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

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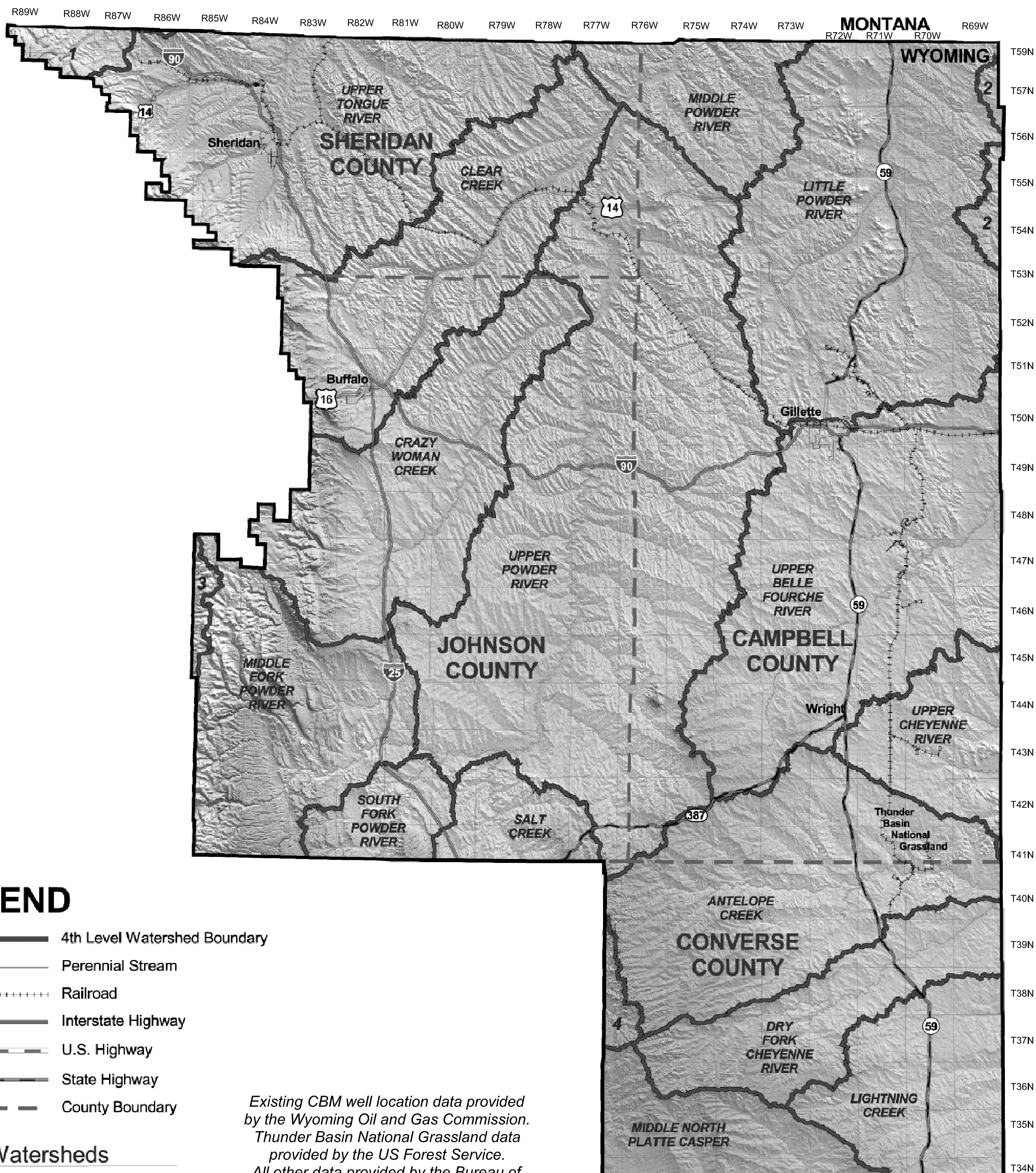
1.0 INTRODUCTION

This groundwater modeling report is a technical support document for the Powder River Basin Oil and Gas Environmental Impact Statement (PRB O&G EIS). The Project Area covers the Wyoming part of the Powder River Basin (PRB), as shown in Figure 1-1. The intent of the EIS is to provide an overall projection of impacts associated with development of coal bed methane (CBM) and non-CBM oil and gas and to address the specific issues that were raised in public meetings held to discuss the proposal to develop CBM on federal lands in the PRB. This technical document describes the groundwater flow modeling that was used to evaluate the impacts associated with CBM development. The modeling did not include development of non-CBM oil and gas but included the impacts associated with coal mining operations.

The majority of the methane gas contained in the PRB coals is adsorbed in coal pores under hydrostatic pressure. The hydraulic pressure is reduced by pumping groundwater from production wells completed in the target coal to develop the methane gas resource. This reduction in hydraulic pressure allows the methane gas to desorb from pores in the coal and migrate to cleats and fractures in the coal by diffusion. The methane is transported to production wells by fractures under the prevailing pressure gradients. The gas and the water typically separate within the production well casing so that the gas can be piped directly from the wellhead. Pumped water would be managed in several ways, including discharge to local surface drainages (with or without prior treatment), infiltration via shallow impoundments, storage in reservoirs (containment), injection into deeper geologic units via wells, and land application.

A major potential impact associated with CBM development involves groundwater resources. Specifically, concern arises from the potential of CBM development to lower groundwater levels significantly. Numerical groundwater flow modeling was used to predict the impacts to groundwater from CBM development in the PRB. The model also included the superimposed influences of surface coal mining operations. Modeling was necessary because of the large extent and variability of the cumulative stresses imposed by mining and CBM development on the aquifer units of the PRB. This work was supplemented with existing trends in data to support conclusions. Produced water is managed in various ways that allow a certain proportion of the produced water to infiltrate into the subsurface and recharge aquifers. The model was used to evaluate the impacts of various water management strategies on recharge to the groundwater system.

Alternative 1 (Proposed Action) would add 39,367 new wells over a 10-year development period from 2002 to 2011, and involves three alternatives for water management. Alternative 1 assumes a mix of surface discharge, infiltration impoundments, containment impoundments, injection, and land application, but emphasizes surface discharge. Alternative 2A emphasizes infiltration and Alternative 2B includes treatment of pumped groundwater for beneficial use. Alternative 3 (No Action) assumes that new production wells would be developed only on non-federal mineral ownership lands over the development period. These development and water management scenarios are described in more detail in Chapter 2 of the final EIS (FEIS).



LEGEND

- 4th Level Watershed Boundary
- Perennial Stream
- Railroad
- Interstate Highway
- U.S. Highway
- State Highway
- County Boundary

Sub-Watersheds

1--Little Bighorn River
2--Little Missouri River
3--North Fork Powder River
4--Salt Creek

Existing CBM well location data provided by the Wyoming Oil and Gas Commission. Thunder Basin National Grassland data provided by the US Forest Service. All other data provided by the Bureau of Land Management-Buffalo Field Office and Casper Field Office.

Transverse Mercator Projection
1927 North American Datum
Zone 13

N

10 0 10 20 30 Miles

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TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 1-1
PROJECT LOCATION MAP

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

Date: 09/04/02	Drawing File: Figure 1-1.dwg
Scale: As Noted	Drawn By: ETC

In developing a CBM project, a portion of the water contained in the coal aquifer is removed at specific locations, releasing methane gas for collection. The primary impact to groundwater associated with development of CBM in the PRB involves removal of groundwater stored within the target coal seams. This removal results in loss of available hydraulic head in the coal seams of the upper portion of the Fort Union Formation. This loss in head (drawdown) could affect water wells completed in the coal seams in the form of reduced well yields and potential emissions of methane.

