured in wells. The measured water levels are called calibration targets or just targets. The targets represent water levels measured at a particular time during the simulation, or they can represent steady-state conditions. In the case of the CMGM, steady-state conditions represent water levels measured prior to the start of groundwater pumping at coal mines and CBNG wells, when water levels were essentially in equilibrium with natural recharge and discharge in the basin.

After each simulation, the target water levels are compared to model-computed water levels. The model-computed water levels are subtracted from the field measurements to produce a residual. Positive residuals represent computed water levels that are lower than those measured in the field. Conversely, negative residuals are those where the model is computing water levels higher than the measured levels.

A statistical analysis is performed on the collection of residuals from all targets used in the model. Simple statistics (e.g., mean, root-mean-square, and absolute mean) are commonly used. The mean residual should be close to zero, indicating that the positive and negative residuals are balanced. The absolute mean is computed by making all residuals positive and thus represents the average error in the calibration. These statistical measures are used to determine the quality of the calibration. Goals have been established in the model protocol (Section 4.1.4, Groundwater Model Calibration and Goals) for acceptable values of the mean, standard deviation, and absolute mean.

In addition to statistics computed at residuals, the distribution of residuals is analyzed during calibration. It is desirable to have positive and negative residuals randomly scattered throughout the model. Clustering of positive or negative residuals over large areas is called spatial bias. One goal of calibration is to reduce spatial bias as much as possible. It is virtually impossible, however, to totally eliminate spatial bias due to the lack of subsurface data in many areas of the model domain.

4.2.2 Notes on Model Construction

Both the regional PRB model and the CMGM were constructed based on the model protocol presented in Section 4.0, Groundwater Modeling Protocol. The protocol, however, does not provide all of the details of the model simulations. Those aspects of the model that were not described in the protocol are provided in this section.

The model was constructed using MODFLOW 2000 (Harbaugh et al. 2000), which was chosen for several reasons. First, it is the newest and most up-to-date version of MODFLOW from the USGS. Secondly, it can mix both steady-state and transient stress periods within the same simulation. That approach was used in the current modeling to simulate steady-state conditions in the first stress period and then transient simulation from 1975 through 2002 in stress periods 2 through 30. Each transient stress period represents 1 year. Pumping from CBNG and coal mine wells was averaged over each year and entered in the model as average annual pumping rates.

Another aspect of MODFLOW 2000 that was useful was the property that drawdown (or water level changes over time) can be computed from any specified stress period. In the original version of MODFLOW (McDonald and Harbaugh 1988), drawdown was always computed from the starting head values. The MODFLOW 2000 approach was used in the current model so that drawdown for each year was computed by subtracting heads at each time step from the steady-state heads computed in the first stress period. This facilitated the analysis of hydrographs during calibration.

4.2.3 Calibration of the Regional PRB Groundwater Model

Calibration of the regional model consisted of several phases. In the first phase, the calibration proceeded based on the model protocol (Section 4.1.4, Groundwater Model Calibration and Goals), which called for comparing the water levels computed by the model to water levels reported in the original calibration by AHA (2002) and to water levels in BLM and USGS databases. Unfortunately, these data did not provide adequate coverage of the coal mine areas in the eastern PRB. Since the purpose of the model was to predict impacts near the coal mines, it was important that the model be calibrated both regionally and in the vicinity of the coal mines. Therefore, additional water level data were used in recalibration of the regional PRB model. These data included the following:

- GAGMO water level data measured prior to 1980. These data are termed “base year” water levels in the GAGMO database and were measured at the time the well was drilled.
- GAGMO water level data for 1990.
- GAGMO water level data for years from 1990 to 2002.
- GAGMO water level hydrographs for 18 wells near the coal mines.
- Wasatch monitoring wells near the coal mines available from WDEQ/LQD files.

These water level data also were used in calibration of the CMGM, which makes it possible to more directly compare the calibration results between the two models.

In the second phase of recalibration, it was found that the drains used in the original regional PRB model (AHA 2002) to represent CBNG wells were very difficult to regulate so that the desired pumping rate was achieved. It was found that water production data for all CBNG wells were available from the WOGCC database for all years of CBNG operation. As a result, the drains were replaced with actual pumping data reported in the WOGCC database. For the coal mine pits, drain cells were retained from the original regional model (AHA 2002) and adjusted based on mine pit configuration data provided by the BLM.

In the third and final phase of the regional recalibration, more attention was paid to the hydrographs for selected wells near the coal mines. The model protocol dictates that 5 to 7 hydrographs should be compared to model results for verification purposes. A total of 18 hydrographs were used to improve the verification process. It proved very difficult to achieve a good match between the model-simulated hydrographs and those from the GAGMO database without making additional modifications to the model. Most of these modifications were related to slight movement of the location of pumping wells at each mine. In most cases, adjustment of pumping well locations produced a better match between the model results and the field measurements. This process pointed out, however, that without knowing where the mine pumping wells were located in the past, it was difficult to achieve a good match at all wells in the vicinity of a mine. Lack of data on mine well pumping rates and locations and mine pit inflow rates (water removed by pit pumps) is one of the most significant uncertainties in both the regional PRB model and CMGM.

4.2.3.1 Calibration Approach

The original regional PRB model (AHA 2002) had a number of different hydraulic conductivity values (zones) in each model layer, and it was not clear how the K values and the position of zone boundaries were determined. Therefore, the model was simplified to start the recalibration effort. The calibration approach employed in the recalibration of the regional model started with homogeneous properties in each model layer. Complexity was added, as warranted, based on the water level data. Since there are six HSUs in the model, the initial model started with six different values of horizontal (Kx) and vertical (Kz) hydraulic conductivity. The calibration proceeded by adjusting the Kx and Kz values in each layer to produce a better match between the measured and simulated water levels.

The approach used in the regional model recalibration is known as structured sensitivity analysis. This method takes each parameter in the model and makes several model runs while changing the value of the parameter over a specified range. After all model runs have been completed, a calibration statistic (usually the sum of squared residuals) is plotted versus each parameter value. The suite of curves representing all parameters is then inspected to find the best parameter change that would improve the calibration the most. The advantage of this technique is that the modeler makes all decisions related to parameter changes.

After the calibration proceeded as far as possible with homogeneous properties in each layer, additional hydraulic conductivity zones were added in an attempt to correct spatial bias in the distribution of errors. As soon as the calibration goals were achieved, the calibration stopped and moved to the local calibration of the CMGM.

4.2.3.2 Calibration Results

There are many ways to assess the quality of a calibration. The regional PRB model calibration was assessed by comparing the calibration statistics to the goals established in the groundwater model protocol, by a visual comparison of hydrographs at selected wells, and through an analysis of spatial bias in the model.

What constitutes an acceptable calibration is very subjective. Woessner and Anderson (1992) suggest that goals should be established before the calibration starts. However, no standards have been put forth by ASTM or in the scientific literature that describe what these goals should be. Goals were established in the protocol for this model, which are based on goals used by ESI in all models and which have undergone peer review from the USEPA and many state government agencies. These goals are summarized in Section 4.1.4, Groundwater Model Calibration and Goals.

As previously discussed, a residual is the difference between a measured water level and the model-computed water level. The residual is calculated as the observed head minus the model-computed head. Thus, a negative residual occurs where the model-computed head is too high and a positive residual is where the model-computed head is too low.

The statistics for the regional calibration meet the calibration goals described above. Goals were met for the model as a whole and for each discrete time (steady-state, 1990, and 2002) individually. The goal for residual mean divided by range in head is a maximum of 5 percent. The residual mean divided by range in head was -0.24 percent, -0.37 percent, -1.41 percent, and 0.19 percent for the whole model, steady-state, 1990, and 2002, respectively. The standard deviation divided by range in head was 2.26 percent, 2.25 percent, 4.74 percent, and 2.98 percent for those same times, respectively. The absolute residual mean divided by range in head was 1.57 percent, 1.74 percent, 3.74 percent, and 2.11 percent for those same times, respectively. The goal for both absolute residual mean and residual standard deviation divided by range in head was 10 percent. Therefore, all of these statistical measures met the goals for the regional model.

In addition to statistics, another standard method of judging calibration quality is to plot the measured water levels versus the computed water levels. In a perfect calibration, the points would lie along a straight line at a 45-degree angle indicating that the computed water levels match the observed water levels exactly. In reality, this never happens; however, the spread of data points about the perfect line is an overall indication of spatial bias in the model. The higher water levels in the regional model represent the southeastern portion of the model domain, while the lower water levels are found in the northern portions of the model. The plots generated for this calibration show that there is no large-scale bias in the calibration, with each broad area having the same degree of scatter about the 45-degree line.

Assessing spatial bias at a more local scale is accomplished by plotting residual circles on maps. A residual circle is a circle drawn with the target well at its center. The size of the circle is proportional to the magnitude of the residual at the target, and the color indicates a positive or negative residual. The calibrated regional model had a grouping of positive residuals west of coal mines north of Gillette, Wyoming, (Subregion 1 coal mines) near the the Buckskin Mine. For the coal mines south of Gillette, Wyoming, (Subregion 2 coal mines), there was a grouping of positive residuals west of the Caballo Mine. For the coal mines near Wright, Wyoming, (Subregion 3 mines), there were positive residuals located west of the North Antelope/Rochelle Mine. Overall, these local spatial biases near individual coal mine subregions tended to average out, and there was no large scale spatial bias in the model domain of the CMGM.

4.2.3.3 Calibrated Parameter Values

Calibration of the regional model, as described above, started with homogeneous properties in each aquifer and then added heterogeneity (more zones) where necessary to achieve the calibration goals. The range of hydraulic conductivity measurements are shown in **Table 4.2-1**. This table also lists the hydraulic conductivity values derived from the model calibration. In all cases, the hydraulic conductivity values used in the model are within the range of reported values from the protocol. In most cases, the values used in the model are close to the median value. The most significant exception to this is in HSUs 1 through 3 (Wasatch) where the predominant value in the model is 0.8 meters per day (m/d) and the median value from the literature is 1.6 m/d. Also, the maximum value of 15 m/d in the model is greater than the maximum of 6.1 m/d reported in the literature from field measurements. There are no measured values for the Lower Fort Union (HSU-6) and no calibration targets in the Lower Fort Union. The hydraulic conductivity of 6.25 m/d was set by the model during calibration. The model is sensitive to this hydraulic conductivity value. The value is reasonable as this layer of the model is used by Gillette for municipal water supply.

Table 4.2-1
Comparison Between Reported Hydraulic Conductivity Values and Those Used in the Regional PRB Model

Aquifer Unit	Model HSU	Reported Hydraulic Conductivity Values (m/d)			Model Hydraulic Conductivity Values (m/d)		
		Minimum	Maximum	Geometric Mean	Minimum	Maximum	Predominant
Alluvium	1 and 2	0.003	107	10.2	6	6	6
Wasatch	1, 2, and 3	--	6.1	1.6	0.1	15	0.8
Confining Unit	4	--	--	--	0.008	11.8	0.95
Upper Fort Union	5	0.012	22.6	0.61	0.008	1.7	0.14
Lower Fort Union	6	--	--	--	6.25	6.25	6.25

Source: ESI 2006.

Table 4.2-2 lists the reported specific storage values and those used in the model. In all cases, each formation was assigned a uniform value of specific storage or specific yield. As with the hydraulic conductivity values described above, the values used in the model are within the range reported in the protocol. Most of these values are somewhat below the median reported value. Specific storage values affect the transient calibrations and affect the drawdown that results from CBNG pumping or mine dewatering. For the Upper Fort Union, the predominant value of 1.25E-07 is suggestive of relatively tight rock in a confined aquifer, which is what would be expected for a buried coal-bearing unit. The Wasatch predominate value of 8.1E-06 is suggestive of considerable clay in an otherwise sandy aquifer. The Wastach is not a true aquifer, so hydraulic parameters measured for the Wasatch in the field or estimated during model calibration are only approximate.

Table 4.2-2
Comparison Between Reported Specific Storage Values and Those Used in the Regional PRB Model

Aquifer Unit	Model Layer	Reported Specific Storage Values (per meter)			Model-specific Storage Values (per meter)		
		Minimum	Maximum	Geometric Mean	Minimum	Maximum	Predominant
Alluvium[1]	1 and 2	0.001	0.23	0.018	0.05	0.05	0.05
Wasatch	1, 2, and 3	7.00E-07	0.03	4.30E-05	6.6E-06	1.0E-05	8.1E-06
Confining Unit	4	--	--	--	1.0E-03	0.001	1.0E-03
Upper Fort Union	5	6.4E-08	0.11	9.1E-05	1.25E-07	1.25E-07	1.25E-07
Lower Fort Union	6	--	--	--	1.00 E-05	1.00 E-05	1.00 E-05

[1]Alluvium values are specific yield (dimensionless).

Source: ESI 2006.

4.2.4 Telescoping Mesh Refinement

4.2.4.1 General Approach

The purpose of the CMGM was to evaluate existing (2002) groundwater conditions (Task 1) and provide predictions of future water level changes around the coal mines in the eastern PRB (Task 3). The model protocol specifies that the grid spacing around the coal mines should be reduced from 0.5 to 0.25 mile so that the predictions could be more precise. A technique known as TMR was used to go from the scale of the regional model to a more local scale surrounding the coal mines. This technique was facilitated through the use of the Groundwater Vistas software.

The standard TMR approach within Groundwater Vistas is to create a sub-model from the regional PRB model in which the sub-model has a uniform grid with smaller spacings than the larger model. Thus, while the protocol only calls for the 0.25-mile grid spacing within 5 miles of the coal mines, the CMGM contains a 0.25-mile grid spacing throughout the entire model.

The standard TMR approach in Groundwater Vistas also produces a rectangular model domain. In the case of the CMGM, the area is not a perfect rectangle, as shown in **Figure 1-1**. A modified TMR technique was added to Groundwater Vistas for this study so that the resulting CMGM could be digitized from a polygon.

4.2.4.2 Construction of the CMGM

The grid spacing in the GMGM is a constant 0.25 mile in both the row and column directions. The model contains the same layering as in the regional PRB model. Specified head boundaries were placed on the south, west, and north boundaries of the CMGM model based on the computed heads in the regional model. Specified head boundaries were chosen because the CHD in MODFLOW 2000 allows the head to vary through time from the beginning to the end of the stress period. All other boundary types require the head to remain fixed for the entire stress period. Thus, the CHD is much more accurate in specifying heads along a boundary where the heads change over time. The eastern boundary of the model domain is represented as a no-flow boundary, because this boundary is along the outcrop zone of the Fort Union Formation. The extent of the Wasatch in HSU's 1 through 3 stops at the coal mines, and for these layers, the eastern extent of the Wastach was modeled as a no-flow boundary. Heads in the western boundary of the CMGM were set by the regional model, so that changes in the heads for the western boundary reflected changes in water levels in the regional model along the western boundary as a result of applied stresses.

CBNG and coal mine wells were taken from the original regional PRB model without modification. Any wells outside the CMGM domain were not included in the TMR model. Most other boundary conditions also were the same as in the regional PRB model.

4.2.5 Calibration of the CMGM

4.2.5.1 General Approach

The same approach that was used in calibrating the regional PRB model initially was used in the CMGM calibration. The CMGM is a subset of the regional model; thus, all of the assumptions that went into calibration of the regional PRB model were applicable to the CMGM. The results of the initial CMGM calibration were not, however, adequate in terms of spatial bias. In addition, the hydrographs did not match well enough in some areas. Thus, additional calibration was performed using another technique known as pilot points.

Each pilot point has an initial estimate of hydraulic conductivity, used to start the calibration process, and an upper and lower bound to constrain the estimated value. The initial estimate of hydraulic conductivity at each pilot point was taken from the recalibrated regional PRB model. The upper and lower limits of hydraulic conductivity were those described in the model protocol (Section 4.1.1.2, Groundwater Flow Systems in the Eastern PRB).

4.2.5.2 Calibration Results

The statistical analysis of the CMGM calibration is provided in **Table 4.2-3**. The table shows the residual mean, residual standard deviation, and absolute residual mean for all data from all times and specifically for steady-state, 1990, and 2002 data. The residual mean uses both positive and negative residuals, and thus, it should be close to zero if the positive and negative residuals balance each other. The absolute residual mean is computed after all residuals are made positive and is thus an average error in the model.

As in the regional PRB model calibration, the statistics for the CMGM calibration meet the calibration goals described in the modeling protocol. Goals were met for the model as a whole and for each discrete time (steady-state, 1990, and 2002) individually. The goal for both absolute residual mean and residual standard deviation divided by range in head was 10 percent. Therefore, all of the statistical measures met the goals. In addition to meeting the goals of the calibration, there was not as much difference, statistically, between the various calibration periods.

Table 4.2-3
Summary of Statistical Analysis of Residuals in the CMGM Calibration

Category	Statistics for All Times	Statistics for Steady-state (1975)	Statistics for 1990	Statistics for 2002	Goal (percent)
Residual Mean	-0.57	0.18	-2.24	0.57	n/a
Residual Standard Deviation	9.15	7.42	9.81	11.21	n/a
Absolute Residual Mean	6.31	5.45	7.42	7.9	n/a
Range in Water Levels (meters)	266.74	203.3	216.01	260.66	n/a
Mean Divided by Range in Water Levels	-0.21%	0.09%	-1.04%	0.22%	5
Absolute Mean Divided by Range in Water Levels	2.37%	2.68%	3.44%	3.03%	10
Standard Deviation Divided by Range in Water Levels	3.43%	3.65%	4.54%	4.3%	10

Note: n/a = not applicable

Source: ESI 2006.

In addition to statistics, another standard method of assessing calibration quality is to plot the measured water levels versus the computed water levels. In a perfect calibration, the points would lie along a straight line at a 45-degree angle indicating that the computed water levels match the observed water levels exactly. In reality, this never happens; however, the spread of data points about the perfect line is an overall indication of spatial bias in the model. The plots generated for this calibration show that there is no significant large-scale bias in the calibration with each broad area having the same degree of scatter about the 45-degree line. These graphs show much less spatial bias than the comparable graphs for the regional PRB model.

Spatial bias at a more local scale was assessed by plotting residual circles on maps as discussed in Section 4.2.3, Calibration of the Regional PRB Groundwater Model. The residual circle maps for the CMGM were similar to those of the regional PRB model. In the northern mine areas (Subregion 1 coal mines), there was a positive 20 meter residual bias in the Upper Fort Union around the Buckskin Mine. There was a negative residual bias around the Rawhide Mine. For the central grouping of coal mines south of Gillette, Wyoming, (Subregion 2 coal mines), there was a strong positive residual bias between the Caballo and Belle Ayr mines. The southern grouping of coal mines near Wright, Wyoming, (Subregion 3 coal mines) had a strong positive residual bias west of the North Antelope/Rochelle Mine.

4.2.5.3 Calibrated Parameter Values

Calibration of the regional model, as described above, started with homogeneous properties in each aquifer and then added heterogeneity (more zones), where necessary, to achieve the calibration goals. In layers 1, 2, 3, and 4, pilot points were used as previously described to better match the water level targets. This resulted in a much more heterogeneous distribution of hydraulic conductivity than in the regional PRB model, although the general trends were the same.

The range of hydraulic conductivity measurements are reported in the model protocol (Section 4.1, Groundwater Modeling Protocol) and also are shown in **Table 4.2-4**. This table also lists the hydraulic conductivity values derived from the model calibration for the CMGM. In all cases, the hydraulic conductivity values used in the model are within the range of reported values from the model protocol. In most cases, the values used in the model are close to the median value. The most significant exception to this is in HSUs 1 through 3 (Wasatch), where the maximum value in the model is 16.9 m/d and the maximum value from the literature is 6.1 m/d. Also, the Upper Fort Union (HSU-5) has the maximum, predominate, and minimum values for hydraulic conductivity noticeably below those reported from aquifer tests near the coal mines.

Table 4.2-4
Comparison Between Reported Hydraulic Conductivity Values and Those Used in the CMGM

Aquifer Unit	Model Layer	Reported Hydraulic Conductivity Values (m/d)			Model Hydraulic Conductivity Values (m/d)		
		Minimum	Maximum	Geometric Mean	Minimum	Maximum	Predominant
Alluvium	1 and 2	0.003	107	10.2	6	6	6
Wasatch	1, 2, and 3	--	6.1	1.6	0.007	16.9	1.02
Confining Unit	4	0.012	22.6	0.61	0.008	4.8	0.12
Upper Fort Union	5	0.012	22.6	0.61	0.007	3.5	0.16
Lower Fort Union	6	--	--	--	6.2	6.2	6.2

Source: ESI 2006.

Table 4.2-5 lists the reported specific storage values and those used in the model. In all cases, each formation was assigned a uniform value of specific storage or specific yield. As with the hydraulic conductivity values described above, the values used in the model are within the range reported in the model protocol. Most of these values are somewhat below the median reported value.

Table 4.2-5
Comparison Between Reported Specific Storage Values and Those Used in the CMGM

Aquifer Unit	Model Layer	Reported Specific Storage Values (per meter)			Model-specific Storage Values (per meter)		
		Minimum	Maximum	Geometric Mean	Minimum	Maximum	Predominant
Alluvium[1]	1 and 2	0.001	0.23	0.018	0.05	0.05	0.05
Wasatch	1, 2, and 3	7.00E-07	0.03	4.30E-05	4.9E-06	1.0E-05	7.0E-06
Confining Layer	4	6.4E-08	.11	9.1E-05	1.0E-03	0.001	1.0E-03
Upper Fort Union	5	6.408E-08	0.11	9.1E-05	1.08E-07	1.08E-07	1.08E-07
Lower Fort Union	6	--	--	--	1.00 E-05	1.00 E-05	1.00 E-05

[1]Alluvium values are specific yield (dimensionless).
Source: ESI 2006.

4.3 Groundwater Modeling Results for Current Conditions

The CMGM described above was used to determine the current (2002) drawdown in groundwater levels in the Wasatch and Fort Union formations associated with coal mine dewatering and CBNG development in the eastern portion of the PRB study area. The modeling results are summarized below. Associated figures are presented in Appendix D.

The purpose of the CMGM is to provide a method for estimating the cumulative impact of CBNG development and coal mine dewatering on groundwater resources in the eastern PRB from the base year of 2002 to year 2020. The CMGM is a regional groundwater model intended to be used as a general guide for evaluating the impacts of CBNG development and coal mine dewatering on a regional scale and then the combined impact of both on groundwater resources for the years 2010, 2015, and 2020. The CMGM is not designed to estimate the local impact of either CBNG or coal mine dewatering to the area around an individual mine pit or to private wells near CBNG fields.

4.3.1 Wasatch Formation

Water levels and groundwater drawdown for 2002 in the Wasatch Formation are shown in **Figures D-1** through **D-5** of Appendix D. Important features of these figures area summarized below. The Wasatch Formation does not constitute a regional aquifer. Rather, it is a sedimentary formation that contains local water-saturated sand lenses that can be locally extensive but not hydraulically interconnected with other sand lenses due to the considerable clay content of the Wasatch. Consequently, a groundwater model cannot accurately model water levels and groundwater drawdown in the Wasatch. The water levels and groundwater drawdown presented in the figures in Appendix D (and discussed below) are, therefore, only approximate and should be used only as a general guide to what may actually be present in the Wasatch for any given modeled year. Also, data on water levels in the Wasatch Formation are only available near the coal mines as part of the groundwater monitoring conducted by the coal mines. Thus, there are essentially no groundwater data on the Wasatch for areas beyond approximately 5 miles to the west of the coal mines.

