Task 3B Report for the Powder River Basin Coal Review Cumulative Water Resources Effects

Prepared for

Bureau of Land Management
High Plains District Office and
and
Wyoming State Office

Submitted by

AECOM, Inc.
Fort Collins, Colorado

December 2009

TASK 3B REPORT FOR THE
POWDER RIVER BASIN COAL REVIEW
CUMULATIVE WATER RESOURCES EFFECTS

Prepared for

BUREAU OF LAND MANAGEMENT
HIGH PLAINS DISTRICT OFFICE
and
WYOMING STATE OFFICE

Submitted by

AECOM, INC.
Fort Collins, Colorado

December 2009

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

The Task 3B report for the Powder River Basin (PRB) Coal Review summarizes the modeled changes in surface water quality and groundwater level changes projected for 2010, 2015, and 2020 in the eastern PRB within approximately 25 miles of the coal mines. The base years used for comparison of groundwater impacts were 2002 (the year used for calibration of the groundwater model for the eastern PRB) and 1990 (a time period before coal bed natural gas [CBNG] pumpage). The base year used for comparison of surface water quality impacts was 2003.

Projected groundwater level changes primarily are due to CBNG groundwater withdrawal in the Upper Fort Union Formation and to both CBNG pumping and discharge along with coal mine dewatering in the Wasatch Formation. Near the coal mines, coal mine dewatering of the Upper Fort Union also has affected groundwater levels in that formation. These changes were modeled using the Coal Mine Groundwater Model (CMGM) that was developed for the PRB Coal Review study. The numerical modeling code used in the CMGM was MODFLOW2000, running within the Groundwater Vistas modeling platform. Groundwater level recovery in the eastern PRB after the cessation of both CBNG development and coal mining, and the effect on groundwater flow paths associated with coal mine pit backfill and reclamation after the cessation of coal mining in the eastern PRB, also were modeled. For purposes of modeling groundwater recovery, it was assumed that CBNG development in the eastern PRB would cease by 2030 and surface coal mining would cease by 2050. Details of the numerical CMGM design, calibration, and projection of 2002 groundwater levels and drawdown between 1990 and 2002 for the Upper Fort Union and the Wasatch are presented in the Task 1B report (AECOM 2009a).

For groundwater modeling purposes, the estimation of future CBNG groundwater production was based on actual permitted pumping rates available from the Wyoming Oil and Gas Conservation Commission (WOGCC) for wells operating through 2004, and the scaling down of pumping rates over the 7-year life cycle of a pod of CBNG wells as estimated by the Bureau of Land Management (BLM) (2007a). The location of CBNG wells through 2006 was based on data available from the WOGCC website and IHS Energy Services (IHS) database files (IHS 2007), with CBNG well locations from 2007 to 2020 based on projections provided by the BLM (2007c). Coal mine groundwater pumpage was developed from data provided by the coal mine operators and from data on projected locations of coal mine pits over time as provided by the BLM (2007b). It was assumed that all discharge of CBNG water would be to ephemeral drainages. A percentage of this discharge was assigned as potential recharge to groundwater.

Projected changes in surface water quality are due to mixing of CBNG production water discharge with natural flow in the modeled drainages. These changes were modeled by Anderson Consulting Engineers, Inc. (ACE) (2009) using a linear mixing model that combines surface water flow and water quality with CBNG discharge volume and water quality using linear equations. A stream channel stability analysis also was conducted by ACE (2009), which evaluated the potential effects to stream channels due to projected CBNG production water discharge. For CBNG discharge, the direct discharge to ephemeral drainages for each drainage basin was used as the guide for modeling water quality or estimating impacts to channel stability and channel properties.

ES.2 GROUNDWATER LEVEL CHANGES

Projected groundwater level changes in the Wasatch generally are due to coal mine dewatering and CBNG pumping and discharge, which generally result in local mounding of groundwater in the Wasatch near CBNG fields and drawdown near the coal mines. Antelope Creek and Wild Cat Creek remove groundwater from the Wasatch because their stream base elevations are below the groundwater levels in the Wasatch. The Belle Fourche River in the CMGM domain does not remove groundwater from the Wasatch because its base elevation is above groundwater elevations in the Wasatch. Along some reaches of the Belle Fourche outside of the model domain, the river is perennial due to groundwater baseflow from the Wasatch. Also, the Wasatch Formation is not a true aquifer in that it has water-bearing sand units, but no consistent and uniform groundwater level over the eastern PRB. In the CMGM, however, the Wasatch was modeled as an aquifer due to the large area covered by the model domain. Consequently, the Wasatch can contribute water to the Belle Fourche and other ephemeral streams in the eastern PRB, whereas the numerical model will show the water level in the Wasatch below the stream bottom and thus will not remove water. For the Upper Fort Union, groundwater level changes are due to CBNG pumpage and coal mine dewatering, with the most substantial groundwater level changes caused by CBNG pumpage located mainly southwest of Wright. Between 2002 and 2020, the projected reduction in coal mine dewatering and the expected reduction in CBNG pumpage from Wright northward toward Gillette are projected to result in groundwater rebound in the Upper Fort Union both within the coal mine boundaries and especially within the basin west of the coal mines.

Modeled Cumulative Groundwater Impacts for Year 2010

Wasatch Formation: Based on model results for 1990 to 2010, groundwater flow in the Wasatch for 2010 is to the northeast south of Wright, Wyoming. East of Wright, the groundwater flow changes to northward and then to northwestward with flow staying on the northwestward course to the north end of the model domain in the eastern PRB. Antelope Creek acts as a drain and removes water from the Wasatch over most of its course in the eastern PRB. There is a 20-foot groundwater mound west of the Subregion 2 coal mines related to water discharge from the CBNG wells. Southeast of Gillette, there is a 50-foot decline in groundwater levels due to municipal pumpage. At the northern end of the model domain, there is a groundwater decline of 20 to 30 feet near Wild Cat Creek due to CBNG pumpage. The main area of drawdown in the Wasatch since 1990 is in the northern pod of the Subregion 3 coal mines, where there is 30 to 70 feet of drawdown within the mine boundaries and 10 to 30 feet of drawdown in the Wasatch west of the mine boundaries due to mine dewatering. CBNG discharge results in a groundwater mound of 10 to 20 feet west of Wright and another mound west of the Subregion 2 coal mines of up to 20 feet. Overall, the primary effects projected for the Wasatch include the drawdown in the Subregion 3 coal mines, the removal of groundwater by Antelope Creek, and 10 to 20 feet of mounding in areas of CBNG discharge.

Based on modeling results for 2002 to 2010, coal mine-related drawdown in the Wasatch in the Subregion 3 coal mine area is up to 70 feet, with most of the drawdown being located in the northern pod of mines. For CBNG-related pumpage and discharge, a predicted decrease in pumpage by 2010 results in groundwater rebound west of Wright in the range of 10 to 20 feet and localized rebound west of the Subregion 2 coal mines.

Upper Fort Union Formation: The most evident feature for projected groundwater levels in the Upper Fort Union for 2010 is a substantial groundwater depression of 25 to 575 feet southwest of Wright caused by CBNG pumpage from 1990 to 2010. Groundwater flow south of Wright, except for the area of the groundwater depression, is to the northeast toward the Subregion 3 coal mines. Groundwater flow north of Wright is to the northwest. Groundwater flows into the Subregion 3 coal mines from both the west and the east. For the Subregion 2 coal mines, groundwater flow into the mines is mainly from the west. Modeled drawdown in the Upper Fort Union in the coal mine areas is in the range of 100 to 200 feet in the Subregion 3 mines, 25 to 100 feet in the Subregion 2 coal mines, and up to approximately 100 feet in the Subregion 1 coal mines north of Gillette. Municipal pumpage at Gillette results in a groundwater depression southeast of Gillette in the range of 50 feet.

Based on modeling results for 2002 to 2010, coal mine-related pumpage in the Fort Union in the Subregion 3 coal mine area results in 25 to 150 feet of drawdown in and near the southern pod of mines, and 25 to 100 feet of drawdown in the northern pod of mines. In the Subregion 2 coal mine area, drawdown from 25 to 125 feet occurs in the southern pod of mines, with 25 to 75 feet in the northern pod of mines. CBNG pumpage results in extensive drawdown southwest of Wright ranging up to 350 feet. West of the northern pod of mines in Subregion 3, groundwater levels rebound up to 150 feet due to the reduction in CBNG pumpage. North of Wright along State Route (SR) 59, groundwater levels rebound up to 125 feet. West of the Subregion 2 coal mines, groundwater levels rebound in the range of 50 to 275 feet, and near the Subregion 1 coal mines, groundwater levels rebound approximately 25 feet.

Modeled Cumulative Groundwater Impacts for Year 2015

Wasatch Formation: Based on model results for 1990 to 2015, groundwater flow in the Wasatch for 2015 is similar to 2010. South of Wright, groundwater flow is to the northeast toward the Subregion 3 coal mines. North of Wright, groundwater flow is to the northwest. Antelope Creek acts as a drain and removes groundwater from the Wasatch over most of its course. There is a projected groundwater mound of 10 to 20 feet west of the Subregion 2 mines due to CBNG discharge, and there is a projected groundwater depression of up to 50 feet southeast of Gillette due to municipal pumpage. Near Wildcat Creek, CBNG pumpage results in an additional drawdown of approximately 10 feet. The most substantial modeled drawdown in the Wasatch since 1990 is in the Subregion 3 coal mines, where there is 30 to 70 feet of drawdown within the mine boundaries and 10 to 30 feet of drawdown in the Wasatch west of the mines. There is groundwater mounding up to 10 feet around Wright due to CBNG discharge. Overall, modeled groundwater levels, groundwater flow patterns, and groundwater drawdown in the Wasatch for 2015 are similar to 2010.

Based on modeling results for 2002 to 2015, coal mine pumpage in the Wasatch results in drawdown in the area of the Subregion 3 coal mines in the range of 10 to 60 feet near the southern pod of mines and from 30 to 80 feet in the northern pod of mines. West of the Subregion 3 coal mines, drawdown in the Wasatch ranges from 10 to 20 feet. Drawdown near the Subregion 1 and Subregion 2 coal mines is less than 10 feet. CBNG pumpage and discharge in the Wasatch results in approximately 20 feet of drawdown west of Wright, approximately 10 feet of drawdown near the Subregion 2 coal mines, and approximately 10 feet of mounding along SR 59.

Upper Fort Union Formation: Based on model results for 1990 to 2015, the substantial groundwater depression southwest of Wright due to CBNG pumpage, as projected for 2010, shifts

to the south. Projected 2015 groundwater drawdown in the Upper Fort Union in this area of CBNG pumpage since 1990 ranges up to 450 feet. Groundwater flow patterns in the Upper Fort Union are similar to 2010, with groundwater flow south of Wright being to the northeast toward the Subregion 3 coal mines, and north of Wright, groundwater flow is to the northwest. Around the Subregion 3 coal mines, groundwater flows into the mine areas from both the west and east. For the Subregion 2 mines, groundwater flow is mainly from the west but also from the east. Drawdown in the Subregion 3 mines ranges from 25 to 150 feet. For the Subregion 2 mines, drawdown ranges from 25 to 50 feet in the northern pod of mines and from 50 to 150 feet at the southern end of the subregion. There is local rebound of groundwater levels in the northern pod of mines in Subregion 1. Southwest of the Subregion 2 mines, there is a CBNG-related groundwater depression of 50 to 125 feet, with drawdown southwest of Wright ranging from 25 to 450 feet.

Model results for 2002 to 2015 show groundwater rebounding in parts of the eastern PRB. In the Subregion 3 coal mines, there is up to 200 feet of rebound in the southern pod of mines. For the Subregion 2 coal mines, there is up to 25 feet of rebound in the northern pod of mines. For the Subregion 1 mines north of Gillette, rebound of water levels is up to 50 feet in the Upper Fort Union. Within the basin area of the eastern PRB, a reduction in CBNG pumpage from Wright northward to the Subregion 2 coal mines has generated substantial rebound in groundwater levels in the Upper Fort Union along SR 59. Southeast of Wright, rebound is up to 275 feet since 2002. From Wright northward along SR 59, the rebound ranges from approximately 25 feet on the margins to 100 feet along the highway area.

Modeled Cumulative Groundwater Impacts For Year 2020

Wasatch Formation: Based on model results for 1990 to 2020, groundwater flow in the Wasatch is similar to that modeled for 2015 and 2010. South of Wright, groundwater flow is to the northeast toward the Subregion 3 coal mines. North of Wright, groundwater flow is to the northwest. There is a groundwater mound of 10 to 20 feet west of the Subregion 2 coal mines, with mounding of approximately 10 feet extending northward, due to CBNG discharge. Southeast of Gillette, there is a groundwater depression of approximately 10 feet due to municipal pumpage. Antelope Creek acts as a drain and removes water from the Wasatch, and in the Wild Cat Creek area there is drawdown of 10 to 30 feet due to CBNG pumpage. Drawdown in the Subregion 3 coal mines ranges from 30 to 70 feet within the mine boundaries and from 10 to 30 feet west of the mines in the basin.

Based on modeling results for 2002 to 2020, drawdown in the Wasatch due to coal mine pumpage is evident only in the Subregion 3 coal mine area, ranging from 10 to 50 feet in the southern pod of mines and from 10 to 20 feet in the northern pod of mines. Drawdown west of the mines in the PRB ranges from 10 to 20 feet. Groundwater rebound of approximately 10 feet is evident in both the northern and southern pod of mines in Subregion 3 due to reclamation of the coal mine pits and resaturation of the backfill material. CBNG-related rebound of approximately 10 feet occurs over most of the model domain due to a decrease in CBNG pumpage.

Upper Fort Union Formation: Based on modeling for 1990 to 2020, the groundwater depression in the Upper Fort Union southwest of Wright shifts more to the southwest as compared to 2015, and the groundwater level decline in the depression ranges up to 400 feet. Groundwater flow is to the northeast toward the Subregion 3 coal mines south of Wright; north of Wright, groundwater flow is to the northwest. Groundwater flows into the Subregion 3 mines from the west and the east; groundwater flows into the Subregion 2 mines mainly from the west. There is a 50-foot groundwater

depression southeast of Gillette due to municipal pumpage. Groundwater drawdown in the coal mine areas ranges from 25 to 100 feet in the Subregion 3 mines, from 25 to 100 feet in the northern pod of mines in Subregion 2, and from 50 to 125 feet in southern pod of mines in Subregion 2. For the Subregion 1 mines, there is local drawdown in groundwater levels of approximately 25 feet.

Based on model results for 2002 to 2020, there is 50 to 100 feet of groundwater rebound in the Upper Fort Union in the Subregion 3 mines due to a reduction in coal mine pumpage and ongoing reclamation. For the Subregion 2 mines, the rebound is up to 50 feet, and for the Subregion 1 mines the rebound is up to 25 feet. Groundwater rebound in the Upper Fort Union within the basin has been substantial due to a reduction in CBNG pumpage. In the area southeast of Wright, rebound is up to 300 feet. West of the Subregion 2 mines, rebound is up to 225 feet. Between Wright and the Subregion 2 mines along SR 59, reduction in CBNG pumpage results in a broad area of rebound ranging from 25 to 100 feet. Overall, the reduction in coal mine dewatering and the substantial reduction in CBNG pumpage since 2002 results in groundwater rebound in the Upper Fort Union.

ES.3 SURFACE WATER QUALITY

The surface water quality analysis focused on reasonably foreseeable development (RFD) scenarios for normal and dry year conditions to show the difference in potential cumulative impacts to surface water quality based on stream flow and climate. Wet years were not analyzed because increased runoff and stream flow would result in potential water quality impacts considerably less than the normal and dry year RFD scenarios.

For this analysis, “mixing” refers to the mixing of CBNG production water discharge and natural stream flow. Electrical conductivity (EC) is a measure of total dissolved solids; sodium adsorption ratio (SAR) is a measure of the amount of sodium in the water than can react with clays and, thus, reduce infiltration into soil and the ultimate use of the soil for growing crops. The Most Restrictive Proposed Limit (MRPL) and Least Restrictive Proposed Limit (LRPL) for SAR and EC are set for each subwatershed by the Wyoming Department of Environmental Quality in conjunction with neighboring states that receive flow across state boundaries from the specified river in the subwatershed. These limits refer to desired concentrations for SAR and EC and are used as guidelines for evaluating potential impacts to water quality.

Normal year Conditions

Antelope Creek: From 2003 to 2020, EC is projected to decline due to mixing with CBNG production waters, and SAR values are projected to increase. The data indicate that the MRPL and LRPL would not be exceeded for either EC or SAR after mixing of CBNG production waters. Based on the data, surface water is projected to be suitable for irrigation use in all months.

Dry Fork of the Cheyenne River: For the Dry Fork of the Cheyenne, there is no projected discharge of CBNG production water to the drainage through 2020. Therefore, surface water quality conditions for 2010, 2015, and 2020 would be the same as for the base year (2003).

Little Powder River: From 2003 to 2020, EC is projected to decline, and SAR is projected to increase slightly due to mixing with CBNG production waters. The data indicate that EC values

would exceed the MRPL except for March and May during 2010, and March during 2015 and 2020; however, it would not exceed the LRPL except for January and August from 2010 to 2020, and also in September, November, and December from 2015 to 2020. SAR values are projected to exceed the MRPL and not exceed the LRPL. Based on the data, surface water is projected to remain suitable for irrigation to 2020.

Upper Belle Fourche: From 2003 to 2015, EC is projected to decline due to mixing with CBNG production water, and SAR is projected to increase slightly. There is no projected discharge of CBNG production water to the drainage in 2020; therefore, EC and SAR values for this time period would be the same as projected for the base year (2003). The data indicate that EC would not exceed the MRPL, except for October in 2010 and October through January in 2015, and would not exceed the LRPL. The projected SAR values would exceed the MRPL from August to January in 2010 and from September to January of 2015, and would not exceed the LRPL for all months. Based on the data, surface water is projected to be suitable for irrigation to 2020.

Upper Cheyenne River: From 2003 to 2010, EC is projected to decrease due to mixing with CBNG production water, and SAR values would not change. There is no projected discharge of CBNG production water to the drainage in 2015 or 2020. Based on the data, EC values would exceed the MRPL, except for August 2010, and exceed the LRPL, except for July through September 2010. SAR values would not exceed the MRPL and LRPL. Based on the data, surface water would remain suitable for irrigation from 2010 to 2020.

Upper Powder River: From 2003 to 2015, EC is projected to decrease slightly, and SAR values would increase slightly, due to mixing with CBNG production water. There is no projected discharge of CBNG production water to the drainage in 2020. The data indicate EC values would exceed the MRPL, except for May and June for 2010 to 2015, and would exceed the LRPL during July through December from 2010 to 2015. SAR values would exceed the MRPL, except for March in 2010 and 2015 and May in 2015, and would not exceed the LRPL. Based on the data, surface water is projected to remain suitable for irrigation from 2010 to 2020.

In summary, for normal year flows, discharge of CBNG production water to these six drainages generally would reduce the EC and increase the SAR slightly; however, the surface water would remain suitable for irrigation in most months. The MRPL and LRPL may be exceeded for EC and SAR in 1 or more years and in any given year for 1 or more months, but not for all months in the year. For most drainages, discharge of CBNG water increases flows substantially and, thus, is responsible for changes in EC and SAR. The Dry Fork Cheyenne River and Upper Powder River subwatersheds are the main exceptions, because they receive little or no contribution from CBNG discharge.

Dry year Conditions

Antelope Creek: From 2003 to 2020, EC values would be reduced due to mixing with CBNG waters, and SAR values would increase. The data indicate that the MRPL and LRPL would not be exceeded for either EC or SAR for all years after mixing of CBNG production water. Based on the data, surface water would remain suitable for irrigation except for June and August from 2010 to 2020.

Dry Fork of the Cheyenne River: For the Dry Fork of the Cheyenne, no CBNG production water discharge is expected to the drainage through 2020. Therefore, water quality conditions would be the same as the modeled base year (2003) for all years to 2020.

Little Powder River: For the Little Powder River, the EC would be reduced and the SAR increased due to mixing with CBNG waters from 2003 to 2020. The MRPL would be exceeded for all years for EC during the months of February, April, June, and August in 2010; during November through February and during April, June, and August in 2015; and all months except March in 2020. EC values would exceed the LRPL in September 2010; August 2015; and January, August, November, and December 2020. SAR values would exceed the MRPL in all months and years except March 2015 and March and May 2020. The LRPL for SAR only would be exceeded in September 2010. The water would remain suitable for irrigation from 2010 to 2020 except for September and October 2010.

Upper Belle Fourche: From 2003 to 2015, EC values would decline due to mixing with CBNG production waters, and SAR values would increase slightly. There is no projected discharge of CBNG production water to the drainage in 2020. EC values would not exceed the MRPL or LRPL from 2010 to 2015. SAR values would exceed the MRPL in 2010, except for March and July, and also would exceed the MRPL from August to January 2015. Based on the data, surface water would be unsuitable for irrigation from August to October during 2010 and in October 2015.

Upper Cheyenne River: From 2003 to 2010, EC values would decline due to mixing with CBNG production waters, and SAR values would increase slightly. There is no projected discharge of CBNG production waters to the drainage in 2015 or 2020. EC values would exceed the MRPL except for August 2010; the LRPL would be exceeded except for July to September 2010. For SAR, neither the MRPL nor the LRPL would be exceeded. Based on the data, surface water would remain suitable for irrigation to 2020.

Upper Powder River: From 2003 to 2015, EC values would decrease slightly due to mixing with CBNG waters, and SAR values would increase slightly. There is no projected discharge of CBNG production water to the drainage in 2020. EC values would exceed the MRPL except for the months of May and June for 2010 and 2015, and the LRPL would be exceeded July through December for 2010 and 2015. SAR values would exceed the MRPL, except for May and June 2015, and would not exceed the LRPL for all years. Based on the data, surface water would remain suitable for irrigation to 2020.

In summary, during dry year flows, the suitability of surface waters in the six modeled drainages for irrigation generally would be reduced due to the greater percentage of CBNG production water in the drainage after mixing. Both EC and SAR values would exceed the MRPL and LRPL more frequently compared to normal year flows. Even though the waters' suitability for irrigation would be reduced (except for the Upper Belle Fourche River) surface water generally would remain suitable for irrigation during the majority of months of the irrigation season.

ES.4 STREAM CHANNEL STABILITY

In general, cumulative impacts to channel stability largely relate to changes in water quantity associated with discharges from existing or projected development activities as compared to the

runoff characteristics of the receiving drainages. Of particular importance is the quantity of discharge water directly conveyed to the receiving drainages. For purposes of this evaluation, it was assumed that the water discharged directly to the receiving drainages would be limited to CBNG activities (ACE 2009), which are projected to be the primary source of discharge water in the study area through 2020. A site-specific assessment also was performed to evaluate the impact of increased stream flows associated with discharge of CBNG production water in Caballo Creek on existing and reclaimed channels, as well as diversion channels and structures constructed in accordance with coal mine permit criteria.

The perennial stream evaluation calculated the change in channel width for the Little Powder River as less than 0.3 percent. For the Belle Fourche River, it was calculated to be less than 0.2 percent (ACE 2009). These results suggest that for the larger perennial streams the effect of CBNG production water discharge would be minimal. Geomorphic relationships provided insight into the potential impacts of the CBNG production water discharge on the mean annual discharge events associated with the perennial drainages. Based on the projected relatively low increase in mean annual discharge in the perennial streams, the potential trends predicted by the geomorphic relationships (increases in channel width, depth, and meander wavelength) would be considered imperceptible.

To have an impact on channel stability that is manifested in active channel erosion, CBNG production water discharge likely would have to represent a substantial portion of the channel-forming discharge in watersheds where the channel slope is steep enough and the width, depth, and sinuosity low enough to impact channel morphology. Based on the magnitude of the projected CBNG production water discharges compared to the channel-forming discharge (1.5- to 2-year recurrence interval), the impact more likely would be evident in small ephemeral drainages that are characterized by steep channel gradients, lower sinuosity, and smaller widths and depths. Overall, as the drainage area increases, the channel slope typically decreases along with an increase in sinuosity, thereby reducing the impact of CBNG production water discharge on channel stability.

The 2-year peak discharge for Caballo Creek at the eastern (downstream) Subregion 2 coal mine boundary was estimated to be approximately 400 cfs. The estimated contribution of CBNG production water discharge of 1.1 cfs represents less than 1 percent of the 2-year peak discharge. Based on the relative magnitude of the flow contribution from CBNG production water discharge, geomorphic relationships confirm the conclusion that the minor contribution from CBNG production water discharge to the flow in Caballo Creek likely would not result in active erosion to the channel. These results were confirmed by observations of the existing channels during the field reconnaissance.

A threshold may exist where the contribution of CBNG production water discharge may create erosion within the receiving drainage channel. Based on the channel slope, channel sinuousity, and watershed area, drainages such as Caballo Creek may not realize an increase in channel erosion but would more likely realize an increase in vegetation diversity and density along the channel. Smaller drainages, such as Bone Pile Creek or Duck Nest Creek (tributaries to Caballo Creek), may be more likely to exhibit channel erosion depending on the magnitude of the flow contribution from CBNG water production compared to the channel-forming discharge. However, field observations in these watersheds found similar increases in vegetation along all of the channels.

ES.5 GROUNDWATER RECOVERY

Groundwater recovery for the Wasatch and Upper Fort Union formations was modeled relative to year 1975. This date was selected as a time before coal mines began substantial pumping of groundwater and before CBNG pumpage. Thus, 1975 represents near steady-state for the eastern PRB in the CMGM model for the Wasatch and Upper Fort Union formations.

Wasatch Formation

Based on the modeling results, the Wasatch Formation is projected to recover from CBNG pumpage and discharge and coal mine dewatering in approximately 300 to 500 years. This recovery is a modeled recovery, and the assumption in the CMGM is that the Wasatch is a continuous aquifer. In reality, the Wasatch is not a continuous aquifer, but a complex fluvial/deltaic depositional system with local areas of groundwater and sometimes fairly continuous zones of groundwater within sand lenses. These areas of groundwater may recover faster than has been estimated by the CMGM model, or in some cases, they may take longer than the model-estimated 300 to 500 years. Therefore, the estimated steady-state for the Wasatch of 300 to 500 years is approximate and based on assumptions that were required for construction of the CMGM that may not apply to all areas of the Wasatch. Also, the Wasatch would continue to be used for stock water and locally for domestic water supply following the end of coal mining and CBNG development. Recovery modeling assumed that no use of groundwater in the Wasatch would continue after year 2050. Thus, some areas of the Wasatch may recover very slowly to pre-mining or pre-CBNG groundwater levels.

Upper Fort Union Formation

Based on the modeling results, the Upper Fort Union is projected to recover to near, or approximately 80 percent of, steady-state conditions in approximately 300 to 500 years. The estimated final steady-state for the Upper Fort Union is approximately 500 years. Pumpage of groundwater from the Upper Fort Union has been from the coal-bearing zones, either for removal of CBNG or for removal of coal in the coal mines in the eastern PRB that follow the outcrop of the coal along the eastern structural boundary of the PRB. For groundwater recovery to occur in the Upper Fort Union, water has to flow back into the coal-bearing formations affected by groundwater removal. In the CMGM model, this flow of groundwater during recovery is controlled by the boundary conditions of the model, the distribution of recharge, and the overall distribution of hydraulic conductivity and storage in the Upper Fort Union (Layer 5 in the CMGM model). Recovery of the Upper Fort Union may take longer than the model-estimated 300 to 500 years. Recovery of a groundwater system that took millions of years to develop often can require considerably more time than that estimated by a numerical model. It has been assumed in the modeling of recovery by the CMGM that all pumpage in the eastern PRB ceases in year 2050. Assuming Gillette continues its municipal pumpage, and other areas of the eastern PRB utilize groundwater in the Upper Fort Union after year 2050, recovery of the groundwater levels in the Upper Fort Union may be a slow process and may take longer than the model-estimated 300 to 500 years.

Transport Modeling Results

Based on data in the Gillette Area Groundwater Monitoring Organization's (2003, 2000) reports, the average total dissolved solids (TDS) in coal mine pit backfill aquifers in the PRB is approximately 3,700 milligrams per liter (mg/L), with the highest average value for any coal mine subregion being approximately 4,800 mg/L for Subregion 1. Coal mine pit backfill aquifer water has an average TDS below Wyoming stock water standards (5,000 mg/L). Thus, movement of pit backfill water westward into the Wasatch and Fort Union aquifers would not degrade the water quality of these aquifers relative to use for stock watering. The westward extent of the 1,000 mg/L TDS isopleth was modeled to represent the location where the TDS of groundwater leaving the coal mine backfill aquifers would be reduced through groundwater flow and dispersion to a level approximately equal to the current average TDS in the Wasatch and Fort Union aquifers. After 500 years (the approximate time for flushing of the backfill aquifers by groundwater) the 1,000 mg/L isopleth is anticipated to extend up to 2,000 feet west of the reclaimed coal mine pits in all of the coal subregions of the eastern PRB. Thus, the maximum projected impact to groundwater quality in the Wasatch and Fort Union aquifers would be limited to a distance of up to 2,000 feet west of the reclaimed coal mine pits.

ES.6 OVERALL SUMMARY OF PROJECTED CUMULATIVE EFFECTS

Overall, changes in the eastern PRB from 2002 to 2020 involve an assumed gradual reduction in pumpage rates for CBNG wells as they mature and continue to migrate to the west and southwest, tapping deeper levels of the coal-bearing units in the Upper Fort Union. Based on modeling results, this leads to a shift in drawdown in the Upper Fort Union to the southwest of Wright, with a corresponding rebound in groundwater levels west of the coal mines along SR 59 as the CBNG wells in this area cease production and pumpage of groundwater. For the Wasatch, discharge of CBNG water from 2002 to 2020 results in mounding of up to 30 feet in the areas of substantial CBNG pumpage. It also is assumed that the coal mines would continue to operate and dewater up to 2050; however, reclamation of mined-out areas would allow groundwater to rebound in the backfill aquifers that develop in the reclaimed areas. Based on modeling results, drawdown within the active coal mine areas and to the west of the mines for approximately 2 to 3 miles the same from 2002 to 2020. Discharge of CBNG water to ephemeral drainages in the eastern PRB leads to a decrease in EC in most drainages and an increase in SAR; however, the final mixed water continues to be suitable for irrigation in most drainages during the normal precipitation years and for most months during the dry years. During the dry year, months with normally low flows often have a mixed water that would not be suitable for irrigation during those months if they receive substantial CBNG discharge.

Based on the groundwater modeling results for 2010, groundwater flow in the Wasatch and Upper Fort Union is to the northeast south of Wright and gradually shifts to the northwest east of Wright. Most drawdown in the Wasatch (up to 70 feet) is in the Subregion 3 coal mines located southeast of Wright. West of the Subregion 3 coal mines, drawdown in the Wasatch is 10 to 20 feet. Groundwater mounds due to CBNG discharge of up to 30 feet are present west of Wright and west of the Subregion 2 coal mines. For the Upper Fort Union, there is a substantial groundwater depression, with up to 575 feet of drawdown since 1990 (350 feet of drawdown since 2002),

southwest of Wright. Drawdown since 1990 in the coal mine areas is up to 250 feet in the Subregion 3 coal mines, up to 125 feet in the Subregion 2 coal mines, and up to75 feet in the Subregion 1 coal mine areas. Drawdown since 2002 is 150 feet or less in the coal mine areas. Rebound in the Upper Fort Union since 2002 is up to 100 feet along SR 59.

Based on groundwater modeling for 2015, groundwater flow patterns in the Upper Fort Union and the Wasatch are the same as projected for 2010. Drawdown in the Wasatch is mostly in the Subregion 3 coal mines and ranges up to 80 feet, with up to 30 feet of drawdown west of the mines since 1990. Drawdown in the Wasatch since 2002 is up to 60 feet in the Subregion 3 mines and up to 30 feet west of the mines. Groundwater mounding up to 20 feet within the Wasatch continues to be present in areas of CBNG water discharge. For the Upper Fort Union, the groundwater depression noted in 2010 southwest of Wright shifts further to the south, and the drawdown is up to 475 feet since 1990 (350 feet since 2002). Drawdown in the Subregion 3 coal mines is up to 150 feet in the Upper Fort Union, with comparable drawdown in the Subregion 2 coal mines and considerably less drawdown in the Subregion 1 coal mines. Rebound of groundwater levels since 2002 is projected in the Upper Fort Union, with up to 200 feet of rebound in some areas of the Subregion 3 coal mines and 25 to 50 feet of rebound in the Subregion 1 and Subregion 2 coal mine areas. There is a general rebound of up to 275 feet in the Upper Fort Union along SR 59 due to the reduction in CBNG pumpage since 2002.

Based on groundwater modeling results for 2020, groundwater flow patterns in the Wasatch and Fort Union are much the same as projected for 2010 and 2015. Drawdown in the Wasatch is up to 70 feet in the Subregion 3 coal mines, and up to 20 feet in both the Subregion 1 and Subregion 2 coal mines. Groundwater mounds up to 20 feet are present near Wright and west of the Subregion 2 coal mines. Since 2002, drawdown in the Wasatch is up to 60 feet in the Subregion 3 coal mines and up to 20 feet in both the Subregion 1 and Subregion 2 coal mines. Drawdown in the Upper Fort Union is 425 feet southwest of Wright since 1990 (350 feet since 2002). Drawdown in the Subregion 3 coal mines is up to 125 feet, with up to 75 feet in the Subregion 2 coal mines and up to 25 feet in the Subregion 1 coal mines. Rebound of groundwater levels up to 125 feet is found in the reclaimed areas of the coal mines. Groundwater rebound of up to 20 feet since 1990 is found in the basin west of the Subregion 2 coal mines and near Wright. Since 2002, rebound of groundwater levels west of the Subregion 2 coal mines is up to 175 feet, and up to 275 feet in the Upper Fort Union along SR 59.

After 2050, modeled groundwater levels in the eastern PRB begin to rebound due to the projected cessation of CBNG pumpage around 2030 and the projected cessation of coal mining around 2050. The Wasatch begins to show noticeable rebound after approximately 50 years (around year 2100) and substantial rebound after 200 years (year 2250). The Upper Fort Union shows recovery after 50 to 100 years (2100 to 2150) and substantial recovery after 200 years (2250). Both the Wasatch and the Upper Fort Union are projected to rebound and reach approximately 80 percent of steady-state in 300 to 500 years after the cessation of coal mining, or around 2350 to 2550.

Resaturation of the coal mine pit backfill to form backfill aquifers may take approximately 100 years after cessation of coal mining and will result in the westward migration of groundwater with elevated TDS levels. Modeling of this westward migration suggests that TDS levels should be down to approximately the current background value of 1,000 mg/L for the Wasatch and Upper Fort Union aquifers within approximately 2,000 feet of the final western extent of the coal mine boundaries in

2050. Thus, no impact to groundwater quality in either the Wasatch or the Upper Fort Union is expected beyond approximately 2,000 feet west of the final coal mine boundaries.

ACRONYMS AND ABBREVIATIONS

µg/L	micrograms per liter
µS/cm	microsiemens per centimeter
ACE	Anderson Consulting Engineers, Inc.
AHA	Applied Hydrology Consultants
amsl	above mean sea level
BLM	Bureau of Land Management
CBNG	coal bed natural gas
cfs	cubic feet per second
CMGM	Coal Mine Groundwater Model
EA	Environmental Assessment
EC	electrical conductivity
EIS	Environmental Impact Statement
ESI	Environmental Simulations, Inc.
GAGMO	Gillette Area Groundwater Monitoring Organization
GEC	Greystone Environmental Consultants
gpm	gallons per minute
HSU	hydrostratigraphic unit
LBA	lease by application
LRPL	least restrictive proposed limit
MCFG	thousand cubic feet of gas
mg/L	milligrams per liter
mmgpy	million gallons per day
MRPL	most restrictive proposed limit
MWL	managed water loss
NEPA	National Environmental Policy Act
PRB	Powder River Basin
RFD	reasonably foreseeable development
SAR	Sodium adsorption ratio
SR	State Route
TDS	total dissolved solids
U.S.	United States
USGS	U.S. Geological Survey
WDEQ	Wyoming Department of Environmental Quality
WOGCC	Wyoming Oil and Gas Conservation Commission
WYPDES	Wyoming Pollution Discharge Elimination System

CONTENTS

EXECUTIVE SUMMARY ES-1

ACRONYMS AND ABBREVIATIONS AA-1

1.0 INTRODUCTION 1-1

1.1 Objectives 1-7

1.2 Agency Outreach, Coordination, and Review 1-8

2.0 TECHNICAL APPROACH 2-1

2.1 Groundwater 2-1
2.1.1 Groundwater Modeling Approach 2-1
2.1.2 Estimation of Future Coal Mine Groundwater Pumpage 2-3
2.1.3 Estimation of Future CBNG Groundwater Pumpage 2-3
2.1.3.1 Antelope Creek Subwatershed 2-5
2.1.3.2 Dry Fork Cheyenne River Subwatershed 2-6
2.1.3.3 Little Powder River Subwatershed 2-6
2.1.3.4 Upper Belle Fourche River Subwatershed 2-6
2.1.3.5 Upper Cheyenne River Subwatershed 2-6
2.1.3.6 Upper Powder River Subwatershed 2-7
2.1.4 Estimation of Future CBNG Discharge to Drainages 2-7

2.2 Surface Water 2-7
2.2.1 Surface Water Quality 2-8
2.2.2 Evaluation Criteria 2-9
2.2.2.1 Irrigation Suitability Diagram 2-9
2.2.3 Surface Water Quality Modeling 2-10
2.2.3.1 Stream Flow 2-11
2.2.3.2 Stream Water Quality 2-11
2.2.3.3 CBNG Well Production Water 2-11
2.2.3.4 CBNG Well Production Water Quality 2-12
2.2.3.5 Managed Water Loss 2-12
2.2.3.6 Conveyance Loss 2-13

3.0 PREDICTED FUTURE CUMULATIVE WATER RESOURCE IMPACTS 3-1

3.1 Introduction 3-1

3.2 Modeled Cumulative Impacts For Year 2010 3-2
3.2.1 Groundwater Level Changes Since 1990 3-2
3.2.1.1 Wasatch Formation 3-2
3.2.1.2 Fort Union Formation 3-3
3.2.2 Groundwater Level Changes Since 2002 3-4
3.2.2.1 Wasatch Formation 3-4

3.2.2.2 Fort Union Formation 3-4
3.2.3 Modeled Cumulative Surface Water Impacts for 2010 3-5

3.3 Modeled Cumulative Impacts for Year 2015 3-12
3.3.1 Groundwater Level Changes Since 1990 3-12
3.3.1.1 Wasatch Formation 3-12
3.3.1.2 Fort Union Formation 3-13
3.3.2 Groundwater Level Changes Since 2002 3-14
3.3.2.1 Wasatch Formation 3-14
3.3.2.2 Fort Union Formation 3-15
3.3.3 Modeled Cumulative Surface Water Impacts for 2015 3-16

3.4 Modeled Cumulative Impacts for Year 2020 3-19
3.4.1 Groundwater Level Changes Since 1990 3-19
3.4.1.1 Wasatch Formation 3-19
3.4.1.2 Fort Union Formation 3-20
3.4.2 Groundwater Level Changes Since 2002 3-21
3.4.2.1 Wasatch Formation 3-21
3.4.2.2 Fort Union Formation 3-22
3.4.3 Modeled Cumulative Surface Water Impacts for 2020 3-23

3.5 Summary 3-25
3.5.1 Groundwater Level Changes 3-25
3.5.1.1 Modeled Cumulative Groundwater Impacts for Year 2010 3-25
3.5.1.2 Modeled Cumulative Groundwater Impacts for Year 2015 3-26
3.5.1.3 Modeled Cumulative Groundwater Impacts For Year 2020 3-27
3.5.2 Surface Water Quality 3-28
3.5.2.1 Normal year Conditions 3-28
3.5.2.2 Dry year Conditions 3-29

4.0 STREAM CHANNEL STABILITY EVALUATION 4-1

4.1 Perennial Stream Channel Evaluation 4-1
4.1.1 Methodology 4-1
4.1.2 Perennial Stream Channel Stability Effects 4-2

4.2 Ephemeral Stream Channel Evaluation 4-3
4.2.1 Methodology 4-3
4.2.2 Ephemeral Stream Channel Stability Effects 4-3

4.3 Caballo Creek Channel Stability Evaluation 4-4
4.3.1 Methodology 4-4
4.3.2 Hydrologic and Meterologic Data Results 4-5
4.3.3 Caballo Creek Channel Stability Effects 4-6

4.4 Summary 4-6

5.0 GROUNDWATER RECOVERY 5-1

5.1 Recovery in the Wasatch Formation 5-2
5.1.1 Year 2050 5-2
5.1.2 Year 2100 5-3
5.1.3 Year 2250 5-3
5.1.4 Steady-state for the Wasatch Formation 5-3

5.2 Recovery In The Upper Fort Union Formation 5-4
5.2.1 Year 2050 5-4
5.2.2 Year 2100 5-5
5.2.3 Year 2250 5-5
5.2.4 Year 2350 5-6
5.2.5 Steady-state for the Upper Fort Union 5-6

5.3 Transport of Elevated TDS Water From Coal Mine Pit Backfill Aquifers 5-7

6.0 SUMMARY 6-1

7.0 REFERENCES 7-1

APPENDIX A ESTIMATE PUMPAGE RATES FOR SIX DRAINAGE BASINS IN THE POWDER RIVER BASIN, WYOMING

APPENDIX B FIGURES SHOWING CMGM RESULTS

LIST OF TABLES

2-1 Estimated Future Groundwater Consumption by CBNG Wells in the Eastern Powder River Basin....2-4
2-2 Summary of Proposed Limits for SAR and EC....2-9
2-3 Percent of Total Water Production from CBNG Wells per Discharge Method....2-12
3-1 Cumulative Surface Water Impact Analysis for Antelope Creek Subwatershed....3-6
3-2 Cumulative Surface Water Impact Analysis for Dry Fork Cheyenne River Subwatershed....3-7
3-3 Cumulative Surface Water Impact Analysis for Little Powder River Subwatershed....3-8
3-4 Cumulative Surface Water Impact Analysis for Upper Belle Fourche River Subwatershed....3-9
3-5 Cumulative Surface Water Impact Analysis for Upper Cheyenne River Subwatershed....3-10
3-6 Cumulative Surface Water Impact Analysis for Upper Powder River Subwatershed....3-11
4-1 Projected Impact of CBNG Production Water Discharge on Perennial Streams....4-2

LIST OF FIGURES

1-1 Study Area....1-2
1-2 Federal Land Management....1-3
2-1 Task 3D Study Area and Subwatersheds....2-5
2-2 Antelope Creek: 2003 Stream Water Quality....2-10

1.0 INTRODUCTION

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

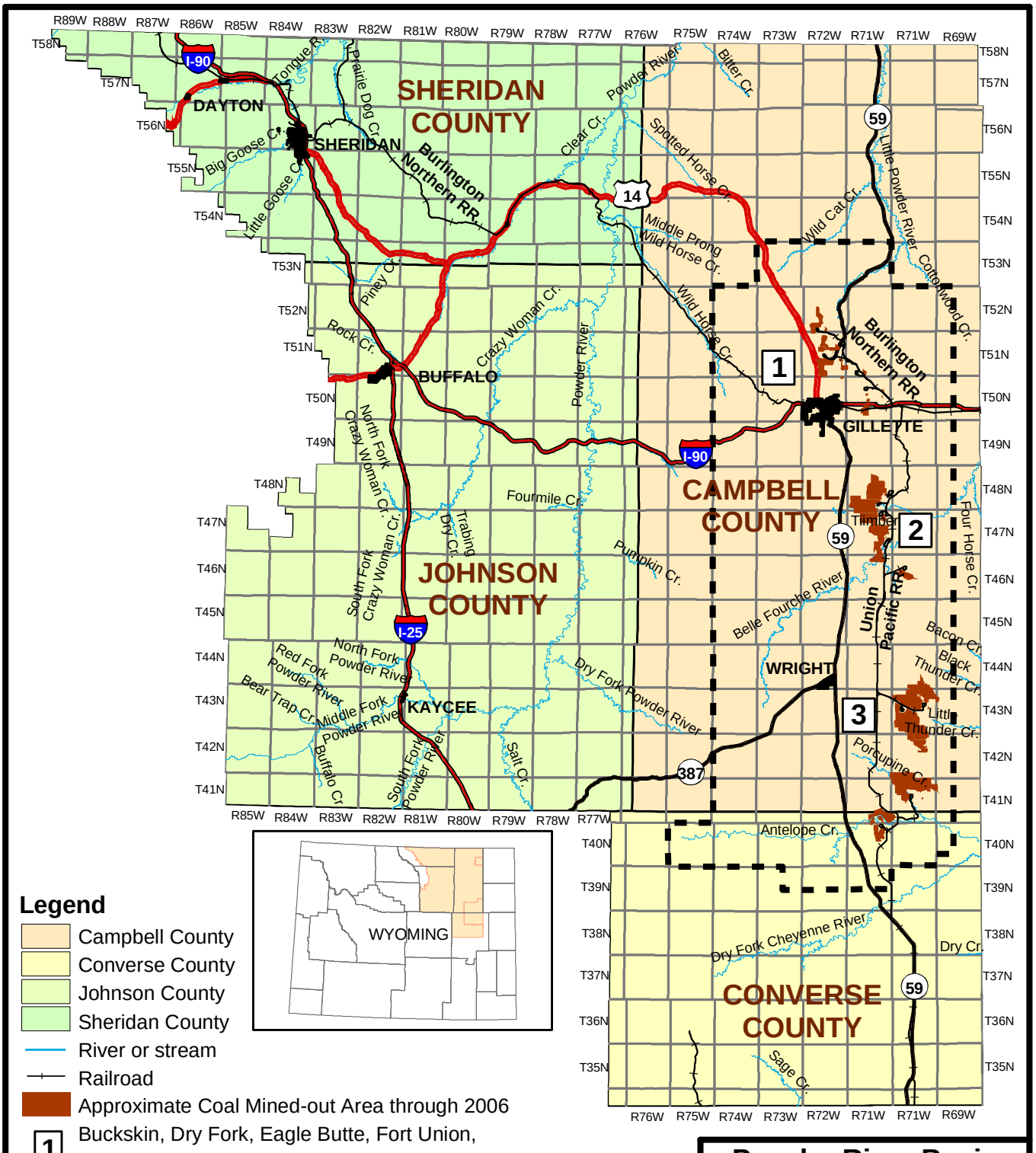
For the purpose of this study, the Wyoming PRB study area (**Figure 1-1**) comprises all of Campbell County, all of Sheridan and Johnson counties less the Bighorn National Forest lands to the west of the PRB, and the northern portion of Converse County. It includes all of the area administered by the Bureau of Land Management (BLM) Buffalo Field Office, a portion of the area administered by the BLM High Plains District Office, and a portion of the Thunder Basin National Grasslands, which is administered by the U.S. Forest Service (**Figure 1-2**). State and private lands also are included in the study area. For water resources, the cumulative effects study area encompasses the groundwater model domain (**Figure 1-1**), with emphasis placed on the overlap in the coal mine- and coal bed natural gas (CBNG)-related groundwater drawdown area.

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

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

BLM is required to complete a National Environmental Policy Act (NEPA) analysis (EIS or environmental assessment [EA]) for each coal lease application as part of the leasing process. In the coal leasing EAs and EISs that have been prepared since decertification, cumulative impacts have been addressed in a separate section of the chapter that describes the expected environmental impacts of the proposed action. This approach was designated to highlight the distinction between site-specific and cumulative impacts.

In the mid-1990s, the BLM conducted a study called the PRB Coal Development Status Check (Status Check) (BLM 1996) to evaluate how actual development levels compared to the development levels predicted in the earlier regional EISs. At the time the Status Check was prepared, the actual levels of cumulative development generally were within the levels that had been predicted. BLM continued updating key portions of the Status Check and used the results in the cumulative impact section of the coal-leasing EAs and EISs. The Status Check update indicated that the actual levels of coal development and associated impacts began to approach the predicted

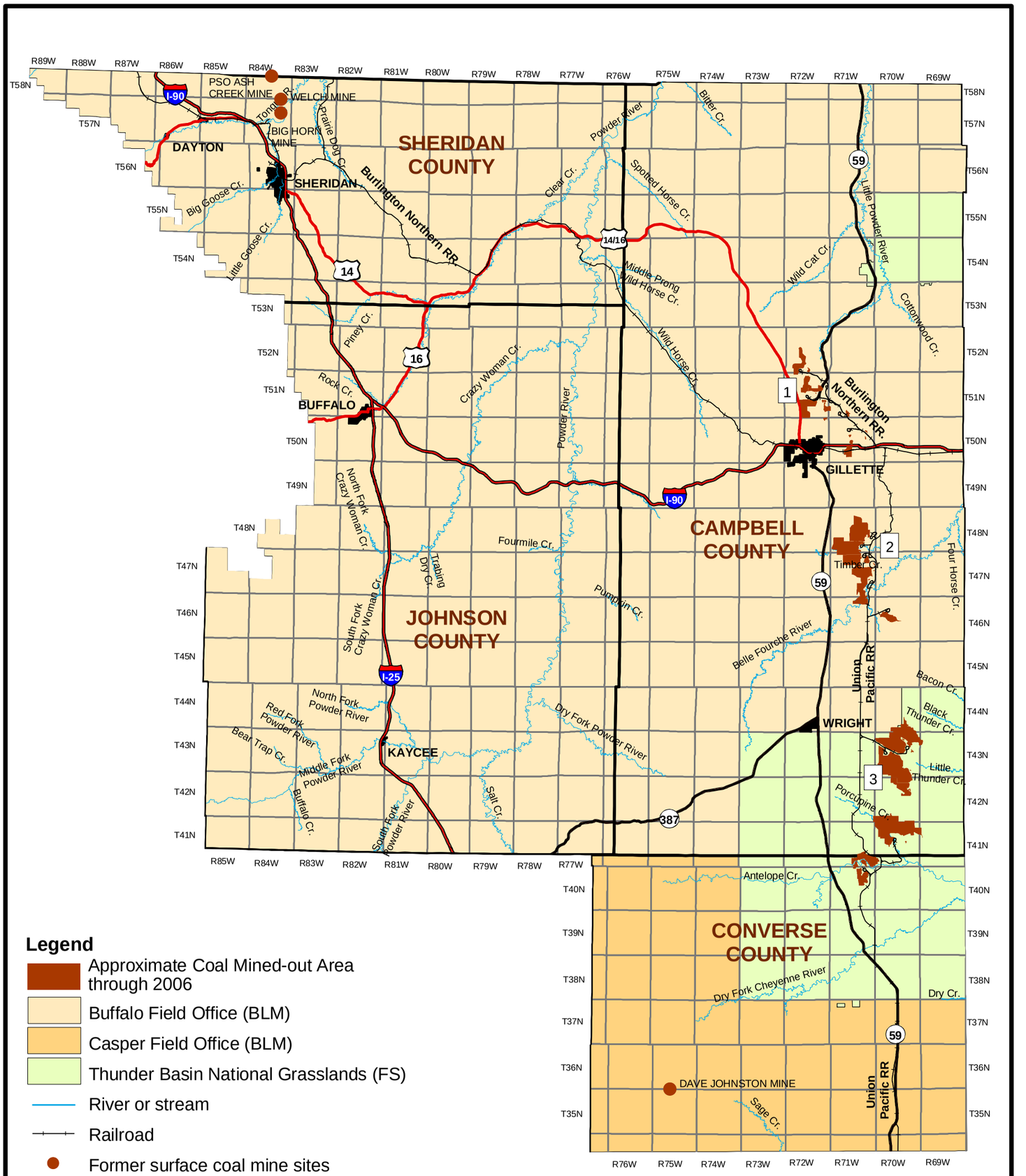


Powder River Basin Coal Review

Figure 1-1

Study Area

11/04/09



Source: BLM 2009.

Powder River Basin Coal Review

Figure 1-2

Federal Land Management

08/10/09

levels in the late 1990s. Around the same time, impacts related to oil and gas development began increasing due to development of CBNG in the PRB.

BLM prepared the Wyodak EIS (BLM 1999) and PRB Oil and Gas EIS (BLM 2003) to address the impacts of projected CBNG development in the Wyoming PRB. Modeling was used to quantify potential cumulative impacts to air and water resources in these two EISs. Surface coal mining operations in the PRB were included in the modeling analyses as reasonably foreseeable future, non-project sources of impacts. For these analyses, future levels of coal development were estimated using market demand projections. BLM used these cumulative impact analyses in the coal leasing EISs as well as in the CBNG EISs.

In early 2003, BLM completed a study of PRB coal demand through 2020 (Montgomery Watson Harza 2003). The study projected production to increase at a steady pace with current mines able to meet the demand as long as the existing mines continue to have access to additional coal reserves; therefore, the need for leasing using LBAs will continue into the foreseeable future. As part of processing these LBAs, BLM will need to maintain a current cumulative impact analysis. An initial step in that direction is this PRB Coal Review, which includes the identification of current conditions (Task 1 reports), identification of reasonably foreseeable development (RFD) actions and future coal production scenarios (Task 2 report), and predicted future cumulative impacts (Task 3 reports) in the PRB.

The Task 2 component of the PRB Coal Review defines the past and present development actions in the study area that have contributed to the current environmental and socioeconomic conditions in the PRB study area. This report also defines the projected RFD scenarios in the Wyoming and Montana PRB for years 2010, 2015, and 2020. For the Wyoming PRB, the past and present development and RFD scenarios include coal mine development as well as coal-related activities (i.e., railroads, coal-fired power plants, major transmission lines, and coal technology projects) and non-coal-related activities (i.e., other mines, CBNG, conventional oil and gas, major transportation pipelines, and key water storage reservoirs). Coal mine development and coal-related activities in the Montana PRB study area are included in this study to provide the basis for the analysis of cumulative air quality impacts. The past and present activities identified in this report are based on the most recent data available at the end of 2003 and provide the basis for the resource-specific descriptions of current conditions presented in the PRB Coal Review Task 1 reports.

The RFD scenarios presented in the Task 2 report provide the basis for the analysis of potential cumulative impacts in the Task 3 component of the study. The accuracy of any projected cumulative impact analysis is dependent on the adequacy and accuracy of information regarding potential future activities in the affected area. While it is impossible to identify all potential future activities over the next 15 years, it is possible and desirable to identify reasonably foreseeable future actions based on current industry announcements, agency plans, economic trends, and technological advances affecting major industry sectors. Information regarding potential new development constantly is changing; however, to facilitate development of the information in this study, the RFDs identified in the Task 2 report reflect information available through the end of 2004.

The past and present actions in the Task 2 report were identified based on information in existing NEPA documents on file with federal and state agencies and the Status Check (BLM 1996). The RFD scenarios in the Task 2 report were developed based on recent information that identifies proposed and anticipated development in the PRB, including NEPA documents; various other

technical reports and studies; federal, state, and local (county) agency management plans; and permit applications. The specific development scenarios and development activities identified in these sources were assessed as to their current status prior to inclusion in the RFD scenarios for the PRB Coal Review. In addition, potential additional projects were identified through interviews with agency and industry representatives, review of published news articles and trade publications, and discussions with community leaders.

The identified RFD activities subsequently were evaluated as to their probability for occurrence. Due to the lack of detailed information for many developments beyond the next few years, the degree of uncertainty associated with the predicted developments and trends increases as the timeframe extends further into the future.

For each of the past and present and RFD projects and activities, project-specific impact-causing parameters (e.g., disturbance acreage, emission levels, employment levels, etc.) have been compiled from the sources identified above. Where specific information was unavailable, assumptions were developed and included based on typical industry-specific standards, permit criteria for similar existing industries, and professional judgment. This information is summarized in the Task 2 report.

In order to account for the variables associated with future coal production, two detailed coal production scenarios (reflecting upper and lower production estimates) were projected for this study to bracket the most likely foreseeable regional coal production level and to provide a basis for quantification of related impact-causing parameters. These future production levels were derived from the analysis of historic production levels and current PRB coal market forecasts, public and private information sources, and input from individual PRB coal operators and are summarized in the Task 2 report.

This Task 3B report describes the modeled cumulative groundwater impacts associated with ongoing coal mine- and CBNG-related groundwater withdrawal and CBNG water discharge in the eastern PRB of Wyoming for the time periods of 2010, 2015, and 2020. The base years used for comparison of groundwater impacts were 2002 (the year used for calibration of the groundwater model for the eastern PRB) and 1990 (a time period before CBNG pumpage and before major expansion by the coal mines). The eastern PRB cumulative effects study area for water resources comprises the Coal Mine Groundwater Model (CMGM) domain as shown in **Figure 1-1**. The study area primarily includes the area encompassed by the coal mines extending from north of Gillette, Wyoming, to south of Wright, Wyoming, near Antelope Creek. Projected cumulative surface water impacts primarily include the impacts of CBNG production water discharge to ephemeral drainages and the surface disturbance and subsequent reclamation of drainages that result from coal mine expansion. The base year used for comparison of surface water quality impacts was 2003, as discussed in the surface water quality and channel stability report for the eastern PRB (Anderson Consulting Engineers [ACE] 2009) and summarized in this Task 3B report. This Task 3B report also includes a discussion of groundwater level recovery in the eastern PRB after the cessation of both CBNG development and coal mining, and the effect on groundwater flow paths associated with coal mine pit backfill and reclamation after the cessation of coal mining in the eastern PRB. For purposes of modeling groundwater recovery, it was assumed that CBNG development in the eastern PRB would cease by 2030 and surface coal mining would cease by 2050.

Coal mine and CBNG development scenarios are discussed in the Task 2 report (AECOM 2009b). For use in groundwater modeling, the estimation of future CBNG groundwater production was based on actual permitted pumping rates available from the Wyoming Oil and Gas Conservation Commission (WOGCC) for wells operating through 2004, and the scaling down of pumping rates over the 7-year life cycle of a pod of CBNG wells as estimated by the BLM (2007a). The location of CBNG wells through 2006 was based on data available from the WOGCC website and IHS Energy Services (IHS) database files (IHS 2007), with CBNG well locations from 2007 to 2020 based on estimates provided by the BLM (2007c). Therefore, pumping rates for CBNG wells beyond 2004 are approximate and based on the estimates of future CBNG development in the eastern PRB provided by the BLM (2007a) for the drainage basins (referred to as subwatersheds in this report) in the eastern PRB for the three time periods analyzed in this study. Appendix A presents the BLM report on future CBNG groundwater production in the eastern PRB (BLM 2007a); a summary of the report is presented in Section 2.3. Coal mine groundwater pumpage was developed from data provided by the coal mine operators and from data on projected locations of coal mine pits over time as provided by the BLM (2007b).

Surface water quality impacts for the target years of 2010, 2015, and 2020 were estimated using a linear mixing model developed by ACE (2009) and the projected water discharge volumes presented in the Task 2 report (AECOM 2009b). For CBNG discharge, the direct discharge to ephemeral drainages for each drainage basin was used as the guide for modeling water quality or estimating impacts to channel stability and channel properties. For the coal mines, most of the water produced was expected to be consumed, according to estimates provided by the mine operators and included in the Task 2 report. Where production of groundwater exceeded estimated consumption for the coal mines in any given drainage basin, it was assumed that the discharged water would go first to holding ponds and then to nearby ephemeral drainages in accordance with Wyoming Pollution Discharge Elimination System (WYPDES) permits, thereby minimizing the potential for degradation of water quality and impacts to channel stability.

Any estimation of water resource impacts in future years requires the use of assumptions. For CBNG development, the key assumptions were: 1) that CBNG development would proceed in the eastern PRB using methods that have been developed and used since 1995; 2) that most of the groundwater produced by CBNG wells would be discharged directly to ephemeral drainages through outfalls because the water quality has relatively low sodium absorption ratios (SAR) and electrical conductance (EC) values; and 3) that 60 to 70 percent of the water discharged to drainages by CBNG wells would infiltrate into the shallow alluvium and the upper Wasatch Formation (AECOM 2009a). For coal mine expansion, the key assumption was that the amount of water discharged to drainages would be approximately equal to the estimated amount of future discharge water provided by the mine operators. These data were presented in the Task 2 report (AECOM 2009b).

The Task 2 report (AECOM 2009b) discusses different methods for the disposal of CBNG-produced groundwater. These methods include direct discharge to drainages, the use of in-channel and off-channel impoundments, active treatment, reinjection, and land application. The predominate method of discharge in the eastern PRB is direct discharge to ephemeral drainages, with the use of impoundments being the second most common method of discharge. These two methods are expected to account for 81 percent of the CBNG-produced groundwater discharged in the study area. As both of these methods would have approximately the same amount of recharge to shallow aquifers, the CMGM developed for the eastern PRB assumed that all CBNG discharge would be to

ephemeral drainages through Wyoming Department of Environmental Quality (WDEQ) approved outfalls near the producing wells. For the purpose of estimating future impacts to groundwater levels using the CMGM, it was assumed that all water produced by the CBNG wells would be discharged to the surface and that 70 percent of all water produced would infiltrate into the top layer of the model (alluvium or shallow Wasatch Formation). It was further assumed that 10 percent of the infiltrating water would be trapped in storage, used by plants, or eventually evaporated, leaving 60 percent of the discharged water as potential recharge to the top layer. This approach attempted to incorporate and average the effects of different CBNG discharge methods. No attempt was made to specifically model infiltration ponds, active treatment of discharged water, land application, or reinjection of water. For surface water quality modeling, it was assumed that 70 percent of the CBNG discharge water would infiltrate into the shallow alluvium and the upper Wasatch Formation; 30 percent of the discharged water would flow down the drainage.

1.1 Objectives

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

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

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

The primary objective of the Task 3B report is to provide an estimate of potential future cumulative impacts to water resources in the eastern PRB of Wyoming due to CBNG development and coal mining for the target years 2010, 2015, and 2020. To accomplish this objective, the following secondary objectives have been established for the Task 3B report:

- Evaluate potential groundwater impacts due only to CBNG development for 2010, 2015, and 2020. Compare groundwater levels to 1990 (the year before major initiation of CBNG activity in the PRB) and 2002 (the calibration year for the CMGM) levels.
- Evaluate potential groundwater impacts due only to coal mine dewatering for 2010, 2015, and 2020. Compare groundwater levels to 1990 (the period when coal mine dewatering began to expand) and 2002 (the calibration year for the CMGM) levels.

- Evaluate potential groundwater impacts due to combined CBNG development and coal mine dewatering for 2010, 2015, and 2020. Compare groundwater levels to 1990 and 2002 levels.

- Evaluate potential surface water quality impacts in the six major drainages of the eastern PRB due to CBNG- and coal mine-related discharge for the years 2010, 2015, and 2020.

- Evaluate groundwater level recovery following the cessation of both CBNG development and coal mining (assumed to be 2030 and 2050, respectively).

- Evaluate potential effects on channel stability in relation to potential changes in the hydrologic regime due to coal mine- and CBNG-related discharges.

- Evaluate the transport of groundwater containing elevated levels of total dissolved solids (TDS) associated with the resaturation of the pit backfill following cessation of coal mining.

The PRB Coal Review Task 3 descriptions of predicted cumulative impacts for air quality, social and economic conditions, and environmental resources are presented in separate stand-alone reports.

1.2 Agency Outreach, Coordination, and Review

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

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

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

As part of this agency outreach and technical oversight, the BLM organized technical advisory groups for air quality, water resources, and socioeconomics. These groups were composed of agency representatives with technical expertise in the applicable resource(s). The PRB Water Resources Advisory Team has been actively involved in review of data; review of the CMGM protocol, development, and calibration; and review of the design of the linear mixing model approach for estimating effects to stream water quality.

2.0 TECHNICAL APPROACH

Two separate technical approaches were used to estimate future groundwater and surface water impacts in the eastern PRB of Wyoming. Groundwater modeling was conducted for the eastern PRB of Wyoming using the CMGM that was developed for the PRB Coal Review study. The protocol for the CMGM, a summary of the calibration report (Environmental Simulations, Inc. [ESI] 2009), and a discussion of the modeling results for the base year (2002) conditions are presented in the Task 1B report (AECOM 2009a).

For surface water, the Surface Water Quality Analysis Technical Report (Greystone and ALL Consulting 2003) was reviewed and updated for the PRB Coal Review. The update included adjustment of the models to include more current data and the application of more current research and field studies to issues such as channel stability and the impacts of CBNG-related groundwater disposal to ephemeral or intermittent drainages. The results of the surface water cumulative effects analysis for the PRB Coal Review are presented in the Task 3B Water Resources Cumulative Impact Assessment Water Quality and Channel Stability (ACE 2009) report and summarized in this Task 3B report.

A separate channel stability evaluation was conducted by ACE, with the results included in the Task 3B Water Resources Cumulative Impact Assessment Water Quality and Channel Stability (ACE 2009). A summary of that evaluation, including a brief description of the technical approach, is presented in Chapter 4.0 of this Task 3B report.

2.1 Groundwater

For groundwater, the technical approach included the development of a groundwater model for the eastern PRB that used as a starting basis the original regional PRB groundwater model developed by Applied Hydrology Associates (AHA) and Greystone Environmental Consultants, Inc. (GEC) (2002) for the PRB Oil and Gas EIS (BLM 2003). The resulting CMGM focused on the coal mines in the eastern PRB of Wyoming and the zone within 25 miles to the west of the coal mines impacted by CBNG development. The CMGM is discussed in detail in the Task 1B report (AECOM 2009a) and in the Groundwater Model Calibration Report (ESI 2009). A brief summary of the CMGM development is presented below.

2.1.1 Groundwater Modeling Approach

To construct the CMGM, AECOM and ESI first enhanced the original regional PRB groundwater model (AHA and GEC 2002) in order to make the regional PRB groundwater model more reflective of hydrologic conditions in the PRB and to allow the model to run more efficiently. Prior to constructing the CMGM model, the original regional PRB groundwater model was revised by making changes to the model layers and the model boundary conditions. These changes, and other enhancements discussed below, resulted in a revised regional PRB groundwater model. The revised regional PRB model was recalibrated and then telescoped to produce the CMGM.

Enhancements made to the regional PRB groundwater model prior to recalibration included: 1) reducing the number of model layers from 17 geologic units to 6 hydrostratigraphic units (HSUs);

2) extending the eastern model domain to the east and adding a MODFLOW general head boundary along the southeastern side of the model domain east of the coal mines located south of Gillette, Wyoming, for the Upper Fort Union HSU (model Layer 5); 3) replacing the constant heads used for ephemeral streams in the PRB with MODFLOW drain cells; 4) replacing drain cells used for CBNG wells with the MODFLOW well package; 5) refining the position of the contact between the Wasatch and Upper Fort Union in the area of the coal mines; 6) adjusting the amount of recharge to model Layer 1 from CBNG discharge to reflect studies estimating recharge from CBNG discharge to ephemeral streams; 7) use of MODFLOW2000 instead of MODFLOW96 for the modeling code; and 8) adding additional monitoring well targets around the coal mines from the Gillette Area Groundwater Modeling Organization (GAGMO) databases for 1990 and 2002. These enhancements resulted in a revised regional PRB groundwater model that more accurately reflects hydrologic conditions and groundwater flow in the PRB, provides the modeler with more flexibility in model construction and operation, and allows the model to run more efficiently.

Once the revised regional PRB groundwater model was recalibrated, the telescoped submodel (the CMGM) was made for the area of the eastern PRB that contains the active coal mines and CBNG activity using the telescopic mesh refinement capabilities of ESI's Groundwater Vistas (version 4.1). Additional enhancements that were made to the CMGM included: 1) a tighter grid spacing of 0.25 mile throughout the model domain, replacing the 0.5-mile grid spacing in the revised regional PRB groundwater model, to better assess groundwater drawdown impacts near the coal mines; 2) merging the stratigraphy in the revised regional PRB groundwater model (Goolsby, Finley, and Associates 2001) with the more detailed coal stratigraphy around the coal mines (BLM 2005), and adjustment of layer thicknesses and transmissivity where the two stratigrpahic models merged to allow for a smooth transition between the stratigraphic models; 3) use of a minimum hydraulic conductivity value of 0.20 meter per day for the Upper Fort Union (model Layer 5); 4) addition of a set of MODFLOW specified head cells along the southern boundary of the model domain in the Upper Fort Union (model Layer 5); and 5) adjustment of the Belle Fourche River base elevation to reflect the actual river base level along its course in the CMGM. These enhancements enable the CMGM to more accurately represent the hydrologic interactions between aquifer units, groundwater flow between aquifers and streams, and groundwater pumpage in the zone of overlap between coal mining and CBNG activity in the eastern PRB. Other changes to the CMGM and the revised regional PRB groundwater model are discussed in the Task 1B report (AECOM 2009a).

Since the purpose of the CMGM was to predict cumulative 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 calibration of both the revised regional PRB groundwater model and the CMGM, thereby making it possible to directly compare the calibration results between the two models. 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 (70 additional monitoring wells).
- BLM monitoring wells in the eastern PRB and private wells east of the coal mines that were screened in the Upper Fort Union.

In total, an additional 70 monitoring wells in the Wasatch Formation were added to the CMGM for better calibration in the Wasatch near the coal mines. The CMGM subsequently was calibrated to year 2002 for the eastern PRB and verified with transient calibration to 18 well hydrographs near the coal mines for year 2003.

Predictive simulations using the CMGM were used to estimate the cumulative impacts on groundwater resources in the model domain due to CBNG development and coal mining activities from the calibration years of 1990 and 2002 to year 2020. Predictive simulations were modeled for years 2010, 2015, and 2020, as selected by the BLM and presented in the report.

Resaturation of coal mine backfill material for the predictive years was simulated based on the projected progression and reclamation of coal mines during the predictive periods (2010, 2015, and 2020) as provided by BLM (2007b). Separate predictive scenarios were simulated for year 2050, a time period representing the hypothetical end of coal mining in the eastern PRB, through steady state. For purposes of post-mining resaturation modeling, it also was assumed that CBNG development would end in 2030. The hypothetical predictive runs for 2050 through steady state were used to determine the final rebound of groundwater levels in the Wasatch and Fort Union aquifers and changes to the hydrology of these aquifers due to the presence of mine backfill in areas previously mined for coal.

2.1.2 Estimation of Future Coal Mine Groundwater Pumpage

The projected locations of coal mine pits from 2002 to 2020, as provided by the BLM (2007b), were used for placement of the MODFLOW drain cells that were used to represent pumpage of groundwater by the coal mines in the CMGM. The conductance of the drain cells used for the mine pits was set during model calibration. Thus, the amount of groundwater removed by the drain cells reflects calibration to GAGMO monitoring wells surrounding each mine, rather than estimated or recorded pumpage rates. Mines that have substantial discharge of groundwater to ephemeral drainages have recharge cells placed at the approximate location of discharge to represent the infiltration of the discharge into HSU-1.

2.1.3 Estimation of Future CBNG Groundwater Pumpage

One of the key issues for predicting impacts to the Wasatch and Fort Union aquifers from CBNG development through the year 2020 is the estimation of future CBNG groundwater pumpage rates. The estimated groundwater pumpage rates used in the PRB Coal Review were determined by the BLM (2007a) through analysis of past patterns in CBNG development and groundwater pumpage in the eastern PRB. This analysis is presented in Appendix A and is summarized below.

The BLM's (2007a) analysis considered six major drainage basins (referred to in this study as subwatersheds) in the eastern PRB: Antelope Creek, Dry Fork Cheyenne River, Little Powder River, Upper Belle Fourche River, Upper Cheyenne River, and Upper Powder River (**Figure 2-1**). **Table 2-1** summarizes the well statistics for CBNG wells in these subwatersheds. The average well life ranges from 6.2 to 8 years, with a mean of approximately 7.0 years. Well depths range from shallow wells in the relatively new Antelope Creek field (788 feet average total depth) and the Upper Cheyenne River drainage (566 feet average total depth) to deep wells in the Dry Fork Cheyenne River field (average total depth of 1,725 feet). The Dry Fork Cheyenne River and Antelope Creek fields are relatively new, with only 1 percent and 26 percent of the projected wells drilled as of October 2006. Current average pumpage rates for groundwater range from 10.57 gallons per minute (gpm) per well in the Dry Fork Cheyenne River field to 1.89 gpm per well in the relatively mature Upper Cheyenne River field. The estimated future pumpage rates for each subwatershed show a decline in water production to approximately 1 to 2 gpm per well in all fields by 2020.