Reduction in head within the coal aquifer can induce leakage from overlying and underlying zones, leading to reduced hydraulic head in these aquifers as well. The extent of leakage (and reduction in head) is largely a function of the vertical permeability of the geologic units that separate these aquifer units from the coal. Natural discharge of springs may be affected by this reduction in hydraulic head in the source aquifer unit. Infiltration of CBM-produced water may cause new springs or seeps to develop.

Surface discharge of extracted groundwater from CBM operations into surface drainages and constructed impoundments will enhance recharge of shallow aquifers below creeks and ponds. Similarly, injection of produced CBM water will recharge the aquifer units within the injection zones where the injection wells are completed. The influence of various water handling options was addressed by the modeling in terms of recharge to the groundwater system.

2.0 HYDROGEOLOGIC FRAMEWORK

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

2.1 Location

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

2.2 Geology of the Powder River Basin

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

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

2.2.1 Alluvium

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

2.2.2 Wasatch Formation

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

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

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

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

2.2.3 Fort Union Formation

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

Tongue River Member

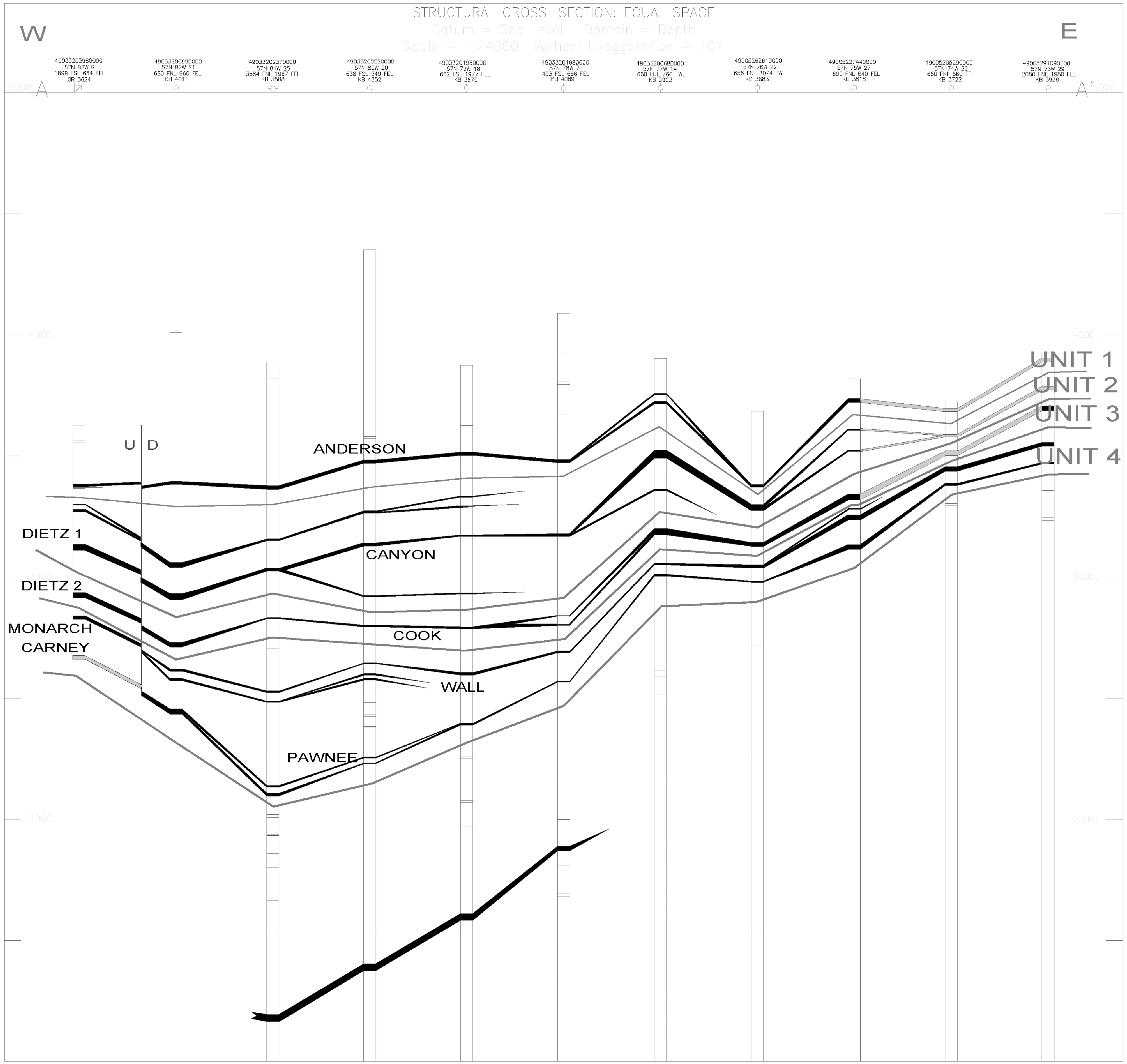
The upper part of the Fort Union Formation has been identified as the Tongue River Member in the northern part of the PRB. It contains seven to nine major coal seams (WSGS 1996a, 1996b, USGS 1999a, 1999b) and many discontinuous, lenticular sandstone layers. CBM development focuses on the thick coal seams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