Figure D-1 shows the modeled groundwater levels in the Wasatch Formation for 1990, a period before the beginning of CBNG pumping and a period when the coal mines were beginning to increase the dewatering of their mines to facilitate increased coal mining. Groundwater elevations decrease from south to north across the model domain, with water levels in the south near the southern group of coal mines (Subregion 3) at approximately 4,700 to 4,850 feet amsl and water elevations near the northern group of coal mines (Subregion 1) at approximately 4,200 to 4,350 feet amsl. The Belle Fourche River and Antelope Creek act as drains and remove water from the Wasatch Formation locally, as is evident in the groundwater level depressions near State Route (SR) 59 for the Belle Fourche and west of SR 59 for Antelope Creek. Groundwater drawdown in the Wasatch is evident around the southern group of mines (Subregion 3). There is a suggestion of a slight groundwater mound west of the central group of coal mines (Subregion 2). The northern group of coal mines (Subregion 1) also show a slight depression in groundwater levels within the mine boundaries.

Figure D-2 shows the modeled groundwater elevations in the Wasatch Formation for 2002. The pattern of groundwater levels is similar to that for 1990 (**Figure D-1**). Groundwater flows from the southern end of the model domain to the northern end of the model domain, with water levels in the south at approximately 4,700 to 4,850 feet amsl and those in the north at approximately 4,200 to 4,350 feet amsl. As in 1990, the Belle Fourche River and Antelope Creek are removing water from the Wasatch Formation. Groundwater drawdown is evident in the southern group of coal mines (Subregion 3), and to some extent in the central group of mines (Subregion 2) and the northern group of mines (Subregion 1). The groundwater mound west of the central group of mines (Subregion 2) is more pronounced, primarily due to CBNG discharge to the Wasatch. Minor "squiggles" in the water level contours north of Wright, Wyoming, are due to groundwater mounding in the Wasatch from CBNG discharge.

Figure D-3 shows the modeled coal mine-related groundwater drawdown in the Wasatch Formation for 2002. Groundwater drawdown in the southern group of mines (Subregion 3) is localized within or very near the coal mine boundaries and is in the range of 10 to 100 feet. For the central group of mines (Subregion 2), drawdown in the Wasatch also is localized near the mines and ranges from 10 to 50 feet. The 10-foot drawdown contour extends a maximum of approximately 3 to 4 miles to the west of the mines. For the northern group of mines (Subregion 1), the drawdown ranges from 10 to 110 feet, and the 10-foot drawdown contour extends west of the coal mines approximately 7 to 8 miles. Groundwater monitoring data in the northern group of mines is limited due to monitoring wells either being capped due to natural gas in the well or going dry, and thus the extent of the 10-foot drawdown contour may be greater than what is actually present. Modeling suggests that dewatering of the Wasatch in the northern group of mines (Subregion 1) has impacts that extend beyond the mine boundaries; however, in the central and southern mine groups (Subregions 2 and 3, respectively), dewatering impacts to the Wasatch are localized in the vicinity of the mine boundaries. For the northern group of mines (Subregion 1), modeling results are only approximate due to the limited number of useable monitoring wells.

Figure D-4 shows the modeled groundwater impacts to the Wasatch Formation due to CBNG pumping and discharge. The feature most evident in this figure is the groundwater mounding due to CBNG discharge. The mounding is most evident between Wright and the central group of coal mines (Subregion 2). Mounding is in the range of 10 to 20 feet, with locally high mounding to 50 feet near the mine boundaries. West of the northern group of mines (Subregion 1), mounding in the Wasatch is in the range of 10 to 50 feet. Mounding in the Wasatch west of the southern group of mines (Subregion 3) is approximately 10 feet. Groundwater mounding indicates that groundwater levels in the Wasatch have risen by the indicated amount since 1990.

Figure D-5 presents the modeled sum of groundwater impacts to the Wasatch due to CBNG pumping and discharge, coal mine dewatering, and water supply wells near Gillette. Near the southern group of mines (Subregion 3), the total effect resulted in drawdown in the range of 10 to 70 feet. Near the central group of coal mines (Subregion 2), the total effect resulted in mounding west of the coal mines in the CBNG fields of approximately 20 feet and drawdown within the mine boundaries of 10 to 40 feet. Near the northern group of mines (Subregion 1), the total effect primarily resulted in drawdown within or close to the mine boundaries in the range of 10 to 100 feet. The Gillette area municipal wells affect the Wasatch and create a drawdown of approximately 10 to 20 feet southeast of Gillette. Thus, for the Wasatch beyond the mine boundaries, the mounding related to CBNG discharge offsets drawdown related to mine dewatering of the Wasatch. Within the mine boundaries, dewatering of the Wasatch by the mines has resulted in drawdown of groundwater levels since 1990.

4.3.2 Upper Fort Union Formation

Water levels and drawdown for the Upper Fort Union are shown in **Figures D-6** through **D-10** in Appendix D. A summary of important features in these figures is presented below. In some areas where CBNG drawdown in the groundwater model was extensive, the potentiometric surface in the Upper Fort Union dropped below the top of the Upper Fort Union HSU, causing the HSU to desaturate. This had a local affect on contouring the drawdown in the Upper Fort Union.

Figure D-6 shows the modeled groundwater elevations in the Upper Fort Union for 1990, the period before the beginning of substantial CBNG pumping. Groundwater generally flows from south to north across the model domain, with water levels in the south at approximately 4,700 to 4,900 feet amsl and those in the north at approximately 4,100 to 4,250 feet amsl. Around and to the west of the southern group of coal mines (Subregion 3), there is a suggestion of groundwater mounding around the mines with groundwater drawdown within the mine boundaries. The mounding may be an artifact of the drawdown caused by dewatering within the mines. The same pattern, only on a more reduced scale, is found in the central group of mines (Subregion 2). For the northern group of mines (Subregion 1), there is minor groundwater drawdown within the mine boundaries. As with the Wasatch Formation, the number of useable monitoring wells was limited near the mines in Subregion 1, due to wells being abandoned due to natural gas or going dry. West of SR 59 near the southern group of mines (Subregion 3), there is a westward bulge in the groundwater contours. This bulge is due to two monitoring wells that have water levels that are not consistent with other monitoring wells in the area. Along the southern boundary of the model domain, there is a steep groundwater gradient that is a result of boundary conditions preserved from the original PRB Oil and Gas EIS (BLM 2003) regional groundwater model. This steep groundwater gradient in the Upper Fort Union as shown in **Figure D-6** is an artifact of model design in the regional model and not a true reflection of groundwater levels. The constant head used in the regional model is constrained by a low hydraulic conductivity in the CMGM needed to keep the drawdown from the Antelope Mine from propagating too far to the south.

Figure D-7 presents the modeled groundwater levels in the Upper Fort Union for 2002. Near the southern group of mines (Subregion 3), there is a complex pattern of drawdown west of the mines probably due to the combined effect of coal mine dewatering and CBNG pumping that has resulted in some localized areas of mounding. In the vicinity of the central group of mines (Subregion 2), groundwater drawdown west of the mines due to CBNG pumping is evident. The area near the northern group of mines (Subregion 1) does not show the effect of CBNG pumping in the 2002 groundwater levels. The sharp groundwater gradient in the Upper Fort Union along the southern model boundary is due to retention of model boundary conditions from the original PRB Oil and Gas EIS (BLM 2003) regional groundwater model, and not a true reflection of groundwater levels.

Figure D-8 presents the modeled coal mine-related groundwater drawdown in the Upper Fort Union. As shown in the figure, drawdown due to coal mine dewatering primarily is limited to the mine boundaries. In the southern group of mines (Subregion 3), the drawdown ranges from 20 to 180 feet, with the 20-foot drawdown contour extending up to approximately 4 miles west of the mines. For the central group of mines (Subregion 2) and the northern group of mines (Subregion 1), the drawdown in the Upper Fort Union is limited to the mine boundaries.

Figure D-9 shows the modeled groundwater drawdown in the Upper Fort Union due to CBNG pumping. The effect of CBNG activity on groundwater levels is very pronounced, especially around Wright, Wyoming. For the area west and northwest of the southern group of coal mines (Subregion 3), CBNG-related drawdown is up to 300 feet in the Upper Fort Union. Near the central group of coal mines (Subregion 2), CBNG-related drawdown is in the range of 60 to 300 feet and localized west of the coal mines. Near the northern group of mines (Subregion 1), CBNG-related drawdown is approximately 40 feet and found in small localized areas to the west of the mines.

Figure D-10 presents the combined modeled effect of CBNG pumping, coal mine dewatering, and municipal pumping near Gillette on the Upper Fort Union. Because the effect of CBNG pumping greatly dominates that of coal mine dewatering, **Figure D-10** is very similar to **Figure D-9**. West of the southern group of mines (Subregion 3), drawdowns of up to 400 feet are observed in the Upper Fort Union. Groundwater drawdown within mine boundaries is in the range of approximately 20 to 200 feet. Near the central group of mines (Subregion 2), groundwater drawdown in the Upper Fort Union west of the coal mines is up to 400 feet in areas of CBNG pumping. Within the mine boundaries, groundwater drawdown is approximately 20 to 100 feet. Drawdown in the Upper Fort Union near the Gillette municipal well fields is approximately 20 to 40 feet. Near the northern group of mines (Subregion 1), the combined drawdown is approximately 20 to 80 feet.

The CMGM has inherent limitations due to the scale of the model (i.e., the entire eastern PRB), the simplification of the geology and hydrogeology into six HSU's, the lack of aquifer property data beyond the area around the coal mines, the limitations in accuracy for CBNG pumping data and coal mine dewatering estimates, and the non-unique nature of the model calibration. The CMGM is calibrated only to heads (i.e., water levels). It is not calibrated to flux (i.e., rates of water flow) due to the lack of flux data for ephemeral streams. The model has a transient calibration to water levels from 1990 to 2002 and a transient calibration to eighteen monitoring well hydrographs for 2003, which serve as a substitute for a calibration to flux. The model is sensitive to recharge, hydraulic conductivity, and especially to storage coefficients as discussed in the CMGM calibration report (ESI 2006). As the calibration is non-unique, the drawdowns calculated by the model for CBNG pumping, coal mine dewatering, and the combined effect of both, are approximate only and should be used only as a guide to what may be expected for the time periods modeled.

4.4 Surface Water Modeling

The analysis of existing (2002) surface water conditions in the eastern PRB relied on the detailed studies and modeling provided to the Wyoming Water Development Commission by HKM Engineering, Inc. in the Powder/Tongue River Basins Plan (HKM Engineering et al. 2002a) and Northeast Wyoming River Basins Plan (HKM Engineering et al. 2002b). This information is summarized in Chapter 3.0. Modeling was used for evaluation of future surface water conditions through 2020 for Task 3. The assumptions and methodology used were similar to those used in the PRB Oil and Gas EIS (BLM 2003a) for surface water modeling and are presented in the Task 3B Report, Water Resources Cumulative Impact Assessment, Water Quality and Channel Stability (Anderson Consulting Engineers, Inc. 2006).

5.0 COMPARISON OF PAST PREDICTIONS AND CURRENT CONDITIONS

In 1996, the BLM issued a Coal Development Status Check summarizing the current level of coal mine activity and comparing the associated environmental impacts to what had been estimated in BLM coal EISs prior to 1996. Since 1996, coal mining has expanded considerably due to the demand for low-sulfur coal by the electric power generating industry. In addition, CBNG development in the eastern PRB coal areas has gone from an industry in its infancy to a major resource extraction industry. For water resources, issues of concern in 1996 were coal mine water use and groundwater level declines due to dewatering by coal mines. For the year 2002, issues of concern included coal mine water use, CBNG water demand, and groundwater level declines due to both CBNG activity and coal mine dewatering.

Past predictions for water use and groundwater level declines related to coal mining in the eastern PRB can be found in the Coal Development Status Check (BLM 1996), coal mine groundwater model predictions summarized by GAGMO (2001), and in the USGS CHIA (Martin et al. 1988). Groundwater level decline in the Fort Union Aquifer is presented in **Table 3.6-2**. The Coal Development Status Check of 1996 (BLM 1996) estimated water use by the coal mines for year 1990 to be 5,971 acre-feet. The actual use in 1990 according to BLM (1996) was 4,679 acre-feet, which translates into 28.78 acre-feet per million tons of coal mined. In 1994, water use by coal mines was 6,911 acre-feet, or approximately 31.87 acre-feet per million tons of coal mined (BLM 1996). The report did not estimate groundwater level declines for coal mine water use beyond 1994. Therefore, the model predictions of individual mines, as summarized by GAGMO (2001) and the predictions of the USGS (Martin et al. 1988) have been used to compare predictions for years 1995 to 2000 to actual data.

This section serves to update the Coal Development Status Check to the year 2002, the last year with a complete database for water resources in the PRB.

5.1 Summary of Current Conditions

5.1.1 Surface Water

Surface water flow and water quality primarily are determined by irrigation practices, precipitation and runoff, and the geology of alluvium and bedrock along individual drainages. Both surface water flow and water quality vary considerably throughout the year in the PRB, so any definitive cause and effect relationship relating surface water flow or quality to either coal mining or CBNG activity requires a considerable amount of data gathered over a number of years (Martin et al. 1988). Active coal mines generally have minimal impact on surface water flow or quality because of the regulation of coal mines by the WDEQ and the requirement for WYPDES permits for any discharges that reach drainages. Following reclamation, areas of past coal mining may affect ephemeral and intermittent drainages as a result of: 1) change in slope of the reclaimed areas from the natural conditions; 2) restoration of only third-order and higher drainages; 3) decreased infiltration of precipitation in reclaimed areas; and 4) increased sediment loading to drainages during storm runoff (Martin et al. 1988). As of 2002, the impacts of coal mining on surface water flow and quality had been minimal, limited to the coal mine lease areas, and generally not recognized in downstream USGS stream gauges. As shown in **Table 3.6-1**, coal mines in 2002 in the eastern PRB collectively were permitted to use 7,460 acre-feet of groundwater. The groundwater that was produced was discharged to the surface for dust control and reclamation, used in coal processing, and potentially discharged directly to drainages in accordance with WYPDES permit criteria.

The discharge of CBNG-produced water is an issue relative to surface water flow and quality. The volume of CBNG discharge to ephemeral and intermittent drainages has increased dramatically. The Powder/Tongue River Basin and Northeast Wyoming River Basins water plans (HKM Engineering et al. 2002a,b) estimated CBNG groundwater pumpage in 2002 at 72,500 acre-feet. In comparison, during 2002, CBNG wells in the PRB pumped approximately 73,287 acre-feet (568.8 million barrels) of water (**Table 3.5-1**). Approximately 257 million barrels (33,100 acre-feet) of this water was discharged in the Northeast Wyoming River Basins. This water was discharged directly to drainages in the eastern PRB near coal mining areas, primarily in the subdrainages of the Belle Fourche and Cheyenne rivers. The discharge of CBNG water is regulated by the WDEQ Water Quality Division. As stipulated by permit criteria, discharged water must be of a quality and quantity that will not degrade the existing water quality classification of the drainage receiving the discharge.

Studies discussed previously have shown that the conveyance loss of CBNG water discharged directly to drainages is high and varies from 70 to 90 percent, depending of the time of year. Most of this loss is through infiltration of the water into the alluvium and eventually into the upper Wasatch Formation. Water discharged directly to drainages generally is not evident beyond a few miles from the discharge point. Stream gauges maintained by the USGS in the Belle Fourche and Cheyenne River drainages have not shown statistically discernable changes in stream flow or water quality that can be attributed to CBNG discharge (BLM 2003a). In the northern part of the PRB, mainly in the Powder/Tongue River Basin, discharge of CBNG production water is to impoundments. These impoundments are mostly unlined, and the water infiltrates into the alluvium and eventually into the Wasatch Formation. Groundwater mounds around these impoundments are limited to approximately 25 feet from the impoundment. Changes in groundwater levels, stream flow, and stream water quality near the impoundments are the subject of ongoing studies in the northwestern part of the PRB. As of 2002, no statistically quantifiable impacts to surface water features had been recorded near these impoundments (BLM 2003a).

5.1.2 Groundwater

Groundwater level changes since 1996 have been the most noticeable impact to water resources in the PRB. Groundwater level declines in the Fort Union Formation coal bed aquifers near the coal mines have been in the range of 20 to 60 feet, with some mines showing up to 120-foot declines within 1 mile of the permit boundaries during the period from 1980 to 2000 (GAGMO 2001). Coal mine water use has been increasing since 1985 and increased noticeably during the 1990s (**Table 3.6-1**). Groundwater level declines within the Wasatch and Fort Union aquifers within approximately 1 mile of the coal mines have been the result of increased groundwater pumpage by the mines since 1996. Beyond approximately 1 mile from the mines, or in areas where CBNG development has approached mine permit boundaries, groundwater declines are probably due more to CBNG groundwater pumpage, as discussed in Section 4.3, Groundwater Modeling Results for Current Conditions.

CBNG development during the 1990s, and especially since about 1995, has had the greatest impact on groundwater levels in the Fort Union Formation aquifer. As shown in **Table 3.6-2**, groundwater level declines of 100 to 240 feet since about 1995 can be attributed to CBNG activity in the eastern PRB within 1 to 3 miles of the operating coal mines (GAGMO 2001). Because of CBNG activity, it is not possible to separate groundwater level declines outside of coal mine permit boundaries into CBNG- and coal mine-related effects using monitor well data alone. Groundwater models can be used to estimate the approximate effects of CBNG development and coal mine dewatering using modeled drawdown and publicly available pumping data for CBNG wells and coal mine wells and sumps. This is done by having only CBNG or only coal mine dewatering wells active in the groundwater model at any given time period. Section 4.3, Groundwater Modeling Results for Current Conditions, presents a discussion of the modeled separation of drawdown in the Wasatch and Fort Union formations due to coal dewatering and CBNG pumping.

5.2 Coal Mine Water Use

Permitted coal mine groundwater use is presented in **Table 3.6-1**. This table, based on WSEO (2004) information, shows that permitted coal mine groundwater use in 1990 was 2,567 acre-feet and in 1994 was 4,608 acre-feet. The Coal Development Status Check of 1996 (BLM 1996) provided total water use values of 4,679 acre-feet for 1990, with an estimate of 5,971 acre-feet and a value of 6,911 acre-feet for 1994. According to the WSEO (2004), permitted groundwater use by coal mines was less than reported in the Coal Development Status Check (BLM 1996) for 1990 and less than total water use provided for 1994. Estimates of water use per million tons of coal mined for 1990 and 1994 from BLM (1996) show values from 28 to 32 acre-feet per million tons of coal mined. Using data from WSEO (2004) and from Montgomery Watson Harza (MWH) (2003), the water use per million tons of coal mined from 1990 to 2000 was in the range of 11 to 22 acre-feet per million tons of coal mined (**Table 5.2-1**).

5.3 Eastern Powder River Basin Groundwater Conditions 2002

In the eastern PRB, coal mine dewatering and CBNG development have resulted in the lowering of groundwater levels in the Fort Union Formation. Locally, discharge from CBNG wells has resulted in a rise in water levels in the Wasatch Formation. CBNG development began in earnest around 1995 and coal mine dewatering began around 1985 and increased during the 1990s as mining of the coal seams progressed to deeper levels, requiring dewatering of the overburden (Wasatch Formation) and the coal seams in the Fort Union Formation. Changes in groundwater levels (i.e., drawdown and mounding) for the Wasatch and Fort Union formations from 1990 to 2002 are presented in Section 4.3, Groundwater Modeling Results for Current Conditions. CBNG development and coal mining affect the Upper Fort Union (HSU-5 in the CMGM) because this HSU represents the Wyodak-Anderson coal, the main coal unit currently being mined in most of the active coal mines of the eastern PRB. The Lower Fort Union (HSU-6) is affected mostly by municipal pumpage near Gillette, Wyoming. The Wasatch is affected by coal mine dewatering and also by both CBNG dewatering of the underlying Upper Fort Union and CBNG discharge to drainages, which ultimately reaches the upper Wasatch and can result in local groundwater mounding in the Wasatch.

Table 5.2-1
Eastern PRB Coal Mine Groundwater Use Related to Coal Production

Coal Mine	1980			1985			1990			1995			2000		
	Coal Production (mmtons)	Water Use (acre-feet)	Water Use/Coal Production (acre-feet/mmton)	Coal Production (mmtons)	Water Use (acre-feet)	Water Use/Coal Production (acre-feet/ mmton)	Coal Production (mmtons)	Water Use (acre-feet)	Water Use/Coal Production (acre-feet/ mmton)	Coal Production (mmtons)	Water Use (acre-feet)	Water Use/Coal Production (acre-feet/ mmton)	Coal Production (mmtons)	Water Use (acre-feet)	Water Use/Coal Production (acre-feet/ mmton)
Subregion 1- North Of Gillette															
Buckskin	0.00	0.00	--	3.90	0.00	--	7.70	0.24	0.03	11.60	214.90	18.53	15.80	276.30	17.49
Eagle Butte	8.40	61.40	7.31	11.80	307.00	26.02	15.40	921.00	59.81	16.90	921.00	54.50	18.60	921.00	49.52
Dry Fork	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rawhide	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Wyodak	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Subregion 2-South Of Gillette															
Caballo	2.00	0.00	--	9.00	0.00	--	14.30	214.90	15.03	18.10	614.00	33.92	25.60	614.00	23.98
Belle Ayr	16.10	0.01	0.00	12.80	24.56	1.92	15.50	3.07	0.20	18.80	307.00	16.33	15.00	214.90	14.33
Cordero-Rojo	6.60	0.00	--	14.30	61.40	4.29	21.50	276.30	12.85	31.40	12.28	0.39	38.70	245.60	6.35
Coal Creek	0.00	0.00	--	2.60	0.00	0.00	0.10	92.10	921.00	4.20	614.00	146.19	4.20	61.40	14.62
Subregion 3-Wright															
Jacobs Ranch	8.20	3.07	0.37	13.00	276.30	21.25	16.80	307.00	18.27	24.60	614.00	24.96	28.30	921.00	32.54
Black Thunder	10.50	0.00	--	23.20	0.00	--	27.90	307.00	11.00	36.10	307.00	8.50	60.10	614.00	10.22
North Rochelle	0.00	0.00	--	0.00	0.00	--	13.20	0.00	0.00	0.70	921.00	1315.71	17.20	921.00	53.55
North Antelope/Rochelle	0.00	0.00	--	5.90	0.00	--	20.30	122.80	6.05	47.30	921.00	19.47	70.80	921.00	13.01
Antelope	0.00	0.00	--	0.70	0.00	0.00	5.20	0.00	0.00	10.90	307.00	28.17	23.00	307.00	13.35
Total All Mines	71.20	8.60	0.12	116.60	761.40	6.53	166.70	2566.50	15.40	248.20	2775.30	11.18	327.30	7432.50	22.71

Note: acre-feet/mmton = acre-feet per million tons
mmtons = million tons

Source: MWH 2003; WSEO 2004.

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APPENDIX A

STREAM WATER QUALITY
(Source: USGS 2004.)