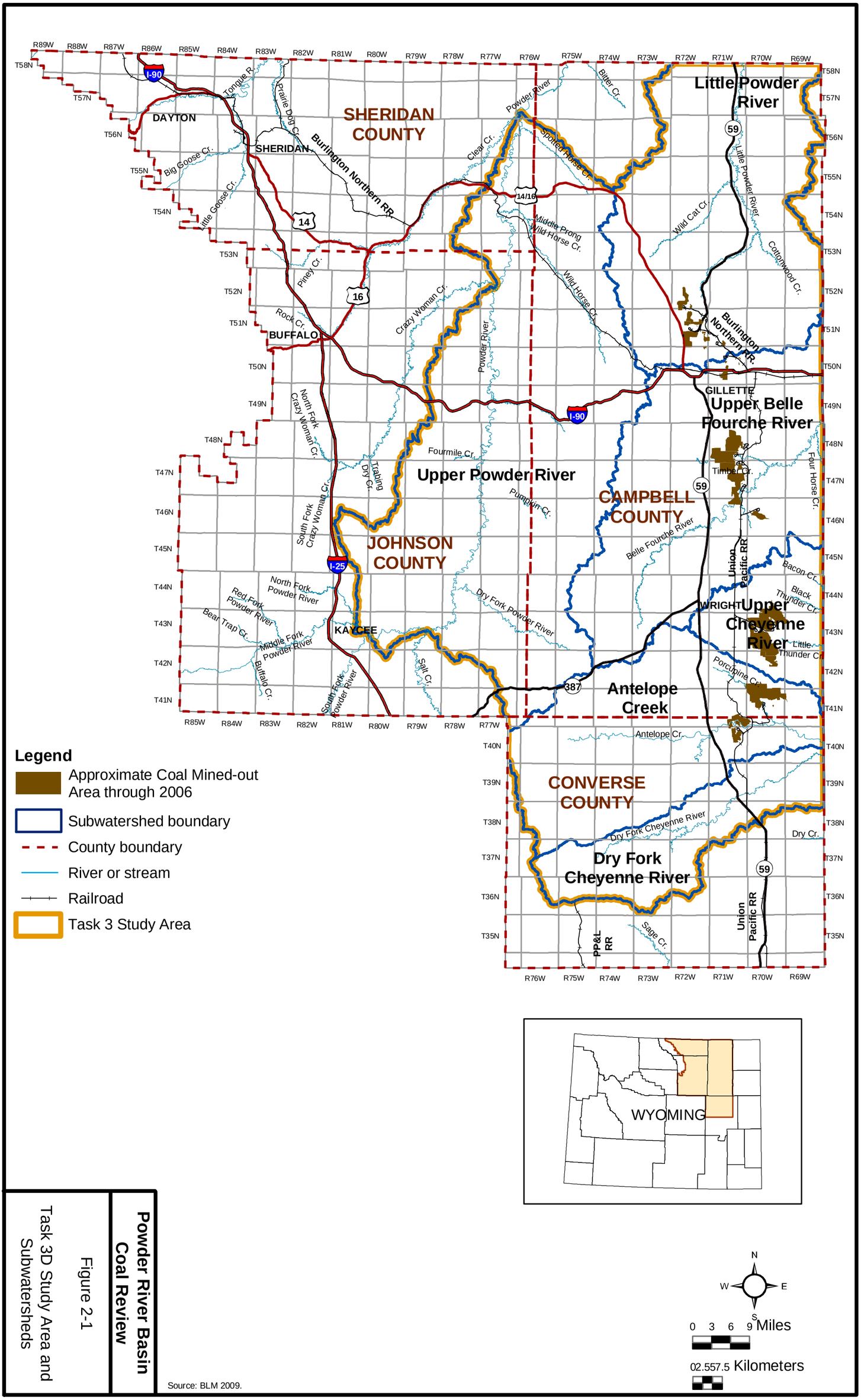
Table 2-1
Estimated Future Groundwater Consumption by CBNG Wells in the Eastern Powder River Basin

Subwatershed (Drainage Basin)	CBNG Well Average Total Depth (feet)	CBNG Average Well Life (years)	Estimated Number of Wells	Drilled Wells as Percent of Projected	June-August 2006 Pumpage (gpm/well)	Decline Rate 2005-2006	Estimated CBNG Pumpage Rates (gpm/well)		
							2010	2015	2020
Antelope Creek	788	8.0	5,020	26%	2.5	29%	2	2	2
Dry Fork Cheyenne River	1,725	no data	1,195	1%	10.57	87%	5	3	2
Little Powder River	655	7.1	7,191	46%	2.23	9%	2	1	1
Upper Belle Fourche River	930	6.8	10,848	63%	5.36	-6%	5	3	1
Upper Cheyenne River	566	6.2	1,212	50%	1.89	28%	2	2	1
Upper Powder River	1,291	8.0	24,930	30%	5.33	-6%	5	4	2

Source: BLM 2007a.

2.1.3.1 Antelope Creek Subwatershed

CBNG groundwater pumpage began in the Antelope Creek subwatershed in 2000. Nominal pumpage rates peaked around 40.5 gpm per well in 2002. Data from July 2006 show that the average rate per well had declined to 2.5 gpm per well. The gas production rate in 2006 was well above the economic limit of 10 thousand cubic feet of gas (MCFG) per day per well, suggesting that there should not be a large decrease in wells in the next few years. The average pumping rate was therefore expected to decline slowly from 2006 to 2020. Through August of 2006, 26 percent of the expected total wells in this subwatershed had been drilled, and total water production from 2000 to



Source: BLM 2009.

Powder River Basin Coal Review

Figure 2-1

Task 3D Study Area and Subwatersheds

11/04/09

August 2006 had been 21,764 acre-feet. The projected CBNG groundwater pumpage rate was estimated at 2 gpm per well from 2010 through 2020.

2.1.3.2 Dry Fork Cheyenne River Subwatershed

CBNG activity in the Dry Fork Cheyenne River subwatershed currently is in the early stages of development, thus making it difficult to project gas production and groundwater pumpage rates into the future. CBNG groundwater pumpage began in 2004 and had not stabilized by August of 2006. By August 2006, only 1 percent of the estimated total 1,195 wells expected in this area had been drilled. No gas production has been reported and groundwater pumage is not expected to stabilize for a few years. The average groundwater pumpage rate in 2005 was 21 gpm per well. By August 2006, this pumpage rate had declined to 10.6 gpm per well. It is estimated, based on preliminary data, that the average groundwater pumpage rate per well will decline to 5 gpm by 2010, declining steadily to 2 gpm per well by 2020.

2.1.3.3 Little Powder River Subwatershed

CBNG groundwater production in the Little Powder River subwatershed began in 1987 and has been continuous since that time. Groundwater pumpage rates generally were below 6 gpm per well until 1996 when pumpage rates began increasing, reaching 14 gpm per well in 1999. Groundwater pumpage rates then began to decrease to the current 2 gpm per well. CBNG groundwater production from the Little Powder River subwatershed is currently approximately 254 acre-feet per month, with the average gas rate per well of 34 MCFG per day declining at a rate of 9 percent per year. It is expected that the average groundwater pumpage rate per well will be 2 gpm in 2010, declining to 1 gpm per well by 2015 and remaining at that rate.

2.1.3.4 Upper Belle Fourche River Subwatershed

CBNG development in the Upper Belle Fourche River subwatershed produced groundwater and gas sporadically from 1989 to 1992, then continuously after 1992. This area is still being developed as suggested by the increasing number of CBNG wells and the increasing production rates for gas and water. The average pumpage rate for groundwater peaked in 1999 and then began declining. The rate has been stable at 5 gpm per well since 2002. The average gas production rate has been steady at 80 MCFG per day per well since 2002. As of August 2006, 63 percent of the estimated total 10,848 CBNG wells had been drilled. Projected groundwater production rates per well are 5 gpm in 2010, declining to 3 gpm in 2015 and 1 gpm in 2020.

2.1.3.5 Upper Cheyenne River Subwatershed

The first CBNG wells were drilled in the Upper Cheyenne River subwatershed in 1994, with groundwater production starting in 1997. Groundwater pumpage peaked at 40 gpm per well in 1998. Groundwater production has been declining since 2001 and reached a nominal rate of 1.9 gpm in August of 2006. It is expected that many wells will reach their economic limit in the next few years. As of August 2006, approximately 50 percent of the expected 1,212 total wells had been drilled, and 26,685 acre-feet of groundwater had been produced. The average rate of groundwater production per well is expected to be 2 gpm in 2010, declining slowly to 1 gpm per well by 2020.

2.1.3.6 Upper Powder River Subwatershed

CBNG groundwater and gas production in the Upper Power River subwatershed began in 1989; however, production rates were erratic and intermittent until 1999. As of August 2006, 124,000 acre-feet of groundwater had been produced. When continuous CBNG production began in 1999, the number of producing wells increased from 5 to 165, and the average groundwater production per well decreased from 55 gpm to 10 gpm by April of 2000. Average groundwater production by 2002 was down to 5.3 gpm per well. As of 2006, approximately 30 percent of the estimated total number of wells of 24,930 had been drilled. Groundwater production is expected to decline to 5 gpm per well by 2010, declining to 2 gpm per well by 2020.

The decline curves and estimated future CBNG groundwater production for each subwatershed provided by the BLM (2007a) were incorporated into the CMGM by assigning a total groundwater production value to each subwatershed and then partitioning that groundwater production among the CBNG wells. Each well was assigned an equal water production rate, so that the total number of wells in each subwatershed multiplied by the water production rate equaled the total production rate for that subwatershed for that modeled year. The CBNG wells were migrated with time westward across the CMGM model domain from 2002 to 2020 according to data and files provided by the BLM (2007b).

2.1.4 Estimation of Future CBNG Discharge to Drainages

CBNG outfalls in the original regional PRB groundwater model that occur within the CMGM domain were used for the CBNG discharge locations in the PRB Coal Review study. These outfalls are represented in the CMGM as recharge cells to allow for infiltration of the CBNG discharge water into HSU-1 (upper model layer) as recharge. The recharge assigned to a recharge cell was set at 60 percent of the total pumping rate for all CBNG wells in the model grid cell. The recharge rate of 60 percent is based on the approximate estimates of a conveyance loss of 70 to 80 percent for CBNG discharge and the approximate estimate that 80 percent of the conveyance loss is due to infiltration. The outfall discharge rates used in the CMGM for the predictive years (2010, 2015, and 2020) reflect the total pumping rate for all CBNG wells in that model grid cell. The per well pumping rates for the predictive years were based on actual permitted pumping rates available from the WOGCC for wells operating through 2004, and the scaling down of pumping rates over the 7-year life cycle of the wells as estimated by the BLM (2007a).

2.2 Surface Water

The Surface Water Quality Analysis Technical Report (Greystone and ALL Consulting 2003) prepared for the PRB Oil and Gas EIS (BLM 2003) was reviewed and updated for the Wyoming PRB study area for use in the PRB Coal Review study. The approach used in the revised surface water analysis is presented in the Task 3B Water Resources Cumulative Impact Assessment Water Quality and Channel Stability (ACE 2009) report and summarized below.

The surface water analysis focused on two main issues for the eastern PRB: 1) the cumulative effects to ephemeral drainages as a result of CBNG water discharge through outfalls that combine the discharge from a number of wells and 2) the cumulative effects to ephemeral and intermittent drainages due to coal mine development. Discharge from CBNG wells varies over time, with the

greatest discharge being during the first year of development. Typically, discharge from a CBNG well ranges from 10 to 25 gpm during the first year, decreasing to approximately 1 to 3 gpm by the third or fourth year in the 7-year life cycle of a well. For coal mines, the expansion of a mine pit through a drainage requires rerouting of the drainage during mining and then reclamation and restoration of the drainage when the mine pit is backfilled and the mine reclaimed. This disruption and subsequent restoration of an ephemeral drainage results in surface water runoff and sediment loading that differ from the original undisturbed drainage. The surface water quality analysis evaluated changes to SAR and EC in affected drainages and compared these changes to: 1) Wyoming, Montana, and South Dakota water quality restrictions for surface waters flowing across state boundaries and 2) the Ayers and Westcot Diagram for irrigation water quality (Ayers and Westcot 1985). The surface water quality analysis considered cumulative effects in both normal years and dry years. In this report, ACE's (2009) surface water analysis is summarized with respect to irrigation suitability of CBNG discharge water after mixing with both normal and dry year flows in the six subwatersheds in the Wyoming PRB study area (**Figure 2-1**).

The cumulative effects surface water analysis addresses current conditions (2003) and three future RFD scenarios for years 2010, 2015, and 2020. Based on the information developed in support of the analysis and documented in the Task 1B Report (AECOM 2009a) and Task 2 Report (AECOM 2009b), the cumulative effects have been addressed on a subwatershed basis. The six subwatersheds in the Wyoming PRB study area are shown in **Figure 2-1** and include: Antelope Creek, Dry Fork Cheyenne River, Little Powder River, Upper Belle Fourche River, Upper Cheyenne River, and Upper Powder River.

The cumulative effects analysis conducted by ACE (2009) focused on the cumulative impacts to surface water quality and channel stability with respect to the surface water resources within the study area. In general, the cumulative impacts directly relate to the water quantity and quality associated with the discharges from base year and RFD coal mining activities, CBNG wells, and conventional oil and gas wells compared to the water quantity and quality of the receiving drainages. Of particular importance is the amount of production water or discharge that is directly conveyed to the receiving drainages. Based on information and data presented in the Task 1B and Task 2 reports, it is assumed that the production water discharged directly to the receiving drainages would be limited to CBNG water discharge. In general, the existing data reflect that water production from coal mining activities would be largely consumed on site. Water production from conventional oil and gas wells typically requires treatment to meet water quality standards associated with the WYPDES permitting requirements, before it is discharged to the surface.

2.2.1 Surface Water Quality

Potential impacts to surface water quality as a result of projected CBNG development were evaluated during completion of the PRB Oil and Gas EIS (BLM 2003) and documented in a supporting technical report (Greystone and ALL Consulting 2003). Key water quality parameters for predicting the potential effects of CBNG development focused on the suitability of surface water for agricultural irrigation. Consequently, SAR and salinity, measured by EC, were utilized for the prediction. The cumulative effects analysis for the PRB Coal Review utilized the same water quality parameters and involved a similar evaluation.

2.2.2 Evaluation Criteria

Table 2-2 summarizes the most restrictive and least restrictive regulatory standards for EC and SAR applicable to the subwatersheds in the Wyoming PRB study area (ACE 2009). The limits presented in **Table 2-2** were utilized during the comparison of EC and SAR values for resulting mixtures of existing stream flows and discharges from CBNG wells under various flow conditions and RFD projections for the years 2010, 2015 and 2020.

Table 2-2
Summary of Proposed Limits for SAR and EC

Subwatershed	Most Restrictive Proposed Limit (MRPL)		Least Restrictive Proposed Limit (LRPL)	
	SAR	EC (μS/cm[1])	SAR	EC (μS/cm[1])
Little Powder River	5	2,000	9.75	2,500
Upper Powder River	2	2,000	9.75	2,500
Upper Belle Fourche River	6	2,000	10	2,500
Dry Fork Cheyenne River, Upper Cheyenne River, Antelope Creek	10	2,000	10	2,500

[1] μS/cm = microsiemens per centimeter.

Sources: WDEQ, MDEQ, and South Dakota Legislative Council.

With respect to the information presented in **Table 2-2**, the WDEQ applies numeric water quality standards for EC and SAR that were adopted for water bodies downstream in South Dakota. Specifically, these standards apply to the Upper Belle Fourche River, Antelope Creek, Upper Cheyenne River, and Dry Fork Cheyenne River. In March of 2003, the Montana Board of Environmental Review adopted numeric standards for EC and SAR for surface water sources. These standards apply to the Little Powder River and Upper Powder River (ACE 2009). Implementation of the guidelines in **Table 2-2** currently is under legal review.

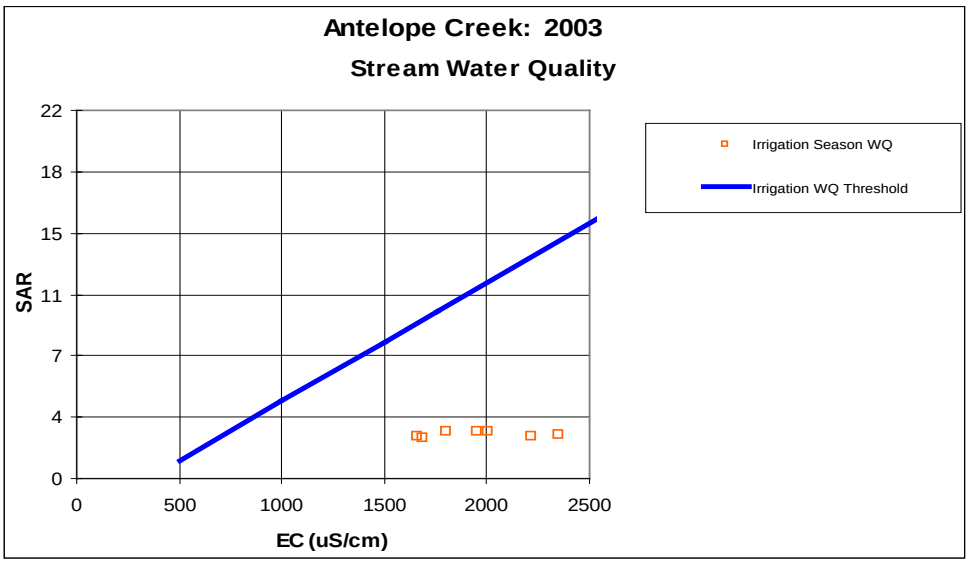
2.2.2.1 Irrigation Suitability Diagram

The Ayers and Westcot (1985) irrigation suitability diagram was used to compare water quality before and after mixing with discharges from CBNG wells (ACE 2009). The diagonal line on the diagram is used as the no-impact threshold for SAR and EC values of the water. Water quality would be expected to cause “no reduction in the rate of infiltration” as a result of dispersion of soils by SAR if the value fall below and to the right of the irrigation threshold line (Ayers and Westcot 1985). Alternatively, waters located to the left and above the threshold line for irrigation would be likely to cause a slight to moderate reduction in the rate of infiltration (Ayers and Westcot 1985).

This EC/SAR relationship in the Ayers Westcot irrigation suitability diagram is utilized to determine the effect of irrigation waters on the infiltration capacity of soils. Elevated SAR values may reduce the permeability in clayey soils, consequently reducing the infiltration rate. It should be noted that the significance of the effects associated with a reduction in infiltration rate varies with soil type, and increases on clay and clay-loam soils. In addition, the EC/SAR relationship typically indicates that

as salinity increases, the potential impacts of SAR decrease; however, this relationship should not be applied without limits (ACE 2009). The potential impact of rainfall on sodic soils can cause SAR problems by substantially lowering the EC, with little change in the SAR. An attempt to address this potential problem, along with the inherent variability in soils, is made through the application of an absolute maximum SAR value during the analysis.

Figure 2-2 provides an example of an Ayers and Westcot diagram and shows the irrigation suitability for the existing stream water quality (2003 current conditions) associated with Antelope Creek. Ayers and Westcot diagrams for the other subwatersheds in the study area are presented in ACE 2009. As indicated in **Figure 2-2**, the existing water quality in Antelope Creek appears to be suitable for irrigation (ACE 2009).



Note: WQ = water quality.

Source: ACE 2009.

Figure 2-2 Antelope Creek: 2003 Stream Water Quality

2.2.3 Surface Water Quality Modeling

The surface water model used for the technical report (Greystone and ALL Consulting 2003) prepared in support of the PRB Oil and Gas EIS (BLM 2003) was used by ACE for the PRB Coal Review surface water cumulative effects analysis. This spreadsheet model uses a steady-state, mass balance approach to estimate steady-state concentrations of EC and SAR.

Input parameters to the spreadsheet model included.

- Estimated CBNG well production water (million gallons per year [mmgpy])
- CBNG well production water SAR
- CBNG well production water EC (µS/cm)
- Channel loss (percent)

- Subwatershed stream flow (acre-feet)
- Subwatershed stream flow SAR
- Subwatershed stream flow EC (µS/cm)

The following assumptions were used by ACE (2009) for purposes of water quality modeling.

- Assuming SAR behaves as a single constituent of water, mixed SAR was estimated using a simple flow-weighted mass balance equation.

- Impacts to the receiving streams were evaluated for hydrologic conditions associated with relatively dry years as well as normal or average years. The dry year analysis evaluated the maximum likely impacts to surface water quality.

- The model assumed complete mixing.

- A channel loss value of 70 percent was used in the model.

2.2.3.1 Stream Flow

Average monthly and annual flows at pertinent gauging stations for the major drainages within each subwatershed were obtained by ACE (2009) from the Powder/Tongue River Basin Water Plan (HKM Engineering et al. 2002a) and the Northeast Wyoming River Basins Water Plan (HKM Engineering et al. 2002b). The development of the stream flow data relied on historic stream flow gaging data to the maximum extent possible. The subwatersheds in the study area, however, are characterized by a scarcity of historic stream flow records. As a result, ACE (2009) developed stream flow data at several locations within the study area. The methodology used to collect the historic records of stream flow, establish a study period, and to extend or fill-in the stream flow data where records were unavailable, was summarized in the basin plans (HKM Engineering et al. 2002a,b).

The impact analysis conducted by ACE (2009) assumed two hydrologic conditions: a dry year study period and a normal year study period. The dry year analysis was used to evaluate the maximum likely impacts to surface water quality, assuming limited flow in the receiving streams.

2.2.3.2 Stream Water Quality

EC and SAR values for the streams within the study area were identical to the values used in the technical report (Greystone and ALL Consulting 2003) in support of the PRB Oil and Gas EIS (BLM 2003). Limited data were available to characterize the water quality in the Dry Fork Cheyenne River; therefore, data available for the neighboring subwatershed (Antelope Creek) were used for the water quality impact analysis (ACE 2009).

2.2.3.3 CBNG Well Production Water

Production water from existing and projected CBNG wells was obtained from the Task 2 report (AECOM 2009b). Sources for these data included, but were not limited to, the IHS Energy Services database and data from the WOGCC.

2.2.3.4 CBNG Well Production Water Quality

EC and SAR values for the production water associated with the CBNG wells in the study area were documented in the technical report by Greystone and ALL Consulting (2003) in support of the PRB Oil and Gas EIS (BLM 2003). In addition, the WDEQ/Water Quality Division provided pertinent and more recent water quality data for effluent water quality from CBNG wells in all subwatersheds, with the exception of Antelope Creek and Dry Fork Cheyenne River (ACE 2009). The water quality data obtained from both of these sources were reviewed by ACE (2009) and used to describe the water quality associated with CBNG production water.

2.2.3.5 Managed Water Loss

The PRB Oil and Gas EIS (BLM 2003) assumed water produced from CBNG wells would be managed through containment, land application disposal, and injection, and would not have direct effects on quality and quantity of surface water because none of the discharged water would reach drainages in the subwatersheds under these water handling options. The percentage of CBNG production water managed through these options is referred to as managed water loss (MWL). The percentage of CBNG production water included in the MWL varies between subwatersheds and is presented in **Table 2-3**. It should be noted that all CBNG water discharged directly into the drainages ultimately may be consumptively used by downstream water users. Based on the profile of water users within the subwatersheds, it is likely that this water would be used for irrigation purposes (ACE 2009).

Table 2-3
Percent of Total Water Production from CBNG Wells per Discharge Method

Subwatershed	Untreated Discharge into Drainages	Passive Treatment	Active Treatment	Infiltration Impoundment	Containment Impoundment	Land Applied Disposal	Injection
Upper Powder River	35	0	10	40	5	5	5
Little Powder River	45	0	0	30	10	10	5
Antelope Creek	55	0	0	35	5	0	5
Upper Cheyenne River	55	0	0	35	5	0	5
Dry Fork Cheyenne River	55	0	0	35	5	0	5
Upper Belle Fourche River	45	0	0	40	5	0	10

Source: BLM 2003.

2.2.3.6 Conveyance Loss

Studies conducted by the BLM (2003) have shown that conveyance losses for direct discharge to drainages are approximately 70 to 90 percent, depending on the time of year. Evaporation losses, which are a large component of conveyance losses, can be 80 percent during the summer months in Wyoming. Thus, most CBNG discharge water either infiltrates or evaporates within a few miles of the discharge outfall and generally is not recorded at U.S. Geological Service (USGS) stream gauging stations. Impacts to surface water flow and quality are thus limited to within a few miles of the discharge outfall and, as of 2002, have not been recorded by the network of USGS gauging stations.

Conveyance losses would vary by subwatershed as a function of the total CBNG production water discharged and the channel, soils, slope of the channel, type of drainage (ephemeral versus perennial), cover/vegetation within the channel, and time of year (ACE 2009). A conveyance loss of 70 percent was selected by ACE (2009) for the water quality assessment and modeling and has been used in the predictive scenarios for surface water quality.

3.0 PREDICTED FUTURE CUMULATIVE WATER RESOURCE IMPACTS

3.1 Introduction

Predicted future cumulative water resource impacts in the Wyoming PRB study area were based on projected rates for CBNG pumpage and subsequent discharge through outfalls as permitted by the WDEQ and coal mine dewatering for years 2010, 2015, and 2020 as discussed in Chapter 2.0. The coal mines in the study area are divided into three subregions: 1) Subregion 1 located north of Gillette, Wyoming; 2) Subregion 2 located south of Gillette, Wyoming; 3) and Subregion 3 located near Wright, Wyoming (see **Figure 1-1**). Projected future CBNG locations in the study area were provided by the BLM (2007c). For projected groundwater level changes, this section presents a summary of the notable features of each figure presented in Appendix B. These figures present the modeling results for coal mine pumpage only, CBNG pumpage and discharge only, and combined coal mine and CBNG pumpage and CBNG discharge. The groundwater level changes for each of these scenarios for each predictive time period (2010, 2015, and 2020) are discussed relative to 1990 conditions, the year that preceded most CBNG pumpage in the eastern PRB. They also are discussed relative to the calibration year for the groundwater model, year 2002. Comparison to 1990 conditions is included to present the cumulative groundwater level changes since the onset of CBNG pumpage in the eastern PRB. Comparison to 2002 conditions is included to present the changes in groundwater levels since 2002, a time period of major CBNG pumpage. Details on the numerical groundwater model design along with estimates of changes in groundwater levels in the eastern PRB from 1990 to 2002, are presented in the Task 1B report (AECOM 2009a).

Surface water impacts were modeled using the estimated CBNG discharge into the Antelope Creek, Dry Fork Cheyenne River, Little Powder River, Upper Cheyenne River, and Upper Powder River subwatersheds as presented in the Task 2 Report (AECOM 2009b). The surface water cumulative impact analysis focused on RFD scenarios for normal and dry years. Wet years were not analyzed because increased runoff and stream flow would result in potential water quality impacts considerably less than the normal and dry year RFD scenarios. Surface water quality in each subwatershed for 2010, 2015, and 2020 was compared to the standards presented in **Table 2-2**. A complete analysis of cumulative impacts to surface water quality in these subwatersheds is presented in the Task 3B Water Resources Cumulative Impact Assessment Water Quality and Channel Stability report prepared by ACE (2009). Cumulative surface water quality impacts were estimated using a liner mixing model that combined stream flows and stream water quality with the predicted CBNG discharge water quantity and quality for each subwatershed for the modeled years of 2010, 2015, and 2020. The base year for comparison for surface water quality impacts was 2003. The surface water quantity and quality conditions for 2003 are presented in ACE's (2009) report and summarized in the Task 1B report (AECOM 2009a). ACE's (2009) predicted future cumulative surface water impacts as summarized in this section focus on changes relative to the base year (2003) conditions.

As with all projections into the future, the predicted future cumulative water resource impacts are based on data available as of 2003 and the assumption that past patterns of water use and water quality would continue into the future. A brief summary of projected groundwater level changes and projected surface water quality changes for the modeled years of 2010, 2015, and 2020 is presented at the end of this section.

3.2 Modeled Cumulative Impacts For Year 2010

3.2.1 Groundwater Level Changes Since 1990

3.2.1.1 Wasatch Formation

Groundwater Levels For 2010

Figure B-1 in Appendix B presents the modeled groundwater levels in the eastern PRB for the Wasatch Formation in year 2010. South of Wright, Wyoming, groundwater in the Wasatch flows to the northeast, toward the Subregion 3 group of coal mines. East of Wright, groundwater flow changes to northward, and north of Wright, groundwater flow in the Wasatch trends northwest, continuing in a northwestward flow pattern out of the model domain at the north end of the model domain. The base of Antelope Creek is mostly below the water levels in the Wasatch, so Antelope Creek acts as a drain and removes water from the Wasatch. The base of the Belle Fourche River is above the groundwater level in the Wasatch, so this drainage does not affect groundwater flow in the Wasatch. Around the Subregion 3 coal mines, groundwater flow in the Wasatch converges on the mines, suggesting dewatering of the Wasatch. The Subregion 1 and 2 coal mines do not show this influence on the Wasatch groundwater levels. Overall, groundwater levels in the Wasatch in the southern part of the model domain range from 4,900 to 5,000 feet above mean sea level (amsl). In the northern part of the model domain, the groundwater levels are in the range of 4,225 to 4,100 feet amsl. There is a suggestion of mounding west of the Subregion 2 coal mines, due to CBNG discharge, and a depression in the groundwater levels southeast of Gillette due to municipal pumpage. Wild Cat Creek at the far northern end of the model domain acts as a drain and removes water from the Wasatch. This area also has local CBNG pumpage that affects the Wasatch.

Coal Mine Pumpage Only

Figure B-2 in Appendix B shows the modeled effect of coal mine pumpage on Wasatch groundwater levels from 1990 to 2010. Only the Subregion 3 coal mines in the southern part of the model domain have a noticeable effect on groundwater levels. Drawdown within the mine boundaries ranges from 30 to 70 feet. West of the mine boundaries, drawdown is 10 to 20 feet, and the 10-foot drawdown isopleth extends approximately 5 miles west of the northern pod of mines. For the Subregion 1 and 2 coal mines, drawdown is 10 feet or less.

CBNG Pumpage and Discharge Only

Figure B-3 in Appendix B shows the modeled effect of CBNG pumpage and discharge on Wasatch groundwater levels from 1990 to 2010. The main effect of CBNG pumpage and discharge is the mounding of 10 to 20 feet in the Wasatch west and south of Wright, west of the Subregion 2 coal mines, and southwest of the Subregion 1 coal mines. There is a decline of 10 to 40 feet in groundwater levels southeast of Gillette due to municipal pumpage. Loss of groundwater from the Wasatch to Wild Cat Creek, and CBNG pumpage in the Wild Cat Creek area, cause a decline in groundwater levels of 10 to 20 feet near the creek.

Combined CBNG Pumpage And Discharge and Coal Mine Pumpage

Figure B-4 in Appendix B shows the combined effect of CBNG pumpage and discharge and coal mine dewatering on the Wasatch from 1990 to 2010. This figure is a composite of **Figures B-2** and **B-3**. As expected, the influence of the Subregion 3 coal mines on the Wasatch is evident, with a decline in groundwater levels of 10 to 70 feet. The influence of CBNG discharge also is evident, with mounding of 10 to 20 feet west and south and west of Wright, west of the Subregion 2 coal mines, and southwest of the Subregion 1 coal mines.

3.2.1.2 Fort Union Formation

Groundwater Levels for 2010

Figure B-5 in Appendix B shows the model-estimated groundwater levels within the Upper Fort Union Formation for year 2010. Groundwater flow along the southern part of the model domain is to the northeast, toward the Subregion 3 coal mines. Southwest of Wright, there is a well-developed depression in the groundwater that covers approximately nine townships. This depression is due to CBNG pumpage, and groundwater levels decline from 4,525 feet amsl along the edges of the depression to 4,150 feet amsl near the center of the depression, which is located along State Route (SR) 387 southwest of Wright. North of Wright, groundwater in the Upper Fort Union flows to the north-northwest. Near the Subregion 3 coal mines there are small local groundwater mounds in the Upper Fort Union due to the interaction between CBNG pumpage and coal mine dewatering. Southeast of Gillette there is a depression in the groundwater levels caused by municipal pumpage. Near the Subregion 2 coal mines, there are small local mounds and depressions west of the mines due mainly to localized CBNG pumpage. East of the coal mines in Subregion 3, groundwater flow in the Upper Fort Union is into the model domain from the east. Between the Subregion 3 and Subregion 2 coal mines, groundwater flow east of the coal mines is northward, converging on a depression east of the Subregion 2 coal mines, where groundwater flows eastward and out of the model domain. Overall, groundwater elevations in the southern part of the model domain are in the range of 4,900 to 5,100 feet amsl; in the northern part of the model domain, groundwater elevations are in the range of 4,100 to 4,000 feet amsl. CBNG activity from 1990 to 2010 has disrupted the northward flow of groundwater south of Wright and near the Subregion 2 and Subregion 3 coal mines.

Coal Mine Pumpage Only

Figure B-6 in Appendix B shows the modeled effect of coal mine pumpage on the Upper Fort Union from 1990 to 2010. Drawdown in the Subregion 3 coal mines ranges from approximately 50 to 250 feet in the southern pod of mines and from 50 to 150 feet in the northern pod of mines. For the Subregion 2 coal mines, drawdown is approximately 50 to 150 feet, with the greatest drawdown in the southern portion of the subregion. In the Subregion 1 coal mines north of Gillette, drawdown in the Upper Fort Union is approximately 25 to 100 feet.

CBNG Pumpage And Discharge Only

Figure B-7 in Appendix B shows the modeled drawdown in the Upper Fort Union due to CBNG pumpage and discharge from 1990 to 2010. This figure reinforces the pattern in groundwater levels for the Upper Fort Union in 2010, showing an extensive area of drawdown southwest of Wright that

covers nearly 15 townships and drawdowns ranging from 25 feet on the southern margin to 575 feet in the center of the depression. Drawdown west of the Subregion 1 and Subregion 2 coal mines is 25 to 50 feet due to CBNG pumpage. Around Wild Cat Creek, drawdown is approximately 25 feet due to CBNG pumpage.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-8 in Appendix B shows the combined modeled effect of CBNG pumpage and discharge and coal mine dewatering in the Upper Fort Union from 1990 to 2010. This figure is a composite of **Figures B-6** and **B-7**. Near the coal mines in Subregion 3, the overlap of CBNG-related drawdown and coal mine-related drawdown west of the mines has produced drawdown in the Upper Fort Union in the range of 125 to 250 feet. West of the Subregion 2 coal mines, drawdown is 25 to 50 feet, except for the southern end of Subregion 2, where there is a pocket of drawdown south of the mines ranging from 50 to 125 feet. Around Wild Cat Creek, there is drawdown of 25 to 50 feet due to CBNG-related pumpage and some overlap with coal mine-related pumpage.

3.2.2 Groundwater Level Changes Since 2002

3.2.2.1 Wasatch Formation

Coal Mine Pumpage Only

Figure B-9 in Appendix B shows the modeled effect of coal mine dewatering on the Wasatch Formation from 2002 to 2010. Drawdown since 2002 is limited to the Subregion 3 coal mines and ranges up to 70 feet, with most of the drawdown located in the northern pod of coal mines.

CBNG Pumpage and Discharage Only

Figure B-10 in Appendix B shows the modeled effect of CBNG pumpage and discharge on the Wasatch from 2002 to 2010. Mounding west of Wright in the range of 10 to 20 feet, and also west of the Subregion 2 coal mines, are the most evident features. There is some localized drawdown west of Wright and near Wild Cat Creek.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-11 in Appendix B shows the combined modeled effect of coal mine dewatering and CBNG pumpage and discharge on the Wasatch from 2002 to 2010. This figure is a composite of **Figures B-9** and **B-10**. Drawdown southeast of Gillette is approximately 10 to 20 feet and is due to municipal pumpage.

3.2.2.2 Fort Union Formation

Coal Mine Pumpage Only

Figure B-12 in Appendix B shows the modeled effect of coal mine dewatering on the Upper Fort Union from 2002 to 2010. Drawdown in the Subregion 3 coal mines ranges from 25 to 150 feet in the southern pod of mines, with the strongest drawdown along the eastern margin near the clinker.

For the northern pod of mines in Subregion 3, drawdown ranges from 25 to 100 feet. In the Subregion 2 coal mines, drawdown is from 25 to 125 feet in the southern pod of mines and from 25 to 75 feet in the northern pod of mines. For the Subregion 1 mines, drawdown in the Upper Fort Union is from 25 to 75 feet.

CBNG Pumpage and Discharge Only

Figure B-13 in Appendix B shows the modeled effect of CBNG pumpage and discharge on the Upper Fort Union from 2002 to 2010. The drawdown southwest of Wright is extensive and covers 12 townships, with drawdown ranging from 25 to 350 feet. West of the northern pod of coal mines in Subregion 3, rebound of groundwater levels is up to 150 feet due to a reduction of CBNG pumpage. North of Wright along SR 59, rebound is 75 to 125 feet. West of the Subregion 2 coal mines, rebound is 50 to 275 feet due to a reduction of CBNG pumpage between 2002 and 2010. Southwest of the Subregion 1 coal mines, rebound is approximately 25 feet.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-14 in Appendix B shows the combined modeled effect of CBNG pumpage and discharge and coal mine dewatering on the Upper Fort Union from 2002 to 2010. As shown in **Figures B-12** and **B-13**, drawdown in the Upper Fort Union in **Figure B-14** is extensive southwest of Wright due to CBNG pumpage and is substantial in the coal mine areas. West of the Subregion 3 coal mines and along SR 59 to the area west of the Subregion 2 coal mines, rebound in the Upper Fort Union due to a reduction of CBNG pumpage results in groundwater levels rebounding from 25 to 100 feet.

3.2.3 Modeled Cumulative Surface Water Impacts for 2010

The modeled cumulative surface water effects for predictive year 2010, as well as for predictive years 2015 and 2020, reflect the projected change in conditions compared to the modeled base year (2003). To aid the reviewer, modeled base year surface water conditions for each subwatershed are presented in the tables in this section. For this analysis, “mixing” refers to the mixing of CBNG production water discharge and natural flow. The methodology used for projecting cumulative effects to surface waters in the study area is presented in Section 2.2.

Antelope Creek: The modeled cumulative surface water effects for Antelope Creek for year 2010 are presented in **Table 3-1** and summarized below.

- Before Mixing. Conditions in 2010 are projected to be the same as base year (2003) conditions (see **Table 3-1**).

- Following Mixing. EC values for the minimum mean monthly flow are projected to decrease from 2,372 to 1,247 µS/cm in December for the normal year and from 2,005 to 1,043 µS/cm in June for the dry year, sufficient to meet the LRPL and MRPL for both hydrologic conditions. SAR values are projected to increase from 2.79 to 6.55 for the normal year and to 7.11 for the dry year; however, they continue to meet the LRPL and MRPL for both hydrologic conditions.

Table 3-1
Cumulative Surface Water Impact Analysis for Antelope Creek Subwatershed

Year	MRPL		LRPL		Existing Stream Water Quality at Minimum Mean Monthly Flow			Resulting Stream Water Quality at Minimum Mean Monthly Flow[4]		
	SAR[1]	EC[1] (µS/cm)	SAR[2]	EC[2] (µS/cm)	Flow (cfs[3])	SAR	EC (µS/cm)	Flow (cfs[3])	SAR	EC (µS/cm)
Normal Year										
2003[5]	10	2,000	10	2,500	0.31	2.79	2,372	1.21	6.38	1,299
2010	10	2,000	10	2,500	---	---	---	1.41	6.55	1,247
2015	10	2,000	10	2,500	---	---	---	1.51	6.62	1,226
2020	10	2,000	10	2,500	---	---	---	1.31	6.47	1,271
Dry Year										
2003[5]	10	2,000	10	2,500	0.13	2.79	2,005	1.03	7.01	1,065
2010	10	2,000	10	2,500	---	---	---	1.23	7.11	1,043
2015	10	2,000	10	2,500	---	---	---	1.33	7.14	1,035
2020	10	2,000	10	2,500	---	---	---	1.13	7.06	1,053

[1] WDEQ.
[2] South Dakota's Legislative Council.
[3] cfs = cubic feet per second.
[4] Following mixing of stream flow with CBNG water discharge.
[5] Modeled base year conditions:

Before Mixing – EC values exceed MRPL during low-flow months (September through February and in June), but are less than LRPL for both dry and normal years. SAR values are less than MRPL and LRPL under similar hydrologic conditions. The Ayers and Westcot diagram indicates that the water is suitable for irrigation during all months in both hydrologic conditions prior to mixing with the CBNG discharge water.

Following Mixing – EC values meet MRPL and LPRL for both dry and normal years. SAR values increase but meet MRPL and LRPL for both hydrologic conditions.

Irrigation suitability – Data for dry year conditions indicate a reduction in infiltration following mixing with CBNG production water, primarily for the months of June and August during the irrigation season when the water becomes unsuitable for irrigation. Data for normal year conditions indicate a minor decrease in infiltration following mixing; overall data indicate mixed water would be suitable for irrigation.

Source: ACE 2009.

- Irrigation Suitability. For dry year conditions, there is a projected substantial reduction in infiltration throughout the irrigation season following mixing with CBNG production water. Overall, however, the data indicate that the mixed water would be marginally suitable for irrigation in dry years, except for June and August when it is not suitable. Under normal year conditions, a projected decrease in infiltration occurs following mixing with CBNG production water. Overall, however, the data indicate that the mixed water would be suitable for irrigation.

Dry Fork Cheyenne River: The modeled cumulative surface water effects for the Dry Fork of the Cheyenne River for year 2010 are presented in **Table 3-2** and summarized below.

- Before Mixing. Conditions in 2010 are projected to be the same as base year (2003) conditions (see **Table 3-2**).

Table 3-2
Cumulative Surface Water Impact Analysis for Dry Fork Cheyenne River Subwatershed

Year	MRPL		LRPL		Existing Stream Water Quality at Minimum Mean Monthly Flow			Resulting Stream Water Quality at Minimum Mean Monthly Flow[2]		
	SAR[1]	EC[1] (µS/cm)	SAR[1]	EC[1] (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)
Normal Year										
2003[3]	10	2,000	10	2,500	0	---	---	0.00	---	---
2010	10	2,000	10	2,500	---	---	---	0.00	---	---
2015	10	2,000	10	2,500	---	---	---	0.00	---	---
2020	10	2,000	10	2,500	---	---	---	0.00	---	---
Dry Year										
2003[3]	10	2,000	10	2,500	0	---	---	0.00	---	---
2010	10	2,000	10	2,500	---	---	---	0.00	---	---
2015	10	2,000	10	2,500	---	---	---	0.00	---	---
2020	10	2,000	10	2,500	---	---	---	0.00	---	---

[1] WDEQ.
[2] Following mixing of stream flow with CBNG water discharge.
[3] Modeled base year conditions:

Before Mixing – EC values exceed MRPL during low-flow months (September through February and June). All mean monthly EC values exceed LRPL.

Following Mixing – SAR values are less than MRPL and LRPL under similar flow conditions.

Irrigation Suitability – Data indicate water would be suitable for irrigation.

Source: ACE 2009.

- Following Mixing. Conditions in 2010 are projected to be the same as base year (2003) conditions (**Table 3-2**) because no CBNG production water discharge is expected to the Dry Fork of the Cheyenne River in 2010.

- Irrigation Suitability. Conditions in 2010 are projected to be the same as base year (2003) conditions (**Table 3-2**) because no discharge of CBNG production water is expected to the Dry Fork of the Cheyenne River in 2010.

Little Powder River: The modeled cumulative surface water effects for the Little Powder River for year 2010 are presented in **Table 3-3** and summarized below.

- Before Mixing. Conditions in 2010 are projected to be the same as base year (2003) conditions (see **Table 3-3**).

- Following Mixing. EC values for the minimum mean monthly flow are projected to decrease from 3,300 to 2,277 µS/cm in December for the normal year and from 2,810 to 1,686 µS/cm in September for the dry year. For the normal year, EC values are sufficient to meet the LRPL except for January and August, but exceed the MRPL except for March and May. For the dry

year, EC values exceed the MRPL in February, April, June, and August, and are less than the LRPL for all months. SAR values are projected to increase from 6.94 to 8.97 for the normal year and from 6.44 to 9.94 for the dry year. For the normal year, SAR values exceed the MRPL for all months except March, and are less than the LRPL for the entire year. For the dry year, SAR values exceed the MRPL for all months, but only exceed the LRPL in September.

Table 3-3
Cumulative Surface Water Impact Analysis for Little Powder River Subwatershed

Year	MRPL		LRPL		Existing Stream Water Quality at Minimum Mean Monthly Flow			Resulting Stream Water Quality at Minimum Mean Monthly Flow[2]		
	SAR[1]	EC[1] (µS/cm)	SAR[1]	EC[1] (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)
Normal Year										
2003[3]	5	2,000	9.75	2,500	1.05	6.94	3,300	2.7	9.08	2,219
2010	5	2,000	9.75	2,500	---	---	---	2.5	8.97	2,277
2015	5	2,000	9.75	2,500	---	---	---	1.5	7.92	2,806
2020	5	2,000	9.75	2,500	---	---	---	1.2	7.25	3,144
Dry Year										
2003[3]	5	2,000	9.75	2,500	0.22	6.44	2,810	1.8	10	1,666
2010	5	2,000	9.75	2,500	---	---	---	1.6	9.94	1,686
2015	5	2,000	9.75	2,500	---	---	---	0.6	9.05	1,971
2020	5	2,000	9.75	2,500	---	---	---	0.3	7.71	2,403

[1] MDEQ.
[2] Following mixing of stream flow with CBNG water discharge.
[3] Modeled base year conditions:

Before Mixing – EC values exceed MRPL for all months except March, and exceed LRPL during low-flow conditions in August, September, and November through January for both dry and normal years. SAR values exceed MRPL for all months except March and May and are less than LRPL for both hydrologic conditions. The Ayers and Westcot diagram indicates that the water is suitable for irrigation during all months in both hydrologic conditions prior to mixing with the CBNG discharge water.

Following Mixing – EC values for the normal year decrease but continue to exceed the MRPL with the exception of March and May and exceed the LRPL during low flow months of January and August. SAR values increase and exceed MRPL, with the exception of March, and are less than LRPL for the normal year. For the dry year, EC values continue to decrease but exceed MRPL for the months of February, April, June, and August, and are less than the LRPL for all months. During the dry year, SAR values exceed MRPL for all months and exceed LRPL in September.

Irrigation Suitability – Data for the dry year indicate a reduction in infiltration following mixing with CBNG production water, and marginal unsuitablility for September through October during the irrigation season. Data for the normal year indicate a minor decrease in infiltration following mixing; overall, data indicate water would be suitable for irrigation during the normal year.

Source: ACE 2009.

- Irrigation Suitability. For the dry year conditions, data indicate a slight reduction in infiltration following mixing with CBNG production water, and the resulting water may be marginally unsuitabe for irrigation for the months of September and October during the irrigation season.

Under normal year conditions, only a minor decrease in infiltration is projected following mixing with CBNG production water; overall, data indicate that the mixed water would be suitable for irrigation during a normal year.

Upper Belle Fourche River: The modeling cumulative surface water effects for the Upper Belle Fourche River for year 2010 are presented in **Table 3-4** and summarized below.

Table 3-4
Cumulative Surface Water Impact Analysis for Upper Belle Fourche River Subwatershed

Year	MRPL		LRPL		Existing Stream Water Quality at Minimum Mean Monthly Flow			Resulting Stream Water Quality at Minimum Mean Monthly Flow[3]		
	SAR[1]	EC[2] (µS/cm)	SAR[2]	EC[2] (µS/cm)	Flow (cfs)	SAR[2]	EC (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)
Normal Year										
2003[4]	6	2,000	10	2,500	3.31	6.77	2,755	7.61	7.94	1,825
2010	6	2,000	10	2,500	---	---	---	9.71	8.13	1,671
2015	6	2,000	10	2,500	---	---	---	5.41	7.57	2,116
2020	6	2,000	10	2,500	---	---	---	3.31	6.77	2,755
Dry Year										
2003[4]	6	2,000	10	2,500	0.42	5.75	2,346	4.72	8.56	1,220
2010	6	2,000	10	2,500	---	---	---	6.82	8.64	1,186
2015	6	2,000	10	2,500	---	---	---	2.52	8.32	1,316
2020	6	2,000	10	2,500	---	---	---	0.42	5.75	2,346

[1] South Dakota's Legislative Council.
[2] WDEQ.
[2] Following mixing of stream flow with CBNG water discharge.
[4] Modeled base year conditions:

Before Mixing – EC values exceed MRPL from September through January and exceed LRPL during low-flow conditions during November through January for both normal and dry years. SAR values exceed MRPL from November through January and are less than LRPL for both hydrologic conditions. The Ayers and Westcot diagram indicates that the water is suitable for irrigation during all months in both hydrologic conditions prior to mixing with the CBNG discharge water.

Following Mixing – EC values decrease and meet both the LRPL and MRPL for dry year conditions and exceed MRPL during October, November, and January for normal year conditions. SAR values increase and exceed MRPL with the exception of the months of February, March, May, and July, and are less than LRPL for the dry year. Normal year SAR values exceed MRPL from August through January and are less than LRPL for all months.

Irrigation Suitability – Data for dry year conditions indicate a reduction in infiltration following mixing with CBNG production water, and is considered unsuitable for September and October during the irrigation season. Data for normal year conditions indicate a minor decrease in infiltration following mixing; overall, data indicate mixed water would be suitable for irrigation during the normal year.

Source: ACE 2009.

- Before Mixing. Conditions in 2010 are projected to be the same as base year (2003) conditions (see **Table 3-4**).

- Following Mixing. EC values for the minimum mean monthly flow are projected to decrease from 2,755 to 1,671 µS/cm in December for the normal year and from 2,346 to 1,186 µS/cm in

October for the dry year, meeting both the LRPL and MRPL for dry year conditions and exceeding the MRPL during January for the normal year. SAR values are projected to increase from 6.77 to 8.13 for the normal year and from 5.75 to 8.64 for the dry year, exceeding the MRPL with the exception of the months of March and July and meeting the LRPL for the dry year. For the normal year, SAR values exceed the MRPL from August through January, and are less than the LRPL for all months.

- Irrigation Suitability. For the dry year conditions, data indicate a reduction in infiltration following mixing with CBNG production water, and the water is generally considered unsuitable for irrigation for the months of August through October during the irrigation season. Under normal year conditions, a decrease in infiltration is projected following mixing with CBNG production water; overall, data indicate that the mixed water would be suitable for irrigation during a normal year.

Upper Cheyenne River: The modeled cumulative surface water effects for the Upper Cheyenne River for year 2010 are presented in **Table 3-5** and summarized below.

Table 3-5
Cumulative Surface Water Impact Analysis for Upper Cheyenne River Subwatershed

Year	MRPL		LRPL		Existing Stream Water Quality at Minimum Mean Monthly Flow			Resulting Stream Water Quality at Minimum Mean Monthly Flow[2]		
	SAR[1]	EC[1] (µS/cm)	SAR[1]	EC[1] (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)
Normal Year										
2003[3]	10	2,000	10	2,500	0.77	7.39	3,405	1.57	7.50	2,144
2010	10	2,000	10	2,500	---	---	---	1.07	7.45	2,711
2015	10	2,000	10	2,500	---	---	---	0.77	7.39	3,405
2020	10	2,000	10	2,500	---	---	---	0.77	7.39	3,405
Dry Year										
2003[3]	10	2,000	10	2,500	0.82	4.82	1,972	1.62	6.20	1,457
2010	10	2,000	10	2,500	---	---	---	1.12	5.57	1,693
2015	10	2,000	10	2,500	---	---	---	0.82	4.82	1,972
2020	10	2,000	10	2,500	---	---	---	0.82	4.82	1,972

[1] WDEQ.
[2] Following mixing of stream flow with CBNG water discharge.
[3] Modeled base year conditions:

Before Mixing – EC values exceed MRPL for all months except August and exceed LRPL from October through June for both normal and dry years. SAR values are less than the MRPL and LRPL for both hydrologic conditions. The Ayers and Westcot diagram indicates that the water is suitable for irrigation during all months in both hydrologic conditions prior to mixing with the CBNG discharge water.

Following Mixing – EC values slightly decrease but continue to exceed MRPL for all months except August in the normal year and both July and August in the dry year. EC values exceed LRPL during November and January through June for the normal year and from during October, November, and January through June for the dry year. SAR values are similar and remain less than the MRPL and LRPL for both hydrologic conditions.

Irrigation Suitability – Data for normal- and dry year conditions indicate a minor reduction in infiltration following mixing with CBNG production water. Overall, data indicate mixed water would be suitable for irrigation during both hydrologic conditions.

Source: ACE 2009.

- Before Mixing. Conditions in 2010 are projected to be the same as base year (2003) conditions (see **Table 3-5**).

- Following Mixing. EC values for the minimum mean monthly flow are projected to decrease from 3,405 to 2,711 µS/cm in December for the normal year and from 1,972 to 1,693 µS/cm in August for the dry year. EC values exceed the MRPL for all months except August, and exceed the LRPL except for July through September for both normal and dry hydrologic conditions. SAR values are projected to increase from 7.39 to 7.45 for the normal year and from 4.82 to 5.57 for the dry year. SAR for both the normal- and dry year conditions is below MRPL and LRPL.

- Irrigation Suitability. Both the normal- and dry year hydrologic conditions show a slight reduction in infiltration; however, the mixed water is projected to be suitable for irrigation in all months.

Upper Powder River: The modeled cumulative surface water effects for the Upper Powder River for year 2010 are presented in **Table 3-6** and summarized below.

Table 3-6
Cumulative Surface Water Impact Analysis for Upper Powder River Subwatershed

Year	MRPL		LRPL		Existing Stream Water Quality at Minimum Mean Monthly Flow			Resulting Stream Water Quality at Minimum Mean Monthly Flow[2]		
	SAR[1]	EC[1] (µS/cm)	SAR[1]	EC[1] (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)	Flow (cfs)	SAR	EC (µS/cm)
Normal Year										
2003[3]	5	2,000	9.75	2,500	103.61	6.40	2,482	105.91	6.75	2,475
2010	5	2,000	9.75	2,500	---	---	---	105.71	6.72	2,476
2015	5	2,000	9.75	2,500	---	---	---	104.61	6.56	2,479
2020	5	2,000	9.75	2,500	---	---	---	103.61	6.40	2,482
Dry Year										
2003[3]	5	2,000	9.75	2,500	38.57	7.83	3,400	40.87	8.66	3,331
2010	5	2,000	9.75	2,500	---	---	---	40.67	8.59	3,337
2015	5	2,000	9.75	2,500	---	---	---	39.57	8.20	3,369
2020	5	2,000	9.75	2,500	---	---	---	38.57	7.83	3,400

[1] MDEQ.
[2] Following mixing of stream flow with CBNG water discharge.
[3] Modeled base year conditions:

Before Mixing – EC values exceed MRPL for all months except May and June and exceed LRPL from July through December for both dry and normal years. SAR data exceed MRPL for all months except May and June and meet the LRPL for both hydrologic conditions. The Ayers and Westcot diagram indicates that the water is suitable for irrigation during all months in both hydrologic conditions prior to mixing with the CBNG discharge water.

Following Mixing – EC values slightly decrease but continue to exceed MRPL for all months except May and June for both normal and dry years. EC values continue to exceed LRPL from July through December for both normal and dry years. SAR values increase and exceed MRPL for all months for the dry year and all months except May and June for the normal year. SAR values meet LRPL for both hydrologic conditions.

Irrigation Suitability – Data for normal- and dry year conditions indicate a slight reduction in infiltration following mixing with CBNG production water. Overall, data indicate mixed water would be suitable for irrigation during both hydrologic conditions.

Source: ACE 2009.

- Before Mixing. Conditions in 2010 are projected to be the same as base year (2003) conditions (see **Table 3-6**).

- Following Mixing. EC values for the minimum mean monthly flow are projected to decrease slightly from 2,482 to 2,476 µS/cm in January for the normal year and from 3,400 to 3,337 µS/cm in September for the dry year, but would continue to exceed the MRPL for all months with the exception of May and June for both normal and dry years. EC values for both normal and dry years are less than the LRPL except for July through December. SAR values are projected to increase from 6.40 to 6.72 in the normal year and from 7.83 to 8.59 in the dry year, and exceed the MRPL for all months for the dry year and all months but May and June for the normal year. SAR values are below the LRPL for all months in both the normal and dry years.

- Irrigation Suitability. For both the normal- and dry year conditions, data indicate a slight reduction in infiltration following mixing with CBNG production water. Overall, data indicate that the mixed water would be suitable for irrigation during both hydrologic conditions.

3.3 Modeled Cumulative Impacts for Year 2015

3.3.1 Groundwater Level Changes Since 1990

3.3.1.1 Wasatch Formation

Groundwater Levels 2015

Figure B-15 in Appendix B shows the model-projected groundwater levels in the Wasatch for year 2015. Groundwater flow is similar to 2010, with flow south of Wright to the northeast toward the Subregion 3 coal mines. Antelope Creek acts as a drain, removing groundwater from the Wasatch because groundwater levels in the Wasatch are above the base elevation of Antelope Creek over most of its course. Near the Subregion 3 coal mines, groundwater in the Wasatch flows into the mine areas. East of Wright, groundwater flow in the Wasatch turns northward, and north of Wright, groundwater flow in the Wasatch is to the northwest. Mounding is present west of the Subregion 2 coal mines, and southeast of Gillette there is a groundwater depression from 4,400 feet amsl to 4,300 feet amsl due to municipal pumpage. North of the Subregion 1 coal mines, Wild Cat Creek acts as a drain, removing groundwater from the Wasatch. This area also is experiencing some decline in groundwater levels due to CBNG pumpage. Groundwater elevations south of Wright in the southern part of the model domain are in the range of 4,950 to 5,025 feet amsl. In the northern part of the model domain, groundwater elevations range from 4,175 to 4,100 feet amsl.

Coal Mine Pumpage Only

Figure B-16 in Appendix B shows the modeled effect to the Wasatch due to coal mine dewatering from 1990 to 2015. Similar to 2010, the Subregion 3 coal mines have the most effect on the Wasatch. Drawdown ranges from 30 to 100 feet within the mine boundaries, with a maximum of 150 feet. West of the mines, drawdown in the Wasatch ranges from 10 to 30 feet and extends approximately 5 miles west of the northern pod of mines in Subregion 3. The Subregion 2 and Subregion 1 coal mines have less than 10 feet of drawdown in the Wasatch.

CBNG Pumpage and Discharge Only

Figure B-17 in Appendix B shows the modeled effect of CBNG pumpage and discharge on the Wasatch from 1990 to 2015. Approximately 10 feet of mounding is present southwest of Wright, and mounding of 10 to 20 feet is present west of the Subregion 2 coal mines due to CBNG discharge. Drawdown of 10 to 30 feet is present north of the Subregion 1 coal mines in the vicinity of Wild Cat Creek due to a localized area of CBNG pumpage.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-18 in Appendix B shows the combined effect of CBNG pumpage and discharge and coal mine dewatering on the Wasatch for the period from 1990 to 2015. This figure is a composite of **Figures B-16** and **B-17**. Drawdown west of the Subregion 3 coal mines is partially offset by mounding due to CBNG discharge; therefore, the sum of both CBNG discharge and coal mine dewatering results in less drawdown west of the mines in comparison to the coal mine pumpage only scenario (**Figure B-16**). Drawdown in the Subregion 3 coal mines ranges from 30 to 100 feet. Municipal pumpage at Gillette is shown in this composite figure and amounts to drawdown in the Wasatch of approximately 20 to 50 feet southeast of Gillette. Drawdown in the Wasatch also is present at Wild Cat Creek due to CBNG pumpage.

3.3.1.2 Fort Union Formation

Groundwater Levels 2015

Figure B-19 in Appendix B shows the model-projected groundwater levels in the Upper Fort Union for year 2015. Southwest of Wright there is an area of extensive drawdown due to CBNG pumpage. Groundwater levels decline from 4,600 feet amsl along the outer edge of the groundwater depression to 4,275 feet near the center of the depression. Outside of the depression, groundwater flow south of Wright is to the northeast in the Upper Fort Union, toward the Subregion 3 coal mines. North of Wright, groundwater flow turns northwestward and continues along that course to the upper model boundary. Groundwater flow in the area of the Subregion 3 coal mines is generally toward the mines from the west; however, the flow is quite variable due to mounding between the southern and northern pods of mines due to the overlap between CBNG pumpage and coal mine dewatering. Between the Subregion 3 and Subregion 2 coal mines, a ridge of elevated groundwater exists due to the drawdown to the west near Wright caused by CBNG pumpage, and also the transition between the coal stratigraphy provided by BLM (2005) and the stratigraphy of Goolsby, Finley, and Associates (2001). Groundwater flow around the Subregion 2 coal mines also is variable, but generally toward the mines from the west. A small groundwater mound is present southwest of the mines, and a small depression is found northwest of the mines due to CBNG pumpage and discharge. Around Gillette, a groundwater depression due to municipal pumpage is present. Groundwater flow around the Subregion 1 mines is from southeast to northwest. East of the Subregion 3 mines, water flows into the model domain from the east in the Upper Fort Union. Between the Subregion 3 and Subregion 2 coal mines, groundwater flow east of the mines is generally from south to north, converging on a depression east of the Subregion 2 mines, where groundwater flow in the Upper Fort Union flows eastward out of the model domain.

Coal Mine Pumpage Only

Figure B-20 in Appendix B shows the modeled drawdown in the Upper Fort Union from 1990 to 2015 due to coal mine dewatering. Drawdown in the Subregion 3 coal mines ranges from 25 to 150 feet, with most drawdown in the northern pod of mines ranging from 50 to 125 feet and drawdown of up to 150 feet in the southern pod of mines. Drawdown of 25 feet extends approximately 2 miles west of the Subregion 3 mine boundaries in the Upper Fort Union. Drawdown in the Subregion 2 coal mines ranges from 25 to 150 feet, with most drawdown ranging from 25 to 50 feet in the northern pod of mines and from 50 to 150 feet in the southern pod of mines. Rebound in the Subregion 1 coal mines is up to 100 feet. In the Subregion 2 mines, there is up to 25 feet of rebound at the north end of the mine pods and in the Subregion 3 mines there is about 50 feet of rebound due to reclamation at the eastern end of the northern pod of mines.

CBNG Pumpage and Discharge Only

Figure B-21 in Appendix B shows the modeled effect to the Upper Fort Union from CBNG pumpage and discharge from 1990 to 2015. Most of the drawdown is southwest of Wright, where drawdown ranges from 25 to 450 feet and covers approximately 12 townships. Southwest of the Subregion 2 coal mines, drawdown ranges from 50 to 125 feet due to CBNG pumpage.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-22 in Appendix B shows the combined modeled effect of CBNG drawdown and discharge and coal mine dewatering on the Upper Fort Union from 1990 to 2015. This figure is a composite of **Figures B-20** and **B-21**. The extensive drawdown due to CBNG pumpage southwest of Wright encompasses approximately 12 townships, with drawdown ranging from 25 to 475 feet. Drawdown southwest of the Subregion 2 coal mines ranges from 75 to 125 feet due to CBNG pumpage, and there is drawdown of 25 to 50 feet in the Wild Cat Creek area at the northern end of the model domain due to CBNG pumpage. In the Subregion 3 coal mines, most of the drawdown is along the eastern edge of the southern pod of mines and ranges up to 125 feet. In the northern pod of mines, drawdown ranges from 50 to 125 feet. In the Subregion 2 coal mines, drawdown ranges up to 125 feet. In the Subregion 1 coal mines, drawdown ranges up to 75 feet, and there is a small area of groundwater rebound up to 25 feet due to reclamation of the coal mine area. There is localized rebound in the Subregion 3 coal mines up to 50 feet due to coal mine reclamation. Municipal pumpage has resulted in approximately 50 feet of drawdown southeast of Gillette.

3.3.2 Groundwater Level Changes Since 2002

3.3.2.1 Wasatch Formation

Coal Mine Pumpage Only

Figure B-23 in Appendix B shows the modeled drawdown in the Wasatch from 2002 to 2015 due to coal mine dewatering. Drawdown is limited to the Subregion 3 coal mines and ranges from 10 to 60 feet in the southern pod of mines and from 30 to 80 feet in the northern pod of mines. West of the mines, drawdown in the Wasatch is 10 to 20 feet, and the 10-foot drawdown isopleth extends approximately 8 to 10 miles west of the mine boundaries. Drawdown in the Subregion 2 and

Subregion 1 coal mines is less than 10 feet. There is a small area of rebound up to 10 feet in the southern pod of mines in the Subregion 3 coal mines.

CBNG Pumpage and Discharge Only

Figure B-24 in Appendix B shows the modeled effect of CBNG pumpage and discharge on the Wasatch from 2002 to 2015. West of Wright, there is approximately 10 to 20 feet of drawdown. West of the Subregion 2 coal mines, there is approximately 10 feet of drawdown, and at the northern end of the model domain near Wild Cat Creek, there is approximately 10 feet of drawdown. Overall, there is approximately 10 feet of mounding west of SR 59 due to CBNG discharge. Southwest of Wright and west of Gillette, there is a general broad mound in water levels of approximately 10 feet due to CBNG discharge.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-25 in Appendix B shows the combined modeled effect of CBNG pumpage and discharge and coal mine dewatering on the Wasatch from 2002 to 2015. The figure is a composite of **Figures B-23** and **B-24**, with the municipal pumpage at Gillette added. Drawdown in the Wasatch due to Gillette municipal pumpage is 10 to 30 feet. Drawdown in the Subregion 3 coal mines is up to 70 feet in the northern pod of mines and up to approximately 50 feet in the southern pod of mines. Drawdown in the Subregion 2 coal mines is mainly west of the mines in the CBNG area and up to 20 feet. Drawdown northwest of Wright is up to 20 feet. Drawdown in the Subregion 1 coal mines is up to 10 feet, and in the Wild Cat Creek area, there is drawdown of 10 to 20 feet due to CBNG pumpage. West of Gillette and southwest of Wright, there are slight rebounds in groundwater levels of up to 10 feet in the Wasatch, possibly due to CBNG discharge.

3.3.2.2 Fort Union Formation

Coal Mine Pumpage Only

Figure B-26 in Appendix B shows the modeled effect of coal mine dewatering, reduced dewatering rates at some mines, and mine reclamation on the Upper Fort Union from 2002 to 2015. In the Subregion 3 coal mines, both the rebound of groundwater levels due to reclamation and drawdown due to coal mine dewatering are evident. For the southern pod of mines, rebound of groundwater levels up to 200 feet is evident along the northwestern part of the pod. Drawdown of 50 to 150 feet is evident at the eastern end of those same mines. In the northern pod of mines in Subregion 3, rebound of up to 50 feet is evident along the southern end of the pod. The remainder of the mines in this area show 25 to 100 feet of drawdown, most of which extends northwest of the mine boundaries. For the Subregion 2 coal mines, rebound of 25 to 50 feet is present locally; however, drawdown of 25 to 100 feet is present in the southernmost mines in this subregion. The Subregion 1 coal mines show 25 to 50 feet of rebound. Groundwater rebound in the coal mine areas is due to a decrease in pumping rate or reclamation of mined-out areas.

CBNG Pumpage and Discharge Only

Figure B-27 in Appendix B shows the modeled effect of CBNG pumpage and discharge from 2002 to 2015 on the Upper Fort Union. Southwest of Wright, drawdown of 25 to 350 feet is evident and covers approximately 8 townships. Around Wright and from Wright northward along SR 59 to the

Subregion 2 coal mines, rebound of groundwater levels of up to 275 feet is evident due to the reduction in CBNG pumpage. West of the Subregion 2 mines and southwest of the northern pod of mines in Subregion 3, rebound of up to 275 feet is evident in the CBNG field. Southwest of the Subregion 1 mines, rebound of up to 25 feet is evident. Groundwater rebound in the Upper Fort Union related to CBNG activity is due to both a reduction in pumping rate and the cessation of pumping in some areas.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-28 in Appendix B shows the combined effect of CBNG pumpage and discharge, rebound due to reduction of CBNG activity along SR 59, and coal mine dewatering on the Upper Fort Union from 2002 to 2015. This figure is a composite of **Figures B-26** and **B-27** and includes municipal pumpage at Gillette, which shows approximately 25 feet of drawdown in the Upper Fort Union. The drawdown southwest of Wright of up to 350 feet and the rebound in groundwater levels along SR 59 from Wright to the Subregion 2 coal mines are the most evident changes to the Upper Fort Union from 2002 to 2015. Rebound of water levels in the coal mines is evident and is due to a reduction in dewatering rates and local reclamation of the mines. Drawdown up to 100 feet is evident west of the southern pod of mines in Subregion 2.

3.3.3 Modeled Cumulative Surface Water Impacts for 2015

Antelope Creek: The modeled cumulative surface water effects for Antelope Creek for year 2015 are presented in **Table 3-1** and summarized below.

- Before Mixing. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-1**).

- Following Mixing. EC values for the minimum mean monthly flow are projected to decrease from 2,372 to 1,226 µS/cm in December for the normal year and from 2,005 to 1,035 µS/cm in June for the dry year, and are sufficient to meet the LRPL and MRPL for both the dry and normal years. SAR values are projected to increase from 2.79 to 6.62 for the normal year and from 2.80 to 7.14 for the dry year, but continue to meet the LRPL and MRPL for both hydrologic conditions.

- Irrigation Suitability. For dry year conditions, data indicate a reduction in infiltration throughout the irrigation season following mixing with CBNG production water due to an increase in SAR and a decrease in EC; however, the data generally indicate that the mixed water would be suitable for irrigation for all months in the normal year and all months except June and August in the dry year.

Dry Fork Cheyenne River: The modeled cumulative surface water effects for the Dry Fork Cheyenne River for year 2015 are presented in **Table 3-2** and summarized below.

- Before Mixing. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-2**).

- Following Mixing. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-2**) because no CBNG production water discharge is expected to the Dry Fork of the Cheyenne River in 2015.

- Irrigation Suitability. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-2**) because no CBNG production water discharge is expected to the Dry Fork of the Cheyenne River in 2015.

Little Powder River: The modeled cumulative surface water effects for the Little Powder River for year 2015 are presented in **Table 3-3** and summarized below.

- Before Mixing. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-3**).

- Following Mixing. For the normal year, EC values for the minimum mean monthly flow are projected to decrease from 3,300 to 2,806 µS/cm in December. However, they continue to exceed the MRPL for all months except March, and exceed the LRPL for the months of August, September, and November through January. For the dry year, EC values decrease from 2,810 to 1,971 µS/cm in September and exceed the MRPL for all months except March, May, July, September, and October, and are less than the LRPL for all months except August. SAR values in the normal year are projected to increase from 6.94 to 7.92 and exceed the MRPL for SAR in all months except March and May, but are projected to be less than the LRPL for the normal year. For the dry year, SAR values increase from 6.44 to 9.05, exceeding the MRPL for all months except March and remaining below the LRPL for all months.

- Irrigation Suitability. For the dry year conditions, data indicate a reduction in infiltration following mixing with CBNG production water, with the water remaining suitable for irrigation. Under normal year conditions, only a minor decrease in infiltration is projected following mixing with CBNG production water; overall, the data indicate that the mixed water is suitable for irrigation during a normal year.

Upper Belle Fourche River: The cumulative surface water effects modeling results for the Upper Belle Fourche River for year 2015 are presented in **Table 3-4** and summarized below.

- Before Mixing. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-4**).

- Following Mixing. EC values for the minimum mean monthly flow are projected to decrease from 2,755 to 2,116 µS/cm in December for the normal year and from 2,346 to 1,316 µS/cm in October for the dry year, and meet both the LRPL and MRPL for dry year conditions. However, the data exceed the MRPL during October, November, December, and January for the normal year. SAR values are projected to increase from 6.77 to 7.57 for the normal year and from 5.75 to 8.32 for the dry year. For the dry year, SAR values exceed the MRPL for the months of August through January. For the normal year, SAR values exceed the MRPL from September through January. Under both hydrologic conditions, SAR values meet the LRPL for all months.