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

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

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

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



LEGEND

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

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

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

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

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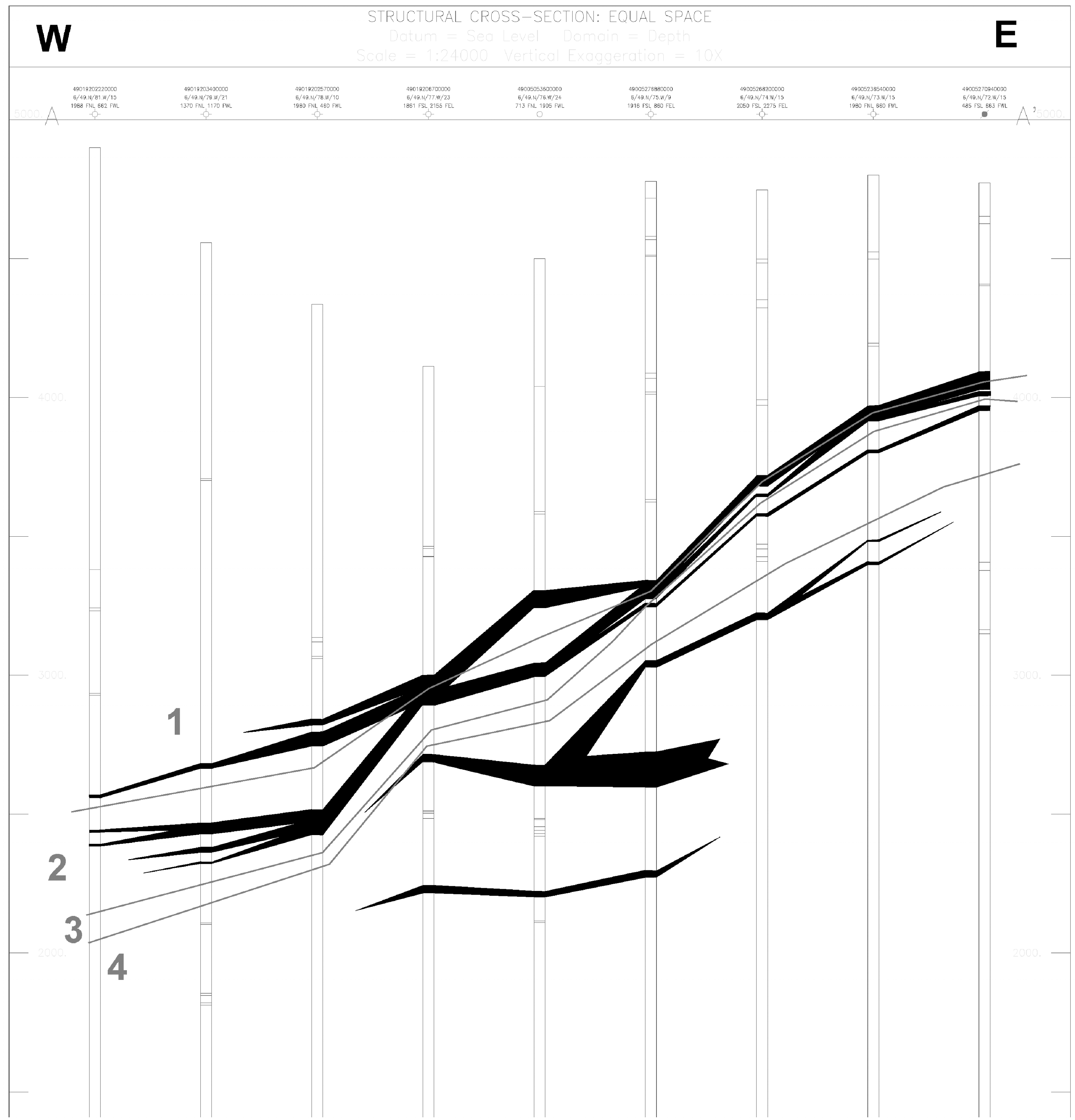
Scale: NTS	Drawn By: ETC

Figure 2-1A continued (11x17)



LEGEND

For Union Hydrologic Groups
(Refer to Figure 2-2)
1 or Unit 1 Represents Group 1
2 or Unit 2 Represents Group 2
3 or Unit 3 Represents Group 3
4 or Unit 4 Represents Group 4

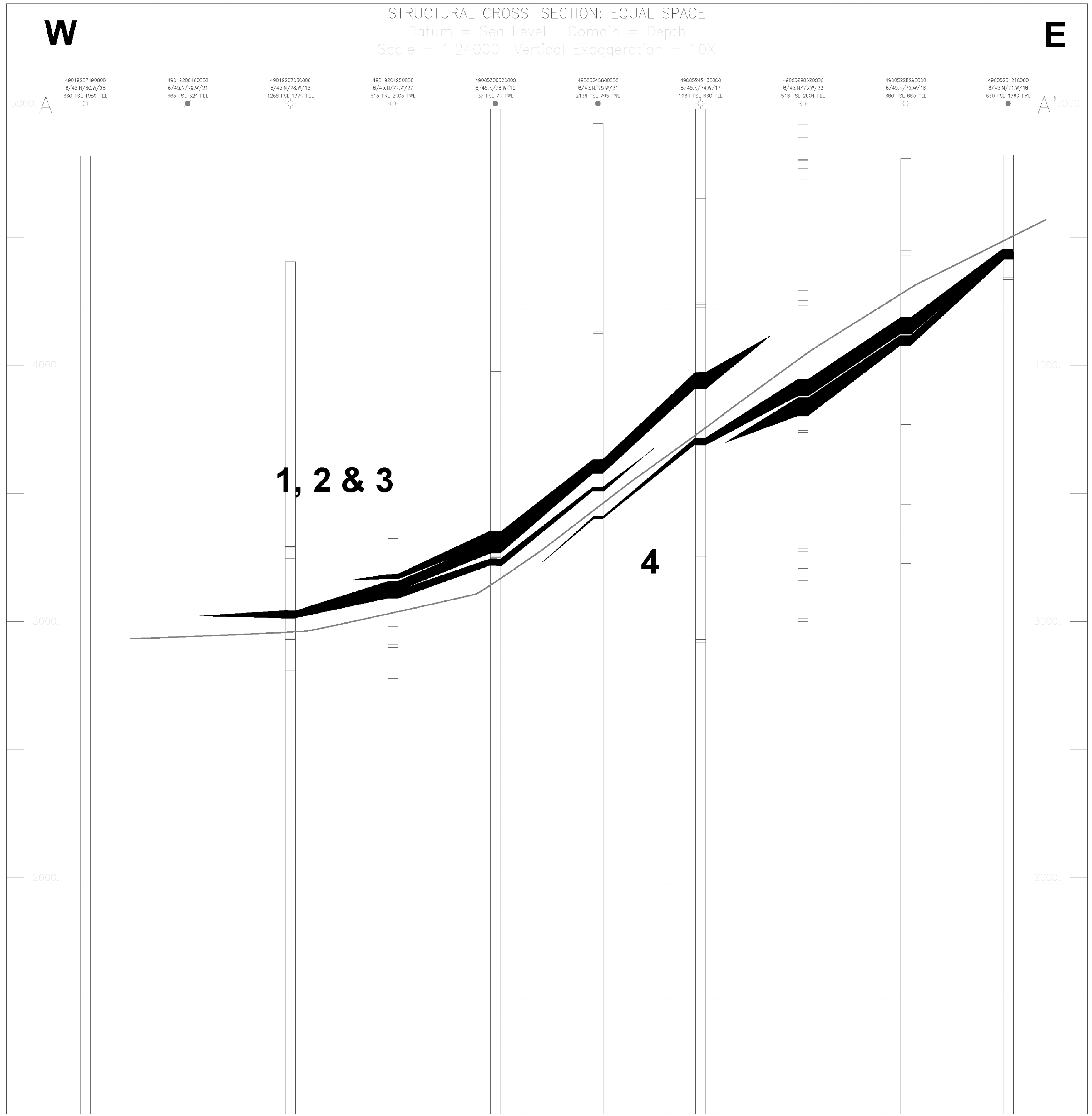
POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

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

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

Figure 2-1B continued (11x17)



