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.

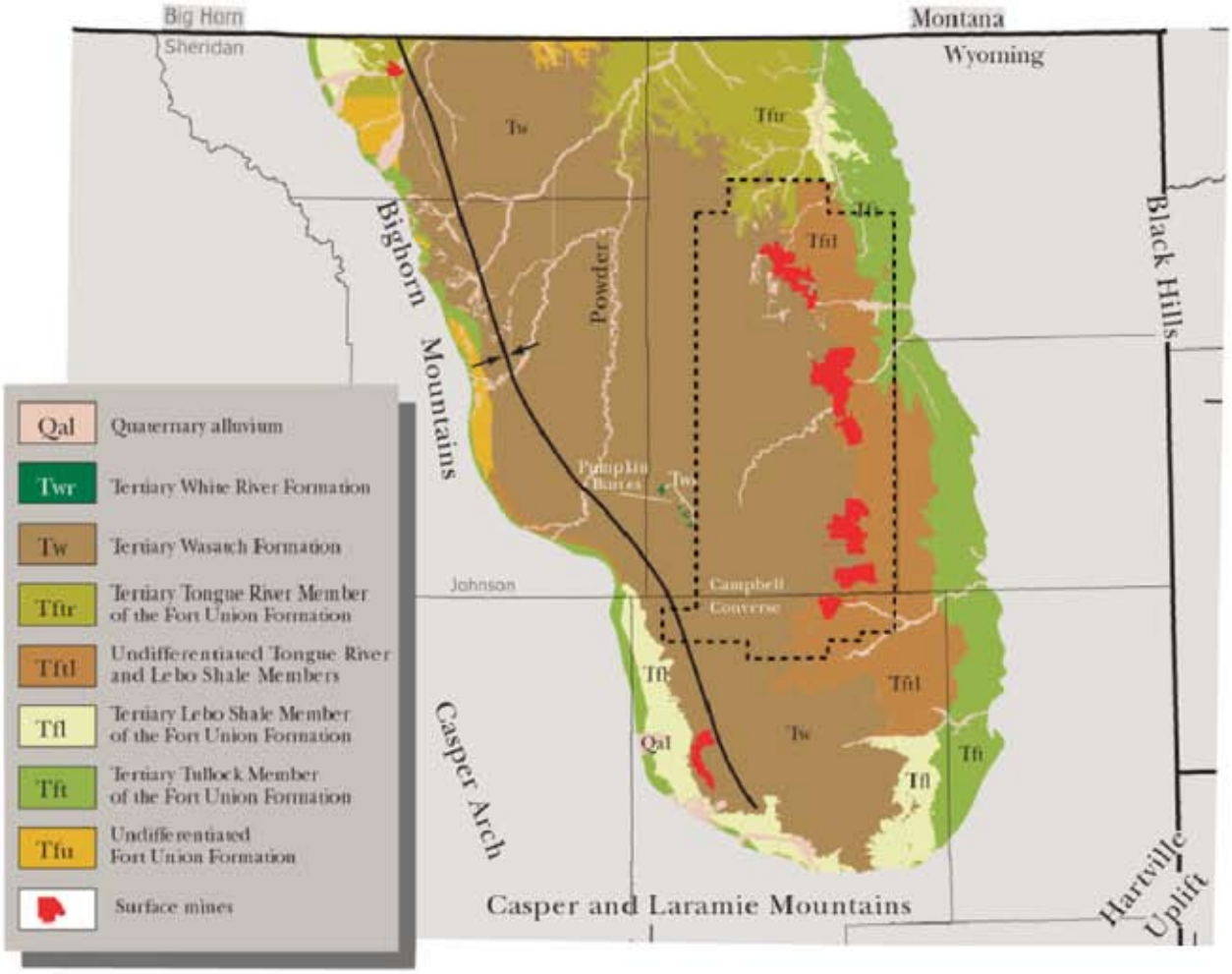
4.1.1.1 Hydrogeologic Framework of the Eastern PRB

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,



Structural axis of the basin

Groundwater Modeling Domain

Powder River Basin Coal Review

Figure 4.1-1

Geologic Map

Source: Flores et al. 2001.