USGS 06320210 CLEAR CREEK ABOVE KUMOR DRAW, NEAR BUFFALO, WY
Johnson County, Wyoming
Hydrologic Unit Code 10090206
Latitude 44°23'21", Longitude 106°37'23" NAD27
Gage datum 4,410 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
10/12/2001	13:10	78.6	32.6	44.2	3.01	5.46	263	0.2	9.64	171	6
11/20/2001	10:20	74.2	30.9	41.5	2.62	4.72	240	0.2	9.75	158	6
12/11/2001	9:10	73.4	28.3	35.9	2.2	3.87	217	0.2	11.3	159	5
1/10/2002	11:20	71.8	28.4	38.4	2.29	3.74	225	0.2	10.7	156	5
2/14/2002	12:40	77	30	40.7	2.24	4.14	241	0.2	10.6	175	6
3/11/2002	9:55	74.1	29.6	41.1	2.55	6.95	238	0.2	9.92	170	6
4/11/2002	10:20	83.6	33.9	42.3	2.83	4.36	275	0.2	6.37	157	6
5/9/2002	10:45	46	17.7	26.1	1.78	3.54	135	0.12	9.87	101	5
6/12/2002	11:00	26.9	11.5	15.7	1.33	2.3	84.3	0.14	7.09	61	4
7/8/2002	13:45	38.4	14.9	20.8	2.49	2.19	118	0.12	8.78	73	4
8/15/2002	8:55	52.4	20.3	27	2.21	3.94	152	0.17	6.87	126	4
9/12/2002	9:40	71.4	24.8	30.4	2.22	3.22	201	0.19	10	128	4

USGS 06324000 CLEAR CREEK NEAR ARVADA, WY
Sheridan County, Wyoming
Hydrologic Unit Code 10090206
Latitude 44°52'18", Longitude 106°04'56" NAD27
Drainage area 1,110.00 square miles
Gage datum 3,506.51 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
10/24/2000	10:25	103	39.3	49.2	4.56	3.4	349	0.2	4.58	198	6
11/16/2000	14:10	122	52.5	63.1	4.28	3.04	403	0.3	11.4	257	7
12/13/2000	11:40	137	56.7	68.4	4.14	4.62	441	0.2	9.84	270	7
1/11/2001	10:35	117	49.4	62.2	3.89	3.79	416	0.3	10.6	251	7
2/14/2001	10:40	129	55.9	68	3.97	4.54	447	0.2	11.2	258	7
3/13/2001	13:45	96.4	41.7	52.1	6.13	5.03	348	0.2	7.21	181	6
4/11/2001	18:30	122	63.3	82.7	5.96	4.09	527	0.2	0.39	207	9
5/10/2001	8:40	71.3	31.9	40.6	3.66	2.65	243	0.2	2.93	153	6
6/7/2001	9:50	108	40.6	49.5	5.54	3	382	0.3	5.29	166	6
7/13/2001	12:50	115	62.6	80.2	6.51	2.83	531	0.2	11.1	149	9
8/14/2001	15:00	128	76.5	108	7.84	4.47	684	0.3	5.35	200	11
9/11/2001	12:15	151	94.3	117	7.18	4.01	870	0.2	7.05	176	11
10/11/2001	14:00	129	61.8	72.3	5.38	3.56	527	0.3	8.1	219	7
11/20/2001	12:50	130	57.9	70.5	4.6	3.62	481	0.2	7.33	247	7
12/12/2001	9:30	139	59.9	72	4.91	5.05	497	0.3	10.6	268	7
1/9/2002	9:05	131	56.3	68.4	4.02	3.47	472	0.3	9.4	266	7
2/13/2002	17:10	115	48.5	60.1	3.81	3.82	419	0.2	7.7	244	7
3/13/2002	12:30	114	48.1	59.4	3.78	5.36	395	0.2	5.22	214	7
4/10/2002	14:15	70.4	31.6	40.2	6.65	2.73	250	0.2	6.12	146	6
5/8/2002	13:45	108	52.1	66.1	4.72	4.88	434	0.15	1.07	204	7
6/11/2002	18:10	113	47.3	67.3	4.7	2.57	395	0.18	4.61	231	8
7/9/2002	8:30	170	84.8	104	8.34	5.24	776	0.25	9.56	224	9
8/14/2002	10:20	156	78.4	93.9	7.48	3.53	710	0.23	7.74	218	9
9/11/2002	13:25	143	70.2	90.4	6.2	3.21	627	0.21	7.59	185	9

USGS 06324970 LITTLE POWDER RIVER AB DRY CREEK, NEAR WESTON, WY
Campbell County, Wyoming
Hydrologic Unit Code 10090208
Latitude 44°55'37", Longitude 105°21'10" NAD27
Drainage area 1,237 square miles
Contributing drainage area 1,237 square miles
Gage datum 3,410 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Carbonate	Bicarbonate	Organic Carbon	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	alkalinity (field)	acid nuetralizing	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	meq/L	meq/L	
3/9/1995	9:30				180	100	490	15	35	1500	0.6	10			409	41
5/24/1995	12:50				130	94	270	15	14	1000	0.4	10			264	26
8/30/1995	12:00				110	68	440	19	110	1100	0.7	7.7			278	47
12/6/1995	12:05				200	130	560	21	58	1800	0.6	11			431	44
3/20/1996	9:00				72	51	140	12	10	540	0.3	9.9			185	18
6/11/1996	14:45				190	130	440	19	24	1600	0.6	9.6			391	35
8/27/1996	12:55				160	130	620	24	47	1900	0.7	9.3			331	51
11/14/1996	8:15				160	100	400	3.4	34	1400	0.6	9.7			300	35
1/28/1997	10:10				130	73	260	18	15	950	0.5	12			246	26
5/6/1997	18:05				218	165	405	20.2	26	1750	0.5	7.4			383	29
7/24/1997	15:10				116	67.3	178	17.9	12.6	777	0.5	10.9			168	19
11/6/1997	11:10				213	147	494	23.2	35.9	1770	0.6	7.1			356	37
2/4/1998	12:30				196	121	446	19.9	44.8	1510	0.7	10.9			429	35
6/2/1998	13:25				151	140	534	21.9	41.6	1820	0.6	5.9			320	44
7/30/1998	16:04															#DIV/0!
7/30/1998	16:05															#DIV/0!
8/27/1998	14:05				105	73	375	17.4	29.4	970	0.7	6.9			325	40
10/7/1998	11:50				14.2	7.33	48.9	5.34	6.58	116	0.3	6	56			15
1/28/1999	15:45		562	9	208	113	454	21.6	49.6	1480	0.7	13.9		461	470	36
2/17/1999	16:55		451	12	163	108	405	19.6	69.8	1280	0.5	11.3		370	368	35
3/16/1999	15:10		213	13	88.7	58.9	175	12.8	22.1	677	0.4	6.83	183	174		20

Date	Time	Carbonate	Bicarbonate	Organic Carbon	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	alkalinity (field)	acid nuetralizing	SAR
3/23/1999	10:20		267	11	99.6	68.2	200	13.9	22.1	743	0.4	9.35		219	229	22
4/7/1999	12:35		305	9.6	133	104	281	15.7	37.8	1100	0.4	6.01	256	250		26
4/28/1999	11:15		366	13	189	139	305	19.2	66.9	1290	0.5	10.4	306	300		24
5/18/1999	18:00		430	13	198	160	365	19.1	77.7	1570	0.5	7.16	364	353		27
6/2/1999	12:15		453	9.9	190	163	444	20.8	35.7	1770	0.6	7.6	366	372		33
6/10/1999	13:15		151	11	61.6	37.8	137	9.41	7.66	473	0.3	8.71	124	124		19
7/15/1999	13:20		385	9.5	164	129	510	20.9	38.3	1680	0.6	12.9	342	316		42
8/23/1999	11:45		377	9.3	132	108	560	23.4	34.7	1750	0.7	4.11	316	309		51
9/29/1999	11:15	2	282	7.7	137	111	476	20.3	26.1	1520	0.7	1.43	300	235		43
10/18/1999	17:20		381	6.8	149	116	541	20.4	51.7	1680	0.6	2.07	334	312		47
11/9/1999	15:40		483	6	160	118	579	18.2	61.6	1630	0.7	6.71	381	396		49
12/13/1999	14:15		535	7.3	198	129	554	25.3	64.5	1720	0.7	11.4	455	439		43
1/6/2000	15:25		573	6.3	200	123	540	24.1	60.5	1710	0.7	12.4	484	470		42
2/23/2000	10:20		466	8.8	156	92.4	428	18.1	49.8	1290	0.6	9.59	393	382		38
3/6/2000	14:00		361	7.3	121	76.5	365	14.8	63.2	1100	0.5	7.09	315	296		37
3/23/2000	10:45		470	8.5	182	128	485	17.3	57.4	1570	0.6	6.7	392	385		39
4/5/2000	8:15		478	9.1	172	135	550	21.8	64.5	1790	0.7	4.61	406	392		44
5/17/2000	8:20		397	9.8	150	105	433	15.4	46.1	1380	0.6	6.99	334	325		38
5/19/2000	15:35		129	6	52.1	28.8	111	9.3	7.95	338	0.4	7.01	106	106		17
6/8/2000	12:45		410	10.6	181	163	538	22.1	47.8	1920	0.6	7.42	339	336		41
7/13/2000	8:15		283	9.3	109	120	534	21.9	45.2	1770	0.6	2.16	232	232		50
8/1/2000	8:45		309	7.8	140	140	596	23.6	79.2	1950	1	3.63	264	253		50
8/16/2000	8:45		340	8.2	174	150	517	20.6	147	2050	0.8	5.52	294	279		41
9/12/2000	14:40		340	9.4	242	203	603	27.1	199	2150	0.6	4.29	283	279		40
10/16/2000	11:25		317	8.1	201	153	552	25.7	37.8	2060	0.7	6.86	269	260		41
10/25/2000	8:00		243	10.4	71.4	40.9	239	14.3	27.3	681	0.6	5.95	206	199		32
11/15/2000	13:40		462	8.9	231	138	514	29.2	103	1680	0.8	11.1	417	379		38
12/12/2000	16:00		589	6.5	215	129	582	25.1	65.5	1730	0.9	12.6	514	483		44
1/10/2001	14:30		575	6.1	185	111	482	21.4	44.3	1520	0.8	12	456	471		40
2/15/2001	16:40		592	5.2	206	111	552	21.9	80.5	1500	0.9	13.7	474	485		44
3/5/2001	12:15		120	38.2	29.3	14.8	73.6	10.8	14.7	202	0.2	5.11	87	98		16
3/14/2001	14:45		149	17.1	48	31.5	120	11.8	12.2	376	0.3	7.7	135	122		19
4/12/2001	8:15		305	15	112	79	303	14.2	6.09	971	0.4	10.4	244	250		31

Date	Time	Carbonate	Bicarbonate	Organic Carbon	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	alkalinity (field)	acid nuetralizing	SAR
5/8/2001	15:30		438	10.4	164	110	460	19.2	40.9	1490	0.6	7.47	363	359		39
6/6/2001	8:45		304	8	150	127	492	24	50.5	1680	0.6	4.04	265	249		42
7/13/2001	9:00		287	11.9	149	108	475	20.1	37	1510	0.7	5.39	251	235		42
7/25/2001	12:35		81	16.4	17.6	7.38	39.2	7.86	8.27	75.9	0.3	5.38	72	66		11
8/15/2001	8:00		466	12.3	159	104	438	20	74.6	1250	0.7	14.6	403	382		38
9/11/2001	8:30		489	8.6	217	140	502	20.8	141	1590	0.7	12.3	419	401		38
10/11/2001	8:15		512		241	144	479	17.2	118	1600	0.9	13.4	440	420		35
11/14/2001	14:00		395		151	107	502	19.1	32.1	1580	0.8	5.04	376	324		44
12/12/2001	12:00		634		172	119	684	23.4	120	1860	0.9	10.6	514	520		57
1/16/2002	14:00		615		240	146	637	25.9	85.8	2010	0.9	13.6	547	504		46
2/20/2002	15:00	10	420		160	91.4	425	15.3	34.6	1290	0.7	10.1	392	360		38
3/19/2002	11:00		434		140	79.7	399	14.2	45.6	1130	0.7	8.26	351	356	352	38
4/9/2002	13:10				92.9	61.1	250	14.7	50.8	774	0.5	8.44	271		276	28
5/7/2002	13:00		456		164	110	483	19	85	1480	0.63	5.78	388	379	389	41
6/11/2002	7:10				153	121	603	22.6	77.9	1770	0.85	4.88	354		357	52
7/16/2002	14:15		493		254	139	449	26.1	234	1480	0.6	13.7	375	411		32
8/13/2002	12:10				198	141	505	20.9	189	1580	0.81	8.7	327		339	39
9/10/2002	16:50		264		101	58.7	214	13.2	77.5	620	0.34	7.27	229	222	229	24

USGS 06364700 ANTELOPE C NR TECKLA WY
Converse County, Wyoming
Hydrologic Unit Code 10120101
Latitude 43°29'07", Longitude 105°13'29" NAD27
Drainage area 959 square miles

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
11/13/2000	12:00	311	124	259	18.6	21.9	1410	0.6	22	458	18
3/15/2001	12:20	303	118	241	15.2	22.8	1360	0.6	18.1	403	17
5/7/2001	9:30	306	119	253	17.4	23.8	1440	0.6	18.4	396	17
6/5/2001	9:40	293	118	257	20.1	23.4	1380	0.7	19.9	397	18
7/10/2001	9:30	78.7	24.7	61.7	10.4	6.53	340	0.3	9.18	83	9
11/13/2001	10:40	303	125	261	17.9	21.2	1460	0.6	20	468	18
12/5/2001	8:00	315	124	256	17	22	1440	0.7	20.1	430	17
1/7/2002	9:55	299	118	218	17.1	17.4	1300	0.7	20.4	442	15
2/11/2002	9:30	280	111	224	16.9	18.4	1290	0.6	18.1	422	16
3/11/2002	13:20	321	119	256	15.8	23.4	1430	0.6	19	426	17
4/8/2002	9:45	292	114	254	16.1	25.6	1460	0.6	17	414	18
5/6/2002	9:40	328	127	277	17.1	28.5	1510	0.55	19.3	412	18
6/10/2002	9:20	305	124	272	18.6	22.5	1460	0.77	20.9	396	19

USGS 06298000 TONGUE RIVER NEAR DAYTON, WY
Sheridan County, Wyoming
Hydrologic Unit Code 10090101
Latitude 44°50'58", Longitude 107°18'14" NAD27
Drainage area 206 square miles
Contributing drainage area 206 square miles
Gage datum 4,060 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Carbonate	Bicarbonate	Organic Carbon	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	alkalinity (field)	acid nuetralizing	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	meq/L	meq/L	
1/14/1999	11:00		163	1	34	11.5	1.41	0.6	0.67	4.3	< .1	7.2		134	133	0.30
2/18/1999	12:00		160	0.8	35.6	12.3	1.53	0.72	0.81	4.7	< .1	7.21		131	135	0.31
3/16/1999	10:25	1	150	1.1	33.6	11.6	1.48	0.71	0.73	4.5	< .1	6.55	132	125		0.31
4/6/1999	13:55	2	141	1.1	34.5	12	1.38	0.68	0.57	4.5	< .1	5.93	141	120		0.29
4/30/1999	9:55		92	4.9	19	5.54	0.87	1.41	0.72	2.3	< .1	5.1	74	76		0.25
5/18/1999	11:50		127	2.9	26.9	8.2	1.43	0.74	1.15	3.3	0.1	7.37	104	102		0.34
6/8/1999	10:30		79	5.2	18.3	5.01	0.94	0.52	0.68	1.9	< .1	6.12	68	65		0.28
6/17/1999	12:00		106	4	20.9	6.06	1.03	0.46	< .29	1.9	< .1	6.21	81	87		0.28
7/16/1999	9:15		138	2.1	30.4	9.95	1.24	0.56	0.75	3.4	< .1	6.77	117	113		0.28
8/23/1999	16:20		154	1.5	31.4	11.3	1.34	0.76	0.67	3.8	< .1	5.74	128	126		0.29
8/31/1999	8:30		152	2.1	30.8	11.1	1.33	0.79	0.79	3.8	< .1	6.01	123	125		0.29
10/18/1999	12:25		157	1.5	30.6	10.8	1.32	0.69	0.37	4.4	< .1	6.22	133	129		0.29
11/9/1999	9:10		172	1.2	34.1	11.9	1.36	0.61	0.41	4.8	0.1	6.42	136	141		0.28
12/13/1999	10:00		178	1.4	33.7	11.6	1.37	0.67	0.45	5.7	< .1	6.52	146	146		0.29
1/5/2000	10:50		172	0.9	35.7	12.2	1.36	0.65	0.45	5.7	< .1	7.1	143	141		0.28
2/22/2000	8:40		156	0.9	34	12	1.32	0.59	0.55	4.4	< .1	6.45	141	128		0.28
3/7/2000	9:30		157	1.1	31.6	11.2	1.27	0.53	0.85	4.6	< .1	5.99	137	129		0.27
4/4/2000	10:40		156	1.1	30.8	11.1	1.28	0.62	0.45	5.2	0.1	5.92	135	128		0.28

Date	Time	Carbonate	Bicarbonate	Organic Carbon	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	alkalinity (field)	acid nuetralizing	SAR
5/5/2000	9:30		76	5.8	17.6	4.87	0.97	0.8	0.59	2	< .1	5.97	63	62		0.29
5/15/2000	16:45		96	4.2	21.3	6.44	1.21	0.63	0.57	2.7	< .1	7.36	87	79		0.32
5/18/2000	11:30		84	5.9	19.5	5.57	1.12	0.67	0.83	2.2	0.1	7.12	74	69		0.32
6/9/2000	9:30		102	3.5	21.2	6.38	1.1	0.48	0.43	2.3	< .1	6.36	86	84		0.30
7/12/2000	11:30		129	1.9	26.3	8.98	1.25	0.56	0.58	3.4	< .1	6.33	111	106		0.30
8/2/2000	11:00		140	1.6	27.3	9.69	1.31	0.6	0.46	3.7	< .1	5.8	119	115		0.30
9/12/2000	10:10		155	1.4	32.3	11.5	1.36	0.71	0.56	3.8	0.3	5.81	130	127		0.29
10/23/2000	15:30		155	1.1	32.7	11.2	1.25	0.67	0.99	4.8	E .1	5.86	133	127		0.27
11/28/2000	14:50		148	0.9	36.9	12.3	1.49	0.75	0.77	5.3	E .1	6.96	141	121		0.30
12/14/2000	10:45		162	1	37.3	13	1.56	0.67	0.62	5.6	E .1	7.34	145	133		0.31
1/12/2001	7:50		165	0.8	33.5	11.5	1.4	0.65	1.1	5.3	E .1	6.63	141	135		0.30
2/12/2001	16:15		171	0.7	34.5	11.8	1.37	0.67	0.99	5.3	E .1	6.41	144	140		0.28
3/12/2001	13:45		168	0.9	35.2	12.3	1.46	0.6	0.96	5.4	E .1	6.45	142	138		0.30
4/11/2001	11:00		149	1.3	34.9	12	1.44	0.57	0.74	5.3	E .1	5.8	137	122		0.30
5/10/2001	12:15		88	4.6	19.6	5.61	1.06	0.87	0.63	2.8	E .1	5.56	75	72		0.30
5/29/2001	14:00		99	3.2	21.3	6.61	1.38	0.61	0.51	3	< .2	6.53	85	81		0.37
6/8/2001	8:30		116	2.5	24.1	7.89	1.29	0.56	0.47	3.4	E .1	6.51	95	95		0.32
7/18/2001	13:30	4	121	2	27.3	10	1.52	0.66	0.56	4.3	E .1	5.65	113	105		0.35
8/15/2001	14:40	4	140	1.5	28.5	10.9	1.49	0.67	0.71	4.8	E .1	5.22	122	121		0.34
9/12/2001	14:20	4	137	1.5	28.7	10.6	1.48	0.78	0.59	4.5	E .1	5.57	122	119		0.33
8/14/2002	15:15				28.4	10.4	1.46	0.71	0.98	4.5	0.15	5.66	119			0.33

USGS 06304500 LITTLE GOOSE CR AT SHERIDAN WY
Sheridan County, Wyoming
Hydrologic Unit Code 10090101
Latitude 44°48'10", Longitude 106°57'10" NAD27
Drainage area 159 square miles
Gage datum 3,740 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Carbonate	Bicarbonate	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	alkalinity (field)	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	meq/L	
6/28/2000	13:20	14	188										178	#DIV/0!
10/12/2001	11:15			68.8	45.9	22.8	2.71	4.75	114	0.4	10.2	282		3.0
11/15/2001	10:45			68.5	42.1	20.1	2.24	4.48	102	0.3	8.89	314		2.7
12/11/2001	11:10			65	40.1	18.5	1.88	3.71	95.5	0.3	10.4	280		2.6
1/10/2002	8:05			58.2	36.4	17.9	1.93	3.63	86	0.3	9.31	258		2.6
2/14/2002	10:55			60.1	35.9	16.8	1.74	3.57	84.8	0.3	8.68	269		2.4
3/18/2002	17:10			60.7	38.3	25.7	2.29	14.5	100	0.2	7	249		3.7
4/11/2002	7:25			62.7	39.9	21.7	2.55	5.21	120	0.3	4.48	246		3.0
5/9/2002	7:30			53.8	33.9	17.8	1.94	4.72	87.2	0.25	7.51	225		2.7
6/12/2002	9:25			69.2	47.7	25.1	2.96	5.02	136	1.24	9.9	294		3.3
7/8/2002	18:40			57.6	60.4	34	3.23	6.82	195	0.41	11.5	263		4.4
8/15/2002	7:05			60.1	41.2	21.6	2.51	4.23	112	0.35	7.97	275		3.0
9/11/2002	17:35			62.2	42.4	22.3	2.62	4.24	109	0.31	10.4	230		3.1

USGS 06305500 GOOSE CREEK BELOW SHERIDAN, WY
Sheridan County, Wyoming
Hydrologic Unit Code 10090101
Latitude 44°49'25", Longitude 106°57'40" NAD27
Drainage area 392.00 square miles
Gage datum 3,701.36 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Carbonate	Bicarbonate	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	alkalinity (field)	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	meq/L	
6/29/2000	14:00	6	140										124	#DIV/0!
10/12/2001	10:00			67.8	45.8	27.9	3.65	6.9	142	0.4	10.2	288		3.7
11/15/2001	9:30			68.6	42.2	25.5	2.83	6.25	130	0.4	9.16	292		3.4
12/11/2001	12:40			63.5	39	25	2.69	6.75	125	0.3	10.2	246		3.5
1/10/2002	9:15			57.9	36.5	21.3	2.56	5.84	116	0.3	9.05	226		3.1
2/14/2002	9:40			59.7	35.9	21.2	2.47	6.09	112	0.3	8.55	248		3.1
3/19/2002	15:50			60.5	37.3	25.4	2.84	7.64	122	0.3	7.46	236		3.6
4/11/2002	8:15			59.8	38.4	24.6	2.91	6.56	139	0.3	3.96	226		3.5
5/9/2002	8:30			50.5	29.9	19.7	2.11	5.3	105	0.2	7.43	188		3.1
6/12/2002	8:20			33	18.6	11.5	1.74	2.96	63.1	0.32	6.99	120		2.3
7/8/2002	17:35			59.5	49.3	42.3	4.86	16.1	189	0.29	5.99	230		5.7
8/14/2002	17:20			54.1	41.4	29.8	3.75	9.24	130	0.32	7.11	222		4.3
9/12/2002	8:00			62.3	40.6	24.9	3.17	6.13	118	0.32	8.15	261		3.5