LEGEND

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

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

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

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

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

Date: 09/04/02	Drawing File: Figure 2-1abc.dwg
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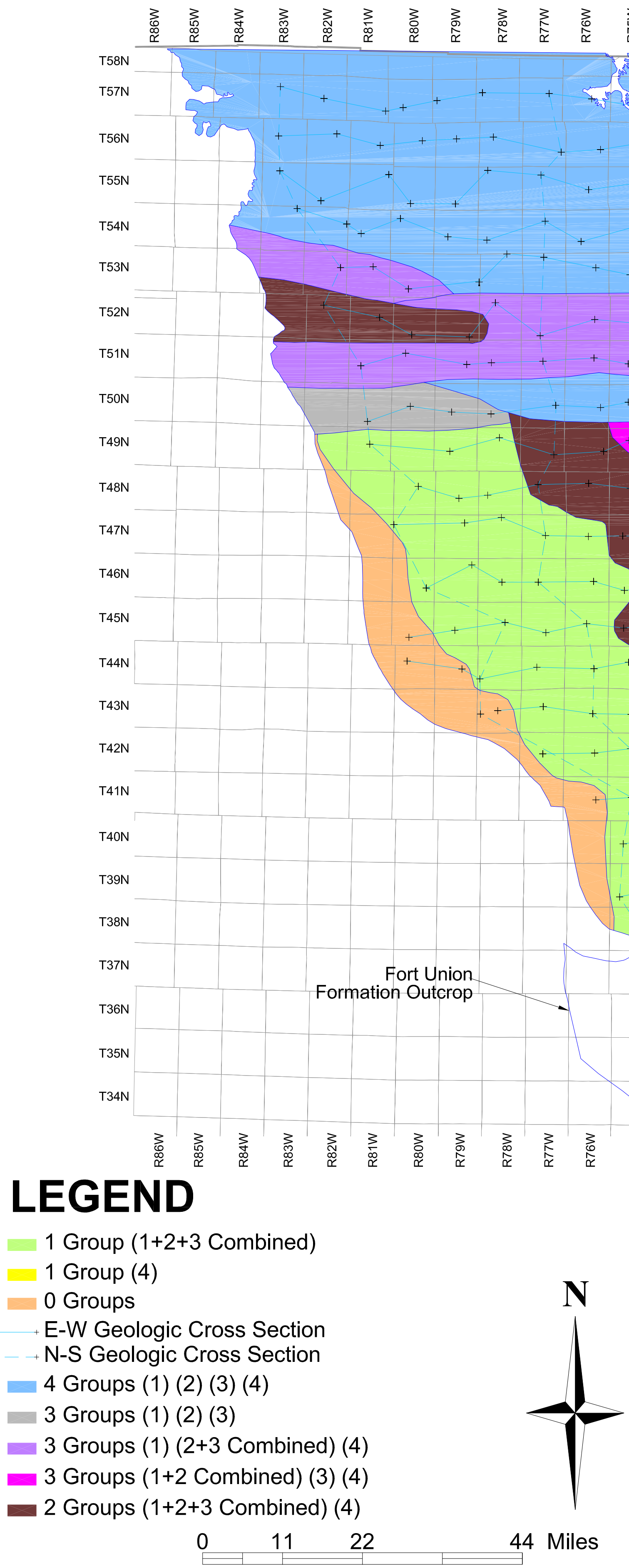
Figure 2-1C continued (11x17)



POWDER RIVER BASIN
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TECHNICAL REPORT GROUNDWATER MODELING

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

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

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

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

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

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

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

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

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

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

Tullock Member

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

2.3 Hydrogeology of the Powder River Basin

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

2.3.1 Recharge

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

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

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

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

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

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

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

2.3.2 Groundwater Flow and Discharge

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

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

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

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

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

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

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

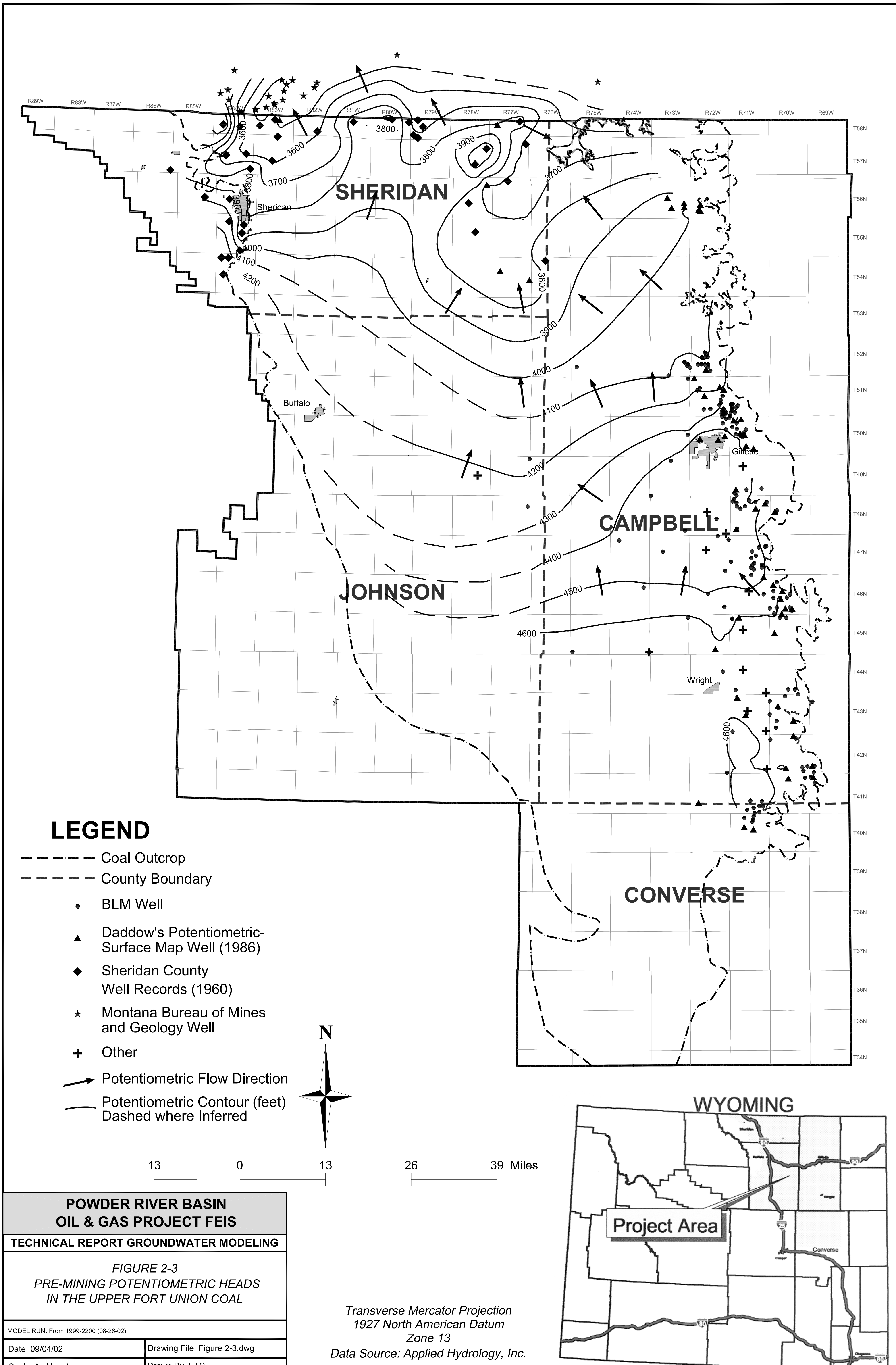
Bartos and Ogle (2002) used major ion chemistry and environmental isotope data to investigate the groundwater flow systems in lower Tertiary aquifers. The authors present two conceptual models for groundwater flow in the Wasatch Formation and the Wyodak–Anderson coal zone. The first conceptual model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

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

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

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

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


SHERIDAN
JOHNSON
CAMPBELL
CONVERSE
Sheridan
Buffalo
Gillette
Wright
R89W
R88W
R87W
R86W
R85W
R83W
R82W
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4000
4100
4200
4300
4400
4500
4600
LEGEND
Coal Outcrop
County Boundary
BLM Well
Daddow's Potentiometric-Surface Map Well (1986)
Sheridan County Well Records (1960)
Montana Bureau of Mines and Geology Well
Other
Potentiometric Flow Direction
Potentiometric Contour (feet) Dashed where Inferred
N
13 0 13 26 39 Miles
WYOMING
Project Area
Converse
POWDER RIVER BASIN
OIL & GAS PROJECT FEIS
TECHNICAL REPORT GROUNDWATER MODELING
FIGURE 2-3
PRE-MINING POTENTIOMETRIC HEADS
IN THE UPPER FORT UNION COAL
MODEL RUN: From 1999-2200 (08-26-02)
Date: 09/04/02
Drawing File: Figure 2-3.dwg
Scale: As Noted
Drawn By: ETC
Transverse Mercator Projection
1927 North American Datum
Zone 13
Data Source: Applied Hydrology, Inc.

