2.0 HYDROGEOLOGIC FRAMEWORK

The hydrogeology of the Project Area is described in detail in Chapter 3 of the FEIS. Additional information on hydrogeology is presented below to establish the basis for construction of the regional groundwater model.

2.1 Location

The PRB O&G EIS Project Area is located in northeastern Wyoming, within Campbell, Converse, Johnson, and Sheridan Counties (Figure 1-1).

2.2 Geology of the Powder River Basin

Coal seams within the upper portion of the Fort Union Formation are the targets for CBM development. The beds dip to the west at 1 to 2 degrees toward the center of the basin on the eastern limb of the PRB. Closer to the outcrop, dips may be more significant, up to 6 degrees. The beds on the western limb of the PRB dip sharply at 20 to 25 degrees to the east near the flanks of the Big Horn Mountains with an average dip of about 2 degrees to the east nearer the center of the basin.

The stratigraphic units of interest for this modeling study occur within the Paleocene age Fort Union Formation and the Eocene age Wasatch Formation (refer to FEIS Figure 2-2). In addition, the Quaternary and Recent alluvial deposits form locally significant aquifer units. A generalized description of the stratigraphy of the Wasatch and Fort Union Formations is provided in Table 2-1.

2.2.1 Alluvium

Alluvium consists of unconsolidated silt, sand, and gravel that occur along rivers and major drainages within the PRB. The water resources contained in the alluvial sediments are described by Whitehead (1996). Coarser alluvial deposits occur in the valleys of the Belle Fourche, Cheyenne, Powder, and Little Powder Rivers (Hodson et al. 1973). Alluvium that overlies formations of Tertiary age in the central part of the PRB is mostly fine-to medium-grained sand and silt (Hodson et al. 1973). The alluvial deposits are usually less than 50 feet thick in areas distant from the mountains but may be as much as 100 feet thick in mountain valleys. The Powder River alluvium ranges from 4 to 45 feet thick but commonly is 10 to 30 feet thick and about one-half mile wide (Ringen and Daddow 1990). Water yield from the alluvium is a function of saturated thickness, grain size, and grain-size distribution. Recharge results from surface infiltration and discharge from underlying strata. Local groundwater movement is primarily along the drainage in a downstream direction.

2.2.2 Wasatch Formation

The Wasatch Formation is exposed at the surface over most of the PRB O&G EIS area and overlies the Fort Union Formation. The Wasatch Formation consists of fine- to medium-grained sandstones, siltstones, claystones, and coals. Its thickness increases from zero at the outcrop area to almost 3,000 feet in the central part of the basin (Seeland 1992). Sandstone makes up an estimated one-third of the sequence and is an important aquifer in the PRB. High percentages of sand (from 30 to 50 percent and more) have been documented along a trend that parallels the western margin of the PRB, beginning east of Buffalo and west of the Powder River and continuing toward the southeast (Seeland 1992). The sandstones tend to be lenticular and discontinuous but locally are used for water supply. Wells completed in sandstone lenses or sand channels yield 10 to 50 gallons per minute (gpm) in the northern portion of the Project Area. Wells completed near the southern portion of the PRB can yield as much as 500 gpm (Martin et al. 1988). Artesian conditions are common away from the outcrop, particularly from deeper isolated sands.

Table 2-1
Generalized Description of the Shallow Geology
In the PRB O&G EIS Project Area

Formation	Description	Aquifer Characteristics
Alluvium	Unconsolidated and poorly consolidated Quaternary and Recent alluvial deposits of silt, sand, and gravel. Underlies floodplains and low terraces. Thickness generally less than 50 feet (WSGS 1974).	Fine-grained alluvium usually yields a few gallons per minute, more in coarser deposits.
Wasatch	Arkosic sandstone, siltstone, claystone, and conglomerate lenses with many coal beds present in the lower part (WSGS 1990). This formation is found at the surface throughout most of the Project Area.	Discontinuous, lenticular, fine- to medium-grained sandstones, generally are of limited areal extent but provide adequate quantities of water for stock use. Coal units are more laterally continuous and form significant aquifer units. Interbedded, low-permeability claystone layers act as aquitards to vertical movement of groundwater throughout the thickness of the Wasatch Formation.
Upper Fort Union (Tongue River/ Lebo)	Interbedded sandstones, siltstones, claystones, and coals. Individual coal units up to 150 feet thick. Coals merge and split over distances of a few miles.	Sandstones are fine- to medium-grained. Sandstones and coals are good water producers and are used for municipal and industrial water supply. Claystones form aquitards and confining layers.
Lower Fort Union/Tullock	Interbedded sandstones, siltstones, claystones, and coal.	Sands somewhat coarser than Upper Fort Union; sand at base of Fort Union (Tullock) is good producer and is used for municipal and industrial water supply.

Coal beds in the Wasatch Formation are thickest in the central and western portions of the PRB (Seeland 1992). The coals in the Wasatch Formation are generally not economic for mining or CBM development except in the area of Lake De Smet on the western side of the PRB. Coals within the Wasatch Formation form localized aquifer units. Siltstones and claystones typically form low-permeability confining units or aquitards within the Wasatch Formation sequence but generally do not yield enough water even for intermittent livestock use.

2.2.3 Fort Union Formation

The Fort Union Formation consists of coals, sandstones, siltstones, and claystones. The Fort Union Formation has been divided into three members in the northern and eastern part of the PRB: the Tongue River, Lebo, and Tullock. The Lebo and the Tongue River members are not identified separately in the southern part of the basin.

Tongue River Member

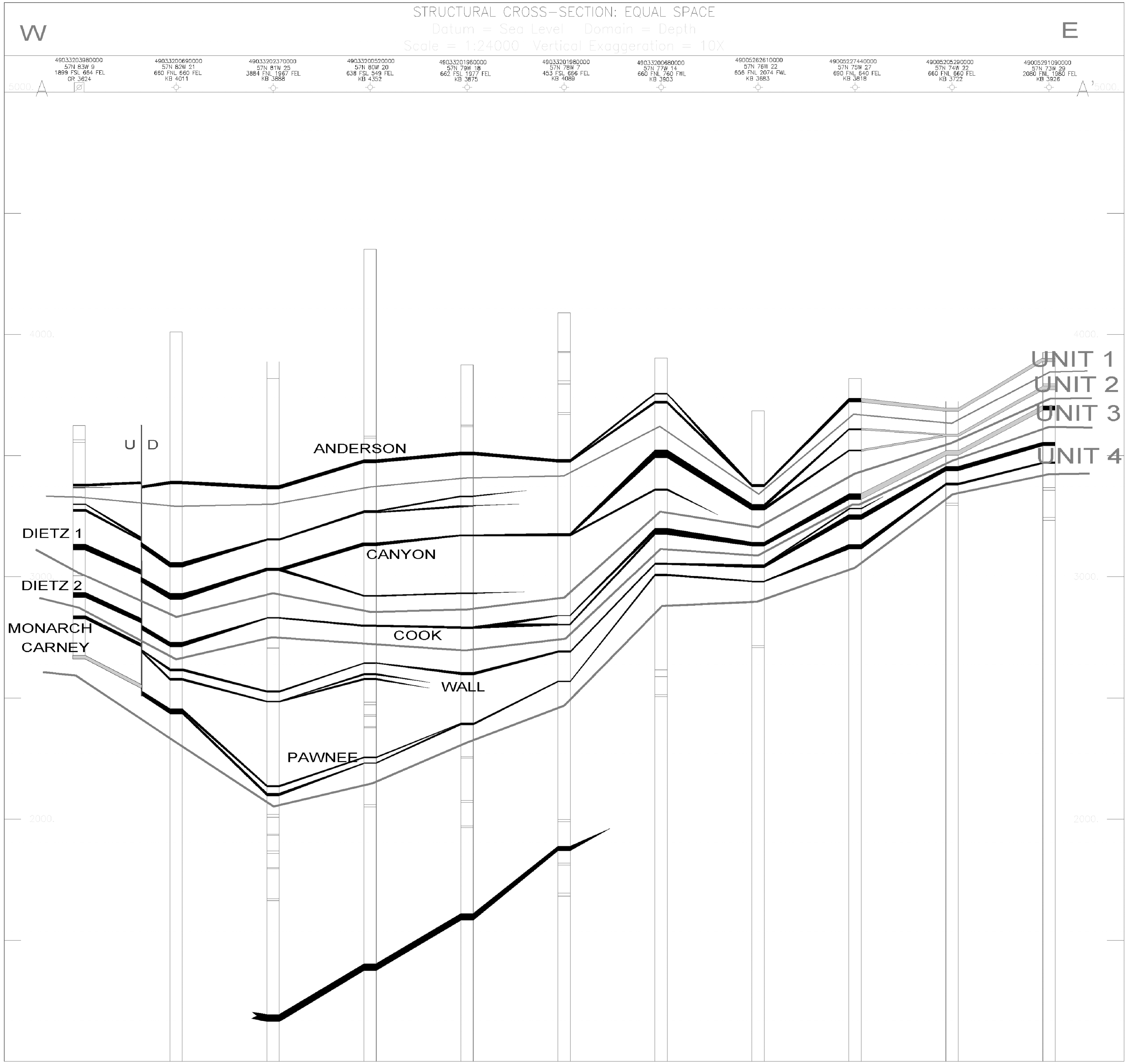
The upper part of the Fort Union Formation has been identified as the Tongue River Member in the northern part of the PRB. It contains seven to nine major coal seams (WSGS 1996a, 1996b, USGS 1999a, 1999b) and many discontinuous, lenticular sandstone layers. CBM development focuses on the thick coal seams of the upper portion of the Fort Union Formation.

The coals of the upper Fort Union Formation show a great deal of variation in thickness and continuity over the PRB. Coal seams split and merge over distances of a few miles, so that it is more appropriate to consider the coals as part of a hydrogeological group rather than as individual aquifers. Correlation of individual seams is difficult because of the splitting and merging, and is further complicated because the same seam may have been given different names in different areas. The U.S. Geological Survey (USGS) has collectively referred to the sequence that contains the major coals as the Wyodak-Anderson Group (Flores et al. 1999). To model the regional groundwater flow, the upper Fort Union Formation has been subdivided into four hydrogeological groups (Group 1, Group 2, Group 3, and Group 4) defined on the basis of stratigraphic correlation of coal seams (Goolsby, Finley and Associates 2001). The model layering as it reflects this interpreted geology is described in detail in Section 4.3.