- Irrigation Suitability. For the dry year conditions, data indicate a reduction in infiltration following mixing with CBNG production water, and the water may be marginally unsuitable for irrigation in

October during the irrigation season. Under normal year conditions, only a minor decrease in infiltration is projected following mixing with CBNG production water; overall, the data indicate that the mixed water would be suitable for irrigation during a normal year.

Upper Cheyenne River: The modeled cumulative surface water effects for the Upper Cheyenne River for year 2015 are presented in **Table 3-5** and summarized below.

- Before Mixing. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-5**).

- Following Mixing. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-5**) because no CBNG production water discharge is expected to the Upper Cheyenne River in 2015.

- Irrigation Suitability. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-5**) because no CBNG production water discharge is expected to the Upper Cheyenne River in 2015.

Upper Powder River: The modeled cumulative surface water effects for the Upper Powder River for year 2015 are presented in **Table 3-6** and summarized below.

- Before Mixing. Conditions in 2015 are projected to be the same as base year (2003) conditions (see **Table 3-6**).

- Following Mixing. EC values for the minimum mean monthly flow are projected to decrease slightly from 2,482 to 2,479 µS/cm in January for the normal year and from 3,400 to 3,369 µS/cm in September for the dry year. EC values continue to exceed the MRPL for all months with the exception of May and June for both the normal and dry years. EC values continue to exceed the LRPL for July through December for both the dry and normal years. SAR values are projected to increase from 6.40 to 6.56 for the normal year and from 7.83 to 8.20 for the dry year. The data exceed the MRPL for all months except May and June for both the normal and the dry year and are less than the LRPL for both hydrologic conditions.

- Irrigation Suitability. For both normal- and dry year conditions, data indicate a slight reduction in infiltration following mixing with CBNG production water. Overall, the data indicate that the mixed water would be suitable for irrigation during both hydrologic conditions.

3.4 Modeled Cumulative Impacts for Year 2020

3.4.1 Groundwater Level Changes Since 1990

3.4.1.1 Wasatch Formation

Groundwater Levels 2020

Figure B-29 in Appendix B shows the model-projected groundwater levels in the Wasatch for the year 2020. Groundwater flow is similar to years 2010 and 2015. South of Wright, groundwater flow in the Wasatch is northeastward toward the Subregion 3 coal mines. Antelope Creek acts as a drain and removes groundwater from the Wasatch, because groundwater levels in the Wasatch are above the base elevation of Antelope Creek over most of its course in the model domain. East of Wright, groundwater flow changes to northward, and north of Wright, groundwater flow is to the northwest. There is a groundwater mound west of the Subregion 2 coal mines, and municipal pumpage at Gillette has produced a groundwater depression southeast of Gillette, with groundwater levels declining from approximately 4,400 to 4,300 feet amsl. North of Gillette, groundwater flow is to the northwest, and Wild Cat Creek acts as a drain, removing groundwater from the Wasatch. Groundwater levels in the southern part of the model domain are 4,950 to 5,025 feet amsl. In the northern part of the model domain, groundwater levels are 4,175 to 4,100 feet amsl.

Coal Mine Pumpage Only

Figure B-30 in Appendix B shows the modeled effect to the Wasatch from 1990 to 2020 due to coal mine dewatering. As with the modeled effects for 2010 and 2015, only the Subregion 3 coal mines affect groundwater levels in the Wasatch. Drawdown within the mine areas ranges from 10 to 80 feet. West of the coal mines, drawdown in the Wasatch ranges from 10 to 30 feet. The Subregion 2 and Subregion 1 coal mines have less than 10 feet of drawdown.

CBNG Pumpage and Discharge Only

Figure B-31 in Appendix B shows the modeled effect of CBNG pumpage and discharge on the Wasatch from 1990 to 2020. Mounding in the range of 10 to 20 feet is evident west of the Subregion 2 coal mines, with mounding of 10 feet extending northward due to CBNG discharge. Southwest of Wright there is slight mounding up to 10 feet. Southeast of Gillette, there is approximately 10 feet of drawdown due to municipal pumpage. Near Wild Cat Creek, there is 10 to 20 feet of CBNG-related drawdown in the Wasatch.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-32 in Appendix B shows the combined modeled effect of CBNG pumpage and discharge and coal mine dewatering on the Wasatch from 1990 to 2020. This figure is a composite of **Figures B-30** and **B-31**, with the addition of a groundwater depression southeast of Gillette due to municipal pumpage. Drawdown in the Subregion 3 coal mines ranges from 30 to 70 feet in the mine areas and from 10 to 30 feet west of the mines. Most of the drawdown is in the northern pod of mines. The Subregion 1 and Subregion 2 coal mines have up to 10 feet of drawdown. CBNG-related mounding of 10 to 20 feet is evident west of Subregion 2 and extending northward.

The municipal pumpage-related groundwater depression southeast of Gillette ranges from 10 to 60 feet.

3.4.1.2 Fort Union Formation

Groundwater Levels 2020

Figure B-33 in Appendix B shows the model-projected groundwater levels in the Upper Fort Union for year 2020. The groundwater depression southwest of Wright caused by CBNG pumpage shifts more to the southwest compared to the model results for 2010 and 2015. The depression covers approximately 5 townships and has a groundwater level decline from 4,600 to 4,425 feet amsl near the center of the depression. Groundwater flow south of Wright is generally to the northeast; however, it is broken into segments by flow to the coal mines and flow into the CBNG-generated groundwater depression. North of Wright, groundwater flow is to the northwest. Near the Subregion 3 coal mines, groundwater flow is irregular with flow coming into the mines from the west and from the east. There is what appears to be an area of groundwater elevation between the southern pod and the northern pod of mines in Subregion 3 due to the overlap of coal mine dewatering. Groundwater enters the model domain from the east for the Upper Fort Union and flows toward the Subregion 3 mines. Between the Subregion 3 and Subregion 2 mines, there is another apparent area of groundwater elevation located east of Wright due to the overlap of coal mine dewatering and the transition from the coal mine stratigraphy provided by BLM (2005) to that of Goolsby, Finely, and Associates (2001) to the west. Around the Subregion 2 coal mines, groundwater flow generally is toward the mines from the west; however, it is interrupted by local groundwater mounds. East of the Subregion 2 mines, groundwater flow in the Upper Fort Union is to the north, except near the mines where groundwater flow is diverted into the mine areas. There is a groundwater depression east of Gillette due mainly to municipal pumpage. Groundwater flow in the Subregion 1 coal mines is northwestward through the mine area.

Coal Mine Pumpage Only

Figure B-34 in Appendix B shows the modeled effects to the Upper Fort Union from 1990 to 2020 caused by coal mine dewatering. Drawdown in the Subregion 3 coal mines ranges from 25 to 125 feet. For the southern pod of mines, most of the drawdown is along the eastern side of the mine areas. For the northern pod of mines, most of the drawdown is along the northwestern side of the mine boundaries and westward into the basin approximately 1 to 2 miles. For the Subregion 2 mines, the southern pod shows a drawdown of up to 125 feet, and the northern pod shows drawdown from 25 to 100 feet. Southwest of the northern pod, drawdown extends approximately 1 mile into the basin from the mine boundaries. For the Subregion 1 mines, drawdown is up to 25 feet.

CBNG Pumpage and Discharge Only

Figure B-35 in Appendix B shows the modeled effect to the Upper Fort Union due to CBNG pumpage and discharge from 1990 to 2020. CBNG pumpage primarily is located southwest of Wright and has produced a groundwater depression of 25 to 400 feet that covers approximately 8 to 9 townships. There is continuing drawdown in the Wild Cat Creek area of approximately 25 feet.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-36 in Appendix B shows the combined modeled effect of CBNG pumpage and discharge and coal mine dewatering on the Upper Fort Union from 1990 to 2020. This figure is a composite of **Figures B-34** and **B-35**, with the addition of municipal pumpage at Gillette. The groundwater depression southwest of Wright overlaps with drawdown in the Upper Fort Union west of the Subregion 3 coal mines, and overall, west of SR 59 there is a broad area of approximately 25 feet of drawdown. Municipal pumpage at Gillette has resulted in approximately 50 feet of drawdown in the Upper Fort Union. The Subregion 1 mines show 25 to 50 feet of drawdown southwest of the mines, due possibly to the overlap between coal mine drawdown and municipal drawdown in the Gillette area. There also is 25 to 50 feet of drawdown near Wild Cat Creek. There is up to 25 feet of rebound in the Subregion 1 coal mines and up to 50 feet of rebound in the Subregion 3 coal mines.

3.4.2 Groundwater Level Changes Since 2002

3.4.2.1 Wasatch Formation

Coal Mine Pumpage Only

Figure B-37 in Appendix B shows the modeled groundwater level changes in the Wasatch due to coal mine dewatering, reductions in dewatering rates at some mines, and mine reclamation from 2002 to 2020. Drawdown is evident only in the Subregion 3 coal mines and ranges from 10 to 50 feet in the southern pod of mines and from 10 to 60 feet in the northern pod of mines. West of the mines into the basin, drawdown ranges from 10 to 20 feet, and the 10-foot drawdown isopleth extends approximately 8 to 10 miles into the basin. Groundwater rebound of approximately 10 feet is present in both the northern and southern pod of mines, due likely to a reduction in dewatering rate.

CBNG Pumpage and Discharge Only

Figure B-38 in Appendix B shows the modeled effect of CBNG pumpage and discharge on the Wasatch from 2002 to 2020. Except for a very localized depression of 10 to 20 feet northwest of Wright, mounding of approximately 10 feet is present west of Gillette and southwest of Wright. There is a groundwater decline of 10 feet near Wild Cat Creek and localized depressions of 10 feet near the Subregion 2 mines and southeast of Gillette.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-39 in Appendix B shows the combined modeled effect of CBNG pumpage and discharge and coal mine dewatering on the Wasatch from 2002 to 2020. This figure is a composite of **Figures 33** and **34**, with the addition of municipal pumpage at Gillette. Municipal pumpage accounts for 10 to 40 feet of groundwater level decline in the Wasatch southeast of Gillette. Drawdown around the coal mines and mounding due to CBNG discharge are similar to those discussed for **Figures 33** and **34**.

3.4.2.2 Fort Union Formation

Coal Mine Pumpage Only

Figure B-40 in Appendix B shows the modeled effect of coal mine dewatering, reductions in dewatering rates at some mines, and mine reclamation from 2002 to 2020. For the Subregion 3 mines, drawdown ranges from 25 to 125 feet in the southern pod of mines, with a localized rebound of groundwater levels of 75 to 100 feet along the northwest corner of the southern pod of mines due to a reduction in coal mine-related pumping rates and/or ongoing mine reclamation. For the northern pod of mines, drawdown ranges up to approximately 100 feet, with localized rebound of 50 feet near the southern tip of the mines. The drawdown extends for approximately 1 to 2 miles northwest of the northern pod of mines and accounts for 25 to 100 feet of drawdown in the basin. For the Subregion 2 mines, drawdown ranges from 50 to 125 feet in the southern pod of mines and from 25 to 75 feet in the northern pod of mines. There is a localized rebound of groundwater levels up to 75 feet in the northern pod of mines. For the Subregion 1 mines, drawdown ranges up to 25 feet. There is up to 25 feet of rebound locally in the Subregion 1 coal mines due to reclamation.

CBNG Pumpage and Discharge Only

Figure B-41 in Appendix B shows the modeled effect of CBNG pumpage and discharge on the Upper Fort Union from 2002 to 2020. The groundwater depression southwest of Wright covers approximately 8 townships and has a groundwater level decline ranging from 50 to 350 feet. West of the Subregion 2 mines and north of Wright along SR 59, groundwater recovery due to the reduction in CBNG pumpage has resulted in a rebound of groundwater levels ranging from 25 to 300 feet. The highest rebound is west of the Subregion 3 mines. West of the Subregion 2 mines, groundwater rebound due to a reduction in CBNG pumpage ranges up to 225 feet. Southwest of the Subregion 1 mines, groundwater rebound is up to 25 feet.

Combined CBNG Pumpage and Discharge and Coal Mine Pumpage

Figure B-42 in Appendix B shows the combined impact of CBNG pumpage and discharge and coal mine dewatering on the Upper Fort Union from 2002 to 2020. This figure is a composite of **Figures B-40** and **B-41**. Most evident is the groundwater depression southwest of Wright, the groundwater rebound west of the northern pod of mines in Subregion 3, and the general rebound north of Wright along SR 59. Also, there is localized rebound west of the Subregion 2 mines. The groundwater depression southwest of Wright has groundwater level declines from 25 to 350 feet. The rebound around Wright and along SR 59 ranges up to about 300 feet. West of the Subregion 2 coal mines, there is localized rebound of up to 175 feet. West of the Subregion 3 coal mines, the rebound in the Upper Fort Union due to CBNG pumpage declines merges with coal mine drawdown. Rebound of groundwater levels in the Subregion 3 coal mines is up to 125 feet, with up to 50 feet of rebound in the Subregion 2 coal mines.

3.4.3 Modeled Cumulative Surface Water Impacts for 2020

Antelope Creek: The modeled cumulative surface water effects for Antelope Creek for year 2020 are presented in **Table 3-1** and summarized below.

- Before Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-1**).

- Following Mixing. EC values for minimum mean monthly flow are projected to decrease from 2,372 to 1,271 µS/cm in December for the normal year and from 2,005 to 1,053 µS/cm in June for the dry year. EC values meet the LRPL and MRPL for both the dry and normal years. SAR values are projected to increase from 2.79 to 6.47 for the normal year and from 2.79 to 7.06 for the dry year but continue to meet the LRPL and MRPL for both hydrologic conditions.

- Irrigation Suitability. For dry year conditions, data indicate a substantial reduction in infiltration throughout the irrigation season following mixing with CBNG production water; however, the water remains suitable for irrigation except for June and August during the irrigation season. Under normal year conditions, a decrease in infiltration is projected following mixing with CBNG production water; overall, however, the data generally indicate that the mixed water would be suitable for irrigation.

Dry Fork Cheyenne River: The modeled cumulative surface water effects for the Dry Fork of the Cheyenne River for year 2020 are presented in **Table 3-2** and summarized below.

- Before Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-2**).

- Following Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-2**) because no CBNG production water discharge is expected to the Dry Fork of the Cheyenne River in 2020.

- Irrigation Suitability. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-2**) because no CBNG production water discharge is expected to the Dry Fork of the Cheyenne River in 2020.

Little Powder River: The modeled cumulative surface water effects for the Little Powder River for year 2020 are presented in **Table 3-3** and summarized below.

- Before Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-3**).

- Following Mixing. EC values for minimum mean monthly flow are projected to decrease from 3,300 to 3,144 µS/cm in December for the normal year and from 2,810 to 2,403 µS/cm in September for the dry year. EC values for the normal year exceed the MRPL for all months except March and exceed the LRPL in August, September, and November through January. For the dry year, EC values exceed the MRPL for all months except March and exceed the LRPL for January, August, November, and December. SAR values are projected to increase

from 6.94 to 7.25 for the normal year and from 6.44 to 7.71 for the dry year. SAR values exceed the MRPL for all months except March and May and are less than the LRPL for the entire year under both hydrologic conditions.

- Irrigation Suitability. For the dry year conditions, data indicate a reduction in infiltration following mixing with CBNG production water, and suitability for irrigation during all months of the irrigation season. Under normal year conditions, only a minor decrease in infiltration is projected following mixing with CBNG production water; overall, the data indicate that the mixed water would be suitable for irrigation during a normal year.

Upper Belle Fourche River: The modeled cumulative surface water effects for the Upper Belle Fourche River for year 2020 are presented in **Table 3-4** and summarized below.

- Before Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-4**).

- Following Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-4**) because no CBNG production water discharge is expected to the Upper Belle Fourche River in 2020.

- Irrigation Suitability. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-4**) because no CBNG projection water discharge is expected to the Upper Belle Fourche River in 2020.

Upper Cheyenne River: The modeled cumulative surface water effects for the Upper Cheyenne River for year 2020 are presented in **Table 3-5** and summarized below.

- Before Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-5**).

- Following Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-5**) because no CBNG production water discharge expected to the Upper Cheyenne River in 2020.

- Irrigation Suitability. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-5**) because no CBNG production water discharge is expected to the Upper Cheyenne River in 2020.

Upper Powder River: The modeled cumulative surface water effects for the Upper Powder River for year 2020 are presented in **Table 3-6** and summarized below.

- Before Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-6**).

- Following Mixing. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-6**) because no CBNG production water discharge is expected to the Upper Powder River in 2020.

- Irrigation Suitability. Conditions in 2020 are projected to be the same as base year (2003) conditions (see **Table 3-6**) because no CBNG production water discharge is expected to the Upper Powder River in 2020.

3.5 Summary

This section summarizes the projected changes in groundwater levels and surface water quality through year 2020 in the eastern PRB of Wyoming within approximately 25 miles of the coal mines. Projected groundwater level changes are due mainly to CBNG groundwater withdrawal in the Upper Fort Union Formation and to both CBNG pumping and discharge along with coal mine dewatering in the Wasatch Formation. Near the coal mines, coal mine dewatering of the Upper Fort Union also has affected groundwater levels in that formation. Projected changes in surface water quality are due to mixing of CBNG discharge water with natural flow in the modeled drainages.

3.5.1 Groundwater Level Changes

Projected groundwater level changes in the Wasatch generally are due to coal mine dewatering and CBNG pumping and discharge, which generally result in local mounding of groundwater in the Wasatch near CBNG fields and drawdown near the coal mines. Antelope Creek and Wild Cat Creek also remove groundwater from the Wasatch because their stream base elevations within the CMGM domain are below the groundwater levels in the Wasatch. The Belle Fourche River does not remove groundwater from the Wasatch within the CMGM domain because its base elevation is above groundwater elevations in the Wasatch. Along some reaches of the Belle Fourche outside of the CMGM domain, the river is perennial due to groundwater baseflow from the Wasatch. For the Upper Fort Union, groundwater level changes are due to CBNG pumpage, mainly southwest of Wright, and coal mine dewatering. Between 2002 and 2020, the projected reduction in coal mine dewatering and a substantial reduction in CBNG pumpage from Wright northward toward Gillette is projected to result in groundwater rebound in the Upper Fort Union both within the coal mine boundaries and especially within the basin west of the coal mines.

3.5.1.1 Modeled Cumulative Groundwater Impacts for Year 2010

Wasatch Formation

Based on model results for 1990 to 2010, groundwater flow in the Wasatch for 2010 is to the northeast south of Wright, Wyoming. East of Wright, the groundwater flow changes to northward and then to northwestward with flow staying on the northwestward course to the north end of the model domain in the eastern PRB. Antelope Creek acts as a drain and removes water from the Wasatch over most of its course in the eastern PRB. Southeast of Gillette, there is a 40-foot decline in groundwater levels due to municipal pumpage. At the northern end of the model domain, there is a groundwater decline of 20 to 30 feet near Wild Cat Creek due to CBNG pumpage. The main area of drawdown in the Wasatch since 1990 is in the northern pod of the Subregion 3 coal mines, where there is 30 to 70 feet of drawdown within the mine boundaries and 10 to 30 feet of drawdown in the Wasatch west of the mine boundaries due to mine dewatering. CBNG discharge results in a groundwater mound of 10 to 20 feet west of Wright and another mound west of the Subregion 2 coal mines of up to 30 feet. Overall, the primary effects projected for the Wasatch include the

drawdown in the Subregion 3 coal mines, the removal of groundwater by Antelope Creek, and 10 to 30 feet of mounding in areas of CBNG discharge.

Based on modeling results for 2002 to 2010, coal mine-related drawdown in the Wasatch in the Subregion 3 coal mine area is up to 70 feet, with most of the drawdown being located in the northern pod of mines. For CBNG-related pumpage and discharge, a predicted decrease in pumpage by 2010 results in mounding west of Wright in the range of 10 to 20 feet and localized mounding west of the Subregion 2 coal mines.

Upper Fort Union Formation

The most evident feature for projected groundwater levels in the Upper Fort Union for 2010 is a substantial groundwater depression of 25 to 575 feet southwest of Wright caused by CBNG pumpage from 1990 to 2010. Groundwater flow south of Wright, except for the area of the groundwater depression, is to the northeast toward the Subregion 3 coal mines. Groundwater flow north of Wright is to the northwest. Groundwater flows into the Subregion 3 coal mines from both the west and the east. For the Subregion 2 coal mines, groundwater flow into the mines is mainly from the west. Modeled drawdown in the Upper Fort Union in the coal mine areas is in the range of 25 to 250 feet in the Subregion 3 mines, 25 to 125 feet in the Subregion 2 coal mines, and up to approximately 75 feet in the Subregion 1 coal mines north of Gillette. Municipal pumpage at Gillette results in a groundwater depression southeast of Gillette in the range of 50 feet.

Based on modeling results for 2002 to 2010, coal mine-related pumpage in the Fort Union in the Subregion 3 coal mine area results in 25 to 150 feet of drawdown in and near the southern pod of mines, and 25 to 100 feet of drawdown in the northern pod of mines. In the Subregion 2 coal mine area, drawdown from 25 to 125 feet occurs in the southern pod of mines, with 25 to 75 feet in the northern pod of mines. CBNG pumpage results in extensive drawdown southwest of Wright ranging up to 350 feet. West of the northern pod of mines in Subregion 3, groundwater levels rebound up to 100 feet due to the reduction in CBNG pumpage. North of Wright along SR 59, groundwater levels rebound up to 100 feet. West of the Subregion 2 coal mines, groundwater levels rebound in the range of 50 to 100 feet, and near the Subregion 1 coal mines, groundwater levels rebound approximately 25 feet.

3.5.1.2 Modeled Cumulative Groundwater Impacts for Year 2015

Wasatch Formation

Based on model results for 1990 to 2015, groundwater flow in the Wasatch for 2015 is similar to 2010. South of Wright, groundwater flow is to the northeast toward the Subregion 3 coal mines. North of Wright, groundwater flow is to the northwest. Antelope Creek acts as a drain and removes groundwater from the Wasatch over most of its course. There is a projected groundwater mound of 10 to 20 feet west of the Subregion 2 mines due to CBNG discharge, and there is a projected groundwater depression of up to 50 feet southeast of Gillette due to municipal pumpage. Wildcat Creek acts as a drain and removes water from the Wasatch. CBNG pumpage in the area results in a drawdown of 20 to 30 feet. Most of the modeled drawdown in the Wasatch since 1990 is in the Subregion 3 coal mines, where there is 30 to 100 feet of drawdown within the mine boundaries and 10 to 30 feet of drawdown in the Wasatch west of the mines. There is groundwater mounding up to

10 feet west of Wright due to CBNG discharge. Overall, modeled groundwater levels, groundwater flow patterns, and groundwater drawdown in the Wasatch for 2015 are similar to 2010.

Based on modeling results for 2002 to 2015, coal mine pumpage in the Wasatch results in drawdown in the area of the Subregion 3 coal mines in the range of 10 to 50 feet near the southern pod of mines and from 30 to 70 feet in the northern pod of mines. West of the Subregion 3 coal mines, drawdown in the Wasatch ranges from 10 to 20 feet. Drawdown near the Subregion 1 and Subregion 2 coal mines is less than 10 feet. CBNG pumpage and discharge in the Wasatch results in approximately 20 feet of drawdown west of Wright, approximately 10 feet of drawdown near the Subregion 2 coal mines, and approximately 10 feet of mounding along SR 387. There is a slight 10 foot rebound in groundwater levels west of Gillette.

Upper Fort Union Formation

Based on model results for 1990 to 2015, the substantial groundwater depression southwest of Wright due to CBNG pumpage, as projected for 2010, shifts to the south. Projected 2015 groundwater drawdown in the Upper Fort Union in this area of CBNG pumpage since 1990 ranges up to 450 feet. Groundwater flow patterns in the Upper Fort Union are similar to 2010, with groundwater flow south of Wright being to the northeast toward the Subregion 3 coal mines, and north of Wright, groundwater flow is to the northwest. Around the Subregion 3 coal mines, groundwater flows into the mine areas from both the west and east. For the Subregion 2 mines, groundwater flow is mainly from the west but also from the east. Drawdown in the Subregion 3 mines ranges from 25 to 150 feet. fFor the Subregion 2 mines, drawdown ranges from 25 to 50 feet in the northern pod of mines and from 50 to 150 feet at the southern end of the subregion. There is local rebound of groundwater levels up to 100 feet in the northern pod of mines in Subregion 1. Southwest of the Subregion 2 mines, there is a CBNG-related groundwater depression of 50 to 125 feet, with drawdown southwest of Wright ranging from 25 to 450 feet. In the northern part of the Subregion 2 coal mines, there is a local rebound of up to 25 feet in a reclaimed area of the mines.

Model results for 2002 to 2015 show groundwater rebounding in parts of the eastern PRB. In the Subregion 3 coal mines, there is up to 200 feet of rebound in the southern pod of mines. For the Subregion 2 coal mines, there is up to 25 feet of rebound in the northern pod of mines. For the Subregion 1 mines north of Gillette, rebound of water levels is up to 50 feet in the Upper Fort Union. Within the basin area of the eastern PRB, a reduction in CBNG pumpage from Wright northward to the Subregion 2 coal mines has generated substantial rebound in groundwater levels in the Upper Fort Union along SR 59. Southeast of Wright, rebound is up to 275 feet since 2002. From Wright northward along SR 59, the rebound ranges from approximately 25 feet on the margins to 250 feet along the highway area.

3.5.1.3 Modeled Cumulative Groundwater Impacts For Year 2020

Wasatch Formation

Based on model results for 1990 to 2020, groundwater flow in the Wasatch is similar to that modeled for 2015 and 2010. South of Wright, groundwater flow is to the northeast toward the Subregion 3 coal mines. North of Wright, groundwater flow is to the northwest. There is a groundwater mound of 10 to 20 feet west of the Subregion 2 coal mines, with mounding of approximately 10 feet extending northward, due to CBNG discharge. Southeast of Gillette, there is

a groundwater depression of approximately 10 feet due to municipal pumpage. Antelope Creek acts as a drain and removes water from the Wasatch, and in the Wild Cat Creek area there is drawdown of 10 to 30 feet due to CBNG pumpage and the creek removing water from the Wasatch. Drawdown in the Subregion 3 coal mines ranges from 30 to 70 feet within the mine boundaries and from 10 to 30 feet west of the mines in the basin.

Based on modeling results for 2002 to 2020, drawdown in the Wasatch due to coal mine pumpage is evident only in the Subregion 3 coal mine area, ranging from 10 to 50 feet in the southern pod of mines and from 10 to 60 feet in the northern pod of mines. Drawdown west of the mines in the PRB ranges from 10 to 20 feet. Groundwater rebound of approximately 10 feet is evident in both the northern and southern pod of mines in Subregion 3 due to reclamation of the coal mine pits. CBNG-related mounding of approximately 10 feet occurs over most of the model domain due to a decrease in CBNG pumpage. There is a localized depression of approximately 10 to 20 feet northwest of Wright.

Upper Fort Union Formation

Based on modeling for 1990 to 2020, the groundwater depression in the Upper Fort Union southwest of Wright shifts more to the southwest as compared to 2015, and the groundwater level decline in the depression ranges up to 400 feet. Groundwater flows to the northeast toward the Subregion 3 coal mines south of Wright; north of Wright, groundwater flow is to the northwest. Groundwater flows into the Subregion 3 mines from the west and the east; groundwater flows into the Subregion 2 mines mainly from the west. There is a 50-foot groundwater depression southeast of Gillette due to municipal pumpage. Groundwater drawdown in the coal mine areas ranges from 25 to 100 feet in the Subregion 3 mines, from 25 to 100 feet in the northern pod of mines in Subregion 2, and from 50 to 125 feet in southern pod of mines in Subregion 2. For the Subregion 1 mines, there is local drawdown in groundwater levels of approximately 25 feet.

Based on model results for 2002 to 2020, there is 50 to 100 feet of groundwater rebound in the Upper Fort Union in the Subregion 3 mines due to a reduction in coal mine pumpage and ongoing reclamation. For the Subregion 2 mines, the rebound is up to 75 feet, and for the Subregion 1 mines the rebound is up to 25 feet. Groundwater rebound in the Upper Fort Union within the basin has been substantial due to a reduction in CBNG pumpage. In the area southeast of Wright, rebound is up to 300 feet. West of the Subregion 2 mines, rebound has been up to 225 feet. Between Wright and the Subregion 2 mines along SR 59, reduction in CBNG pumpage results in a broad area of rebound ranging from 25 to 100 feet. Overall, the reduction in coal mine dewatering and the substantial reduction in CBNG pumpage since 2002 results in groundwater rebound in the Upper Fort Union.

3.5.2 Surface Water Quality

3.5.2.1 Normal year Conditions

Antelope Creek: From 2003 to 2020, EC is projected to decline due to mixing with CBNG production waters, and SAR values are projected to increase. The data indicate that the MRPL and LRPL would not be exceeded for either EC or SAR after mixing of CBNG production waters. Based on the data, surface water is projected to be suitable for irrigation use in all months.

Dry Fork of the Cheyenne River: For the Dry Fork of the Cheyenne, there is no projected discharge of CBNG production water to the drainage through 2020. Therefore, surface water quality conditions for 2010, 2015, and 2020 would be the same as for the base year (2003).

Little Powder River: From 2003 to 2020, EC is projected to decline, and SAR is projected to increase slightly due to mixing with CBNG production waters. The data indicate that EC values would exceed the MRPL except for March and May in 2010, and March in 2015 and 2020; however, it would be less than the LRPL except for January and August from 2010 to 2020, and also in September, November, and December from 2015 to 2020. SAR values are projected to be greater than MRPL and less than LRPL. Based on the data, surface water is projected to remain suitable for irrigation to 2020.

Upper Belle Fourche: From 2003 to 2015, EC is projected to decline due to mixing with CBNG production water, and SAR is projected to increase slightly. There is no projected discharge of CBNG production water to the drainage in 2020; therefore, EC and SAR values for this time period would be the same as projected for the base year (2003). The data indicate that EC would not exceed the MRPL, except for October in 2010 and October through January in 2015, and would not exceed the LRPL. The projected SAR values would exceed the MRPL from August to January in 2010 and from September to January of 2015, and would be less than LRPL for all months. Based on the data, surface water is projected to be suitable for irrigation to 2020.

Upper Cheyenne River: From 2003 to 2010, EC is projected to decrease due to mixing with CBNG production water, and SAR values would increase. There is no projected discharge of CBNG production water to the drainage in 2015 or 2020. Based on the data, EC values would be greater than the MRPL, except August 2010, and greater than LRPL, except for July through September 2010. SAR values would be less than the MRPL and LRPL. Based on the data, surface water would remain suitable for irrigation from 2010 to 2020.

Upper Powder River: From 2003 to 2015, EC is projected to decrease slightly, and SAR values would increase slightly, due to mixing with CBNG production water. There is no projected discharge of CBNG production water to the drainage in 2020. The data indicate EC values would exceed the MRPL, except for May and June for 2010 to 2015, and would be less than LRPL, except for July through December from 2010 to 2015. SAR values would exceed the MRPL, except for March in 2010 and 2015 and May in 2015, and would be less than the LRPL. Based on the data, surface water is projected to remain suitable for irrigation from 2010 to 2020.

In summary, for normal year flows, discharge of CBNG production water to these six drainages generally would reduce the EC and increase the SAR slightly; however, the surface water would remain suitable for irrigation in most months. The MRPL and LRPL may be exceeded for EC and SAR in 1 or more years and in any given year for 1 or more months, but not for all months in the year.

3.5.2.2 Dry year Conditions

Antelope Creek: From 2003 to 2020, EC values would be reduced due to mixing with CBNG waters, and SAR values would increase. The data indicate that the MRPL and LRPL would not be exceeded for either EC or SAR for all years after mixing of CBNG production water. Based on the

data, surface water would remain suitable for irrigation except for June and August from 2010 to 2020.

Dry Fork of the Cheyenne River: For the Dry Fork of the Cheyenne, no CBNG production water discharge is expected to the drainage through 2020. Therefore, water quality conditions would be the same as the modeled base year (2003) for all years to 2020.

Little Powder River: For the Little Powder River, the EC would be reduced and the SAR increased due to mixing with CBNG waters from 2003 to 2020. The MRPL would be exceeded for EC during the months of February, April, June, and August in 2010; during November through February and during April, June, and August 2015; and all months except March in 2020. EC values would exceed the LRPL in September 2010; August 2015; and January, August, November, and December 2020. SAR values would exceed the MRPL in all months and years except for March in 2015 and March and May in 2020. The LRPL for SAR only would be exceeded in September 2010. The water would remain suitable for irrigation from 2010 to 2020 except for September and October 2010.

Upper Belle Fourche: From 2003 to 2015, EC values would decline due to mixing with CBNG production waters, and SAR values would increase slightly. There is no projected discharge of CBNG production water to the drainage in 2020. EC values would not exceed the MRPL or LRPL from 2010 to 2015. SAR values would exceed the MRPL in 2010, except for March and July, and also would exceed the MRPL from August to January 2015. Based on the data, surface water would be unsuitable for irrigation from August to October during 2010 and in October 2015.

Upper Cheyenne River: From 2003 to 2010, EC values would decline due to mixing with CBNG production waters, and SAR values would increase slightly. There is no projected discharge of CBNG production waters to the drainage in 2015 or 2020. EC values would exceed the MRPL except for August 2010; the LRPL would be exceeded except for July to September 2010. For SAR, neither the MRPL nor the LRPL would be exceeded. Based on the data, surface water would remain suitable for irrigation to 2020.

Upper Powder River: From 2003 to 2015, EC values would decrease slightly due to mixing with CBNG waters, and SAR values would increase slightly. There is no projected discharge of CBNG production water to the drainage in 2020. EC values would exceed the MRPL except for the months of May and June for all years, and the LRPL would be exceeded July through December for all years. SAR values would be greater than the MRPL, except for May and June 2015, and would be less than LRPL for all years. Based on the data, surface water would remain suitable for irrigation to 2020.

In summary, during dry year flows, the suitability of surface waters in the six modeled drainages for irrigation generally would be reduced due to the greater percentage of CBNG production water in the drainage after mixing. Both EC and SAR values would exceed the MRPL and LRPL more frequently compared to normal year flows. Even though the waters' suitability for irrigation would be reduced (except for the Upper Belle Fourche River) surface water generally would remain suitable for irrigation during the majority of months of the irrigation season.

4.0 STREAM CHANNEL STABILITY EVALUATION

The PRB Coal Review includes an evaluation of cumulative impacts to stream channel stability in the PRB Wyoming study area. This evaluation was conducted by AEC (2009). In general, cumulative impacts to channel stability largely relate to changes in water quantity associated with discharges from existing or projected development activities as compared to the runoff characteristics of the receiving drainages. Of particular importance is the quantity of discharge water directly conveyed to the receiving drainages. For purposes of this evaluation, it was assumed that the water discharged directly to the receiving drainages would be limited to CBNG activities (ACE 2009), which are projected to be the primary source of discharge water in the study area through 2020.

Typically, runoff from tributary watersheds is considered the primary factor in channel development. For the subwatersheds in the semiarid study area, this runoff may be infrequent and occur only in response to precipitation events. With respect to the PRB, Martin et al. (1988) concluded that "the fluvial system currently (1987) is stable. Although some gullying and headcutting is occurring, the processes appear to be related to natural rejuvenation of the basins and generally are of a local nature." Therefore, it is likely that active erosion is occurring in some of the ephemeral drainages (ACE 2009).

To the extent possible, the impact to perennial drainages was addressed quantitatively at the subwatershed level using regression equations related to discharge and channel width (ACE 2009). Due to limited data, geomorphic relationships between mean annual discharge, channel gradient and geometry, bed material load, and median sediment size (Lane 1955; Schumm 1977) also were used to provide a qualitative assessment of potential cumulative impacts associated with the discharge of CBNG production water. These relationships provided a qualitative assessment of the response of the receiving drainages to an increase in discharge related to the introduction of CBNG production water.

A site-specific assessment also was performed to evaluate the impact of increased stream flows associated with discharge of CBNG production water in Caballo Creek on existing and reclaimed channels, as well as diversion channels and structures constructed in accordance with coal mine permit criteria. Data available for Caballo Creek in the vicinity of the Subregion 2 coal mines was obtained, reviewed, and utilized to complete the site-specific assessment of channel stability.

4.1 Perennial Stream Channel Evaluation

4.1.1 Methodology

USGS records for the Belle Fourche River below Moorcroft, Wyoming (USGS Gage 06426500), and the Little Powder River above Dry Creek, near Weston, Wyoming (USGS Gage 06324970), provided the basis for the evaluation of perennial stream channel stability (ACE 2009). The daily discharge data for the Little Powder River showed that days with zero discharge occurred less than 3 percent of the days of record, while the daily discharge data for the Belle Fourche River showed that days with zero discharge occurred approximately 23 percent of the days of record. Based on

the projected CBNG discharge data (ACE 2009, Appendix A), the modeled annual stream flow in the Little Powder and Belle Fourche rivers is projected to increase by a maximum of 2.2 and 4.3 cfs, respectively, and essentially may eliminate records of zero stream flow (ACE 2009).

Channel-forming discharge was estimated using the peak annual discharge recurrence interval and the common range for channel-forming discharge of between the 1.5- and 2-year recurrence interval. The channel-forming discharge for both the Little Powder and Belle Fourche rivers is presented in **Table 4-1**.

Hydraulic geometry relationships for channel width were developed as a function of discharge for the Little Powder and Belle Fourche rivers from all USGS field measurements classified as "good" during data collection. Using the relationships developed, channel width in the range of the channel-forming discharge was computed by ACE (2009) for the existing condition and for the maximum CBNG production water discharge condition by adding the predicted CBNG discharge rate to the existing condition discharge (see **Table 4-1**).

4.1.2 Perennial Stream Channel Stability Effects

Based on the results of the evaluation as shown in **Table 4-1**, the calculated change in channel width for the Little Powder River is less than 0.3 percent. For the Belle Fourche River, it was calculated to be less than 0.2 percent (ACE 2009). These results suggest that for the larger perennial streams the effect of CBNG production water discharge would be minimal.

Table 4-1
Projected Impact of CBNG Production Water Discharge on Perennial Streams

Location	Channel-forming Discharge[1] (cfs)	CBNG Discharge		Estimated Width		Potential Impact (increased channel width)	
		(cfs)	(percent)	Existing Conditions (feet)	Combined Discharge (feet)	(feet)	(percent)
Little Powder River above Dry Creek near Weston, Wyoming (USGS Gage 06324970)	270 to 420	2.2	0.5 to 0.8	47.3 to 56.3	47.4 to 56.4	0.15 to 0.12	0.3
Belle Fourche River below Moorcroft, Wyoming (USGS Gage 06426500)	652 to 789	3.9	0.5 to 0.6	66.9 to 72.1	67.0 to 72.2	0.16 to 0.14	0.2

[1] Discharge associated with the 1.5- to 2-year recurrence interval.

Source: ACE 2009.

Geomorphic relationships were used to provide insight into the potential impacts of the CBNG production water discharge on the mean annual discharge events associated with the perennial drainages. Based on the projected relatively low increase in mean annual discharge in the perennial streams, the potential trends predicted by the geomorphic relationships (increases in channel width, depth, and meander wavelength) would be considered imperceptible.

4.2 Ephemeral Stream Channel Evaluation

4.2.1 Methodology

Limited data on stream flows are available for the smaller, ephemeral drainage channels in the study area that may receive CBNG production water discharge (ACE 2009). In addition, projected future CBNG production water discharge rates for the PRB Coal Review were developed on a subwatershed basis. Therefore, for purposes of this study it was assumed that CBNG production water would represent a much higher percentage of the mean annual discharges in some of the ephemeral drainages within the study area. As a result, impacts to channel stability may include increases in channel erosion, headcutting, and incision (ACE 2009).

Geomorphologic studies using data developed from different locations to infer landform development through time commonly use a technique termed location-for-time substitution. This technique was used to develop a Channel Evolution Model (CEM) for Oaklimeter Creek, an incised stream in northern Mississippi (Schumm et al. 1984, 1981). Simon and Hupp (1987) later developed a similar model of channel evolution based on Schumm et al. (1984, 1981). The CEM consists of five channel-reach types that describe the evolutionary phases typically encountered in an incised channel. The model is based on the assumption that moving downstream through the system is equivalent to remaining in place and monitoring changes due to the passage of time (ACE 2009). Therefore, the response at any given location in the channel can be estimated from the morphology of downstream channel locations. As noted above, some of the ephemeral channels that are projected to receive CBNG production water discharge currently are actively eroding.

Fundamentally, the cause for channel incision (gully formation) is an imbalance between the sediment transport capacity and the sediment supply. The primary value of the CEM sequence is that it supports the identification of the evolutionary state of the channel based on field reconnaissance (ACE 2009). The physical characteristics of the channel reach types also can be correlated with hydraulic, geotechnical, and sediment transport parameters (Harvey and Watson 1986; Watson et al. 1988). The evolution sequence provides an understanding that while reaches of a stream may differ markedly in appearance, the channel form in one reach is associated with that in adjacent and remote reaches by an evolutionary process.

4.2.2 Ephemeral Stream Channel Stability Effects

The projected discharge of CBNG production water into the ephemeral drainages in the study area may initiate or increase erosion within ephemeral stream channels. Should erosion be initiated, it is anticipated that a small incision may occur, given the relatively minor flow compared to the typical gully section in the typical ephemeral drainage channel. In addition, the sustained nature of the projected CBNG production water discharge also may generate and support an increase in diversity

and density of the vegetation along the channel. An increase in vegetation may prevent channel erosion, or partially stabilize existing erosion, within the ephemeral drainage channels.

Similar to the perennial stream channels, the geomorphic relationships were used to provide insight into the potential impacts of CBNG production water discharge on the mean annual discharge events associated with the ephemeral drainages. Given that the incremental increase in mean annual discharge would be more substantial in the ephemeral drainage channels, and that the increases attributable to CBNG production water would be sustained, it is likely that potential increases in channel width and depth would occur along with local reductions in channel gradient.

4.3 Caballo Creek Channel Stability Evaluation

4.3.1 Methodology

For purposes of this evaluation, stream flow data were collected in Caballo Creek from above and below the Subregion 2 coal mines, and annual mine reports that contained information regarding CBNG production water discharges in the area were obtained. In addition, precipitation data were analyzed to evaluate the impact of potential drought conditions on the hydrologic period of record selected for this evaluation. Data available from a precipitation gage near Gillette, Wyoming, were used for this analysis. Further evaluation of the impact of potential drought conditions was conducted through evaluation of the Palmer Drought Index on the Belle Fourche drainage basin in Wyoming. The Palmer Drought Index, typically used as a measure of dryness, is based on a supply and demand model of soil moisture and has proven most effective in determining long-term drought. In addition, field reconnaissance was performed to document the condition of stream banks, channels, and stream flows within the study area.

A USGS water quality sampling site (USGS 06425800 - Caballo Creek near Gillette, Wyoming) is located near the crossing of Caballo Creek and SR 59, upstream and on the western side of the Subregion 2 mine permit boundary. Near the USGS sampling site is the first of two Caballo Creek stream gages (Gage BA-6). This USGS sampling site includes a drainage area of 122 square miles. A second gage (Gage BA-4) is located at the downstream or eastern Subregion 2 mine permit boundary. Mine permit documents indicate that Caballo Creek is an intermittent stream with a drainage area from the eastern mine permit boundary of 200 square miles (Western Water Consultants, Inc. 1997). The 2-year peak flow recurrence interval storm was estimated to range from 400 to 441 cfs for this drainage area (Western Water Consultants, Inc. 1997). Included in this drainage area (and tributary to Caballo Creek) are Bone Pile Creek and Duck Nest Creek, both located north of Caballo Creek and flowing across the western Subregion 2 mine permit boundary. As documented in annual mine reports, the majority of the CBNG production water discharge has been contributed from the Bone Pile Creek and Duck Nest Creek watersheds.

Observations made during a field reconnaissance showed no evidence of active erosion within the natural channels of Caballo Creek, Bone Pile Creek, or Duck Nest Creek. Also, there was no evidence of active erosion within the diversion channels or adjacent to the structures within the diversion channels. Increases in vegetation diversity and density were noted within all drainage channels receiving CBNG production water discharge.

4.3.2 Hydrologic and Meterologic Data Results

Hydrologic data from Caballo Creek gages BA-4 and BA-6 for the time period from 1984 to 2004 indicate that discharges recorded at both gages started increasing in approximately 1992. The noted increases in flow were consistent with CBNG production water discharges from wells located within the Caballo Creek, Bone Pile Creek, and Duck Nest Creek watersheds. Based on a review of the Caballo Creek stream flow data:

- Both gages may have received CBNG production water discharge for approximately 10 years.

- The average annual discharge for the BA-4 gage (downstream gage) increased from 0.5 cfs (from 1984 to 1992) to 1.6 cfs (from 1993 to 2004). This represents an increase of 1.1 cfs that potentially is attributable to the contribution of CBNG production water.

- The average annual discharge for the BA-6 gage (upstream gage) increased from 0.02 cfs (from 1984 to 1992) to 0.21 cfs (from 1993 to 2004). This represents an increase of 0.19 cfs that potentially is attributable to the contribution of CBNG production water.

It should be noted that the BA-6 gage is located upstream of the CBNG wells within the Bone Pile Creek and Duck Nest Creek watersheds. Therefore, the impact of the CBNG-related discharge is more evident on the flow data reflected for the BA-4 gage.

The precipitation data reflect the same general trend as the gage data. A general increase in average annual precipitation from 14.36 inches (for the time period from 1984 to 1992) to 18.14 inches (for the time period form 1993 to 2004) was recorded. This represents an increase of 3.78 inches (or 19 percent) in average annual precipitation. Based on a comparative evaluation of the gage data at BA-4, the increase in annual precipitation tends to minimize the impact of the CBNG production water discharge on the increase in stream flow observed at the gage.

Evaluation of the Palmer Drought Index resulted in the following observations:

- Drought conditions were present during the time period from 1984 to 1992, with noticeable improvement or absence of drought conditions beginning in 1993. Minor drought conditions were evident in 2000, the last year of the available data.

- As expected, a correlation between the index values and precipitation data was observed. The increase in annual precipitation beginning in 1993 was refelected in an increase in the Palmer Drought Index and an absence of drought conditions from 1993 to 1999.

- The increase in the Palmer Drought Index beginning in 1993 supports a corresponding increase in stream flow within the Belle Fourche drainage basin.

- With the addition of CBNG production water discharge into Caballo Creek in 1992, the data for the Palmer Drought Index tend to minimize the impact of the CBNG-related discharge on the increase in stream flow observed at the BA-4 gage.

4.3.3 Caballo Creek Channel Stability Effects

A dominant or channel-forming discharge implies that the natural channel morphology (width, depth, slope, and plan form) adjusts to a discharge that is largely responsible for the channel geometry. Dominant discharge generally is considered to be in the range of the 1.5- to 2-year recurrence interval. The 2-year peak discharge for Caballo Creek at the eastern (downstream) Subregion 2 coal mine boundary was estimated to be approximately 400 cfs. The estimated contribution of CBNG production water discharge of 1.1 cfs represents less than 1 percent of the 2-year peak discharge. Based on the relative magnitude of the flow contribution from CBNG production water discharge, geomorphic relationships confirm the conclusion that the minor contribution from CBNG production water discharge to the flow in Caballo Creek likely would not result in active erosion to the channel. Furthermore, given the relatively flat channel gradient and the highly sinuous channel, a sustained discharge of this magnitude likely would promote an increase in diversity and density of the vegetation along the channel. These results were confirmed by observations of the existing channels during the field reconnaissance.

A threshold may exist where the contribution of CBNG production water discharge may create erosion within the receiving drainage channel. Based on the channel slope, channel sinuosity, and watershed area, drainages such as Caballo Creek may not realize an increase in channel erosion but would more likely realize an increase in vegetation diversity and density along the channel. Smaller drainages, such as Bone Pile Creek or Duck Nest Creek, may be more likely to exhibit channel erosion depending on the magnitude of the flow contribution from CBNG water production compared to the channel-forming discharge. However, field observations in these watersheds found similar increases in vegetation along the channels.

4.4 Summary

To have an impact on channel stability that is manifested in active channel erosion, CBNG production water discharge likely would have to represent a substantial portion of the channel-forming discharge in watersheds where the channel slope is steep enough and the width, depth, and sinuosity low enough to impact channel morphology. Based on the magnitude of the projected CBNG production water discharges compared to the channel forming discharge (1.5- to 2-year recurrence interval), the impact more likely would be evident in small ephemeral drainages that are characterized by steep channel gradients, lower sinuosity, and smaller widths and depths. Overall, as the drainage area increases, the channel slope typically decreases along with an increase in sinuosity, thereby reducing the impact of CBNG production water discharge on channel stability.

5.0 GROUNDWATER RECOVERY

Groundwater in the eastern PRB is projected to recover to near pre-mining and pre-CBNG development levels once these industrial uses of groundwater have ceased. Because neither activity is expected to be completed by the year 2020, estimates of groundwater recovery are longer term and are based on assumed dates for the cessation of CBNG development and coal mining in the eastern PRB. For CBNG development, it was assumed that CBNG development and associated groundwater pumping and discharge in the eastern PRB would end in 2030. This assumption was based on the currently projected rate of CBNG development through 2020 and the expected decline in gas reserves in the coal seams of the eastern PRB. For coal mining, it was assumed that open-pit coal mining and associated dewatering of the Fort Union and Wasatch Formations in advance of mining, as well as mine reclamation, would end in 2050. The BLM selected this date based on the currently projected rate of coal mining through 2020 and because of the lack of geologic data needed to extend coal mining projections much beyond 2050. Therefore, for modeling purposes, groundwater recovery related to the cessation of CBNG development started in year 2030, with CBNG-related groundwater pumpage and discharge rates remaining constant at the projected 2020 rate from year 2020 to year 2030. Groundwater recovery related to the cessation of coal mining started in year 2050, with groundwater pumpage rates remaining constant at the projected 2020 rate from year 2020 to year 2050.

Groundwater recovery following cessation of CBNG pumping in 2030 was modeled by letting the CMGM resaturate with groundwater after all CBNG wells had been turned off, but with the coal mines continuing to remove groundwater at the 2020 rate up to the year 2050. For recovery after the cessation of coal mining in 2050, the CMGM was allowed to resaturate with no dewatering of the mines and no pumping by CBNG wells. Also, the municipal wells at Gillette were turned off in the CMGM at year 2050 in order to better evaluate CBNG and coal mining effects. The full resaturation of the CMGM thus began in year 2050.

For the resaturation modeling to estimate groundwater recovery in the eastern PRB, recharge from regional precipitation was continued in the model based on precipitation recharge for year 2020. All model boundary conditions were left unchanged. MODFLOW drain cells that represented coal mine pit dewatering were replaced with regular model cells to represent the mine pit backfill aquifers that would replace the mine pits as the pits are backfilled with spoils material following cessation of mining. The hydraulic conductivity of the backfill aquifer model cells was set at 0.5 feet per day. This value was selected based on review of published coal mine pit backfill aquifer hydraulic properties for reclaimed coal mines in the western U.S., with emphasis on values from the PRB of Wyoming and Montana (Martin et al. 1988). The recharge to these coal mine pit backfill aquifers was set at 5 percent of precipitation because of the higher porosity of the pit backfill material compared to the bedrock formations (Wasatch and Fort Union) that had been mined.

When the Fort Union and Wasatch formations of the eastern PRB recover to near steady-state conditions, approximately 300 to 500 years following the assumed completion of coal mining in 2050 based on the resaturation modeling, groundwater will flow through the coal mine backfill aquifers and westward into the PRB. This will result in the transport of groundwater with elevated TDS from the pit backfill aquifers into the Wasatch and Fort Union aquifers of the eastern PRB. The extent of the transport of elevated TDS groundwater from the coal mine pit backfill aquifers

westward into the basin was modeled by coupling the CMGM with the U.S. Geological Service fate and transport code MT3DMS (Zeng and Wang 1999).

Data on the TDS in coal mine pit backfill aquifers was obtained from GAGMO reports (GAGMO 2003, 2000). Each of the coal mine pods in the three coal mine subregions was assigned a starting TDS value for transport modeling purposes based on the average TDS in pit backill aquifers available from the GAGMO reports. For modeling purposes, it was assumed that the starting TDS would remain constant through time, thus resulting in a conservative estimate of the extent of transport of elevated TDS westward from the mines. In reality, the TDS in the pit backfill aquifers will decrease with time due to repeated flushing of the backfill aquifers by groundwater and infiltration of precipitation. According to Martin et al. (1988), the pit backfill aquifers may be flushed after two to three pore volumes of groundwater have passed through the aquifers. Assuming a maximum of 5 pore volumes is needed to reduce the elevated TDS to a value below 1,000 mg/L, and assuming it takes approximately 100 years for each pore volume flush, the coal mine backfill aquifers are anticipated to have a TDS well below 1,000 mg/L after 500 years.

5.1 Recovery in the Wasatch Formation

Groundwater recovery for the Wasatch Formation was modeled relative to year 1975. This date was selected as a time before coal mines began serious pumping of groundwater and before CBNG pumpage. Thus, 1975 represents near steady-state for the eastern PRB in the CMGM model for the Wasatch Formation.

5.1.1 Year 2050

Figure B-43 in Appendix B presents modeled groundwater levels in the eastern PRB for year 2050, which is 20 years after the cessation of CBNG pumpage and discharge (2030) and the last year of coal mine pumpage. The groundwater levels show an eastward flow of groundwater in the Wasatch south of Wright, with Antelope Creek acting as a gaining stream (i.e., receiving flow of groundwater). East of Wright, groundwater flow turns northward and flows west-northwest toward Montana and out of the model domain. Groundwater flows into the Subregion 3 coal mines. For the Subregion 2 coal mines, groundwater flows northward through the mine areas, and there is a groundwater mound west of the mines that is the result of past CBNG discharge. The area south of Gillette shows the effect of municipal pumpage, which stops in 2050 in the modeled resaturation scenario. Groundwater in the Subregion 1 coal mines flows northwestward through the mines.

Figure B-44 in Appendix B shows the modeled groundwater level changes relative to 1975 in the Wasatch Formation for year 2050. Groundwater drawdown exists around the Subregion 3 coal mines due to continued pumpage by the mines through 2050. Some of the drawdown isopleths are west of the base year (2002) extent of mine workings; however, they are within the projected extent of mine workings for 2050. The Subregion 2 and Subregion 1 coal mine areas show very little drawdown, suggesting that groundwater levels by 2050 are nearing those of 1975. Up to 20 feet of drawdown exists in the Wasatch south of Gillette, due to past municipal pumpage.

5.1.2 Year 2100

Figure B-45 in Appendix B shows the modeled groundwater levels in the eastern PRB model domain for year 2100, which is 50 years after cessation of coal mining and 70 years after cessation of CBNG pumpage and discharge. The groundwater flow patterns are similar to those for year 2050. Groundwater flows into Antelope Creek, which is a gaining stream. Groundwater in the Wasatch flows into the reclaimed mine pits for the Subregion 3 coal mines, as it did in 2050. For the Subregion 2 and Subregion 1 coal mines, groundwater flows north to northwest through the reclaimed pit areas. There is still a groundwater mound west of the Subregion 2 mines, and there is still residual drawdown in the Wasatch south of Gillette. Groundwater flow south of Wright is to the east-northeast, toward the Subregion 3 coal mines. North of Wright, groundwater flow is north to northwest.

Figure B-46 in Appendix B shows the modeled groundwater drawdown for year 2100 relative to the pre-mining steady-state year of 1975. Drawdown around the Subregion 3 coal mines is up to 40 feet in the western extension of the mine pit areas. There is little drawdown around the Subregion 2 and Subregion 1 coal mines. There is residual drawdown of up to 20 feet south of Gillette.

5.1.3 Year 2250

Figure B-47 in Appendix B shows the modeled groundwater levels and groundwater flow patterns in the Wasatch for year 2250, which is 200 years after cessation of coal mining (2050) and 220 years after cessation of CBNG pumpage (2030). Groundwater flow patterns are similar to those found in the model results for year 2100. Antelope Creek is a gaining stream, and groundwater south of Wright flows northeast into the Subregion 3 reclaimed coal mine areas. North of Wright, groundwater flows northwest toward Montana. In the Subregion 2 and Subregion 1 coal mine areas, groundwater flows northwest through the reclaimed mine areas. A groundwater depression still exists south of Gillette, and a slight groundwater mound is present west of the southern group of mines in Subregion 2.

Figure B-48 in Appendix B, which shows the modeled drawdown for year 2250, shows that the modeled drawdown in the western extension of the reclaimed mine pits in Subregion 3 has decreased to 10 to 20 feet. There is still a slight drawdown around the Subregion 1 and Subregion 2 coal mines and south of Gillette.

5.1.4 Steady-state for the Wasatch Formation

Figure B-49 in Appendix B presents the modeled steady-state for the Wasatch Formation following recovery. Groundwater levels are projected to rebound and reach approximately 80 percent of steady-state in 300 to 500 years after the cessation of coal mining, which places it around 2350 to 2550. Groundwater flow paths are similar to those modeled for year 2250 (**Figure B-47**). South of Wright, groundwater in the Wasatch flows to the northeast toward the Subregion 3 coal mines. Antelope Creek is a gaining stream, with groundwater flowing into the stream from the Wasatch aquifer. Groundwater flows into the reclaimed Subregion 3 coal mines in the Wasatch in part because the reclaimed mine pits have not fully recovered and reached steady-state. Recovery occurs somewhat faster west of the mine pits because of the merging of stratigraphic databases

and in part due to lower hydraulic conductitivity values for the Wasatch than are found in the reclaimed pit backfill aquifers. For the Subregion 2 and Subregion 1 coal mines, groundwater flows northwest through the reclaimed mines. North of Wright, groundwater flows to the northwest into Montana. A slight groundwater mound continues to exist west of the Subregion 2 coal mines, and a slight groundwater depression continues to exist south of Gillette. There is no remaining residual drawdown compared to 1975.

Overall, the Wasatch Formation is projected to recover from CBNG pumpage and discharge and coal mine dewatering in approximately 300 to 500 years (**Figure B-49**). This recovery is a modeled recovery, and the assumption in the CMGM is that the Wasatch is a continuous aquifer. In reality, the Wasatch is not a continuous aquifer, but a complex fluvial/deltaic depositional system with local areas of groundwater and sometimes fairly continuous zones of groundwater within sand lenses. These areas of groundwater may recover faster than has been estimated by the CMGM model, or in some cases, they may take longer than the model-estimated 300 to 500 years. Therefore, the estimated steady-state for the Wasatch of 300 to 500 years is approximate and based on assumptions that were required for construction of the CMGM that may not apply to all areas of the Wasatch. Also, the Wasatch would continue to be used for stock water and locally for domestic water supply following the end of coal mining and CBNG development. Recovery modeling assumed that no use of groundwater in the Wasatch would continue after year 2050. Thus, some areas of the Wasatch may recover very slowly to pre-mining or pre-CBNG groundwater levels.

5.2 Recovery In The Upper Fort Union Formation

Groundwater recovery for the Fort Union Formation was modeled relative to year 1975. This was a time before coal mines began serious pumping of groundwater and before CBNG pumpage. Thus, 1975 represents near steady-state for the eastern PRB in the CMGM model for the Fort Union Formation.

5.2.1 Year 2050

Figure B-50 in Appendix B shows the modeled groundwater levels in the Fort Union for year 2050. As with the Wasatch Formation, year 2050 represents the time of cessation of coal mining and 20 years after cessation of CBNG pumpage and discharge. Groundwater flow south of Wright is to the northeast toward the Subregion 3 coal mines. In the vicinity of the coal mines, the groundwater flow patterns are complex due to pumpage by the mines. Groundwater flows into the reclaimed mine areas. Between the coal mine group on the north and the one to the south in Subregion 3, there is a small groundwater high resulting from overlapping drawdown areas from the two mine groups. Northwest of the northern group of coal mines in Subregion 3, there is a groundwater high that may be the result of drawdown between the high and the coal mines (see **Figure B-51**). Groundwater flow in the vicinity of the Subregion 2 coal mines is toward the mines; however, west of the mines, groundwater flow is to the northwest. In the Subregion 1 coal mines, groundwater flow is to the northwest and through the mined areas. There is a groundwater depression northeast of Gillette. Along the southeastern boundary of the model domain, groundwater in the Upper Fort Union east of the Subregion 3 mines flows eastward out of the model domain due to the general head boundary along that part of the model boundary. East of the Subregion 2 coal mines, groundwater flow in the Upper Fort Union east of the mines is to the north. North of Wright, groundwater flow is to the northwest.

Figure B-51 in Appendix B shows the modeled residual drawdown in year 2050 compared to 1975 for the Upper Fort Union in year 2050. Drawdown west of the Subregion 3 coal mines is in the range of 10 to 50 feet, with local zones of tight drawdown up to 110 feet centered on the western extent of mine pits. For the Subregion 2 coal mines, there is very tight drawdown up to 120 feet centered on the southern group of mines, and a zone of tight drawdown centered on the western extent of coal mine pits in the southern portion of the northern group of mines. Drawdown west of the Subregion 2 mines is approximately 10 to 20 feet. For the Subregion 1 mines, drawdown is approximately 20 to 40 feet, and for Gillette, residual drawdown is approximately 10 feet in the Upper Fort Union.

5.2.2 Year 2100

Figure B-52 in Appendix B shows the modeled groundwater levels and groundwater flow patterns for the Upper Fort Union in year 2100, 50 years after the cessation of coal mining and 70 years after the cessation of CBNG pumpage and discharge. The groundwater level contours are similar to those for 2050. Flow south of Wright is to the northeast and toward the Subregion 3 coal mines. North of Wright, flow is to the northwest and toward Montana. Around the Subregion 3 reclaimed coal mines, the groundwater level contours indicate continued flow into the former mine pits from the west. East of the coal mines in the Subregion 3 area, groundwater in the Upper Fort Union is flowing eastward and leaving the model domain, suggesting that groundwater in the Upper Fort Union in the southeastern part of the model domain is flowing eastward through the reclaimed coal mines and out of the model domain. For the Subregion 2 coal mines, groundwater flow is northward through the coal mine areas. The same is true for the Subregion 1 coal mines. Around Gillette, a groundwater depression is present east of the town due to pumping of municipal wells. Areas of elevated groundwater levels are present in the Subregion 2 and Subregion 3 coal mine areas that probably are the result of differential drawdown in surrounding areas, leaving residual areas of elevated groundwater levels between the areas of drawdown.

Figure B-53 in Appendix B shows the modeled residual drawdown for year 2100 in the Upper Fort Union. Drawdown exists in most of the same areas as was observed in year 2050 (**Figure B-51**), but to a lesser degree. Drawdown west of the Subregion 3 coal mines ranges from 10 to 30 feet, with localized drawdown up to 45 feet in the western most extension of the former coal mine pits. Drawdown around the Subregion 2 coal mines is 10 to 20 feet, and around the Subregion 1 coal mines the residual drawdown is 20 feet or less. Approximately 10 feet of residual drawdown continues east of Gillette.

5.2.3 Year 2250

Figure B-54 in Appendix B shows the modeled groundwater levels for the Upper Fort Union in year 2250. The groundwater level contours are similar to those modeled for year 2100 (**Figure B-52**). South of Wright, groundwater flow in the Upper Fort Union is to the northeast, toward the Subregion 3 coal mines. This flow continues through the reclaimed mine areas and eastward out of the model domain through the general head boundary condition along the southeastern boundary of the model domain. Groundwater flow for the Subregion 2 mines continues to be northward through the reclaimed mines, and for the Subregion 1 mines, groundwater flow is northwestward through the mines. There is a small groundwater depression east of Gillette, and the areas of groundwater

elevation around and west of the Subregion 3 and Subregion 2 coal mines observed in 2050 (**Figure B-50**) continue to be present. The groundwater mounds found in Subregion 3 and Subregion 2 for year 2100 also are present in year 2250.

Figure B-55 in Appendix B shows the modeled residual drawdown compared to the steady-state year 1975 for the Upper Fort Union in year 2250. Drawdown is considerably less than in year 2100 (**Figure B-53**), and for the Subregion 3 coal mines, the residual drawdown is in the range of 10 to 20 feet. For the Subregion 2 coal mines, drawdown is 10 feet or less. There is no residual drawdown for the Subregion 1 coal mines.

5.2.4 Year 2350

Figure B-56 in Appendix B presents the modeled groundwater levels for year 2350. This would be 300 years after cessation of coal mining and 320 years after cessation of CBNG pumpage and discharge in the Upper Fort Union. The groundwater level contours are similar to those for year 2250 (**Figure B-54**), as would be expected this long after the cessation of coal mining. South of Wright, groundwater flow in the Upper Fort Union is to the northeast, toward the Subregion 3 coal mines. This flow continues into the reclaimed mine areas. East of the reclaimed mines, groundwater flow is eastward out of the model domain through the general head boundary along the southeastern boundary of the model. This eastward flow may be due to a groundwater divide east of the clilnker areas in the Subregion 3 coal mines, resulting in eastward flow for the Upper Fort Union east of the mines. Groundwater flow for the Subregion 2 mines continues to be northward through the reclaimed mines, and for the Subregion 1 mines, groundwater flow is northwestward through the mines. A small groundwater depression continues east of Gillette. Groundwater mounds observed in year 2050, that are the result of model design rather than actual conditions, continue in the Subregion 3 coal mines. Similar mounds are found around the Subregion 2 coal mines. Groundwater flow north of Wright is northwestward toward Montana and out of the model domain.

Figure B-57 in Appendix B presents the modeled residual drawdown compared to 1975 for the Upper Fort Union in modeled year 2350. Little drawdown remains around the coal mines, suggesting that the model is approaching steady-state. For the Subregion 3 coal mines, residual drawdown is in the range of 10 to 15 feet and localized in specific areas of the former mine pits. For the Subregion 2 coal mines, residual drawdown is approximately 10 feet. For the Subregion 1 coal mines, there is no apparent residual drawdown. East of Gillette, there is a residual drawdown of approximately 10 feet.

5.2.5 Steady-state for the Upper Fort Union

Figure B-58 in Appendix B presents the modeled groundwater levels for estimated steady-state for the Upper Fort Union, which is approximately 300 to 500 years after cessation of coal mining. The modeled groundwater level contours are very similar to those for year 2350, as would be expected since there was little residual drawdown for year 2350. The discussion presented for year 2350 (**Figure B-56**) also applies to this figure and to modeled steady-state in the Fort Union. Important features to note are the northeastward flow of groundwater south of Wright that continues into the reclaimed coal mines and the eastward flow out of the model domain for areas east of the mines, due possibly to a groundwater divide east of the clinker zones. East of Wright, groundwater flow

turns north, and north of Wright, groundwater flow in the eastern PRB for the Upper Fort Union is northwestward toward Montana and out of the model domain. For the Subregion 2 and Subregion 1 reclaimed coal mine areas, groundwater flow is north-northwest through the coal mine areas.

Overall, the Upper Fort Union recovers to near steady-state conditions in approximately 300 to 500 years (**Figure B-57**). The estimated final steady-state for the Upper Fort Union is approximately 500 years. Pumpage of groundwater from the Upper Fort Union has been from the coal-bearing zones, either for removal of CBNG or for removal of coal in the coal mines in the eastern PRB that follow the outcrop of the coal along the eastern structural boundary of the PRB. For recovery to occur in the Upper Fort Union, water has to flow back into the coal-bearing formations affected by groundwater removal. In the CMGM model, this recovery is controlled by the boundary conditions of the model, the distribution of recharge, and the overall distribution of hydraulic conductivity and storage in the Upper Fort Union (Layer 5 in the CMGM model). Also, recovery of the Upper Fort Union may take longer than the model-estimated 300 to 500 years. Recovery of a groundwater system that took millions of years to develop often can be a slow process and require more time than that estimated by a numerical model. It is assumed in the modeling of recovery by the CMGM, that all pumpage in the eastern PRB ceases in year 2050. Assuming Gillette continues its municipal pumpage, and other areas of the eastern PRB utilize groundwater in the Upper Fort Union after year 2050, recovery of the groundwater levels in the Upper Fort Union may take longer than the model-estimated 300 to 500 years.

5.3 Transport of Elevated TDS Water From Coal Mine Pit Backfill Aquifers

Based on data in the GAGMO (2003, 2000) reports, the average TDS in coal mine pit backfill aquifers in the PRB is approximately 3,700 milligrams per liter (mg/L), with the highest average value for any coal mine subregion being approximately 4,800 mg/L for Subregion 1. Coal mine pit backfill aquifer water has an average TDS below Wyoming stock water standards (5,000 mg/L). Thus, movement of pit backfill water westward into the Wasatch and Fort Union aquifers would not degrade the water quality of these aquifers relative to use for stock watering. The westward extent of the 1,000 mg/L TDS isopleth after 500 years was modeled to represent the location where the TDS of groundwater leaving the coal mine backfill aquifers would be reduced through groundwater flow and dispersion to a level approximately equal to the current TDS in the Wasatch and Fort Union aquifers. The distance from the reclaimed coal mine pit boundaries after 500 years for the 1,000 TDS isopleths is approximately 1,000 to 2,000 feet for both the Fort Union and the Wasatch aquifers. This distance is approximately the same for all three coal mine subregions in the eastern PRB, because the hydraulic conductivity of the Wasatch and Fort Union aquifers west of the three subregions is approximately the same. Thus, after 500 years (the estimated time for the backfill aquifers to be flushed by groundwater flow) potential impacts to the Wasatch and Fort Union aquifers are projected to be limited to a distance of up to 2,000 feet west of the reclaimed coal mine pits. West of the projected 1,000 TDS isopleth, groundwater in the Upper Fort Union and Wasatch aquifers is projected to be similar to pre-mining conditions.

6.0 SUMMARY

Overall, changes in the eastern PRB from 2002 to 2020 involve an assumed gradual reduction in pumpage rates for CBNG wells as they mature and continue to migrate to the west and southwest tapping deeper levels of the coal-bearing units in the Upper Fort Union. Based on modeling results, this leads to a shift in drawdown in the Upper Fort Union to the southwest of Wright, with corresponding rebound in groundwater levels west of the coal mines along SR 59 as the CBNG wells in this area cease production and pumpage of groundwater. For the Wasatch, discharge of CBNG water from 2002 to 2020 results in mounding of up to 30 feet in areas of substantial CBNG pumpage. It also is assumed that the coal mines would continue to operate and dewater up to 2050: however, reclamation of the mined-out areas allows groundwater to rebound in the reclaimed mine areas. Based on modeling results, drawdown within the mine areas and within about 2 to 3 miles west of the mines continues to be about the same from 2002 to 2020. Discharge of CBNG water to drainages in the eastern PRB leads to a decrease in EC in most drainages and an increase in SAR; however, the final mixed water continues to be suitable for irrigation in most drainages during a normal precipitation year and for most months during a dry year. During the dry year, months with low normal flows often have mixed water that would not be suitable for irrigation during those months, if they receive substantial CBNG discharge.

Based on the groundwater modeling results for 2010, groundwater flow in the Wasatch and Upper Fort Union is to the northeast south of Wright and gradually shifts to the northwest east of Wright. Most drawdown in the Wasatch (up to 70 feet) is in the Subregion 3 coal mines located southeast of Wright. West of the Subregion 3 coal mines, drawdown in the Wasatch is 10 to 20 feet. Groundwater mounds due to CBNG discharge of up to 30 feet are present west of Wright and west of the Subregion 2 coal mines. For the Upper Fort Union, there is a substantial groundwater depression, with up to 575 feet of drawdown since 1990 (350 feet of drawdown since 2002), southwest of Wright. Drawdown since 1990 in the coal mine areas is up to 250 feet in the Subregion 3 coal mines, up to 125 feet in the Subregion 2 coal mines, and up to 75 feet in the Subregion 1 coal mine areas. Drawdown since 2002 is 150 feet or less in the coal mine areas. Rebound in the Upper Fort Union since 2002 is up to 100 feet along SR 59.