Figure 2-3 continued (11x17)

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

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

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

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

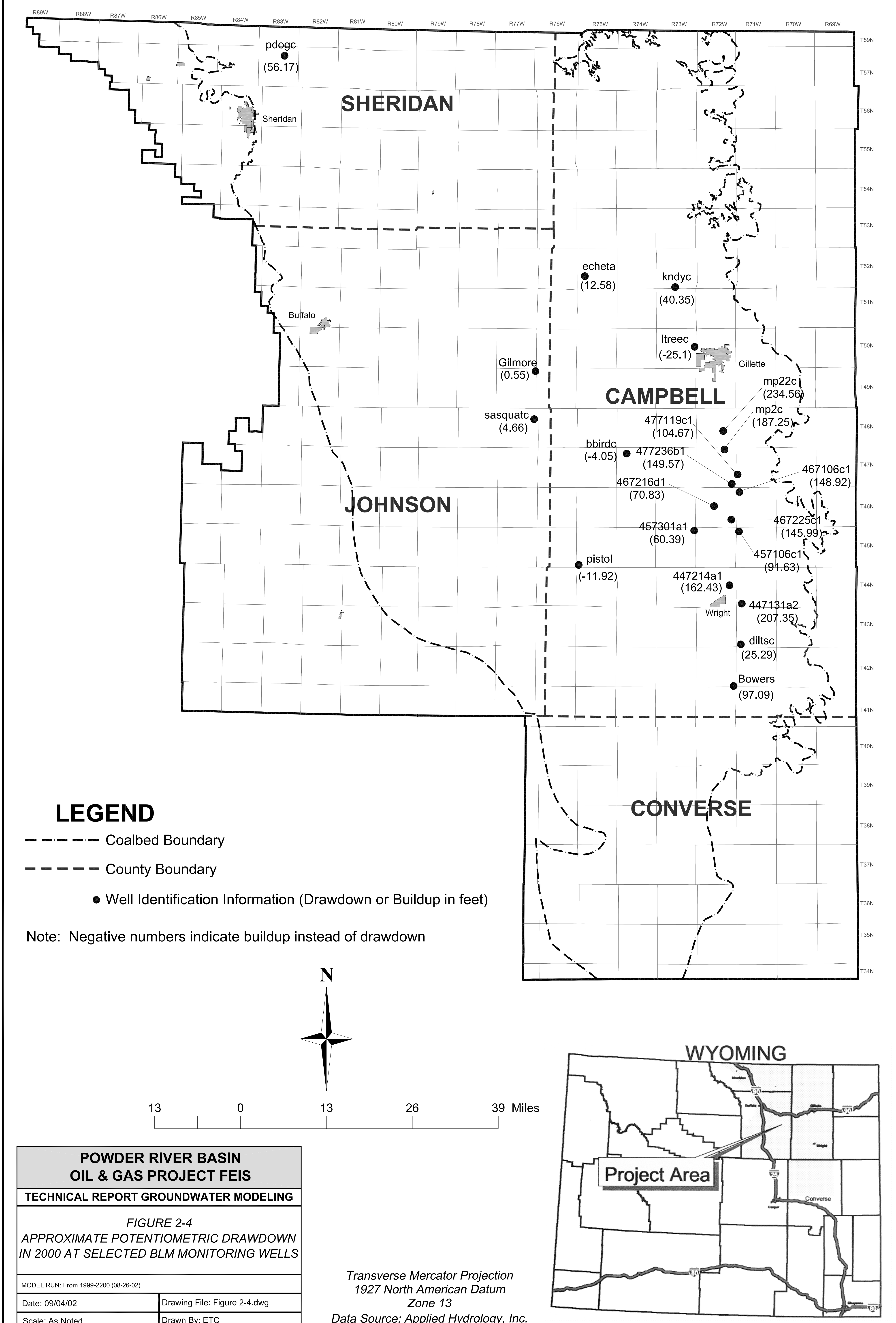
NA = Not Available

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

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

Groundwater Discharge to the Powder River

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



POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

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

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

Date: 09/04/02	Drawing File: Figure 2-4.dwg
Scale: As Noted	Drawn By: ETC

Figure 2-4 continued (11x17)

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

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

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

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

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

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

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

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

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

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

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

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

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

2.3.3 Recoverable Groundwater in the Powder River Basin

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

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

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

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

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

Methodology for Estimating Volume of Recoverable Groundwater

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

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

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

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

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

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

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

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

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

Estimating the Specific Yield for Sandstone and Coal Units

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

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

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

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

Volume of Recoverable Groundwater

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

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

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

Hydrogeologic Unit	Surface Area (acres)	Average Formation Thickness (ft)	Percentage of Sand/Coal	Average Sand/Coal thickness	Specific Yield (percent)	Recoverable Groundwater (acre-ft)
Wasatch-Tongue River Aquifer Sandstones	5,615,609	2,035	50	1,018	13	743,121,790
Wasatch-Tongue River Aquifer Coals	4,988,873	2,035	6.2	126	0.40	2,516,519
Lebo Confining Layer Sandstones	6,992,929	1,009	33	250	13	227,137,336
Tullock Aquifer Sandstones	7,999,682	1,110	52	430	13	447,246,784

2.4 Groundwater Use

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

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

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

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

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

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

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

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

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

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

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

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

3.0 CBM WATER HANDLING SCENARIOS

Three alternatives were analyzed in detail in the PRB O&G FEIS. The alternatives analyzed were: (1) Proposed Action, (2) Proposed Action with Reduced Emission Levels and Expanded Produced Water Handling Scenarios [2A and 2B], and (3) No Action. These alternatives are described in detail in Chapter 2 of the FEIS.

The method of handling CBM-produced water would vary with changes in the quality and volume of water and desires of the surface owner. Potential water handling methods are summarized in Tables 2-9, 2-21, and 2-22 of the FEIS and include:

- Direct surface discharge (with or without prior treatment),
- Discharge to infiltration impoundments,
- Containment of produced water in impoundments (negligible infiltration),
- Land application, and
- Injection into the Fort Union Formation below the coal zone or a lower injection zone via wells

The method of water handling significantly influences the amount of CBM-produced water that is likely to recharge the shallow groundwater system as a result of infiltration.

Discharge to surface streams is currently the primary method of handling CBM-produced water. Discharges are permitted by the WDEQ under a National Pollutant Discharge Elimination System (NPDES) permit. Field measurements of flow loss during dry weather along the reaches of various ephemeral streams that receive CBM discharge water indicate that significant conveyance losses (70 to 95 percent) occur (AHA 2001, Meyer 2000b) within a few miles of the discharge point. Most of the conveyance loss, estimated to average about 82 percent, is a result of infiltration into the alluvium and underlying shallow Wasatch sandstone aquifers. The remainder of the conveyance loss occurs through direct evaporation or consumption by vegetation (evapotranspiration).