The variability of the coal seams in the upper portions of the Fort Union Formation, and the corresponding hydrogeologic groupings, can be visualized in a series of geologic cross sections. Typical east-west cross-sections for the northern, central, and southern parts of the PRB are shown in Figures 2-1A, 2-1B, and 2-1C. All four coal groups are identifiable in the northern part of the PRB (Figure 2-1A). Groups 1, 2, and 3 merge to form a thick coal unit, known as the Big George, in the central part of the PRB (Figure 2-1B). Only Group 4 is present in the southeastern part of the PRB, where it is known locally as the Wyodak coal (Figure 2-1c). Additional cross sections are included in Appendix A. Figure 2-2 summarizes the areas where individual coal groups can be identified.

Over most of the PRB, the coals in the upper portion of the Fort Union Formation are separated from sands in the overlying Wasatch Formation by continuous, low-permeability claystone and siltstone units of variable thickness. Examination of drilling and geophysical logs from U.S. Bureau of Land Management (BLM) monitoring wells, CBM production wells, coal mine permits, and exploration drillholes shows that the thickness of this confining unit ranges from 11 to 363 feet. In most cases, the claystone confining unit is at least 30 feet thick. The large variation in thickness is mostly a function of the presence of any significant sands in the lower part of the Wasatch Formation. Sandstones occur in direct contact with the coal, but occurrences are over limited discrete areas because of the lenticular nature of the sandstone units in the upper portion of the Fort Union Formation and lower portion of the Wasatch Formation.

Groundwater in the upper Fort Union Formation coals, downdip of the outcrop, tends to be confined by the overall predominance of low-permeability claystone of the overlying Wasatch Formation and a thick underlying sequence of siltstone and claystone (Martin et al. 1988). Localized lenticular sandstone units that are in direct contact with the coal are themselves confined by overlying claystones and can be considered part of the confined coal aquifer. Confined aquifer conditions in these coals are documented by the USGS (1986a) and in various mine permit application packages (PAPs) on file with the Wyoming Department of Environmental Quality, Land Quality Division (WDEQ/LQD). Flowing artesian conditions occur in the vicinity of the Powder River.



LEGEND

For Union Hydrologic Groups
(Refer to Figure 2-2)

1 or Unit 1 Represents Group 1
2 or Unit 2 Represents Group 2
3 or Unit 3 Represents Group 3
4 or Unit 4 Represents Group 4

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

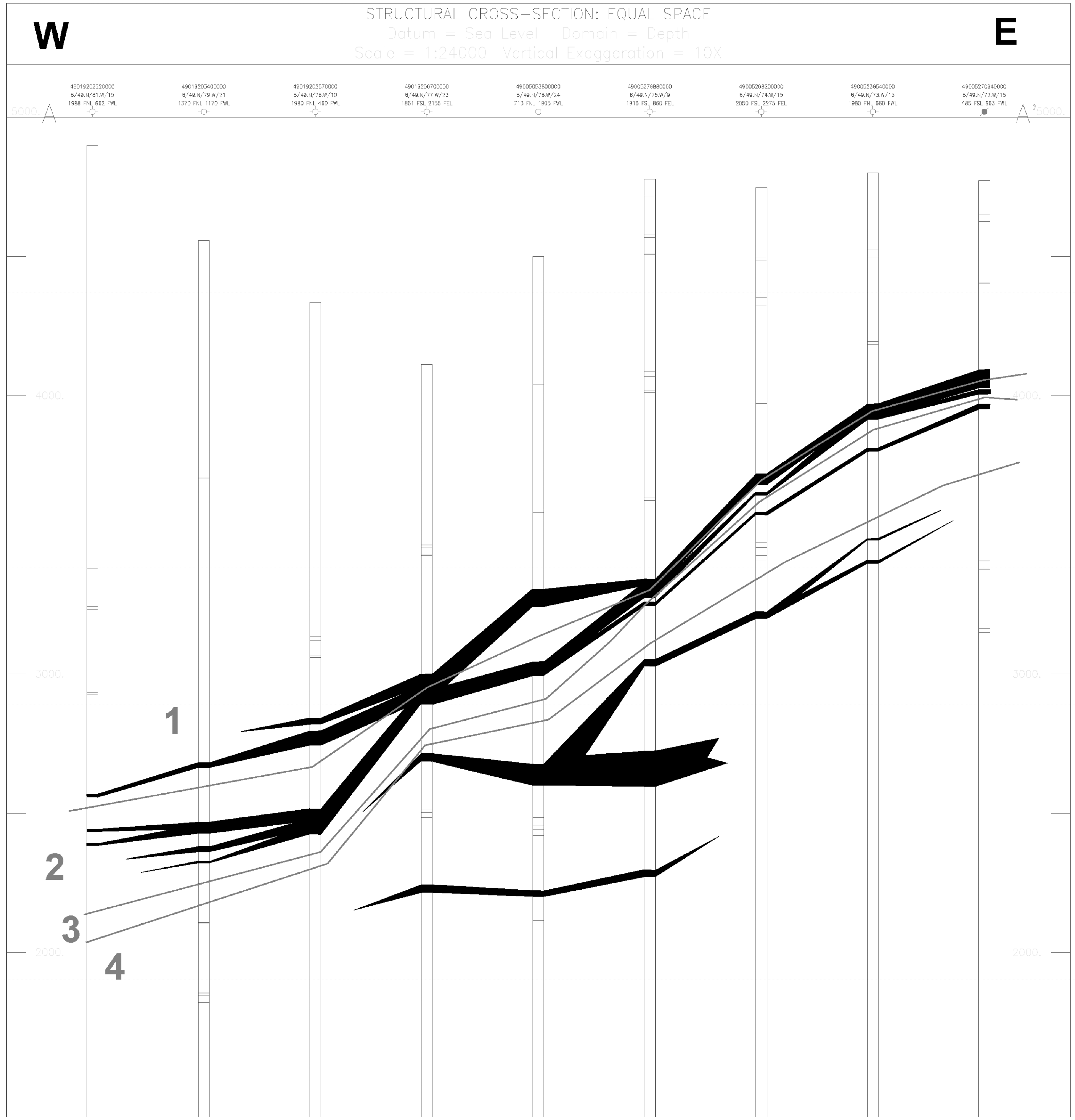
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 2-1A
TYPICAL GEOLOGIC CROSS SECTION
IN THE NORTHERN POWDER RIVER BASIN

MODEL RUN: From 1999-2200 (8-26-02)

Date: 09/04/02	Drawing File: Figure 2-1abc.dwg
Scale: NTS	Drawn By: ETC

Figure 2-1A continued (11x17)



LEGEND

For Union Hydrologic Groups
(Refer to Figure 2-2)

1 or Unit 1 Represents Group 1
2 or Unit 2 Represents Group 2
3 or Unit 3 Represents Group 3
4 or Unit 4 Represents Group 4

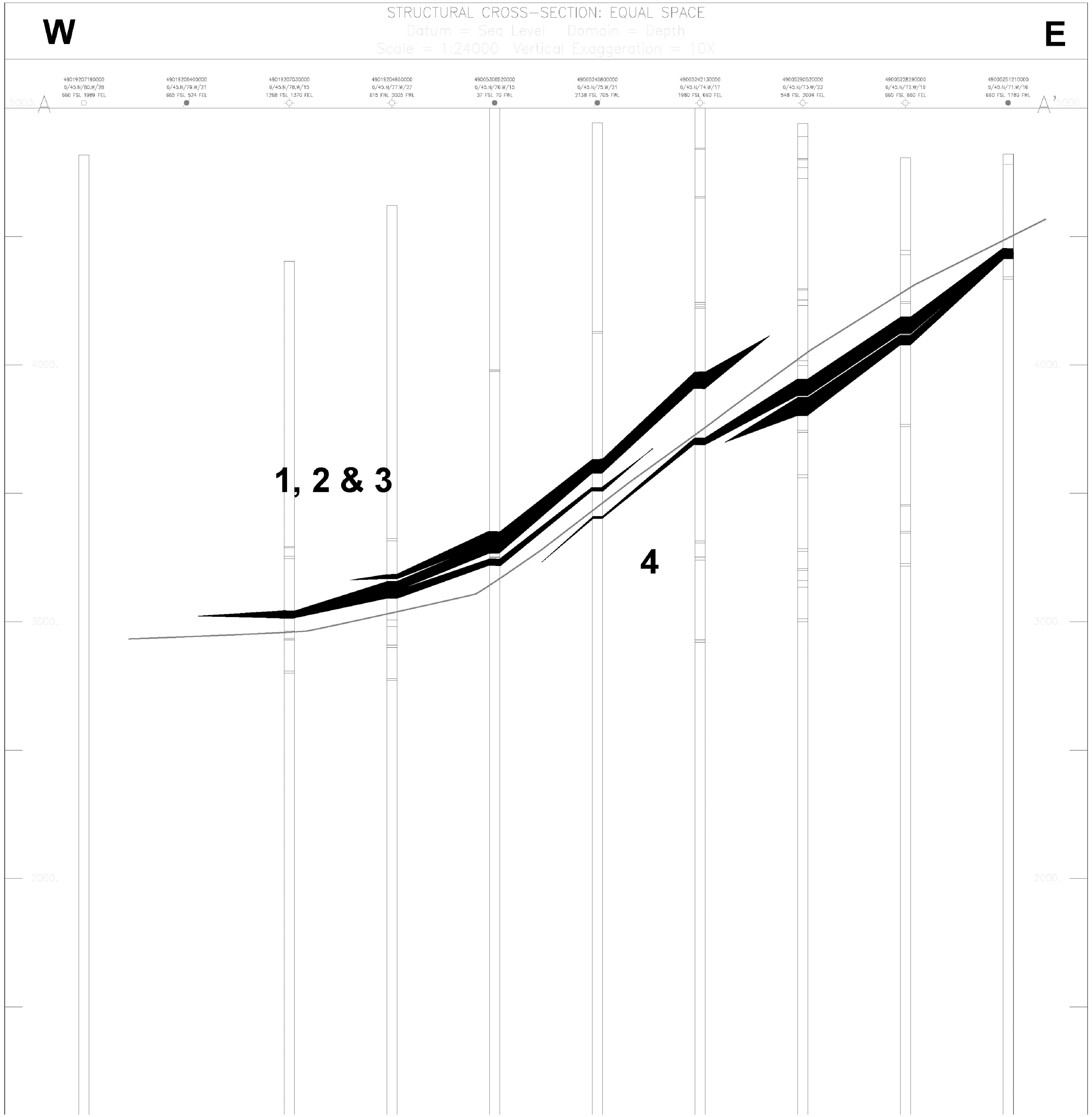
POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 2-1B
TYPICAL GEOLOGIC CROSS SECTION
IN THE CENTRAL POWDER RIVER BASIN

MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/04/02	Drawing File: Figure 2-1abc.dwg
Scale: NTS	Drawn By: ETC

Figure 2-1B continued (11x17)



LEGEND

For Union Hydrologic Groups
(Refer to Figure 2-2)

1 or Unit 1 Represents Group 1
2 or Unit 2 Represents Group 2
3 or Unit 3 Represents Group 3
4 or Unit 4 Represents Group 4

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

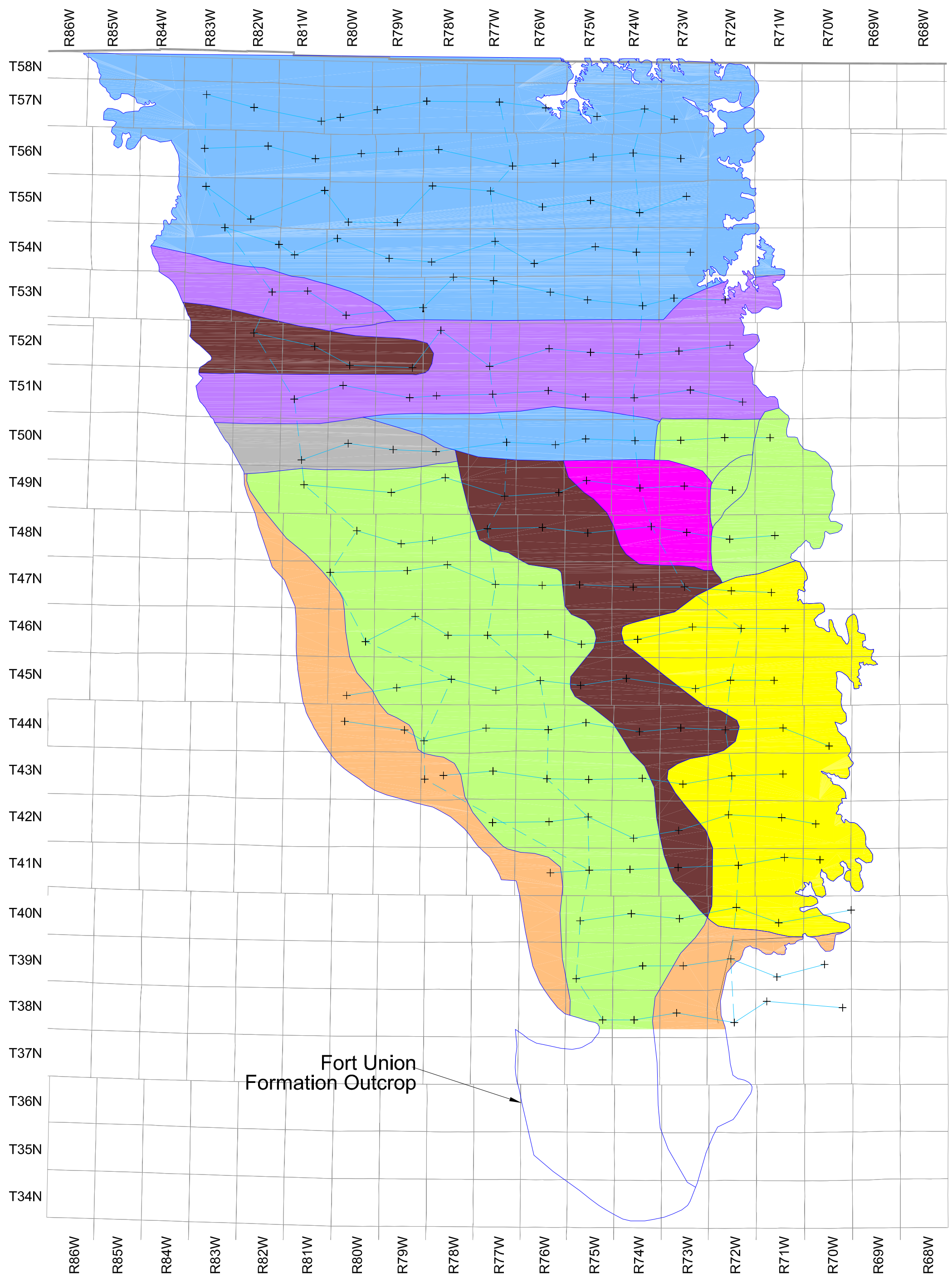
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 2-1C
TYPICAL GEOLOGIC CROSS SECTION
IN THE SOUTHERN POWDER RIVER BASIN

MODEL RUN: From 1999-2200 (08-26-02)

Date: 09/04/02	Drawing File: Figure 2-1abc.dwg
Scale: NTS	Drawn By: ETC

Figure 2-1C continued (11x17)



LEGEND

- 1 Group (1+2+3 Combined)
- 1 Group (4)
- 0 Groups
- E-W Geologic Cross Section
- N-S Geologic Cross Section
- 4 Groups (1) (2) (3) (4)
- 3 Groups (1) (2) (3)
- 3 Groups (1) (2+3 Combined) (4)
- 3 Groups (1+2 Combined) (3) (4)
- 2 Groups (1+2+3 Combined) (4)

0 11 22 44 Miles

N

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 2-2
AREAL EXTENT
FORT UNION FORMATION
HYDROLOGICAL GROUPS
POWDER RIVER BASIN

ANALYSIS AREA: CAMPBELL, CONVERSE, JOHNSON & SHERIDAN COUNTIES, WYOMING

Date: 09/04/02	Drawing File: Figure 2-2.dwg
Scale: As Noted	Drawn By: ETC

The thickness and structure of the upper Fort Union Formation coal seams are significantly influenced by faulting that was believed to be active during as well as after deposition of the coal-forming materials (Denson et al. 1980). The coal seams vary in thickness from a few feet to more than 200 feet and tend to thin out toward the southeast. The coals may lens out in the western and southwestern parts of the PRB. The combined thickness of the coal seams exceeds 50 feet over much of the eastern PRB, and this area is the focus of most commercial surface mining operations.

Groundwater flow in the coal seams is affected by differences in aquifer properties caused by varying patterns and degrees of fracturing in the coal and by faulting. The permeability of a coal is a function of fracturing and tends to be anisotropic (non-uniform) because flow occurs primarily through the fractures within the coal. Wells completed within coal seams generally yield from 10 to 50 gpm (approximately 0.02 to 0.1 cubic feet per second [cfs]) (Hadley and Keefer 1975), although some hydraulically fractured CBM production wells in the central PRB have initially yielded more than 100 gpm.

The coal and overburden are eroded where the upper Fort Union Formation coals intercept the land surface. Range fires and spontaneous combustion have ignited the areas of exposed coal at the land surface. The burning of the coal created a landform composed of highly permeable material (clinker) formed from the baking and subsequent collapse of the sediments overlying the coal. The clinker forms a source of recharge for the coal. However, the rate of recharge from the clinker units to the coal is often limited by a zone of relatively low permeability that typically occurs at the contact between the clinker and the underlying coal or shale. In many areas, this low-permeability zone causes ponding of water within the clinker that can result in the occurrence of springs at the coal contact. The Moyer Spring near Gillette is a good example of a contact spring that has its source in the clinker. Ponding of water in clinker has caused problems with pit inflow in coal mines when the clay-rich contact zone was breached.

Recharge to the upper portion of the Fort Union Formation also occurs on a regional basis through leakage from the overlying Wasatch Formation. This leakage occurs in areas where the hydraulic head in the Wasatch Formation is higher than in the Fort Union Formation (in other words, where the vertical hydraulic gradient is downward). Recharge and discharge also occur locally where coal underlies valley fill deposits (Martin et al. 1988). As more operating mines are reclaimed, these areas may become recharge areas for adjacent, unmined coal.

<u>Lower Tongue River/Lebo Shale Member</u>

The lower part of the Tongue River/Lebo member consists of sandstone lenses contained in a predominantly shale and siltstone matrix (Martin et el. 1988). Thick coal beds occur in the upper part of the Lebo Shale member (USGS 1974). Wells in the lower Tongue River/Lebo unit typically yield adequate quantities of water for domestic and livestock use if a sufficient thickness of saturated sandstone is penetrated. The communities of Gillette and Wright, as well as many of the subdivisions that surround Gillette, obtain most of their municipal water supply from wells screened in the sands of the lower Tongue River, Lebo, and Tullock members of the Fort Union Formation (HKM 1994). The City of Gillette and some of the nearby subdivisions have installed new water supply wells screened in the lower Tongue River, Lebo, and Tullock members during the past decade (Wester-Wetstein & Associates 1999e). Generally, these water supply wells are not screened through the upper part of the Tongue River member and are screened several hundred feet below the commercial coals in the uppermost part of the Fort Union Formation.

The claystones that underlie the upper Fort Union Formation coals act as a confining layer, partially isolating the coals from underlying strata. Stratigraphically lower aquifers are partially isolated from impacts that would result from dewatering associated with coal mining and CBM production in the coal aquifers in the upper portion of the Fort Union Formation. As with other aquifers in the Fort Union Formation, recharge is primarily from inflow at outcrop areas. Groundwater generally flows north.

Tullock Member

The Tullock member consists of fine- to medium-grained sandstone layers and thin coal seams interbedded with siltstone, shale, and carbonaceous shale (Martin et al. 1988). Sandstone content of the Tullock member ranges from 21 to 88 percent (Hotchkiss and Levings 1986). The sandstone layers in the Tullock member tend to be somewhat coarser and more massive than in the overlying Tongue River/Lebo members. In areas where the Lebo Shale is well defined, it provides a hydraulic separation between the Tullock member and the coals in the upper part of the Fort Union Formation. Some of the sandstone units within the Tullock member form important aquifers. Water yields of 200 to 300 gpm are available from the Tullock member, making this zone attractive for municipal and industrial uses. Many water supply wells for mine facilities are completed in this aquifer. Recharge to the Tullock member results from leakage through overlying strata and infiltration along the outcrop areas.

2.3 Hydrogeology of the Powder River Basin

The PRB is semi-arid and receives between 10 and 15 inches of annual precipitation (USDC/NOAA 1979). Most of the precipitation occurs during April, May, and June. With the exception of the largest rivers, most of the streams are intermittent or ephemeral. This section describes the overall hydrogeology of the Powder River Basin.