Based on groundwater modeling for 2015, groundwater flow patterns in the Upper Fort Union and the Wasatch are the same as projected for 2010. Drawdown in the Wasatch is mostly in the Subregion 3 coal mines and ranges up to 80 feet, with up to 30 feet of drawdown west of the mines since 1990. Drawdown in the Wasatch since 2002 is up to 60 feet in the Subregion 3 mines and up to 30 feet west of the mines. Groundwater mounding up to 20 feet within the Wasatch continues to be present in areas of CBNG water discharge. For the Upper Fort Union, the groundwater depression noted in 2010 southwest of Wright shifts further to the south, and the drawdown is up to 475 feet since 1990 (350 feet since 2002). Drawdown in the Subregion 3 coal mines is up to 150 feet in the Upper Fort Union, with comparable drawdown in the Subregion 2 coal mines and considerably less drawdown in the Subregion 1 coal mines. Rebound of groundwater levels since 2002 is projected in the Upper Fort Union, with up to 200 feet of rebound in some areas of the Subregion 3 coal mines and 25 to 50 feet of rebound in the Subregion 1 and Subregion 2 coal mine areas. There is a general rebound of up to 275 feet in the Upper Fort Union along SR 59 due to the reduction in CBNG pumpage since 2002.

6.0 Summary

Based on groundwater modeling results for 2020, groundwater flow patterns in the Wasatch and Fort Union are much the same as projected for 2010 and 2015. Drawdown in the Wasatch is up to 70 feet in the Subregion 3 coal mines, and up to 20 feet in both the Subregion 1 and Subregion 2 coal mines. Groundwater mounds up to 20 feet are present near Wright and west of the Subregion 2 coal mines. Since 2002, drawdown in the Wasatch is up to 60 feet in the Subregion 3 coal mines and up to 20 feet in both the Subregion 1 and Subregion 2 coal mines. Drawdown in the Upper Fort Union is 425 feet southwest of Wright since 1990 (350 feet since 2002). Drawdown in the Subregion 3 coal mines is up to 125 feet, with up to 75 feet in the Subregion 2 coal mines and up to 25 feet in the Subregion 1 coal mines. Rebound of groundwater levels up to 125 feet is found in the reclaimed areas of the coal mines. Groundwater rebound of up to 20 feet since 1990 is found in the basin west of the Subregion 2 coal mines and near Wright. Since 2002, rebound of groundwater levels west of the Subregion 2 coal mines is up to 175 feet, and up to 275 feet in the Upper Fort Union along SR 59.

After 2050, modeled groundwater levels in the eastern PRB begin to rebound due to the projected cessation of CBNG pumpage around 2030 and the projected cessation of coal mining around 2050. The Wasatch begins to show noticeable rebound after approximately 50 years (around year 2100) and substantial rebound after 200 years (around year 2250). The Upper Fort Union shows recovery after 50 to 100 years (2100 to 2150) and substantial rebound after 200 years (year 2250). Both the Wasatch and the Upper Fort Union are projected to rebound and reach approximately 80 percent of steady-state after 300 to 500 years, or between years 2350 and 2550.

Resaturation of the coal mine pit backfill to form backfill aquifers may take approximately 100 years after cessation of mining and is projected to result in the westward migration of groundwater with elevated TDS levels. Modeling of this westward migration indicates that TDS levels should be down to the average background value of approximately 1,000 mg/L within 2,000 feet of the final western extent of the coal mine boundaries. Thus, no impact to groundwater quality in either the Wasatch or the Upper Fort Union aquifers is expected beyond approximately 2,000 feet west of the final coal mine boundaries.

7.0 REFERENCES

AECOM. 2009a. Update of the Task 1B Report for the Powder River Basin Coal Review, Current Water Resources Conditions. Prepared for the Bureau of Land Management Casper Field Office and Wyoming State Office. November 2009.

_____. 2009b. Update of the Task 2 Report for the Powder River Basin Coal Review Past and Present and Reasonably Foreseeable Development Activities. Prepared for the Bureau of Land Management, Casper Field Office and Wyoming State Office. December 2009.

Applied Hydrology Associates and Greystone Environmental Consultants (AHA and GEC). 2002. Technical Report Powder River Basin Oil and Gas Environmental Impact Statement: Groundwater Modeling of Impacts Associated with Mining and Coal Bed Methane Development in the Powder River Basin. Prepared for Bureau of Land Management, Buffalo Field Office.

Anderson Consulting Engineers (ACE). 2009. Task 3B Report Water Resources Cumulative Impact Assessment Water Quality and Channel Stability. Prepared in support of Powder River Basin Coal Review. Prepared for: ENSR International. November 2009.

Ayers, R. S. and D. W. Westcot. 1985. Water Quality for Agriculture. FAO Irrigation and Drainage, Paper 29 (Rev 1). Food and Agriculture Organization of the United Nations.

Bureau of Land Management (BLM). 2007a. Estimation of Pumpage Rates for Six Drainage Basins in the Powder River Basin, Wyoming. Prepared by F. Crockett, Wyoming State Office, Reservoir Management Group. Cheyenne, Wyoming.

_____. 2007b. Estimated coal mine pit migrations and pit bottom elevation changes with time from 2002 to 2020. BLM internal report prepared by Casper Field Office. July 27, 2007 (supplied to AECOM).

_____. 2007c. Estimated future locations of CBNG wells in the eastern PRB through 2020. BLM internal report prepared by Wyoming State Office, Reservoir Management Group. October 2007 (supplied to ENSR).

_____. 2005. Stratigraphy of the Coal Mines of the Eastern Powder River Basin. Provided by N. Braz, BLM Coal Resources Group, High Plains District Office, Casper, Wyoming.

_____. 2003. Final Environmental Impact Statement and Proposed Plan Amendment for the Powder River Basin Oil and Gas Project. Wyoming State Office and Buffalo Field Office Cheyenne and Buffalo, Wyoming. January 2003.

_____. 1999. Wyodak Coalbed Methane Project – Final Environmental Impact Statement.

_____. 1996. Coal Development Status Check Powder River Federal Coal Region Montana & Wyoming Data Tables. Data compiled by: Wyoming bureau of Land Management Buffalo Resource Area, Casper District, & State Offices, and Montana Bureau of Land Management Powder River Resource Area, Miles City District & State Offices.

Environmental Simulations, Inc. (ESI). 2009. Calibration of the Coal Mine Groundwater Model for the Eastern Powder River Basin. Prepared for Bureau of Land Management, Casper Field Office, June 2009.

Gillette Area Groundwater Monitoring Organization (GAGMO). 2003. GAGMO 2002 Annual Report. Prepared for GAGMO by Hydro-Engineering, LLC, Casper, Wyoming.

_____. 2000. GAGMO 20-Year Report. Report summarizing data over 20-year period from 1980 to 2000 for active coal mines in the eastern Powder River Basin. Gillette, Wyoming.

Greystone and ALL Consulting. 2003. Surface Water Quality Analysis Technical Report. Surface Water Modeling of Water Quality Impacts Associated with Coal Bed Methane Development in the Powder River Basin. Report prepared for Bureau of Land Management, Buffalo Field Office, Buffalo, Wyoming in support of the Final Environmental Impact Statement and Proposed Plan Amendment for the Powder River Basin Oil and Gas Project.

Goolsby, Finely, and Associates. 2001. Correlation of Fort Union Coals in the Powder River Basin. Part of the administrative record for BLM (2003).

Harvey, M. D. and C. C. Watson. 1986. Fluvial Processes and Morphological Thresholds in Incised Channel Restoration. Water Resources Bulletin, 3(3):359-368.

HKM Engineering, Inc., Lord Consulting, and Watts and Associates (HKM et al.). 2002a. Powder/Tongue River Basin Plan. Prepared for Wyoming Water Development Commission Basin Planning Program. February 2002.

_____. 2002b. Northeast Wyoming River Basins Plan. Prepared for Wyoming Water Development Commission Basin Planning Program. February 2002.

IHS Energy Services (IHS). 2007. Oil and Gas Production and Well History Database.

Lane, E. W. 1955. The Importance of Fluvial Morphology in Hydraulic Engineering. American Society of Civil Engineering Proceedings, v 81, No. 745.

Martin, L. J., D. L. Naftz, H. W. Lowham, and J. G. Rankl (Martin et al.). 1988. Cumulative Potential Hydrologic Impacts of Surface Coal Mining in the Eastern Powder River Structural Basin, NE Wyoming. USGS WRI 88-4046.

Montgomery Watson Harza. 2003. Coal Planning Estimates Report. Prepared for the Bureau of Land Management, Wyoming State Office. March 2003.

Schumm, S. A., M. D. Harvey, and C.C. Watson. 1984. Incised Channels: Morphology, Dynamics and Control. Littleton, Colorado: Water Resources Publications.

_____. 1981. Yazoo Basin geomorphology. Soil Conservation Service, Project SCS-23-MS-80.

Schumm, S. A. 1977. The Fluvial System. John Wiley and Sons, Inc.

Simon, A. and C. R. Hupp. 1987. Channel Evolution in Modified Alluvial Streams. U.S. Geological Survey, Washington, DC.

Watson, C. C., M. D. Harvey, D. S. Biedenharn, and P. G. Combs (Watson et al.). 1988. Geotechincal and Hydraulic Stability Numbers for Channel Rehabilitation: Part I, The Approach. Proc., ASCE Hyd. Div. 1988 National Conf., Abt, Sr. R., and J. Gessler (Eds.).

Western Water Consultants, Inc. 1977. Reclamation Plan for Portion of Caballo Creek, Belle Ayr Mine, Campbell County, Wyoming.

Zeng and Wang. 1999. Fate and transport code MT3DMS. U. S. Geological Service.

APPENDIX A

ESTIMATED PUMPAGE RATES FOR SIX DRAINAGE BASINS IN THE POWDER RIVER BASIN, WYOMING

(Source: BLM 2007a.)

Estimated Pumpage Rates for Six Drainage Basins in the Powder River Basin, Wyoming

Introduction

Several areas in the Wyoming portion of the Powder River Basin have been subject to substantial ground water drawdown in coal aquifers due to production of coalbed natural gas (CBNG) which is also called coalbed methane. This report identifies historical rates of water production for six drainage basins (sub-watersheds) in northeast Wyoming. It also predicts average pumpage rates for CBNG wells in the drainage basins for the years 2010, 2015, and 2020. The drainage basins are listed in Table 1. Locations of the drainage basins are shown on a map of northeast Wyoming, Figure 1.

Purpose

In order to model ground water depletion as the projected development of CBNG continues through 2020, it is necessary to develop assumptions of average pumping rates as wells are drilled, produced and abandoned in future years. It has been observed that as the number of wells in a given area are drilled and produced, there is a relationship between the number of wells and the average water production rate per well. The number of wells for a given area (drainage basin a of sub-watershed) was predicted through 2020 and is reported in the Task 2 report (ENSR 2005).

	Drainage Basin	Average Total Depth	Est. Average Well Life	Est. Average EUR in MMCFG
1	Antelope Creek	788	8.0	221
2	Dry Fork Cheyenne	1,725	No data	No data
3	Little Powder	655	7.1	123
4	Upper Belle Fourche	902	6.8	171
5	Upper Cheyenne River	566	6.2	217
6	Upper Powder River	1,291	8.0	177

Table 1 Summary of well statistics for CBNG wells in the six drainage basins reviewed. The average well life and EUR numbers are for wells with first production dates before 2003.

Procedure

The API numbers for all CBNG wells in each drainage basin listed in Table 1 were provided by ENSR Corp. The API numbers were used to identify wells in the IHS Energy well and production databases. Only CBNG well data were retrieved from the databases. Duplicate entries were culled. The number of wells was totaled for each drainage basin by year based on the spud date.

Estimated well life and estimated ultimate recovery (EUR) of coalbed gas for wells which began

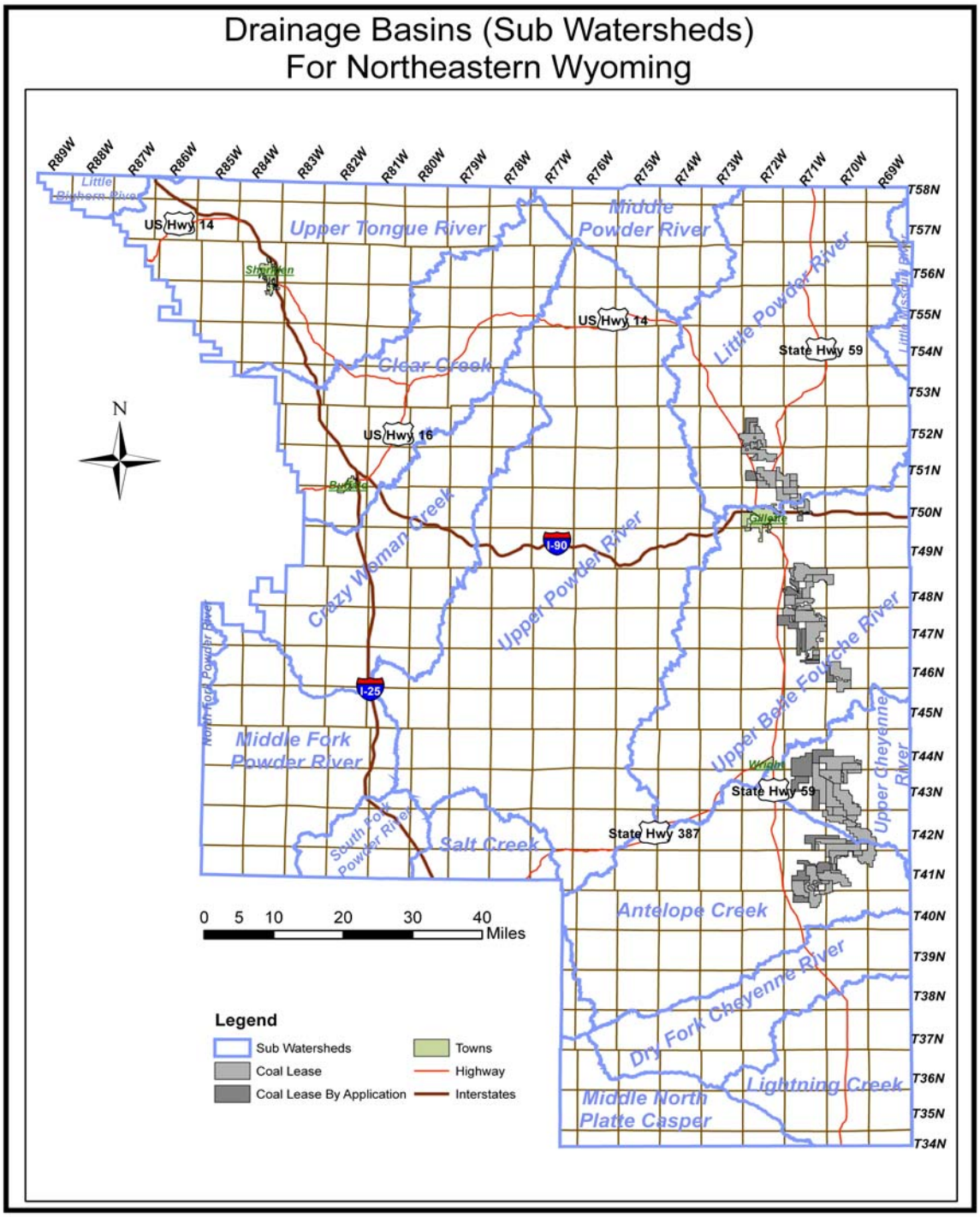


Figure 1. Map of northeast Wyoming showing the locations of drainage basins analyzed in this report.

	Drainage Basin	Estimated Wells	Drilled Wells as % of Projected	Total Withdrawal in Acre Feet	Avg. Well Depth in Ft.
1	Antelope Creek	5,020	26%	21,764	788
2	Dry Fork Cheyenne	1,195	1%	481	1,725
3	Little Powder River	7,191	46%	67,563	655
4	Upper Belle Fourche	10,848	63%	122,726	930
5	Upper Cheyenne River	1,212	50%	26,685	566
6	Upper Powder River	24,930	30%	124,259	1,291

	gpm/mo/ well Jun-Aug06	Decline. Rate Aug05 -Aug06	Est. Pumpage in gpm/well				Remarks
			2005	2010	2015	2020	
1	2.50	29%	3.6	2	2	2	
2	10.57	87%	20.8	5	3	2	Uncertain estimates.
3	2.23	9%	2.5	2	1	1	
4	5.36	-6%	5.1	5	3	1	
5	1.89	28%	2.5	2	2	1	
6	5.33	-6%	5.0	5	4	2	

Table 2. List of the drainage basins with estimated water pumpage rates in five year increments. The number of projected wells is the total number of wells projected to be drilled by 2020. The percentage indicates the number of wells that have been drilled as of October 2006. Data are compiled from the IHS Energy production and well databases. The number of wells projected to be drilled by 2020 was obtained from a 2003 study by ENSR Corp. The 2005 pumpage rate was averaged from the 2005 monthly production figures in IHS Energy's historical database.

production before 2003 were calculated. Calculations were based on averaged production rates. Wells with first production later than January 1, 2003 were not used because there was considered to be too great a chance that gas production had not reached the decline portion of the production curve. If gas production was not declining then the exponential decline equation would not accurately predict the remaining reserves, thus making the EUR calculation too low. Wells which had not produced since September 2005 were considered to be depleted. No further reserves were credited to those wells. Weighted average cumulative production from the depleted wells, combined with estimated ultimate gas recovery (EUR) for wells which were still producing were used to calculate an average EUR for wells in five of the six drainage basins. The average well life and EUR were not calculated for the Dry Fork Cheyenne drainage basin due to insufficient data. An exponential decline rate of 40 percent and an economic limit of 10 MCFG/day were used in the calculations. Results are shown in Table 1.

Monthly production data were also retrieved for each drainage basin. Cumulative production histories for each drainage basin were compiled and graphs drawn (figures 5 through 10). Each drainage basin listed in Table 1 was individually evaluated and future pumpage rates were predicted. Nominal pumpage rates were used. The nominal pumpage rate assumes every well produced every day of the month in which there is recorded production. The actual pumpage rate, which was calculated but not used, is a measure of the actual water production rate based on the days a well was active.

This report uses various units of measurement. There has been an attempt to relate water and gas production rates and the ratios between them in units that are appropriate and relate to the disciplines of people who may use this report The relationships between these units are listed

in Table 2.

Study Area: T. 47-48 N., R 72 W. (sometimes referred to as the "Fairway Area" or the "Marquis-Lighthouse" area) Campbell County, Wyoming was the first large area with fully developed CBNG production. The producing horizon is the Wyodak-Anderson coal interval. The Wyodak-Anderson interval is the main coalbed gas producing interval on the east side of the Powder River Basin, and it is the main coal producing interval in all the large coal mines in the eastern Powder River Basin. Because the Fairway area has been fully developed, it was selected as a study area in an attempt to determine how pumpage rates vary compared to other production data. Figures 3a, 3b, and 3c show the average nominal pumpage rate in gpm/well compared to several other factors. Figure 4 shows the relationship between these two rates. The nominal rate was used because it requires less information to calculate and closely approximates the actual rate.

1.00	gallons/minute
34.3	barrels/day
1,035	barrels/month
0.133	acre feet/month
0.00223	cubic feet/second

Table 2. Rate equivalents assuming 30.4 days/month. One barrel is 42 gallons.

Data from the study area are displayed in Figures 3a, 3b, and 3c, and show that other data and ratios do not give a clear indication of future average pumpage rates. Parameters such as total gas production and average gas production per well do not begin to decline until several months or years after the average pumpage rate starts declining. Figure 4 is a graph of pumpage rates and well numbers for the entire Wyoming portion of the Powder River Basin. Notice that even on a basin scale pumpage rates began declining when the number of wells was relatively low. When about six percent of the total estimated wells for the Powder River Basin had been drilled, production began declining in a more of less regular pattern. This allowed future pumpage rates to be forecast.

Evaluation of Drainage Basins

An evaluation and discussion of each drainage basin is given below. Historical and estimated future pumpage rates for each drainage basin are listed in Table 2. Historical data are presented graphically in figures 5-10. The average pumpage rates for five of the six drainage basins have stabilized between two and five gallons per minute. An estimate of future rates based on projected pumpage rate declines is not needed for any of these five drainage basins. The Dry Fork Cheyenne drainage basin has few producing wells and pumpage rates have not

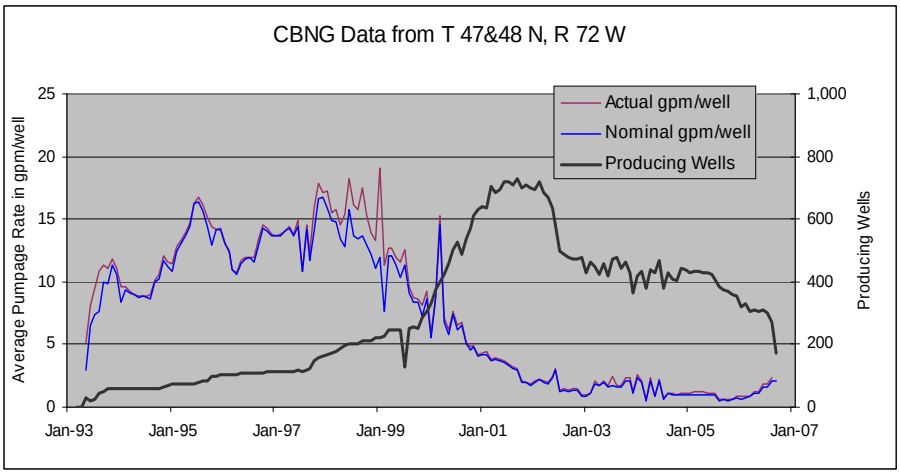


Figure 2. This shows a comparison of the actual and nominal pumpage rates in the study area. The nominal rate was used because it requires less data to calculate.

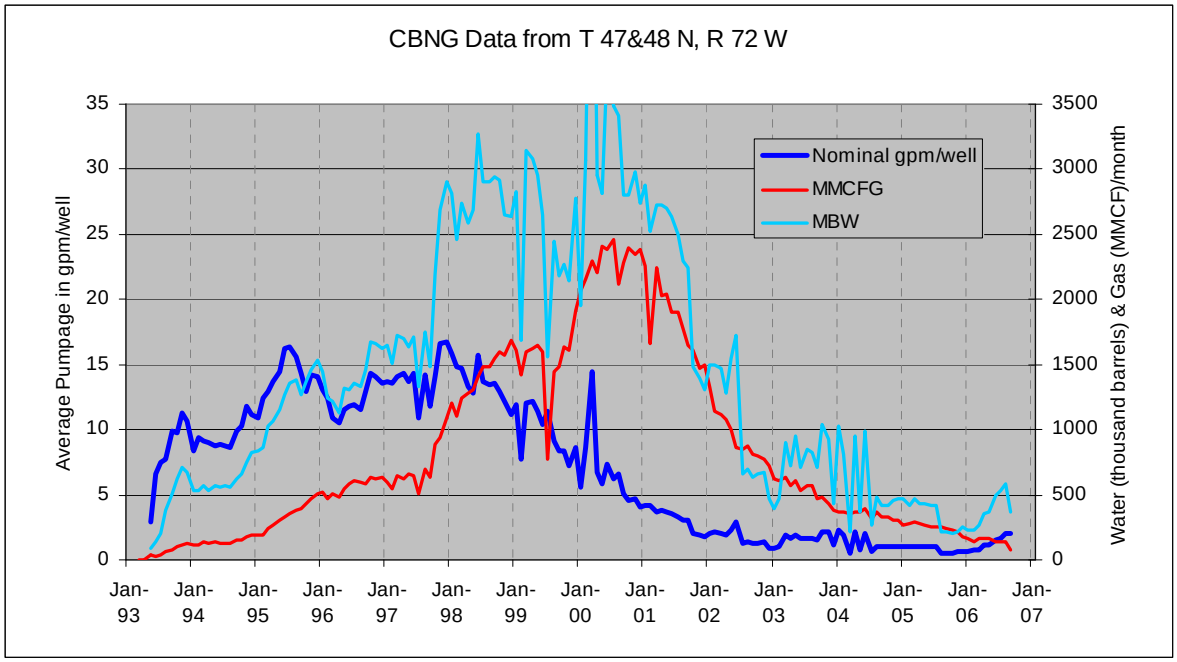


Figure 3a. Monthly data from CBNG wells in the Fairway area. Notice that the average nominal pumpage rate began to decline in a more or less predictable way before either total water production or total gas production began to decline. Data are from the IHS Energy production database.

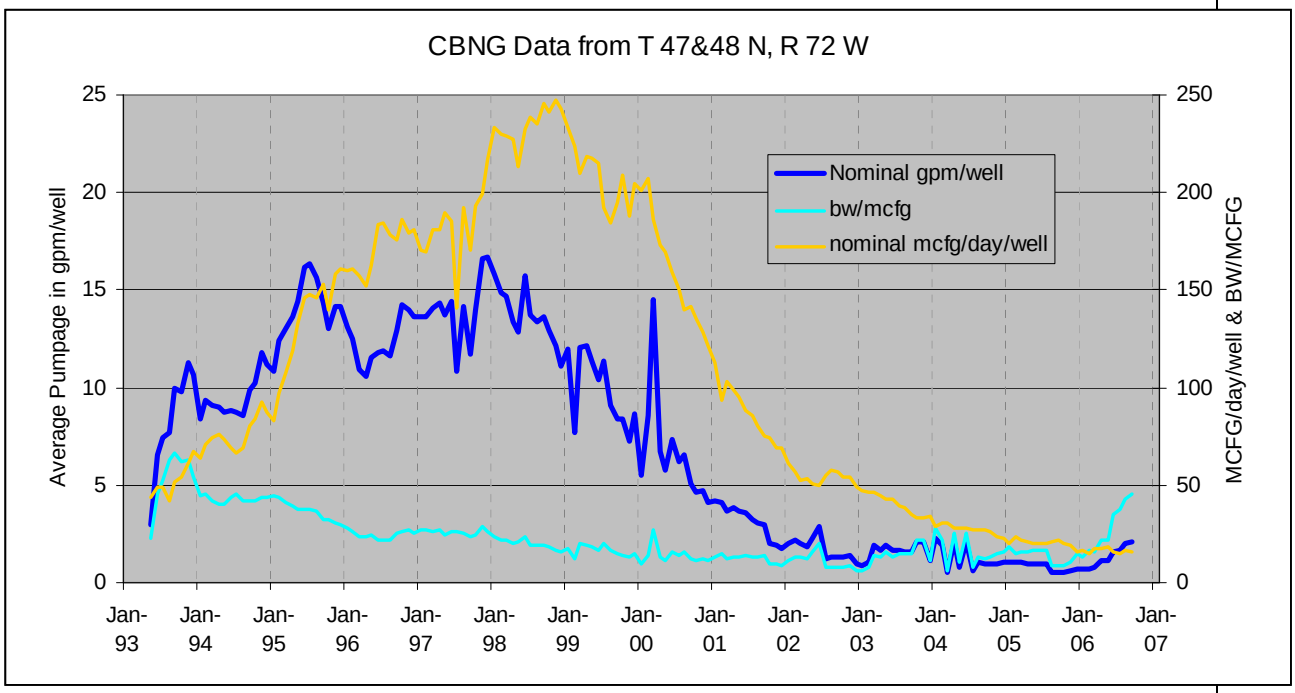


Figure 3b. Monthly data from CBNG wells in the Fairway area. Notice that the average nominal pumpage rate began to decline before the average per well gas production started declining. The water/gas ratio began declining early and appears to have little relationship to the average pumpage rates. Data are from the IHS Energy production database.

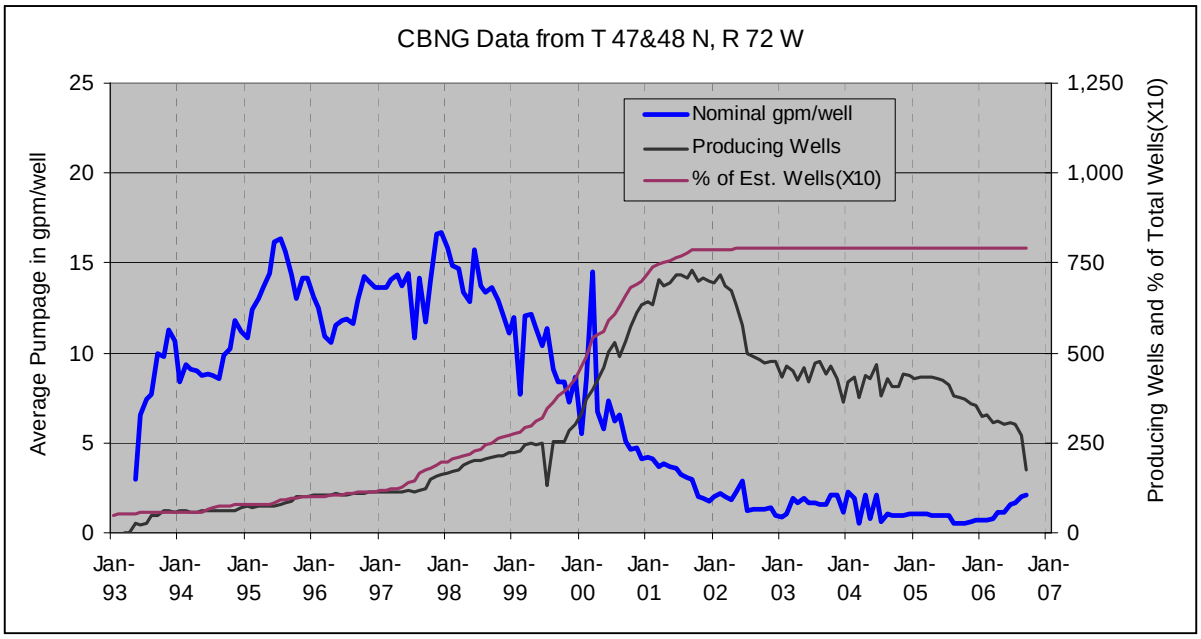


Figure 3c. Monthly data from CBNG wells in the Fairway area. Notice that the average nominal pumpage rate began to decline as the number of productive wells was increasing. Also notice the average pumpage rate began declining when about 20 percent of the total predicted wells had been drilled. The total predicted number of wells (1,104) was calculated by the author and is based on well spacing authorized by the WOGCC. Data are from the IHS Energy production database.

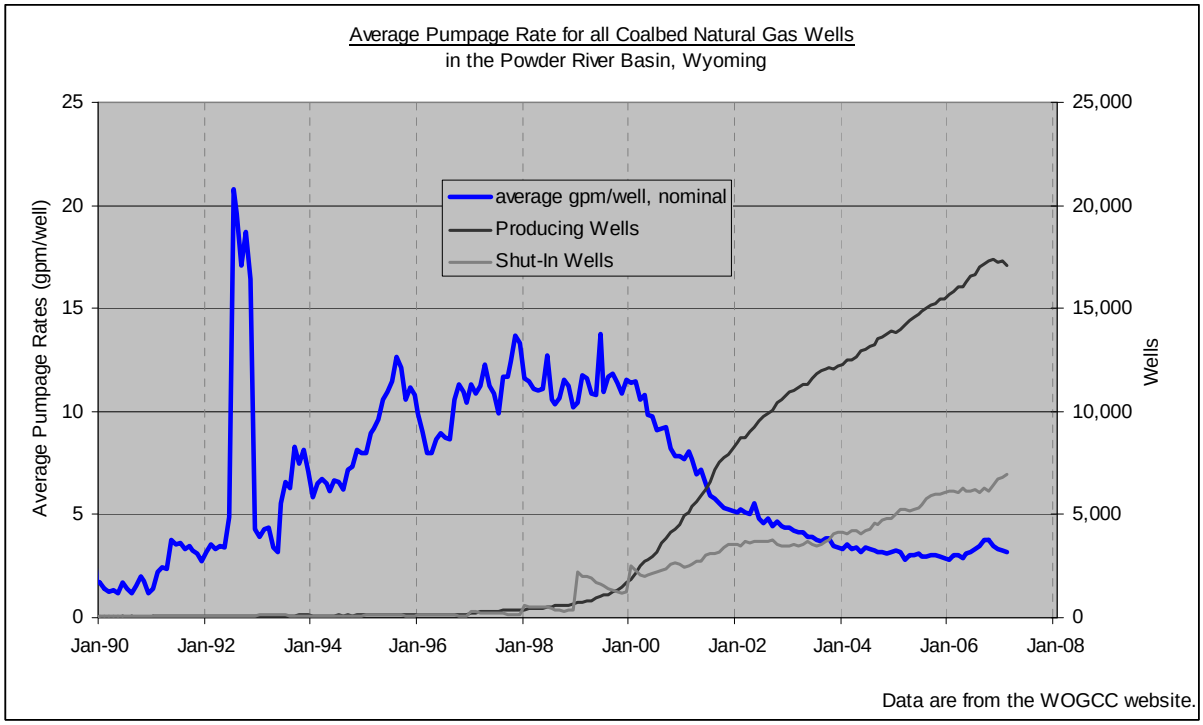


Figure 4. Average nominal pumpage rate for all producing coalbed natural gas wells in the entire Powder River Basin, Wyoming.

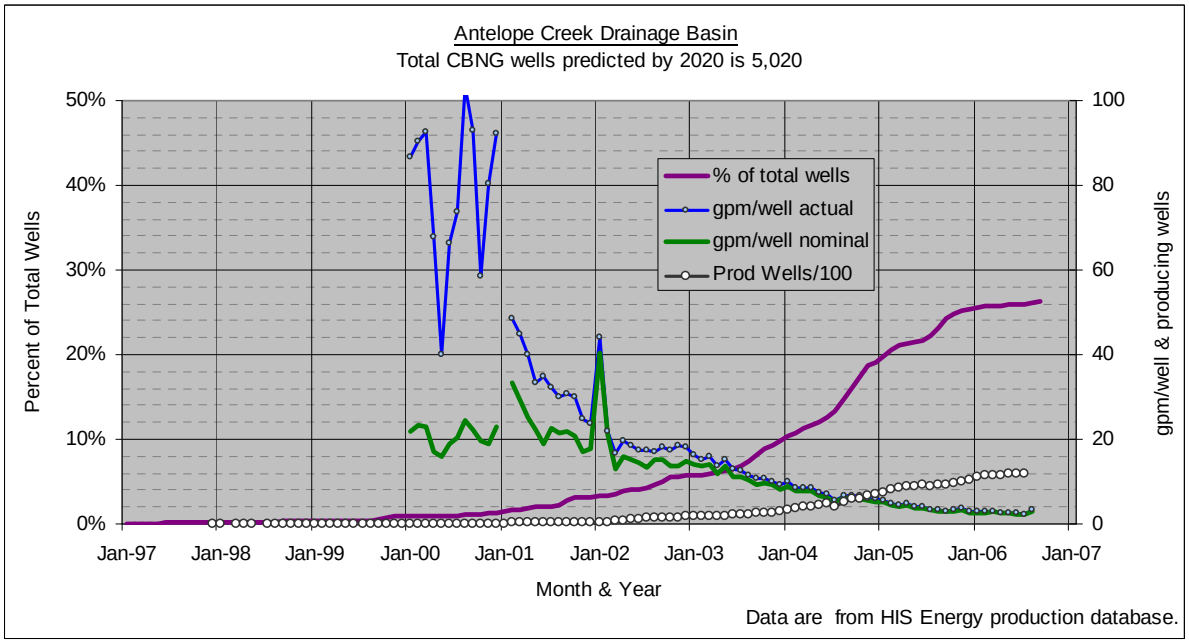


Figure 5a. Historical water production from the Antelope Creek drainage basin. Water production has been continuous since 1998. Historical production data from September 2006 indicate water production is 3.0 gallons per minute per well. The number of producing wells was divided by 100 so the data would plot on the graph.

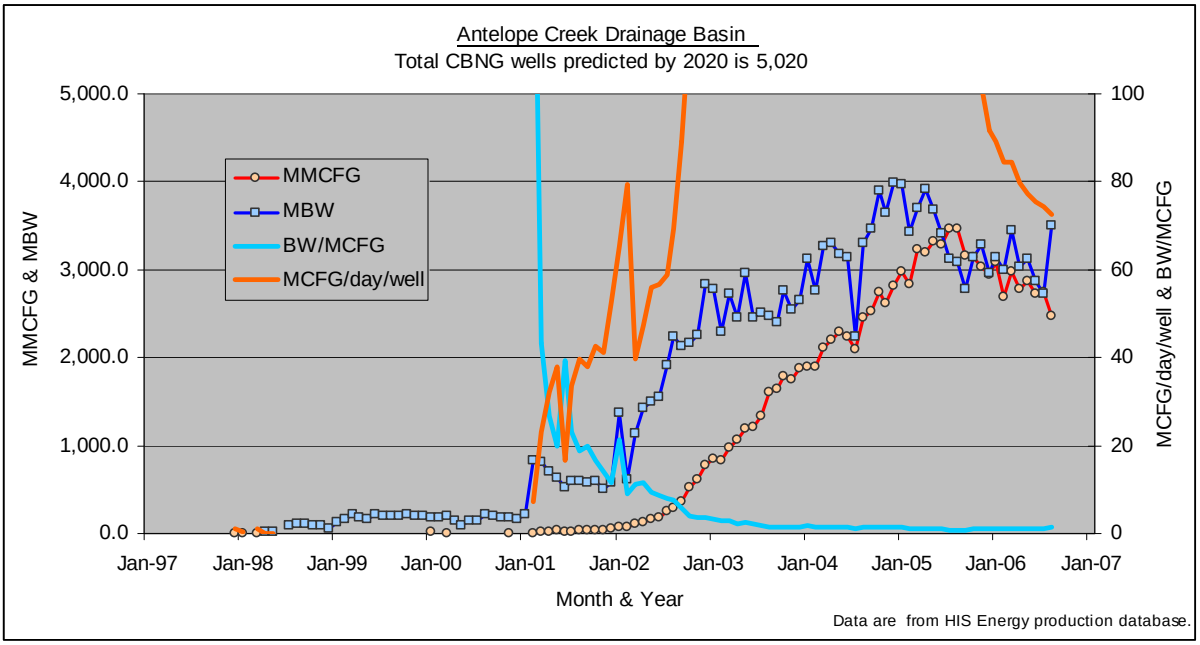


Figure 5b. This graph shows historical gas and water production, and average per well gas and water production for the Antelope Creek drainage basin. During January 2006 – August 2006 water production from the drainage basin averaged 401 acre feet/month.

progressed to a point where a projection can be calculated with much certainty.

Antelope Creek Drainage Basin: Water production began in 2000. Nominal pumpage rates peaked at 40.5 gpm/well in January 2002 (Figure 5a). Data from July 2006 indicated the average

pumpage rate was 2.2 gpm/well which was 41 percent less than a year earlier. The average per well gas rate declined at an annual rate of 15 percent during June-August 2006 (Figure 5b). The gas rate is still well above the economic limit (about 10 MCFG/day/well) and the decline appears to be moderating. This suggests that there will not be a large decrease in the number of producing wells in the next few years. Therefore it should be expected that the average pumpage rate will continue to slowly decline even though there was an abrupt increase in August 2006. As the number of producing wells declines the pumpage rate may increase slightly before again declining.

Through August 2006 a total of 21,764 acre feet of water had been produced from the Antelope Creek drainage basin. During August 2006, 451 acre feet of water were produced. Only 26 percent of the total estimated wells had been drilled through August 2006. Because such a low percentage of the estimated total wells have been drilled, it is anticipated that the average pumpage rate will remain at about 2 gpm/well through 2020.

Dry Fork Cheyenne Drainage Basin: This drainage basin is in the early stages of development. Data are insufficient to determine with any degree of certainty what pumpage rates will be at specific future times. Water production began in 2004 and has probably not yet stabilized (Figure 6a). At the end of August 2006, only 14 wells of an estimated 1,195 total ultimate wells had been drilled. There is no reported gas production. There may not be a stabilized pumpage rate for at least a few years. Existing wells produce from the Pawnee coal which is several hundred feet deeper than the main producing coal in the eastern Powder River Basin.

The average pumpage rate in 2005 was 21 gpm/well. The pumpage rate in August 2006 was 9.5 gpm/well. Estimates of future pumpage rates for this drainage basin contain substantial uncertainty. If water production from the Dry Fork Cheyenne drainage basin is similar to most other drainage basins examined in this review, pumpage rates may remain high and erratic for at least a few years then decline in a somewhat predictable pattern to approximately 5 gpm/well after five to fifteen years from the onset of production. Estimates of approximately 5 gpm/well

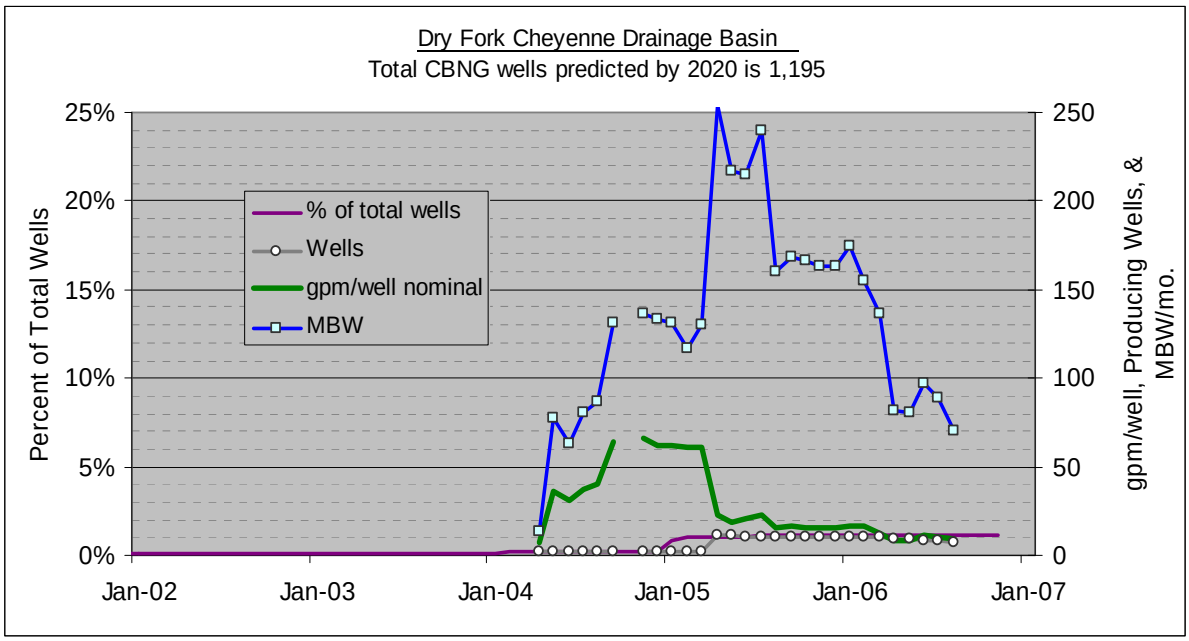


Figure 6a. Historical water production from the Dry Fork Cheyenne drainage basin. Water production began in 2004. There is no recorded gas production for this drainage basin. The most recent available data indicate water production is 9.5 gallons per minute per well.

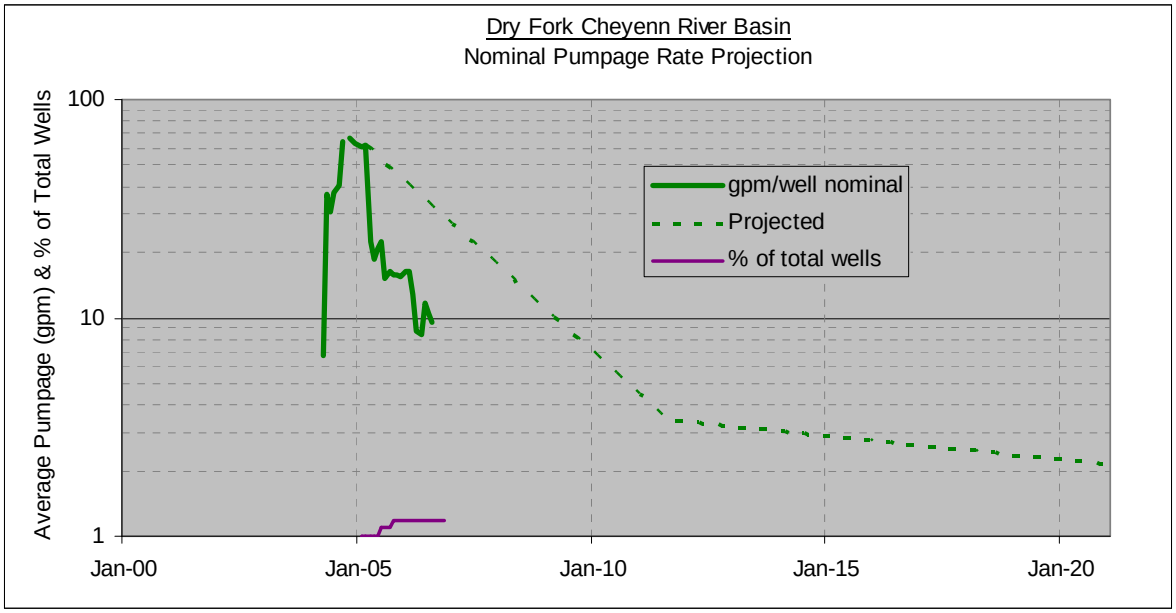


Figure 6b. This figure shows a two stage exponential decline to project future average pumpage rates. An initial rate of 45 percent/year was used until the average pumpage rate reached three gallons/minute. Then the decline rate was changed to 5 percent/year. This projection should be used with caution because fewer than two percent to the projected total wells have been drilled. Production data are from the IHS Energy production database.

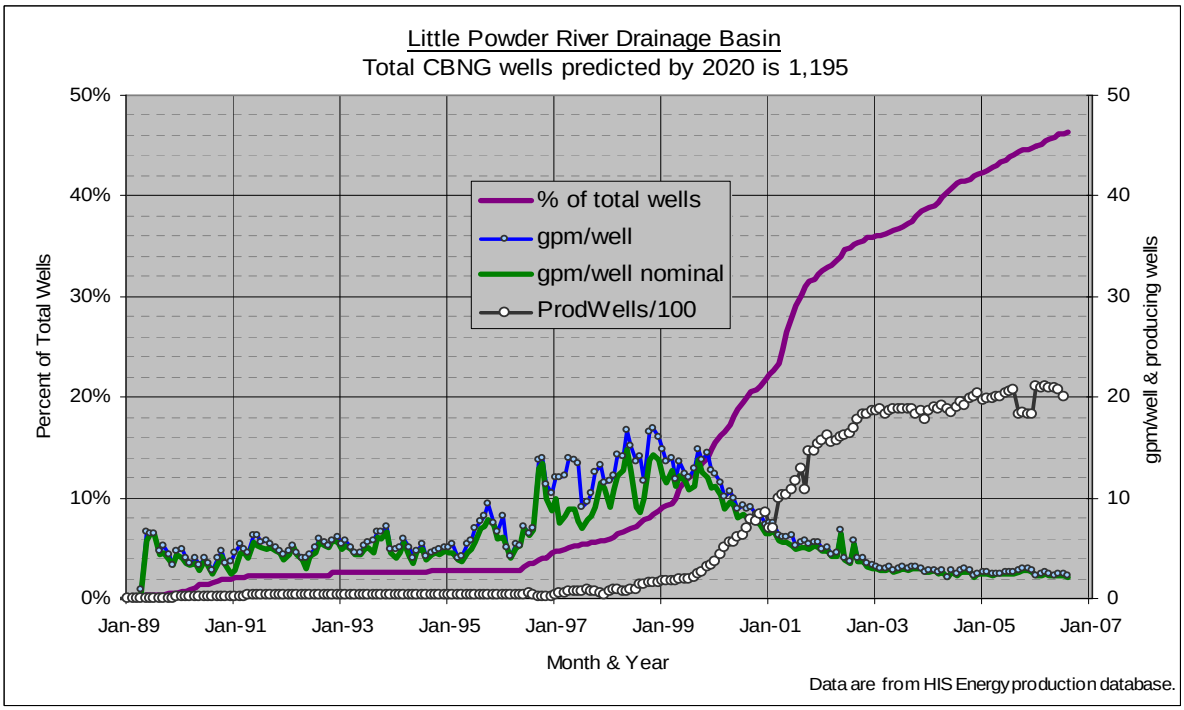


Figure 7a. Historical water production from the Little Powder River drainage basin. Water production has been continuous since 1989. The most recent available data indicate water production is 2.3 gallons per minute per well. The number of producing wells was divided by 100 so the data would plot on the graph.

for 2010, 3 gpm/well for 2015, and 2 gpm/well for 2020 are reasonable based on the available data from other drainage basins. As of September 2006 only about one percent of the estimated total wells had been drilled, therefore these estimates contain considerable uncertainty and may be significantly higher or lower than estimated. They should be used with great caution.

One might try to draw an analogy to the Upper Powder River drainage basin. Pumpage rates in the Upper Powder River drainage basin began declining in May 1999 when less than one percent of the predicted total wells had been drilled. However, the number of producing wells increased from six in May 1999 to almost 1,000 (eight percent of estimated total wells) two years later, and to over 4,000 (28 percent of predicted total wells) by May 2006. Dry Fork Cheyenne drainage basin shows a very different pattern of development. Average pumpage rates began declining in April 2005 when there were only 11 producing wells (one percent of the predicted total). Eighteen months later the number of producing wells had decreased by about half. It is unlikely that the pumpage rates have stabilized. However, if they have, Figure 6b was drawn to show a projection of future rates even though there is great uncertainty. The reader is urged to use Figure 6b and predicted future pumpage rates with great caution.

Little Powder Drainage Basin: Production began in December 1987 and has been continuous since then. Pumpage rates were generally below 6 gpm/well until 1996 when they began increasing to a maximum of 14 gpm in 1999 (figures 7a and 7b). Rates then decreased to the current 2 gpm. The average pumpage rate during August 2006 was 2.3 gpm/well. Total

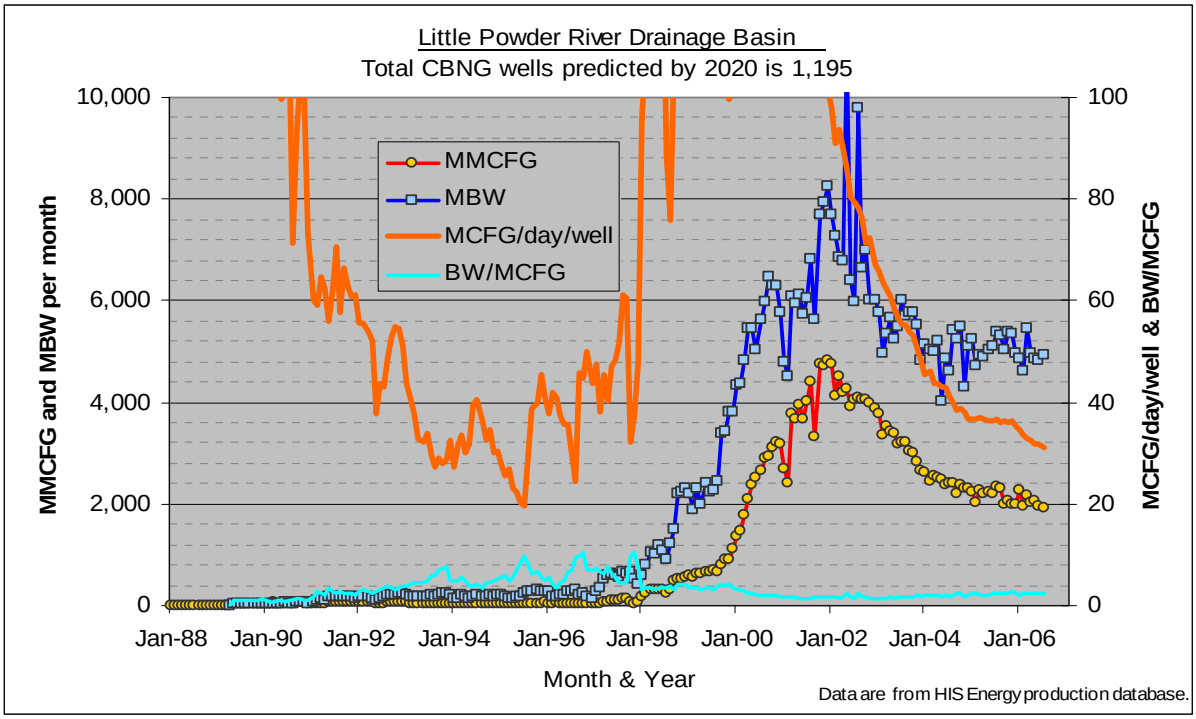


Figure 7b. This graph shows historical gas and water production, and average per well gas and water production for the Little Powder River drainage basin. During July 2004 – July 2006 total water production from the drainage basin has averaged 684 acre feet/month. The average gas production rate is declining 17 percent/year.

monthly water production began a rapid increase in January 1997, and gas began a rapid increase one year later. Both reached a maximum in 2002 then declined. Water production from the Little Powder drainage basin is currently averaging about 254 acre feet per month. The average gas rate per well is currently 34 MCFG/day and declining 17 percent per year. These data are shown graphically in figures 5a and 5b.

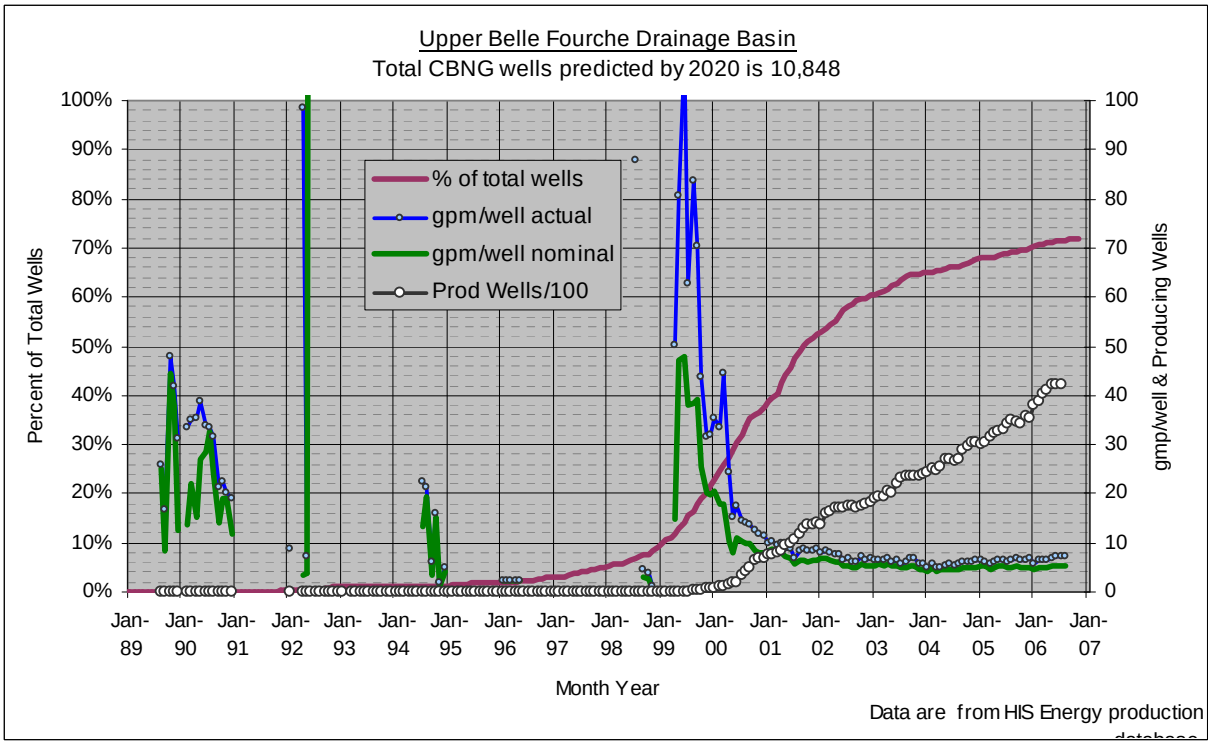


Figure 8a. Historical water production from the Upper Belle Fourche drainage basin. Production appears to be stable at four to six gpm/well. The percent of estimated total wells was modified to eliminate the numerous stratigraphic tests drilled before 1998.

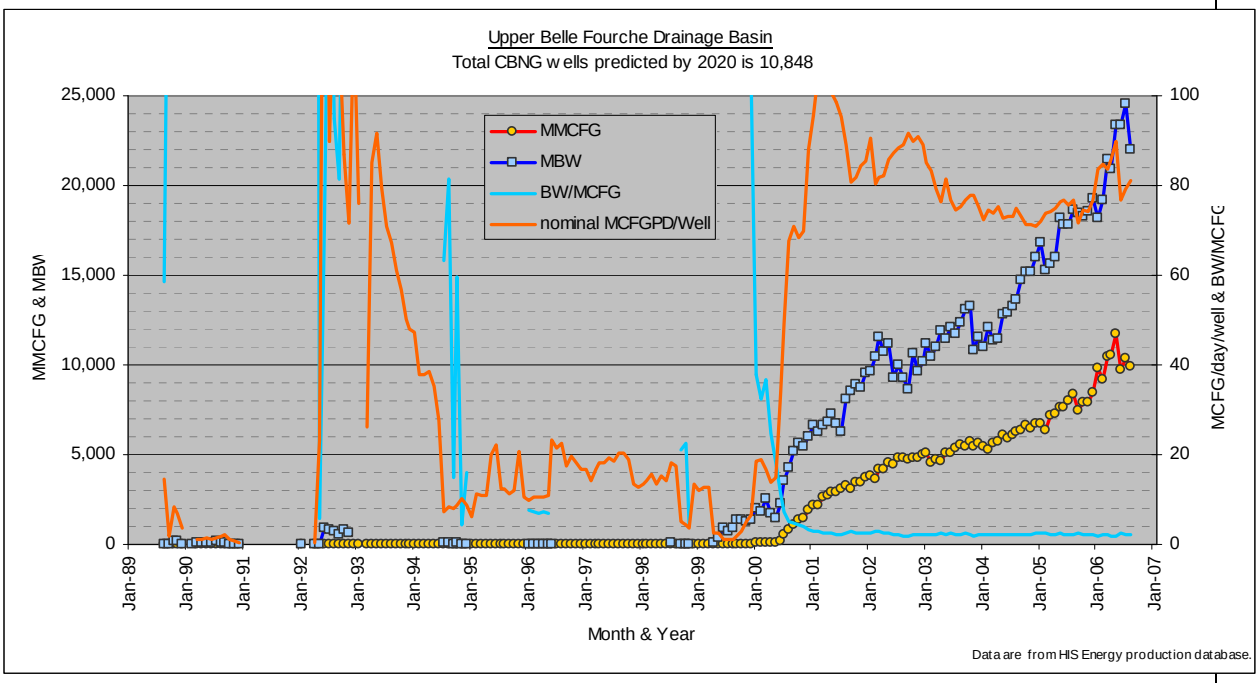


Figure 8b. Historical gas and water production, and average per well gas and water production for the Upper Belle Fourche drainage basin. During 2002-2006 per well gas and water production has remained relatively constant even though total gas and water production has increased. Note that gas production per well has not declined significantly since January 2002.

It is anticipated that the average per well pumpage rate will be 2gpm/well in 2010 then decline to 1 gpm/well in 2015 and remain at 1 gpm/well in 2020.

Upper Belle Fourche Drainage Basin: The area produced water and CBNG sporadically from 1989 to 1992, and continuously since 1992. There is no record of water production during extended periods before 1999 (see figures 8a and 8b). The area is still being developed as evidenced by the increasing number of producing wells and increases in the production rates for both gas and water. Although water production is still increasing, the average pumpage rate peaked in 1999 then declined, and has been stable at about 5gpm/well since 2002. Also, the average gas rate per well is remaining more or less steady at 80 MCFG/day/well. It is anticipated that water pumpage rates will remain stable through 2010 as more wells are drilled. As gas and water production decline, pumpage rates are anticipated to decrease to about 3 gpm/ well in 2015 and to about 1 gpm/well in 2020. As of August 2006, 72 percent of the estimated 10,848 wells had been drilled.

Upper Cheyenne River Drainage Basin: The first wells were drilled in 1994 and water production began in 1997. Water production peaked at 40 gpm/well in July 1998. It has declined in a predictable pattern since January 2001 when 29 percent of the total estimated wells had been drilled (figures 9a and 9b). The pumpage rate declined at a nominal rate of 12 percent from August 2005 to August 2006. However, the average gas production rate is declining about 40 percent annually. Many wells will probably reach an economic limit in the next few years. In August 2006 water production was 1.9 gpm/well. Figures 3a and 3b show water and gas production and pumpage rates for the upper Cheyenne River drainage basin. The number of producing wells has declined steadily since March 2005. As of August 2006, only 50 percent of the estimated 1,242 wells had been drilled. A total of 26,685 acre feet of water has been produced from the Upper Cheyenne River drainage basin.

It is estimated that the number of producing wells will continue to decline in the short term, and that pumpage rates will remain more or less steady at 2 gpm/well until 2015 then decline to 1 gpm/well by 2020. The sharp decline in average per well gas production indicates that many new wells will be needed within a few years if production from this drainage basin is to be sustained. If numerous additional wells are not drilled, continued decline should be expected.

Upper Powder River Drainage Basin: Water and gas production first occurred in 1989 and was intermittent until April 1999. Before April 1999 average water rates were erratic. Although short term water rates were very high the available data indicates less than 1,000 acre feet of water had been produced by April 1999. As of August 2006 about 124,000 acre feet have been had been produced.

When continuous production began the number of producing wells increased rapidly from five in April 1999 to 165 in April 2000. Average per well water production decreased rapidly from a nominal rate of 55 gpm in May 1999 to 10 gpm in April 2000 (see Figure 10a). Average water production continued to decline to 5.2 gpm/well in June 2002, then remained relatively constant (average 5.0 gpm/well) through August 2006. Although the decline rate was high water production rates began to form a more or less predictable pattern in May 1999 when less than one percent of the estimated total wells had been drilled. This number is very low compared to other drainage basins and may suggest that the number of total wells predicted is too high. During the time interval when average per well water production remained relatively steady, the number of producing wells more than doubled, increasing from 1,726 in June 2002

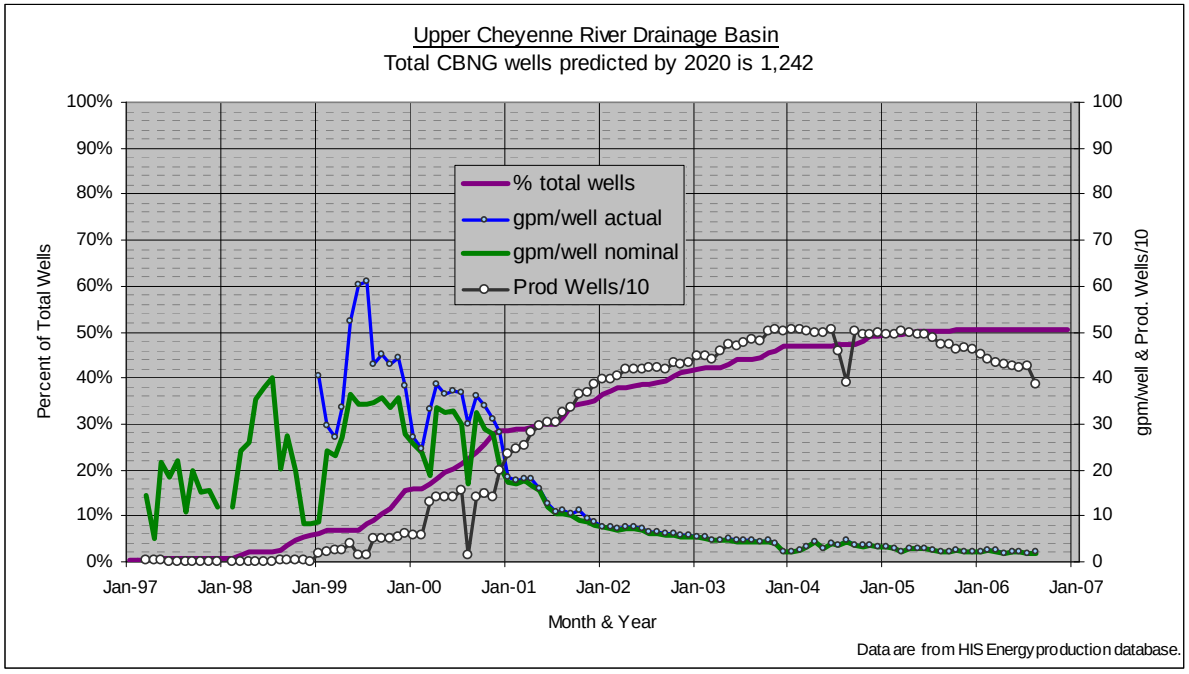


Figure 9a. Historical water production from the Upper Cheyenne River drainage basin. Production declined at a nominal rate of 29.3 percent from Jan-02 through Aug-06, and at a rate of only 11.5 percent from Sep-05 through Aug-06. The number of producing wells was divided by 10 so the data would plot on the graph.

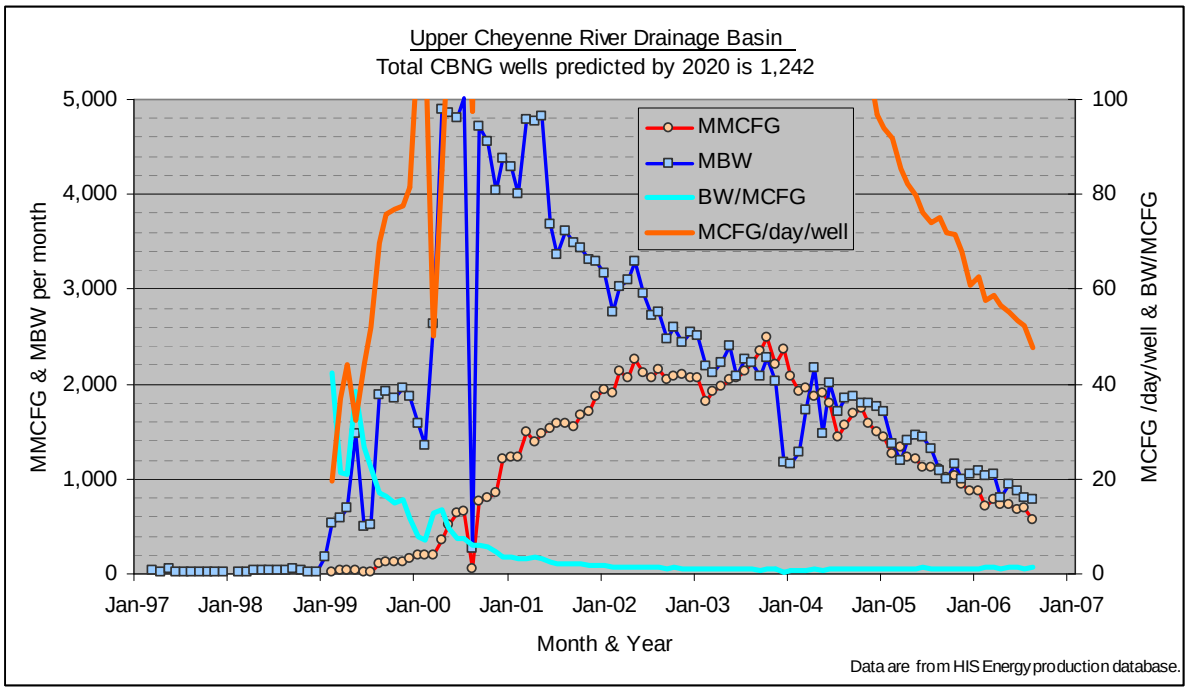


Figure 9b. Historical gas and water production, and average per well gas and water production for the Upper Cheyenne River drainage basin. Both water and gas production are declining rapidly. Average per well gas production is declining 46 percent per year.

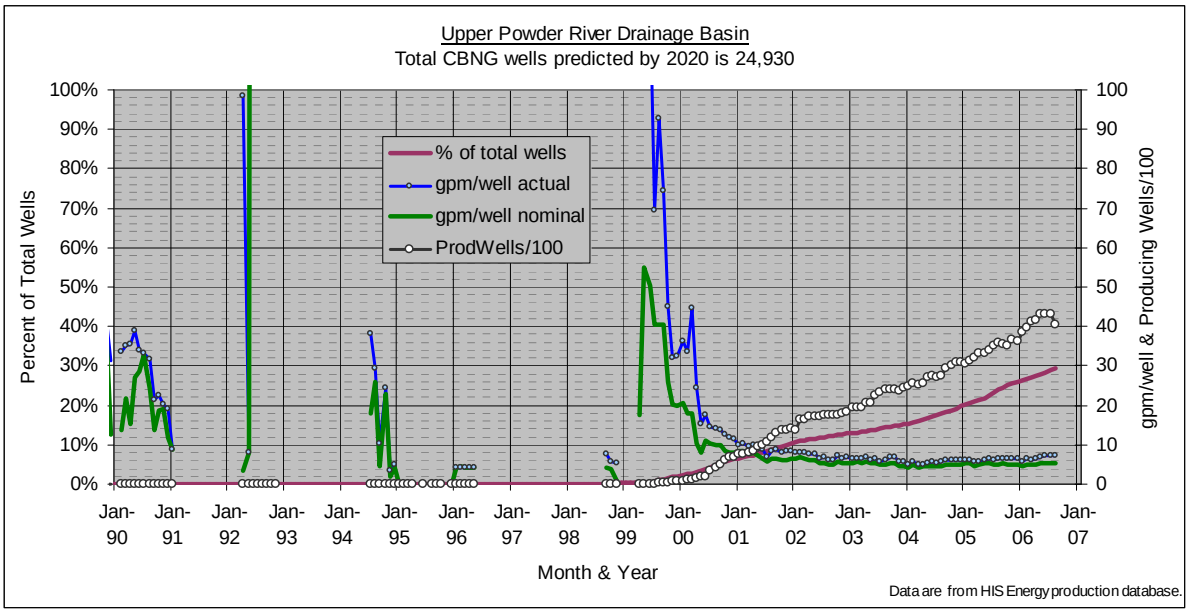


Figure 10a. Historical water production from the Upper Powder River drainage basin. Production was intermittent from 1989 to 1999. Nominal water production rate declined from 55 gpm in May 1999 to 5 gpm in June 2002 and has held steady since then. The number of producing wells was divided by 100 so the data would plot on the graph.

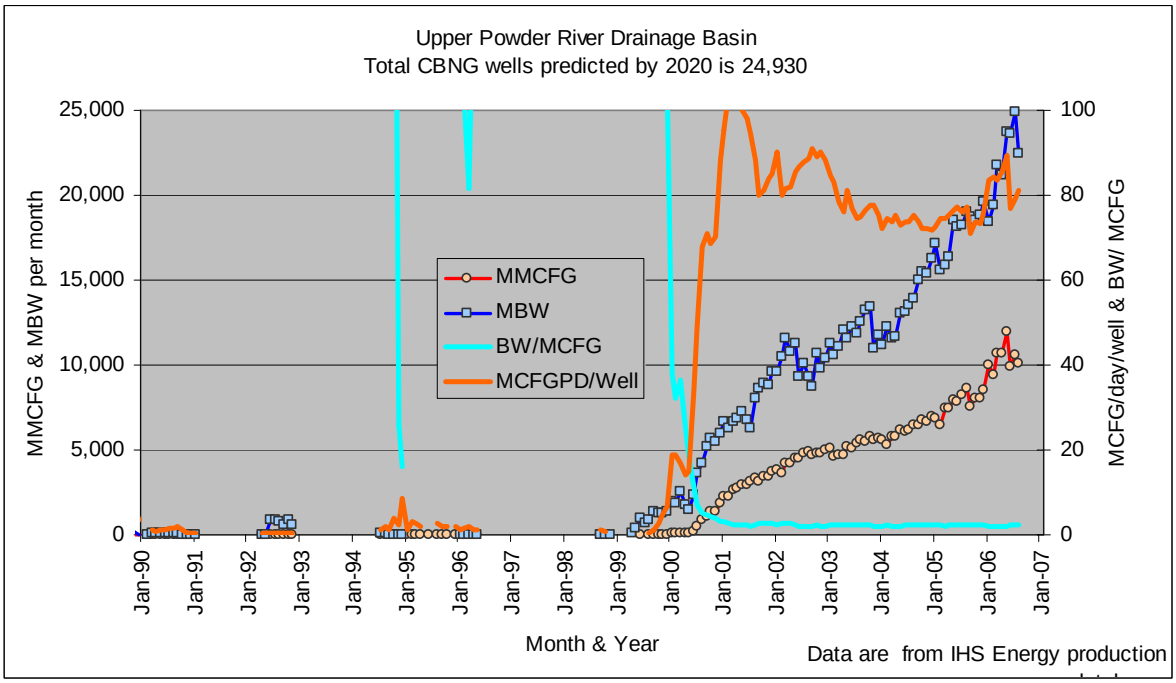


Figure 10b. Historical gas and water production, and average per well gas and water production for the Upper Powder River drainage basin. During 2001-2006 per well gas production has remained relatively constant even though total gas production has increased. Note that gas production per well has not yet begun to decline significantly.

to 4,036 in August 2006. It is interesting to note that during 2000 when the average gas production per well increased about ten fold, water production declined by half in a predictable pattern. The average gas production rate held relatively steady averaging 79 MCFG/day/well from September 2001 – August 2006 (see Figure 10b).