The modeling analysis assumed that discharge of CBM-produced water to surface drainages results in a 20 percent conveyance loss, 82 percent of which is attributable to infiltration and 18 percent a result of evapotranspiration. It is therefore estimated that about 16 percent of the CBM-produced water that is discharged to ephemeral creeks infiltrates to recharge the shallow groundwater system within a few miles of the point of discharge.

Another common method of handling CBM water is to discharge the produced water into infiltration impoundments. These impoundments are typically unlined; in some cases, the bottom surface of an impoundment area may contain key trench-type excavations or closely spaced boreholes to enhance infiltration. Evaporation also may be enhanced by atomizers placed on towers situated on floating islands, with spray from these units directed above the water surface only. Water balance studies on existing reservoirs (Meyer 2000b) indicate that rates of infiltration range from 4 feet to more than 20 feet per year, depending on the soil type that underlies the impoundments. In areas of sandy soil, the rate of infiltration may be considerably higher than 20 feet per year. An average rate of infiltration of 8 feet per year is assumed for the regional modeling analysis. In contrast, average evaporation rates from a reservoir are about 4 feet per year. This analysis estimated that 15 percent of the water that is discharged to impoundments would resurface and enter the surface drainage system. Of the remaining 85 percent, about 67 percent would infiltrate to recharge the shallow groundwater system, and the remaining 33 percent would evaporate.

Containment impoundments, which are designed for complete containment so that only negligible infiltration occurs, would be considered as an alternative for water management in areas where discharge of produced water to surface streams or infiltration to shallow groundwater is not desirable based on water quality concerns. It is assumed that no leakage from these impoundments would occur. This analysis also assumed that none of the water discharged to containment impoundments infiltrates into the shallow groundwater system.

Produced water can be managed by land application. These methods involve spreading the water over the ground using atomizers or irrigation equipment. This analysis assumed that 100 percent of the water handled in this manner would be consumptively used and, consequently, none of the water would infiltrate into the shallow groundwater system.

In the case of water management by injection, the produced water would be returned directly to the subsurface, into the geologic units where the injection wells are completed. This analysis assumed that all injection wells would be completed in Fort Union sandstone units below the coal zone or lower injection zones. All injection would occur below the coal units developed for CBM.

The percentage of produced water that may infiltrate or recharge the groundwater system has been estimated for each water handing method, as summarized in Table 3-1.

Table 3-1
Summary of the Percentage Recharge for Each Water Handling Method

Water Management Method	Description of Percentage Recharge
Surface Discharge	20 percent of conveyance loss in surface discharge; 82 percent of conveyance loss infiltrates and 18 percent of the loss is evapotranspired.
Infiltration Impoundment	Of the water discharged to impoundments, 15 percent resurfaces and enters drainage; of the remaining 85 percent, 67 percent is lost to infiltration, 33 percent is stored or lost to evaporation.
Containment Impoundment	100 percent is stored or lost to evaporation and soil moisture
Land Application	100 percent of water is consumptively used
Injection	100 percent of water injected into disposal wells recharges groundwater below the Fort Union coal zone.

4.0 DEVELOPMENT OF GROUNDWATER MODEL

Numerical groundwater flow modeling was used to predict the regional impacts of CBM development in the PRB. Modeling was necessary because of the large extent of development, geographic variability throughout the basin, and cumulative stresses imposed by mining and CBM development on the Fort Union and Wasatch aquifer units. Impacts from development of CBM have been evaluated in earlier environmental assessments for the Marquiss, Lighthouse, North Gillette, South Gillette, and Wyodak development areas (USDI BLM 1992, 1995, 1996, 1997, and 1999). The information from earlier studies was reviewed and has been incorporated wherever practical into modeling for the PRB Oil and Gas EIS.

Numerical groundwater models can be particularly useful tools for refining the conceptual model of the groundwater flow systems within a regional basin. A calibrated numerical groundwater model ensures that groundwater flow systems are reasonably consistent with all hydrogeologic data, including all data from groundwater monitoring and aquifer testing available over most parts of the basin. Transient calibration of the model to measured mine water inflows, CBM well production, river baseflow, and measured drawdown in overlying and underlying zones, as well as the stressed zone, is a particularly effective method for refining the conceptual model of the groundwater flow systems. The horizontal and vertical hydraulic conductivities for individual model layers, developed using transient model calibration and vertical gradient data, provide more definition concerning the interconnectivity of the hydrogeologic units.

Any numerical groundwater model of a regional basin is a simplification of a complex hydrogeologic system. There is never a unique set of calibration parameters for any model. Nevertheless, the calibrated model should be reasonably consistent with hydrogeologic observations, and particularly with information that is developed on a regional scale, even if the data available to calibrate the model are relatively sparse. There are several parameters that are used to calibrate the model in both steady state and transient state. For example, in steady state, model results are compared with premining groundwater elevation in wells. Another consideration in model calibration is that modeled groundwater discharge rates must be consistent with observations of contributions from river baseflow (Section 2.3.3).

The regional model is an adequate tool for the analysis of the effects of CBM development, but the results should be used with caution when considering a sub-regional or local area. The regional model is constructed using averaged and smoothed values so that localized conditions typically are not highly refined.

Two sub-area models, developed at a much smaller scale, complement the regional model and were used to demonstrate specific aspects of CBM development in the PRB. The Caballo Creek sub-area, model described in Chapter 8, was used to match data on transient conditions in an area having a relatively long history of CBM development. This sub-area model allowed an evaluation of hydrologic parameters for confining zones that have a major influence on projections of shallow aquifer drawdown and coal recovery after CBM pumping ceases. The LX-Bar sub-area, model described in Chapter 9, was developed specifically to examine the potential influences of infiltration impoundments on groundwater levels in shallow Wasatch sands and adjacent creek flows. The sub-area model targets an area where surface discharge probably would be limited by water quality considerations.

4.1 Conceptual Model

The regional groundwater flow model for the PRB was based on the conceptual model that has its foundation in the geology and hydrogeology described in Chapter 2. The coal-bearing units of the upper portion of the Fort Union Formation are considered to have sufficient lateral continuity, and they act as a regional aquifer system. Individual coal seams split and merge; however, there is sufficient hydraulic communication on a regional scale to allow movement of groundwater from areas of recharge predominantly at the higher topographic elevations along the eastern, western, and southern margins of the basin, toward the lower topographic elevation areas along the northern margin of the basin. The structure of the Fort Union Formation is reasonably well documented and can be used as a framework for the layers in the regional model.

The Wasatch Formation is the surficial unit over most of the PRB. Most of the recharge to the basin occurs through this formation. Recharge is primarily through infiltration of runoff in the extensive network of ephemeral drainages that characterize the surface topography of the PRB. Most of the recharge occurs during the spring snowmelt. At other times of the year, the ephemeral streams are dry, except when high-intensity thunderstorms cause short-term runoff. This recharge occurs in the discrete channels of the surface drainage system, but the extensive drainage network results in an overall areal recharge when considered in a regional perspective.

Groundwater flow within the Wasatch Formation is dominated by local rather than regional flow systems. The general lack of laterally extensive transmissive units and the dissection of the shallow portions of the formation by surface drainages result in shorter, more localized flow paths from recharge to discharge areas. Much of the recharge that enters the Wasatch aquifer probably remains in a relatively shallow groundwater flow system and eventually discharges in topographically lower areas in the form of transpiration, springs or seeps. The alluvium within larger drainage channels conducts some of this shallow groundwater flow.