2.3.1 Recharge

Recharge to the groundwater system occurs from infiltration of direct precipitation (rain and snowmelt), runoff in creek valleys, and standing water in playas and impoundments. Direct infiltration of precipitation provides a minimal source of recharge over most of the area because it is limited by the climate and surface features. Infiltration can be significant in areas of more permeable surface geologic units such as the clinker that occurs in the outcrop areas of the coal units in the Wasatch and Fort Union Formations. Early (pre-mine) data for water levels indicate that hydraulic gradients for the coal/clinker are steep near the outcrop with the highest potentials in the clinker, suggesting that the clinker provides recharge to the coal. However, as noted in Section 2.2, the rate of recharge from the clinker units to the coal is often limited by a zone of relatively low permeability that typically occurs at the contact between the clinker and the underlying coal or shale.

Infiltration of surface water in creek valleys is considered the most important source of recharge to the underlying alluvium and shallow bedrock aquifers. Recharge from runoff in creek valleys is difficult to quantify in a predominantly ephemeral drainage system. A USGS study of two ephemeral drainages in the southern part of the PRB indicated stream losses of between 0.43 to 1.44 acre-feet per mile from individual storm runoff events (Lenfest 1987); these values were acknowledged to be underestimated. Recharge to shallow aquifers from stream valleys ranged from 3.56 to 26.5 acre-feet per mile for individual storm runoff events in the same study. In the Project Area, the average loss of flow per valley mile along the Powder River below Arvada was 0.31 cfs during late fall and early winter, as reported by Rankl and Lowry (1990).

Recent studies of surface water losses in several drainages of the PRB that receive CBM-produced water during dry weather conditions indicate that conveyance losses range from 64 percent to 100 percent of inflows (AHA 2001, Meyer 2000b, Babb 1998). Conveyance losses include both evapotranspiration and leakage into alluvium and bedrock that underlie the streams. Evapotranspiration varies seasonally, but probably accounts for less than 20 percent of the conveyance losses over the course of a year. A monthly water balance estimate for the Wild Horse Creek drainage found that evapotranspiration accounted for 18 percent of the conveyance loss associated with surface discharge of CBM-produced water within the drainage basin (HCI 2001). Recharge of shallow aquifers by leakage from rivers or streams is likely to account for more than 80 percent of the conveyance loss.

Hydraulic connection between the deep sandstones of the Wasatch Formation and the coals of the upper portion of the Fort Union Formation is limited by the low-permeability claystones in the lower part of the Wasatch Formation that separate the two units. However, there is potential for leakage from the sands into the coal if the hydraulic head (water level) in the coal is lower than in the overlying sands. Based on observation of water levels in nested monitoring wells, significant leakage into developed coals is expected to occur only where sands exist within about 100 feet above the coal. The leakage rate typically would be extremely small, but can amount to a significant portion of the total recharge into the coal taken over a large area. As sands in the Wasatch Formation tend to be discontinuous, the amount of leakage is also limited by the areal extent of the sands that exist within 100 feet of the coal.

Locally, the hydraulic connection between the coal and Wasatch sandstones may be enhanced if the integrity of the claystone units that act as a confining layer is compromised by water supply wells screened through both the coal and the overlying sands, deteriorating well casings, or poorly plugged oil and gas wells or exploratory drill holes. Leakage from the Wasatch sands into the coal also may be enhanced if water levels in the coal are lowered as a result of dewatering. Based on the limited hydraulic communication between the coal and the overlying Wasatch sands, a significant period (typically several years) likely would pass before noticeable drawdown (drop in water level) in the sands would be apparent.

Partial isolation of the sand aquifers that overlie the coal is indicated in the results of the BLM groundwater monitoring of the Marquiss CBM project, which has had the longest history of operation (since 1993). The BLM has monitored two paired wells since the project began. Well MP-22C is completed in the coal, and Well MP-22S completed in the first overlying sand zone, which occurs about 40 feet above the coal. A decline in the water level of more than 250 feet has been observed in the coal monitoring well during 9 years of monitoring. A water level decline of about 20 feet has been observed in the overlying sand aquifer during the same monitoring period. A significant lag time of about 4 years lapsed before any measurable drawdown was seen in the sandstone well. A second set of paired wells in the area (MP-2C and MP-2S) shows a similar trend.

The two sets of paired monitoring wells in the Marquiss field have yielded the only long-term monitoring data available for a Wasatch sandstone in a CBM development area within the PRB that has been active for several years. The BLM has been active in setting up and monitoring paired wells in other areas of the PRB, but the history for these wells is relatively short. The data from these nested wells can, however, be used to evaluate the vertical permeability and rate of leakage through the 40-foot thick claystone unit that separates the coal from the sandstone in this area (Chapter 8). The nature of the separation between the upper Fort Union coals and the overlying sandstones in the Wasatch Formation varies greatly over the PRB. Still, the data for the Marquiss area demonstrate that a 40-foot thick claystone unit provides a significant hydraulic barrier but allows a small amount of leakage from the overlying sandstone into the pumped coal. This leakage is important when the recovery of water levels after CBM pumping ceases is considered. Thicker sequences of claystone that separate the coal from the sandstone would be expected to provide even more effective isolation because induced vertical gradients through the claystone unit would be less. This analysis assumed that the partial isolation of the sand aquifers that overlie the coal, documented by BLM monitoring, applies to other areas of the PRB.

2.3.2 Groundwater Flow and Discharge

Conceptual models of the groundwater flow systems in the various lower Tertiary aquifers in the PRB have been presented in a number of previous studies, including Hagmaier (1971), Brown (1980), Feathers and others (1981), Hotchkiss and Levings (1986), Slagle et al. (1985), Martin et al. (1988), Rankl and Lowry (1990) and Bartos and Ogle (2002). All of these studies describe regional and local groundwater flow systems, although many of the studies reach different conclusions about the relative importance of these systems especially with respect to specific hydrogeologic units.

Hagmaier (1971) provides the first description of regional, intermediate, and local groundwater flow systems within the Powder River Basin of Wyoming. The author indicates that two major groundwater discharge areas significantly affect groundwater flow in the Powder River Basin. He suggests that the Powder River valley between Sussex and the Wyoming-Montana state line is the most significant groundwater discharge area. He further suggests that the topographic low along the valley influences groundwater flow to a depth of at least 2,000 feet below the valley. The second major discharge area is along the Dry Fork of the Cheyenne River and Antelope Creek. The topographic low along these valleys is thought to affect local and intermediate groundwater flow systems to a depth of less than 1,000 feet below the valley.

Brown (1980) developed regional potentiometric surface maps for the alluvial aquifers, the Wasatch Formation, and the Wyodak-Anderson coal zone for the eastern portion of the PRB. The author concludes that flow in the Wasatch Formation within the Project Area must be considered as a local system. The author also suggests that the coal is recharged by downward leakage through the Wasatch Formation.

Feathers and others (1981) describe groundwater flow for the Lower Tertiary Wasatch/Fort Union aquifer system and for the Upper Cretaceous Fox Hills/Lance aquifer system. The authors interpret groundwater recharge as occurring primarily through outcrop areas, although they indicate that downward leakage may also occur. Flow in the shallow water table is controlled by topography, while deep groundwater is thought to be stratigraphically controlled. The authors report that recharge rates, groundwater flow paths, and the extent of flow between hydrogeologic units are not well understood.

Hotchkiss and Levings (1986) completed a regional characterization and simulation model for five hydrogeologic units above the Bearpaw Shale in the PRB of Wyoming and Montana. The shallowest aquifer was the Tongue River aquifer, which in this study included the Wasatch Formation. The Lebo shale was represented as a confining layer that separates the Tullock aquifer (lower Fort Union Formation) from the Tongue River aquifer. The lowest aquifer was the Fox Hills-lower Lance Formation aquifer that is separated from the Tullock aquifer by the upper Hell Creek confining layer. The authors identify the importance of losing streams as a source of recharge for the shallowest aquifer. Potentiometric surface maps for all five hydrogeologic units indicate generally northward regional flow in the Wyoming part of the basin. The modeling study indicated discharge from the Tongue River aquifer to the Powder River along the northeastern boundary of the Project Area in Montana and via leakage through the Lebo shale.

Rankl and Lowry (1990) completed a regional study of the groundwater flow systems in the PRB of Wyoming and Montana. This study also addressed the hydrogeologic units above the Bearpaw Shale. Potentiometric data indicate stratigraphically controlled northward regional groundwater flow toward the

Powder River. However, the authors could not identify hydrologic or geochemical evidence of regional groundwater discharge. The authors found that the alluvial and clinker aquifers have more measurable effect on streamflow than do the bedrock aquifers. They conclude that the regional groundwater discharge to the north in the Powder River structural basin may be less than was previously thought.

Bartos and Ogle (2002) used major ion chemistry and environmental isotope data to investigate the groundwater flow systems in lower Tertiary aquifers. The authors present two conceptual models for groundwater flow in the Wasatch Formation and the Wyodak–Anderson coal zone. The first conceptual model indicates separate shallow and deep aquifer systems with little vertical migration between these flow systems. In this model, the deep flow system in the Wyodak–Anderson coal zone of the Fort Union Formation and the Wasatch Formation below 200 feet is represented as geochemically stagnant with little intermixing with shallow flow. The second conceptual model describes significant vertical flow through the Wasatch Formation into the underlying Wyodak-Anderson coal. In this model, the vertically migrating water evolves geochemically. Either conceptual model can explain the observed major ion chemistry and data on environmental isotopes. The authors conclude that both conceptual models as wells as the clinker recharge model of Heffern and Coates (1999) operate at the basin scale. The authors reach the same conclusions that Feathers and others (1981) reached 20 years earlier — that groundwater flow paths and the extent of flow between hydrogeologic units are not well understood.

A similar model for shallow and deep groundwater flow is summarized by Slagle et al. (1985) in their description of groundwater resources and groundwater flow in the northern PRB within Montana. The groundwater system can be divided into two general flow patterns: an upper, localized flow pattern controlled by topography that occurs in aquifers at depths of 200 feet or less; and a lower, regionalized, northward flow pattern that occurs at depths between 200 and 1,200 feet. Groundwater discharge areas for aquifers less than 200 feet deep primarily coincide with the valleys of perennial and intermittent streams. Water enters the shallow system by infiltration, flows downslope, and discharges to streams and rivers. Discharge areas for deeper aquifers generally coincide with the major drainages. Vertical movement between the aquifers is known to exist, but the rate of exchange is unknown. Subsurface inflow from Wyoming into the northern PRB enters Montana primarily in three areas: along the Tongue River; along Hanging Woman Creek; and between the Powder and Little Powder Rivers.