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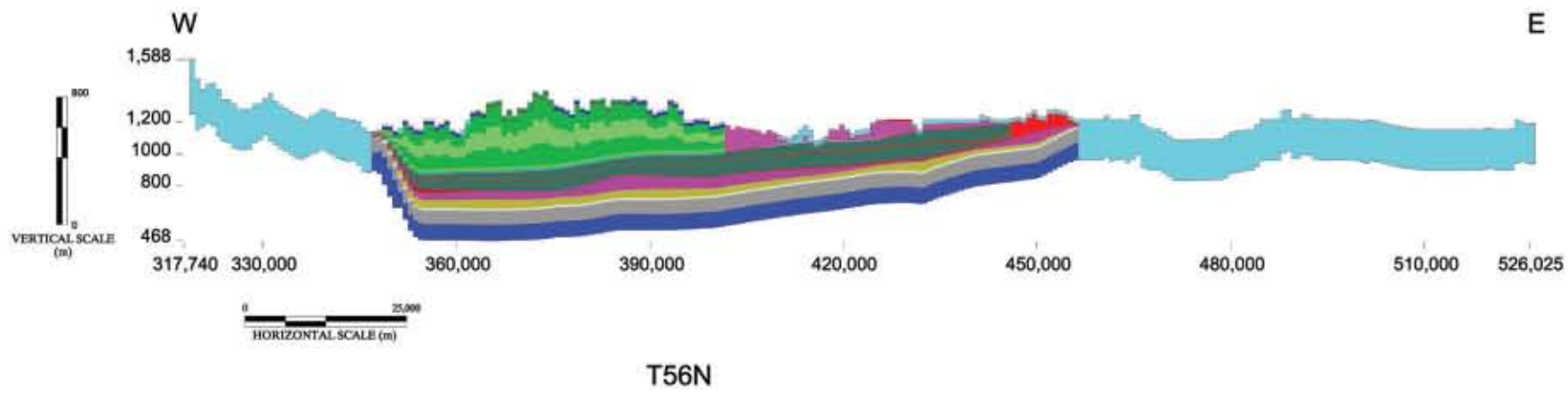
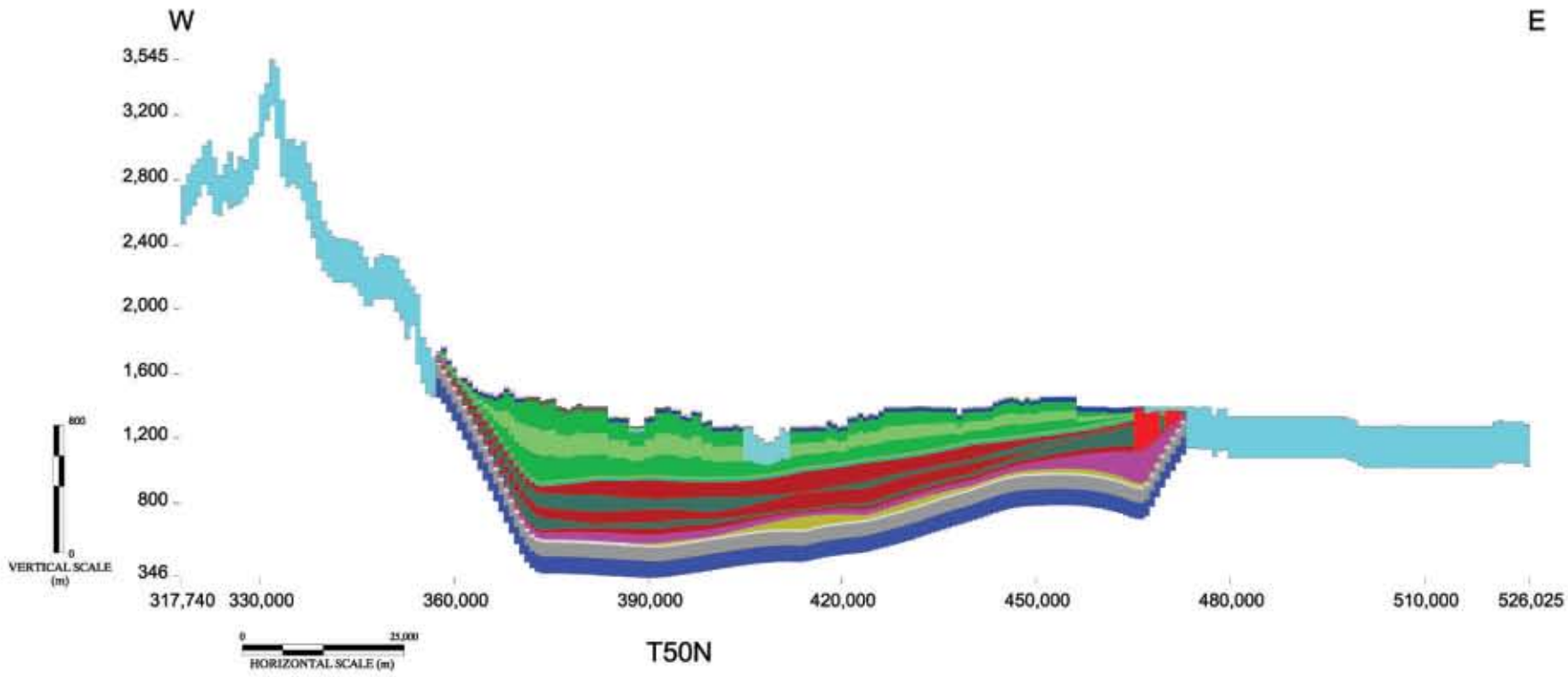
Table 4.1-1
Regional Model Layers[1]