Over most of the PRB, the potentiometric pressure within the shallow Wasatch sandstones is higher than in the deeper Wasatch sandstones and the underlying Fort Union Formation coals. This downward hydraulic gradient induces a component of vertical groundwater flow, so that some portion of the Wasatch recharge may eventually leak into deeper regional flow systems. Low-permeability claystone and siltstone units retard the downward movement of groundwater and may locally divert flow laterally, but on a regional scale, this slow component of downward flow provides most of the recharge to the Fort Union coal zone aquifer. Some recharge to the Fort Union coals occurs in coal subcrop areas through clinker zones. Although the clinker has a high capacity for infiltration, the low permeability of the contact zone between the clinker and the underlying, unburned coal or shale usually limits the rate of recharge to the coal and may cause ponding clinker. Springs are likely to occur at the contact between the clinker and unburnt rocks.

The regional groundwater system discharges to the lower topographic valleys in the PRB, primarily to the lower reaches of the Powder, Little Powder, and Tongue Rivers in the northern portion of the PRB. The groundwater discharge is relatively small and diffuse and is not readily discernable as stream baseflow. Flowing artesian wells along the Powder River Valley form a small component of this bedrock discharge. Some discharge also occurs in the Cheyenne and Belle Fourche River drainages, but tends to be from shallow local groundwater flow systems rather than deeper regional flow systems.

4.2 Model Code

The hydrogeologic model used in this study to assess both vertical and lateral flows under various mine dewatering and CBM development scenarios is a transient (time variable), three-dimensional (multi-layered) flow model. The groundwater flow code used was MODFLOW 96 developed by the U.S. Geological Survey (USGS). This model is widely accepted by regulatory agencies and is packaged in a pre- and post processing software package, Visual MODFLOW (VMODFLOW) by Waterloo Hydrogeologic. MODFLOW is a widely accepted model code, but has limitations, which are discussed in Section 4.7. The VMODFLOW program (v.3.0.0) was used to complete pre-processing, modeling, and post-processing. The package also allows for zone water budgets. Modeled potentiometric surfaces for groundwater were exported from VMODFLOW and contoured using the software program SURFER v.7 (Golden Software) and were displayed using AutoCAD Map 2000.

4.3 Model Area

The Project Area extends from T34N R69W in the southeast to T58N R89W in the northwestern part of the PRB within Wyoming. The Project Area covers slightly less than 12,500 square miles (almost 8 million acres). The model itself encompasses the entire PRB (including the portion of the PRB within Montana) and extends a few miles beyond the Fort Union outcrop. The boundary of the model extends beyond the outcrop of the Tullock member in most of the western, southern, and eastern portions of the model area and beyond the outcrop of the upper portion of the Fort Union Formation in the north. A portion of the southwestern boundary of the model is set within the outcrop of the Tullock member. The model area is shown in Figure 4-1. The boundary of the model extends beyond the Project Area to establish boundary conditions using natural flow boundaries, such as the northern outcrop of the Fort Union Formation in Montana.

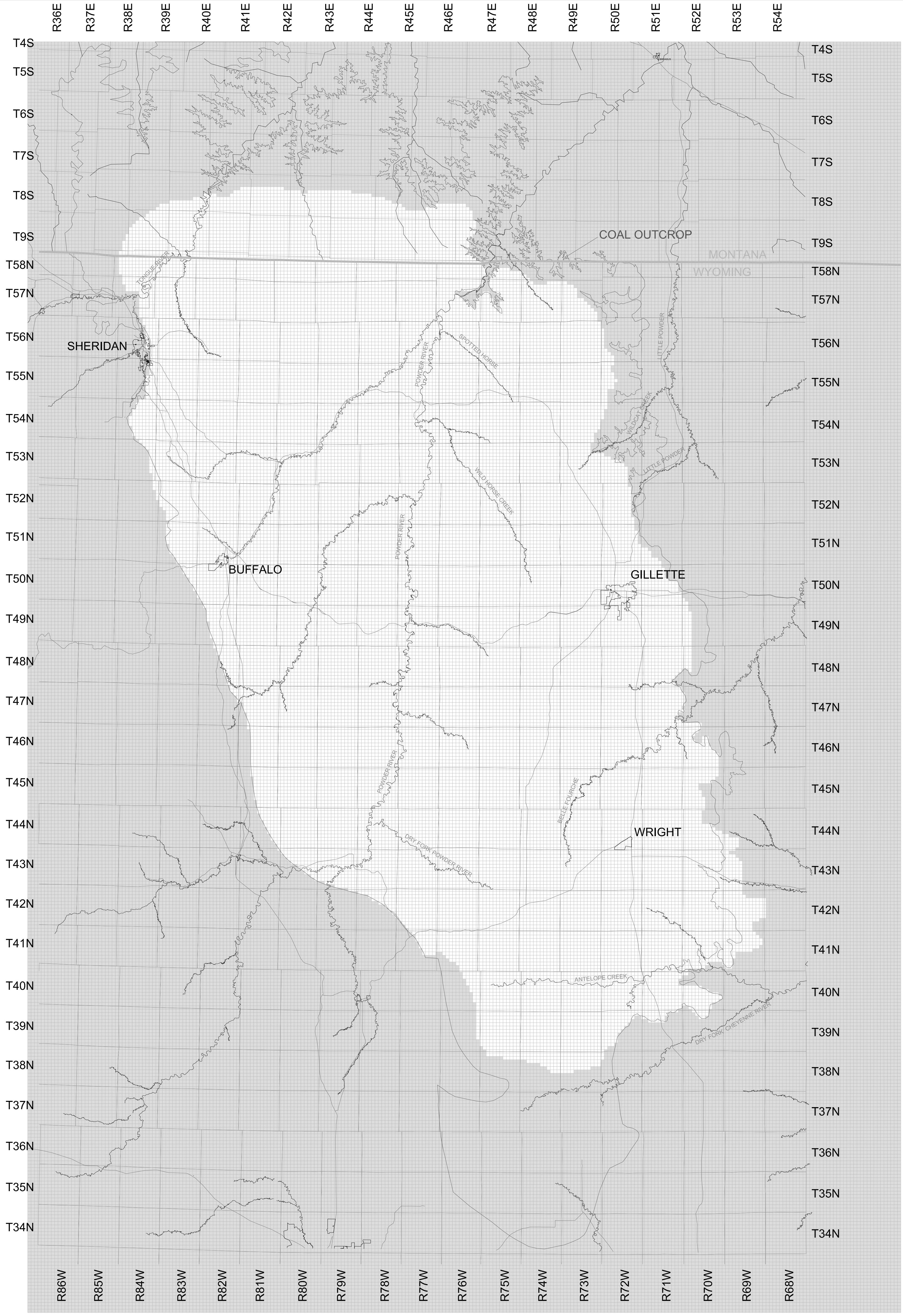
Typically, a model is oriented parallel to the axes of maximum and minimum transmissivity in the aquifers of interest so that anisotropy can be included. However, available data for the PRB indicate that, although local anisotropy exists, the directions vary regionally, and no single direction is dominant. Accordingly, the model was oriented north-south and east-west for ease of use.