Martin et al. (1988) also summarize groundwater flow systems within the PRB. They conclude that local flow systems are predominant in the Wasatch Formation, with regional groundwater flow toward the north. The quantity of water and the flow rate are small because of the fine-grained nature of the rocks, which impedes the flow of water. Regional flow in the Fort Union coal zone is toward the northwest; however, the water in the coal in the southern PRB is not moving north but is moving toward local discharge areas where Antelope and Porcupine Creeks cross the coal subcrop.

Before significant coal mining and CBM development began, regional groundwater flow in the eastern part of the PRB was generally to the northwest (downdip), away from the recharge areas and towards potential discharge areas in the north-central part of the PRB. This regional flow is illustrated by the pre-mining potentiometric surface map, modified after Daddow (Daddow 1986), that is based on selected water level data from wells completed in the coal zone within the upper portion of the Fort Union Formation (Figure 2-3). The actual screened elevation was used for each well incorporated within the steady-state calibration. The calibration wells were placed in each layer that represented the Fort Union coal zone (Layers 8 through 12), since the potentiometric surface for each coal layer is nearly identical in steady state. Data to compile this map are relatively sparse because water levels reported for the wells often are suspect for a variety of reasons. The record also is skewed by the preponderance of data from mining activities that occur in the eastern PRB. Sources of the data used to generate the pre-mining map include the following: Daddow (1986), Lowry and Cummings (1966), Martin et al. (1988), USGS (1974), Hodson et al. (1973), the Gillette Area Groundwater Monitoring Organization (GAGMO) database for 1980 water levels, data for individual mines, and BLM monitoring data. The data used are considered relatively unaffected by mining because they were collected before significant mining began in the area (generally 1977 to 1980), or the wells are located far enough from mining or CBM development that these operations have minimal effect (Table 2-2).

Coal wells in the vicinity of the Powder River exhibit flowing artesian conditions that indicate upward flow gradients. These observations support the potential for groundwater discharge along the northern part of the Powder River, although physical evidence, in the form of springs and sustained base flow in rivers, is not readily apparent. It is assumed that most of the discharge is diffuse and may occur as underflow in the alluvium or be consumed by evapotranspiration so that it does not appear as surface flow. A significant portion of deeper groundwater flow in the PRB probably discharges farther north, into the Yellowstone River drainage basin.

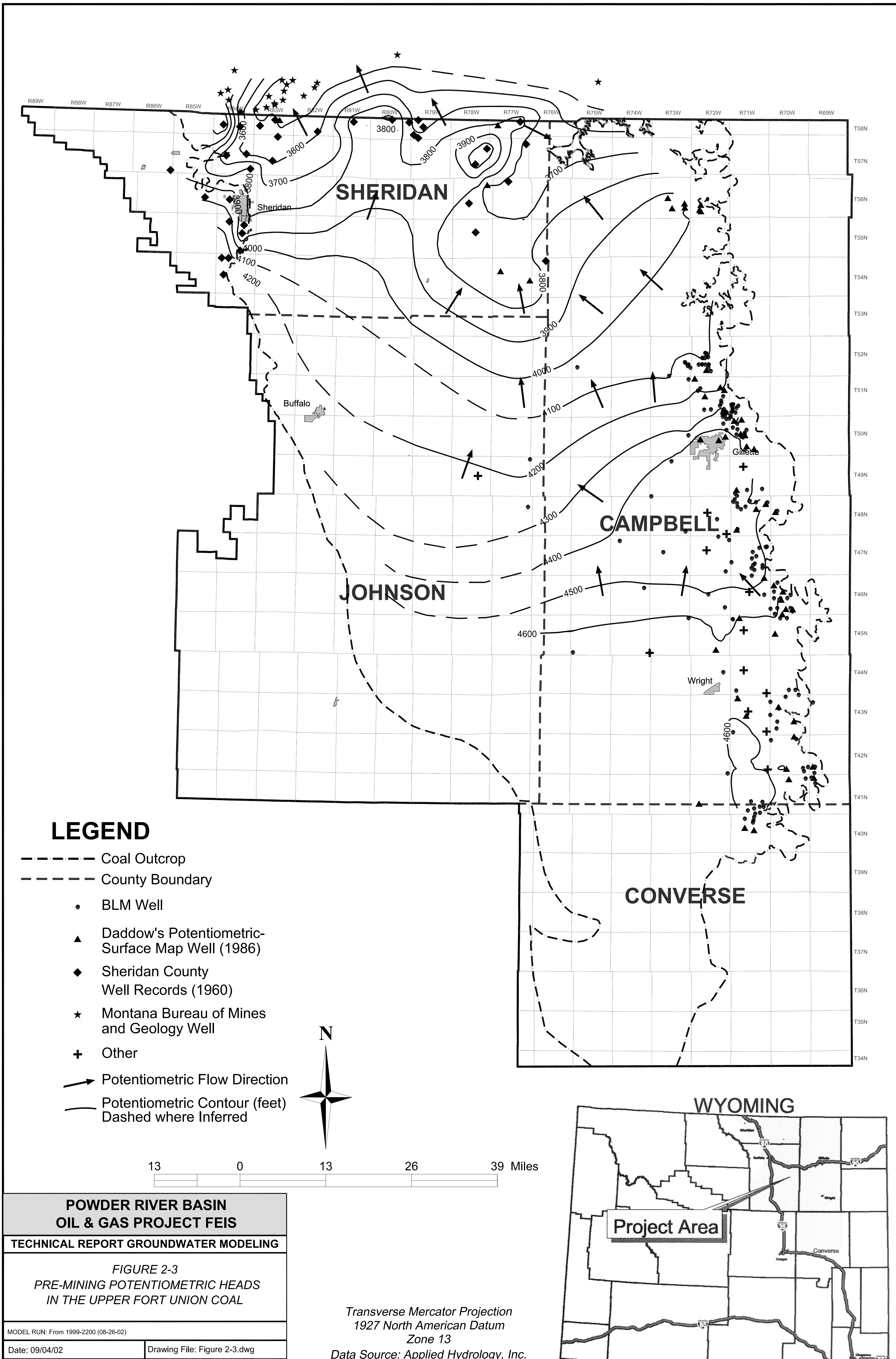


FIGURE 2-3
PRE-MINING POTENTIOMETRIC HEADS IN THE UPPER FORT UNION COAL

Figure 2-3 continued (11x17)

Table 2-2
Pre-Mining Potentiometric Head Data in the Upper Fort Union Formation

Name of Observation Well	Source Of Data	Township	Range	Section	Water Level Date	Observed head (ft)
40N71W17(BR-11)	Daddow	40N	71W	17	Oct-81	4695.0
41N69W6(42R17)	Daddow	41N	69W	6	Dec-80	4778.0
41N70W10(NA51)	Daddow	41N	70W	10	Dec-80	4642.0
41N72W29(TCSE-1)	Daddow	41N	72W	29	Nov-82	4658.0
42N69W31(42R11P)	Daddow	42N	69W	31	Dec-80	4744.0
42N70W17(BTR-1)	Daddow	42N	70W	17	NA	4608.0
42N70W3(BTR-20)	Daddow	42N	70W	3	NA	4653.0
42N70W33(SEAM-18)	Daddow	42N	70W	33	Aug-78	4595.0
43N70W27(BTR-154)	Daddow	43N	70W	27	Oct-73	4621.0
43N71W21	Daddow	43N	71W	21	Jul-79	4605.0
43N71W5(CDLTR-12)	Daddow	43N	71W	5	Aug-78	4616.0
447131a1	BLM	44N	71W	31	NA	4679.3
447214a1	BLM	44N	72W	14	1998	4594.75
457106c1	BLM	45N	71W	6	1997	4576.87
457301a1	BLM	45N	73W	1	1997	4606.23
457301a2	BLM	45N	73W	1	NA	4594.6
45N70W20(CDH-2)	Daddow	45N	70W	20	Aug-78	4639.0
45N70W4(CCR-3)	Daddow	45N	70W	4	NA	4600.0
45N71W5	Daddow	45N	71W	5	May-77	4612.0
45N72W36(HWY)	Daddow	45N	72W	36	NA	4600.0
467216d1	BLM	46N	72W	16	NA	4463.8
467225c1	BLM	46N	72W	25	1996	4600.2
467225c2	BLM	46N	72W	25	NA	4618.0
467236b1	BLM	46N	72W	36	NA	4612.6
46N70W16(CCR-22)	Daddow	46N	70W	16	NA	4628.0
46N70W18(CCR-27)	Daddow	46N	70W	18	NA	4582.0
46N70W27(CCR-13)	Daddow	46N	70W	27	NA	4712.0
46N70W29(CCR-15)	Daddow	46N	70W	29	NA	4596.0
46N70W33(CCR-6)	Daddow	46N	70W	33	NA	4660.0
46N70W34(CCR-7A)	Daddow	46N	70W	34	NA	4704.0
46N71W2(CORD-9)	Daddow	46N	71W	2	NA	4486.0
477119c1	BLM	47N	71W	19	1995	4405.0
477236b1	BLM	47N	72W	36	1995	4445.2
48N70W18(CA-317)	Daddow	48N	70W	18	May-76	4665.0
48N71W11(CA-321)	Daddow	48N	71W	11	May-76	4466.0
48N71W12(CA-319)	Daddow	48N	71W	12	May-76	4518.0
48N71W31(WRRI-10A)	Daddow	48N	71W	31	Nov-79	4457.0
49N71W31(HWY)	Daddow	49N	71W	31	Dec-77	4463.0
50N71W20	Daddow	50N	71W	20	Mar-77	4418.0
50N71W21	Daddow	50N	71W	21	May-77	4387.0
50N71W33(HWY)	Daddow	50N	71W	33	Jun-74	4379.0
50N71W34(M-17)	Daddow	50N	71W	34	Aug-78	4429.0
50N71W5(EG6C)	Daddow	50N	71W	5	Oct-76	4285.0
50N71W6(EG4)	Daddow	50N	71W	6	Oct-76	4306.0
50N72W13(Morries)	Daddow	50N	72W	13	Jun-78	4414.0
50N72W20	Daddow	50N	72W	20	NA	4467.0
50N72W23	Daddow	50N	72W	23	NA	4441.0
51N72W11(NRH-2)	Daddow	51N	72W	11	NA	4164.0