The number of producing wells will eventually stop increasing and begin to decline due to wells being shut-in because of low water and/or gas production rates. When this occurs, perhaps before, the average water production rate will almost certainly begin to decline. It is anticipated that the water production rate will hold steady to about 2010 then decline to approximately 4 gpm/well by 2015 and 2 gpm/well by 2020. This would be a 14 percent annual decline rate from 2015 to 2020.

Summary

Water and CBNG production data from the six drainage basins listed in Table 1 is variable and sometimes erratic. CBNG production and ratios of gas and water are not good indicators of average per well water pumpage rates within a drainage sub-basin. Pumpage rates often decline when the number of producing wells and gas production are increasing. By the time producing CBNG wells are about 10 to 20 percent of the total estimated number of wells that will be drilled pumpage rates are usually stable enough so that future rates can be predicted with reasonable certainty. In some areas pumpage rates stabilized earlier in the development history, however the lower levels of development may produce more uncertainty in estimates of future pumpage rates.

Fred Crockett 6-1-2007
Petroleum Geologist (WY PG-408), Casper, WY
BLM, Wyoming Reservoir Management Group-Wyoming State Office

Acronyms and Glossary

Acre feet — The amount of space occupied by an area of one acre (43,560 square feet) one foot deep. Water volumes are sometimes measured in acre feet.

Actual pumpage rate — As used in this report is the actual rate of water production from a well based on the actual days the well produced during the month. For example, if a well produced for only 10 days during the month of June and produced a total of 1,500 barrels of water, the actual pumpage rate would be 150 barrels per day (4.38 gallons/minute) but the nominal pumpage rate would be 50 barrels per day (1.46 gallons/minute).

API number--The American Petroleum Institute (API) number is a unique eleven digit number assigned to each wellbore. It is based on state, county, and a sequential well number. It is sometimes displayed as a hyphenated number (state-county-well number).

BW — Barrel of water, one barrel contains 42 gallons.

CBNG — Coalbed natural gas, also known as coalbed methane (CBM).

Economic limit — The minimum amount of gas production from a well required to provide enough cash flow to pay the operating cost and royalty expenses for that well.

EUR -- Estimated ultimate recovery of natural gas and/or crude oil for a specific well or group of wells.

gpm — Gallon per minute, a standard measurement of water production from wells.

MBW — Thousand barrels of water

MCFG — Thousand cubic feet of natural gas, MCF is a standard unit of measurement for natural gas usually at one atmosphere (14.7 psi) and 60°F.

MMCFG — Million cubic feet of natural gas.

Nominal pumpage rate — As used in this report is the rate of water production from a well or group of wells assuming all the wells produced for every day during the month.

Spud — To begin drilling, or when the drill bit begins to drill below the earth's surface.

WOGCC — Wyoming Oil and Gas Conservation Commission, a state of Wyoming agency that regulates oil and gas production

References

Braz, Norman, 2007, Geologist, solid minerals, Casper Wyoming BLM Field Office, personal communication.

ENSR, 2005, Powder River Basin Coal Review-Task 2, Preliminary Results, April 2005.

IHS Energy Group, 2006 & 2007, Petroleum Information/Dwights production and well databases on CD ROM.

Karbs, Mike, 2006, Assistant Field Manager Solid Minerals, Casper Wyoming BLM Field Office, written communication.

Thompson, Robert, S. and John D. Wright, 1985, Oil Property Evaluation, Thompson-Wright Associates, P.O. Box 892, Golden, Colorado 80402.

U.S. Geological Survey, 1999, Professional Paper No. 1625, Resource assessment of Selected Tertiary Coal Beds and Zones in the Northern Rocky Mountains and great Plains Region, on CD ROM, Chapters

Wyoming Oil and Gas Conservation Commission, 2007, online data.

Appendix A

Estimates of future pumpage rates may be calculated by using the two equations listed below. Estimates are based on production history and decline rates. Such estimates may be problematic however. Figure A-1 shows pumpage rates for a two-township area in the Powder River Basin. In this area the coalbed gas potential has been fully developed. The area has been referred to as the Fairway area and Marquis-Lighthouse area.

Erratic pumpage rates often occur during early stages of coalbed gas development in a drainage basin. It is difficult to determine when and at what rate the pumpage will stabilize. Before rates stabilize at a more or less constant level, there is a decline period during which pumpage rates decrease in a more or less predictable way. Once this decline begins, rates can be predicted by the equations shown below. The historical rate q_i (initial pumpage rate, usually the last month for which there is reliable date) can be used to predict a future rate q, if the rate of decline is known. If a monthly pumpage rate is calculated, a decline curve can be constructed.

Exponential decline: $q = q_i e^{-at}$

Hyperbolic decline: $q = q_i (1 + b\, a_i\, t)^{-1/b}$

The two decline equations listed above are commonly used in the oil and gas industry. The variables are:

- q_i-initial production rate,
- q-the production rate you wish to determine at some time after q_i,
- a-the decline rate for a specific time period (time periods must be consistent),
- t-the time period for the decline rate a (for example 20%/year) and
- b-a factor based on rock and fluid properties (generally the less permeable the reservoir rocks the higher the b value).

For a more complete discussion of decline curve analysis the reader is referred to Thompson and Wright (1985) or any good petroleum property evaluation text. Figures A-2 and A-3 show that the projected pumpage rates and resultant water production are relatively insensitive to the type of decline curve used. A convenient way of displaying data is on a semi log plot as shown in figures three and four. Exponential declines will form a straight line on semi log plots. In the examples shown, which used the same data as Figure 3, the difference between projections based on exponential and hyperbolic declines are shown. Although significant, the use of different decline equations is relatively minor compared to selecting the wrong starting point for the decline. In this illustration a two stage approach was used. A decline rate of 45 percent/year was used until the average pumpage rate reached two gallons/minute. Then the decline rate was changed to 10 percent/year. This two stage approach more closely approximates the actual average pumpage rates observed. During the time period shown in Figures two, three, and four the number of producing wells increased from 1 to 730 then declined to about 300. The maximum number of producing wells occurred in September 2001. Figure 2 shows the percent of wells drilled. The estimated total number of wells is based on well spacing as provided by the WOGCC. In the case of the two townships reviewed in this appendix, it was assumed that every spacing unit will be drilled. In some drainage basins estimated drilling will not cover the entire drainage basin.

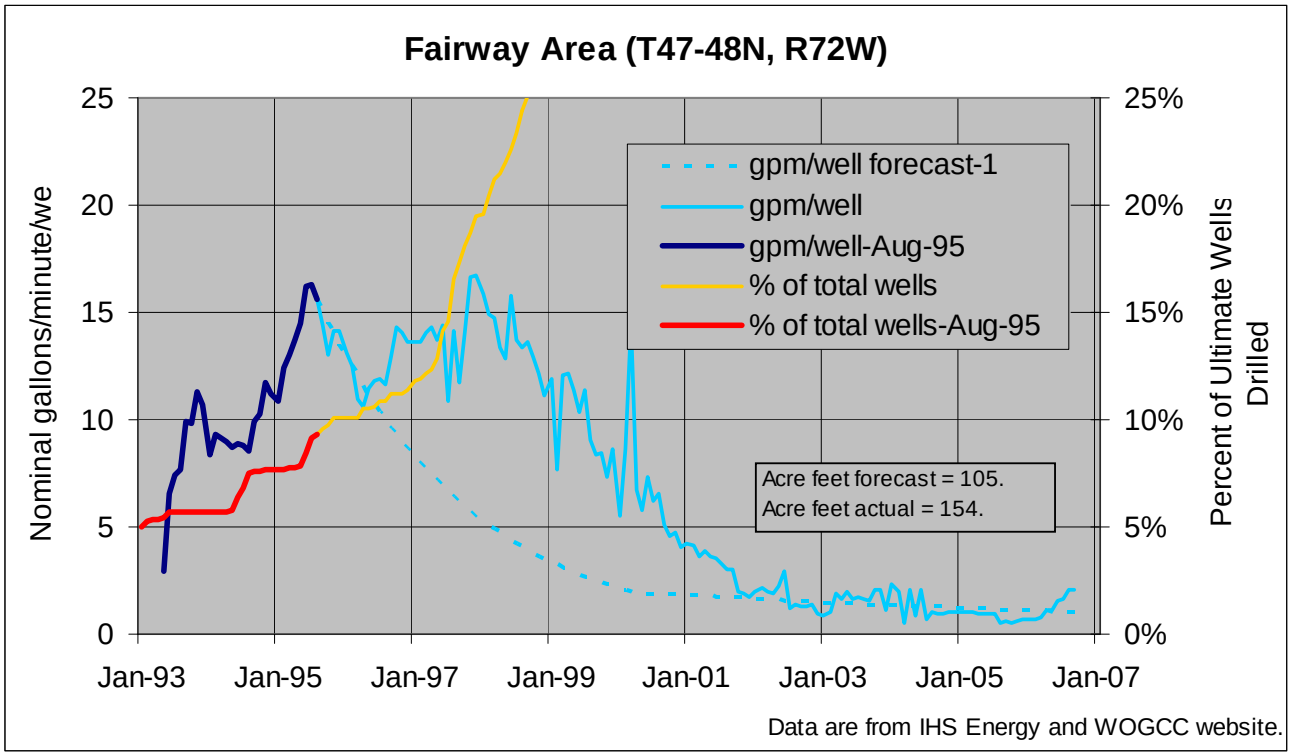


Figure A-1. Graph of the average pumpage rate in nominal gallons/minute for the Fairway area. An estimate of future rates is shown based on the assumption that the maximum rate was reached in August 1995. This assumption is in error. The resultant total per-well estimated water production through September 2006 would be only 68 percent of what actually was produced.

Exponential decline usually occurs in highly permeable strata such as the majority of Powder River Basin coals. The hyperbolic decline equation is used for less permeable rocks such as may occur in deeper horizons of the Powder River Basin and in other intermountain basins. The hyperbolic decline equation is of little use when calculating estimates for most Powder River Basin coals. When using this method to predict pumpage rates, it is important to keep units consistent. Production exhibiting exponential decline in a well will form a more or less straight line on a semi log graph. Production exhibiting hyperbolic decline will form a curved line on a semi log graph. When using the hyperbolic decline equation it is necessary to recalculate the decline rate a for each time period (day, month, year, etc.). The decline rate can be determined by the equation:

$$a = \ln(q_i/q)$$

where q_i and q are the initial and final rates over a time period.

Application of this method of estimating pumpage rates is almost always complicated by the difficult task of selecting a point on the pumpage rate graph where decline begins. If a decline is projected too soon the quantity of water withdrawn may be significantly underestimated. Examples from the Fairway area are shown below. In Figure A-2 the exponential decline formula was used to forecast the average pumpage rate. An annual decline rate of 45 percent was used until the pumpage rate was two gallons/minute then it was changed to 10 percent. Figure A-1 is a linear plot therefore the projected pumpage rate decline is a curved line. Figure A-1 shows how critical it is to calculate a projected decline rate only after the average pumpage rate has started to decline. In August 1995 only nine percent

of the total wells had been drilled. By January 1998 twenty percent of the wells had been drilled and the projected pumpage rates are much more accurate. The reader is urged to use this method with great caution. The reader should also remember that during the time period shown in Figure A-2 the number of producing CBNG wells changed substantially (see Figure 3c).

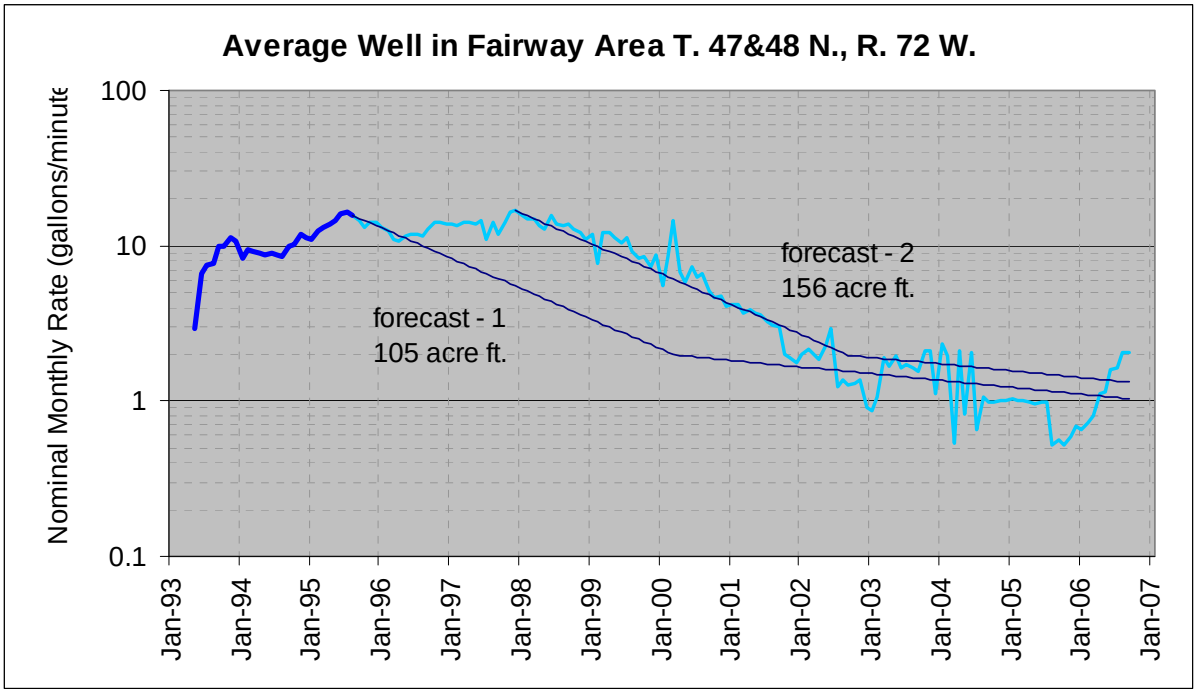


Figure A-2. This figure shows a two stage exponential decline to project future average pumpage rates. A two stage decline was used. An initial rate of 45 percent/year was used until the average pumpage rate reached two gallons/minute. Then the rate was changed to 10 percent/year. This two stage approach more closely approximates the actual average pumpage rates observed in the Fairway area. As pumpage rates decline to about one gallon/minute the decline rate may need to be reduced to zero.

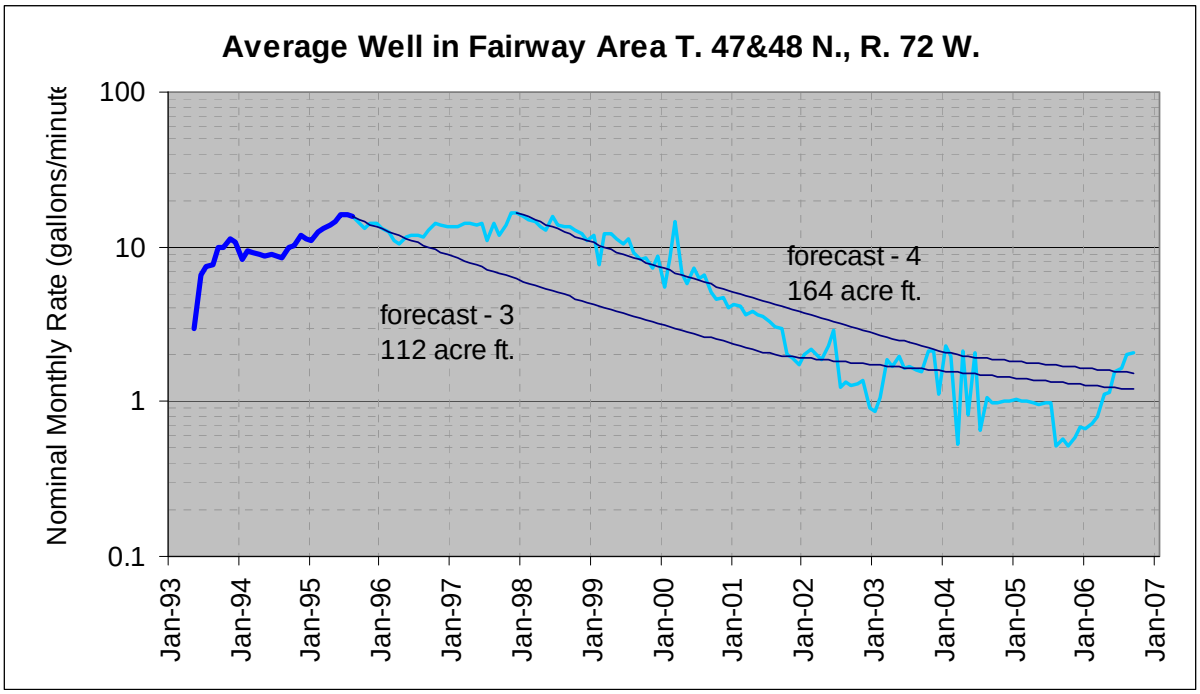
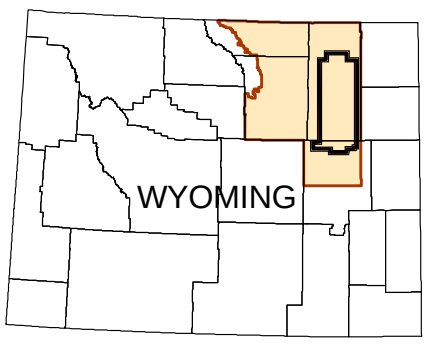


Figure A-3. This figure shows how the hyperbolic equation predicts future average pumpage rates. A two stage decline was used. An initial stage starts with a decline rate of 45 percent/year and a hyperbolic decline was used until the average pumpage rate reached two gallons/minute. Then the rate was changed to an exponential rate of 10 percent/year. This two stage approach more closely approximates the actual average pumpage rates observed in the Fairway area.

APPENDIX B

FIGURES SHOWING CMGM RESULTS



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

Groundwater level contours (Range = 4000 to 5050 feet)

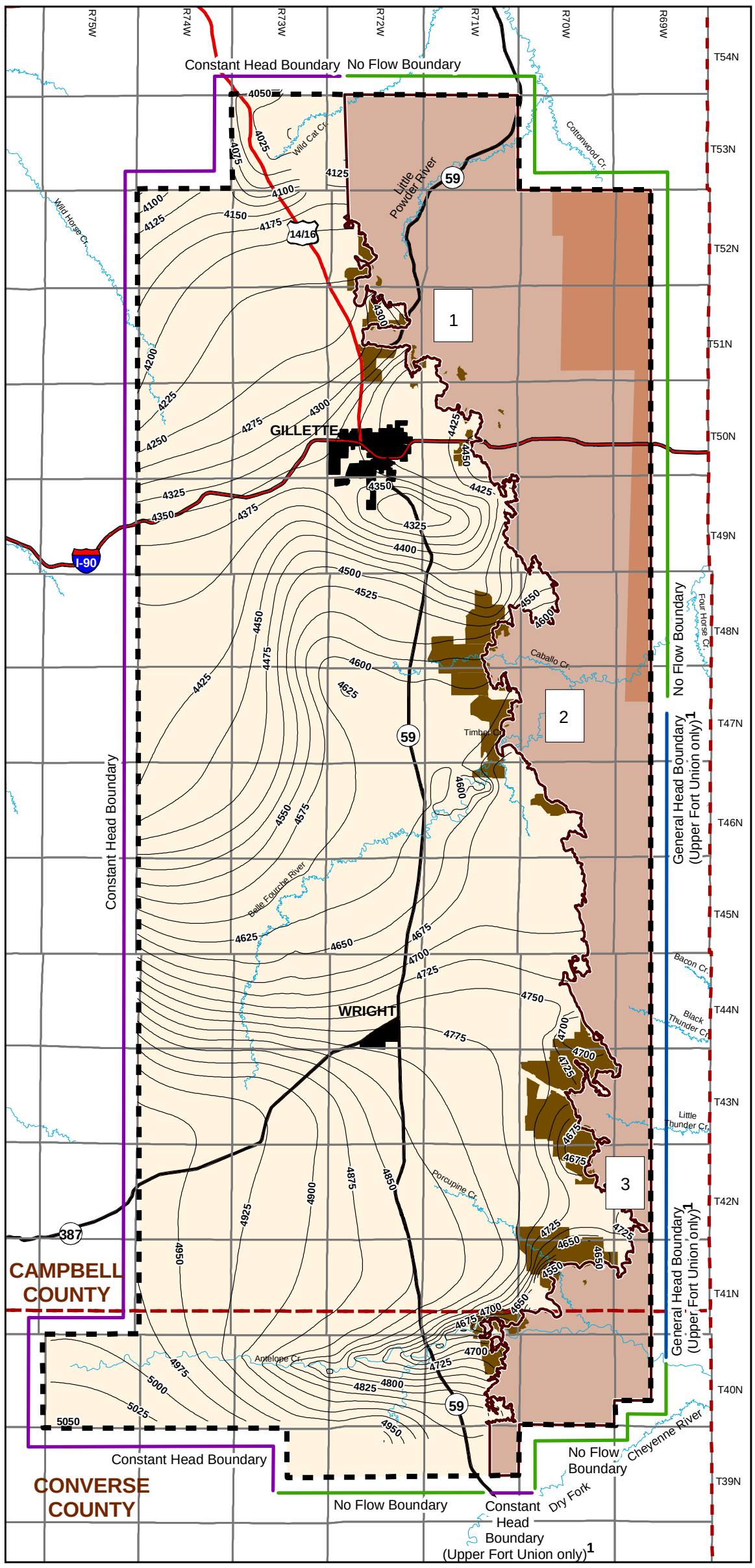
Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

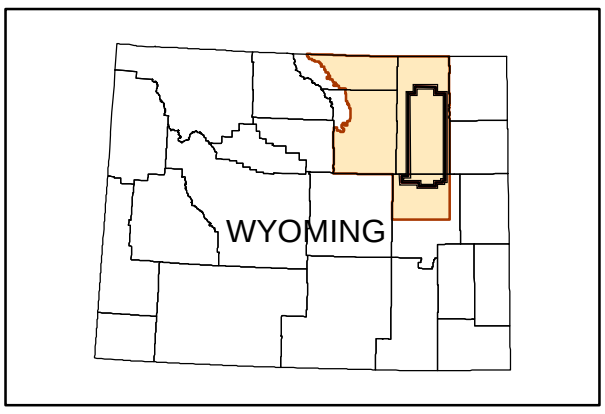
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-1

2010 Water Levels
Wasatch Formation

11/01/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 10 feet

- Groundwater drawdown level contours

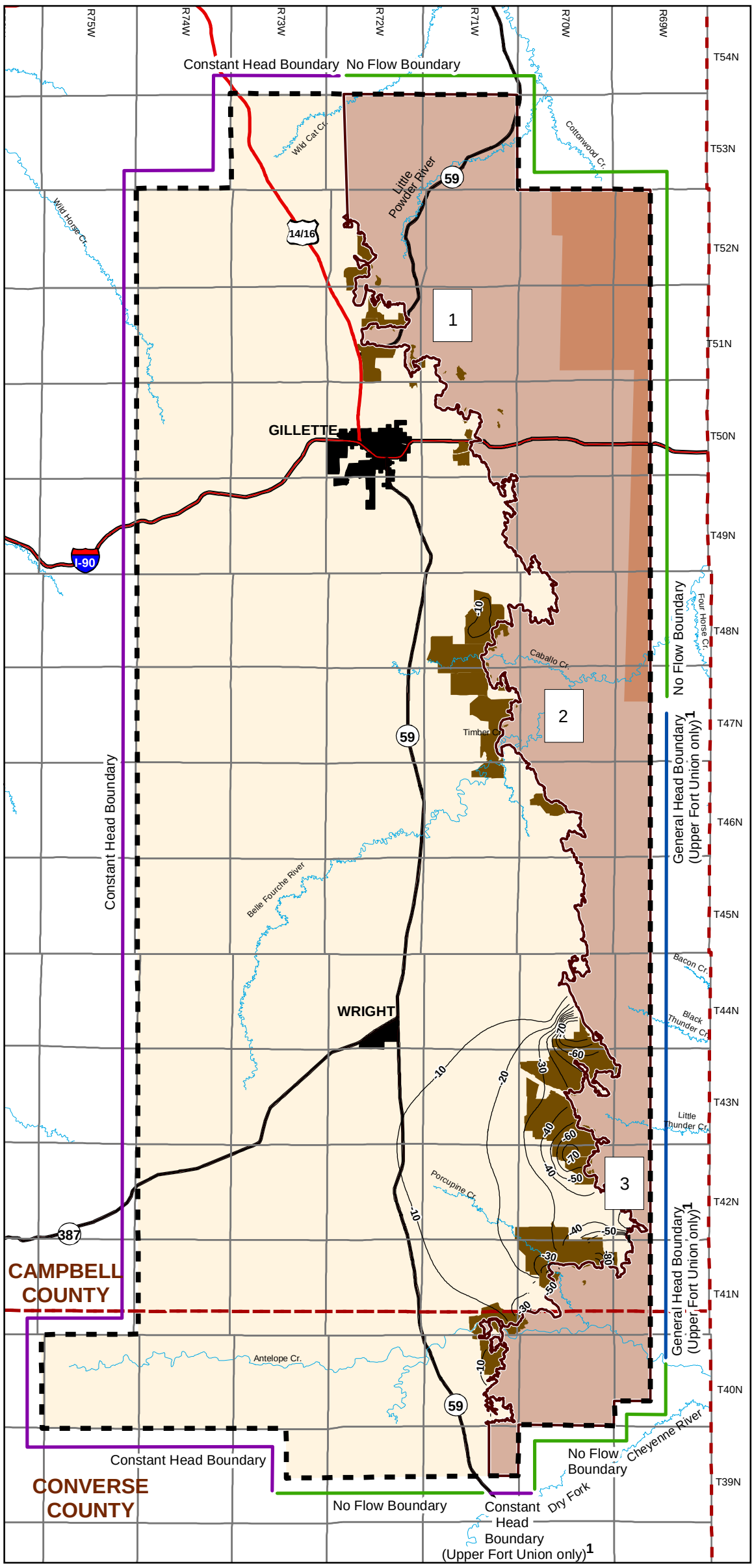
Coal Mine Subregions

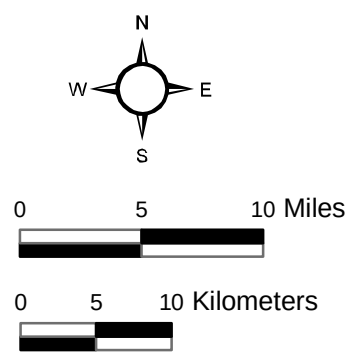
1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine groundwater pumping.





[1]Boundary condition is No Flow Boundary for all other layers.

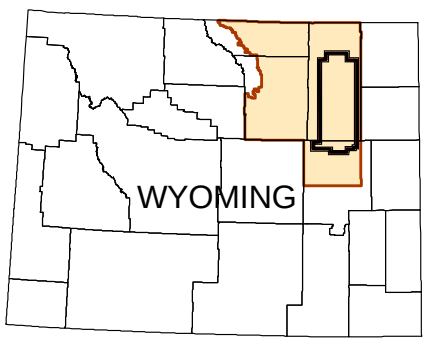
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-2

Wasatch Formation
1990 Base Year/2010 Prediction
Coal Mine-related
Groundwater Level Changes

12/12/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

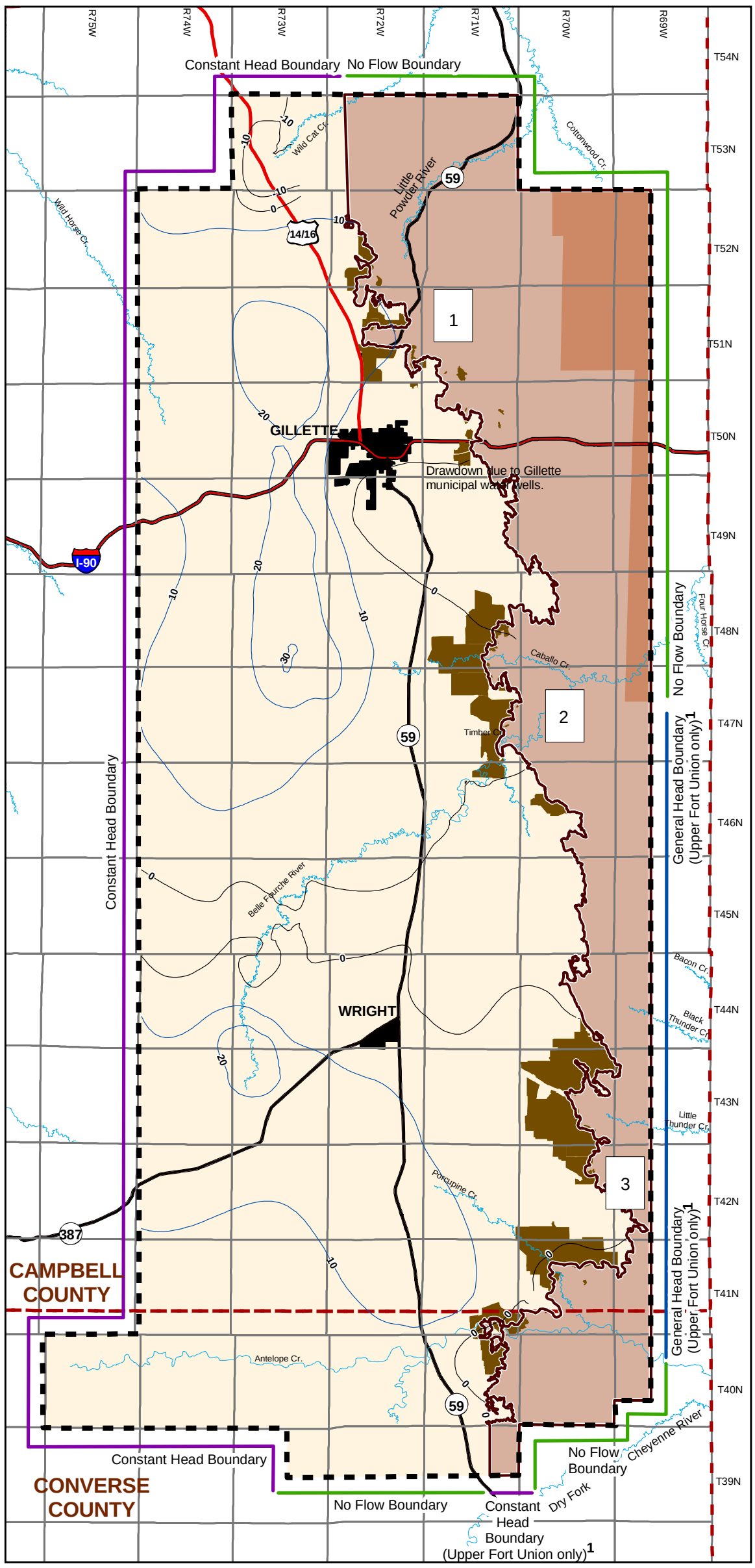
Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of CBNG groundwater pumping and water discharge.



[1]Boundary condition is No Flow Boundary for all other layers.

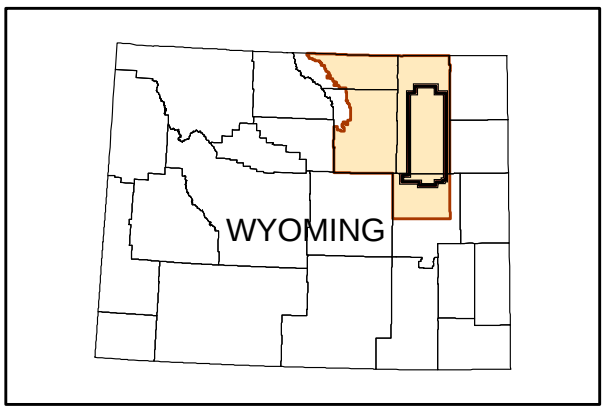
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-3

Wasatch Formation
1990 Base Year/2010 Prediction
CBNG-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

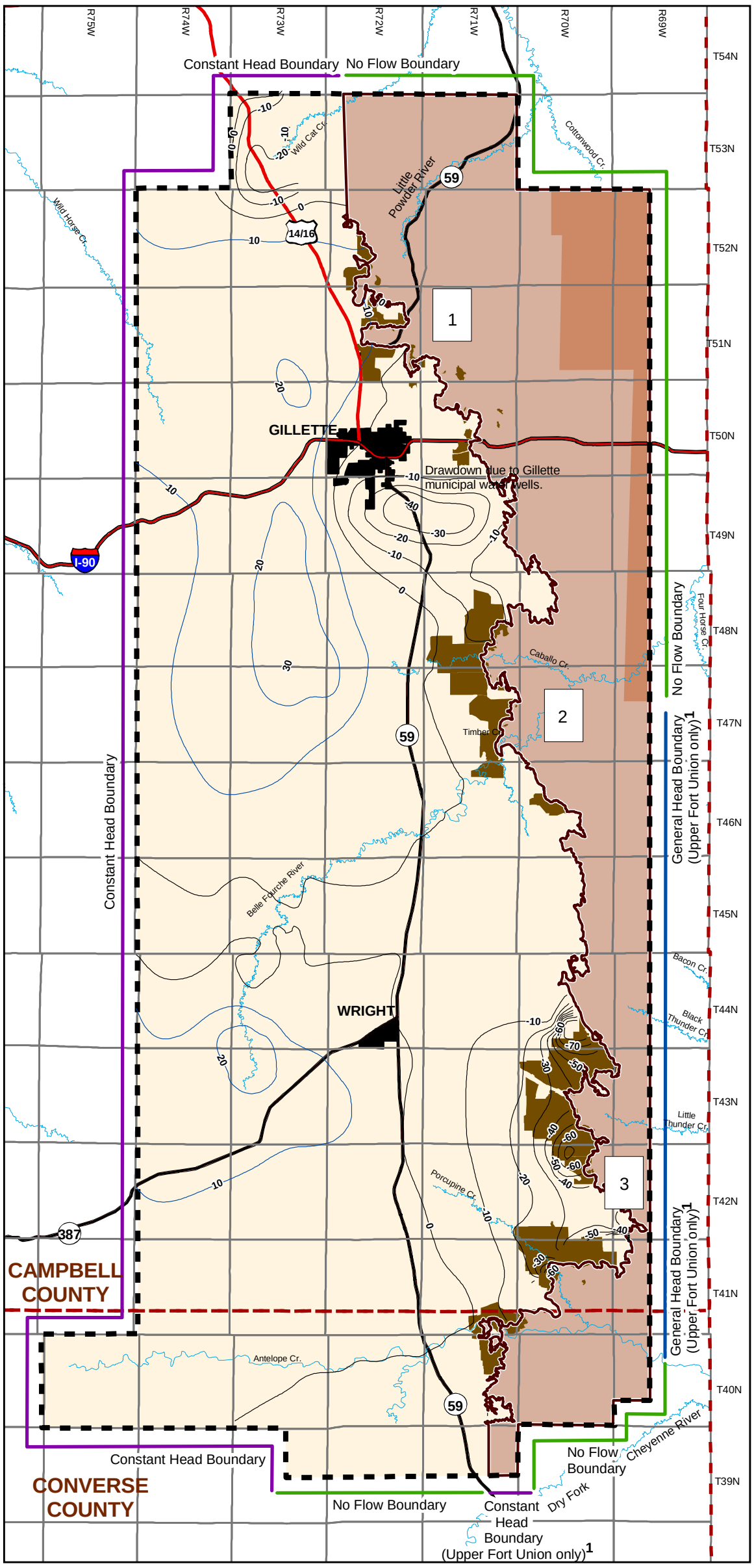
Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

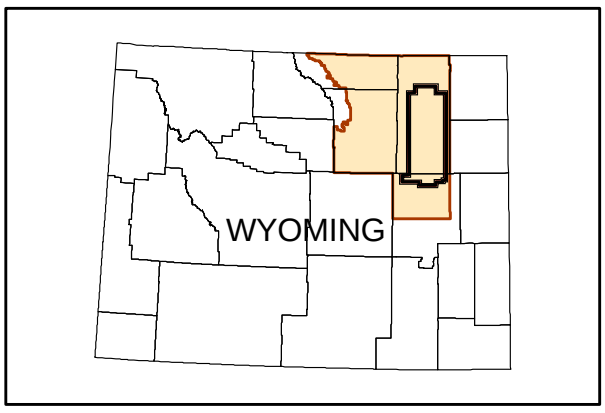
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-4

Wasatch Formation
1990 Base Year/2010 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/01/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

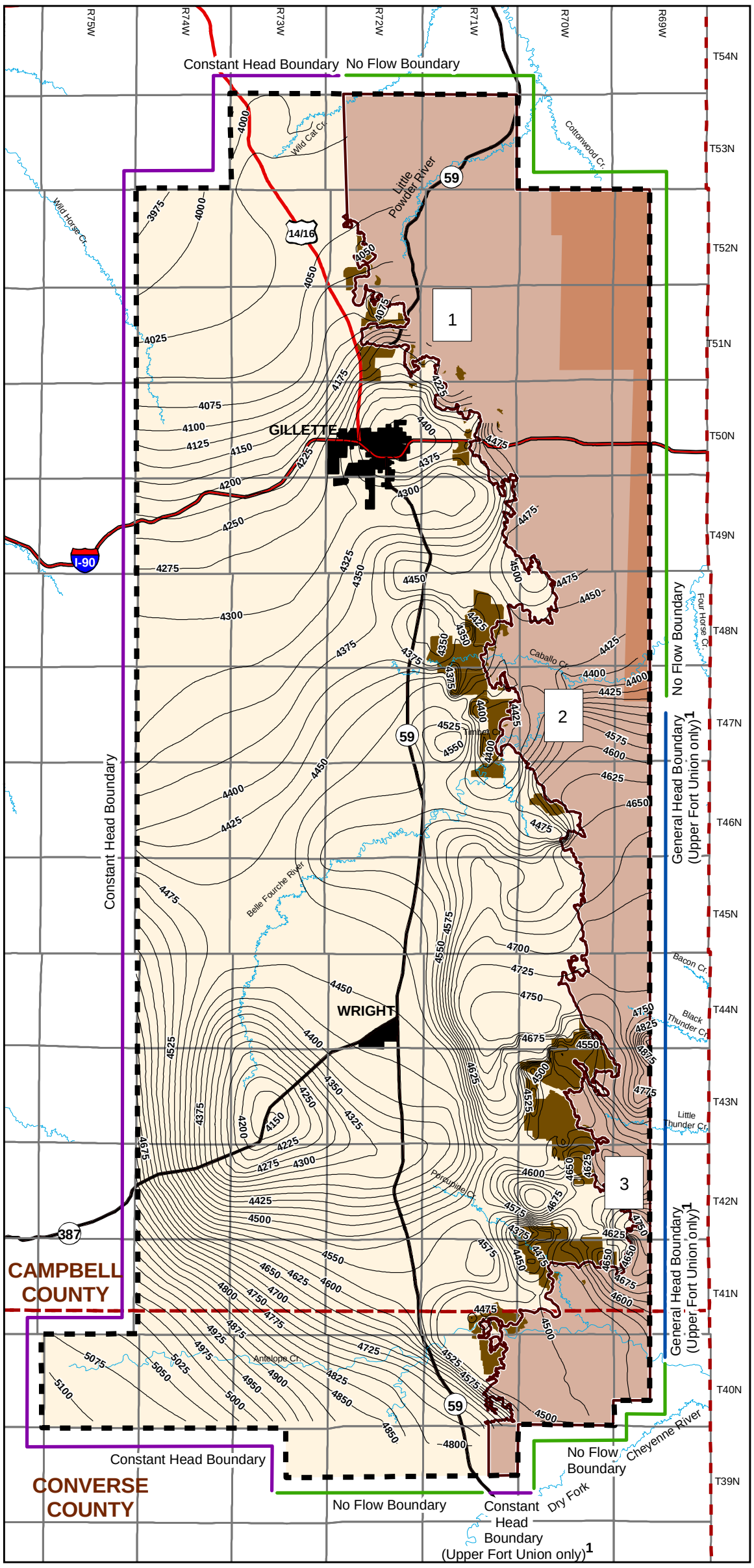
Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

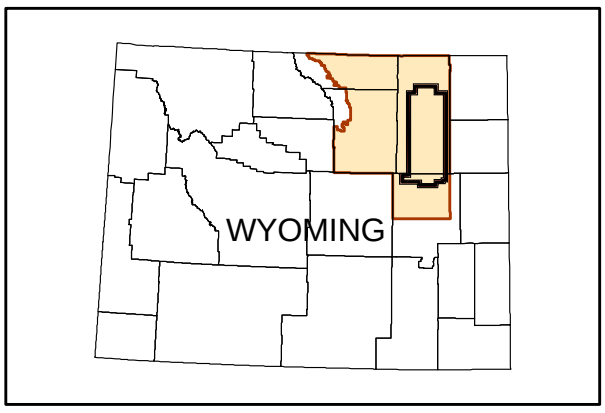
Source: BLM 2009a, b.

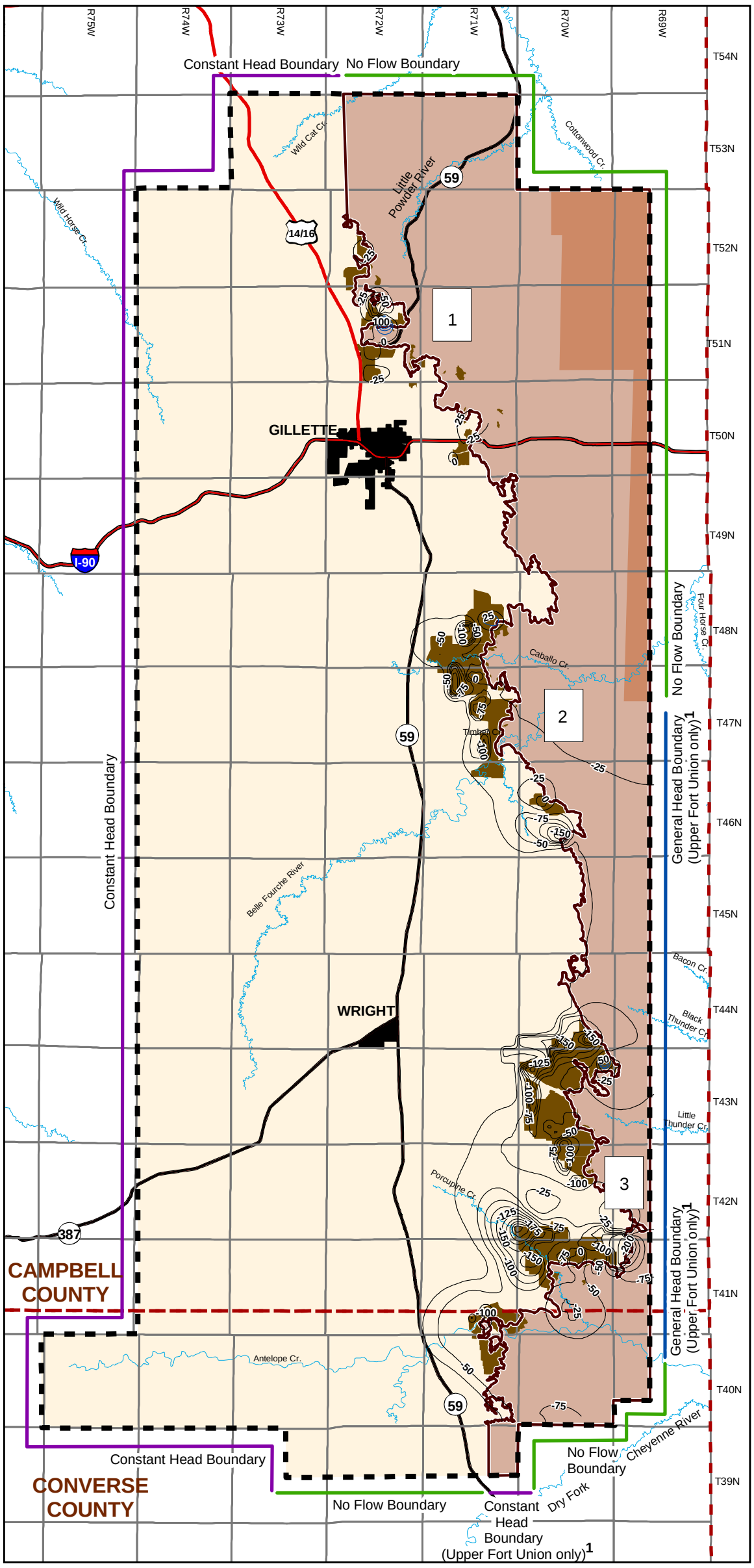
Powder River Basin Coal Review

Figure B-5

2010 Water Levels
Upper Fort Union Formation

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine groundwater pumping.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

Powder River Basin Coal Review

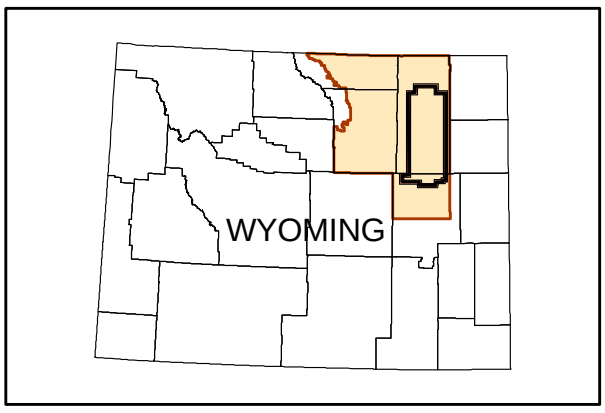
Figure B-6

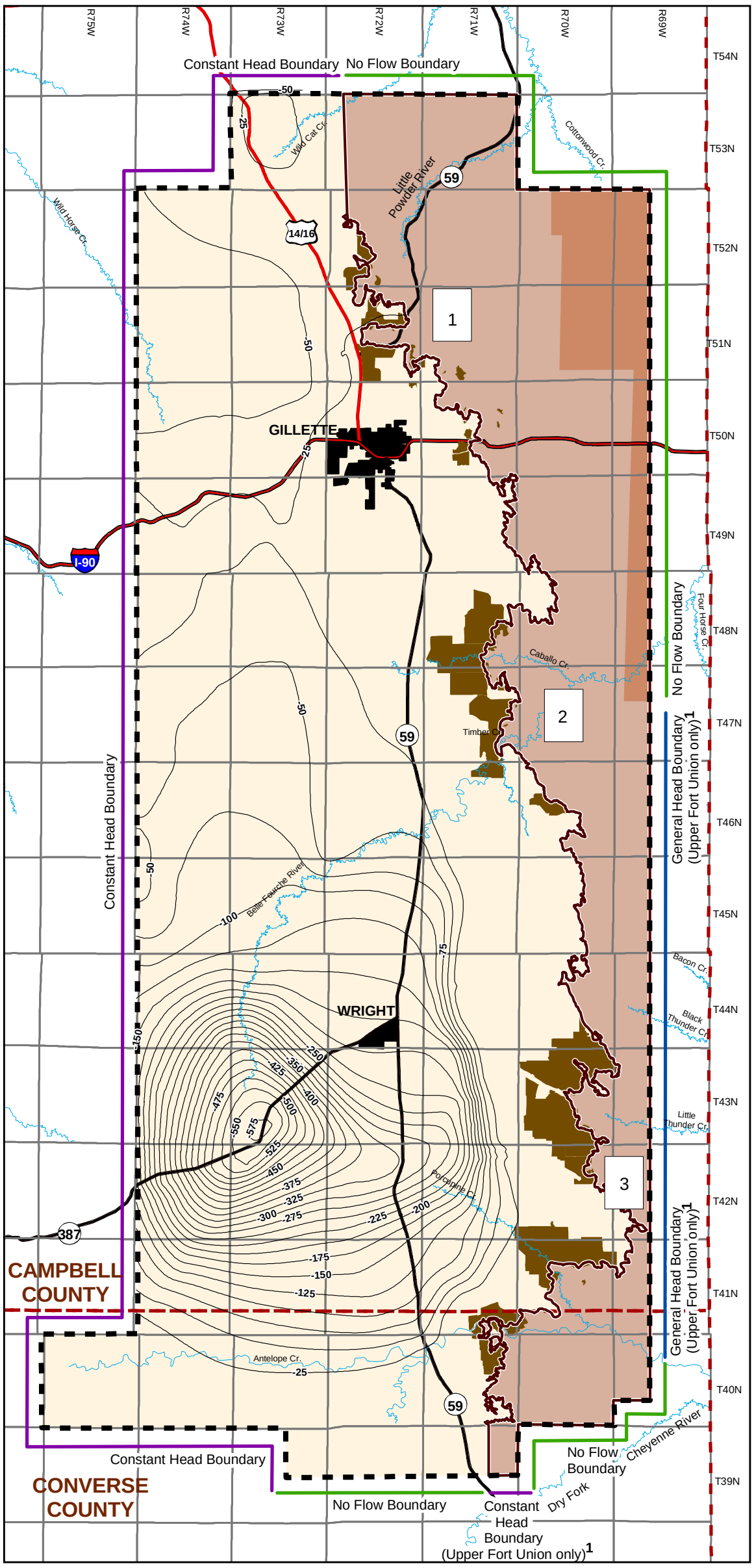
Upper Fort Union Formation
1990 Base Year/2010 Prediction
Coal Mine-related
Groundwater Level Changes

[1]Boundary condition is No Flow Boundary for all other layers.

Source: BLM 2009a, b.

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of CBNG groundwater pumping and water discharge.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

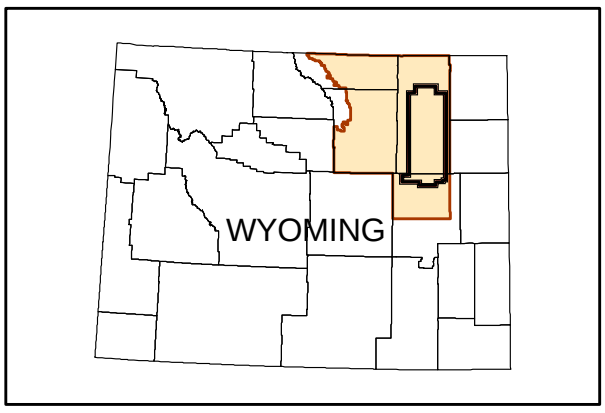
Source: BLM 2009a, b.

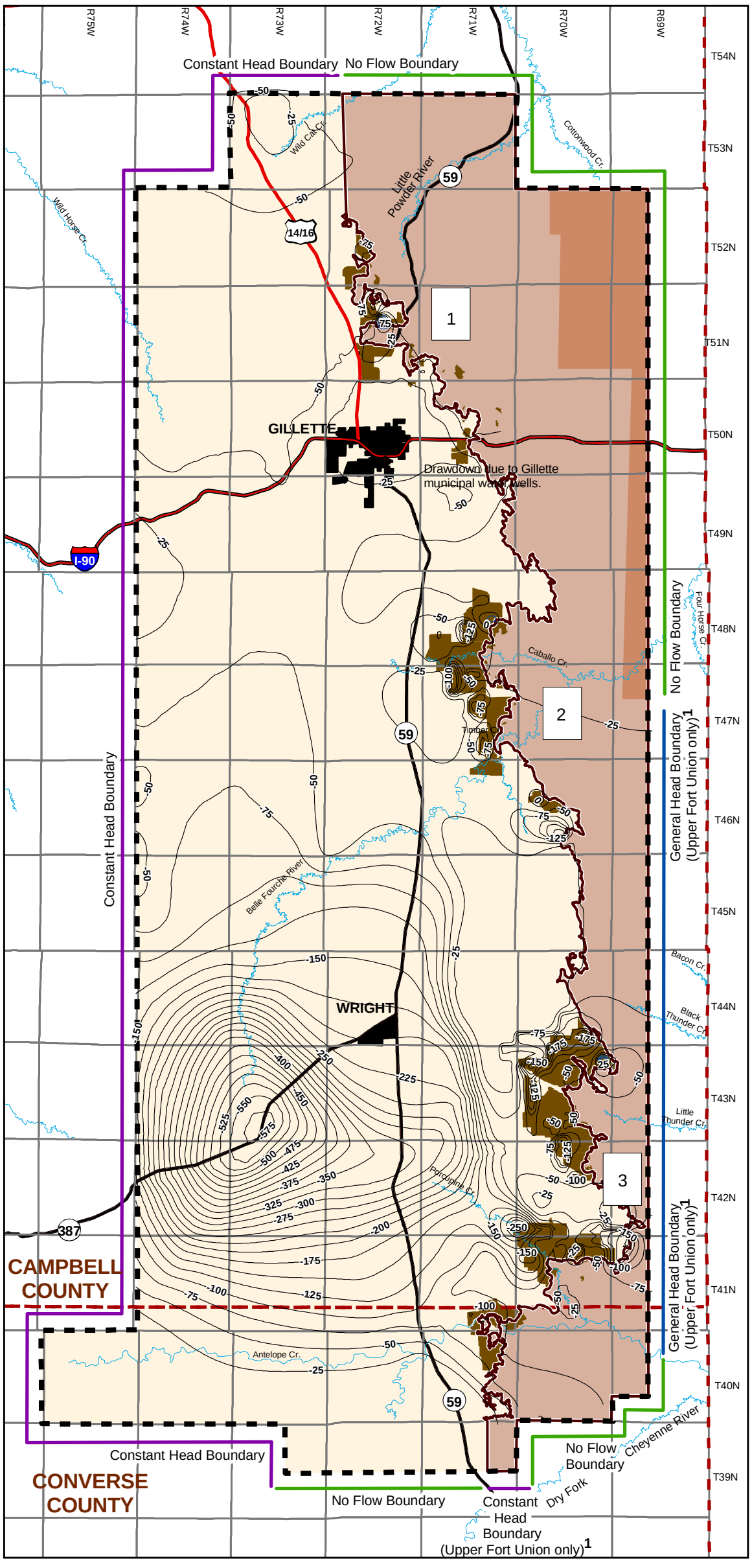
Powder River Basin Coal Review

Figure B-7

Upper Fort Union Formation
1990 Base Year/2010 Prediction
CBNG-related
Groundwater Level Changes

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N W E S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

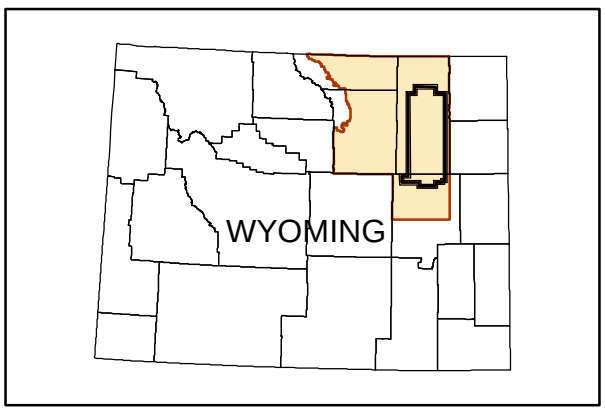
Source: BLM 2009a, b.

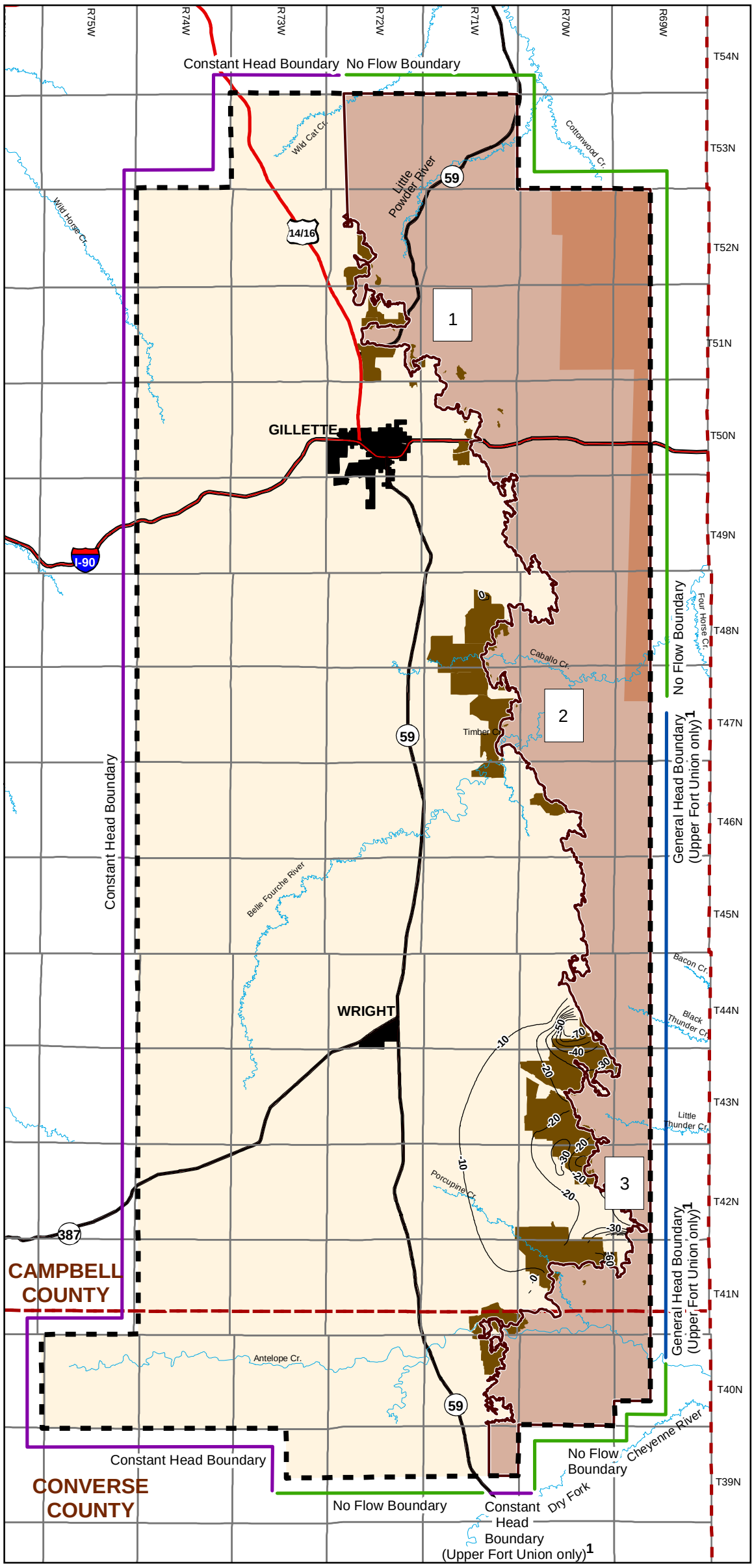
Powder River Basin Coal Review

Figure B-8

Upper Fort Union Formation 1990 Base Year/2010 Prediction Coal Mine- and CBNG-related Groundwater Level Changes

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 10 feet

- Groundwater drawdown level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine groundwater pumping.

N W E S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

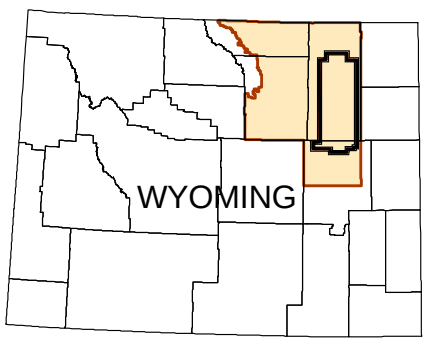
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-9

Wasatch Formation
2002 Base Year/2010 Prediction
Coal Mine-related
Groundwater Level Changes

12/12/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

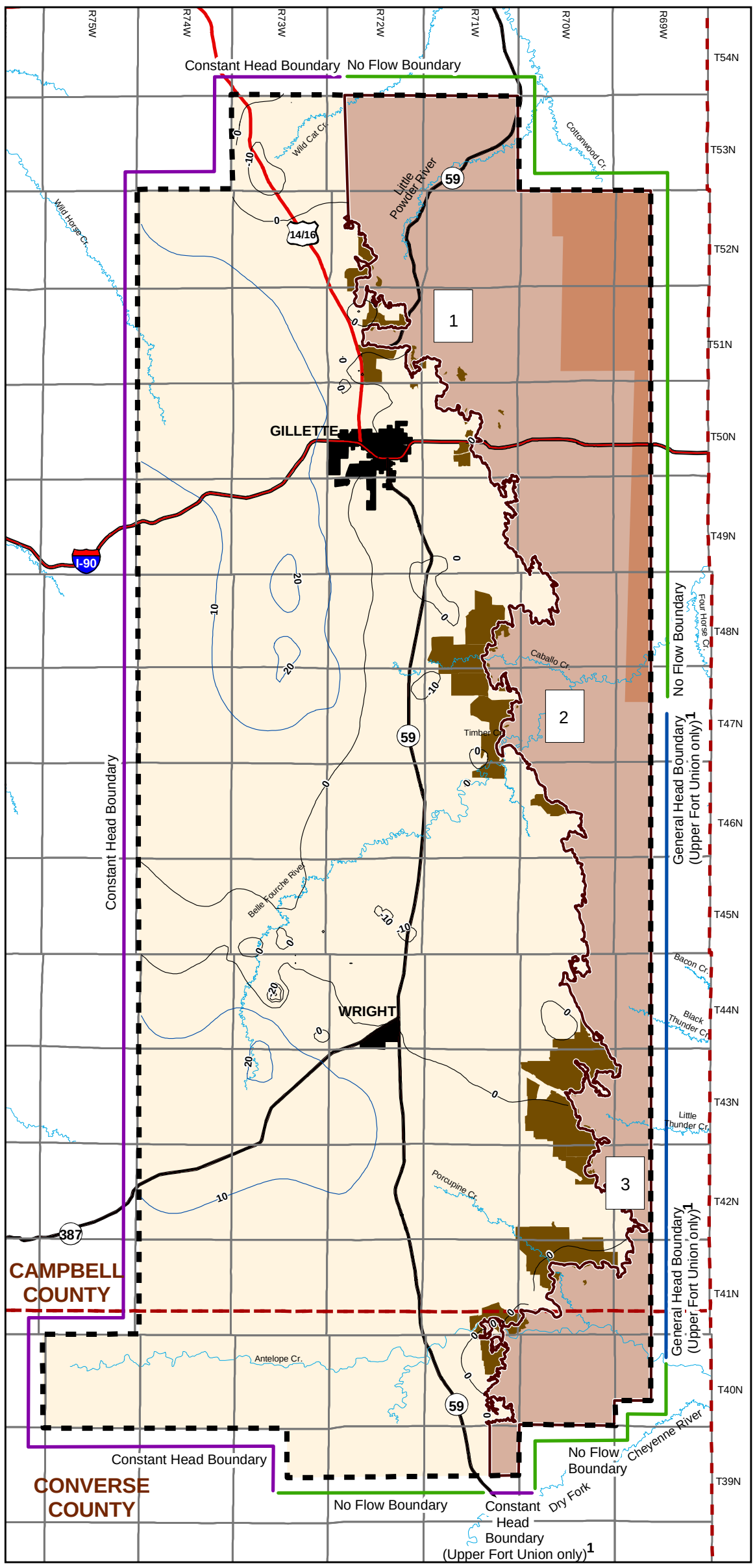
Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of CBNG groundwater pumping and water discharge.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

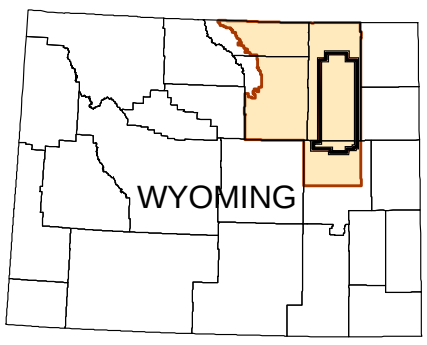
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-10

Wasatch Formation
2002 Base Year/2010 Prediction
CBNG-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

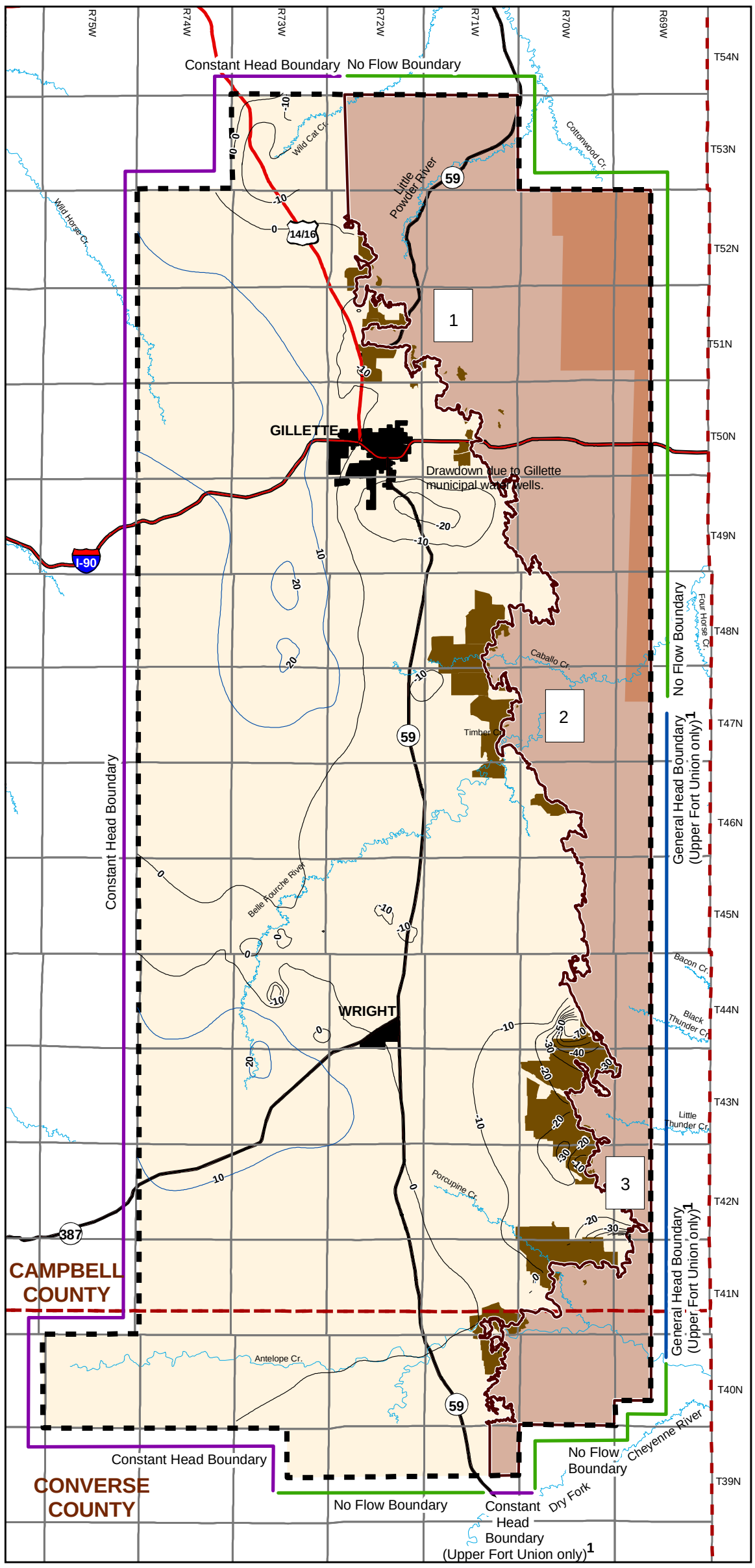
Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

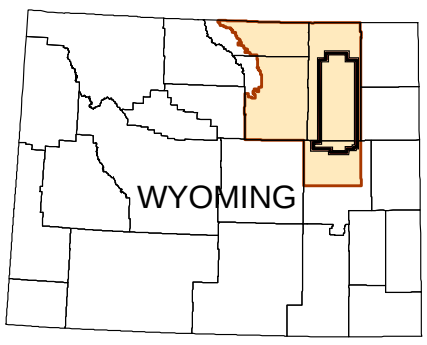
Source: BLM 2009a, b.