USGS 06306250 PRAIRIE DOG CREEK NEAR ACME, WYO.
Sheridan County, Wyoming
Hydrologic Unit Code 10090101
Latitude 44°59'05", Longitude 106°50'15" NAD27
Drainage area 358.00 square miles
Gage datum 3,450.00 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
5/15/2000	14:20	117	80.4	89.5	6.71	3.81	540	0.2	12.2	246	9
8/2/2000	17:45	133	92.7	111	10.2	5.14	683	0.2	13.2	227	10
10/24/2000	8:05	131	84.4	63.6	7.46	4.56	466	0.3	11	351	6
11/28/2000	10:30	147	88.3	64.3	7.04	4.81	476	0.3	13.4	390	6
12/14/2000	8:15	172	106	80	8.13	5.52	594	0.3	15.1	440	7
1/11/2001	16:50	143	88.6	72.3	7.52	4.18	502	0.3	13.6	398	7
2/13/2001	9:45	150	95.5	79	6.92	5.26	532	0.3	13.7	407	7
3/13/2001	9:40	80.6	54.6	47.4	12.4	5.72	325	0.2	8.61	227	6
4/11/2001	14:15	140	92.5	79.3	8.51	6	525	0.3	8.12	330	7
5/9/2001	16:15	111	79.7	88.1	7.69	4.33	510	0.3	10.4	275	9
6/8/2001	19:00	121	88.6	102	8.45	4.32	606	0.4	9.94	279	10
7/19/2001	7:50	152	105	127	9.09	3.94	720	0.3	14	352	11
8/15/2001	11:50	157	127	169	11.9	5.78	935	0.3	12.9	298	14
9/12/2001	12:00	118	75.4	68.5	7.08	4.58	475	0.3	13.8	298	7
10/12/2001	8:30	119	71.1	52.6	5.8	3.11	401	0.3	12.8	280	5
11/15/2001	7:45	142	91.4	74.1	7.59	4.16	581	0.3	11.9	384	7
12/11/2001	14:50	146	93.1	73.8	7	4.01	528	0.3	13	391	7
1/9/2002	16:50	136	84.9	68	6.47	3.74	529	0.4	12.9	388	6
2/14/2002	7:55	135	84.8	72.3	6.69	4.14	512	0.3	12.6	379	7
3/19/2002	14:30	123	79.7	68.2	8.16	4.75	465	0.3	11.8	332	7
4/10/2002	17:55	87.2	57.1	52.1	10.7	3.93	343	0.3	9.8	232	6
5/8/2002	16:25	143	103	99.2	8.94	3.31	670	0.28	8.42	334	9
6/12/2002	6:40	179	125	157	9.53	5.42	891	0.46	15.1	418	13
7/8/2002	15:55	181	136	182	10.3	7.68	983	0.39	17.5	363	14
8/14/2002	12:50	113	63.8	61.3	6.34	2.57	392	0.28	14.1	279	7

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
9/11/2002	16:00	70.3	36.4	26.9	3.57	2.35	192	0.2	10.6	202	4

L ↄS 06313400 SALT CREEK NEAR SUSSEX, WYO.
Johnson County, Wyoming
Hydrologic Unit Code 10090204
Latitude 43°37'19", Longitude 106°22'04" NAD27
Drainage area 769 square miles
Contributing drainage area 769 square miles
Gage datum 4,480 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	acid nuetralizing	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	meq/L	
1/25/1995	9:15	280	130	1200	30	950	2300	2.6	27		384	84
5/23/1995	8:45	260	260	1700	23	630	4100	1.2	12		373	105
8/3/1995	9:05	230	120	1200	27	930	2200	2.4	19		230	91
1/12/1996	13:15	200	86	1200	28	1100	1500	2.6	26		437	100
3/14/1996	9:40	160	91	770	18	390	1700	1.5	16		300	69
5/29/1996	9:15	210	250	1400	19	650	3800	1	9		324	92
8/21/1996	9:15	51	57	1500	33	1600	1200	2.4	10		485	204
10/24/1996	9:45	190	90	1100	39	990	1700	2.6	26		299	93
3/21/1997	10:00	210	110	870	25	590	1900	1.8	17		306	69
6/3/1997	12:25	130	72.1	639	13.5	327	1360	1.1	7.2		215	64
9/2/1997	9:25	155	70.2	1070	26.4	1000	1320	2.1	18.1		234	101
11/24/1997	9:15	223	95.3	1080	36.8	1000	1780	2.6	27.9		348	86
3/20/1998	8:50	159	97.8	679	15.5	284	1600	1	10.6		236	60
5/8/1998	9:05	194	110	1160	7.46	924	2110	2.2	18.6		244	94
8/25/1998	8:45	255	122	1080	29.7	633	2470	2.1	17.5		208	79
11/12/1998	10:20	222	255	1380	19.3	419	3910	1.2	14.6		341	89
2/24/1999	10:20	208	120	1150	25.4	731	2080	2.1	23.8		378	90
5/19/1999	9:30	257	297	1790	5.18	674	4350	1.6	14.6		427	108
7/28/1999	9:00	108	68.7	1260	15.7	1250	1290	2.6	29.5		322	134
11/4/1999	8:40	180	75.1	1130	31.8	1100	1480	2.7	31.5		360	100
2/2/2000	9:00	204	84.9	1290	34.5	1150	1600	2.9	34.8		525	107
5/10/2000	8:55	157	80.1	1050	30.9	971	1650	2.5	21		328	96
8/16/2000	12:00	77.1	56.5	1190	35.1	1210	1110	3.3	24.5		324	146
11/24/2000	11:45	149	56	1060	29.9	1110	1190	2.4	34.8	390		105
3/7/2001	9:30	134	89.1	705	15.3	273	1580	1.1	10.3	226		67
6/21/2001	8:30	151	79.8	1100	34.9	935	1610	2.5	23.3	250		102

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	acid nuetralizing	SAR
8/20/2001	9:45	114	57.1	1000	6.48	958	1170	2.9	26.1	201		108
10/23/2001	11:10	112	53.7	1090	31.9	1240	1210	2.5	27.8	285		120
1/14/2002	10:00	208	62.7	876	33.8	890	1280	3.3	31.8	348		75
2/19/2002	10:20	132	51.1	1340	28.9	1530	973	2.4	27.9	469		140
3/18/2002	11:05	157	72.5	957	24.9	840	1400	2.3	22.2	356		89
4/11/2002	14:00	138	70.7	1010	29.1	911	1520	2.3	19	345		99
5/9/2002	14:40	131	81.3	1210	31.4	1030	1600	2.16	19.7	365		117
6/12/2002	14:15	87.7	66.5	1300	32.1	1270	1290	2.69	18.5	341		148
7/8/2002	10:05	105	37.4	576	17.1	542	612	1.29	12.8	287		68
8/15/2002	12:30	65.6	49.4	1240	31.3	1250	998	2.53	21.8	310		164
9/12/2002	13:40	84.3	50.9	1100	28.6	1120	1040	2.46	25	274		134

USGS 06313500 POWDER RIVER AT SUSSEX, WY
Johnson County, Wyoming
Hydrologic Unit Code 10090202
Latitude 43°41'44", Longitude 106°18'24" NAD27
Drainage area 3,090.00 square miles
Gage datum 4,362.16 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	acid nuetralizing	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	meq/L	
1/25/1995	12:25	160	56	240	6	160	760	0.6	10		242	23
3/16/1995	8:50	140	53	270	6.4	110	810	0.6	9.1		214	27
4/24/1995	8:30	130	46	240	5.5	97	720	0.6	8.3		180	26
5/23/1995	11:15	80	30	140	3	35	450	0.4	8.3		117	19
6/27/1995	10:15	99	43	170	4	59	560	0.4	8.9		168	20
8/3/1995	11:05	220	88	500	12	280	1400	0.8	11		208	40
8/28/1995	10:30	190	77	440	10	160	1400	0.7	8.1		181	38
9/28/1995	11:00	130	51	190	5.2	100	610	0.4	8		202	20
11/7/1995	10:45	140	51	190	4.9	96	680	0.5	8.5		207	19
1/12/1996	11:15	120	43	180	5.3	150	480	0.6	11		236	20
3/14/1996	14:00	130	51	270	6.1	84	830	0.7	8.7		167	28
5/7/1996	9:40	82	31	130	3.8	78	390	0.4	7.9		166	17
5/29/1996	12:40	88	38	180	5.4	33	640	0.5	8.5		126	23
7/10/1996	9:30	200	91	610	19	490	1400	1.2	10		239	51
8/2/1996	11:50	220	96	590	19	440	1500	1.1	8.7		206	47
8/21/1996	11:15	160	90	760	17	460	910	0.8	5.2		284	68
9/10/1996	9:10	190	93	630	19	530	1400	1.3	3.5		209	53
9/25/1996	9:05	150	64	350	11	280	820	0.8	8.3		215	34
10/24/1996	11:50	130	51	190	6	140	620	0.6	7.8		207	20

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	acid nuetralizing	SAR
12/10/1996	9:30	98	36	130	4.3	110	520	0.6	10		196	16
1/22/1997	12:00	130	44	190	1.4	85	420	0.4	8.2		205	20
3/21/1997	12:00	130	48	220	6.2	100	730	0.7	9.1		205	23
5/12/1997	10:45	61.9	24.3	92.7	2.89	45.4	277	0.4	8.4		127	14
6/3/1997	10:05	69.1	30	188	6.3	79.9	477	0.5	8.54		154	27
6/13/1997	13:30	61.6	26.6	213	7.88	76.4	519	0.6	5		175	32
7/31/1997	11:00	146	40.6	203	8.27	44.7	772	0.8	8.4		165	21
9/2/1997	12:10	131	51.7	222	7.19	142	629	0.6	9.07		201	23
9/24/1997	9:10	89.8	32	223	6.31	65.5	672	0.8	6.9		135	29
10/23/1997	9:30	133	48.7	212	6.97	156	646	0.7	8.1		191	22
11/24/1997	11:40	129	50.6	180	5.75	133	534	0.5	9.89		229	19
1/23/1998	10:10	130	46.1	163	5.07	111	475	0.5	10.7		219	17
3/20/1998	10:55	161	57	268	6.48	73.4	889	0.5	8.29		188	26
5/8/1998	10:50	51.5	17.2	57.2	3.13	26	185	0.3	7.29		118	10
8/25/1998	10:30	192	66.7	298	9.07	122	1110	0.8	9.22	212		26
11/12/1998	11:50	158	81.1	350	6	89.8	1130	0.5	10		222	32
2/24/1999	12:15	156	65.6	338	6.47	153	893	0.7	10.9		229	32
5/19/1999	11:25	77.9	39.3	145	3.28	41.1	464	0.4	9.7		169	19
7/28/1999	11:00	190	85.5	597	17	509	1230	1.1	17		239	51
11/4/1999	11:05	140	50.5	234	6.9	166	646	0.6	9.1		221	24
2/2/2000	10:50	159	58.8	265	7.69	183	672	0.7	13.6		269	25
5/10/2000	11:00	69.5	26.9	135	4.41	85.4	336	0.5	9.6		144	19
8/16/2000	14:00	134	77.2	925	27.1	961	1310	2.1	17.2	262		90
11/24/2000	13:55	119	44.1	196	5.95	156	439	0.6	12.1	250		22
3/7/2001	11:40	118	51.2	301	7.45	112	865	0.7	8.5	162		33
6/21/2001	10:00	180	87.7	713	19.1	530	1320	1.3	14.4	267		62
8/20/2001	11:30	151	83.8	894	4.61	734	1260	1.9	16.6	214		83
10/23/2001	12:40	131	52.4	337	9.69	303	644	0.8	8.83	205		35
11/20/2001	8:20	134	49.5	254	7.76	212	590	0.7	13.4	225		27
12/17/2001	9:05	150	51.8	214	8.27	179	608	0.8	12.9	236		21
1/14/2002	12:00	129	43.8	190	6.44	166	532	0.8	11.5	229		20

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	acid nuetralizing	SAR
2/19/2002	12:15	120	42.9	284	6.93	280	506	0.7	11.5	234		31
3/18/2002	9:20	152	53.4	264	6.53	179	764	0.8	10.2	214		26
4/11/2002	12:30	126	48.4	243	6.77	162	663	0.6	8.64	208		26
5/9/2002	13:15	92.8	36.6	187	5.34	125	490	0.53	7.75	167		23
6/12/2002	13:05	194	91.2	800	18.3	610	1440	0.82	11.5	279		67
7/8/2002	10:20	136	53.3	329	12.8	273	721	0.83	9.18	228		34
8/15/2002	11:15	118	66	996	24.2	960	1160	1.91	16.7	252		104
9/12/2002	12:05	164	52.3	256	7.44	188	726	0.64	10.3	160		25

USGS 06313605 POWDER RIVER BELOW BURGER DRAW, NEAR BUFFALO, WY
Johnson County, Wyoming
Hydrologic Unit Code 10090202
Latitude 44°08'50", Longitude 106°08'34" NAD27
Gage datum 3,990 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
11/16/2000	8:45	168	68.9	325	9.79	208	797	0.6	10.5	169	30
1/10/2001	8:55	131	48	219	6.93	168	528	0.7	10.9	254	23
5/8/2001	11:40	94.5	39.9	197	6.09	119	493	0.6	7.97	178	24
6/6/2001	15:15	168	73.6	447	12.2	216	1170	0.8	7.78	222	41
7/12/2001	16:30	162	59.9	382	12.4	65.2	1210	0.7	8.34	103	36
8/14/2001	9:30	199	108	795	22.9	475	1670	0.8	7.64	399	64
10/10/2001	15:45	154	71	474	13.4	366	912	0.9	7.52	219	45
11/21/2001	11:10	128	51.3	246	7.56	189	619	0.6	7.66	205	26
12/12/2001	14:50	156	61.3	273	7.78	205	712	0.7	11.3	256	26
1/8/2002	14:00	135	48.6	188	6.36	138	526	0.6	10.7	270	20
2/12/2002	17:20	104	38.2	267	6.52	256	421	0.7	10.3	259	32
3/12/2002	15:30	115	40.9	236	6.78	166	528	0.6	8.89	239	27
4/9/2002	16:30	143	54.2	310	9.16	180	794	0.8	9.58	226	31
5/7/2002	16:55	111	45.4	295	7.96	125	756	0.69	8.13	220	33
6/11/2002	12:25	164	87	687	18.4	443	1300	0.2	9.03	320	61
7/9/2002	16:10	97.2	66.3	1040	23.9	926	1240	1.73	6.31	393	115
8/13/2002	17:45	126	56.6	759	23.7	431	1300	1.3	9.68	361	79
9/10/2002	19:30	164	53	287	9.39	180	863	0.68	9.89	173	28

USGS 06313700 DEAD HORSE CREEK NEAR BUFFALO, WY
Johnson County, Wyoming
Hydrologic Unit Code 10090202
Latitude 44°12'54", Longitude 106°06'41" NAD27
Drainage area 151.00 square miles
Gage datum 3,970.00 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
6/6/2001	16:50	405	88.6	83.2	12.7	4.08	1420	0.5	7.93	83	5
7/12/2001	14:50	159	25.5	45.8	10.4	4.39	563	0.4	6.68	75	5
3/12/2002	16:55	196	117	414	10.7	19.4	1500	0.5	5.81	361	33
4/9/2002	17:40	338	213	554	13.5	20.1	2180	0.3	1.43	334	33
7/9/2002	14:50	414	80.2	71.6	15.8	8.19	1370	0.52	5.18	80	5

USGS 06316400 CRAZY WOMAN CREEK AT UPPER STA, NEAR ARVADA, WY
Johnson County, Wyoming
Hydrologic Unit Code 10090205
Latitude 44°29'28", Longitude 106°10'38" NAD27
Drainage area 937 square miles
Contributing drainage area 937 square miles
Gage datum 3,750 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
3/28/2001	14:30	127	66	102	3.16	6.83	627	0.2	6.36	187	10
5/9/2001	13:20	144	88.9	139	5.76	8.55	772	0.3	4.67	222	13
6/7/2001	15:00	223	153	241	7.27	15.7	1460	0.3	3.85	228	18
7/12/2001	18:55	78.5	23.8	17.9	6.98	1.69	265	0.3	4.92	72	3
8/14/2001	11:45	262	120	267	10.5	11.8	1480	0.4	5.35	249	19
9/11/2001	14:30	280	128	326	10.2	12.5	1630	0.3	5.84	263	23
10/11/2001	12:30	268	115	279	7.05	11.6	1450	0.4	6.07	294	20
11/21/2001	8:25	243	150	232	7.28	14.7	1510	0.3	3.46	278	17
12/12/2001	12:50	194	114	156	4.73	10.5	966	0.4	8.72	288	13
1/9/2002	11:20	185	101	148	4.21	11.5	916	0.4	8.4	311	12
2/13/2002	15:20	128	64.6	88.8	3.27	6.17	588	0.3	8.51	245	9
3/18/2002	14:40	113	59.6	81	2.86	6.01	530	0.2	6.36	190	9
4/10/2002	11:20	93	51.5	81.1	2.63	5.01	482	0.2	2.99	127	10
5/8/2002	11:45	162	90.2	148	4.84	7.85	912	0.28	0.79	213	13
6/11/2002	14:15	219	151	226	7.31	14.9	1380	0.46	2.79	234	17
7/9/2002	12:55	280	151	291	9.48	15.7	1650	0.44	6.17	286	20
8/13/2002	15:20	226	112	179	13.1	12.5	1300	0.47	1.59	210	14

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
9/11/2002	10:55	183	75.8	123	10.2	7.87	842	0.37	3.37	200	11

USGS 06317000 POWDER RIVER AT ARVADA, WY
Sheridan County, Wyoming
Hydrologic Unit Code 10090202
Latitude 44°39'00", Longitude 106°07'37" NAD27
Drainage area 6,050.00 square miles
Gage datum 3,620 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	SAR	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	acid neutralizing	SAR
		mg/L	mg/L	mg/L	number	% equivalents	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	meq/L	
3/16/1995	17:30	160	54	260			6.8	100	870	0.5	7.6		169	25
6/20/1995	14:45	72	28	100	3	43	3.6	22	360	0.3	9.7		111	14
8/30/1995	16:30	280	110	370			2.3	180	1500	0.5	7.2		191	26
12/14/1995	16:10	190	87	300			6.4	150	1100	0.5	9		273	25
3/20/1996	13:05	140	60	240			6.5	91	820	0.5	7.8		189	24
6/10/1996	16:30	70	29	100			4.4	36	310	0.4	9.9		123	14
8/27/1996	9:40	250	140	430			59	190	1700	0.3	1.4		173	31
11/21/1996	17:15	180	80	280			6.8	130	960	0.5	9.7		242	25
1/27/1997	15:15	140	50	190			5.5	110	670	0.5	11		235	19
5/6/1997	15:45	154	67.3	364			7.47	77.7	1170	0.7	8.3		169	35
7/24/1997	9:45	121	39.4	199			7.35	60	695	0.5	9.6		141	22
11/6/1997	8:30	137	53.9	217			5.56	88.5	737	0.5	7.3		226	22
2/4/1998	9:45	133	54	178			5.54	112	600	0.5	10.5		230	18
5/5/1998	17:20	50.1	21.8	66.2			3.59	21.5	236	0.4	7.9	108		11
8/27/1998	10:45	170	70.4	316			8.71	94.7	1000	0.7	8.6		190	29
10/7/1998	15:05	140	59	191			5.91	97.9	623	0.5	7.1		222	19

Date	Time	Calcium	Magnesium	Sodium	SAR	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	acid neutralizing	SAR
1/28/1999	9:25	151	59	233			5.42	123	750	0.6	11.7		247	23
5/20/1999	10:25	74.5	36.9	136			3.88	32.1	483	0.4	10.4		140	18
7/21/1999	11:00	147	68.7	256			6.51	128	779	0.4	10.4		205	25
10/15/1999	8:40	118	59.2	215			6.33	123	661	0.5	6.5		217	23
1/5/2000	15:45	133	57.3	226			5.78	141	617	0.5	12		219	23
5/16/2000	17:50	112	46.8	302			5.67	103	841	0.5	9.3	158		34
8/1/2000	17:30	202	112	483			13.2	292	1490	0.4	4.3		186	39
10/24/2000	13:00	124	63.2	272			7.99	182	762	0.6	4.29	206		28
11/16/2000	11:20	174	81.4	343			8.99	183	973	0.6	8.88	317		30
12/13/2000	14:30	141	56.3	227			6.6	155	592	0.6	10.5	281		23
1/11/2001	14:05	130	49.9	211			6.18	165	557	0.6	10.1	265		22
2/14/2001	16:15	143	57.1	240			6.46	149	586	0.6	11.2	267		24
3/13/2001	18:00	105	43.1	225			5.3	87.6	666	0.5	5.72	143		26
4/11/2001	16:45	164	75.5	418			9.56	145	1230	0.7	10.7	222		38
5/9/2001	11:10	87.4	41.7	175			6.09	103	489	0.6	7.18	172		22
6/7/2001	12:40	146	66.3	293			9.72	100	1030	0.7	6.54	147		28
7/12/2001	10:20	160	54.3	249			10.6	106	860	0.6	7.23	115		24
10/18/2001	9:00	159	71.3	446			13.1	337	968	0.8	5.9	215		42
11/20/2001	14:45	127	56.6	267			7.96	195	689	0.7	6.4	214		28
12/12/2001	11:20	179	81.4	297			9.24	194	896	0.7	9.76	287		26
1/9/2002	13:30	149	59.1	237			7.19	163	654	0.6	11	307		23
2/13/2002	13:50	123	47.3	280			7.06	247	534	0.6	10.2	280		30
3/13/2002	15:15	127	49.7	243			7.04	174	581	0.6	9.12	247		26
4/10/2002	9:30	138	55.1	282			9.21	157	820	0.7	7.71	215		29
5/8/2002	10:00	114	47	264			7.3	152	734	0.65	7.14	197		29
6/11/2002	16:20	169	98.8	547			13.8	345	1330	0.8	6.47	258		47
7/9/2002	10:30	224	133	752			21.9	488	2010	0.65	3.14	211		56
8/14/2002	8:45	307	106	488			18.2	227	1770	0.6	6.82	215		34
9/11/2002	9:15	184	51.9	270			9.65	146	956	0.73	8.11	155		25

USGS 06317020 WILD HORSE CREEK NEAR ARVADA, WY
Sheridan County, Wyoming
Hydrologic Unit Code 10090202
Latitude 44°37'57", Longitude 106°01'53" NAD27
Drainage area 250 square miles
Gage datum 3,730 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
3/13/2001	15:30	45.3	43.5	241	6.23	7.76	483	0.4	4.72	333	36
5/9/2001	10:15	165	189	808	15.5	22.1	2100	0.6	0.81	796	61
4/10/2002	8:15	29.5	21.7	199	4.46	5.29	268	0.4	3.11	350	39
5/8/2002	8:20	146	125	561	10.2	19.5	1570	0.44	3.77	581	48

NORTHEAST WYOMING RIVER BASINS

Converse County, Wyoming
HU Code 10120101
Lat: 43-29-07
Long: 105-13-29
NAD27
Drainage area: 959 sq. miles