Table 2-2 (continued)
Pre-mining Potentiometric Head Data in the Upper Fort Union Formation

Name of Observation Well	Source Of Data	Township	Range	Section	Water Level Date	Observed head (ft)
51N72W14(NRH-268)	Daddow	51N	72W	14	NA	4203.0
51N72W21(GN-6)	Daddow	51N	72W	21	Feb-77	4268.0
51N72W6(NRH-246)	Daddow	51N	72W	6	NA	4140.0
52N72W33(NRH-245)	Daddow	52N	72W	33	NA	4180.0
53-80-18ca1-Qal	Sheridan	53N	80W	18	NA	4072.2
53-83-1bc-Qal	Sheridan	53N	83W	1	NA	4406.5
54-76-4bc-Tf	Sheridan	54N	76W	4	NA	3846.8
54N77W17bc01	BLM	54N	77W	17	Aug-84	3694.0
54N77W24(Malli)	Daddow	54N	77W	24	Feb-79	3703.0
55-78-15ba-Tf	Sheridan	55N	78W	15	NA	3699.1
56-77-4bd-Tf	Sheridan	56N	77W	4	NA	3682.1
56-78-21ca-Tf	Sheridan	56N	78W	21	NA	3742.1
56-83-14aa-Qal	Sheridan	56N	83W	14	NA	3664.7
56N72W32(BR76-102)	Daddow	56N	72W	32	Sep-76	4004.0
56N72W32(RM-2)	Daddow	56N	72W	32	Aug-75	3999.0
56N73W21(RM-6)	Daddow	56N	73W	21	Aug-75	3928.0
56N73W25(RM-3)	Daddow	56N	73W	25	Nov-79	3988.0
56N73W25(RM4-NE)	Daddow	56N	73W	25	May-76	4068.0
56N73W27(RM-5)	Daddow	56N	73W	27	Sep-75	3973.0
56N78W1(15-6-M)	Daddow	56N	78W	19	Aug-84	3672.0
57-77-1dc-Tf	Sheridan	57N	77W	1	NA	3670.9
57-79-6cd-Qal	Sheridan	57N	79W	6	NA	3761.5
57-81-7cb-Tw	Sheridan	57N	81W	7	NA	3637.1
57-84-13cc-Tf	Sheridan	57N	84W	13	NA	3562.0
58-79-31bd-Tf	Sheridan	58N	79W	31	NA	3722.4
58-79-32cc-Tf?	Sheridan	58N	79W	32	NA	3716.9
58-80-24ad-Tf	Sheridan	58N	80W	24	NA	3666.0
58-81-22cb-Tf	Sheridan	58N	81W	22	NA	3858.6
58N77W19d(7-11-M)	BLM	58N	78W	1	Aug-84	3802.0
58N83W22(BND-15)	Daddow	58N	83W	22	Apr-84	3475.0
bbirdc	BLM	47N	74W	5	NA	4412.3
bbirds	BLM	47N	74W	5	NA	4524.6
Bowers	BLM	42N	72W	36	NA	4567.9
diltsc	BLM	43N	71W	31	NA	4590.1
diltss	BLM	43N	71W	31	NA	4810.7
drywilos	BLM	44N	76W	35	NA	4852.7
Echeta	BLM	52N	75W	30	Apr-84	4020.9
Gilmore	BLM	49N	77W	1	NA	4166.8
hoes	BLM	47N	72W	7	NA	4637.3
ltreec	BLM	50N	73W	13	NA	4308.3
ltrees	BLM	50N	73W	13	NA	4445.4
mp22s	BLM	48N	72W	22	NA	4474.3
mp22ss	BLM	48N	72W	22	NA	4520.9
mp22vss	BLM	48N	72W	22	NA	4539.1
mp2s	BLM	47N	72W	2	NA	4490.6
Pistol	BLM	45N	75W	31	1997	4653.3
Sasquatc	BLM	48N	77W	12	1997	4244.8
mp22ss	BLM	48N	72W	22	NA	4520.9

NA = Not Available

Groundwater flow is to the north in the southern portion of the Project Area, moving toward local discharge areas where Antelope and Porcupine Creeks cross coal outcrops (Martin et al. 1988). Local patterns may differ from regional flow. The influence of faulting and areas of coal cutout near T46N, R71W, and R72W are apparent in the significant steepening of the potentiometric gradient across this area. The pre-mining potentiometric gradient in the coal is flat south of this area, suggesting relatively high permeability.

Static water levels in some water wells and water yields from wells completed in the coal and to a lesser extent from wells completed in the Wasatch Formation have been affected by CBM development in the PRB. Meyer (1999) summarizes the drawdown of hydrostatic head in the Wyodak Anderson coal zone from 1980 to 1998. The estimated potentiometric drawdown in selected BLM monitoring wells within the Project Area through 2000 is shown in Figure 2-4. This figure was developed by calculating the drawdown from the initial measurements at these wells until the end of 2000. The calculated drawdowns could underestimate the actual drawdown at these locations because some of these wells already may have been affected by development when measurements started. At the end of 2000, drawdown of the hydrostatic head in wells is interpreted to be 100 to 200 feet in extensively developed areas. However, water levels can vary considerably over short distances as a result of changes in geologic conditions. The greatest existing drawdown that is documented is interpreted to occur in the following four townships: T47N R72W; T48N R72W; T47N R73W; and T48N R73W.

Groundwater Discharge to the Powder River

As discussed previously, the Powder River valley between Sussex, Wyoming, and Moorhead, Montana, has been interpreted as a significant area of groundwater discharge (Hagmaier 1971). However, Rankl and Lowry (1990) found no measurable effect of regional groundwater discharge on streamflow in this reach. Gain-loss studies of the Powder River presented in Ringen and Daddow (1990) indicate loss of flow to the alluvium for many months, including the low evaporation months of December, January, and February. The authors suggest that groundwater storage in the alluvium is so depleted by evapotranspiration during the growing season that the river is still replenishing the water in the alluvial aquifer during the winter.

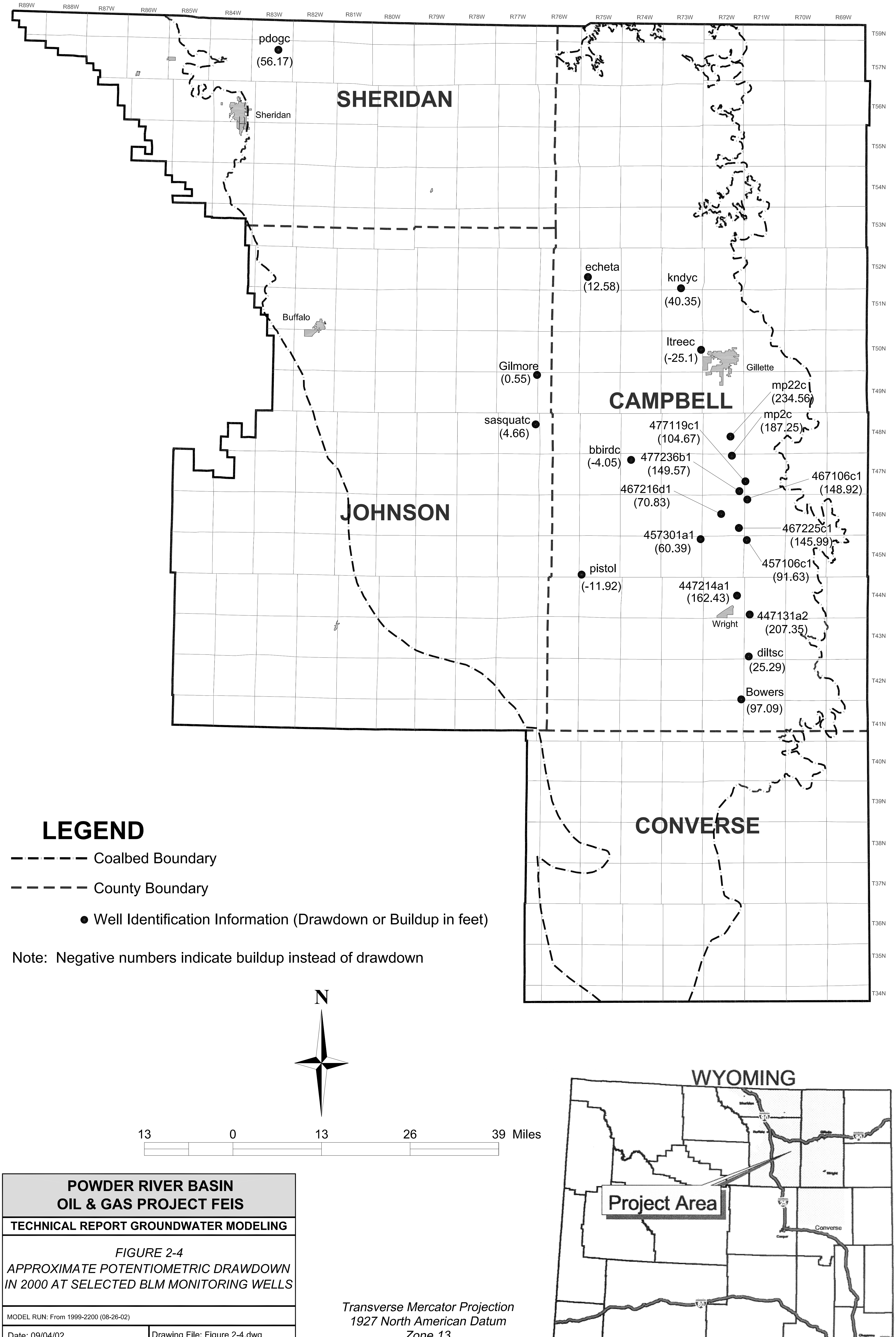


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FIGURE 2-4
APPROXIMATE POTENTIOMETRIC DRAWDOWN IN 2000 AT SELECTED BLM MONITORING WELLS

MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/04/02	Drawing File: Figure 2-4.dwg
Scale: As Noted	Drawn By: ETC

Transverse Mercator Projection
1927 North American Datum
Zone 13
Data Source: Applied Hydrology, Inc.

Figure 2-4 continued (11x17)

From these studies, it appears that that most of the bedrock discharge is diffuse and may occur as underflow in the alluvium or be consumed by evapotranspiration so that it does not appear as surface flow. A water balance by O'Hayre (2002) for the alluvium of the Powder River between Sussex and Moorhead was performed to estimate the likely magnitude of regional bedrock discharge to the alluvium.