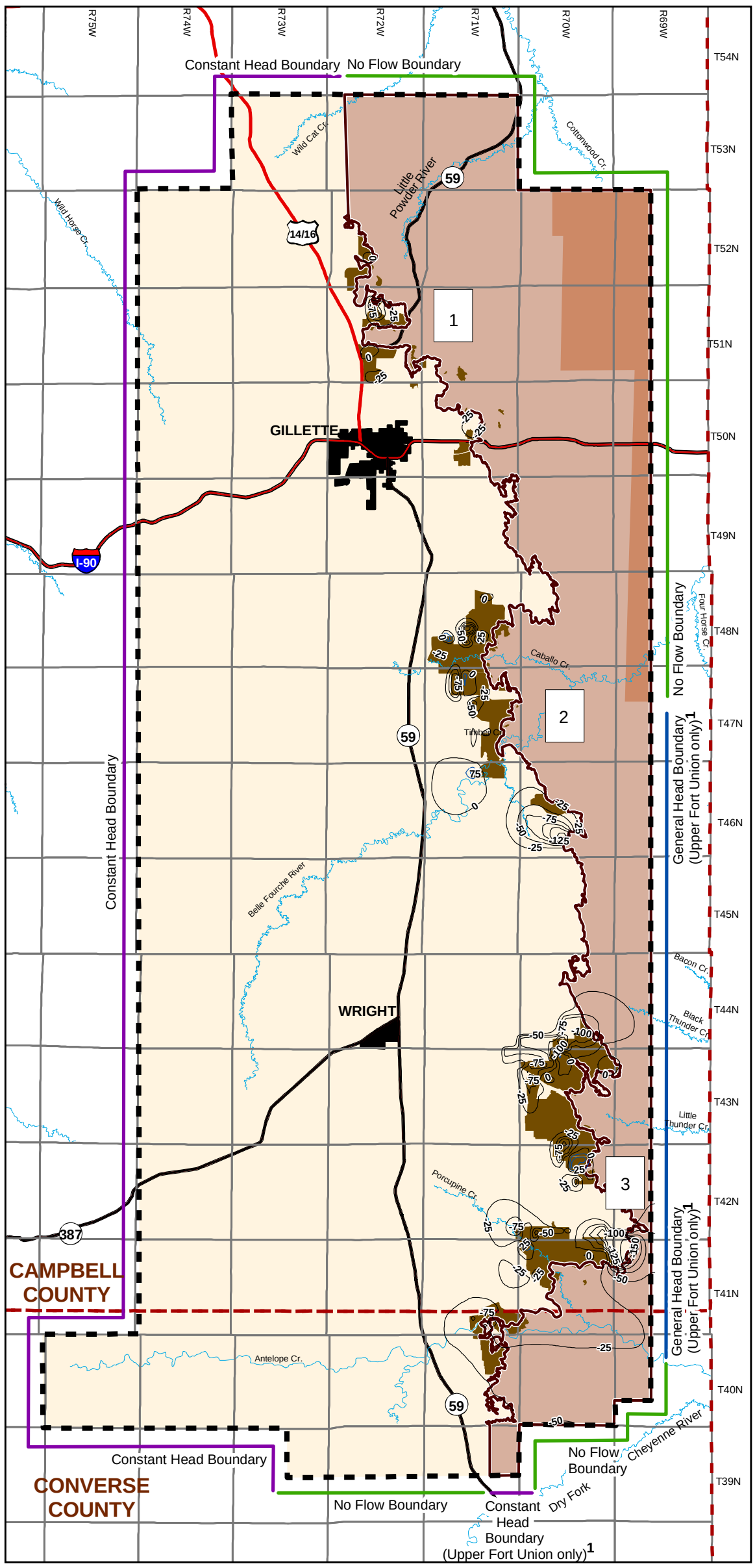
Powder River Basin Coal Review

Figure B-11

Wasatch Formation
2002 Base Year/2010 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine groundwater pumping.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N W E S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

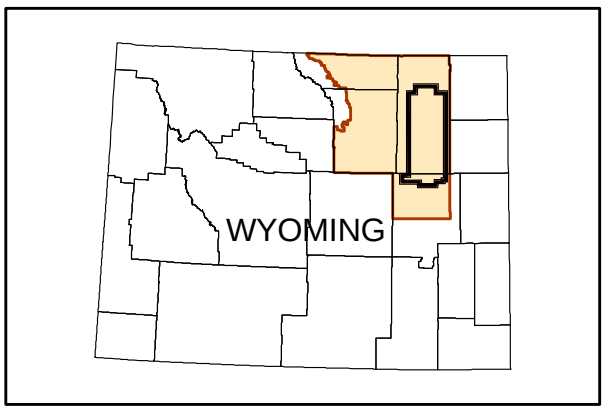
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-12

Upper Fort Union Formation
2002 Base Year/2010 Prediction
Coal Mine-related
Groundwater Level Changes

11/01/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

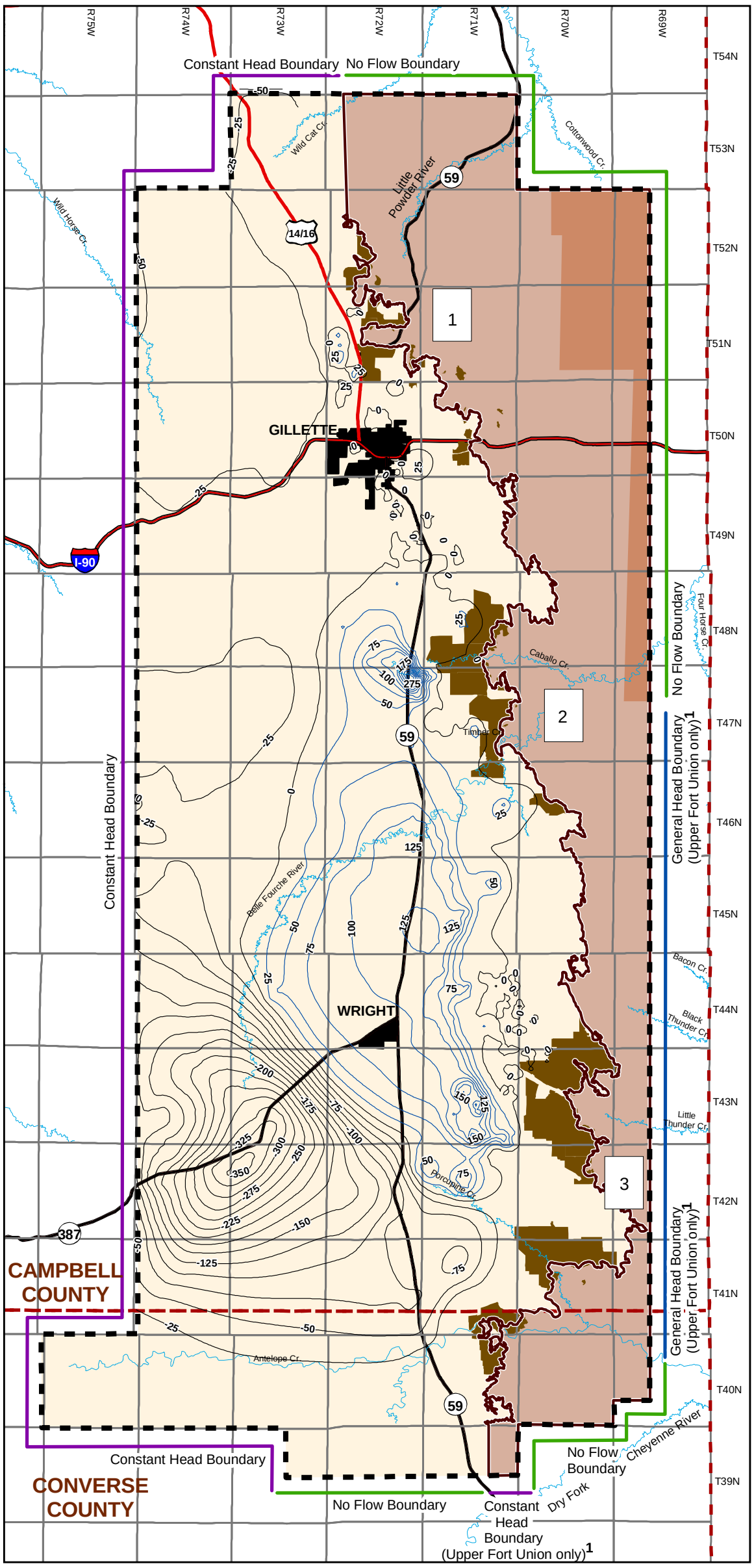
Coal Mine Subregions

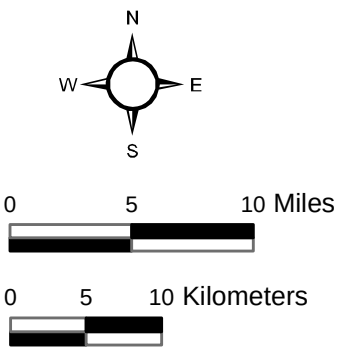
1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of CBNG groundwater pumping and water discharge.





[1]Boundary condition is No Flow Boundary for all other layers.

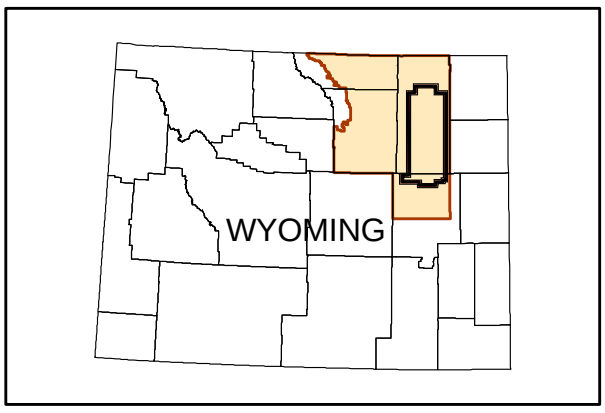
Source: BLM 2009a, b.

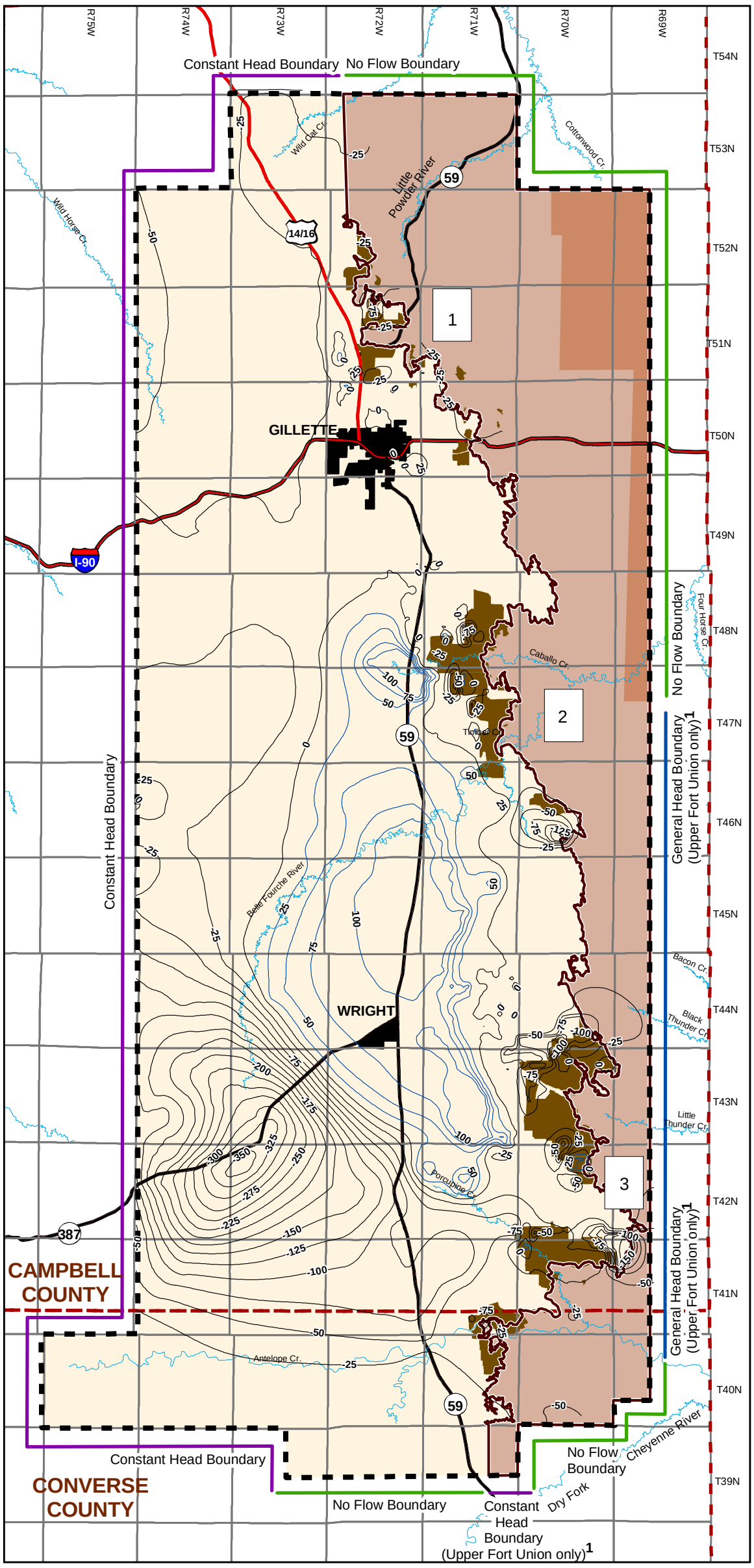
Powder River Basin Coal Review

Figure B-13

Upper Fort Union Formation
2002 Base Year/2010 Prediction
CBNG-related
Groundwater Level Changes

11/01/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

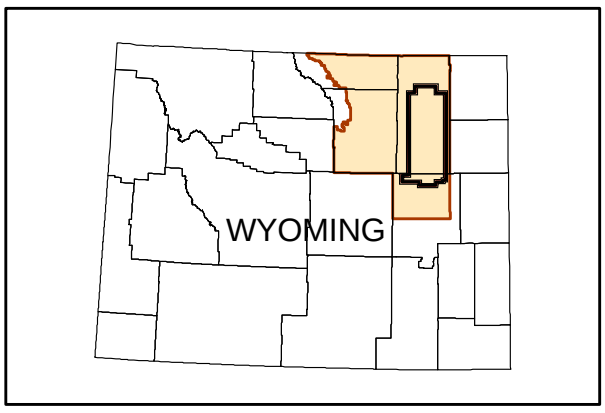
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-14

Upper Fort Union Formation
2002 Base Year/2010 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/01/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

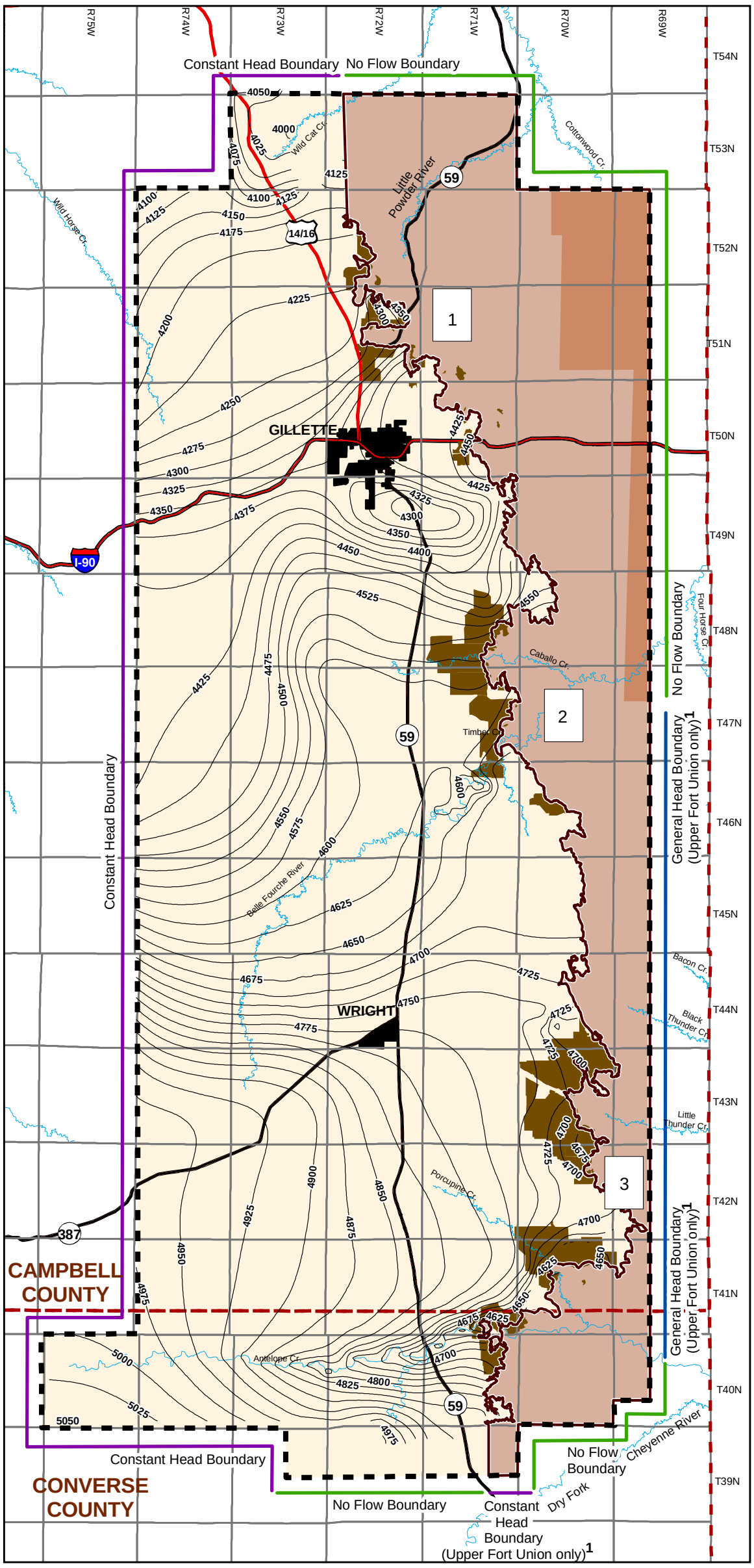
Coal Mine Subregions

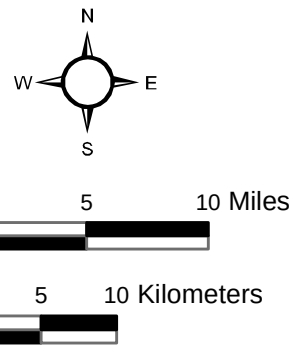
1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.





[1]Boundary condition is No Flow Boundary for all other layers.

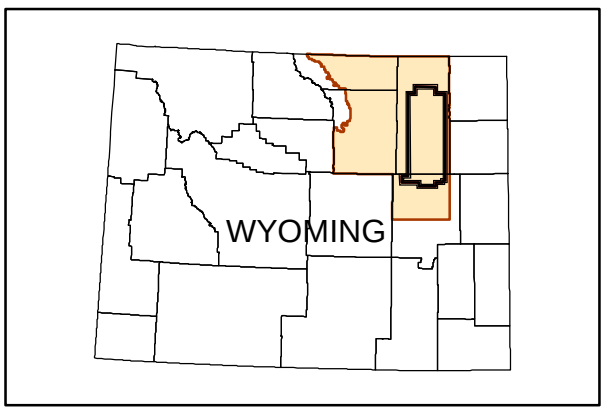
Source: BLM 2009a, b.

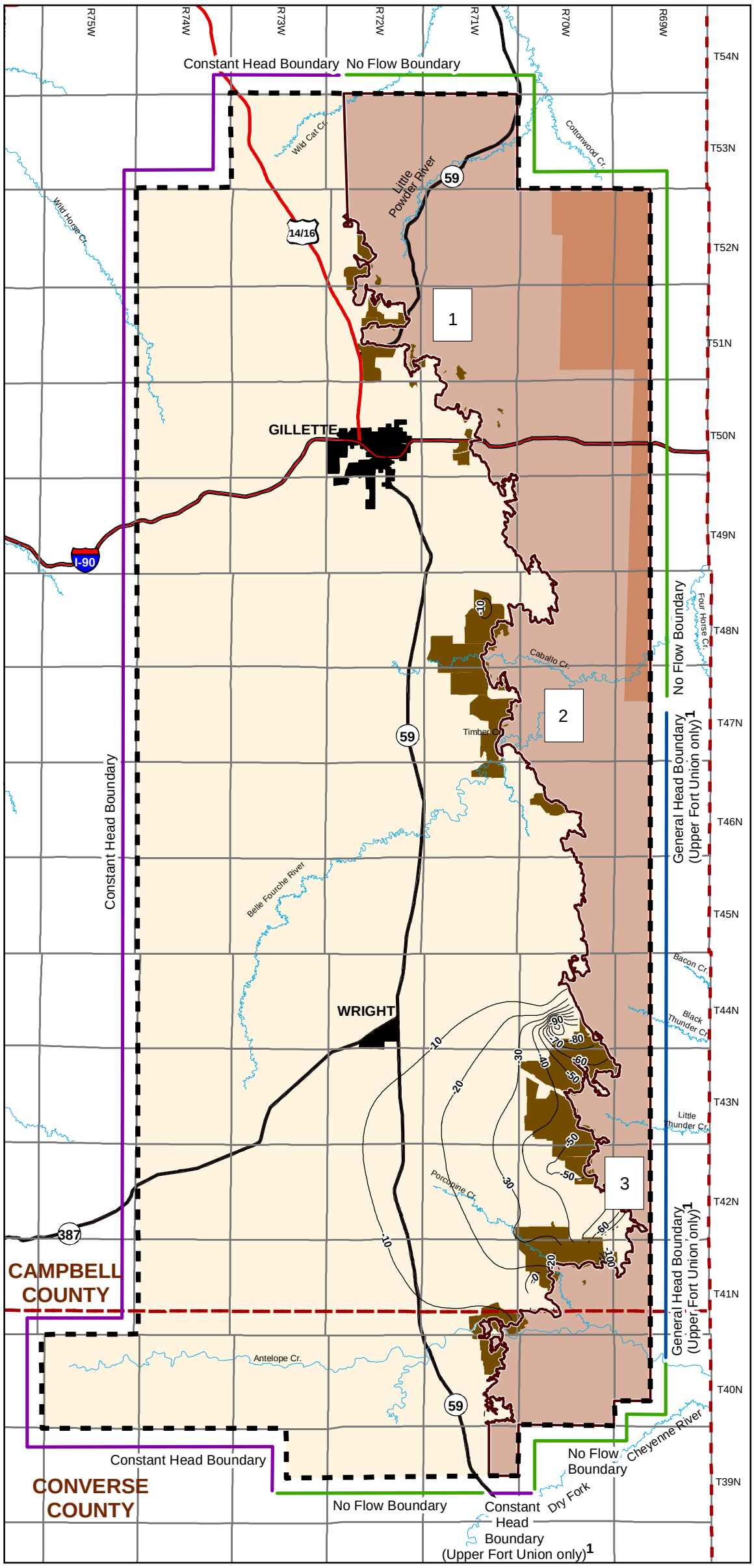
Powder River Basin Coal Review

Figure B-15

2015 Water Levels
Wasatch Formation

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 10 feet

- Groundwater drawdown level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine groundwater pumping.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

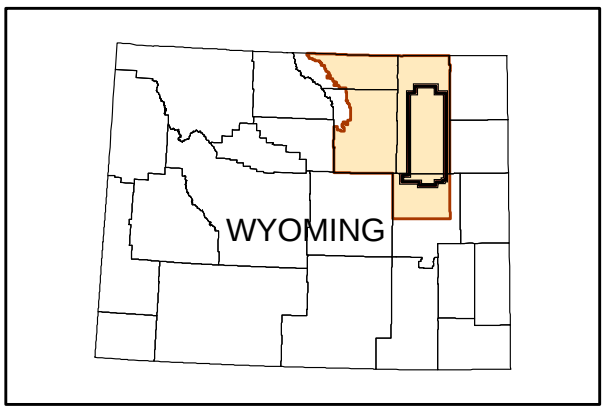
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-16

Wasatch Formation
1990 Base Year/2015 Prediction
Coal Mine-related
Groundwater Level Changes

12/12/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

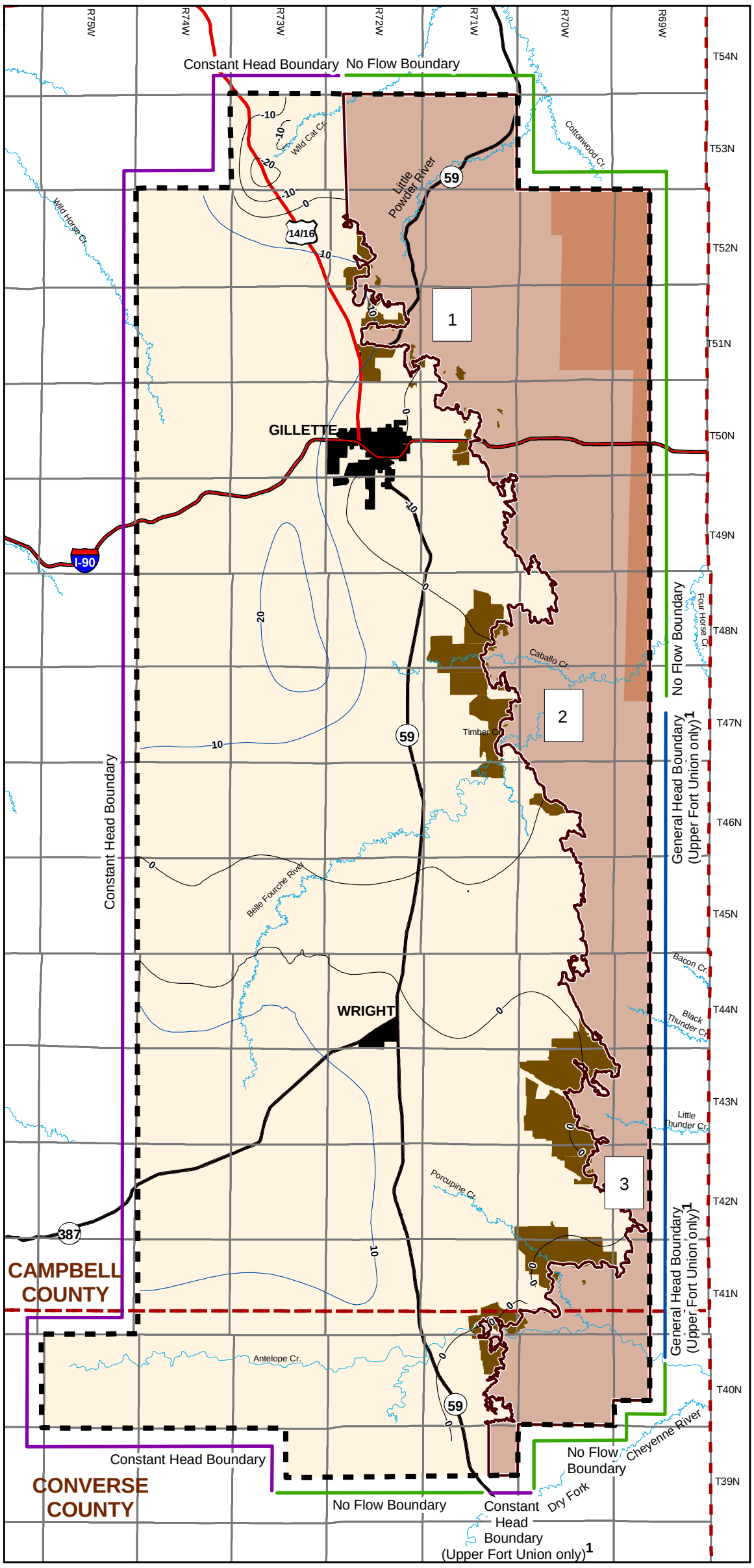
Contour Interval = 10 feet

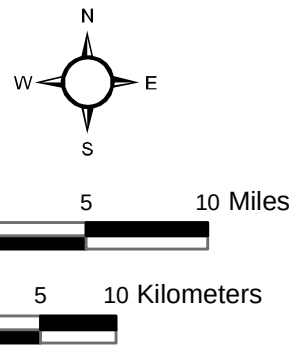
- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of CBNG groundwater pumping and water discharge.





[1]Boundary condition is No Flow Boundary for all other layers.

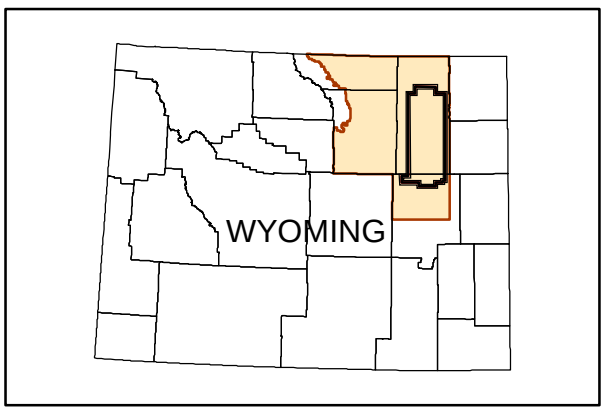
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-17

Wasatch Formation
1990 Base Year/2015 Prediction
CBNG-related
Groundwater Level Changes

11/01/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

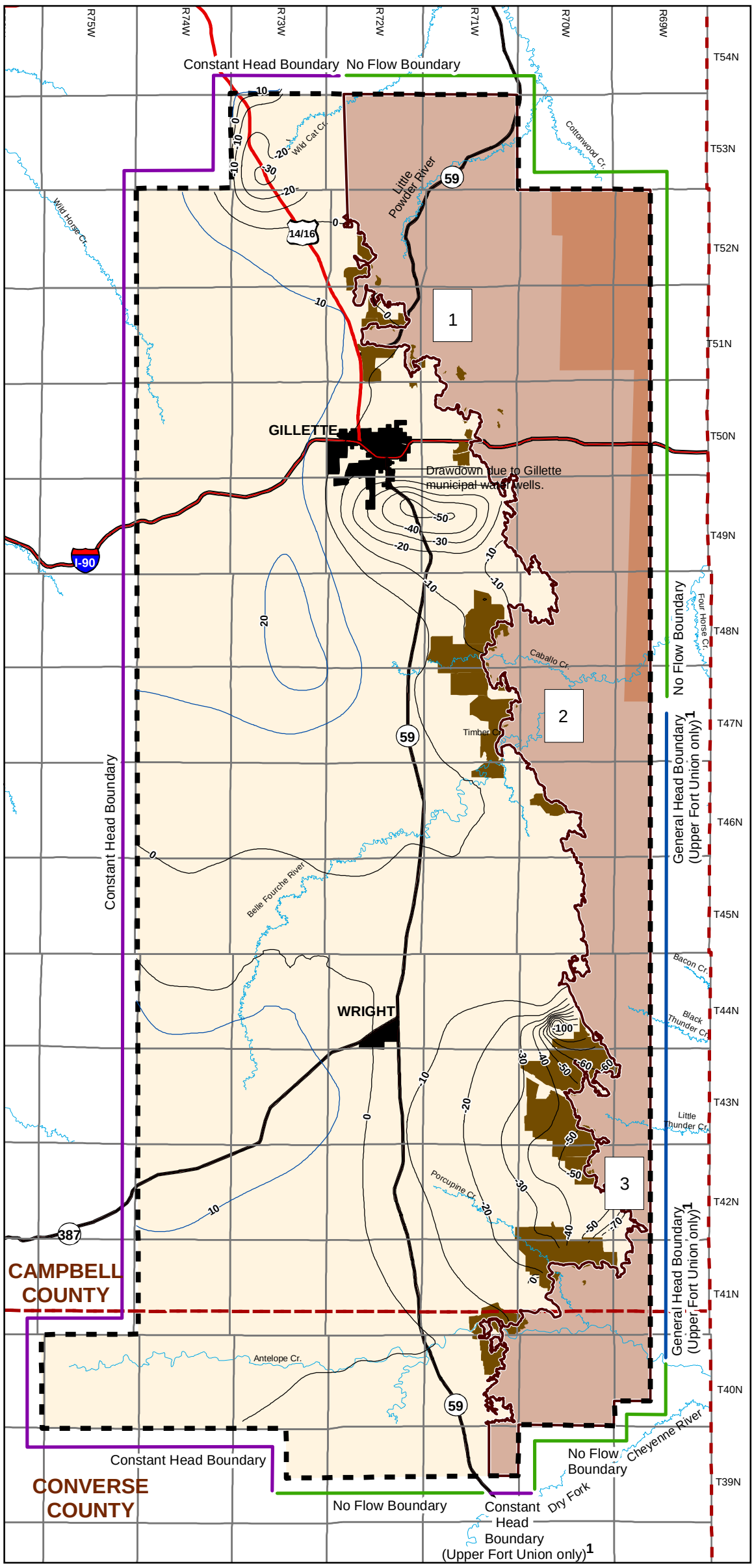
Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

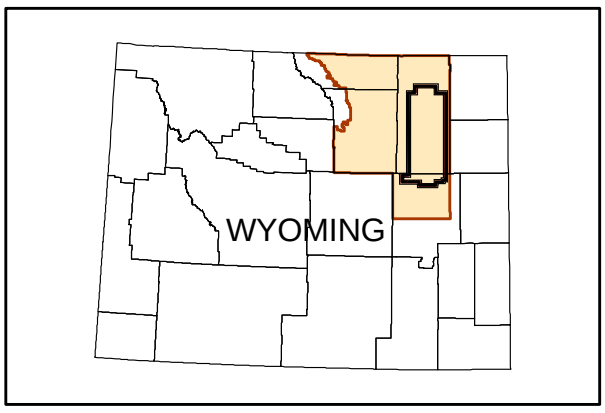
Source: BLM 2009a, b.

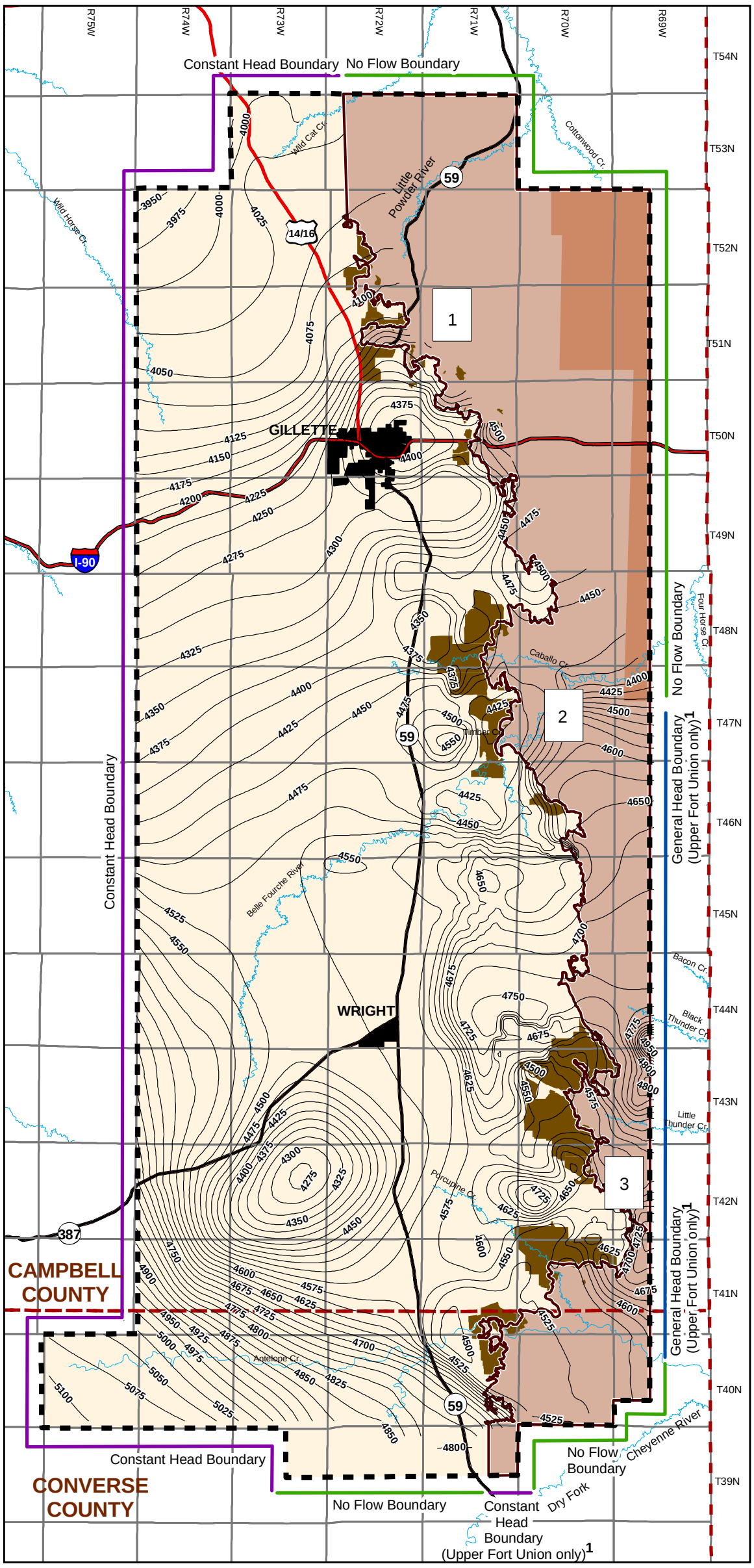
Powder River Basin Coal Review

Figure B-18

Wasatch Formation
1990 Base Year/2015 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

12/17/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

Groundwater level contours (Range = 3950 to 5100 feet)

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

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

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

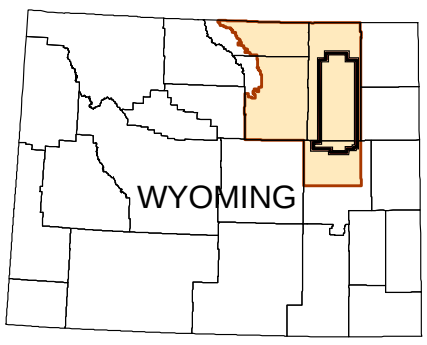
Source: BLM 2009a, b.

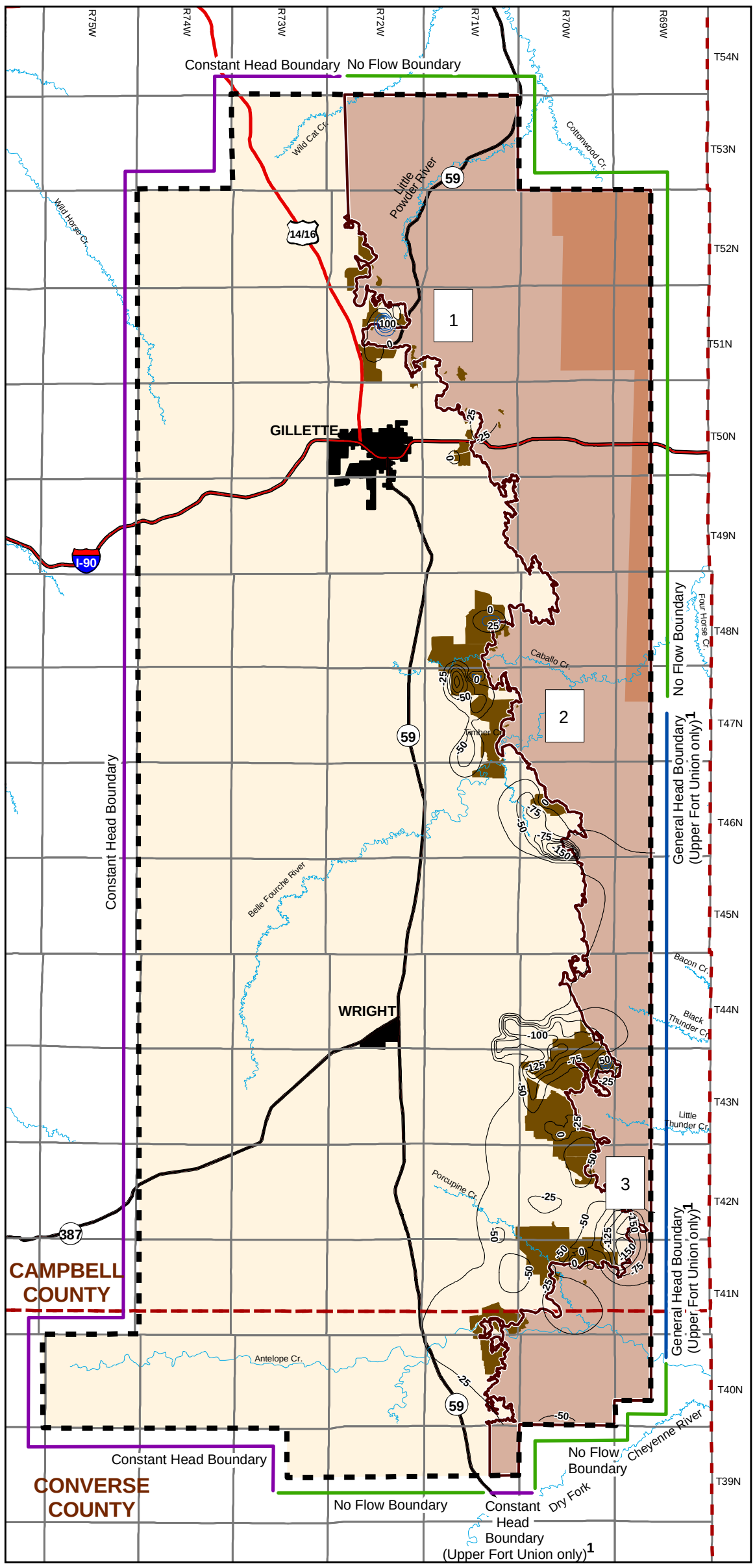
Powder River Basin Coal Review

Figure B-19

2015 Water Levels
Upper Fort Union Formation

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine groundwater pumping.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

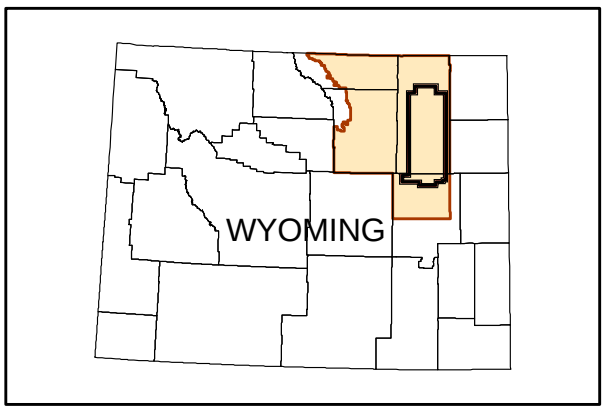
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-20

Upper Fort Union Formation
1990 Base Year/2015 Prediction
Coal Mine-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours

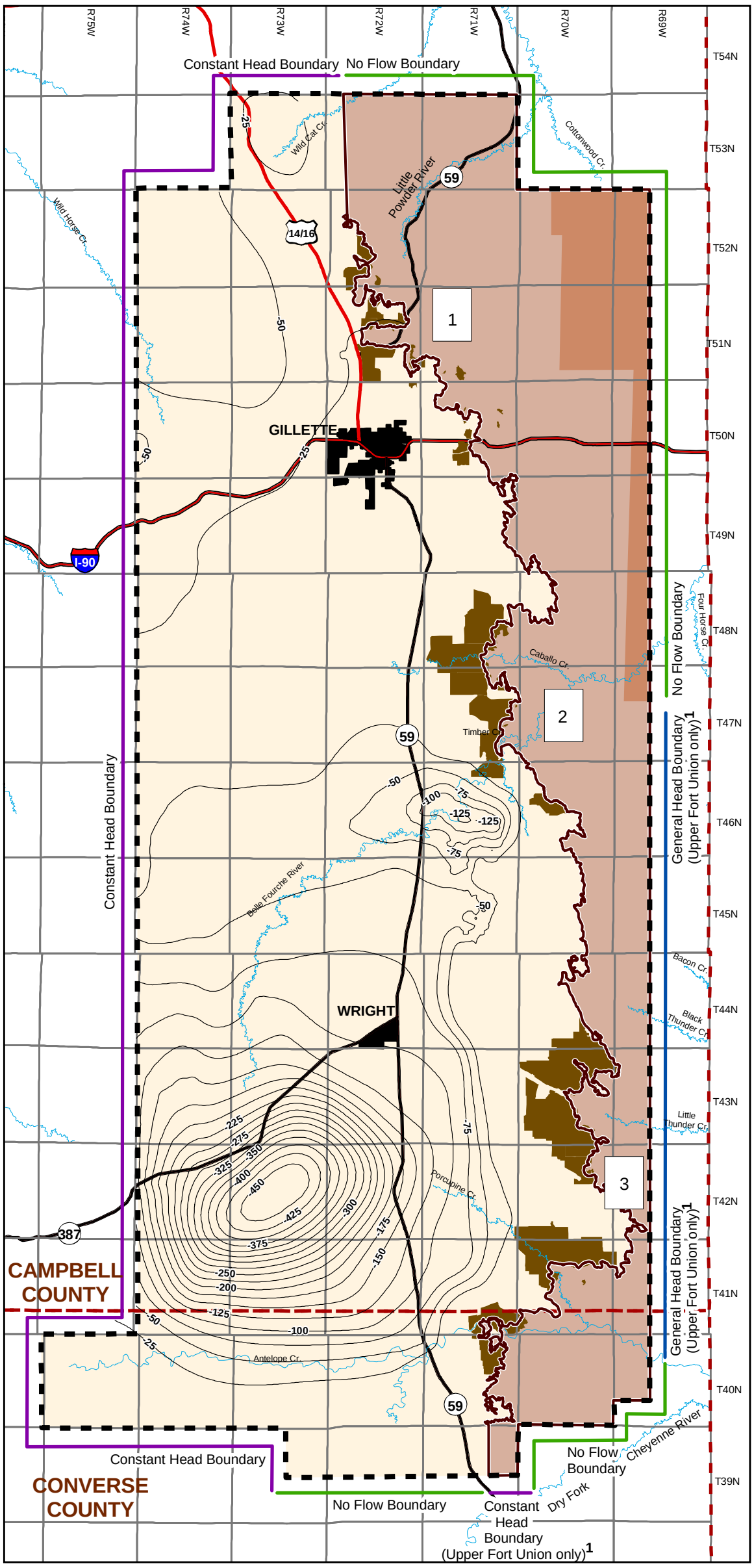
Coal Mine Subregions

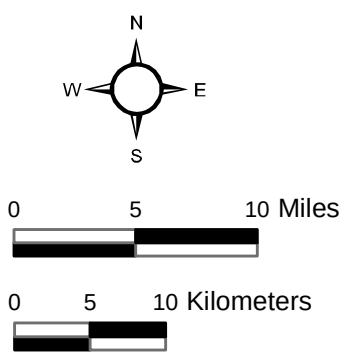
1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

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





[1]Boundary condition is No Flow Boundary for all other layers.

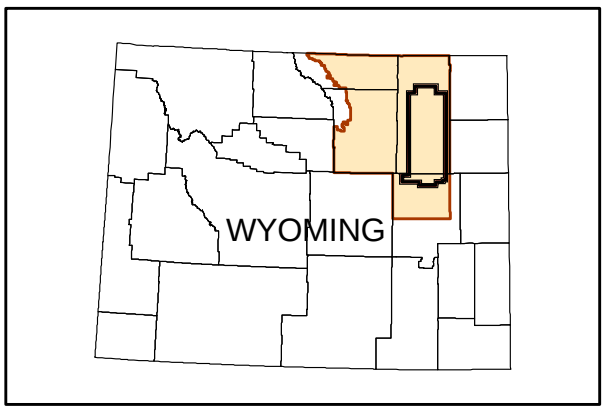
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-21

Upper Fort Union Formation
1990 Base Year/2015 Prediction
CBNG-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

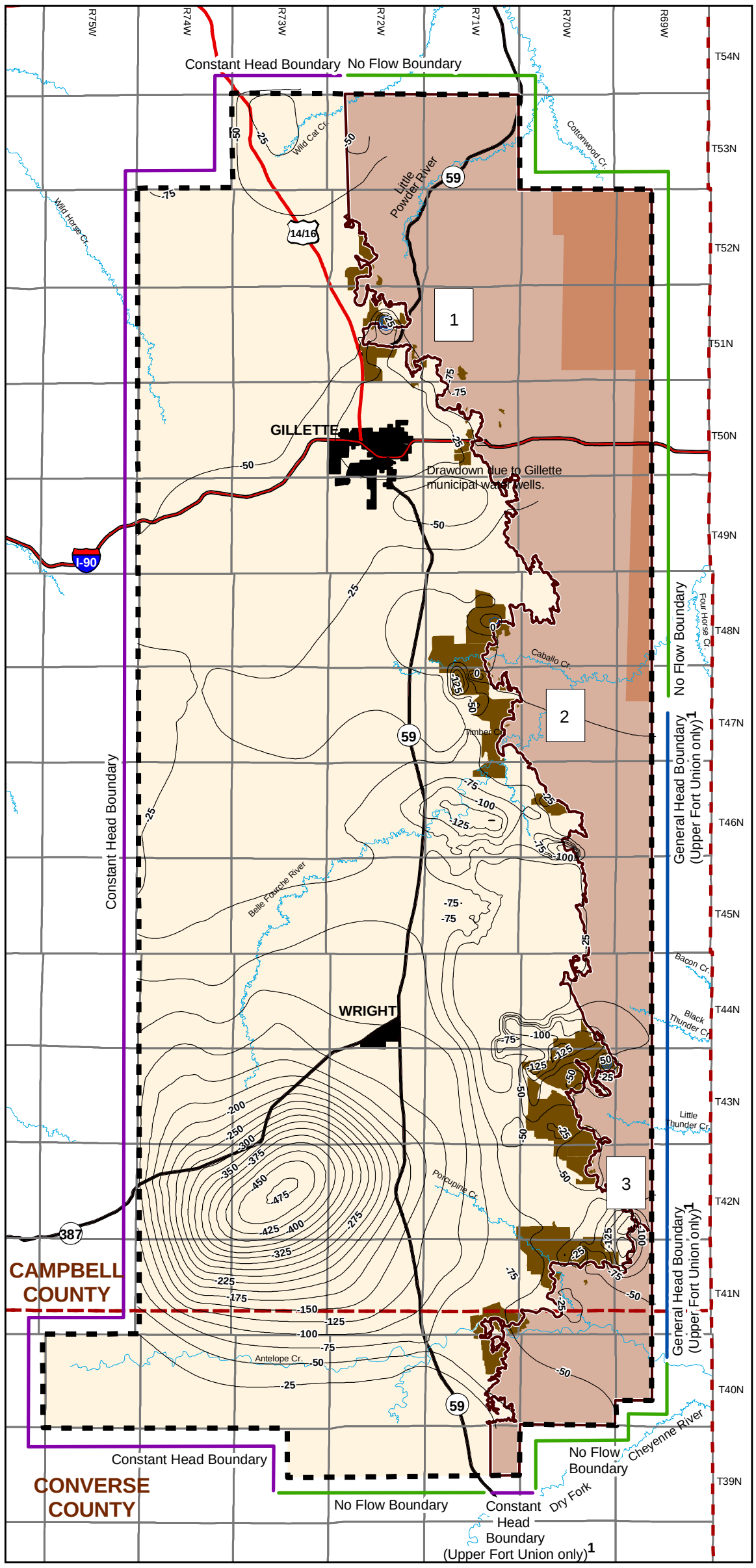
1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

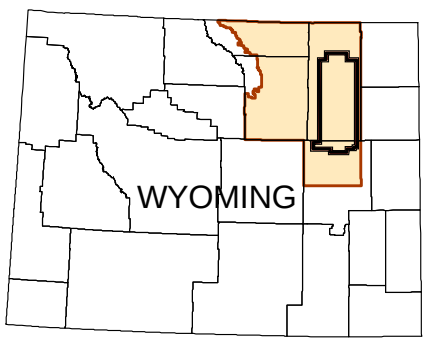
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-22

Upper Fort Union Formation
1990 Base Year/2015 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

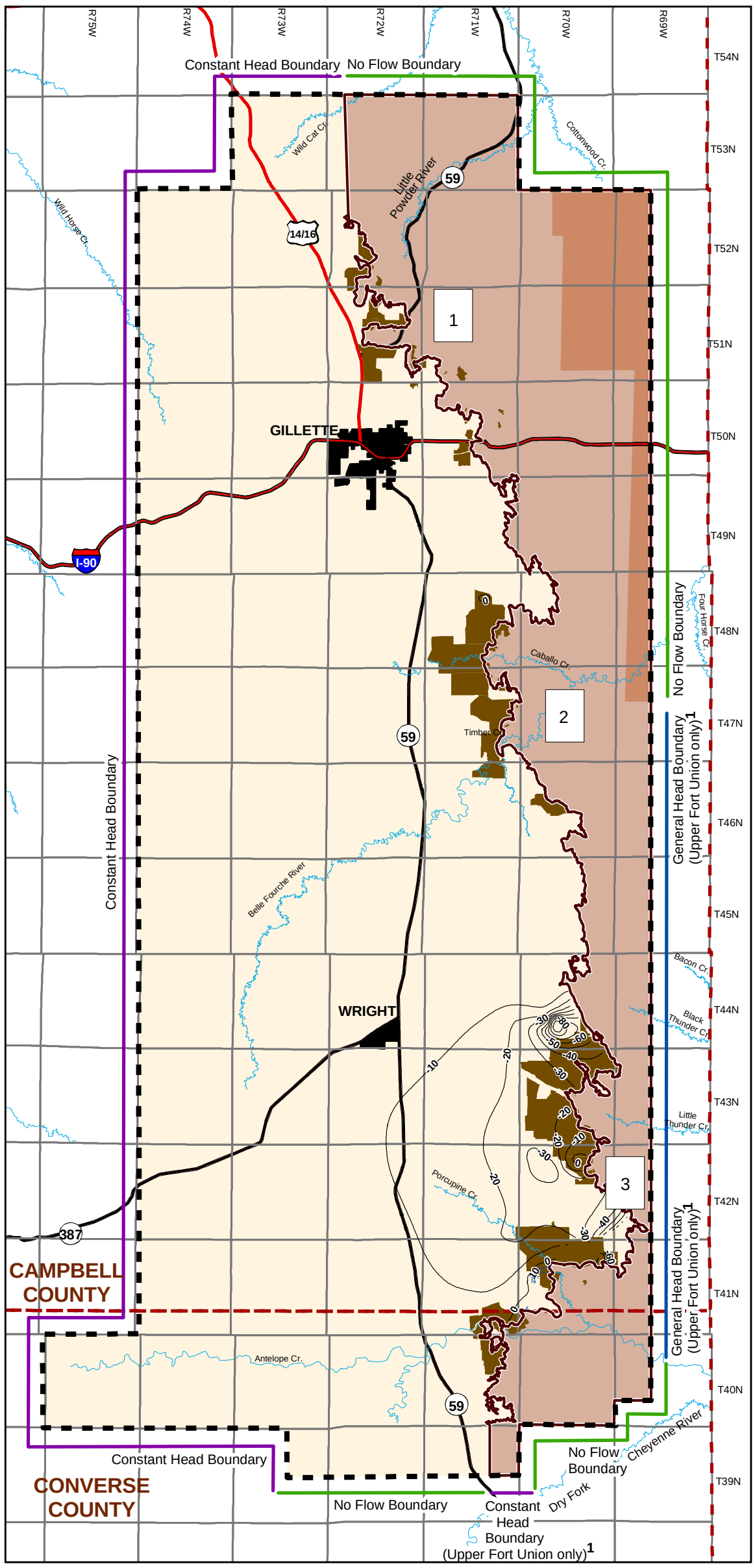
Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine groundwater pumping.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

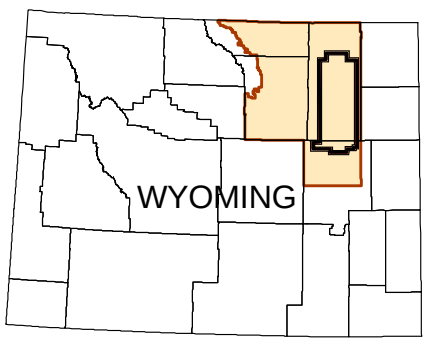
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-23

Wasatch Formation
2002 Base Year/2015 Prediction
Coal Mine-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

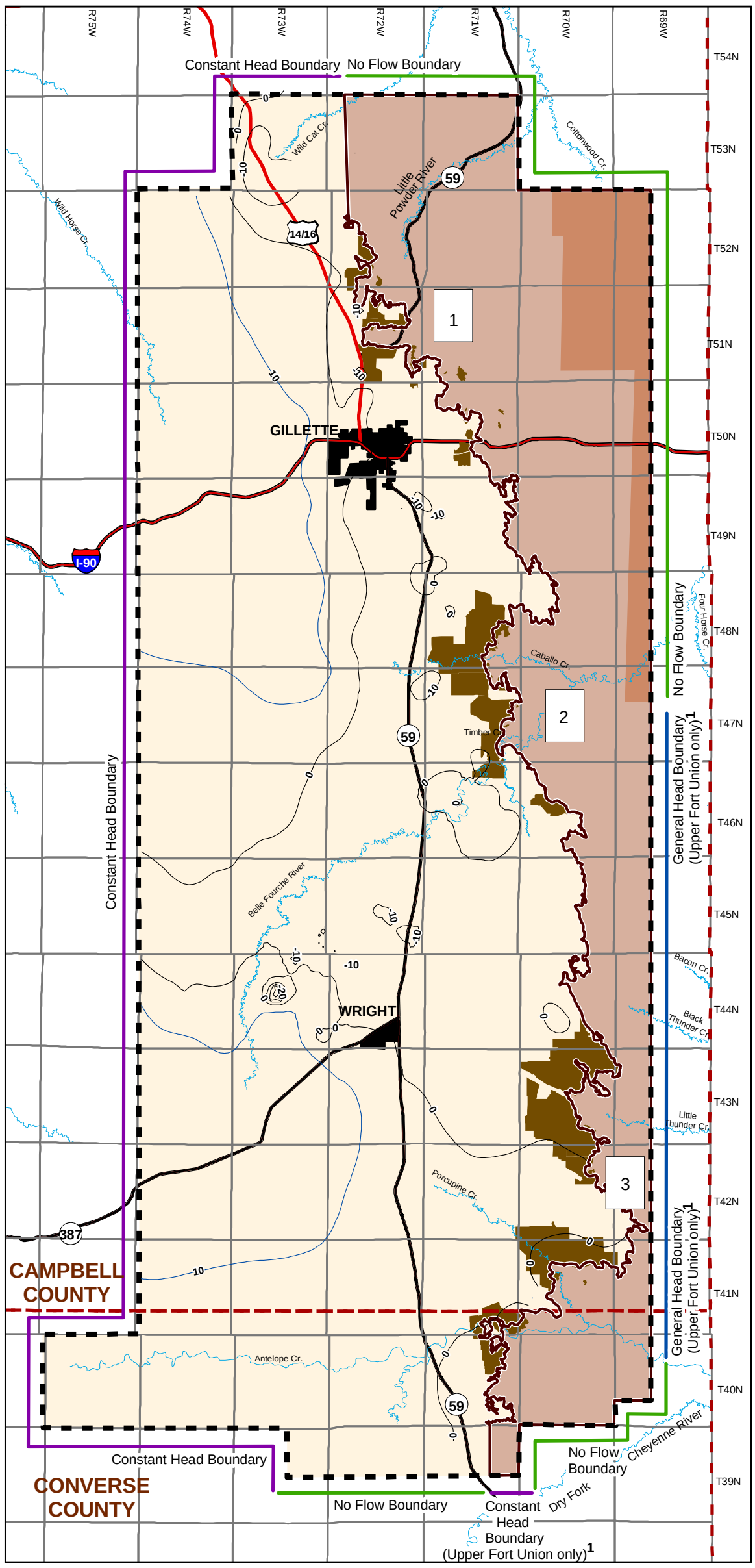
Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

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



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

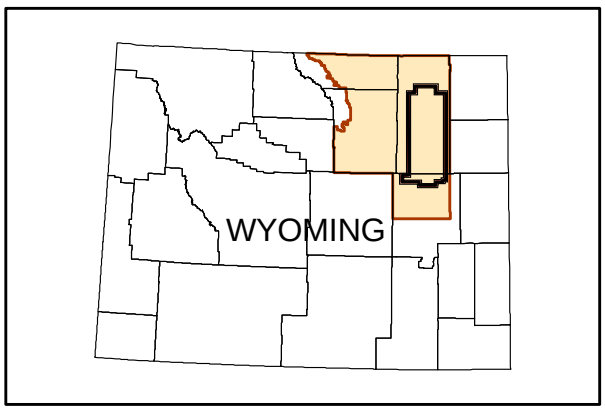
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-24

Wasatch Formation
2002 Base Year/2015 Prediction
CBNG-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

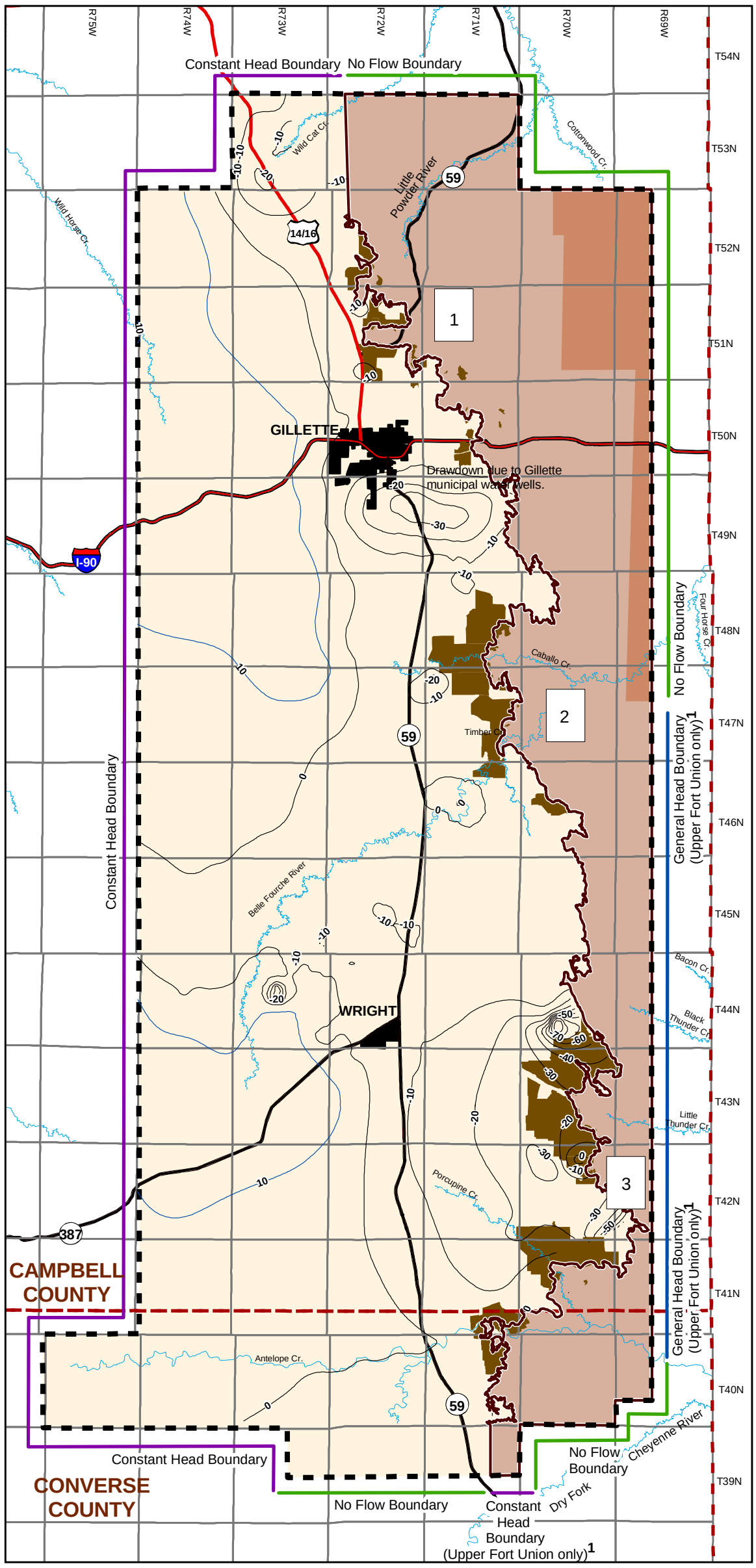
Contour Interval = 10 feet

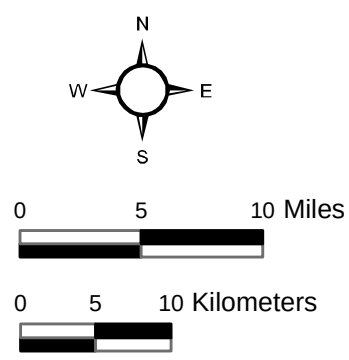
- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.





[1]Boundary condition is No Flow Boundary for all other layers.

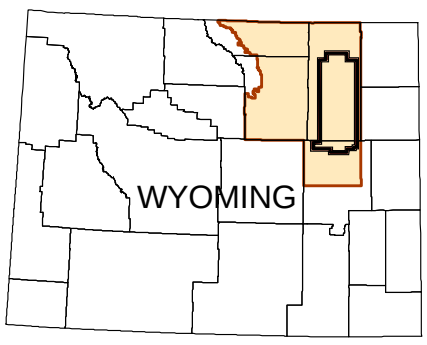
Source: BLM 2009a, b.

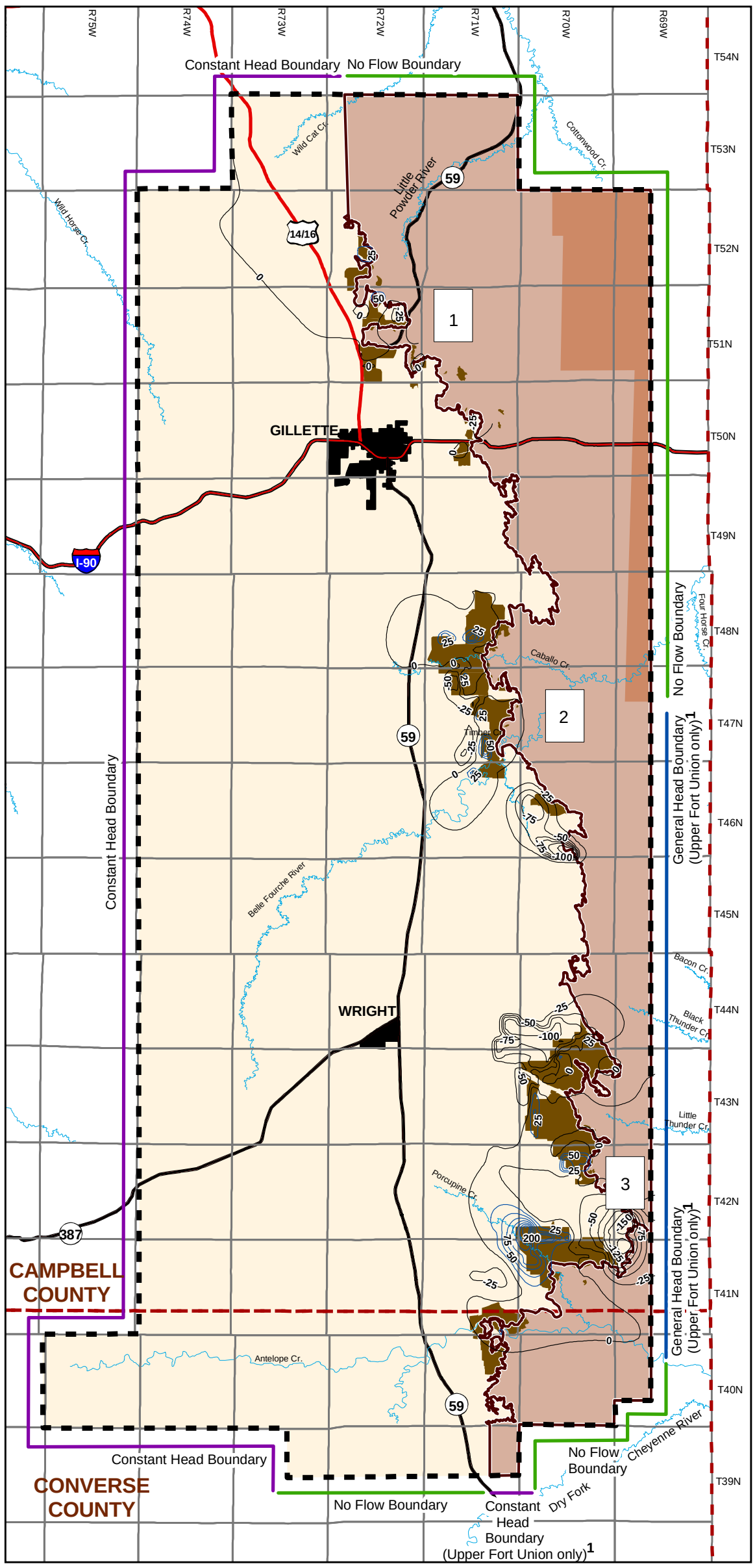
Powder River Basin Coal Review

Figure B-25

Wasatch Formation
2002 Base Year/2015 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine groundwater pumping.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

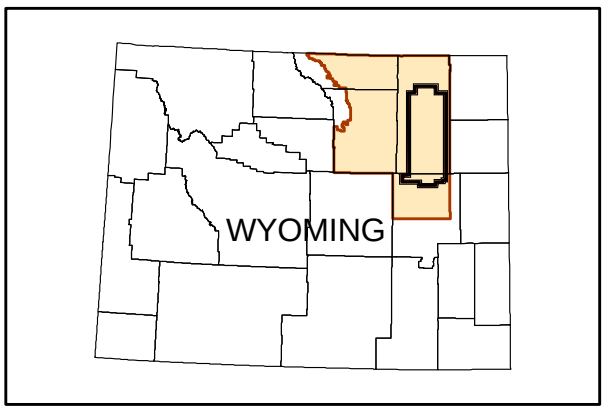
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-26

Upper Fort Union Formation
2002 Base Year/2015 Prediction
Coal Mine-related
Groundwater Level Changes

11/01/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

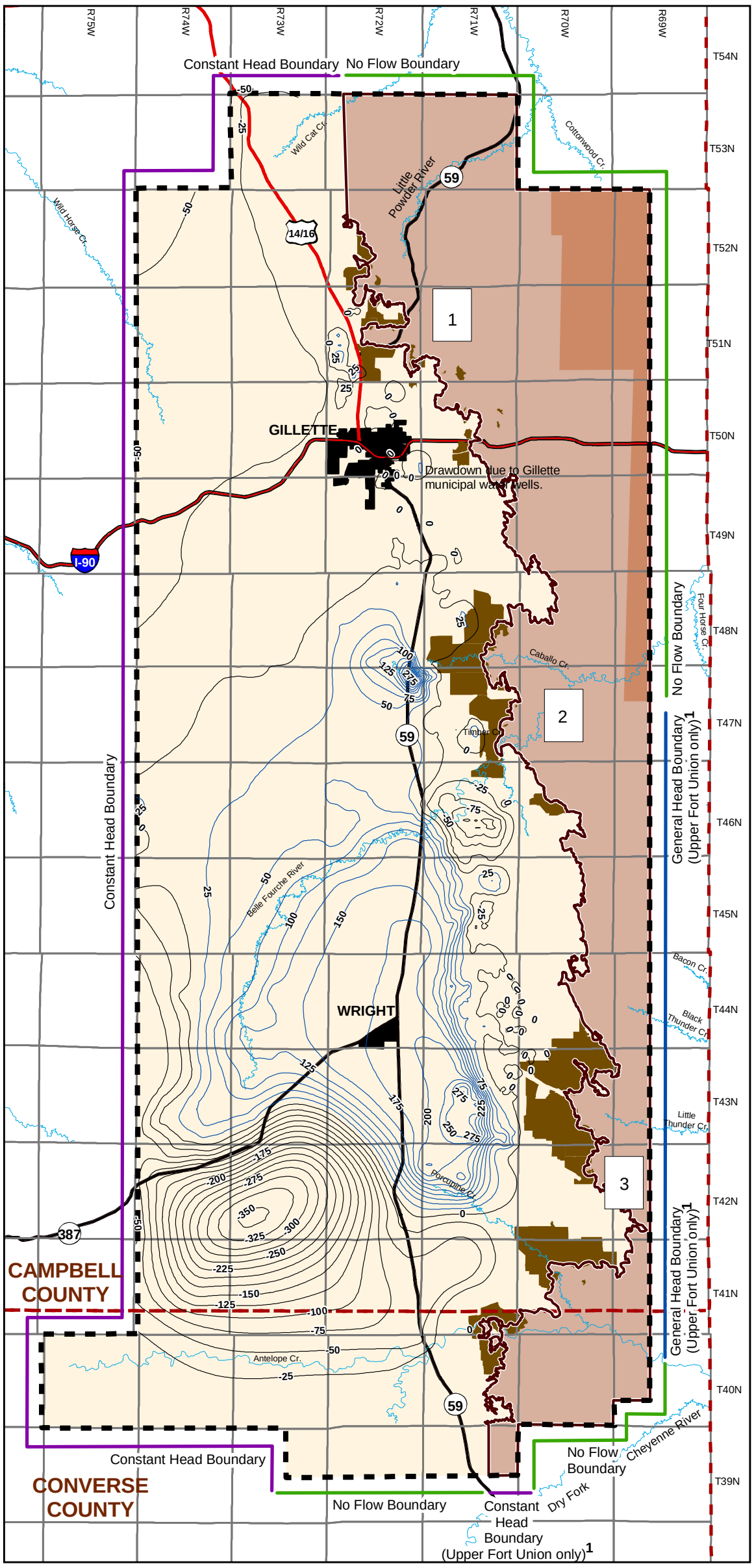
Contour Interval = 25 feet

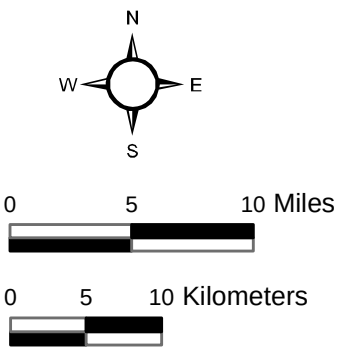
- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

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





[1]Boundary condition is No Flow Boundary for all other layers.