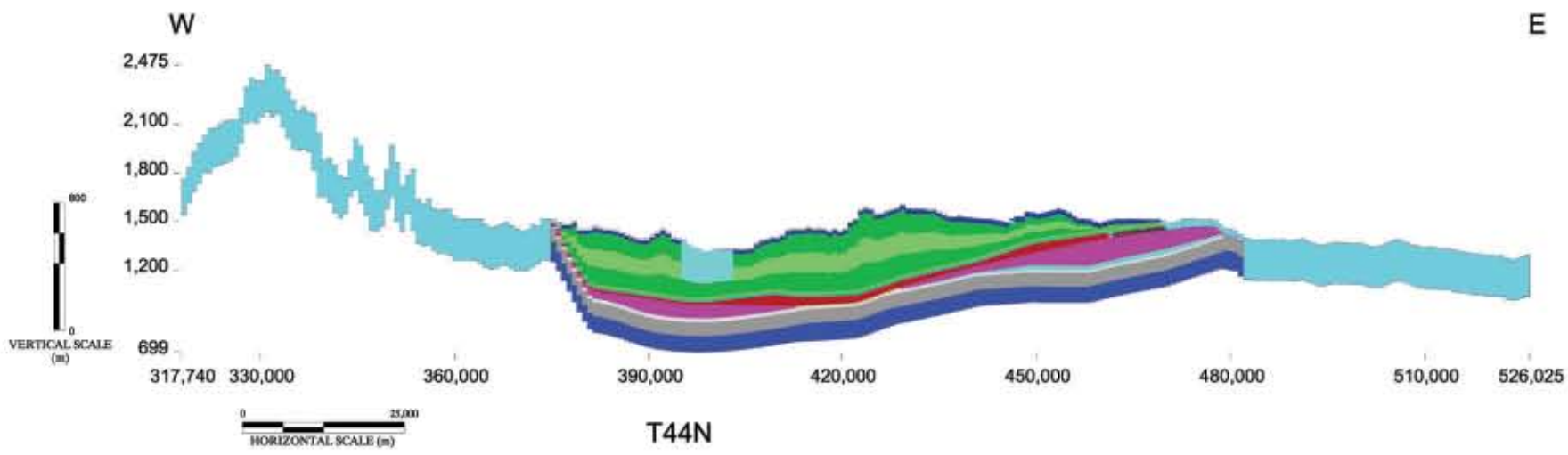
PRB Oil and Gas EIS Regional Model Layer	Geologic Formation	Coal Unit Designation	Geologic Unit	Predominant Lithologies	CMGM HSU
1	Wasatch Formation	--	Upper Wasatch Formation and alluvium	Sandstone, siltstone, claystone	1
2	Wasatch Formation	--	Shallow Wasatch sands	Sandstone, siltstone	1
3	Wasatch 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







LEGEND

- No Flow Node
- Alluvium
- Shallow Wasatch Sands
- Confining Unit within Wasatch
- Intermediate Wasatch Sands
- Deep Wasatch Sands
- Confining Unit at Wasatch Base
- Ft. Union Coal (Wyodak)
- Ft. Union Coal Units
- Confining Unit Between Ft. Union Coals
- Confining Unit at Base of Coal Units
- Lower Ft. Union
- Lower Ft. Union Sand Aquifer Units