The surface area of alluvium within the 155-mile reach of the Powder River valley from Sussex to Moorhead is 32,600 acres. The vegetation along the valley is grass with many stands of cottonwood and underbrush. Most of the valley is undeveloped rangeland, although there are six small areas irrigated areas: one at Sussex, two downstream of Sussex, one near the confluence with Clear Creek, and two downstream of Clear Creek (Ringen and Daddow 1990).

Surface flow in the Powder River was analyzed using the historical streamflow records for the USGS gauging stations on the Powder River at Sussex, Wyoming, and at Moorhead, Montana, and for Clear Creek and Crazy Woman Creek near their confluence with the Powder River. Concurrent measurements are available at all of these stations for 11 water years (1951 through 1957 and 1978 through 1981). The average annual gain in flow in the Powder River during these years is 20 cfs.

Ringen and Daddow (1990) suggest that the annual gain in flow within the reach of the Powder River between Sussex and Moorhead is attributable to runoff from the unmeasured ephemeral streams along the reach. The average annual runoff from the unmeasured watershed area along the reach between Sussex and Moorhead was estimated using two methods. First, the method of Lowham (1988) was used to estimate average annual streamflow of 50 cfs for this 2,932-square-mile watershed area. Second, an average annual water yield of 0.0211 cfs/square mile for this reach of the Powder River was estimated from 9 years of streamflow measurements for Headgate Draw near Buffalo, Wyoming, an ephemeral stream that drains a 3.32–square-mile watershed. This draw was the only ephemeral stream within the Powder River watershed between Sussex and Moorhead that was used in the study by Lowham (1988). The estimated average annual water yield for this relatively small drainage was similar to the average annual water yield water yield estimated for the 1,235-square-mile drainage of the Little Powder River above Dry Creek near Weston, Wyoming.

Average annual alluvial groundwater discharge to evapotranspiration (ET) was estimated from the study by Lenfest (1987). The author estimated alluvial groundwater loss to ET during the growing season at 12 sites located within the Powder River basin. Groundwater loss to ET ranged from 8.3 inches to 14.9 inches and averaged 12.7 inches. Using the average rate of 12.7 inches of alluvial groundwater loss to ET, the total annual groundwater loss over the reach of the Powder River would average 47.7 cfs.

With these estimates, a water balance of the alluvial aquifer was completed and is summarized in Table 2-3. The regional groundwater inflow from the bedrock units is estimated as a residual in the water balance analysis. The water balance evaluation also assumes that the inflow of alluvial groundwater at the upstream boundary near Sussex is approximately the same as the outflow of alluvial groundwater at the downstream boundary near Moorhead. Differences between flow of alluvial groundwater at the boundaries would have negligible effect on the overall water balance because outflow of groundwater in the alluvium near Moorhead is low relative to the other terms in the water balance.

Table 2-3
Water Balance Analysis of Powder River Valley from Sussex, Wyoming, to Moorhead, Montana

		Powder River @Moorhead	Powder River @Sussex	Clear Creek @mouth	Crazy Woman Creek @mouth	Outflow-Inflow (Sussex to Moorhead Reach)	Inflow Ungauged Areas (1)	Average Alluvial Groundwater Discharge to ET (cfs) (2)	Bedrock Groundwater Inflow (cfs)
Drainage Area (sq mi)		8088	3090	1110	956		2932		
Ave. Annual Flow (cfs)	Record	424.4	183.1	166.9	41.4	33.0			
	Comparable Record	365.4	167.7	141	36.7	20.0	50.0	47.65	17.65
Alternative Water Balance using Yield for Headgate Draw						20.0	61.8	47.65	5.83

(1) Two methods were used to estimate the average discharge from ungauged watershed areas

Method	Watershed	Area (sq mi)	Annual Q (cfs)	Water Yield (cfs/sq mi)
Method of Lowham (1988)	Ungauged Areas	2932	50.0	0.0171
Using average annual water yield for Headgate Draw near Buffalo, Wyoming	Headgate Draw Sta 6316480	3.32	0.07	0.0211
	Ungauged Areas	2932	61.8	0.0211

(2) Method used to estimate annual alluvial groundwater discharge to ET from:
Lenfest (1987).

The water balance analysis in Table 2-3 indicates that regional inflow of groundwater from bedrock may be in the range from 5 cfs to perhaps as high as 20 cfs. If the regional discharge of groundwater from bedrock to the valley of the Powder River is assumed to be 5 cfs, the inflow of groundwater from bedrock at the contact with the alluvium of the Powder River would average only 1.3 inches/year or about 10 percent of the groundwater loss to evapotranspiration. With inflow rates of this magnitude, it is unlikely that Rankl and Lowry (1990) or Ringen and Daddow (1990) would have been able to detect a measurable effect of regional groundwater discharge in their studies of surface water chemistry and fluctuations in alluvial groundwater along this reach of the Powder River. However, if the regional groundwater discharge from bedrock to the valley of the Powder River is on the order of 20 cfs, the contribution would be more than 40 percent of the estimated loss to ET. In this case, Ringen and Daddow (1990) likely would have been able to detect a measurable effect of regional groundwater discharge on the seasonal fluctuations in water levels and major ion chemistry of groundwater within the alluvium along this reach of the Powder River, unless the locations of monitoring wells completed in the alluvium are unrepresentative of alluvial groundwater conditions along this reach.

An additional component of regional groundwater discharge occurs at the flowing artesian wells located along the Powder River valley in this reach between Sussex and Moorhead. A study of the groundwater resources of Sheridan County by Lowry and Cummings (1966) identified 35 flowing artesian wells located along the Powder River valley within Sheridan County. Estimates or measurements of flow rates were reported for 31 of the 35 wells. The combined flow rate from these 31 wells was 0.57 cfs. Based on these results, it is expected that discharge of groundwater from flowing artesian wells located along the entire Powder River valley from Sussex to Moorhead probably exceeds 1 cfs.

2.3.3 Recoverable Groundwater in the Powder River Basin

The Lower Tertiary aquifers consist of sandstone beds and coals within the Wasatch Formation and the Fort Union Formation. The water-yielding sandstones and coals are interbedded with claystones and siltstones. Although numerous studies have been conducted on the Lower Tertiary aquifers of the Powder River Basin, there have been no estimates of the volume of recoverable groundwater in these aquifers.

Recoverable groundwater is the water present within an aquifer that can be extracted using pumping wells. Recoverable groundwater is considerably less than the total volume of water in storage because a portion of water is retained in the voids by capillary forces and cannot flow to wells. The cumulative impacts of CBM development on groundwater supplies should consider the relative proportion of recoverable groundwater within the basin that is removed during CBM operations as well as the extent of drawdown of potentiometric levels in the produced coals and overlying and underlying units.

Recoverable groundwater is usually calculated from the specific yield of the aquifers. The specific yield is the amount of water that can be removed from the saturated pores of the aquifer by gravity drainage to wells. The specific yield can be determined or estimated through one or more of the following methods:

- Results for observation wells obtained during pumping tests conducted within the unconfined portion of the aquifer
- Laboratory analysis of cores of aquifer materials, or
- Literature values for aquifers with similar characteristics.

These calculations of recoverable groundwater do not consider the economics of groundwater recovery. As aquifer storage is depleted, the cost of pumping and required well spacing will usually increase to maintain yields. Generally, the recovery of groundwater becomes uneconomic before all recoverable groundwater has been removed. Estimates of recoverable groundwater do not consider the component of groundwater stored in the claystones and siltstones that will leak into the sandstones and coals when these units are pumped for water supply or CBM production. However, the volume of groundwater released from storage in the claystones and siltstones is small relative to the recoverable groundwater in the sandstones and coals.

Methodology for Estimating Volume of Recoverable Groundwater

The volume of recoverable groundwater in the Wasatch and Fort Union Formations within the Project Area was estimated as follows:

- The thickness of the sandstones and coal units within the Wasatch and Fort Union Formations within the study area was determined.

- The volume of sandstones and coal units within the formations was multiplied by the specific yield of the sandstone and coal units to calculate the volume of recoverable groundwater within each unit.

Estimating the Volume of Sandstone and Coal Units within the Wasatch and Fort Union Formations

The volume of sandstone in the Wasatch and Fort Union Formations within the Project Area was estimated from the USGS Miscellaneous Investigations Series Map I-1317, "Thickness, Percent Sand, and Configuration of Shallow Hydrological Units in the Powder River Basin, Montana and Wyoming (Hotchkiss and Levings 1981)." This investigation provides maps of the thickness of sand for the following geologic units:

- Tongue River-Wasatch Aquifer
- Lebo Confining Layer
- Tullock Aquifer

The volume of recoverable groundwater was estimated for the sandstones in these three geologic units. Boundaries, thickness (in feet), and the percentage of sand in these geologic units were digitized in AutoCAD. Digitized layers were then geo-referenced and interpolated to obtain the thickness and percentage of sand for 750-meter spaced grids within the boundaries of the geologic unit. The interpolated percentages of sand were multiplied by the corresponding interpolated thickness values for each grid and were summed to calculate the volume of sandstone within each of the geologic units.

All the potential target coal units for CBM development are located within the Tongue River-Wasatch aquifer. The volume of the target coals within the Tongue River-Wasatch aquifer was estimated from a database provided by Goolsby, Finley and Associates (2001). The database identified the coal units with development potential in each township within the PRB. The database includes the top and bottom depth below the topographic surface elevation and the thickness of each coal at each of 182 wells or core holes that were determined to be most representative of each township in the Project Area. The data did not extend south of T38N, so the coals located south of T38N are not included in the estimated volume. However, the coals south of T38N are very thin and would not contribute much to the cumulative volume.

The thickness and percentage of coal in the Tongue River-Wasatch aquifer were interpolated in ArcView using an inverse distance weighting method. The interpolated percentages of coal were multiplied by the corresponding interpolated thickness values and were summed for each grid to estimate the volume of coal in the Tongue River-Wasatch aquifer within the Wyoming portion of the PRB, north of T37N.

Estimating the Specific Yield for Sandstone and Coal Units

The estimates of specific yields for the sandstone and coal units within the Lower Tertiary aquifers were based on existing literature and interpretations from results for observation wells obtained during pumping tests conducted within the unconfined portion of these aquifer units.