USGS 06364700 ANTELOPE CREEK NEAR TECKLA, WYOMING

Date	Instan-taneous dis-charge, cfs	Specif. conduc-tance, wat unf uS/cm 25 degC	Dis-solved oxygen, mg/L	pH, water, unfltrd lab, std units	Calcium water, fltrd, mg/L	Magnes-ium, water, fltrd, mg/L	Sodium, water, fltrd, mg/L	Potas-sium, water, fltrd, mg/L	Chlor-ide, water, fltrd, mg/L	Sulfate water, fltrd, mg/L	Fluor-ide, water, fltrd, mg/L	Silica, water, fltrd, mg/L	Barium, water, unfltrd recover-able, ug/L	Iron, water, fltrd, ug/L	Mangan-ese, water, fltrd, ug/L	Turbidity sever-ity, code	Alka-linity, wat flt fxd end lab, mg/L as CaCO3	Specif. conduc-tance, wat unf lab, uS/cm 25 degC
11/13/00	0.15	3010		7.6	311	124	259	18.6	21.9	1410	0.6	22	32.3	547	2400		458	3050
3/15/01	0.28	2890	8.2	7.8	303	118	241	15.2	22.8	1360	0.6	18.1	26.6	E 15	2190	1	403	2830
5/7/01	0.41	2860	8	7.7	306	119	253	17.4	23.8	1440	0.6	18.4	29.7	< 30	1730	0	396	3010
6/5/01	0.21	2950	6.5	7.7	293	118	257	20.1	23.4	1380	0.7	19.9	27.6	< 30	1460	1	397	2900
7/10/01	84	885	5.5	7.4	78.7	24.7	61.7	10.4	6.53	340	0.3	9.18	141	20	20.1	3	83	870
8/13/01	0																	
9/10/01	0																	
10/9/01	0																	
11/13/01	0.14	2990	6.8	7.7	303	125	261	17.9	21.2	1460	0.6	20	28	74	1150		468	3030
12/5/01	0.2	3010	6.6	7.6	315	124	256	17	22	1440	0.7	20.1	29.1	74	1850		430	3000
1/7/02	0.16	2820	3.8	7.4	299	118	218	17.1	17.4	1300	0.7	20.4	31.3	531	3220		442	2840
2/11/02	0.15	2720	3.9	7.6	280	111	224	16.9	18.4	1290	0.6	18.1	27.7	297	2710		422	2780
3/11/02	0.11	2930		7.6	321	119	256	15.8	23.4	1430	0.6	19	27.1	E 8	2880		426	2980
4/8/02	0.17	3050	9	7.8	292	114	254	16.1	25.6	1460	0.6	17	27.5	12	2050		414	3020
5/6/02	0.3	3110	5.7	7.8	328	127	277	17.1	28.5	1510	0.55	19.3	28.5	< 30	1260		412	3070
6/10/02	0.16	3020	8.1	7.8	305	124	272	18.6	22.5	1460	0.77	20.9	27.7	< 30	545		396	2950
7/10/02	0																	
8/12/02	0																	
9/2/02	0																	

USGS 06376300 BLACK THUNDER CREEK NEAR HAMPSHIRE, WY
Weston County, Wyoming
Hydrologic Unit Code 10120103
Latitude 43°34'54", Longitude 104°43'11" NAD27
Drainage area 535.00 square miles
Gage datum 4,080.00 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
11/13/2000	14:15	63.8	56	272	13.9	25.6	527	1.2	2.87	453	35
1/8/2001	11:45	98.6	63.8	309	15.2	26.1	555	1.6	6.17	615	34
5/7/2001	13:30	96.6	72.3	263	13.9	23.1	753	1	0.87	352	29
6/5/2001	13:55	73.2	62.8	278	12.8	24.5	760	0.9	1.42	274	34
7/10/2001	15:00	24.9	11.3	24.2	8.23	3.11	88	0.4	5.77	76	6
12/5/2001	10:00	107	83.9	328	18.8	29.2	935	1.2	3.43	440	34
3/11/2002	15:20	183	143	665	21.5	60.9	1960	1.1	5.14	553	52
4/8/2002	13:30	56	34.4	139	9.28	10.5	372	0.6	3.04	208	21
5/6/2002	13:30	113	77	329	14.1	29.7	1040	0.74	1.23	327	34
6/10/2002	12:45	175	162	744	21.1	56.3	2350	0.86	E .28	296	57
8/12/2002	12:20	39.4	14.8	65.6	9.08	4.82	179	0.4	6.38	121	13
9/9/2002	12:30	32	13.2	37.5	8.84	3.84	129	0.37	5.68	88	8

USGS 06386400 CHEYENNE RIVER AT RIVERVIEW, WY
Niobrara County, Wyoming
Hydrologic Unit Code 10120106
Latitude 43°25'41", Longitude 104°11'45" NAD27
Gage datum 3,600 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
10/9/2001	15:20	260	118	662	11.5	63.6	2230	0.5	7.72	240	48
11/13/2001	13:55	281	119	639	10.8	62.6	2280	0.6	9.53	325	45
12/5/2001	11:40	306	127	656	10.2	67.8	2390	0.7	11.4	335	45
1/7/2002	13:25	418	191	1170	11.4	127	3840	0.6	14.4	484	67
2/11/2002	15:15	304	129	664	12	61	2390	0.6	10.6	319	45
3/11/2002	17:15	259	99.8	512	8.07	53	1890	0.5	8.46	270	38
4/8/2002	15:05	135	59.1	427	9.33	54.3	1220	0.6	6.96	293	43
5/6/2002	14:50	167	80.9	629	11.2	82.2	1750	0.77	5.37	329	56
6/10/2002	14:05	258	124	793	14.4	83.1	2460	0.7	7.19	271	57
7/10/2002	12:25	360	211	1390	17.6	149	4550	0.62	5.88	193	82
8/12/2002	13:55	180	124	1200	16.5	137	2980	1.07	1.5	296	97
9/9/2002	14:25	155	57.6	310	8.95	31.8	1100	0.53	8.51	189	30

USGS 06425720 BELLE FOURCHE R BL RATTLESNAKE C NR PINEY WY
Campbell County, Wyoming
Hydrologic Unit Code 10120201
Latitude 43°59'04", Longitude 105°23'16" NAD27
Drainage area 495.00 square miles

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
3/15/2001	10:00	111	74.2	173	9.21	10.3	677	0.6	3.48	269	18
5/7/2001	11:15	176	131	277	12.3	15.7	1210	0.7	2.98	373	22
6/5/2001	11:30	157	132	305	11.3	15.5	1230	0.9	1.06	333	25
7/10/2001	11:30	91.1	115	312	11.2	16.2	1070	0.8	1.65	244	31
8/13/2001	11:00	78.3	177	383	19.5	28.4	1410	1	1.23	377	34
9/10/2001	17:30	143	254	561	23.9	36.5	2230	1	0.69	365	40
10/9/2001	11:10	73.1	93.7	372	15.9	26.5	1030	1	0.73	425	41
2/11/2002	11:20	120	82.9	240	9.61	16	791	1	3.39	432	24
5/6/2002	11:30	167	119	267	12.1	17.1	1150	0.88	2.42	376	22
9/9/2002	10:20	134	134	505	19.3	31.9	1620	1.14	0.68	392	44

USGS 06425900 CABALLO C AT MOUTH NR PINEY WY
Campbell County, Wyoming
Hydrologic Unit Code 10120201
Latitude 44°04'48", Longitude 105°15'59" NAD27

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
12/12/2000	10:05	103	72.2	342	14.1	21.8	783	1	6.72	526	37
1/10/2001	11:25	69.9	49.1	248	11	18	510	1.1	6.2	458	32
2/15/2001	13:50	64.3	41.4	210	9.2	13.3	379	1	5.6	417	29
3/15/2001	8:15	86.7	65	159	9.96	16.8	616	0.5	4.34	205	18
4/12/2001	14:45	125	89.8	244	13.2	37.2	839	0.8	2.08	326	24
5/9/2001	7:30	64.2	56.8	259	10.1	18.5	596	1	1.21	389	33
6/6/2001	12:35	69.1	59.7	264	10.5	20	601	1	2.05	387	33
7/11/2001	8:50	47.7	46.8	250	10.7	14.1	460	0.9	6.16	375	36
8/14/2001	7:20	33.4	36.6	265	11.9	17.2	400	1.1	3.09	415	45
9/10/2001	19:00	35.5	35.1	240	11.1	16.1	339	1.1	1.55	422	40
10/10/2001	13:30	39.6	32.7	214	10.3	15.1	320	1	1.68	402	36
11/14/2001	12:05	53.9	39.2	218	10.1	14.6	399	1	1.25	411	32
12/6/2001	10:35	69.1	50.4	231	10.3	17.9	521	0.9	1.68	419	30
1/8/2002	11:25	78.2	52.6	297	15.2	21.3	520	1.2	6.25	550	37
2/12/2002	13:50	50.8	32.5	198	8.72	12.4	325	0.9	5.61	393	31
3/13/2002	9:30	51.1	33.7	165	7.42	11.1	336	0.7	3.66	306	25
4/9/2002	10:50	55.8	40.8	170	7.9	13.1	392	0.7	2.07	285	24
5/7/2002	10:30	68.7	55.5	232	10.7	19.3	570	0.83	2.3	383	29
6/11/2002	9:35	84.7	71.1	257	13	36.7	660	1.09	3.93	355	29
7/9/2002	18:10	31.2	25.9	122	12.1	23.7	298	0.65	3.48	136	23
9/10/2002	12:05	120	117	453	24.2	47.2	1440	1.09	0.48	355	42

USGS 06426400 DONKEY C NR MOORCROFT WY
Crook County, Wyoming
Hydrologic Unit Code 10120201
Latitude 44°16'58", Longitude 105°03'48" NAD27

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
11/15/2000	7:50	177	153	425	13.1	108	1380	1	5.12	491	33
1/9/2001	15:10	162	138	326	16.6	204	1020	1.2	13.5	371	27
5/8/2001	9:30	98.3	140	378	13.8	158	1240	1.1	2.27	235	35
6/5/2001	18:15	145	123	185	16.7	78.3	940	0.8	14	216	16
7/10/2001	17:30	144	132	206	11.4	124	921	1.1	0.41	240	18
8/13/2001	19:30	93	141	635	15.3	133	1610	1.5	0.62	483	59
9/10/2001	15:20	86.4	105	400	15.2	200	917	1.4	< .27	335	41
10/10/2001	11:30	109	91.4	276	14.7	246	711	1.2	1.28	286	28
11/14/2001	10:25	122	109	306	13.3	220	815	1.4	0.39	324	28
12/6/2001	9:25	141	125	316	16.5	209	917	1.5	5.59	383	27
1/8/2002	9:50	140	104	337	17.2	233	767	1.4	12.9	462	31
2/12/2002	12:40	116	90	309	15	228	645	1.8	12.1	414	30
3/12/2002	13:05	165	125	301	14.8	270	934	1.1	10.6	318	25
4/9/2002	9:45	119	91.7	219	10.7	163	692	0.9	6.26	249	21
5/7/2002	9:30	141	167	286	13.2	115	1310	1.13	5.95	252	23
6/10/2002	20:10	177	155	271	15.2	129	1090	1.16	5.51	392	21
7/10/2002	7:20	106	105	281	14.1	187	752	1.15	1.4	310	27
8/13/2002	9:40	108	147	798	17.1	91.7	1940	1.48	5.48	626	71
9/10/2002	11:05	105	69.8	225	14.2	176	529	1.1	1.12	265	24

USGS 06426500 BELLE FOURCHE RIVER BELOW MOORCROFT, WY
Crook County, Wyoming
Hydrologic Unit Code 10120201
Latitude 44°19'19", Longitude 104°56'24" NAD27
Drainage area 1,690 square miles
Gage datum 4,119.20 feet above sea level NGVD29

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
10/25/2000	11:35	124	128	356	14.8	163	1150	1	< .27	267	32
11/15/2000	9:20	146	123	491	14.8	211	1280	0.9	2.56	400	42
12/12/2000	12:45	174	127	379	16.9	130	1160	1.1	8.54	456	31
1/9/2001	13:30	187	143	430	15	137	1330	1.1	11	497	33
2/15/2001	10:30	214	138	446	13.9	99.2	1500	1	10.4	437	34
3/27/2001	11:30	119	78.4	191	10.7	48	728	0.6	5.07	261	19
4/12/2001	12:15	115	87.2	214	10.8	43.9	782	0.7	3.32	274	21
5/8/2001	8:00	125	114	312	13.5	68.8	1070	0.9	2.3	319	29
6/5/2001	16:30	134	117	234	13.2	71.9	961	0.8	8.01	260	21
7/10/2001	16:15	38.4	25.2	82	8.23	20.1	256	0.4	3.33	95	15
8/13/2001	18:00	57.1	71.6	389	20.6	76.4	814	1	0.74	369	48
9/10/2001	14:15	51	71.2	408	14.2	146	725	1.2	0.35	388	52
10/10/2001	10:00	49	54	348	12.8	114	565	1	0.18	404	48
11/14/2001	8:10	91.1	83.3	318	12.2	122	793	1	0.21	365	34
12/6/2001	7:50	126	106	341	14.7	112	978	1.2	1.92	419	32
1/8/2002	8:50	178	138	527	19.3	167	1250	1.5	6.81	714	42
2/12/2002	10:55	108	78.1	302	12.9	103	688	1.3	7.07	469	31
3/12/2002	11:10	107	79.1	265	12.5	93.8	694	1	6.03	382	27
4/9/2002	8:20	71.1	52.9	146	7.36	60.7	442	0.6	3.35	199	19
5/7/2002	8:00	80.9	98.3	246	12.3	79.3	877	0.78	1.86	199	26
6/10/2002	19:20	120	95.4	244	13.2	72.3	841	0.97	3.66	326	24
7/11/2002	7:40	87.5	107	442	15.1	103	1140	0.92	0.85	340	45
8/13/2002	8:00	40.8	18.9	50.2	10.2	14.8	160	0.45	5.02	125	9
9/10/2002	10:05	70.9	46.7	183	12.3	76.1	439	0.69	2.49	239	24

USGS 06428050 BELLE FOURCHE R BELOW HULETT WY
Crook County, Wyoming
Hydrologic Unit Code 10120201
Latitude 44°42'04", Longitude 104°35'07" NAD27

SAR = Sodium/Square Root((calcium+magnesium)/2)

Date	Time	Calcium	Magnesium	Sodium	Potassium	Chloride	Sulfate	Fluoride	Silica	alkalinity	SAR
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	
10/10/2001	7:50	303	77.8	80	8.87	20.7	1050	0.5	9.92	190	6
11/13/2001	16:40	270	71.3	87.6	7.32	15.4	942	0.4	10.1	204	7
12/5/2001	15:45	276	70.4	89.9	6.93	23.3	970	0.5	11.4	220	7
1/7/2002	16:35	343	84	89	8.56	23.5	1140	0.5	15	276	6
2/12/2002	8:10	293	68.3	76.7	6.61	17.5	925	0.6	13.2	244	6
3/12/2002	8:45	263	62.9	77	6.29	13.7	905	0.4	11.1	230	6
4/8/2002	17:45	191	50.4	62.2	5.98	10.1	666	0.3	5.96	143	6
5/6/2002	17:55	267	74.1	79.1	8.08	12	978	0.31	5.92	160	6
6/10/2002	16:55	89.5	53.5	172	10.9	39.2	596	0.7	1.88	203	20
7/10/2002	9:05	89.5	60.4	196	11.4	41.1	596	0.69	0.99	208	23
8/12/2002	17:25	88	55.7	188	13.5	42.8	627	0.69	1.74	207	22
9/10/2002	8:15	90.5	55.4	179	11.8	41.7	613	0.69	0.92	193	21

APPENDIX B

GROUNDWATER QUALITY IN THE WYOMING PRB
(Sources: BLM 2003b, 2004b; Larson 1984; Larson and Daddow 1984; Meyer 2004; Ogle 2001.)

TABLE B-1
GROUNDWATER QUALITY DATA
FORT UNION AQUIFER
PRB WYOMING

Location	Township	Range	Section	Date	County or Geologic Unit	Depth (feet)	pH (units)	TDS (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Cloride (mg/L)	Flouride (mg/L)	Boron (umg/L)	Iron (ug/L)	SAR
42N 069W 07BAC	47	69	7	1968	CAMPBELL	120	8	613	32	17	161	8	396	186	4	0	5	550	6
43N 69W 19AB	43	69	19	1968	CAMPBELL	170	9	1,490	61	30	385	9	333	828	4	1	10	490	10
43N 72W 36BCC	43	72	36	1978	CAMPBELL	693	8	2,570	310	180	180	10	320	1,600	4	0	--	120,000	2
45N 71W 05BAD	45	71	5	1977	CAMPBELL	400	7	792	30	12	240	10	790	62	41	1	160	700	9
47N 72W 18CA	47	72	18	1975	CAMPBELL	--	7	1,430	180	52	210	8	340	790	7	0	50	630	4
47N 72W 18DA	47	72	18	1975	CAMPBELL	--	8	697	35	11	210	10	515	160	8	0	60	40	8
48N 69W 11DC	48	69	11	1976	CAMPBELL	420	8	1,210	8	3	400	3	542	510	8	1	120	50	31
48N 69W 22AC	48	69	22	1976	CAMPBELL	400	8	1,260	8	3	410	3	408	610	13	1	90	110	31
48N 69W 35ABD	48	69	35	1968	CAMPBELL	170	9	1,190	15	5	410	4	590	440	7	1	80	70	23
48N 70W 17BC	48	70	17	1968	CAMPBELL	300	7	1,950	367	81	78	7	32	1,360	9	0	50	670	1
49N 75W 29CAC	49	75	29	1958	CAMPBELL	2,111	8	1,290	15	9	510	--	1,231	118	34	--	--	--	26
49N 75W 32DCC	49	75	32	1958	CAMPBELL	2,832	8	1,010	19	5	380	--	781	150	70	--	--	--	20
50N 71W 21BBB	50	71	21	1974	CAMPBELL	220	8	2,790	330	150	380	40	753	1,500	11	1	80	20	4
50N 71W 27ABA	50	71	27	1975	CAMPBELL	--	8	333	6	1	130	5	354	3	5	1	50		13
50N 71W 27BCB	50	71	27	1949	CAMPBELL	540	8	270	8	4	91	3	283	3	7	1	190	50	7
50N 71W 33BAC	50	71	33	1974	CAMPBELL	152	8	3,070	290	160	500	23	895	1,600	44	1	120	430	6
51N 69W 20BD	50	69	20	1968	CAMPBELL	206	9	1,340	28	4	450	5	620	530	1	3	100	90	21
51N 71W 23CD	50	71	23	1968	CAMPBELL	219	8	1,440	119	65	261	16	519	703	8	1	250	80	5
51N 71W 32CDC	50	71	32	1968	CAMPBELL	311	8	1,020	57	29	320	11	1,150	1	10	1	70	600	9
51N 76W 9BB	51	76	9	1968	CAMPBELL	1,800	8	1,160	24	3	455	17	1,231	0	21	101	100	60	23
52N 70W 02AB	52	70	2	1968	CAMPBELL	750	9	781	7	1	300	2	629	144	6	2	150	70	28
52N 70W 11CA	52	70	11	1968	CAMPBELL	635	9	825	5	5	325	2	702	123	10	2	180	270	25
52N 70W 25DB	52	70	25	1968	CAMPBELL	505	9	948	5	2	360	2	594	266	7	3	70	160	34
53N 70W 26CC	53	70	26	1968	CAMPBELL	720	9	790	5	3	309	2	655	130	7	3	160	120	27
53N 71W 12DD	53	71	12	1968	CAMPBELL	780	9	820	3	1	320	2	729	117	6	2	140	110	41
53N 73W 24AC	53	73	24	1968	CAMPBELL	173	8	2,740	379	102	431	17	1,350	1,120	9	1	30	580	5
53N 74W 35AB	53	74	35	1976	CAMPBELL	210	7	3,220	300	130	480	10	259	2,100	6	0	120	190	6
53N 76W 26AAA	53	76	26	1968	CAMPBELL	1,043	9	1,160	22	10	440	14	1,304	0	13	1	110	1,400	20
54N 70W 9DCC	54	70	9	1968	CAMPBELL	900	8	740	3	0	285	1	580	148	4	3	130	60	45
54N 71W 01CD	54	71	1	1968	CAMPBELL	270	9	924	10	1	335	2	569	281	6	1	30	210	27
55N 69W 35BB	55	69	35	1968	CAMPBELL	320	8	1,650	145	82	280	9	652	781	14	1	120	1,000	5
55N 70W 14ADC	55	70	14	1968	CAMPBELL	930	9	701	3	0	268	1	524	151	6	2	280	100	43
55N 72W 25CA	55	72	25	1975	CAMPBELL	spring	8	209	36	12	14	9	177	24	3	1	160	50	1
55N 73W 26	55	73	26	1977	CAMPBELL	465	7	1,120	49	34	360	12	1,290	8	6	1	90	20	10
55N 75W 9BC	55	75	9	1968	CAMPBELL	1,095	9	1,220	12	7	490	8	1,377	1	16	2	120	460	28
56N 70W 34BDA	56	70	34	1968	CAMPBELL	580	9	792	3	1	300	2	539	206	6	1	190	60	38
56N 72W 31DDA	56	72	31	1976	CAMPBELL	683	7	891	33	19	260	10	542	290	8	1	--	60	9

TABLE B-1
GROUNDWATER QUALITY DATA
FORT UNION AQUIFER
PRB WYOMING

Location	Township	Range	Section	Date	County or Geologic Unit	Depth (feet)	pH (units)	TDS (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Cloride (mg/L)	Flouride (mg/L)	Boron (umg/L)	Iron (ug/L)	SAR
56N 73W 25BBA	56	73	25	1977	CAMPBELL	442	8	1,940	73	83	480	15	580	990	6	0	100	60	9
56N 74W 4CB	56	74	4	1976	CAMPBELL	3,850	8	1,330	1	0	450	2	1,609	24	41	7	380	40	124
56N 76W 25CB	56	76	25	1976	CAMPBELL	850	8	2,060	26	18	800	12	2,330	24	21	1	160	160	29
57N 70W 19DD	57	70	19	1976	CAMPBELL	606	9	657	2	0	220	1	380	230	7	1	110	110	43
57N 71W 14BD	57	71	14	1968	CAMPBELL	615	9	661	2	1	254	1	521	129	5	2	130	150	37
57N 74W 8BA	57	74	8	1976	CAMPBELL	212	7	1,210	16	9	470	6	1,370	11	9	1	120	230	23
58N 71W 26DA	58	71	26	1968	CAMPBELL	350	8	668	3	0	252	1	433	183	4	2	160	90	40
58N 73W 24DC	58	73	24	1968	CAMPBELL	12	8	2,380	268	68	370	52	585	1,310	5	1	5,400	50	5
39N 72W 6BD	39	72	6	1968	CONVERSE	1,104	8	287	9	1	94	1	176	81	3	0	50	30	8
39N 73W 23DCD	39	73	23	1980	CONVERSE	1,092	8	351	47	6	60	5	207	110	4	0	--	490	2
40N 68W 23DD	40	68	23	1969	CONVERSE	433	8	377	3	2	152	2	400	4	7	1	20	--	17
41N 68W 28DB	41	68	28	1974	CONVERSE	99	8	1,840	180	87	290	16	288	1,110	4	0	70	790	4
51N 77W 20CC	51	77	20	1961	JOHNSON	758	8	1,000	7	3	410	5	--	0	13	3	14	180	33
52N 77W 3AB	52	77	3	1960	JOHNSON	828	8	1,220	14	3	500	5	--	1	23	1	70	450	32
53N 77W 10CDC	53	77	10	1960	SHERIDAN	424	8	1,540	22	8	620	7	--	1	24	1	110	470	29
54N 76W 5AC	54	76	5	1961	SHERIDAN	710	8	1,290	19	3	524	6	--	0	16	1	70	720	29
54N 77W 5DB	54	77	5	1961	SHERIDAN	1,185	8	981	6	2	400	5	--	0	17	1	150	80	36
55N 77W 11BA	55	77	11	1978	SHERIDAN	800	8	1,390	8	5	760	12	976	23	72	4	210	70	52
55N 77W 28DD	55	77	28	1962	SHERIDAN	500	8	915	12	3	374	5	--	1	16	2	--	200	25
56N 78W 22AC	56	78	22	1961	SHERIDAN	165	8	981	7	3	400	4	--	2	7	2	150	140	32
56N 85W 31BD	56	85	31	1976	SHERIDAN	116	8	547	31	14	140	4	390	150	7	1	140	20	5
57N 76W 20BD	57	76	20	1960	SHERIDAN	265	8	1,340	12	2	555	4	--	2	21	1	120	880	39
57N 83W 3AB	57	83	3	1962	SHERIDAN	120	8	1,160	8	3	490	5	--	0	8	2	--	190	37
57N 84W 19BD	57	84	19	1962	SHERIDAN	126	8	1,900	31	29	810	17	--	55	23	201	--	100	25
57N 85W 19AA	57	85	19	1962	SHERIDAN	180	8	888	14	5	360	4	--	0	57	2	--	140	21
58N 84W 29CDD	58	84	29	1962	SHERIDAN	1,260	8	742	3	3	335	2	--	0	13	4	--	580	33
433652 105075501	42	69	15	1999	S1-TR clinker	spmg	8	187	35	10	8	7	141	28	3	1	--	--	0
442232 105264101	51	71	30	1999	S2-TR clinker	spmg	8	1,200	210	65	46	25	195	720	12	1	--	--	1
433408 105270101	42	72	36	1999	C1-Wyodak	--	7	395	17	9	130	6	439	0	7	2	--	--	6
435411 105294001	45	72	3	1999	C4-Wyodak	--	7	571	23	15	190	9	615	0	24	2	--	--	8
440808 106070601	48	77	16	1999	C11-BigGeor	--	7	2,720	51	39	1,000	48	3,134	0	21	1	--	--	26
4410471 105535401	49	75	32	1999	C15-Wyodak	--	7	624	25	14	190	13	707	1	7	1	--	--	8
443241 105360802	53	73	26	1999	C17-Canyon	--	8	1,040	62	33	330	12	962	1	11	1	--	--	8
43.88 105.73	45	74	10	1999	Canyon	1,400	7	900	52	16	300	7	1,000	12	9	1	--	--	9
43.887 105.73128	45	74	10	1999	Anderson	1,200	7	970	38	18	340	6	1,020	5	48	1	--	--	11
44.0887 105.60644	48	73	35	1999	Wyodak	1,000	7	660	34	18	210	12	760	0	9	1	--	--	7
44.08138 105.61156	47	73	3	1999	Wyodak	950	7	710	37	24	220	12	800	2	14	1	--	--	7