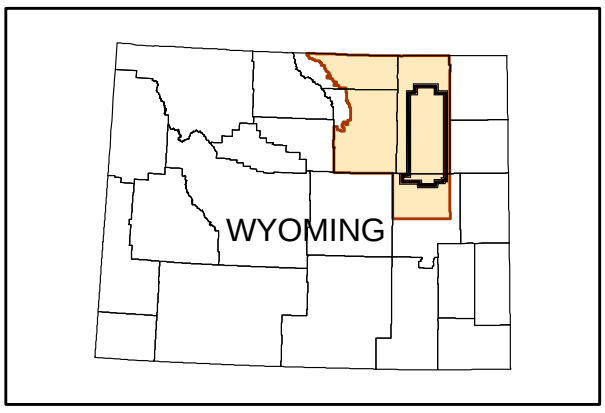
Source: BLM 2009a, b.

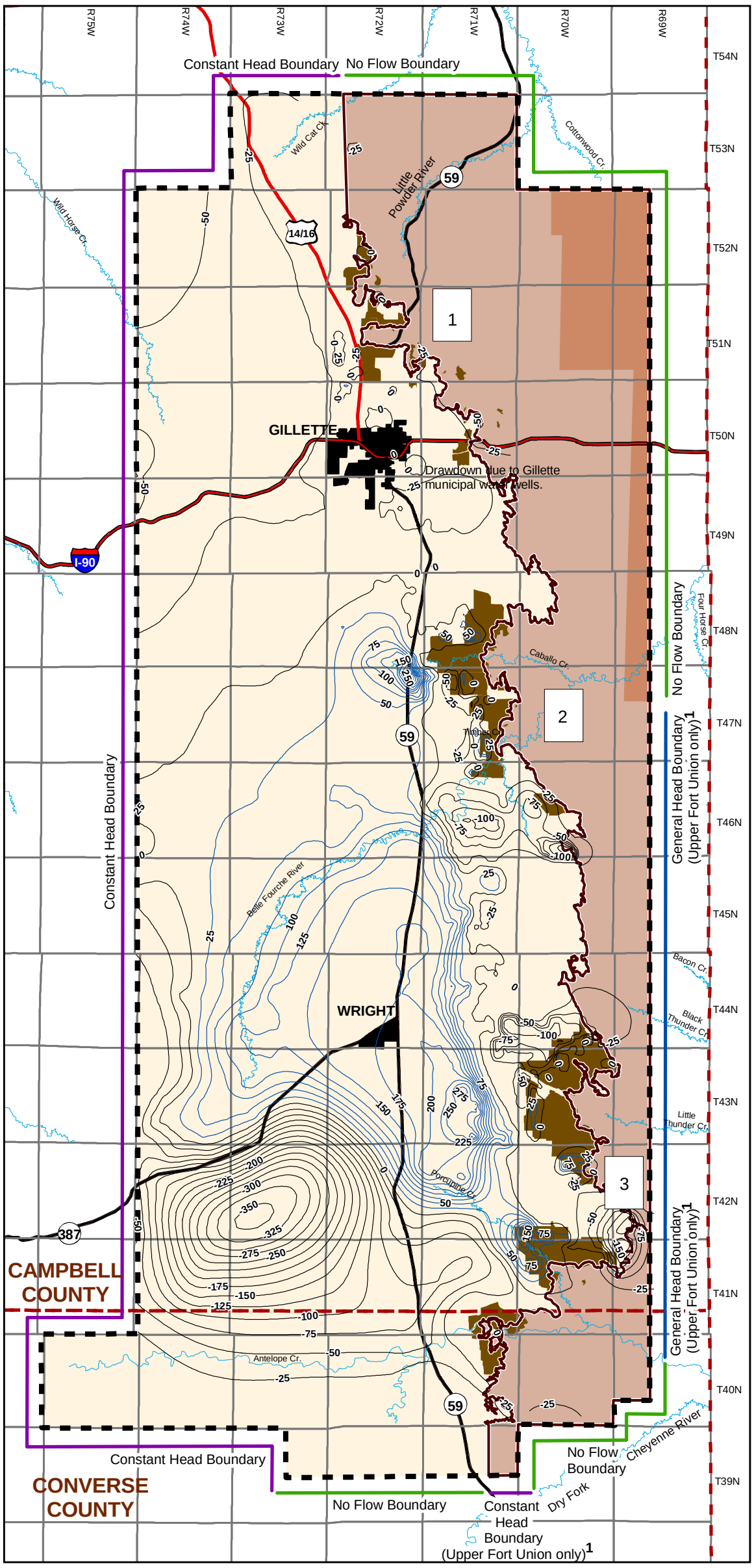
Powder River Basin Coal Review

Figure B-27

Upper Fort Union Formation
2002 Base Year/2015 Prediction
CBNG-related
Groundwater Level Changes

11/01/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

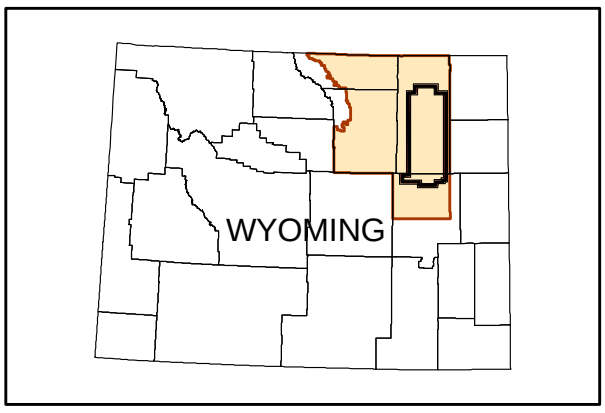
Source: BLM 2009a, b.

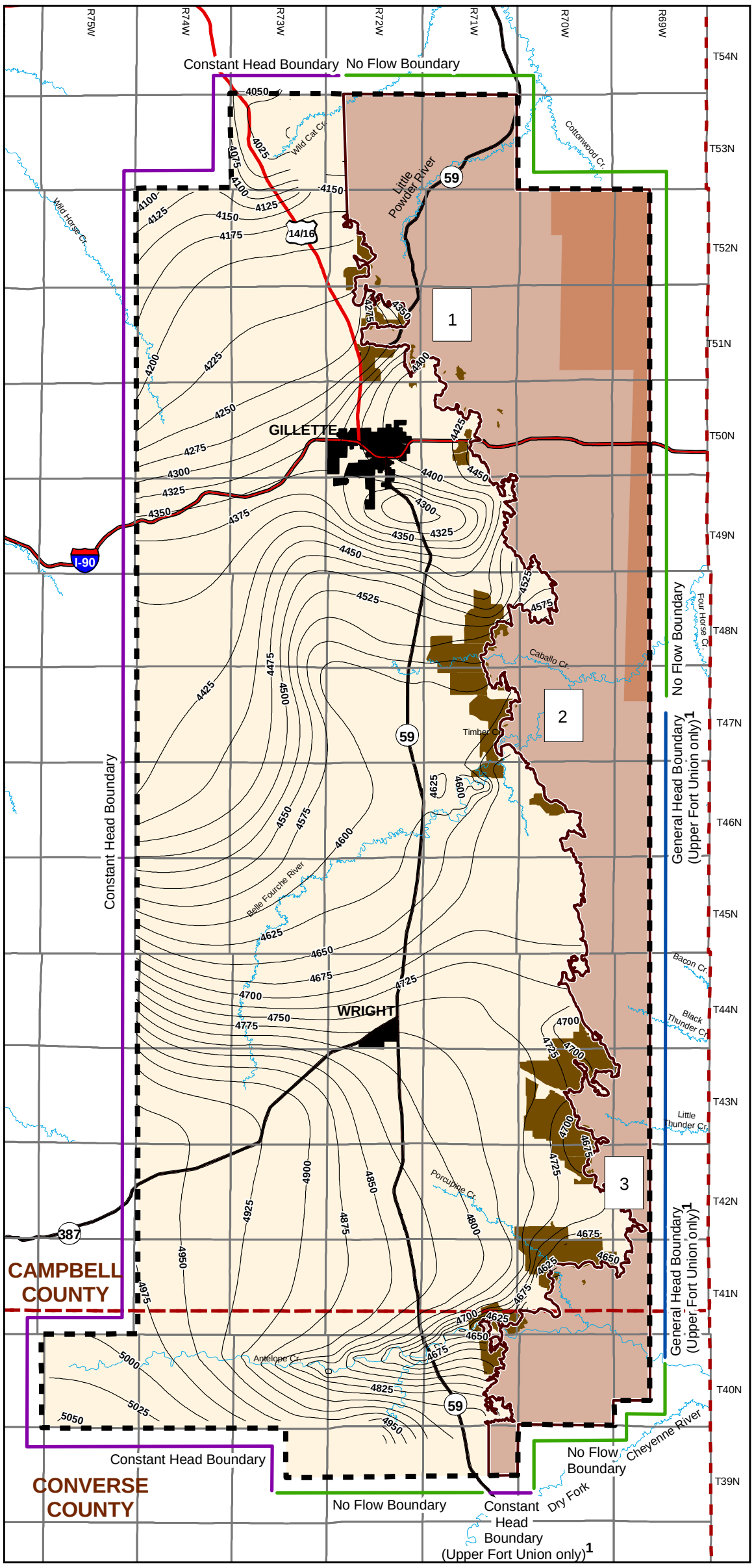
Powder River Basin Coal Review

Figure B-28

Upper Fort Union Formation
2002 Base Year/2015 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/01/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

Groundwater level contours (Range = 4000 to 5050 feet)

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

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

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

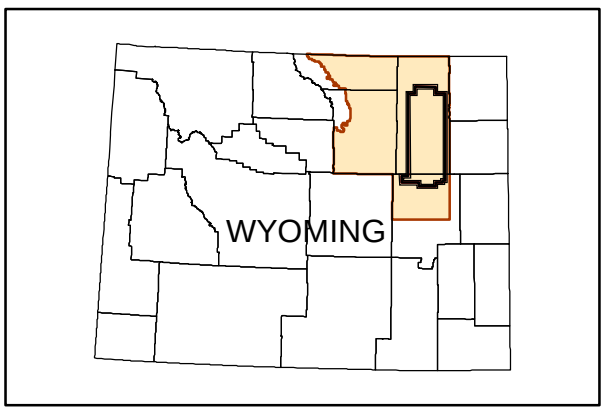
Source: BLM 2009a, b.

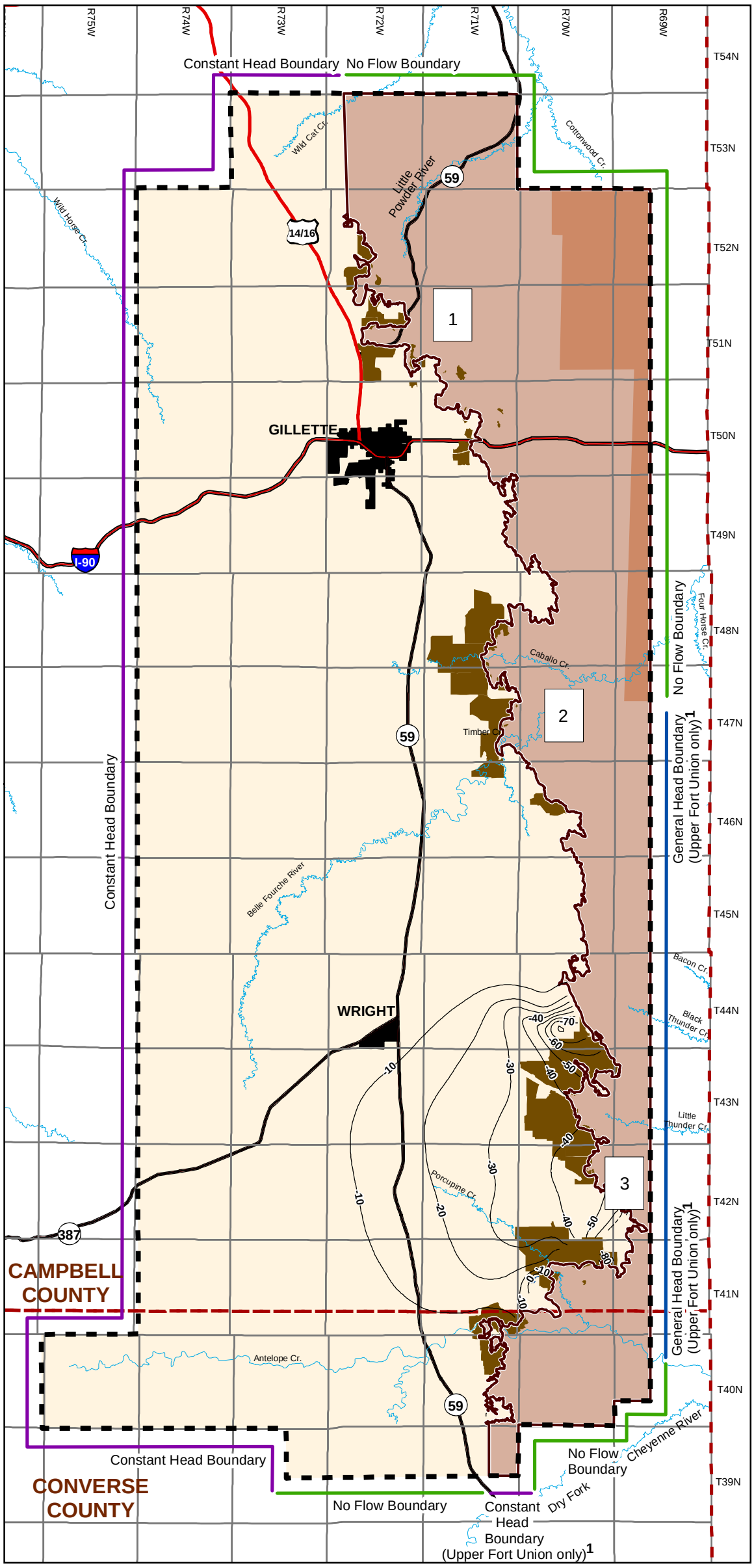
Powder River Basin Coal Review

Figure B-29

2020 Water Levels
Wasatch Formation

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 10 feet

- Groundwater drawdown level contours

Coal Mine Subregions

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

Note: Includes effects of coal mine groundwater pumping.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

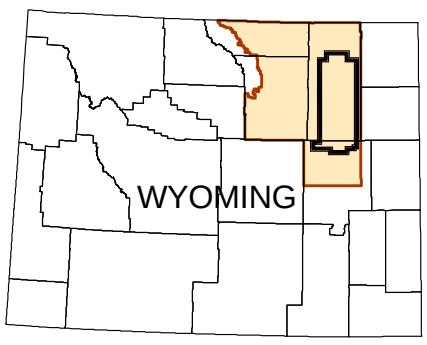
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-30

Wasatch Formation
1990 Base Year/2020 Prediction
Coal Mine-related
Groundwater Level Changes

12/12/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

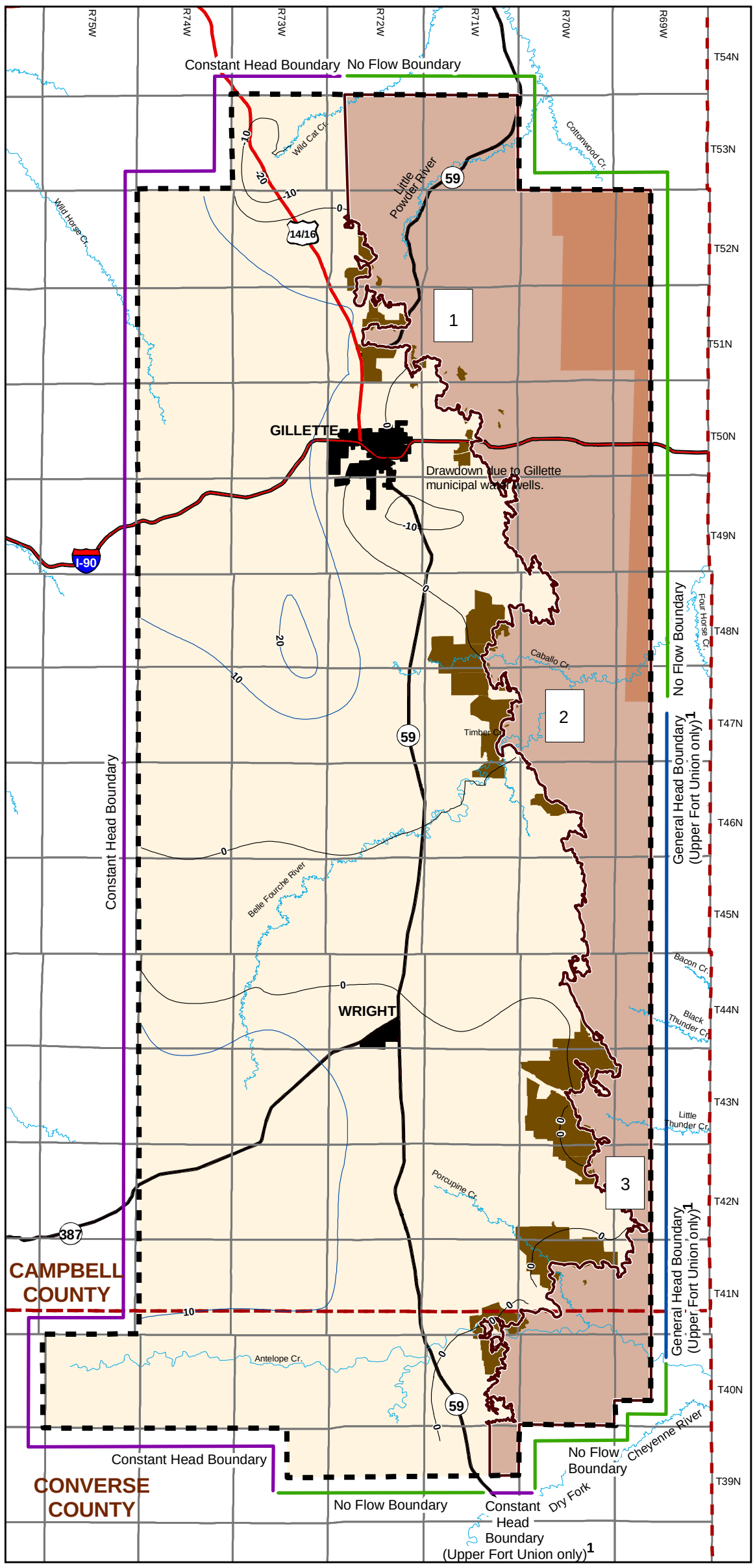
Contour Interval = 10 feet

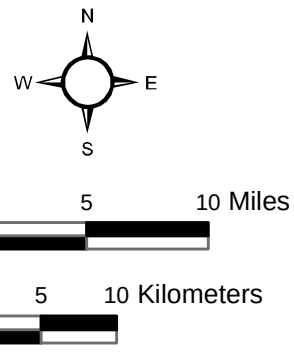
- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

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





[1]Boundary condition is No Flow Boundary for all other layers.

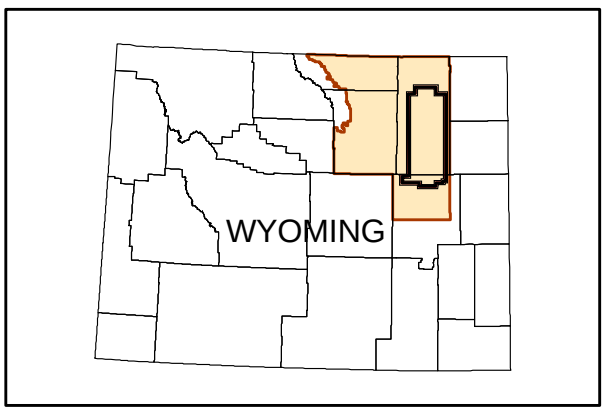
Source: BLM 2009a, b.

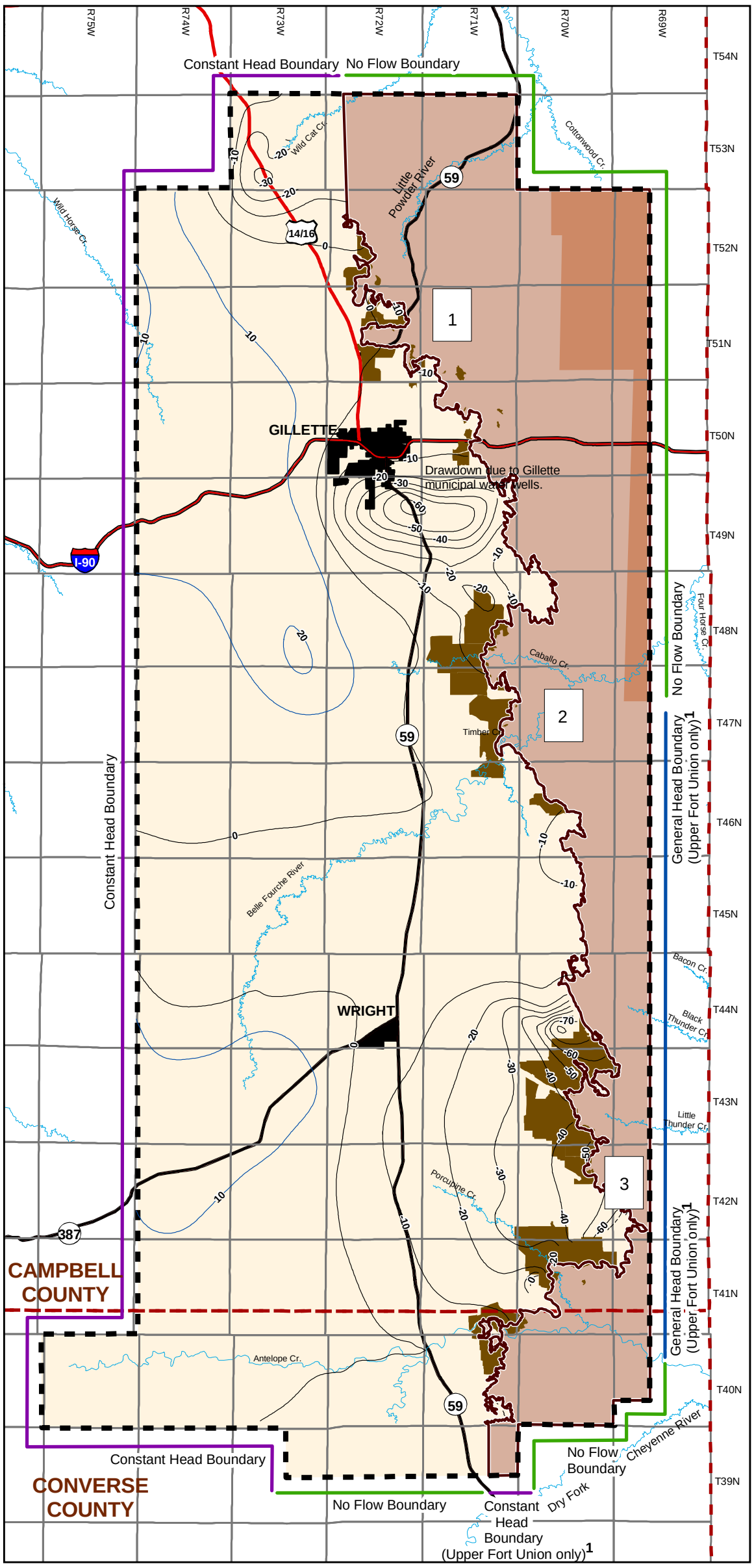
Powder River Basin Coal Review

Figure B-31

Wasatch Formation
1990 Base Year/2020 Prediction
CBNG-related
Groundwater Level Changes

11/01/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

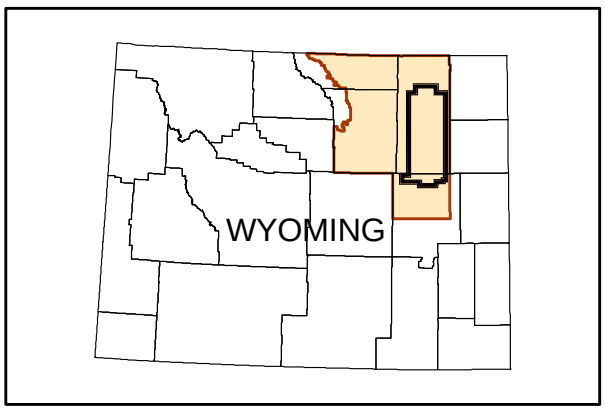
Source: BLM 2009a, b.

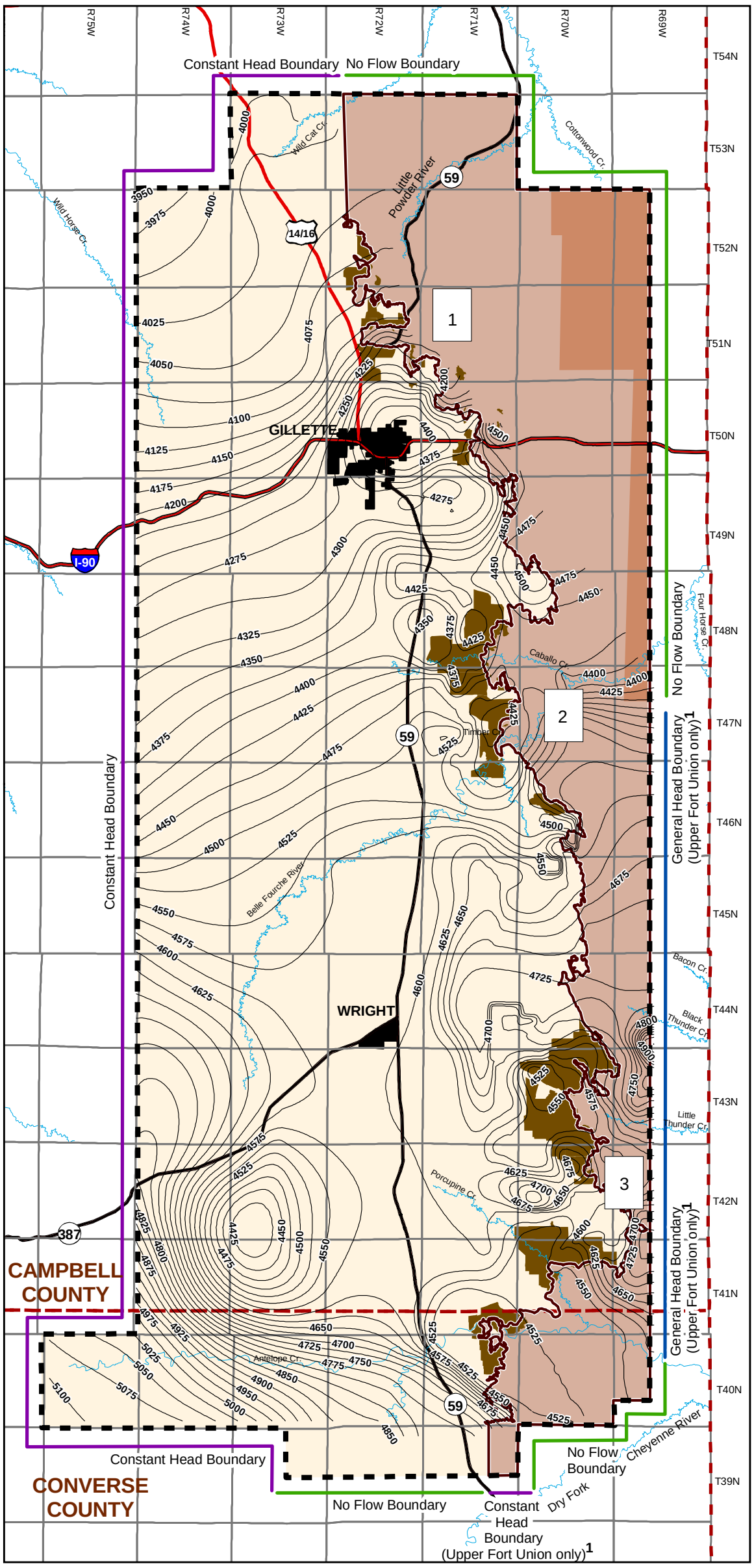
Powder River Basin Coal Review

Figure B-32

Wasatch Formation
1990 Base Year/2020 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/01/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

Groundwater level contours (Range = 3950 to 5100 feet)

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

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

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

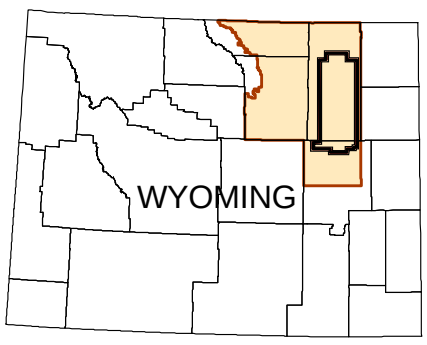
Source: BLM 2009a, b.

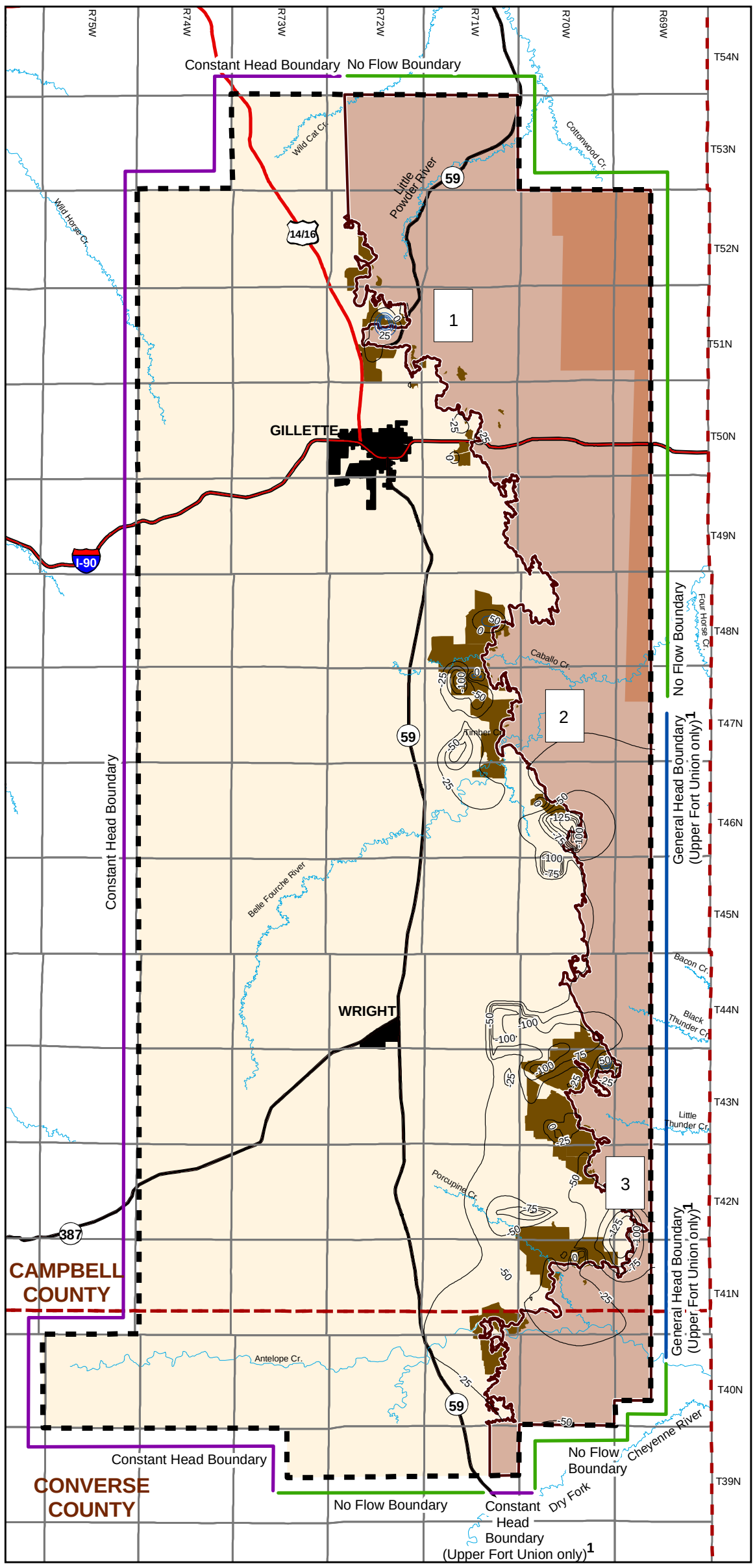
Powder River Basin Coal Review

Figure B-33

2020 Water Levels
Upper Fort Union Formation

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine groundwater pumping.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

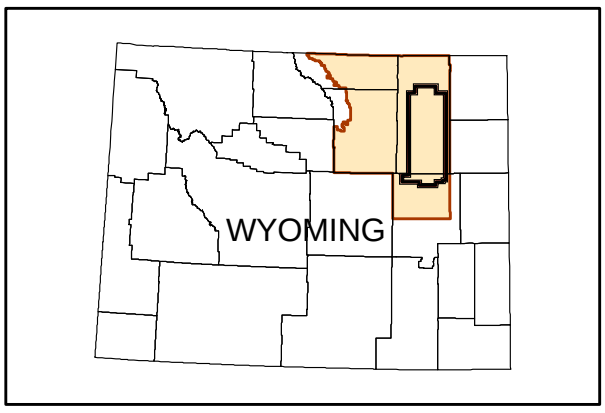
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-34

Upper Fort Union Formation
1990 Base Year/2020 Prediction
Coal Mine-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

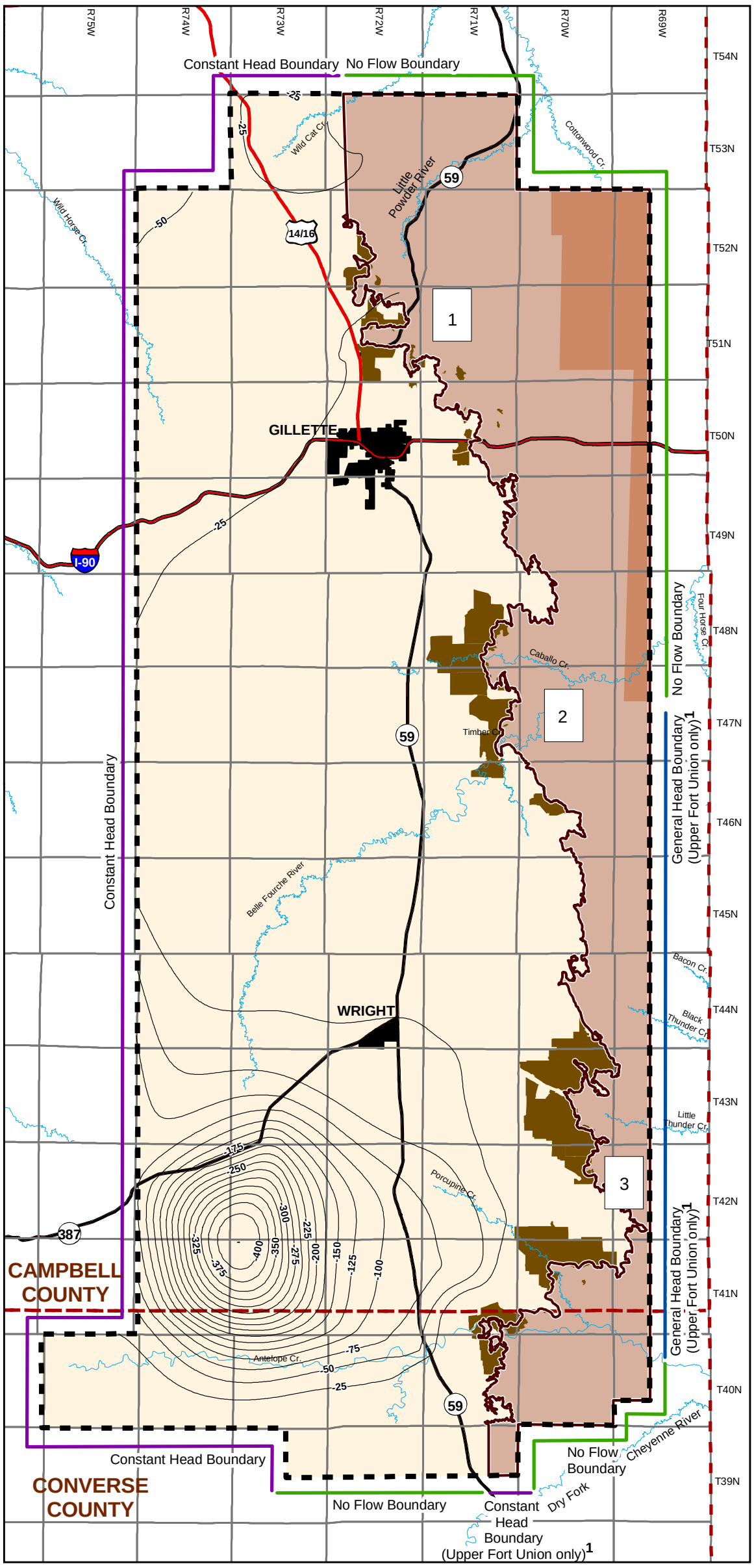
Contour Interval = 25 feet

- Groundwater drawdown level contours

Coal Mine Subregions

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

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



Powder River Basin Coal Review

Figure B-35

Upper Fort Union Formation
1990 Base Year/2020 Prediction
CBNG-related
Groundwater Level Changes

N W E S

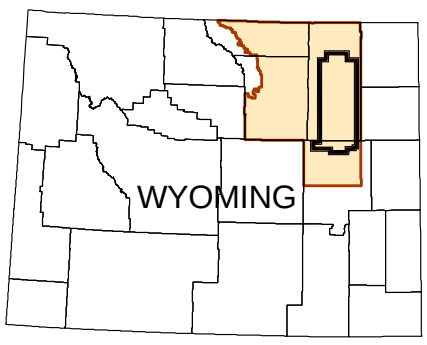
0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

Source: BLM 2009a, b.

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

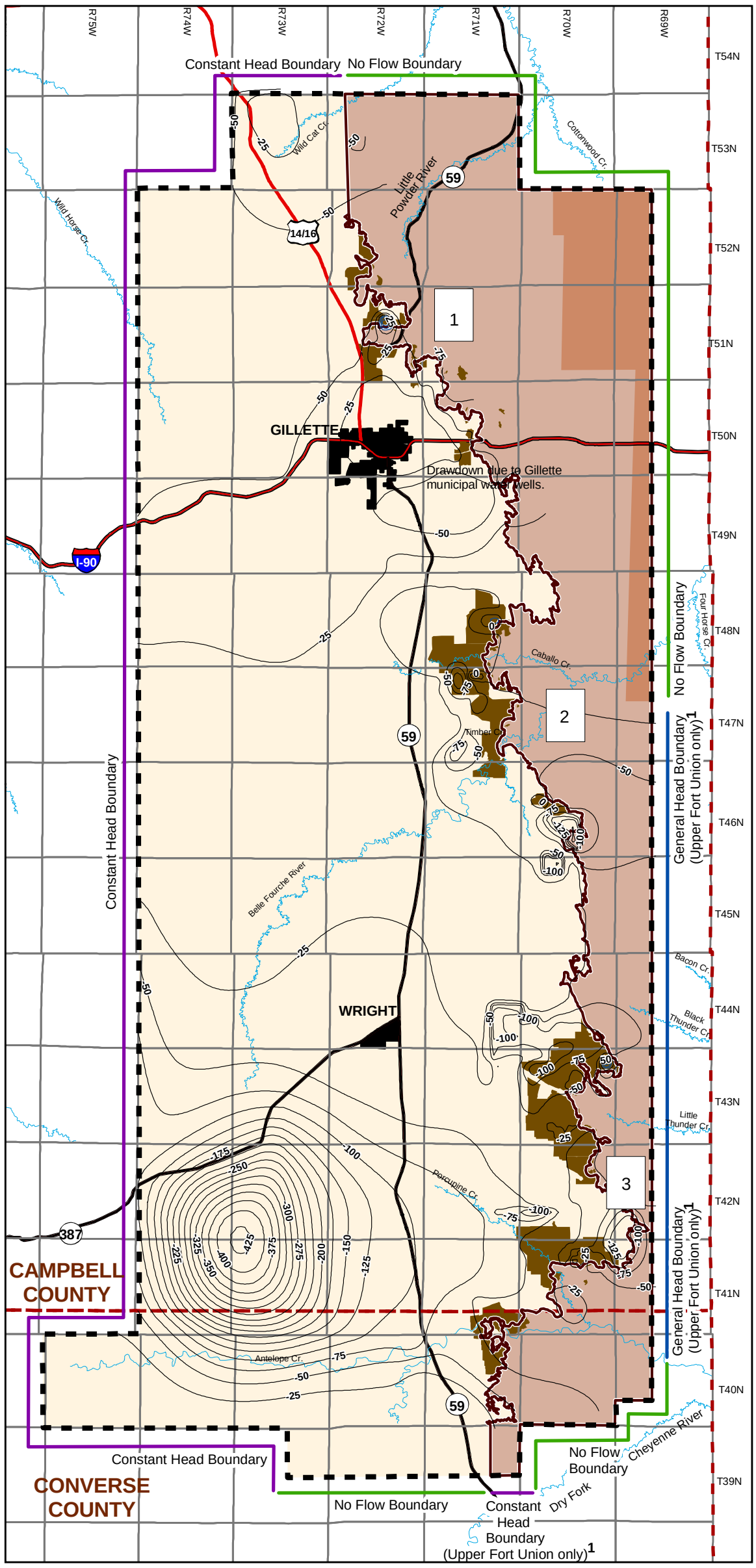
1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

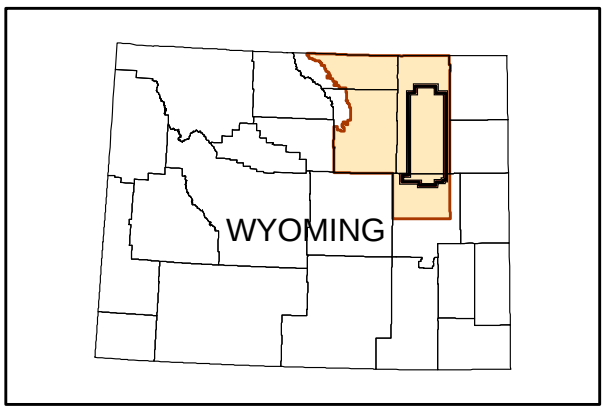
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-36

Upper Fort Union Formation
1990 Base Year/2020 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

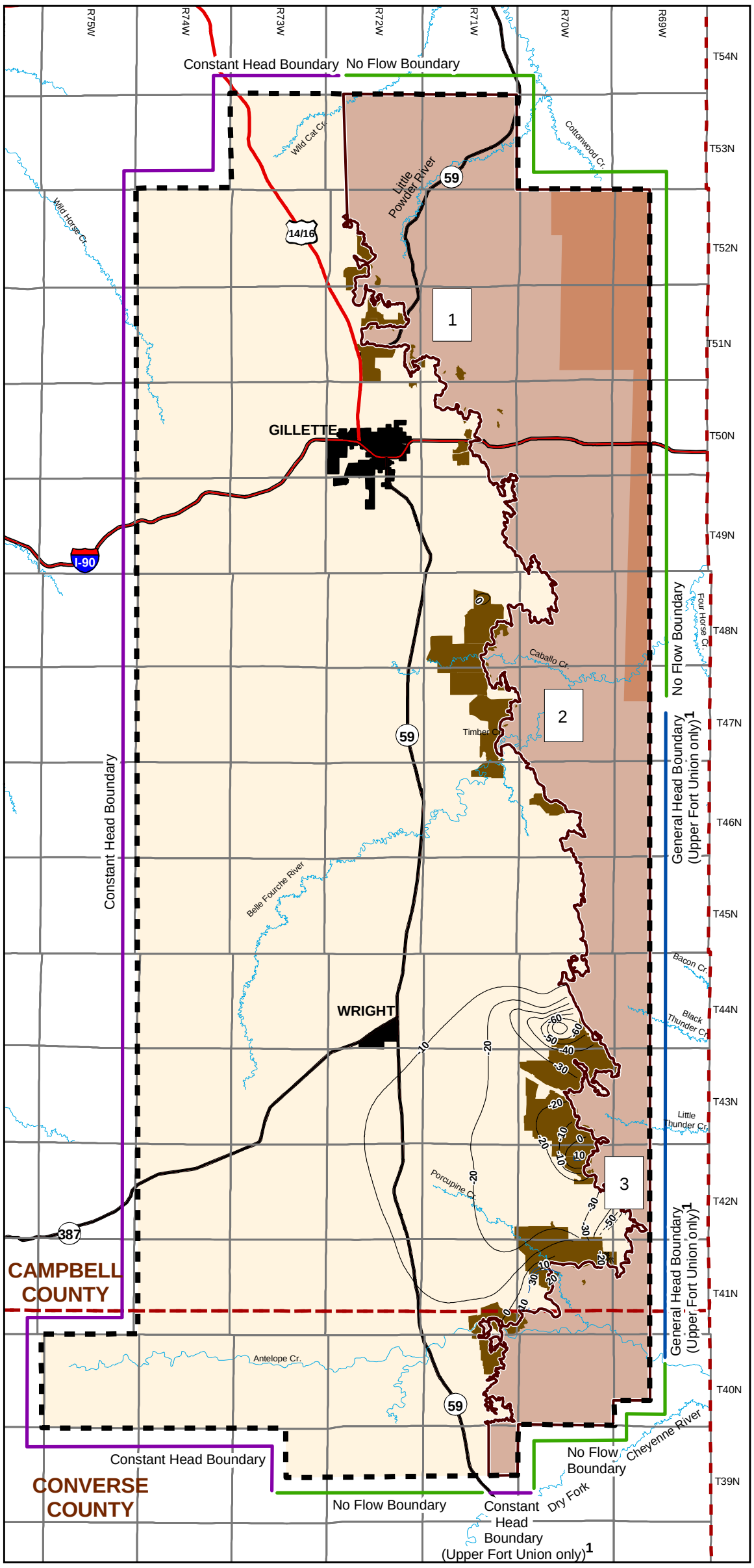
Contour Interval = 10 feet

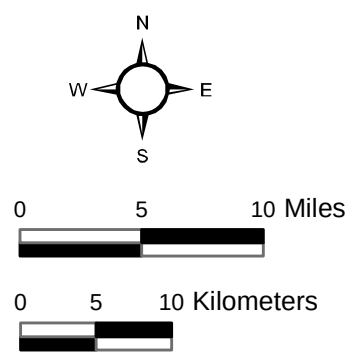
- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Note: Includes effects of coal mine groundwater pumping.





[1]Boundary condition is No Flow Boundary for all other layers.

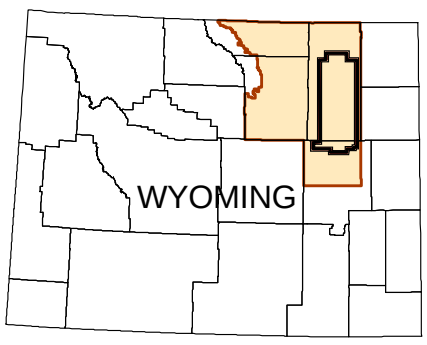
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-37

Wasatch Formation
2002 Base Year/2020 Prediction
Coal Mine-related
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

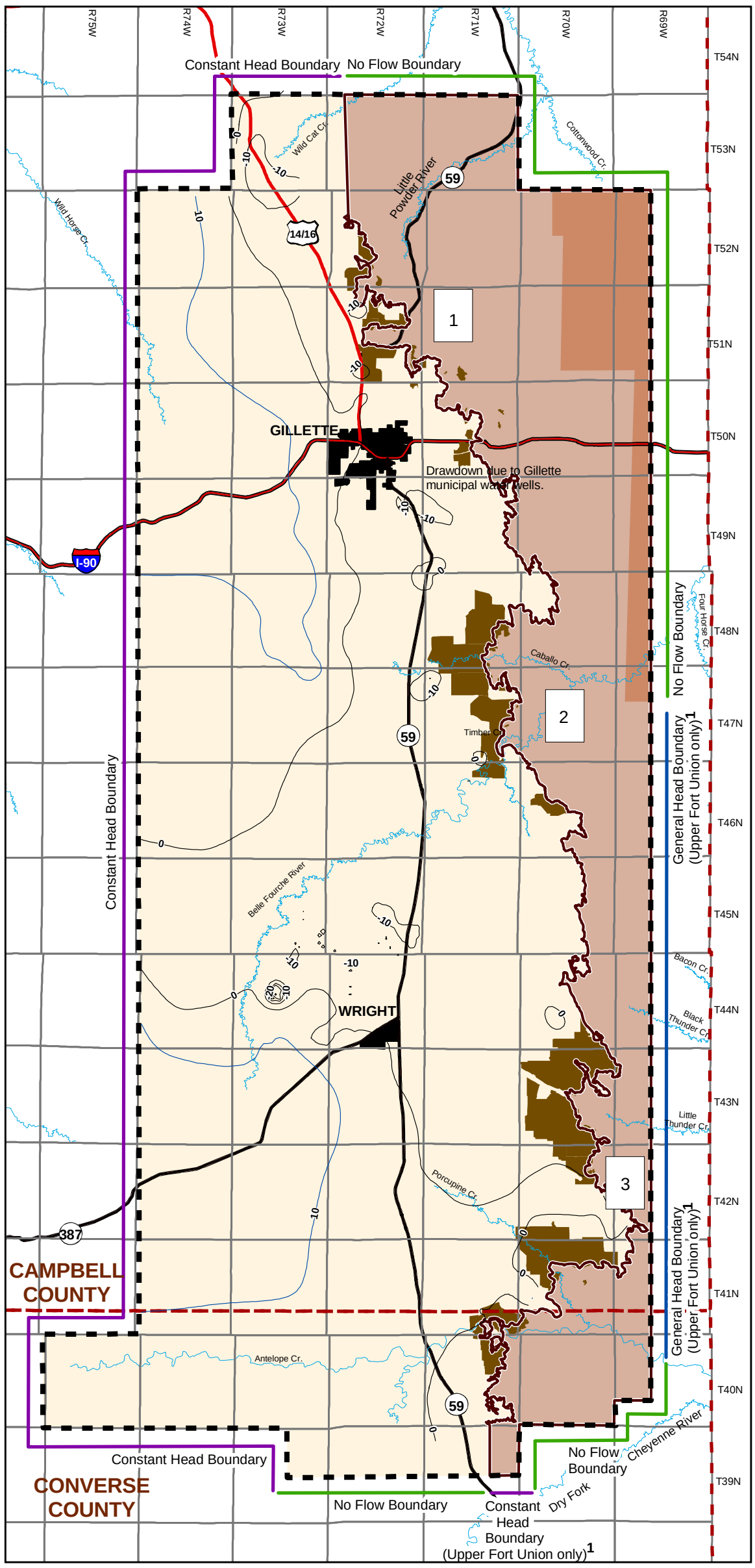
Contour Interval = 10 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

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



Powder River Basin Coal Review

Figure B-38

Wasatch Formation
2002 Base Year/2020 Prediction
CBNG-related
Groundwater Level Changes

N W E S

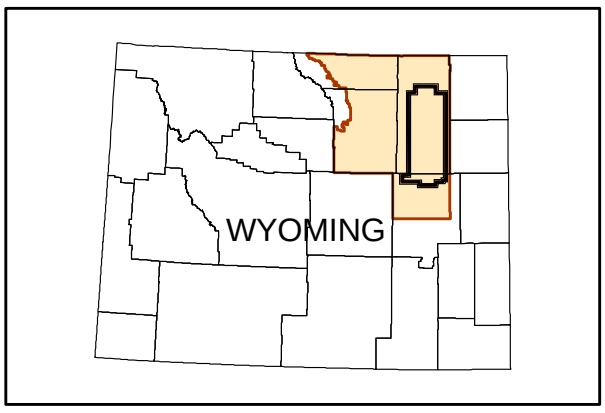
0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

Source: BLM 2009a, b.

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

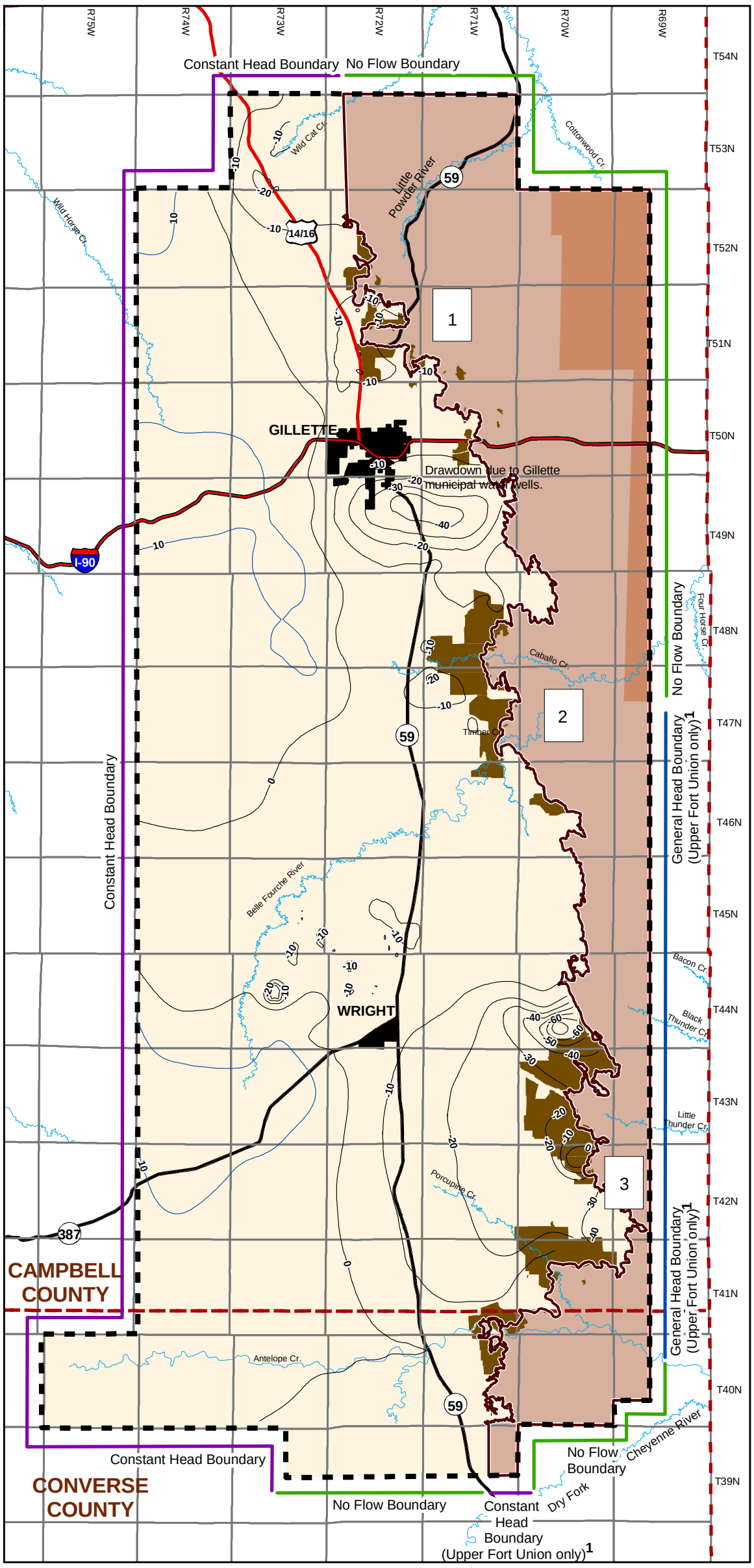
Contour Interval = 10 feet

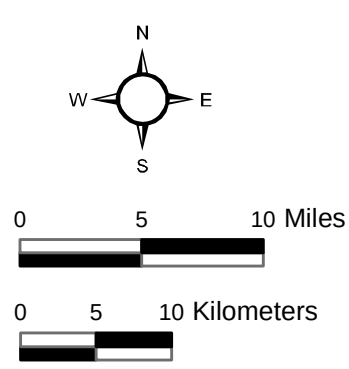
- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

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





[1]Boundary condition is No Flow Boundary for all other layers.

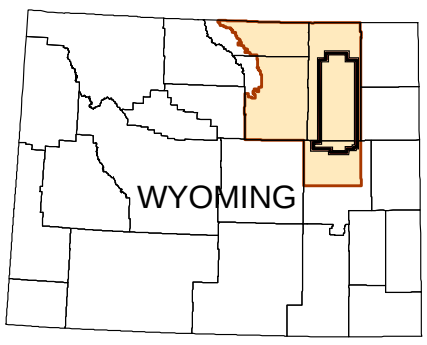
Source: BLM 2009a, b.

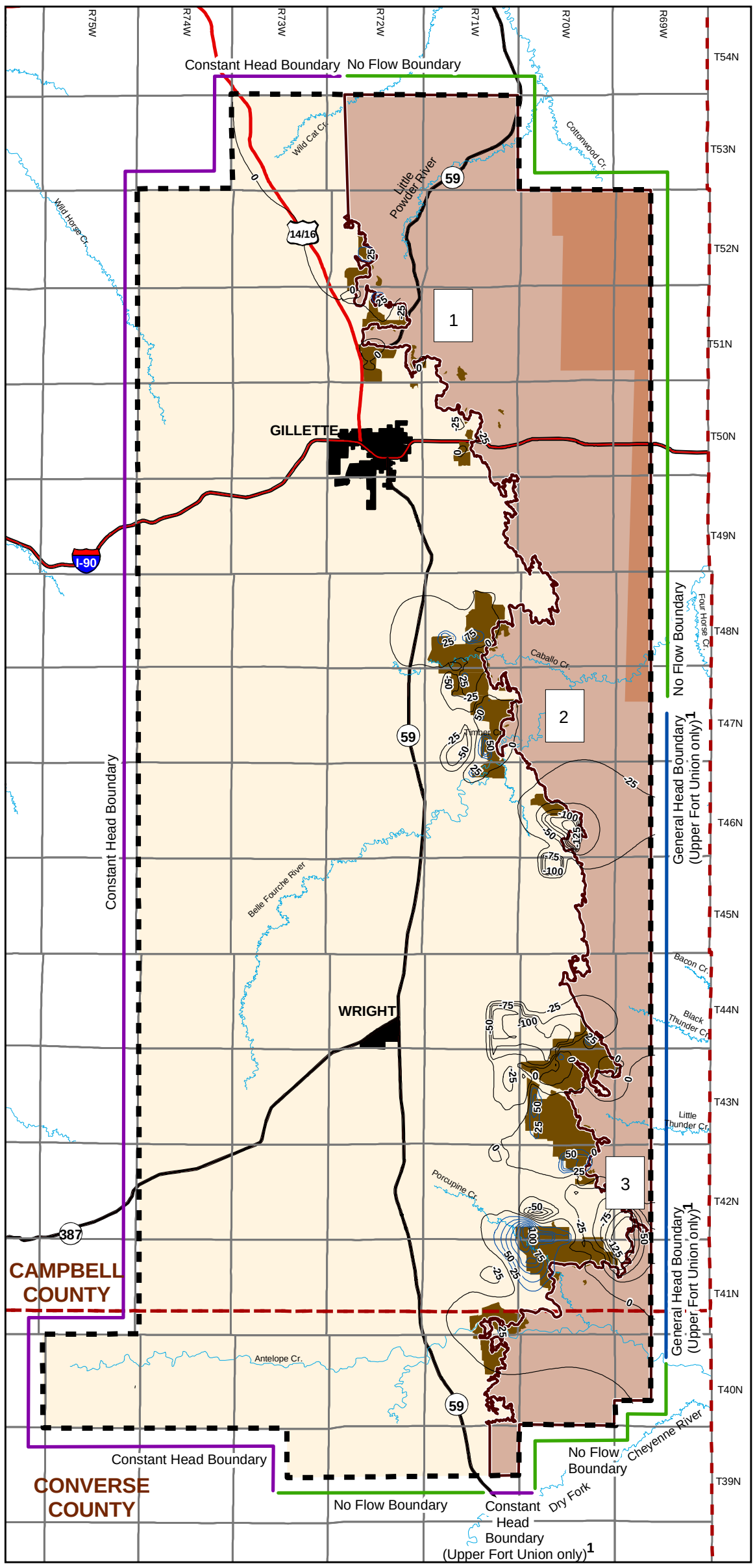
Powder River Basin Coal Review

Figure B-39

Wasatch Formation
2002 Base Year/2020 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine groundwater pumping.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

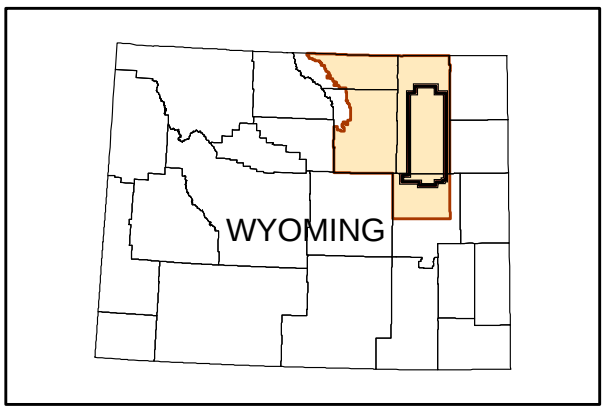
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-40

Upper Fort Union Formation
2002 Base Year/2020 Prediction
Coal Mine-related
Groundwater Level Changes

11/01/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

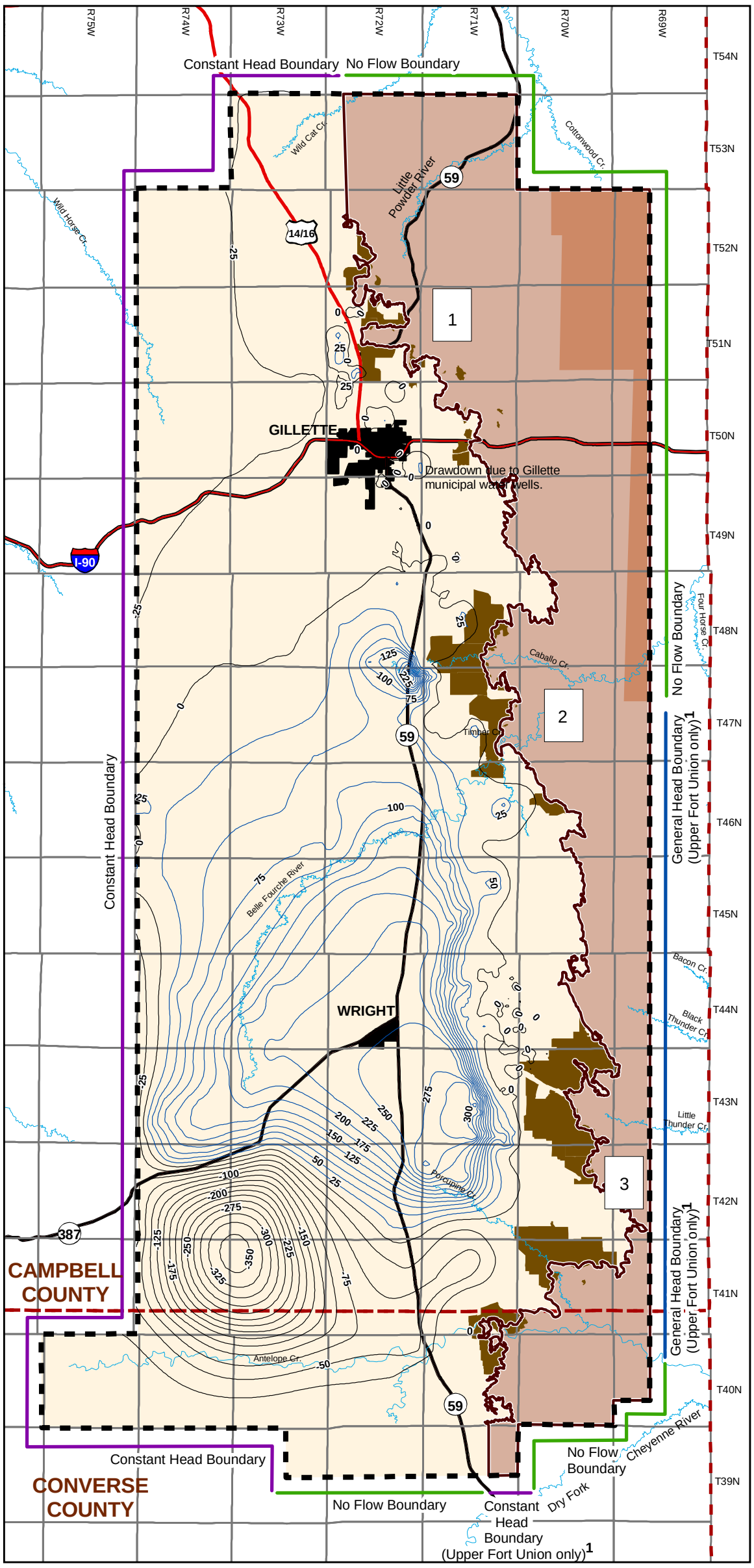
Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

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



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

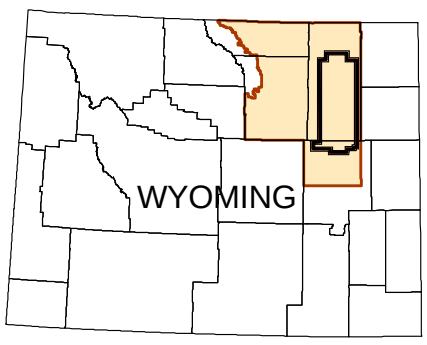
Source: BLM 2009a, b.

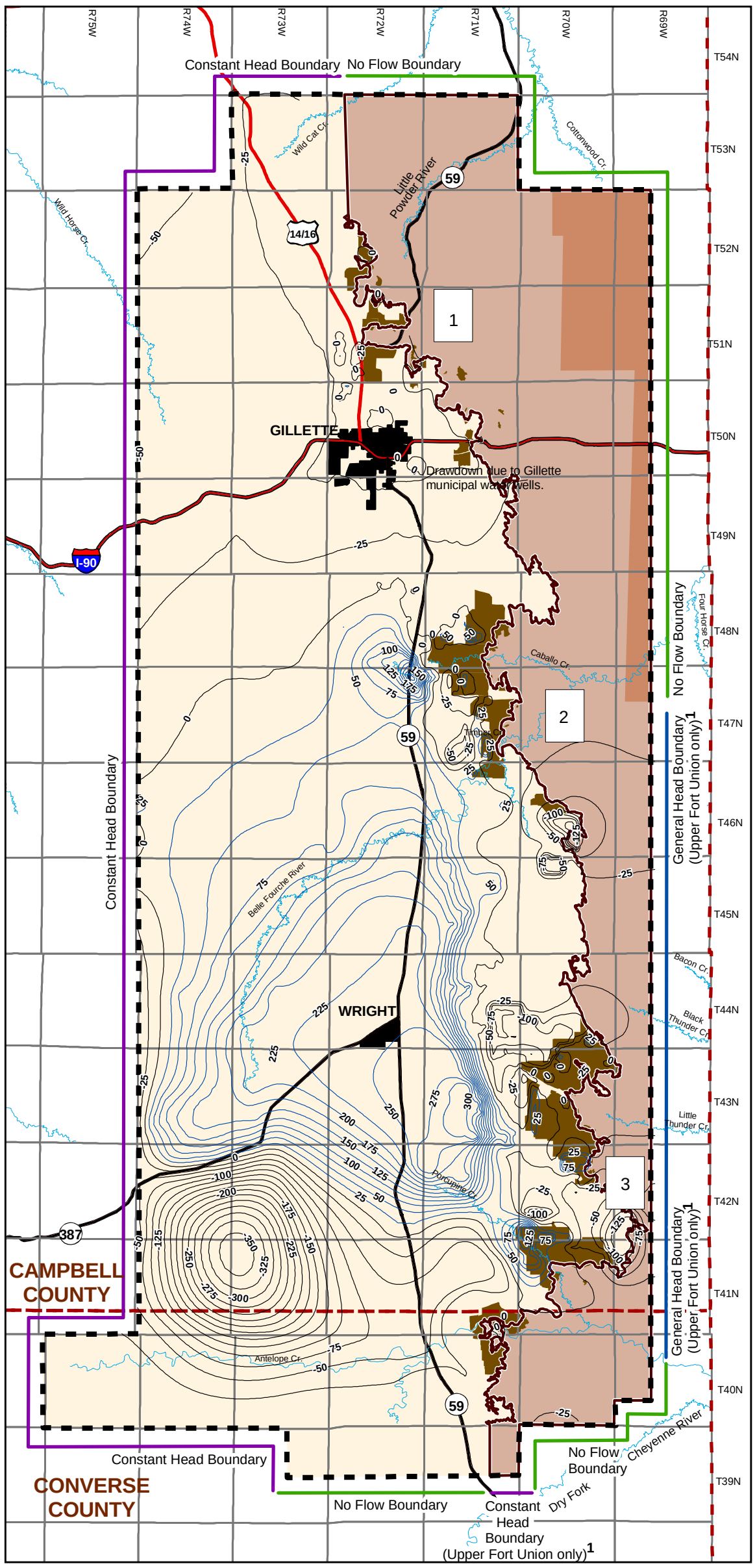
Powder River Basin Coal Review

Figure B-41

Upper Fort Union Formation
2002 Base Year/2020 Prediction
CBNG-related
Groundwater Level Changes

11/01/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater drawdown level contours
- Groundwater mounding level contours

Coal Mine Subregions

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

Notes: Includes effects of coal mine and CBNG groundwater pumping and CBNG water discharge.

In the Upper Fort Union, mounding in the coal mine areas is the result of groundwater rebound after mining.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

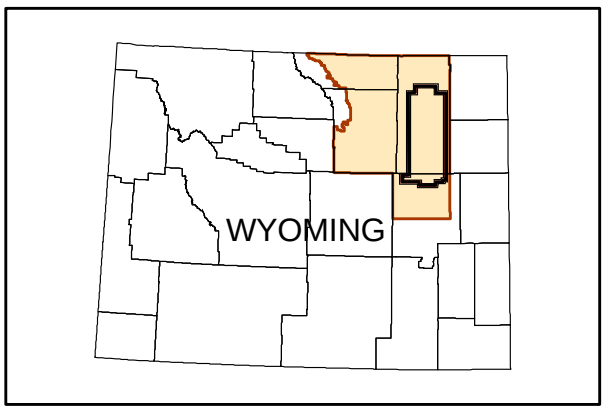
Source: BLM 2009a, b.