Johnson (1967) provides a comprehensive review of specific yields for sedimentary materials. The specific yield decreases with the particle size of the sediments. The specific yields were reported to range from 10 percent to 32 percent for fine sands and from 15 percent to 32 percent for medium sands. The geologic formation and characteristics of the Lower Tertiary aquifers of the Denver Basin in Colorado and the Powder River Basin in Wyoming are similar. Values for specific yield of the Denver Basin aquifers in Colorado are specified by rule (2 Colorado Code of Regulations [CCR] 410-1, Section 5.7) for determining the volume of recoverable groundwater in adjudication of water resources. The specific yield designated for the shallower Dawson aquifer is 20 percent, and the specific yield for the Denver and Arapahoe aquifers is 17 percent.

Estimates of specific yield for scoria (30 percent) and the Smith Coal (7 percent) were used in a groundwater modeling study for the EIS completed for the Dry Fork Mine near Gillette (Sato and Associates and Koch and Associates 1989). This study included a review of results for pumping tests from the proposed Dry Fork Mine and seven other nearby mining operations. The estimate of specific yield for the scoria was comparable to the storage coefficient calculated from the pumping tests in the scoria. The 7 percent estimate for specific yield of the coal was higher than would be expected based on the water storage characteristics of coal. This estimate was not based on the storage coefficient calculated from the pumping tests of the coal.

A comprehensive review of aquifer characteristics identified from pumping tests was used to support the groundwater modeling and interpretations developed in this EIS (Appendix B). Most of these pumping tests have been conducted in support of plans for coal mining and reclamation. This review found only a few tests that provided estimates of specific yield for the coals and overburden. The median value for specific yield of the coal was found to be 0.4 percent, while the median value for specific yield of the overburden was 13 percent. The 0.4 percent value for specific yield for the coal is consistent with the approximate value for cleat porosity of the coals and was used to estimate recoverable groundwater in the coals. The value for specific yield of the overburden (13 percent) is for a well completed in sandstone with interbeds of mudstone and siltstone and is lower than might be expected for clean sandstones. The estimated value for specific yield of sandstones that contain interbeds (13 percent) was used to estimate recoverable groundwater in the sandstone units within the Tongue River-Wasatch aquifer, the Lebo confining layer, and the Tullock aquifer. This estimated specific yield is lower than the estimates based on rules for the Lower Tertiary aquifers in the Denver Basin. This estimate provides a lower bound estimate of recoverable groundwater in the sandstone units within the Lower Tertiary aquifers of the PRB.

Volume of Recoverable Groundwater

The volume of recoverable groundwater in the sandstones within the Tongue River-Wasatch aquifer, the Lebo confining layer, and the Tullock aquifer was calculated from the volume of sandstone in each of these units multiplied by the estimated percent-specific yield value for sandstone (13 percent). The volume of recoverable groundwater in the coals within the Tongue River-Wasatch aquifer was calculated from the volume of coal multiplied by the estimated percent-specific yield value for coal (0.4 percent). These results are summarized in Table 2-4.

These results show the large volumes of recoverable groundwater that occur in the Lower Tertiary Aquifers within the Project Area. Most of the recoverable groundwater occurs in the sandstone units. The recoverable groundwater in the coals is only a small fraction of the recoverable groundwater in the sandstones.

Table 2-4
Estimates of Recoverable Groundwater in the Wyoming Portion of the Powder River Basin

Hydrogeologic Unit	Surface Area (acres)	Average Formation Thickness (ft)	Percentage of Sand/Coal	Average Sand/Coal thickness	Specific Yield (percent)	Recoverable Groundwater (acre-ft)
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	227,137,336
Tullock Aquifer Sandstones	7,999,682	1,110	52	430	13	447,246,784

2.4 Groundwater Use

There are almost 27,000 Wyoming State Engineer's Office (WSEO)-permitted, non-CBM water wells in and around the Project Area. Table 3-7 in the FEIS summarizes data on the type and number of wells in the Project Area. Where information on total depth was available for a well, it was categorized as either a Wasatch or Fort Union Formation well based on location and the estimated depth of the Wasatch-Fort Union contact at that location. If there was no information on depth, the well was classified as "Unknown." Almost 25 percent of the nearly 27,000 permitted, non-CBM water wells in the PRB are used for domestic purposes. About 1.5 percent of the permitted wells provide for irrigation or municipal uses. The remaining nearly 75 percent of the water wells in the Project Area are used for stock watering and other purposes. Figure 3-4 in the FEIS shows the relative numbers of permitted water wells and existing CBM wells located within the Project Area. The Upper Belle Fourche River and the Upper Tongue River sub-watersheds contain the most permitted non-CBM water wells, 23 percent of the totals for the Project Area for the Upper Belle Fourche River, and 16 percent for the Upper Tongue River.

Permitted groundwater withdrawals are summarized by type and sub-watershed in Table 2-5 for 1995. Groundwater consumption in the Project Area in 1995 was about 90.8 million gallons per day, or about 101,770 acre-feet per year (USGS 2001). About 26 percent of this consumption was in the Belle Fourche

River watershed. Mining-related withdrawals associated with pit dewatering and operational consumption accounted for about 70 percent of the groundwater use in the Project Area 1995.

Groundwater for domestic consumption is derived predominantly from the Fort Union and Wasatch aquifers. About 65 percent of domestic consumption of groundwater occurs in the Belle Fourche River and upper Tongue River basins, where most of the population resides. Stock watering and irrigation accounted for slightly more than 12.2 million gallons of groundwater used per day (13,720 acre-feet per year) in 1995. The Wasatch and Fort Union aquifers are the most important local sources of groundwater in the PRB (Feathers et al. 1981). They are developed extensively for shallow domestic and livestock wells. Domestic and livestock wells usually are low-yield (less than 25 gpm), intermittent producers. Water suitable for domestic and livestock uses typically can be found less than 1,000 feet below the surface.

Municipal water supply wells in the Project Area are predominantly associated with the City of Gillette's use of the Fort Union Formation for part of its water supply. The winter base demand for municipal water use in Gillette is 3.0 to 3.5 million gallons per day (gpd) and the peak demand is 10 million gpd (Wester-Wetstein 1994). Peak demands for the Gillette area are projected to grow to 18.1 million gpd by 2020 (HKM 1994). The town of Wright and several subdivisions around Gillette, including Antelope Valley, Crestview, and Sleepy Hollow, also draw water supplies from the Fort Union Formation. Generally, these water supply wells are not screened through the upper part of the Tongue River member, but instead are screened several hundred feet below the commercial coal seams of the uppermost Fort Union Formation. The communities of Sheridan and Buffalo obtain municipal water supplies from surface water sources.

CBM water withdrawals were not significant in 1995, averaging only about 2 million gallons per day or 2,200 acre-feet per year (Table 2-5) (WOGCC 2001). The increase in water production from CBM operations from 1987 through 2000 is summarized by watershed in Table 2-6 based on water production reported to the Wyoming Oil and Gas Conservation Commission (WOGCC). Water production has increased dramatically since 1999.

Table 2-5
1995 Groundwater Withdrawals[1] within the PRB Project Area

Sub-Watershed	Public Supply	Commercial Use	Domestic Use	Industrial Use	Mining Use	CBM Use[2]	Livestock Use	Irrigation Use	Total
Little Bighorn River	0	0	0	0	0.01	0	0.03	0	**0.04**
Upper Tongue River	0	0.03	0.56	0.05	0.1	0	0.19	0	**0.93**
Middle Fork Powder River	0.09	0.01	0.02	0	0.73	0	0.07	0.24	**1.16**
Upper Powder River	0	0	0	0	1.86	0	0.23	0	**2.09**
South Fork Powder River	0	0	0	0	2.53	0	0.05	0.18	**2.76**
Salt Creek	0.02	0.01	0.01	0	1.35	0	0.03	0.1	**1.52**
Crazy Woman Creek	0	0	0	0	0.32	0	0.06	0	**0.38**
Clear Creek	0.03	0.02	0.2	0.01	0.29	0	2.01	0	**2.56**
Middle Powder River	0	0	0	0	0.42	0	0.03	0	**0.45**
Little Powder River	0	0	0	0	9.4	0.29	0.15	0.02	**9.86**
Little Missouri River	0.04	0	0.01	0	1.33	0	0.07	0.46	**1.91**
Antelope Creek	0	0	0	0	6.3	0	0.08	0.15	**6.53**
Dry Fork Cheyenne River	0	0	0	0	0.52	0	0.03	0.11	**0.66**
Upper Cheyenne River	0	0	0	0	15.27	0	0.14	3.42	**18.83**
Lighting Creek	0	0	0	0	0.72	0	0.06	2.21	**2.99**
Upper Belle Fourche River	3.78	0.04	0.78	0.07	15.5	1.68	0.29	1	**23.14**
Middle North Platte River	6.52	0.1	0.49	0.08	7.01	0	0.17	0.67	**15.04**
Total Project Area	**10.48**	**0.21**	**2.07**	**0.21**	**63.66**	**1.97**	**3.69**	**8.56**	**90.85**

Sources: USGS 2001, WOGCC 2001
1 Water use is expressed in millions of gallons per day (mgd).
2 CBM water production during 1995 based on WOGCC database.
For Reference:
One gallon = 0.134 cubic feet, One acre-foot = 43,560 cubic feet, One acre-foot = 325,829 gallons

Table 2-6
Coal Bed Methane Water Production[1] (1987-2000)

Year	Belle Fourche	Little Powder	Powder River	Cheyenne	Tongue	Total
1987	0.00	0.00	0.00	0.00	0.00	0.00
1988	0.00	0.00	0.00	0.00	0.00	0.00
1989	0.00	0.03	0.02	0.00	0.00	0.06
1990	0.00	0.06	0.00	0.00	0.00	0.06
1991	0.00	0.18	0.00	0.00	0.00	0.18
1992	0.02	0.21	0.00	0.00	0.00	0.22
1993	0.45	0.20	0.00	0.00	0.00	0.65
1994	0.84	0.19	0.00	0.00	0.00	1.03
1995	1.68	0.29	0.00	0.00	0.00	1.97
1996	1.97	0.34	0.00	0.00	0.00	2.31
1997	4.42	0.75	0.00	0.02	0.00	5.19
1998	6.34	1.86	0.00	0.10	0.00	8.30
1999	10.34	3.78	1.05	2.34	0.29	17.80
2000	23.06	7.67	5.80	5.78	0.76	43.07

Source: WOGCC 2001
[1] All water production is expressed in million gallons per day (mgd) for comparison with Table 2-5.