TABLE B-1
GROUNDWATER QUALITY DATA
FORT UNION AQUIFER
PRB WYOMING

Location	Township	Range	Section	Date	County or Geologic Unit	Depth (feet)	pH (units)	TDS (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Cloride (mg/L)	Flouride (mg/L)	Boron (umg/L)	Iron (ug/L)	SAR
44..482 105.47708	47	72	14	1999	Wyodak	600	7	530	26	12	170	7	600	0	12	1	--	--	7
43.7796 105.45448	44	72	24	1999	Wyodak	800	7	400	20	8	130	6	460	0	10	1	--	--	6
44.09563 106.0562	48	77	36	1999	Big George	1,300	8	2,010	9	28	780	18	2,320	0	16	--	--	--	29
44.3671 105.75997	51	74	28	1999	Anderson	750	8	540	14	5	220	4	580	1	12	1	--	--	13
44.21950 105.48659	49	72	14	1999	Anderson	500	7	780	44	21	240	9	890	9	9	1	--	--	7
44.3682 105.55089	51	72	30	1999	Wyodak	400	7	990	57	36	300	13	1,130	1	9	1	--	--	8
44.7492 105.597	55	73	14	1999	Pawnee	500	8	800	30	14	290	8	880	3	10	1	--	--	11
44.6267 105.7655	54	74	28	1999	Wall	1,220	7	1,060	50	22	350	14	1,220	1	12	1	--	--	10
43.892 105.467	45	72	11	2000	Anderson	550	7	410	17	9	140	6	450	0	12	1	--	--	7
44.24217 105.44584	49	71	7	2000	Anderson	300	7	850	45	21	270	9	980	2	10	1	--	--	8
44.62621 106.02277	54	76	29	2000	Anderson	640	8	1,240	19	9	500	7	1,380	0	11	1	--	--	24
44.803 105.894	56	75	28	2000	Wall	--	8	1,550	15	9	630	8	1,740	0	18	1	--	--	32
44.7936 105.82395	56	75	36	2000	Anderson	370	8	1,390	35	19	530	8	1,570	2	6	0	--	--	18

TABLE B-2
GROUNDWATER
QUALITY DATA
WASATCH AQUIFER
PRB WYOMING

Location	Township	Range	Section	Date	County	Depth (feet)	pH (units)	TDS (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Cloride (mg/L)	Flouride (mg/L)	Boron (µmg/L)	Iron (µg/L)	SAR
42N 70W 32AA	42	70	32	1968	CAMPBELL	280	8	929	66	30	241	7	745	185	23	1	30	700	6
42N 71W 26BBC	42	71	26	1968	CAMPBELL	110	8	1,720	17,935	310	8	197	1,080	7	0	40	170	--	0
42N 74W 6AC	42	74	6	1968	CAMPBELL	225		941	146	33	112	7	210	515	16	0	20	80	2
42N 70W 11DA	43	70	11	1968	CAMPBELL	45	8	1,440	244	66	83	18	227	885	3	1	--	30	1
43N 71W 21ADB	43	71	21	1978	CAMPBELL	100	8	1,320	96	23	310	8	240	750	9	0	--	150	7
43N 72W 16CC	43	72	16	1968	CAMPBELL	345	9	1,790	340	100	68	9	318	1,100	2	0	100	890	1
44N 70W 28CBC	44	70	28	1968	CAMPBELL	261	9	785	40	10	221	5	366	306	13	1	10	440	8
44N 71W 10DD	44	71	10	1968	CAMPBELL	124	8	1,710	299	110	74	7	242	1,080	6	0	60	30	1
44N 72W 15BA	44	72	15	1966	CAMPBELL	145	7	2,660	448	157	122	13	340	1,730	7	1	310	1,030	1
44N 73W 35CC	44	73	35	1968	CAMPBELL	205	8	1,070	75	17	238	3	118	672	3	0	10	30	6
45N 71W 2AAA	45	71	2	1968	CAMPBELL	155	8	1,240	100	26	268	6	361	630	19	1	60	2,300	6
45N 72W 36BCC	45	72	36	1978	CAMPBELL	218	8	3,760	460	250	300	12	410	2,500	16	0	--	3,200	3
45N 74W 17CB	45	74	17	1968	CAMPBELL	259	8	1,520	136	19	309	5	82	1,000	5	0	20	60	7
45N 75W 34BB	45	75	34	1968	CAMPBELL	160	8	487	92	36	26	4	358	135	2	0	10	970	1
46N 72W 27AAC	46	72	27	1968	CAMPBELL	125	8	705	55	8	176	5	268	308	12	1	30	--	6
46N 73W 34CCD	46	73	34	1968	CAMPBELL	200	8	1,300	130	31	271	5	573	555	12	0	50	610	6
46N 74W 9CB	46	74	9	1968	CAMPBELL	281	8	726	34	8	195	2	120	410	9	0	10	40	8
46N 75W 9BD	46	75	9	1968	CAMPBELL	400	7	983	44	11	250	3	88	604	18	0	20	520	9
46N 76W 10DA	46	76	10	1968	CAMPBELL	90	8	1,890	198	123	231	4	274	1,160	15	0	120	20	3
47N 72W 7CBD	47	72	7	1976	CAMPBELL	156	8	649	35	8	200	5	475	98	11	--	70	10	8
47N 75W 13BCC	47	75	13	1968	CAMPBELL	355	8	1,310	225	74	96	5	350	720	3	0	30	40	1
47N 73W 8DDC	47	73	8	1968	CAMPBELL	311	8	766	33	6	205	3	98	457	5	0	20	80	9
47N 76W 26CD	47	76	26	1968	CAMPBELL	300	8	1,040	61	10	257	3	90	656	5	0	0	130	8
48N 71W 34CB	48	71	34	1968	CAMPBELL	114	7	1,450	151	51	307	12	984	412	10	1	90	4,860	6
48N 72W 13AA	48	72	13	1968	CAMPBELL	122	8	1,880	300	156	62	8	375	1,110	7	1	150	180	1
48N 73W 31AD	48	73	31	1968	CAMPBELL	305	8	1,520	151	31	285	6	180	948	2	0	30	20	6
48N 75W 14BD	48	75	14	1976	CAMPBELL	195	9	312	5	1	110	1	223	61	16	1	40	90	12
49N 75W 34CA	49	75	34	1976	CAMPBELL	515	9	646	9	2	190	2	180	330	16	0	40	90	15
49N 76W 27AAA	49	76	27	1968	CAMPBELL	1,000	8	726	9	2	300	3	779	7	10	2	110	460	24
50N 71W 20ADC	50	71	20	1949	CAMPBELL	6	7	1,490	195	112	58	67	304	856	8	1	630	10	1
50N 72W 20CAA	50	72	20	1949	CAMPBELL	160	8	430	85	32	9	6	249	149	4	1	0	270	0
50N 74W 31CB	50	74	31	1968	CAMPBELL	290	7	1,220	50	17	312	3	123	768	2	1	20	0	10
50N 75W 30BD	50	75	30	1968	CAMPBELL	400	8	395	7	2	138	2	217	121	9	1	20	20	12
51N 71W 22CDC	50	71	22	1949	CAMPBELL	spmg	8	286	53	11	14	11	164	79	3	1	230	10	0
51N 72W 22CB	51	72	22	1968	CAMPBELL	100	8	1,070	79	38	306	10	1,120	73	1	1	360	370	7
52N 73W 25DD	52	73	25	1968	CAMPBELL	210	7	273	58	13	10	2	146	100	1	1	10	1,400	0
52N 75W 17AD	52	75	17	1968	CAMPBELL	938	8	506	10	4	198	3	549	1	9	1	30	40	13
53N 74W 7BCC	53	74	7	1968	CAMPBELL	120	8	4,080	440	159	640	15	366	2,630	5	0	100	2,600	7

TABLE B-2
GROUNDWATER
QUALITY DATA
WASATCH AQUIFER
PRB WYOMING

Location	Township	Range	Section	Date	County	Depth (feet)	pH (units)	TDS (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Cloride (mg/L)	Flouride (mg/L)	Boron (µmg/L)	Iron (µg/L)	SAR
53N 75W 4AC	53	75	4	1968	CAMPBELL	130	8	3,180	153	145	660	12	236	2,070	7	0	60	20	9
53N 76W 22AB	53	76	22	1976	CAMPBELL	1,050	8	891	7	3	350	7	970	15	18	1	110	190	28
40N 73W 8CD	40	73	8	1969	CONVERSE	310	8	588	30	4	165	2	189	277	4	0	40	20	8
40N 74W 21AC	40	74	21	1969	CONVERSE	30	8	395	100	22	8	4	295	102	2	0	10	10	0
44N 76W 8CDC	44	76	8	1969	JOHNSON	760	8	420	8	1	141	15	--	201	2	0	80	30	12
44N 78W 24ACA	44	78	24	1969	JOHNSON	265	8	781	17	4	246	3	--	413	7	1	140	160	14
44N 79W 20DAC	44	79	20	1969	JOHNSON	103	8	720	53	19	182	5	--	232	4	0	120	1,400	5
45N 78W 14CDD	45	78	14	1969	JOHNSON	480	8	320	1	2	112	2	--	92	6	1	40	180	15
45N 80W 1DAC	45	80	1	1969	JOHNSON	141	8	1,690	60	16	459	2	--	1,040	18	1	110	500	14
46N 77W 31BA	46	77	31	1961	JOHNSON	203	8	359	4	0	121	1	--	149	10	1	100	150	17
46N 80W 20BB	46	80	20	1961	JOHNSON	370	7	2,150	118	35	510	5	--	1,360	22	0	60	70	11
49N 81W 33BB	49	81	33	1961	JOHNSON	255	7	1,010	117	44	141	5	--	593	12	0	90	720	3
49M 82W 2BB	49	82	2	1961	JOHNSON	318	8	486	75	40	36	5	--	139	4	0	100	1,600	1
50N 79W 19BC	50	79	19	1960	JOHNSON	600	8	1,210	156	45	181	3	--	569	19	0	90	420	3
50N 82W 11CB	50	82	11	1961	JOHNSON	460	7	1,350	183	48	175	4	--	780	7	0	210	2,700	3
51N 79W 16BA	51	79	16	1960	JOHNSON	164	8	668	27	11	202	3	--	183	10	1	90	190	8
51N 82W 26BB	51	82	26	1967	JOHNSON	60	8	814	119	25	159	2	--	97	4	0	20	--	3
52N 79W 12CC	52	79	12	1960	JOHNSON	160	8	581	5	2	235	2	--	1	12	1	120	200	22
52N 82W 13DB	52	82	13	1961	JOHNSON	246	7	4,620	321	313	660	25	--	3,020	19	0	530	13,000	6
53N 79W 7BC	53	79	7	1962	SHERIDAN	280	8	625	6	2	252	2	675	2	18	1	--	80	23
53N 80W 2DB	50	80	2	1962	SHERIDAN	260	7	3,410	317	282	342	10	--	1,990	9	1	--	410	3
53N 82W 11CD	53	82	11	1962	SHERIDAN	143	8	920	15	5	378	3	--	15	2	1	--	240	22
53N 83W 7DD	53	83	7	1961	SHERIDAN	42	8	141	34	11	2	1	--	1	0	0	10	10	0
54N 79W 21BDD	54	79	21	1960	SHERIDAN	121	8	860	20	5	317	2	--	145	3	1	110	260	16
54N 80W 24BC	54	80	24	1962	SHERIDAN	120	8	4,950	457	403	450	26	--	3,010	8	1	--	8,100	4
54N 81W 14BC	54	81	14	1961	SHERIDAN	110	8	1,090	46	3	379	4	--	157	3	0	70	10	15
54N 82W 29BA	54	82	29	1962	SHERIDAN	60	7	672	136	36	49	7	--	157	1	0	--	3,700	1
54N 83W 3BA	54	83	3	1961	SHERIDAN	245	8	2,090	108	34	567	10	--	1,020	6	0	--	1,200	12
54N 84W 11AB	54	84	11	1960	SHERIDAN	160	8	383	3	62	22	2	--	64	2	0	180	240	1
55N 79W 30BBA	55	79	30	1960	SHERIDAN	200	8	821	8	2	336	5	--	3	11	1	120	410	27
55N 82W 5DC	55	82	5	1962	SHERIDAN	155	8	897	13	3	405	3	--	1	11	1	--	90	26
56N 81W 29BD	56	81	29	1960	SHERIDAN	378	8	627	3	0	243	1	--	118	6	2	120	120	39
56N 82W 35AA	56	82	35	1962	SHERIDAN	87	7	6,620	470	519	800	13	--	4,080	45	1	--	25,000	6
57N 79W 25CC	57	79	25	1961	SHERIDAN	95	8	4,920	220	136	1,140	12	--	3,110	7	0	190	40	15
57N 80W 31BB	57	80	31	1961	SHERIDAN	160	8	2,880	106	10	816	6	--	1,690	8	0	110	120	20
57N 81W 7CB	57	81	7	1962	SHERIDAN	510	8	834	6	2	350	3	--	3	16	2	--	140	32
440253 105385702	47	73	16	1999	W1-wasatch	--	9	263	6	2	97	2	251	13	8	1	--	--	9
440542 105351802	48	73	36	1999	W-2 wasatch	--	8	562	12	7	180	7	461	100	17	1	--	--	10

TABLE B-2
GROUNDWATER
QUALITY DATA
WASATCH AQUIFER
PRB WYOMING

Location	Township	Range	Section	Date	County	Depth (feet)	pH (units)	TDS (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Cloride (mg/L)	Flouride (mg/L)	Boron (µmg/L)	Iron (µg/L)	SAR
440724 105291301	48	72	22	1999	W-3 wasatch	--	8	527	19	6	180	5	555	23	6	1	--	--	9
440724 105291302	48	72	22	1999	W-4 wasatch	--	8	3,490	450	93	480	12	157	2,400	5	0	--	--	5
441019 105414502	49	74	36	1999	W-6 wasatch	--	8	1,010	8	24	330	13	1,244	10	0	2	--	--	13
441451 105375502	49	73	3	1999	W-7 wasatch	--	9	1,660	7	94	280	18	882	740	14	1	--	--	6

TABLE B-3
GROUNDWATER QUALITY
ALLUVIAL AQUIFER
WYOMING PRB

Location	Township	Range	Section	Date	County	Depth (feet)	pH	TDS (mg/L)	Calcium (mg/l)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Flouride (mg/L)	Boron (µmg/L)	Iron (µg/L)	SAR
50N 71W 27AAC	50	71	27	1974	CAMPBELL	18	7.7	2,180	260	130	290	14	443	1,100	160	1	280	50	4
50N 71W 27BAD	50	71	27	1975	CAMPBELL	19	7.5	6,610	370	520	980	18	746	4,300	38	1	480	--	8
53N 73W 12AB	53	73	12	1968	CAMPBELL	108	7.8	566	19	9	205	6	604	7	11	1	40	990	10
54N 71W 1CD	54	71	1	1968	CAMPBELL	37	8.7	757	25	12	241	4	513	204	7	1	60	120	10
55N 72W 32CDD	55	72	32	1968	CAMPBELL	60	8.4	992	35	40	262	18	709	258	13	1	120	410	7
56N 71W 30DBB	56	71	30	1977	CAMPBELL	23	7	2,110	280	120	160	27	370	1,300	8	1	500	120	2
58N 71W 25DC	58	71	25	1968	CAMPBELL	18	7.9	3,460	225	129	712	21	688	1,980	25	1	240	20	9
43N 79W 11DD	43	79	11	1950	JOHNSON	12	7.4	3,320	395	197	355	13	--	1,820	207	1	200	140	4
43N 80W 20CC	43	80	20	1950	JOHNSON	16	7.4	1,400	137	69	218	8	--	668	119	0	100	1,500	4
43N 82W 12AD	43	82	12	1950	JOHNSON	17	7.4	1,250	171	58	149	6	--	608	106	0	100	610	3
43N 82W 29AC	43	82	29	1950	JOHNSON	18	7.5	4,320	305	146	895	4	693	2,540	70	1	300	240	11
44N 82W 17DD	44	82	17	1969	JOHNSON	12	8.1	1,550	280	95	200	4	373	712	58	0	140	50	3
45N 78W 33AD	45	78	33	1950	JOHNSON	22	7.4	3,380	403	137	495	9	418	1,890	177	1	100	--	5
49N 77W 20BA	49	77	20	1960	JOHNSON	31	7.4	2,240	302	87	287	9	--	1,220	194	0	210	5,000	4
50N 82W 6AD	50	82	6	1962	JOHNSON	26	7.3	106	22	5	6	0	96	10	0	0	--	--	0
53N 86W 27CD	53	86	27	1960	JOHNSON	spring	6.7	72	10	3	5	1	58	3	0	0	10	220	0
53N 80W 18CA	50	80	18	1961	SHERIDAN	23	7.6	1,700	201	124	181	13	--	883	9	0	320	270	2
54N 84W 14BB	54	84	14	1962	SHERIDAN	65	7.6	272	72	18	12	1	--	8	0	0		80	0
56N 82W 34DC	56	82	34	1961	SHERIDAN	56	7.8	1,960	273	136	168	15	--	1,020	6	1	220	4,300	2

TABLE B-4
GROUNDWATER QUALITY
TULLOCK AQUIFER
POWDER RIVER BASIN
WYOMING

Location	Township	Range	Section	Date	County	Depth (feet)	pH	TDS (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Flouride (mg/L)	Baron (µmg/L)	Iron (µg/L)	SAR
55N 77W 11BA	55	77	11	1978	SHERIDAN	2,470	8	2,290	9	4	1,200	14	1,440	32	290	6	820	70	48

APPENDIX C

SUMMARY OF GROUNDWATER MODEL MODIFICATIONS

APPENDIX C

GROUNDWATER MODEL MODIFICATIONS

The original regional PRB groundwater model as prepared for the PRB Oil and Gas EIS (BLM 2003a) and developed for the BLM by AHA (2002) was modified as part of the Task 1B effort for water resources to produce a groundwater model more suited to modeling the combined impacts of CBNG development and coal mine dewatering in the eastern PRB. These modifications primarily were made to the regional PRB model, as this model had to be calibrated before it was telescoped down to produce a model focused on the overlap zone of coal mine dewatering and CBNG development using the TMR module of Groundwater Vistas. The modifications to the original regional PRB groundwater model and modifications to the telescoped Coal Mine Groundwater Model (CMGM) are summarized below:

Modifications to the Original Regional PRB Groundwater Model:

1. Hydrogeologic data on the PRB were not sufficient to model 17 individual layers; therefore, the original 17 layers were combined into 6 HSUs to facilitate running of the model.
2. Cells not used in the original regional PRB model (i.e., “dead space”) were removed to reduce storage requirements for the model and decrease run times.
3. The original regional PRB model was converted from Visual MODFLOW files to Groundwater Vistas file format. The model was then run using MODFLOW 2000.
4. CBNG wells were converted from the MODFLOW Drain Package used in the original regional PRB model to the MODFLOW Well Package.
5. Constant heads used for perennial rivers in the original regional PRB model were converted to the MODFLOW River Package. The Powder River and its tributaries were left as constant heads.
6. Streams that are perennial over only part of their reach, such as the Belle Fourche and Antelope Creek, were converted from the MODFLOW River Package to the MODFLOW Drain Package. All ephemeral streams were modeled as the MODFLOW Drain Package in the original regional PRB model, and this was maintained in the modified regional PRB model.
7. Recharge from precipitation was changed in the modified regional PRB model to 5 percent of precipitation for regional precipitation recharge and to 10 percent of precipitation for recharge along the clinker zones east of the coal mines.
8. The solver used in the original regional PRB model was changed to the PCG2 solver in the modified model.
9. Grid spacing in the original PRB model was a uniform 0.5 x 0.5 mile. In the modified model, a grid spacing of 0.25 x 0.25 mile was used in the area of the coal mines and the CBNG well fields.
10. Calibration targets from GAGMO (2001, 2003) reports were incorporated into the modified regional PRB model (approximately 350 monitoring wells). In addition,

approximately 70 monitoring wells in the Wasatch Formation were obtained from WDEQ/LQD files and incorporated into the modified regional PRB model. BLM and USGS wells also were added.