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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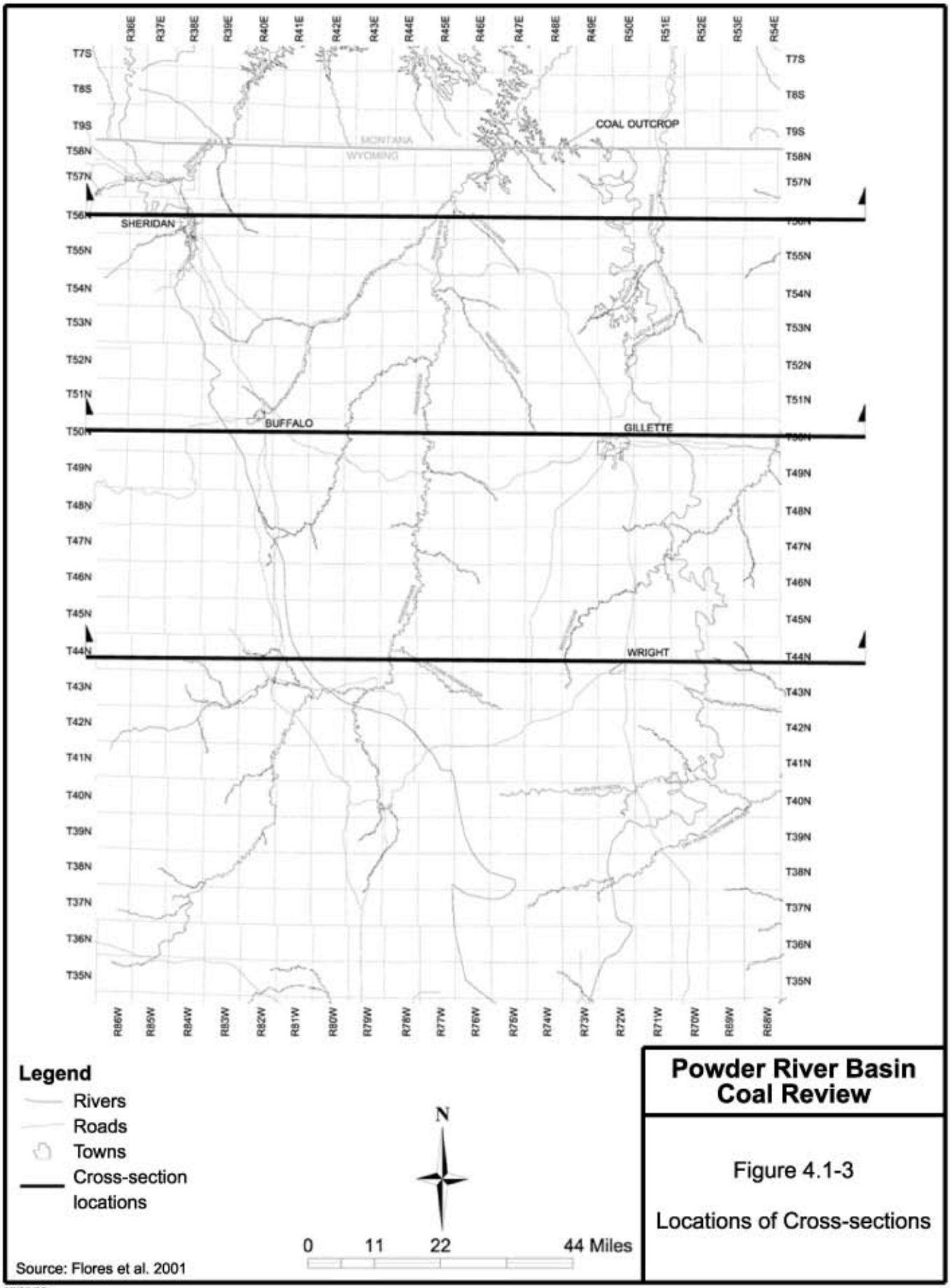

Powder River Basin Coal Review

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 7.9×10^{-5} to 2.3×10^{-1} per foot with a median value of 1.3×10^{-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 2.1×10^{-7} to 1.1×10^{-1} per foot with a median value of 3.0×10^{-4}. The specific yield ranges from 4.1×10^{-5} to 1.1×10^{-1} with a median value of 3.1×10^{-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 2.3×10^{-6} to 1.0×10^{-1} per foot with a median value of 1.4×10^{-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 2.4×10^{-5} to 3.1×10^{-2} ft/day with a median value of 6.6×10^{-5} ft/day. The specific storage ranges from 5.3×10^{-5} to 6.2×10^{-5} per foot with a median value of 2.1×10^{-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).