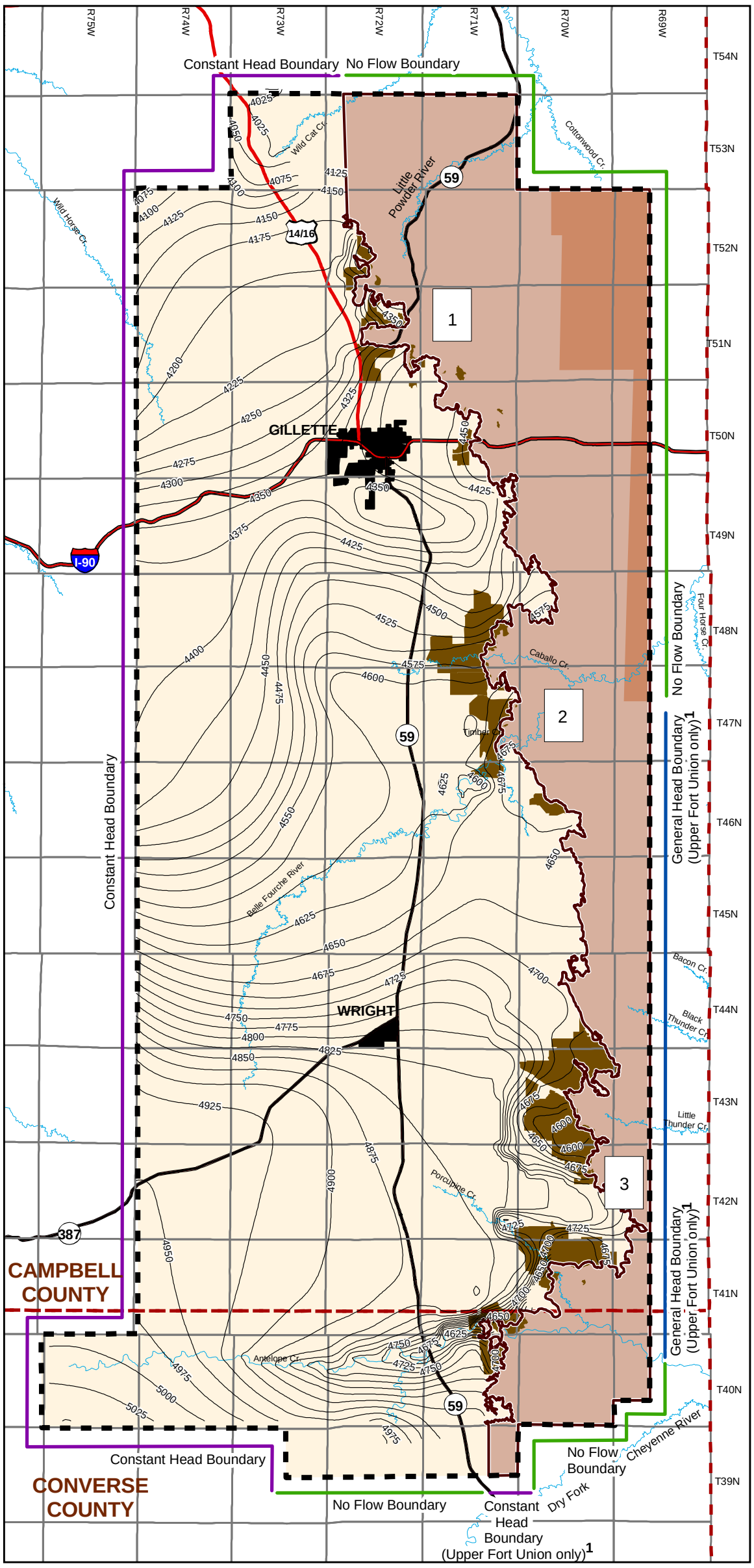
Powder River Basin Coal Review

Figure B-42

Upper Fort Union Formation
2002 Base Year/2020 Prediction
Coal Mine- and CBNG-related
Groundwater Level Changes

11/01/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

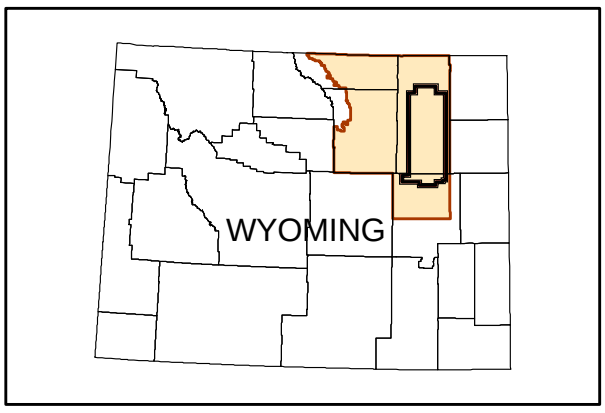
Source: BLM 2009a, b.

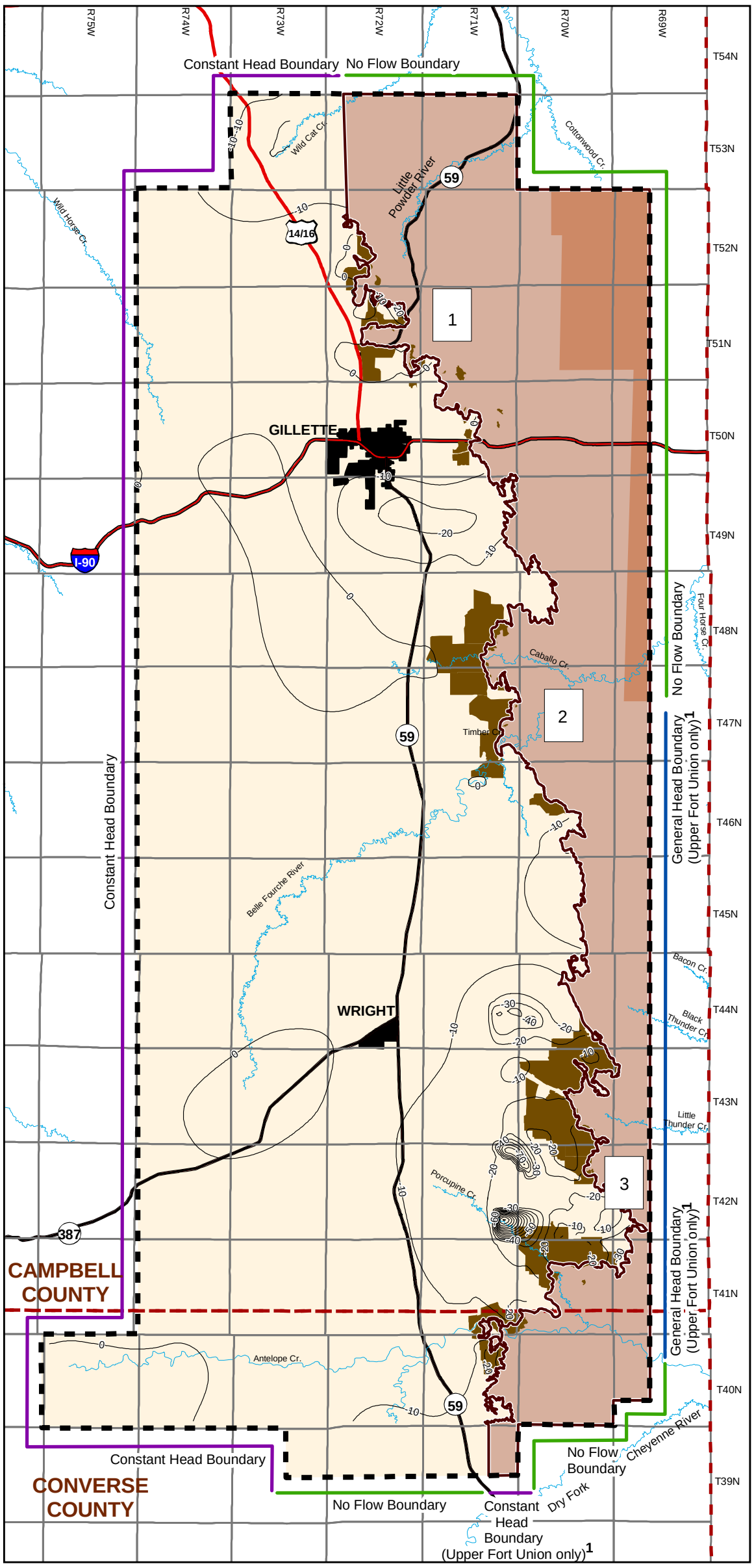
Powder River Basin Coal Review

Figure B-43

Wasatch Formation
1975 Base Year/2050 Prediction
20 Years of CBNG-related Recovery
Groundwater Levels

10/30/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 10 feet

- Groundwater rebound level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

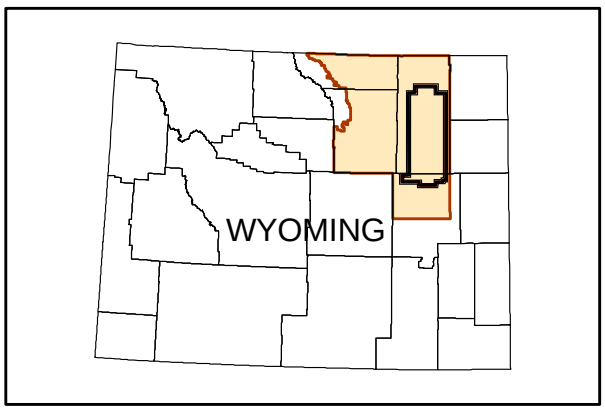
Source: BLM 2009a, b.

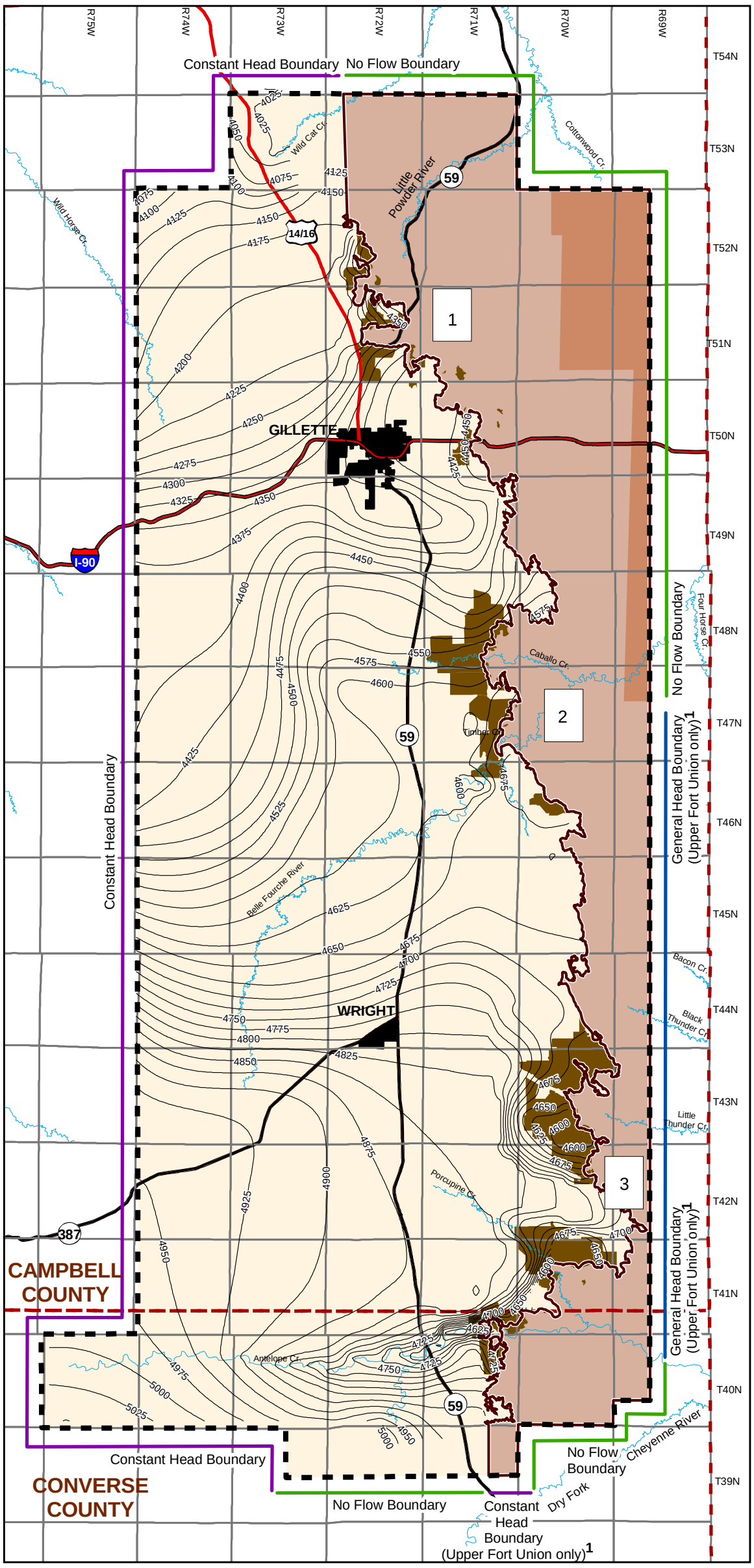
Powder River Basin Coal Review

Figure B-44

Wasatch Formation
1975 Base Year/2050 Prediction
20 Years of CBNG-related Recovery
Groundwater Level Changes

10/30/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

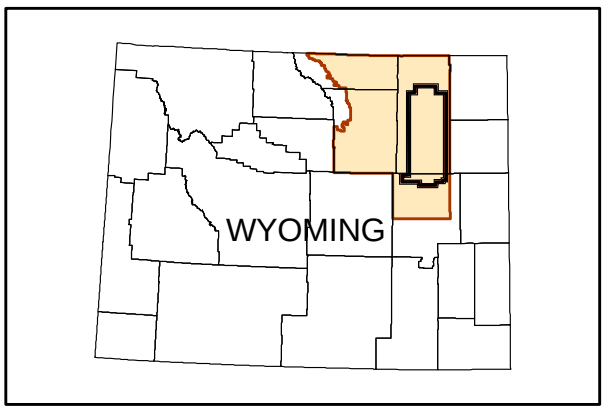
Source: BLM 2009a, b.

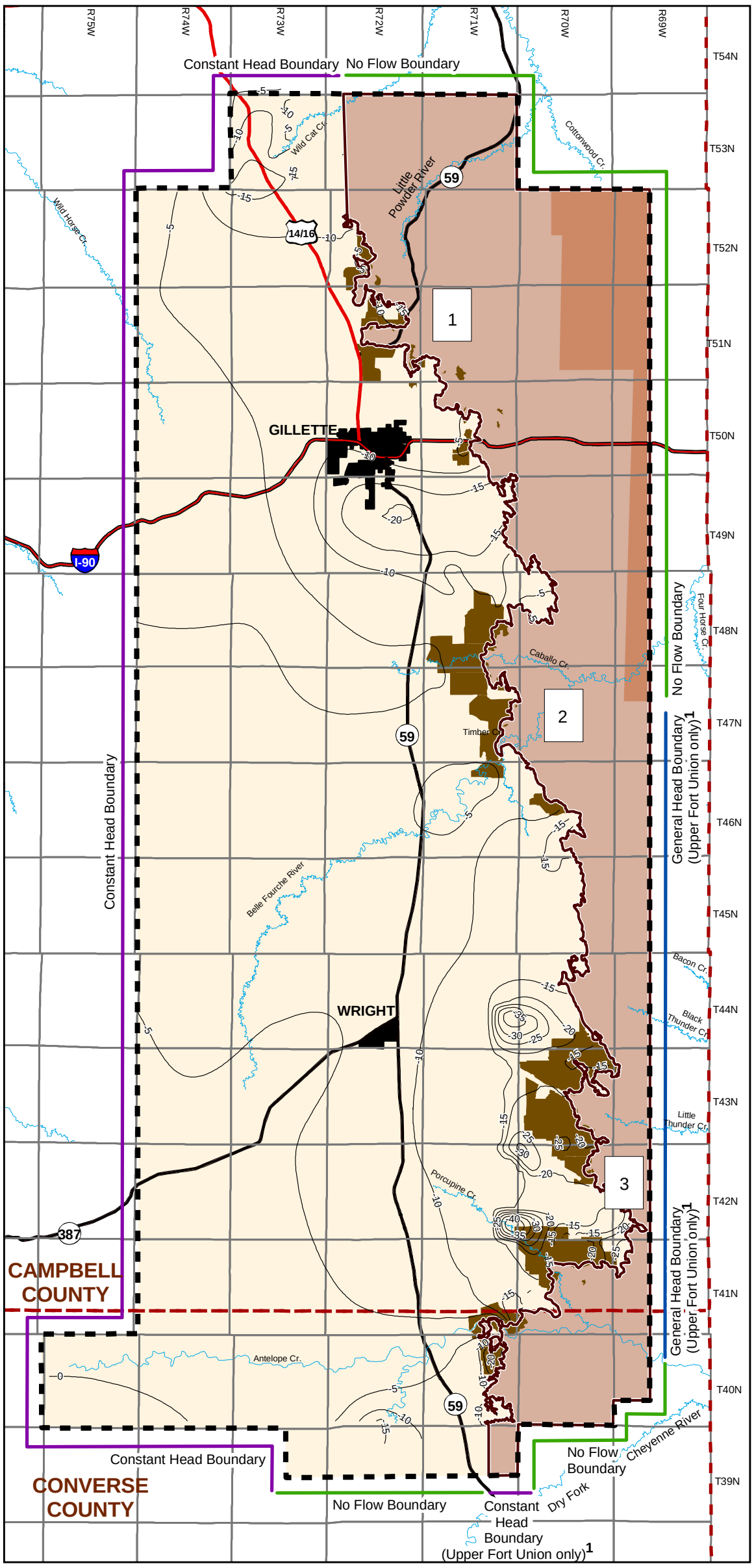
Powder River Basin Coal Review

Figure B-45

Wasatch Formation
1975 Base Year/2100 Prediction
50 Years of Recovery
Groundwater Levels

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 5 feet

- Groundwater rebound level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

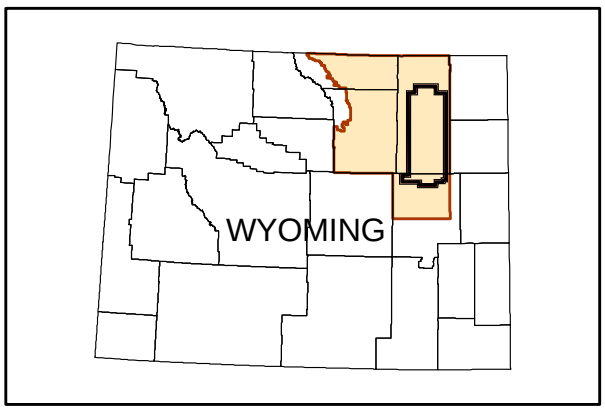
Source: BLM 2009a, b.

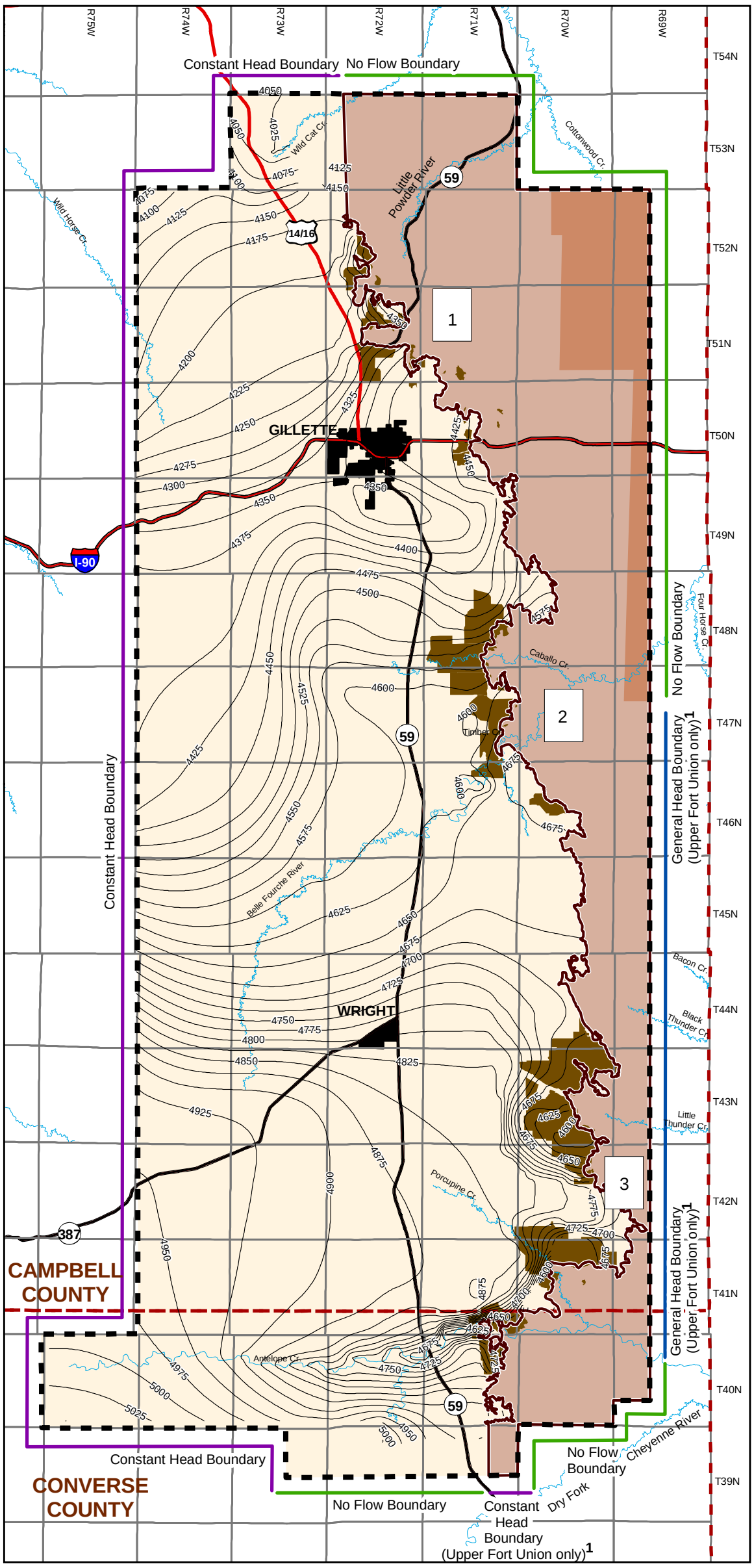
Powder River Basin Coal Review

Figure B-46

Wasatch Formation
1975 Base Year/2100 Prediction
50 Years of Recovery
Groundwater Level Changes

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

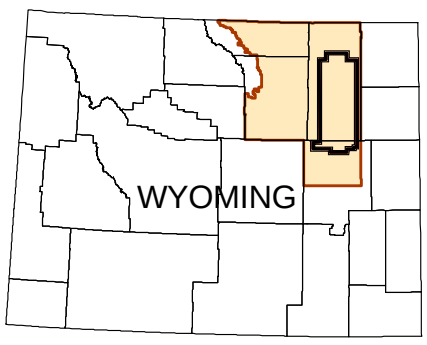
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-47

Wasatch Formation
1975 Base Year/2250 Prediction
200 Years of Recovery
Groundwater Levels

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 5 feet

- Groundwater rebound level contours

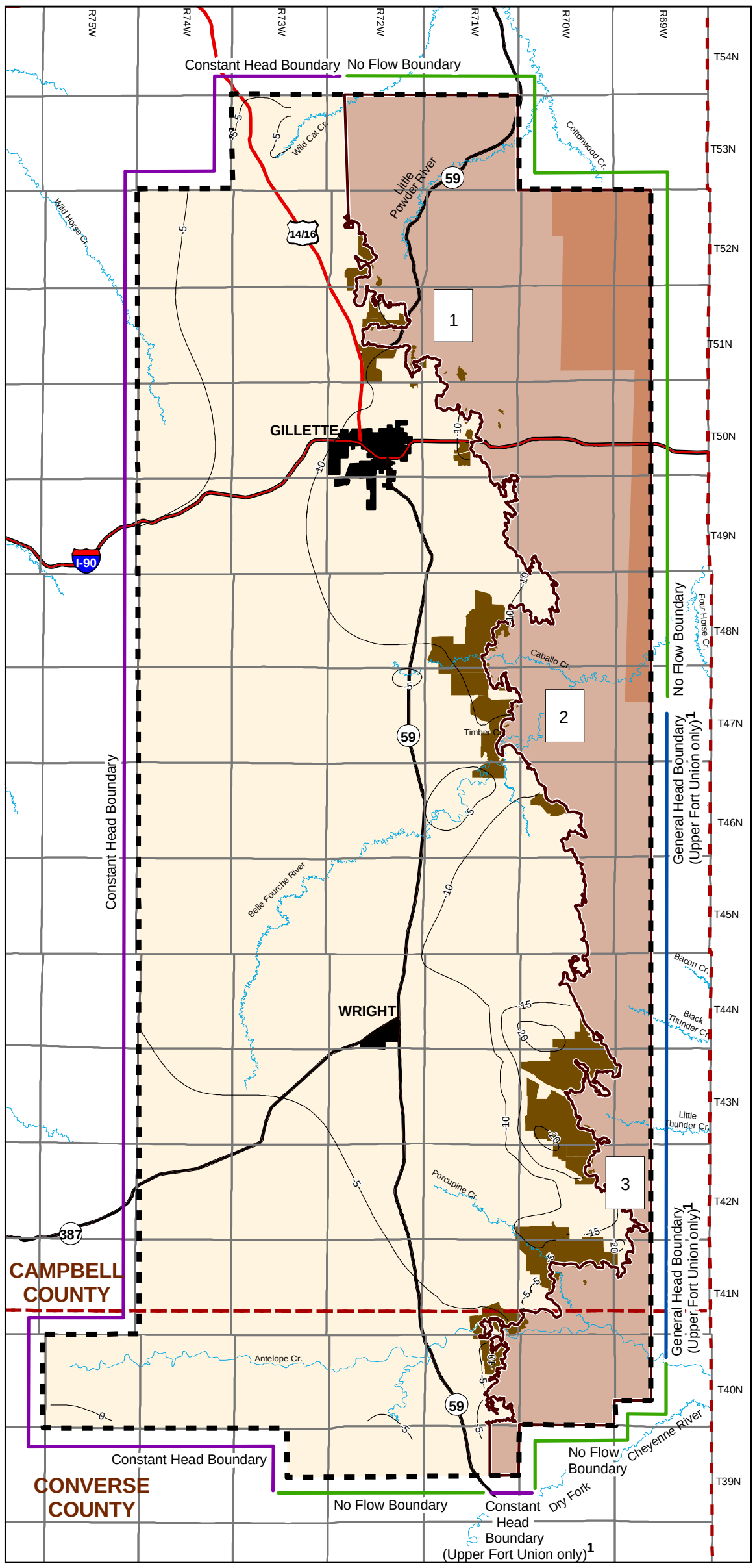
Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.



[1]Boundary condition is No Flow Boundary for all other layers.

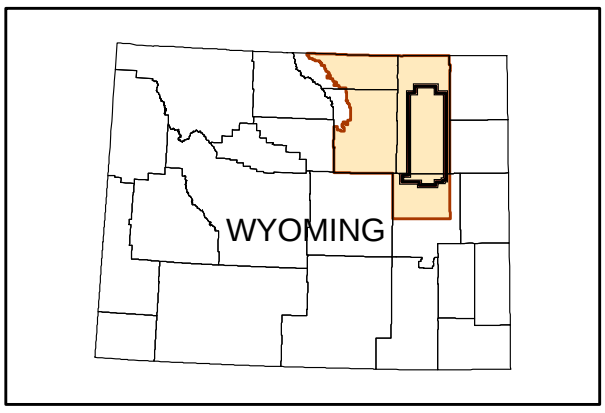
Source: BLM 2009a, b.

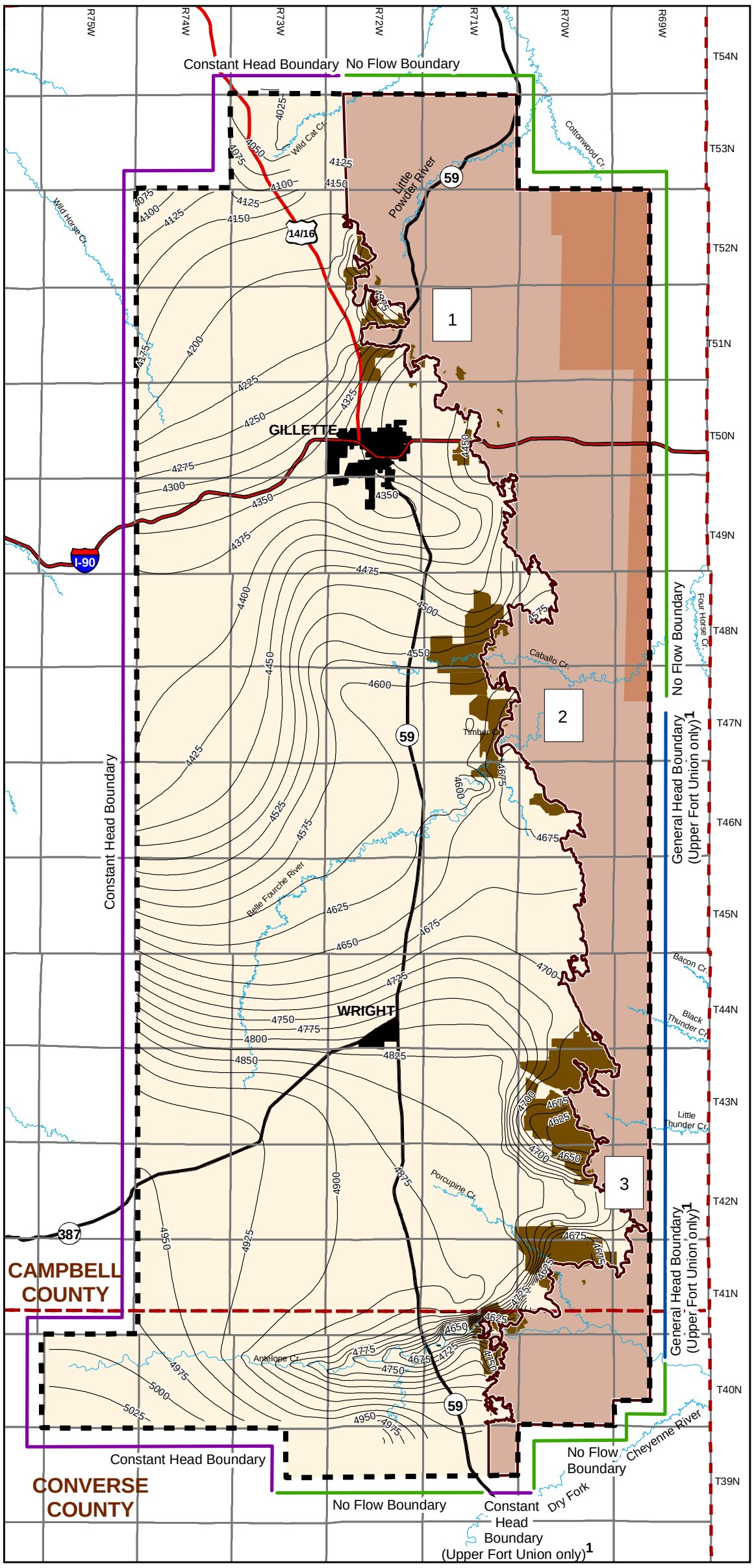
Powder River Basin Coal Review

Figure B-48

Wasatch Formation
1975 Base Year/2250 Prediction
200 Years of Recovery
Groundwater Level Changes

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

Groundwater level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

N W E S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

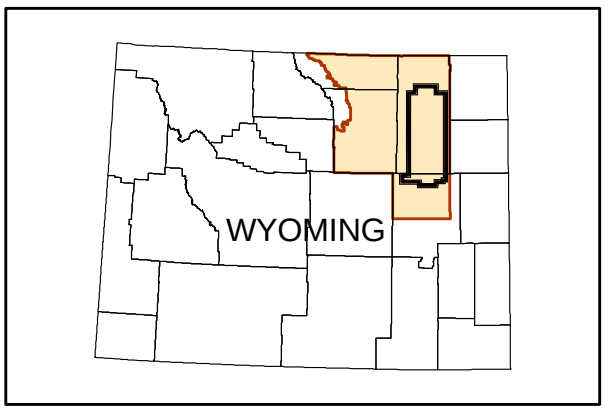
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-49

Wasatch Formation
Steady-state
Approximately 300-500 Years of Recovery
Groundwater Levels

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

Groundwater level contours

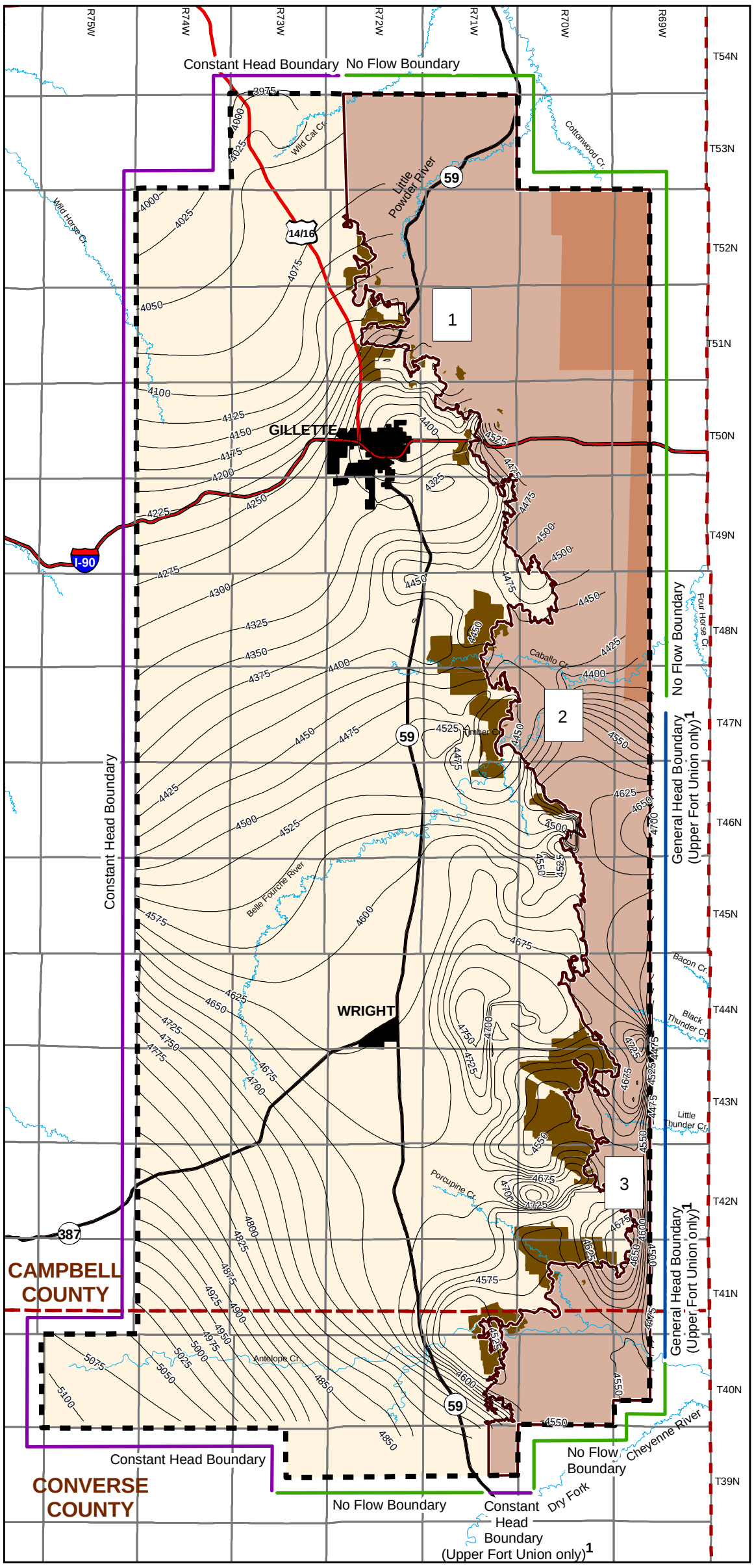
Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

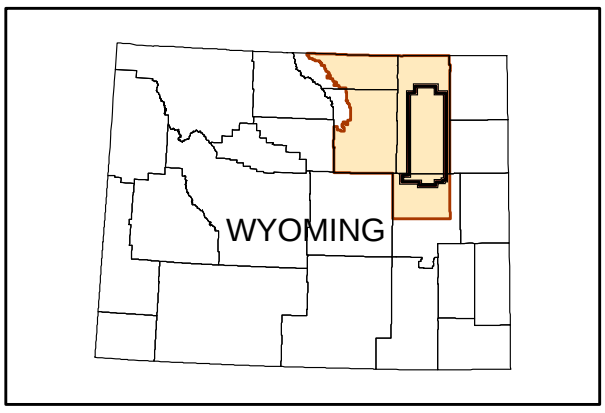
Source: BLM 2009a, b.

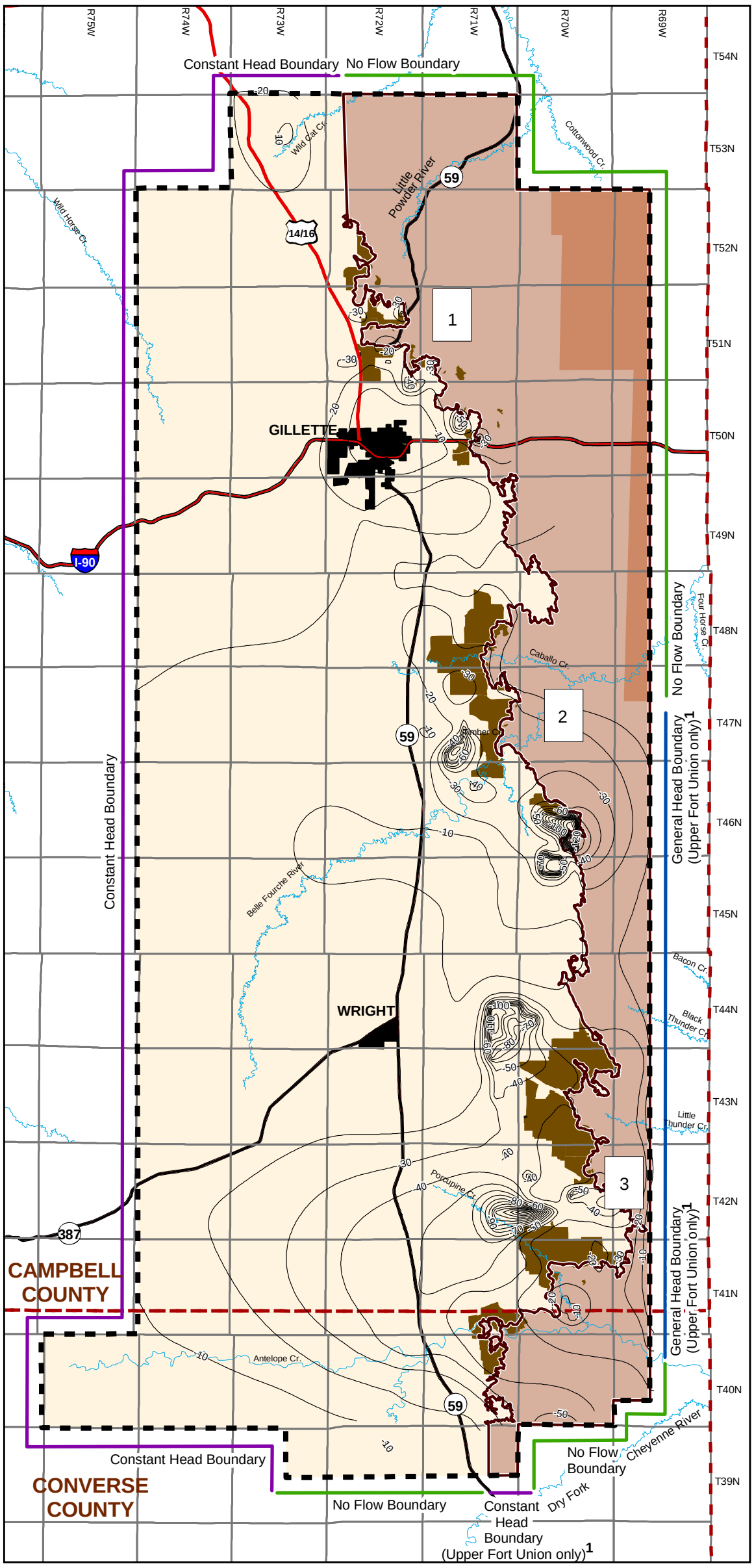
Powder River Basin Coal Review

Figure B-50

Upper Fort Union Formation
1975 Base Year/2050 Prediction
20 Years of CBNG-related Recovery
Groundwater Levels

10/30/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 10 feet

- Groundwater rebound level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

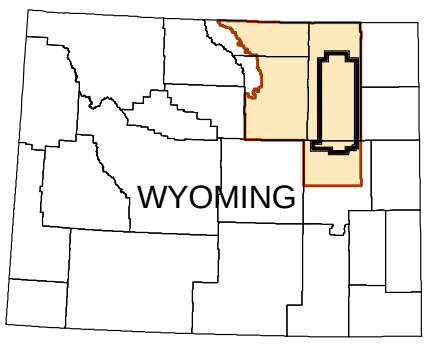
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-51

Upper Fort Union Formation
1975 Base Year/2050 Prediction
20 Years of CBNG-related Recovery
Groundwater Level Changes

12/11/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

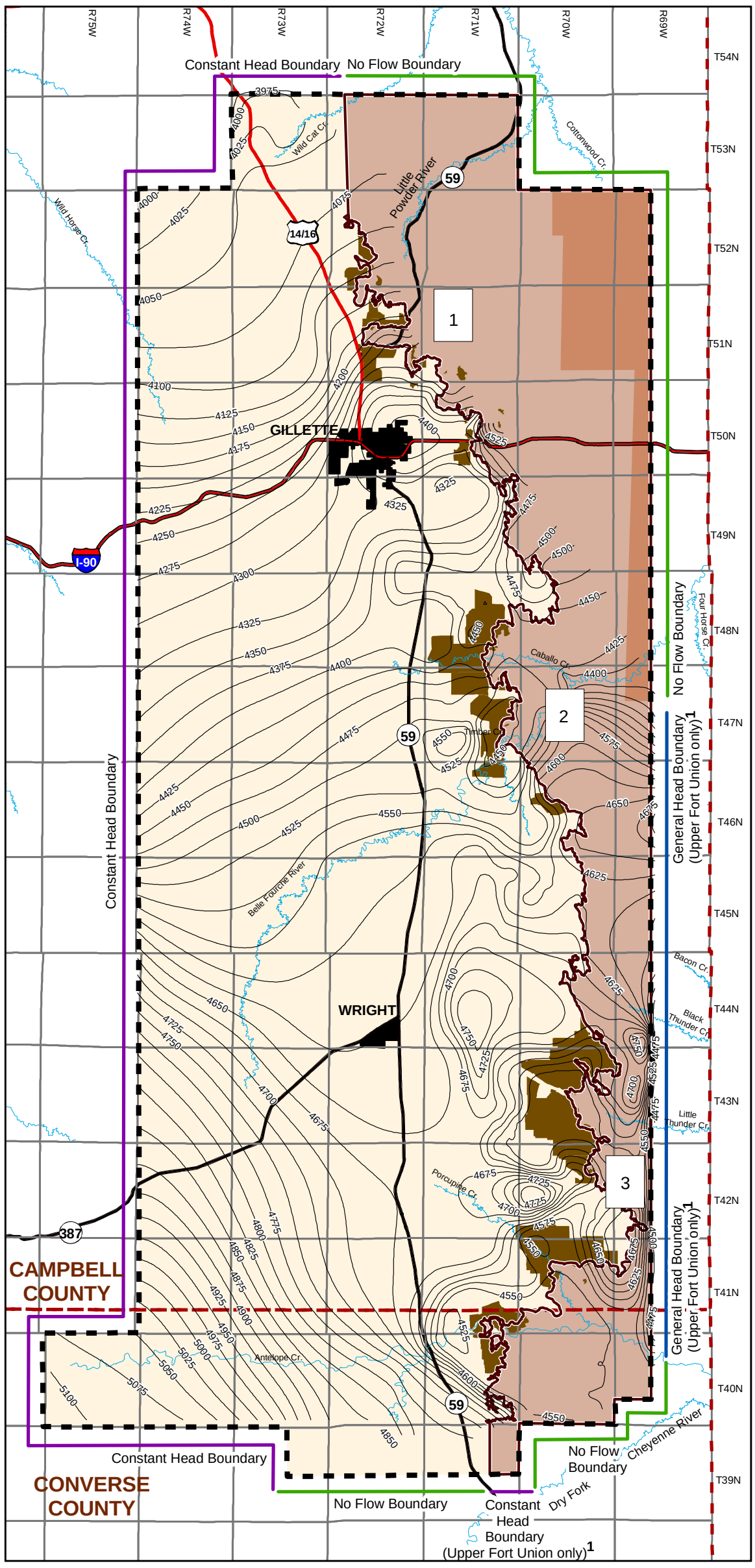
Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.



N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

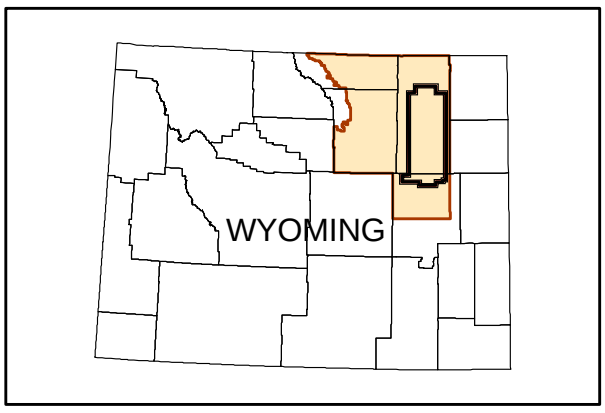
Source: BLM 2009a, b.

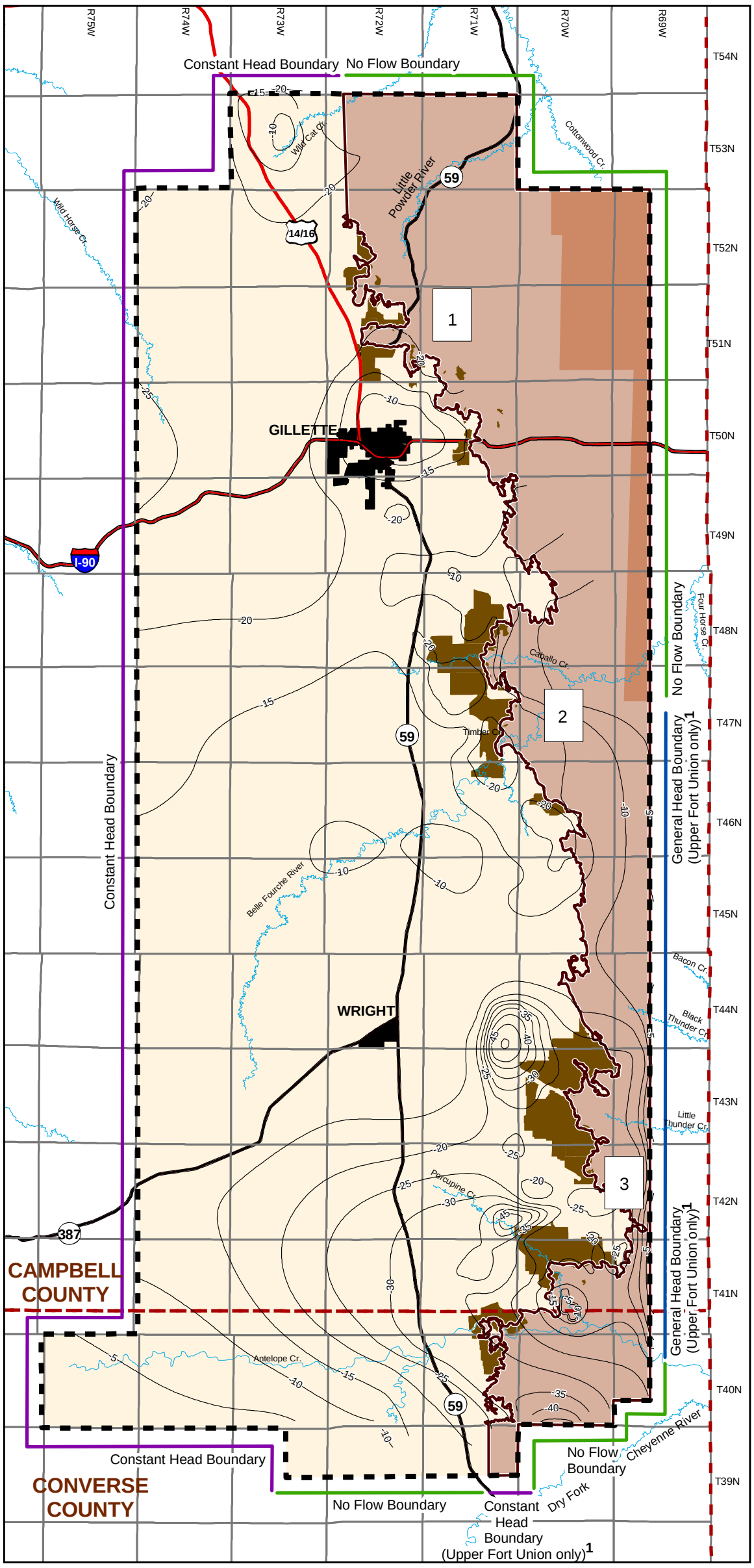
Powder River Basin Coal Review

Figure B-52

Upper Fort Union Formation
1975 Base Year/2100 Prediction
50 Years of Recovery
Groundwater Levels

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 5 feet

- Groundwater rebound level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

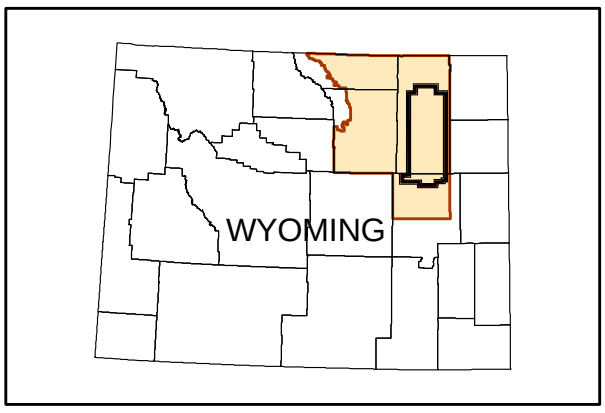
Source: BLM 2009a, b.

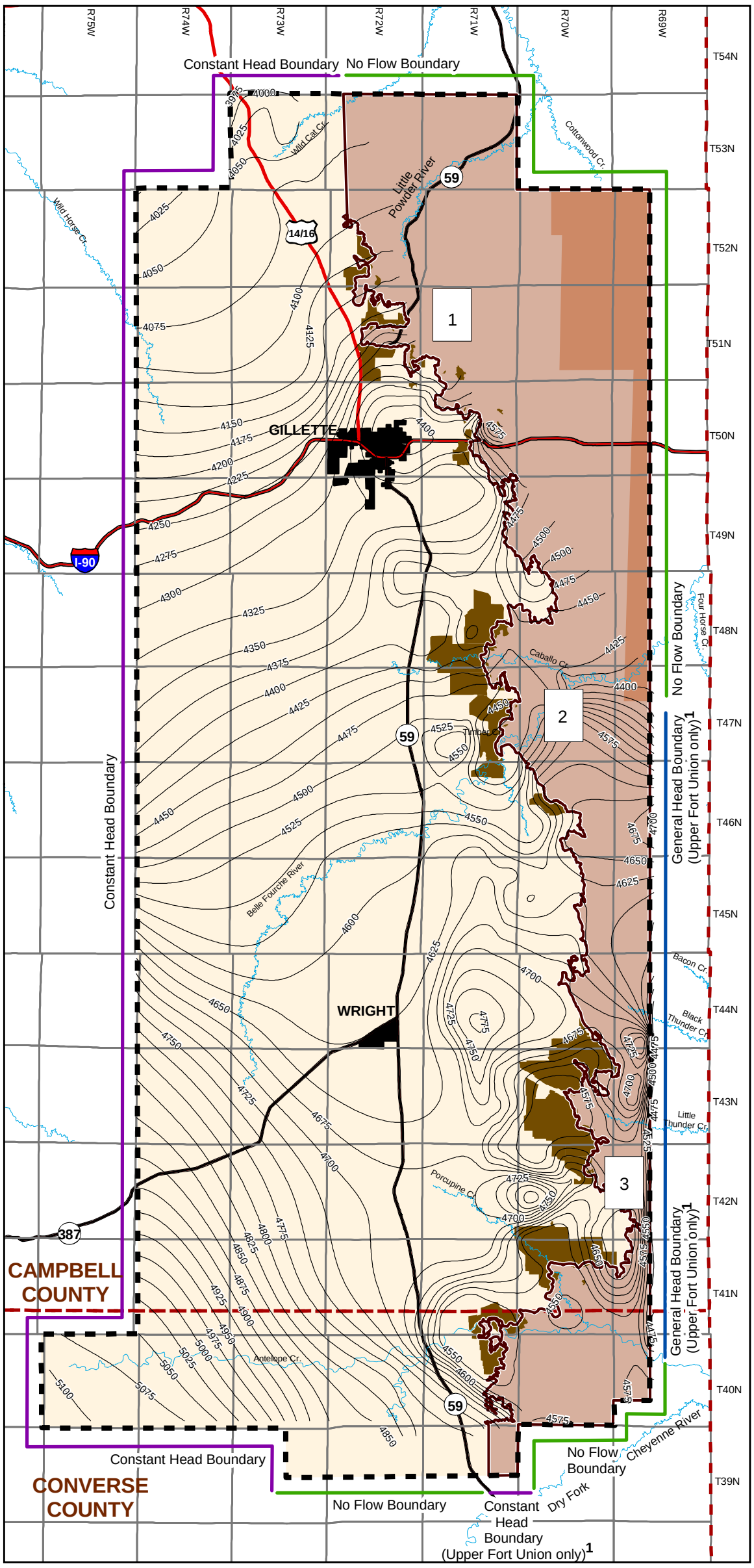
Powder River Basin Coal Review

Figure B-53

Upper Fort Union Formation
1975 Base Year/2100 Prediction
50 Years of Recovery
Groundwater Level Changes

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

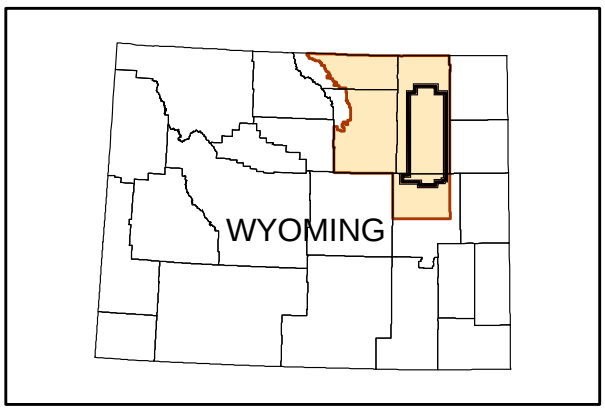
Source: BLM 2009a, b.

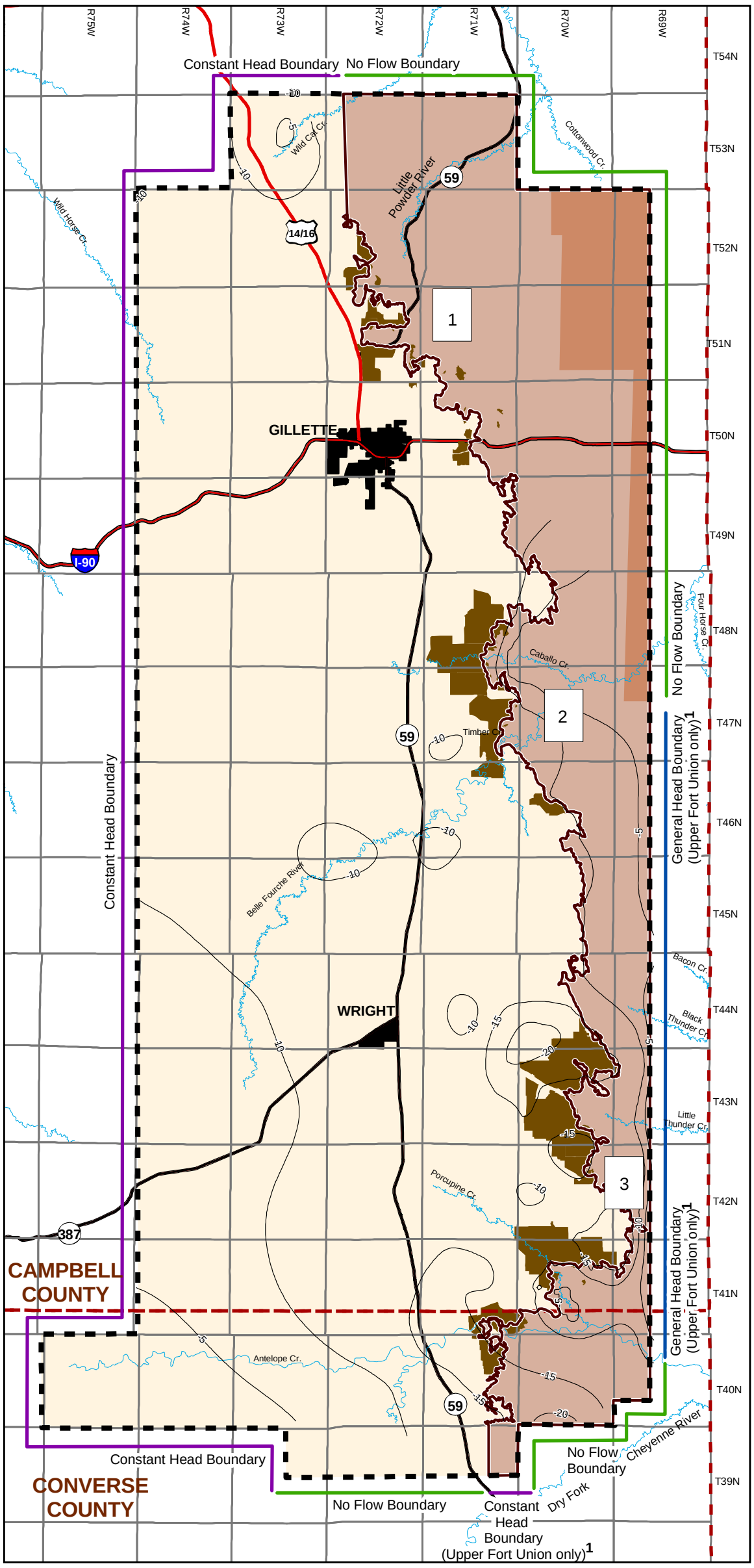
Powder River Basin Coal Review

Figure B-54

Upper Fort Union Formation
1975 Base Year/2250 Prediction
200 Years of Recovery
Groundwater Levels

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 5 feet

- Groundwater rebound level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

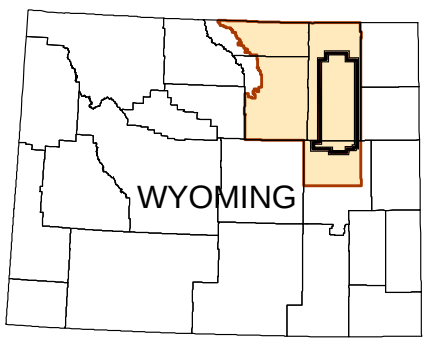
Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-55

Upper Fort Union Formation
1975 Base Year/2250 Prediction
200 Years of Recovery
Groundwater Level Changes

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

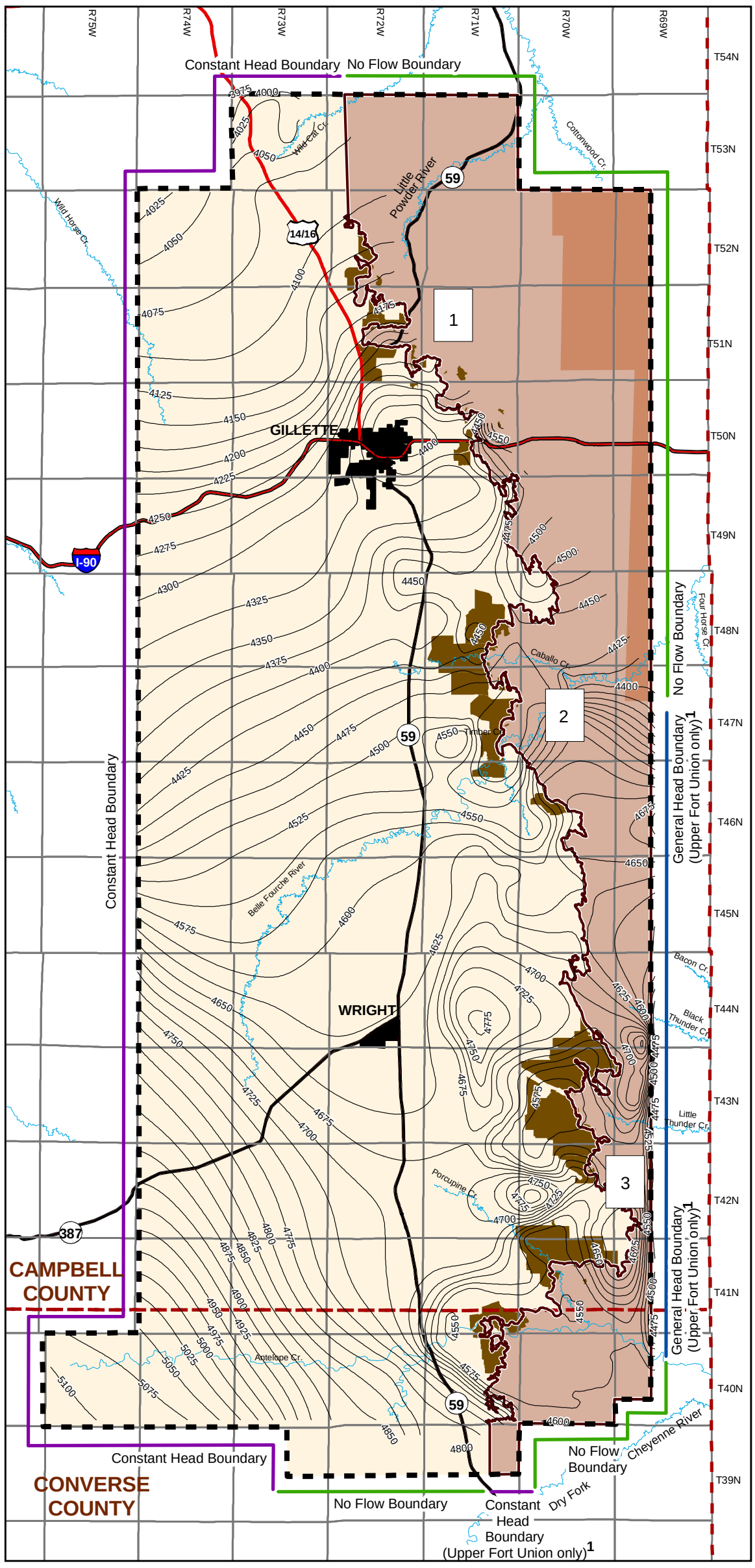
Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.



Powder River Basin Coal Review

Figure B-56

Upper Fort Union Formation
1975 Base Year/2350 Prediction
300 Years of Recovery
Groundwater Levels

N
W E
S

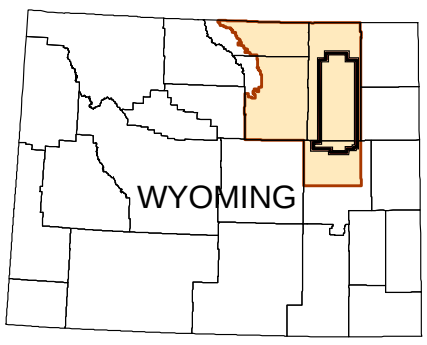
0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

Source: BLM 2009a, b.

11/02/09



Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 5 feet

- Groundwater rebound level contours

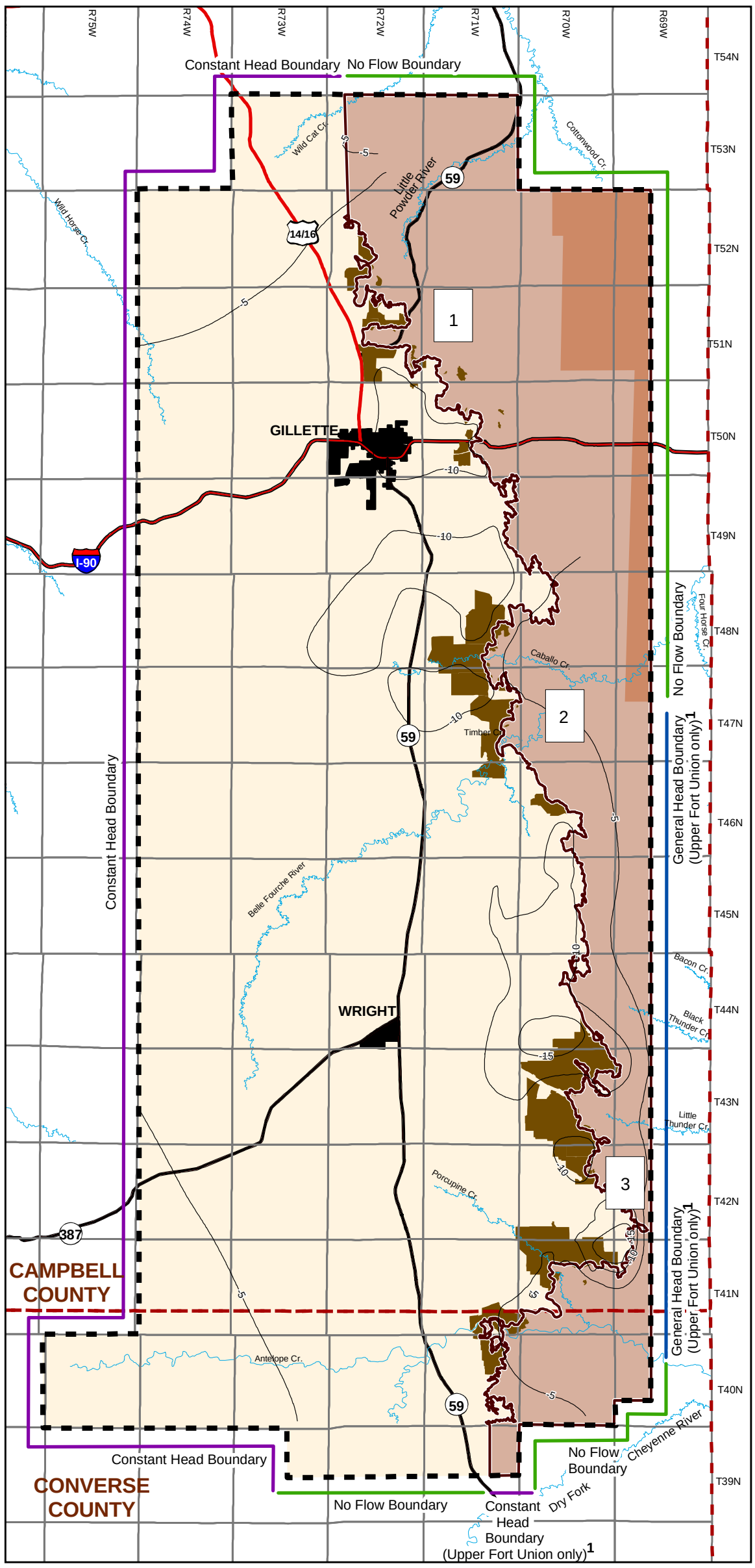
Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

Note: For resaturation modeling, CBNG activity was assumed to end in 2030. Coal mine pumpage and reclamation were assumed to end in 2050.



Powder River Basin Coal Review

Figure B-57

Upper Fort Union Formation
1975 Base Year/2350 Prediction
300 Years of Recovery
Groundwater Level Changes

N W E S

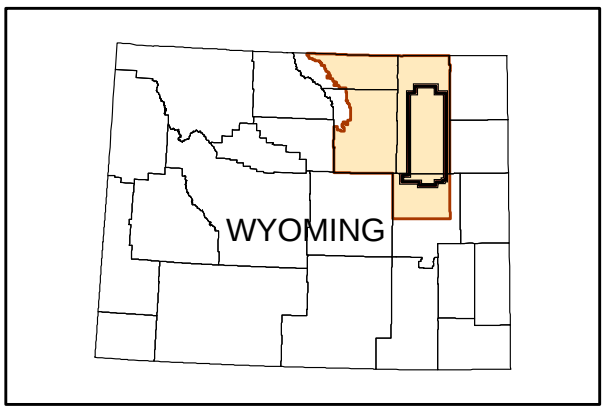
0 5 10 Miles

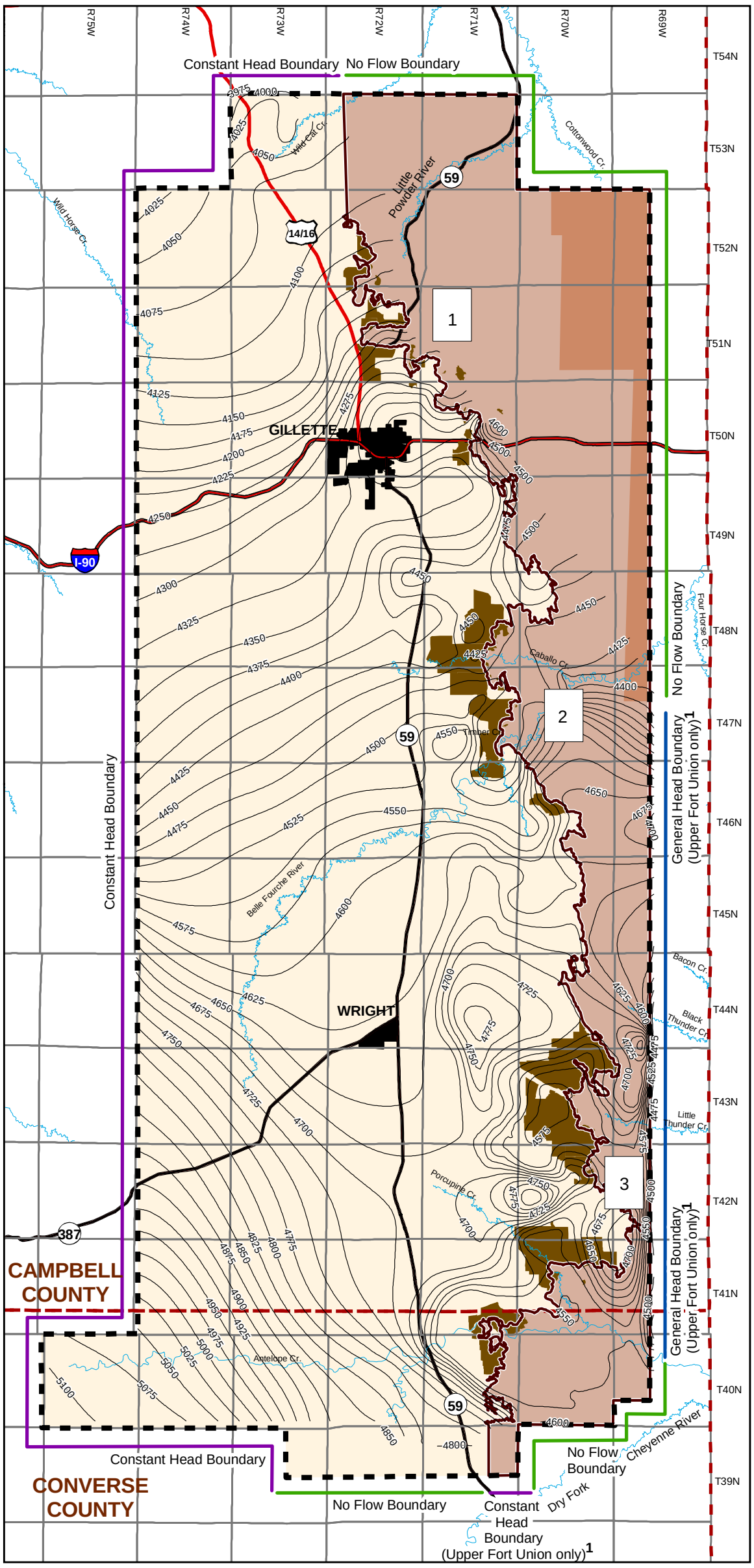
0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

Source: BLM 2009a, b.

11/02/09





Coal Mine Groundwater Model

Legend

- Approximate Coal Mined-out Area through 2006
- Groundwater Model Domain
- Wasatch Outcrop Area
- Upper Fort Union Outcrop Area
- Lower Fort Union Outcrop Area
- BLM Coal Outcrop Line
- Constant Head Boundary
- General Head Boundary
- No Flow Boundary
- County Line

Contour Interval = 25 feet

- Groundwater level contours

Coal Mine Subregions

1 Subregion 1 (North Gillette)

2 Subregion 2 (South Gillette)

3 Subregion 3 (Wright)

N
W E
S

0 5 10 Miles

0 5 10 Kilometers

[1]Boundary condition is No Flow Boundary for all other layers.

Source: BLM 2009a, b.

Powder River Basin Coal Review

Figure B-58

Upper Fort Union Formation
Steady-state
Approximately 300-500 Years of Recovery
Groundwater Levels

11/02/09