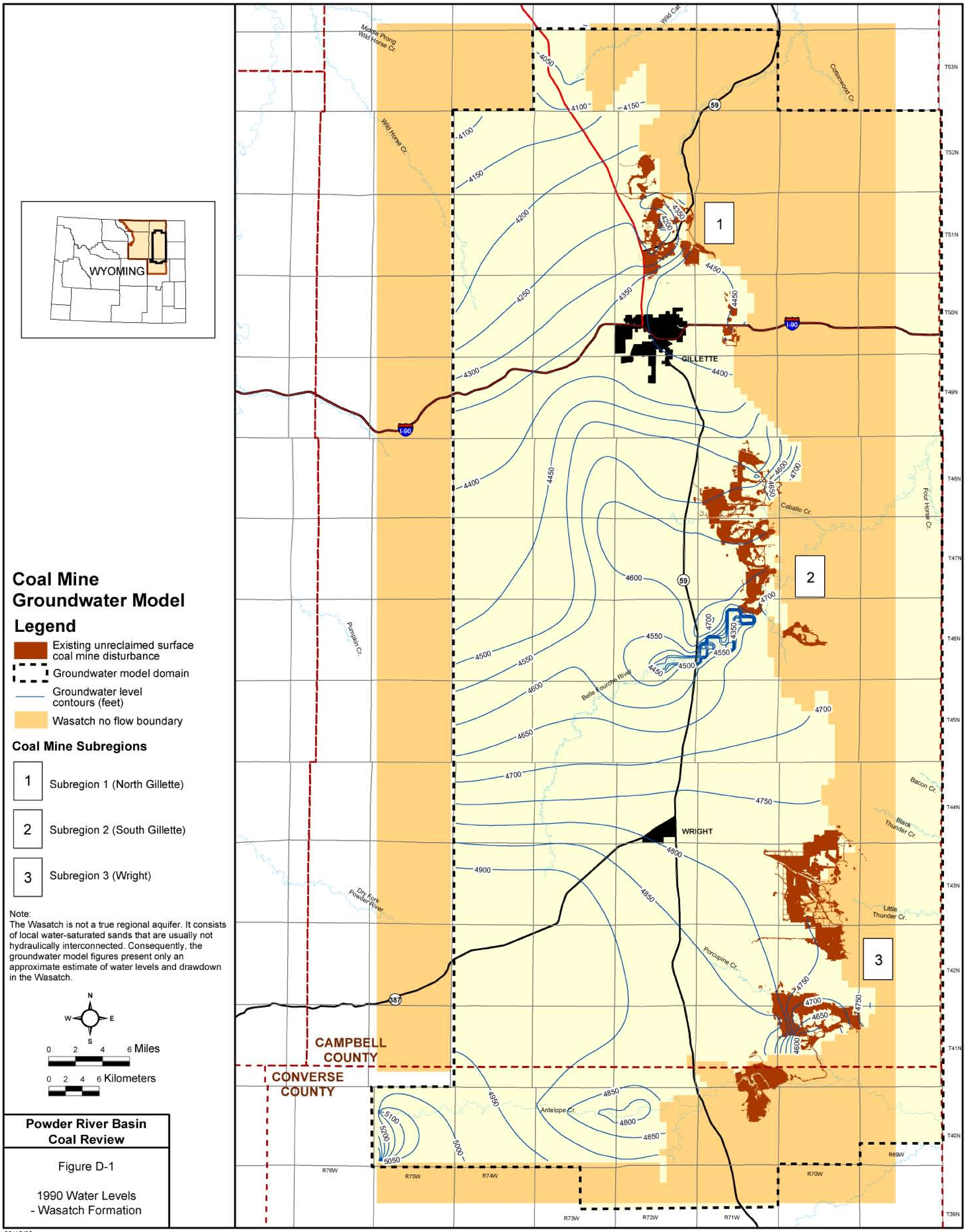
11. The Wasatch Formation (HSU-3) in the modified regional model was extended to the east based on geologic data provided by the BLM. In addition, the location of the clinker outcrop areas was revised based on geologic mapping provided by the BLM.
12. A low-permeability layer was placed between the Wasatch and the Fort Union formations (between HSU-3 and HSU-5) to represent the thick clay and claystone units that separate the Wasatch and the upper coals of the Fort Union. This layer was assigned as HSU-4.

Additions to the CMGM:

1. The CMGM was telescoped down from the modified regional PRB model using the TMR capability of Groundwater Vistas to focus on the overlap zone of coal mine dewatering and CBNG development. The CMGM preserved many of the boundary conditions and features of the modified regional PRB model.
2. The model domain boundaries of the CMGM on the west, north, and south were set as MODFLOW Constant Head Boundaries with time varying heads to match changes in water levels in the modified regional model just beyond the domain boundaries. The eastern boundary was set as a no-flow boundary along the outcrop of the Wasatch for HSU's 1-3 and along the outcrop of the Fort Union for HSU's 4-6. The time varying heads in the west, north, and south boundaries were set according to water level changes in the regional model near these boundaries.
3. The coal mine pits were changed to the MODFLOW Drain Package, and the 3-D configuration of the mine pits over time was obtained from the BLM (Braz 2005) for past mining conditions and from the mine operators (Task 2 report) for expected future mining conditions. Drain elevations were placed 5 meters above the pit floor bottoms, and the drain conductances were set during calibration.
4. HSU-5 was set as the Upper Fort Union and includes all the coal units of the eastern PRB and represents the Wyodak-Anderson coal. HSU-6 was set as the Lower Fort Union and represents the Lebo and Tullock members of the Fort Union.
5. Outside of the coal mine boundaries, the stratigraphy of the original regional PRB model obtained from Goolsby, Finley, and Associates (2001) was preserved. Within the coal mine boundaries, the coal stratigraphy provided by the BLM (Braz 2005) was used. These two stratigraphic packages were merged to the west of the coal mine boundaries. The merged data set was then contoured to form a new data set with consistent elevations for the coal layers.
6. Modifications made to the original regional PRB model discussed above were preserved and used in the telescoped CMGM model.

APPENDIX D

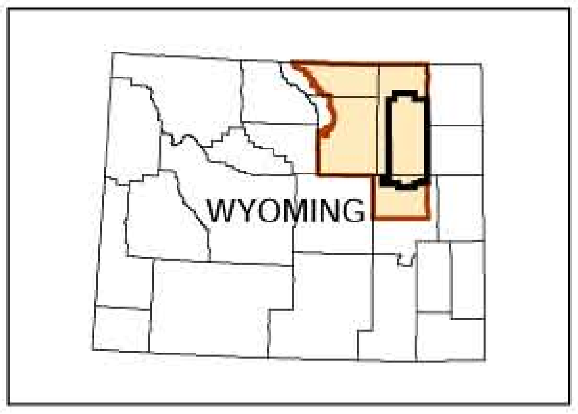
MODELED GROUNDWATER LEVELS



Powder River Basin Coal Review

Figure D-1

1990 Water Levels - Wasatch Formation



Coal Mine Groundwater Model

Legend

- Existing unreclaimed surface coal mine disturbance
- Groundwater model domain
- Groundwater level contours (feet)
- Wasatch no flow boundary

Coal Mine Subregions

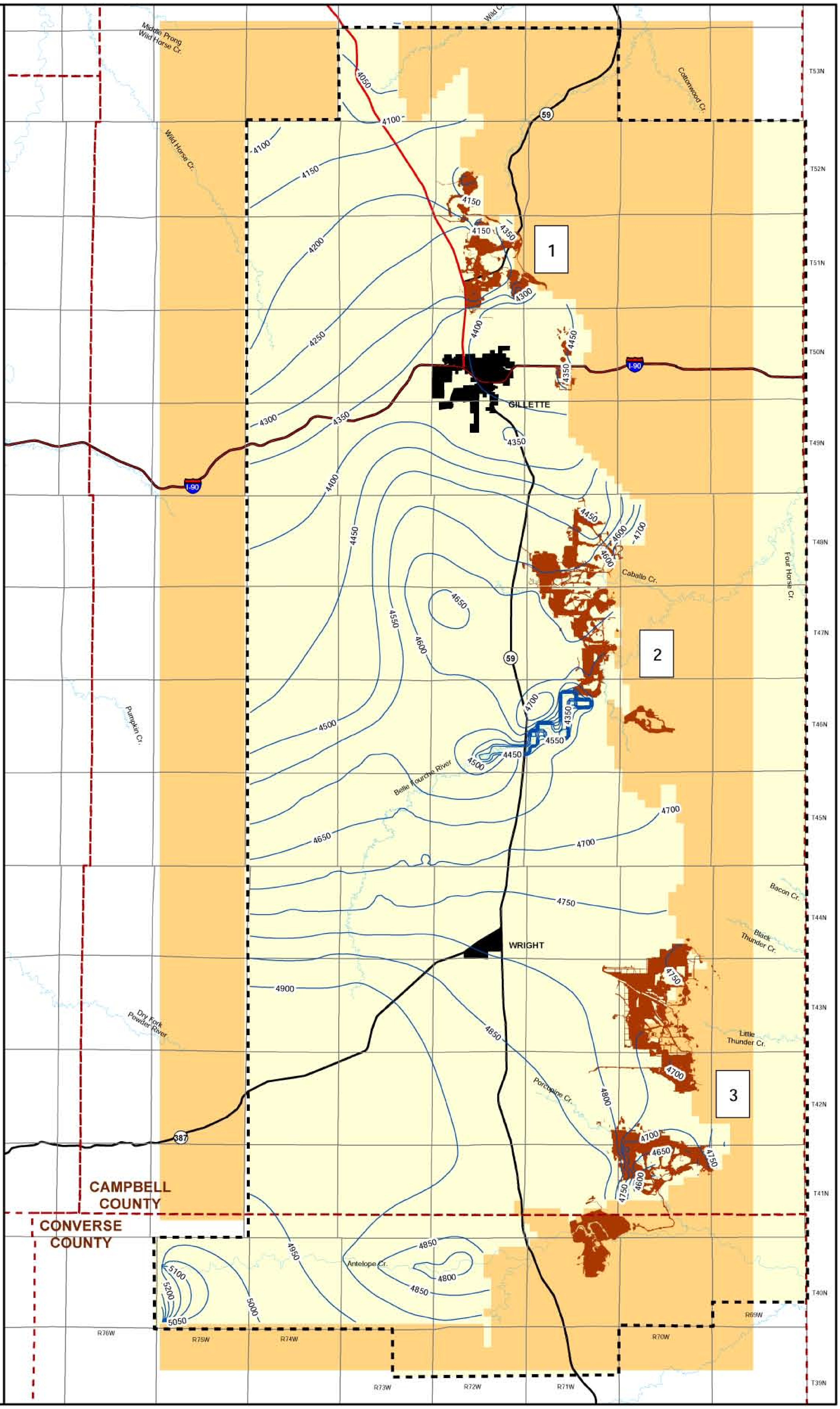
- 1 Subregion 1 (North Gillette)
- 2 Subregion 2 (South Gillette)
- 3 Subregion 3 (Wright)

Note:
The Wasatch is not a true regional aquifer. It consists of local water-saturated sands that are usually not hydraulically interconnected. Consequently, the groundwater model figures present only an approximate estimate of water levels and drawdown in the Wasatch.

N W E S

0 2 4 6 Miles

0 2 4 6 Kilometers

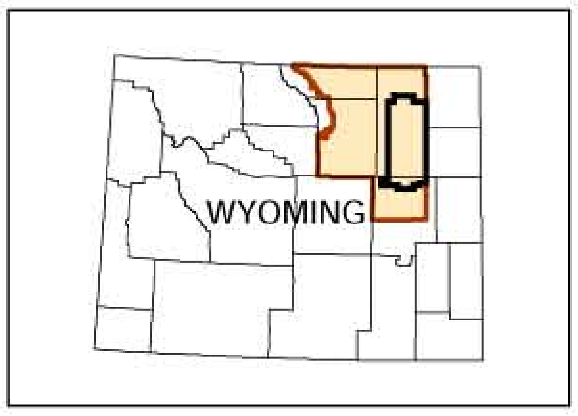


Powder River Basin Coal Review

Figure D-2

2002 Water Levels - Wasatch Formation

09/19/06



Coal Mine Groundwater Model

Legend

- Existing unreclaimed surface coal mine disturbance
- Groundwater model domain
- -20 = Drawdown of 20 feet
- Groundwater drawdown level contours (feet)
- Wasatch no flow boundary
- Wasatch Formation model dry cells

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

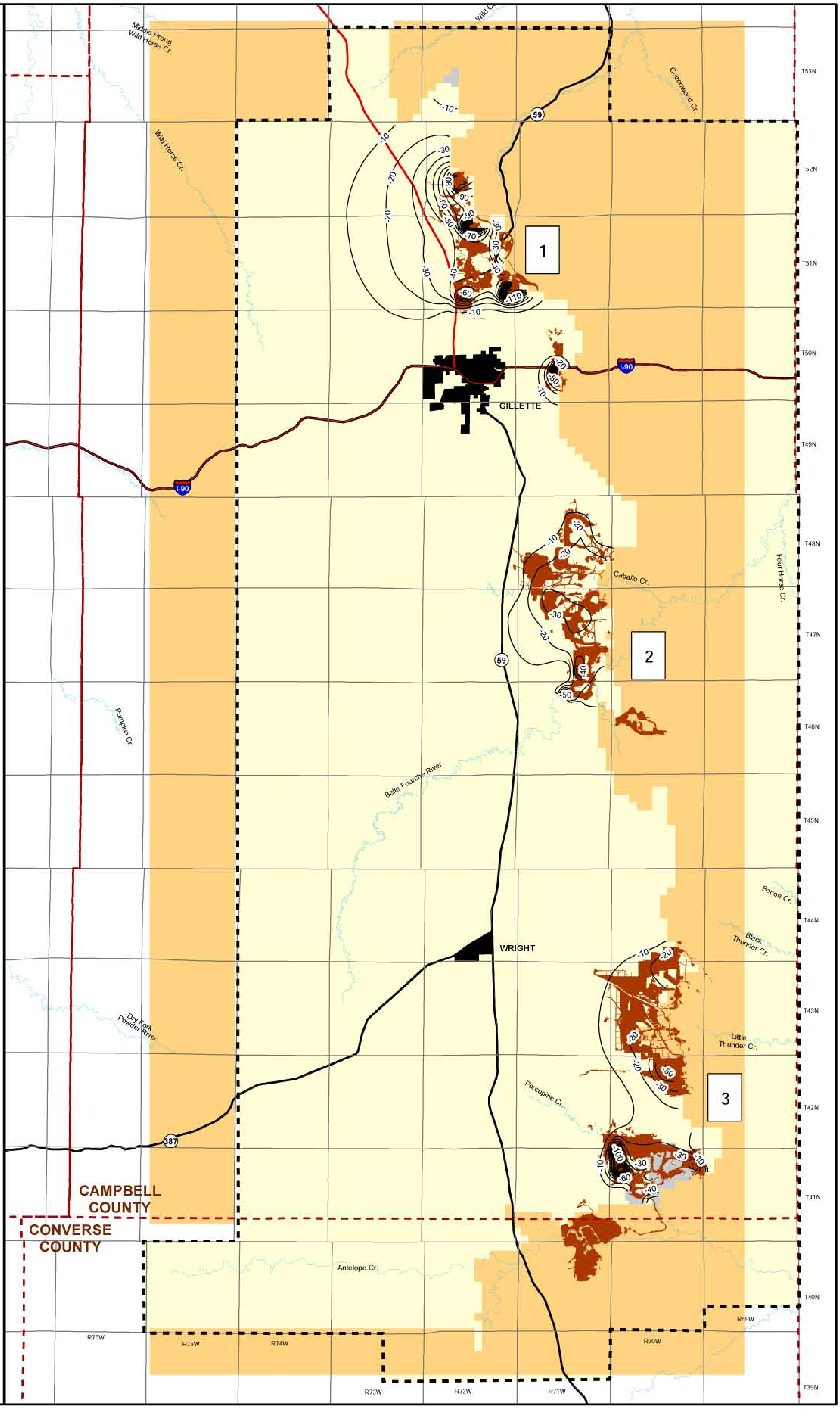
3 Subregion 3 (Wright)

Note:
The Wasatch is not a true regional aquifer. It consists of local water-saturated sands that are usually not hydraulically interconnected. Consequently, the groundwater model figures present only an approximate estimate of water levels and drawdown in the Wasatch.

N W E S

0 2 4 6 Miles

0 2 4 6 Kilometers

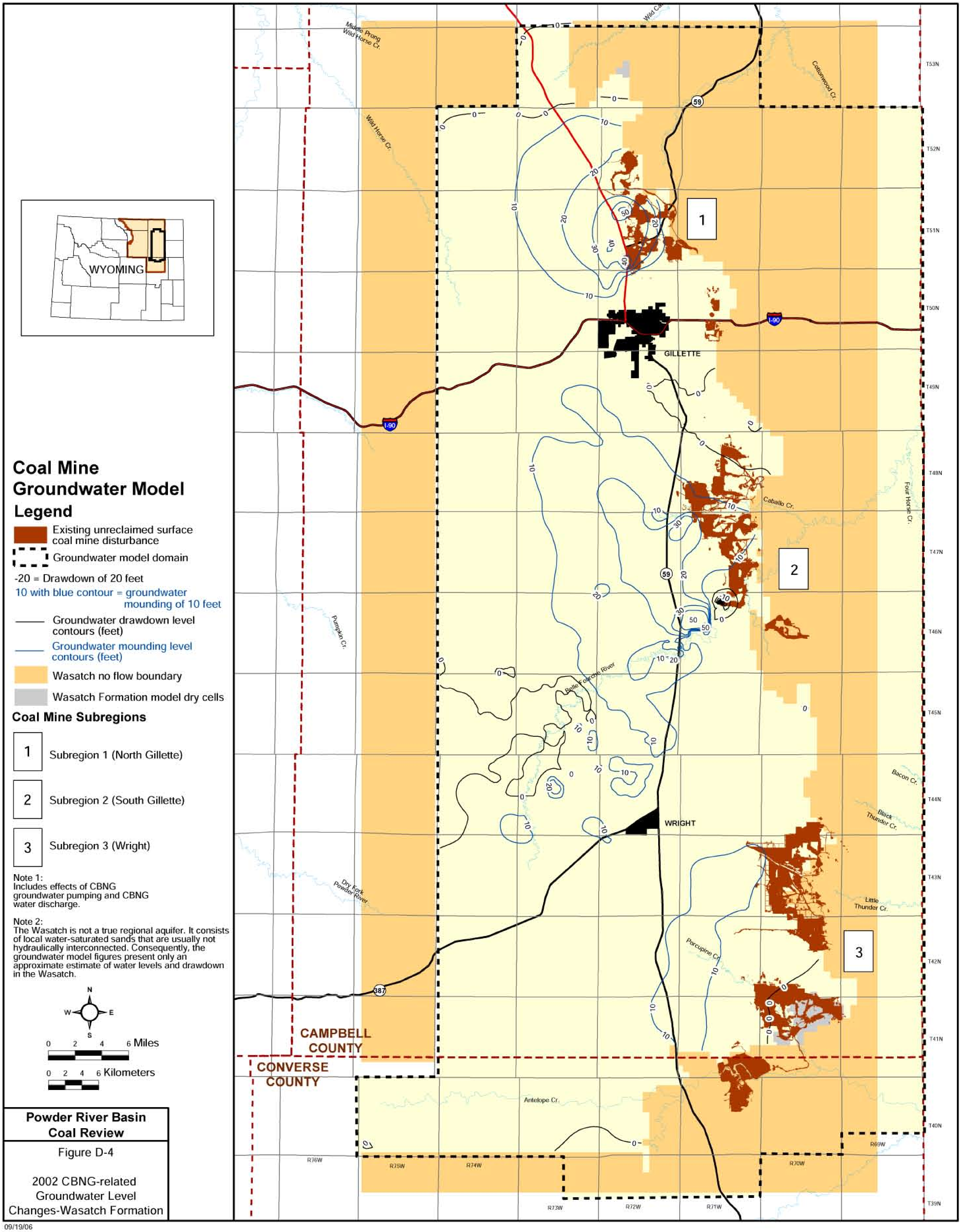


Powder River Basin Coal Review

Figure D-3

2002 Coal Mine-related Groundwater Drawdown Levels-Wasatch Formation

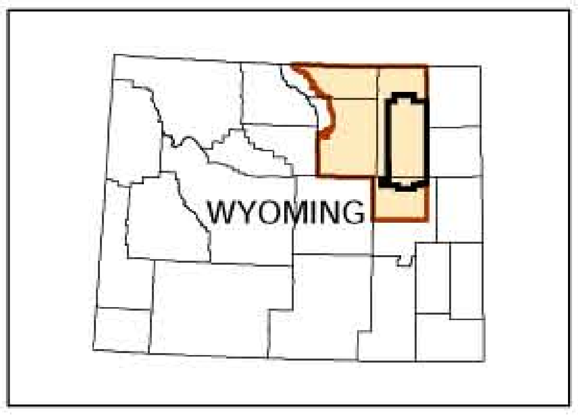
09/19/06



Powder River Basin Coal Review

Figure D-4

2002 CBNG-related Groundwater Level Changes-Wasatch Formation



Coal Mine Groundwater Model

Legend

- Existing unreclaimed surface coal mine disturbance
- Groundwater model domain
- -20 = Drawdown of 20 feet
- 10 with blue contour = groundwater mounding of 10 feet
- Groundwater drawdown level contours (feet)
- Groundwater mounding level contours (feet)
- Wasatch no flow boundary
- Wasatch Formation model dry cells

Coal Mine Subregions

- 1 Subregion 1 (North Gillette)
- 2 Subregion 2 (South Gillette)
- 3 Subregion 3 (Wright)

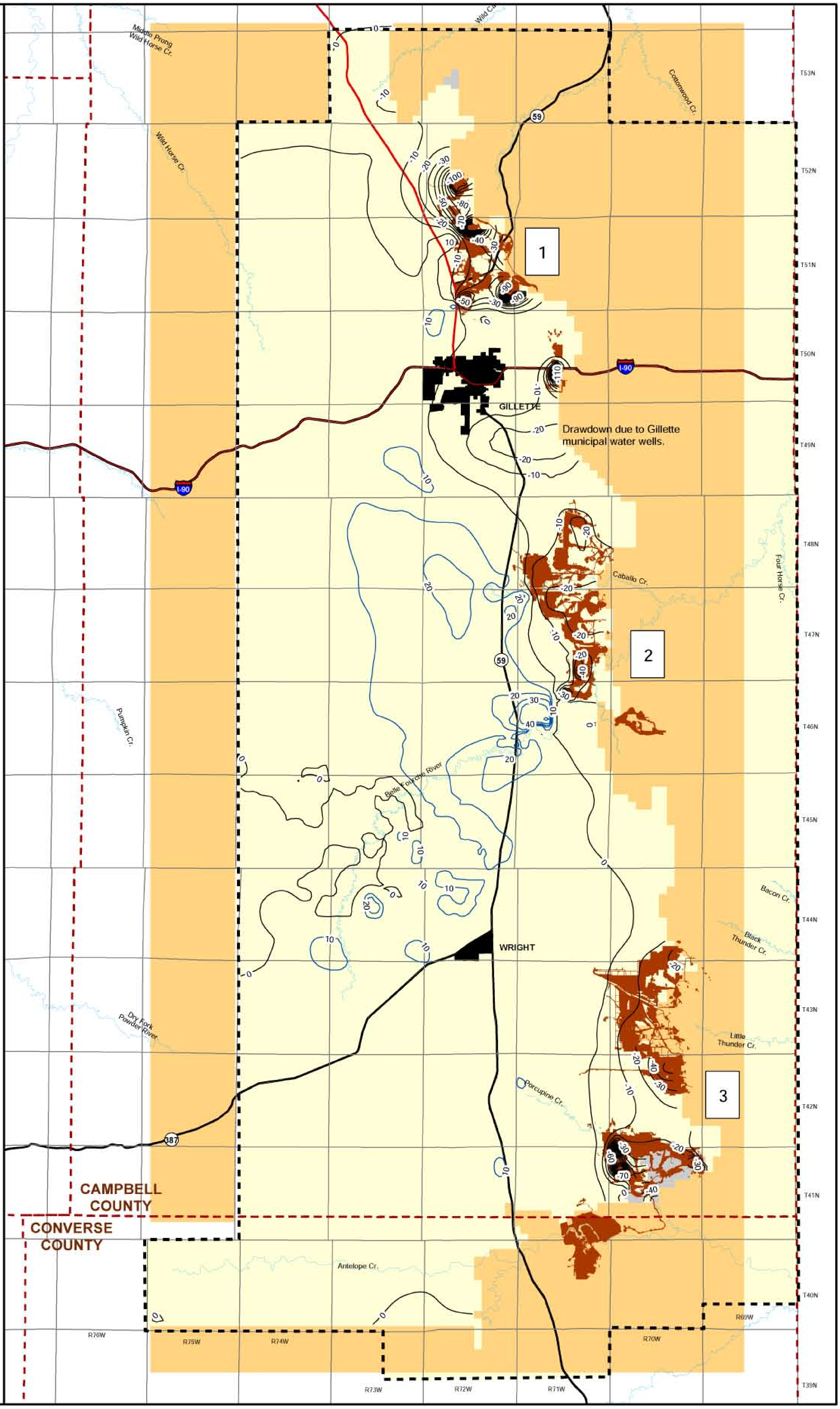
Note 1:
Includes effects of CBNG groundwater pumping and CBNG water discharge.

Note 2:
The Wasatch is not a true regional aquifer. It consists of local water-saturated sands that are usually not hydraulically interconnected. Consequently, the groundwater model figures present only an approximate estimate of water levels and drawdown in the Wasatch.

N W E S

0 2 4 6 Miles

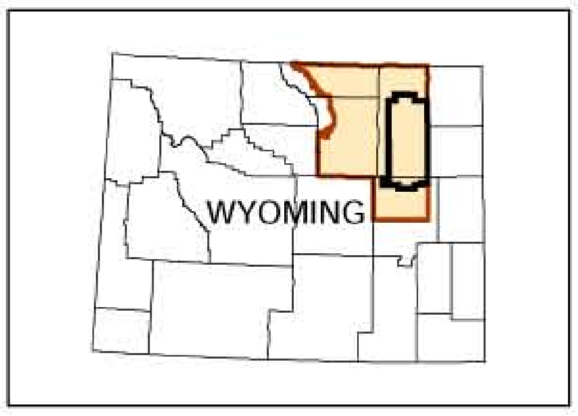
0 2 4 6 Kilometers



Powder River Basin Coal Review

Figure D-5
2002 Coal Mine- and CBNG-related and Water Supply Groundwater Level Changes-Wasatch Formation

09/19/06



Coal Mine Groundwater Model

Legend

Existing unreclaimed surface coal mine disturbance

Groundwater model domain

Groundwater level contours (feet)

Fort Union no flow boundary

Coal Mine Subregions

1 Subregion 1 (North Gillette)

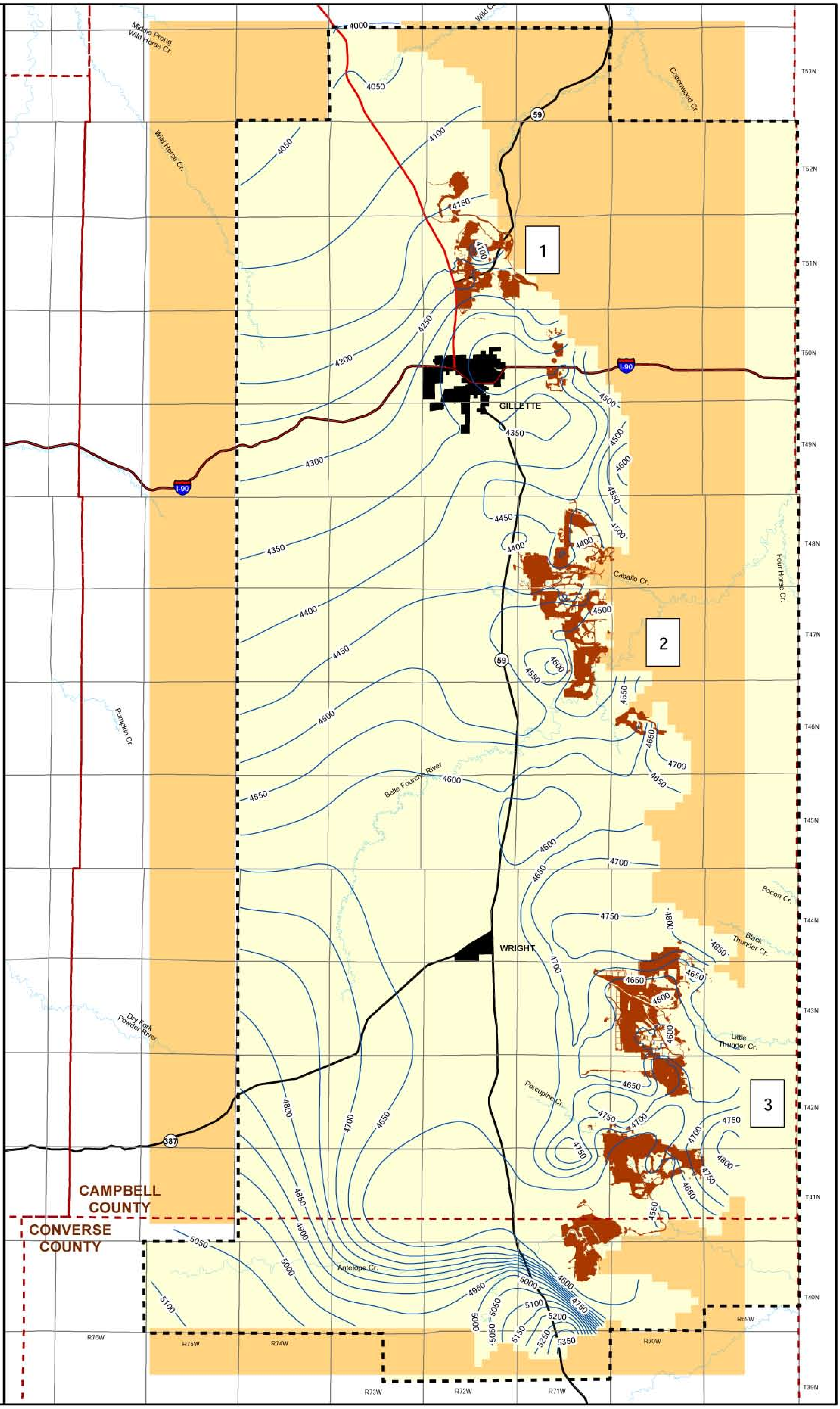
2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

N W E S

0 2 4 6 Miles

0 2 4 6 Kilometers

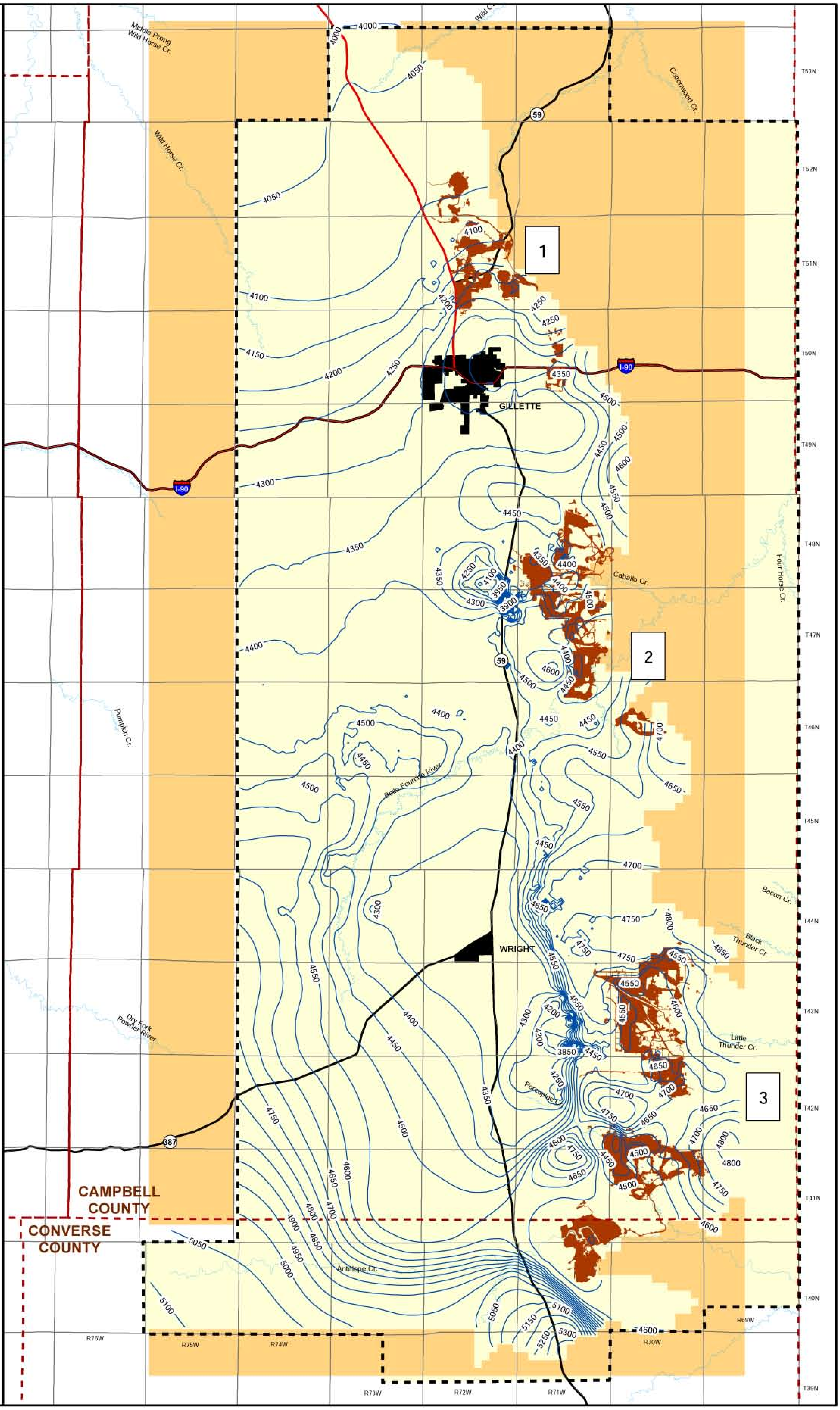


Powder River Basin Coal Review

Figure D-6

1990 Water Levels - Upper Fort Union Formation

09/19/06



Coal Mine Groundwater Model

Legend

- Existing unreclaimed surface coal mine disturbance
- Groundwater model domain
- Groundwater level contours (feet)
- Fort Union no flow boundary

Coal Mine Subregions

- 1 Subregion 1 (North Gillette)
- 2 Subregion 2 (South Gillette)
- 3 Subregion 3 (Wright)

0 2 4 6 Miles

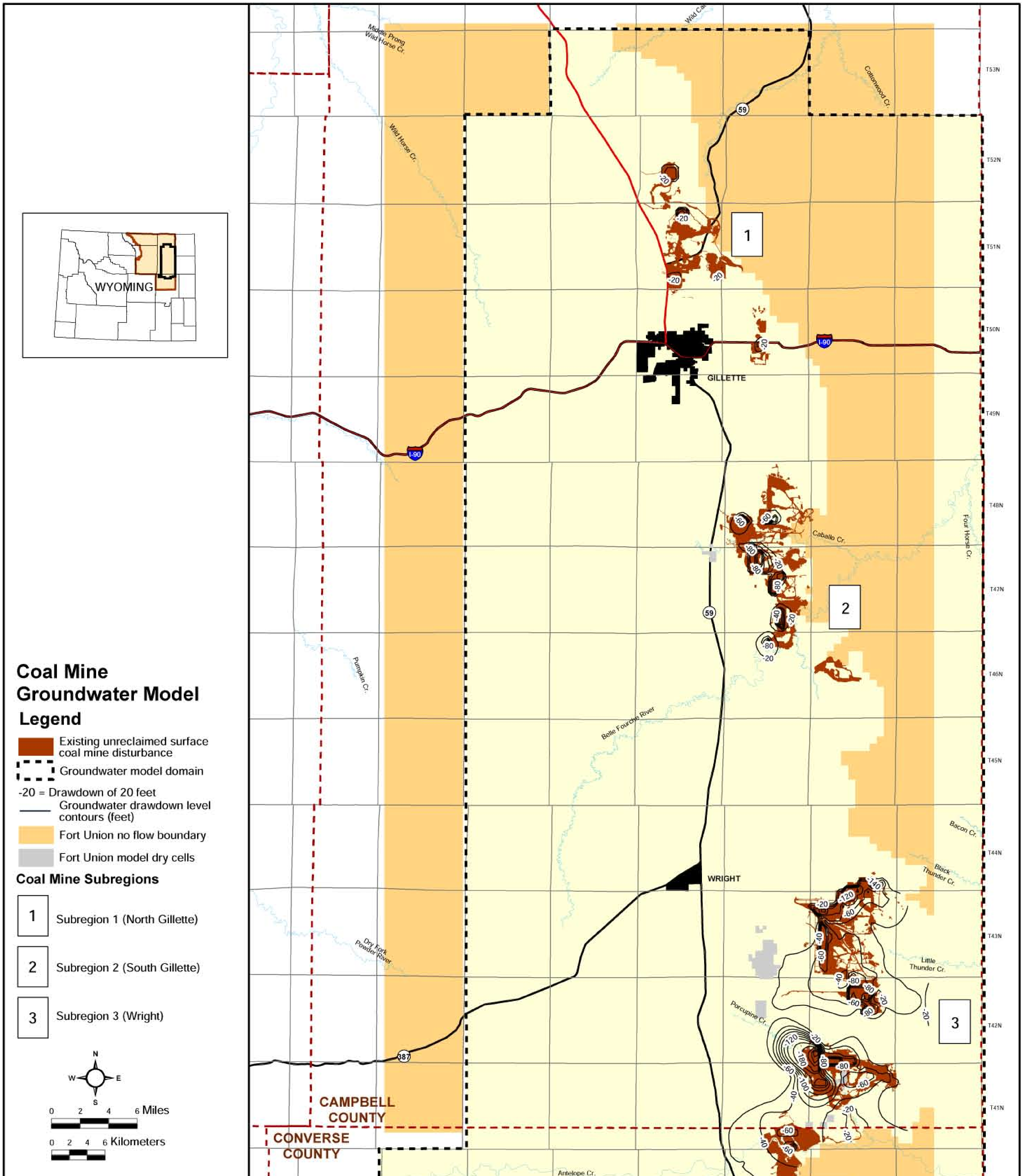
0 2 4 6 Kilometers

Powder River Basin Coal Review

Figure D-7

2002 Water Levels - Upper Fort Union Formation

09/19/06

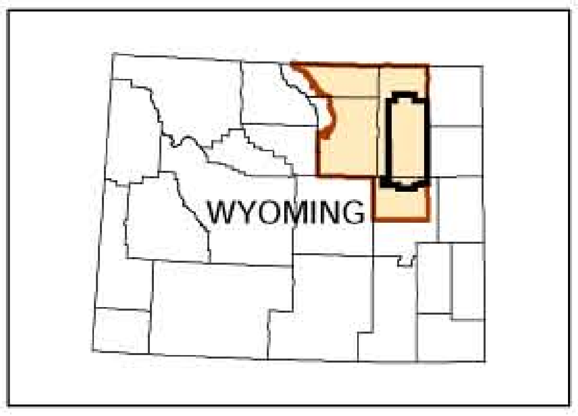


Powder River Basin Coal Review

Figure D-8

2002 Coal Mine-related Groundwater Drawdown Levels-Upper Fort Union Formation

09/19/06



Coal Mine Groundwater Model

Legend

- Existing unreclaimed surface coal mine disturbance
- Groundwater model domain
- -20 = Drawdown of 20 feet
- Groundwater drawdown level contours (feet)
- Fort Union no flow boundary
- Fort Union model dry cells

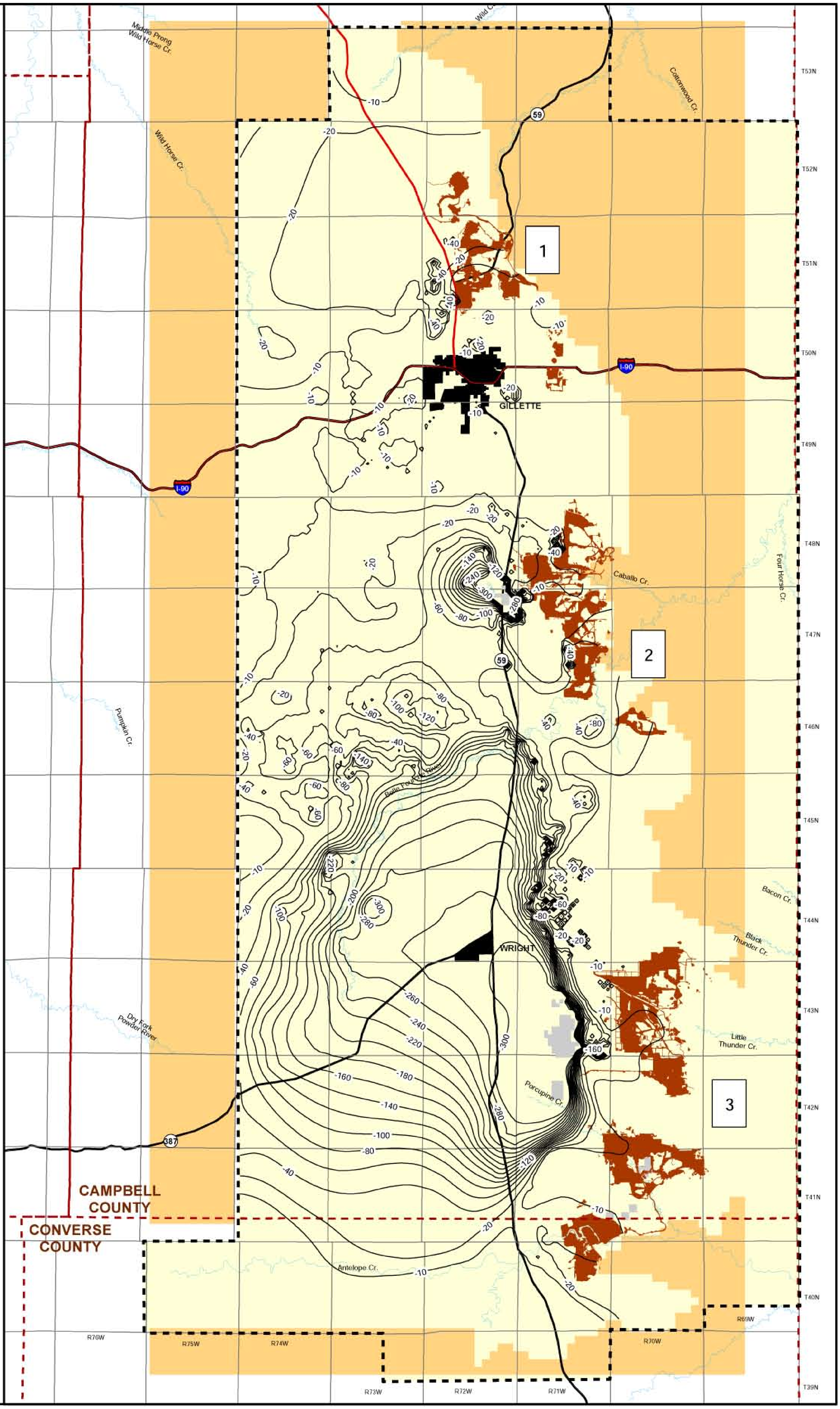
Coal Mine Subregions

- 1 Subregion 1 (North Gillette)
- 2 Subregion 2 (South Gillette)
- 3 Subregion 3 (Wright)

N W E S

0 2 4 6 Miles

0 2 4 6 Kilometers

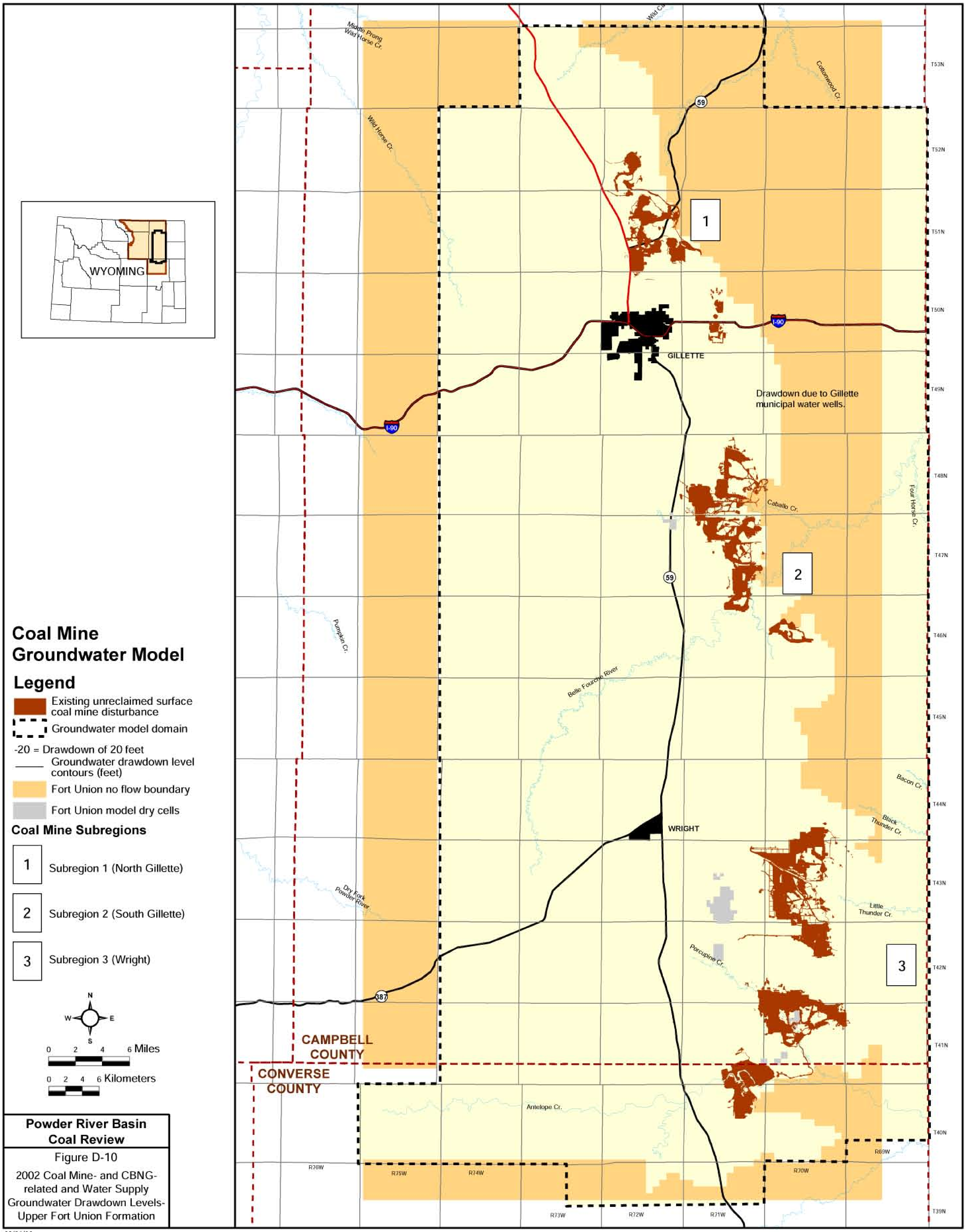


Powder River Basin Coal Review

Figure D-9

2002 CBNG-related Groundwater Level Changes-Upper Fort Union Formation

09/21/06



Powder River Basin Coal Review

Figure D-10

2002 Coal Mine- and CBNG-related and Water Supply Groundwater Drawdown Levels-Upper Fort Union Formation

09/21/06