4.4 Grid Setup

The model setup and assumptions are summarized in Table 4-1. The model grid (Figure 4-1) consists of 377 cells in the north-south direction (rows) and 259 cells in the east-west direction (columns), for a total of 97,643 cells per layer. The grid spacing is uniform throughout the model and is one-half mile (about 800 meters) in both the north-south and east-west directions. The uniform grid spacing allows for easier manipulation of the model in ArcView, Surfer, and MS Access, while maintaining the integrity of the model. The model grid was set up in the North American Datum (NAD) 27 Universal Transverse Mercator (UTM) Zone 13 meters coordinate system to allow easy transfer of model results into BLM's ArcView Geographic Information System (GIS).

4.5 Layer Setup

The model consists of 17 layers, which are summarized in Table 4-2. The top of the uppermost layer (Layer 1) is the topographic surface. This surface was constructed from 1:250,000 USGS digital elevation models (DEMs) that cover the entire model area. Using Surfer software, the x,y,z data from the DEMs were extracted into a .dat file. Every other point was extracted, except along the eastern boundary (which is outside the Project Area and active model domain), where every third point was extracted. The



MODEL GRID SPACING 1/2 MILE x 1/2 MILE

LEGEND

- Rivers
- Roads
- Towns
- No Flow Cells
- Model Grid

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-1
MODEL AREA GRID
AND NO-FLOW NODES

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

Date: 09/04/02	Drawing File: Figure 4-1.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-1 continued (11x17)

resolution of each original DEM is one point every 100 meters; therefore, one point every 200 meters (656 feet) was extracted. Extraction was necessary because the file was too large to grid otherwise (the row limit for Surfer is 5 million).

The extracted files (as .dat files) were combined, and, using Tralaine conversion software, the coordinates were converted from Lat/Long to NAD27 UTM Zone 13 meters. This extracted, converted file is called PRB_Topo_UTM.dat. Surfer was then used to grid this file at a spacing of one-half mile by one-half mile using the "Natural Neighbor" algorithm. Surfer was used to grid the data rather than the VMODFLOW interpolation because the gridding algorithms in Surfer are superior. The Surfer grid file was then imported into the VMODFLOW model as the topographic surface for the model (Figure 4-2).

Model layers 1 through 7 represent the Wasatch Formation. Layers 8 through 14 represent the upper part of the Fort Union Formation. The lowermost three layers (layers 15, 16, and 17) represent the lower members of the Fort Union Formation and the claystone aquitard that separates these members from the overlying coals in the upper portion of the Fort Union Formation.

The uppermost layer (layer 1) represents the surface geologic units that include shallow Wasatch geologic units (claystone, siltstone, and sandstone) and unconsolidated alluvial sands within creek valleys. This layer was assigned a uniform thickness of 30 feet (10 meters). The hydrologic properties within this layer, described later in Section 4.5, were varied to reflect the different characteristics of alluvial areas compared with the shallow Wasatch geologic units.

Layers 2, 4, and 6 represent shallow, intermediate, and deep zones of the Wasatch Formation, where discontinuous sandstone units occur. The discontinuous nature of the sandstone units is difficult to accurately simulate in a regional model with limited data. However, simulation was attempted by assigning hydrologic parameters to these layers that represent mixed sandstones and siltstone/claystone.

Layers 3 and 5 represent low-permeability claystone and siltstone units that separate the discontinuous sand units in the Wasatch Formation. Overlying the Fort Union coal zone is a layer (layer 7) which represents claystones within the Wasatch Formation that act as a confining unit between the coal zone and the discontinuous sandstones. This layer was set at a uniform thickness of 30 feet (10 meters) above the top of the coal zone in the upper portion of the Fort Union Formation. The vertical permeability of this layer in any location reflects its ability to act as a confining unit between the Fort Union coal zone and the overlying deep Wasatch sandstones. It is recognized that the assigned thickness and vertical hydraulic conductivity of this unit influence the rate of leakage from the discontinuous layers of the sandstone unit (primarily layer 6). However, since the leakage is proportional to the product of the thickness and the vertical hydraulic conductivity, the vertical permeability assigned to the layer in any area can be varied to compensate for variations in thickness.

The thickness of layer 1 was set at a minimum of 30 feet (10 meters) and follows the configuration of the surface topography. The base of layer 2, the shallow, discontinuous sand layer within the Wasatch Formation, was set at a uniform 100 feet (31 meters) below the topographic surface. The thicknesses of layers 3, 4, and 5 were created in Surfer by taking the total thickness between the base of layer 2 minus the top of layer 6, and dividing the result evenly among the three layers, and importing it into VMODFLOW. The top surface of layer 6, which represents the lower sands within the Wasatch Formation, was created by adding 100 feet (31 meters) to the top surface of the uppermost coal unit in the Fort Union Formation (layer 8). The top surface of layer 7, which represents the lower confining unit within the Wasatch Formation, was created by adding 50 feet (15.5 meters) to the surface of the uppermost coal unit (layer 8) in the Fort Union Formation. This procedure results in a uniform thickness of 50 feet (15.5 meters) for both layers 6 and 7.

Table 4-1
Summary of Regional Model Setup and Assumptions

Project	Powder River Basin (PRB) Environmental Impact Statement (EIS) - Powder River Basin Groundwater Impacts
Area	Powder River Basin in northeast Wyoming
Code	MODFLOW-96. Pre- and post-processor: VMODFLOW v.3.0.0
Time modeled	Steady State: 1975 (Pre-mining); Transient State: 1975 to 2200
Dimensions	X = 208.6 Km, Y = 303.3 Km (63,255 Km^2, 24,423 sq. miles)
X coords	317,470 – 526,025 m
Y coords	4,732,100 – 5,035,400 m
Coordinates	NAD27 UTM Zone 13, meters
Rows, columns	No. of rows: 377 No. of columns: 259 (97,643 cells/layer)
Grid spacing	804.6 m x 804.6 m (½ mile x ½ mile) for the entire model
Layers/type	No. of layers: 17. Layer 1: Unconfined: Layers 2-17 Variable T, S
Surfaces	**Coal surfaces and isopachs:** Established from data provided by Goolsby, Finley and Associates (2001) **Steady-state potentiometric surface:** Modified after Daddow 1986, U.S. Geological Survey (USGS) Ground-Water Resources of Sheridan County 1966, Bureau of Land Management (BLM) Well Data, Wyoming State Engineers Office Well Data **Surface topography:** USGS digital elevation models (DEMs)
Geology	**Coal Units:** Goolsby, Finley and Associates (2001) **Surface Geology:** USGS: “National Coal Resource Assessment, 1999 Resource Assessment of Selected Tertiary Coal Beds and Zones in the Northern Rocky Mountains and Great Plains Region” (USGS 1999a)
No-flow Boundaries	The no-flow boundary of each layer is different and is determined by the formation the layer represents.
Infiltration	Basin-wide infiltration: 0.03 inches per year Clinker infiltration: 0.1 to 0.6 inches per year Infiltration for each sub-watershed fluctuates depending on how much water is produced by the CBM wells and the prevailing water management practices.
Rivers (constant head)	**Perennial Rivers:** Set as constant head nodes trending linearly downstream between two topographic elevations. The perennial rivers are: Powder River, Belle Fourche River, Clear Creek, Crazy Woman, and Tongue River. **Intermittent Rivers**: Major ephemeral rivers set as drain nodes with the drain node elevations trending linearly downstream between points of the topographic surface. **Flow to the Yellowstone River**: Drain nodes were put in the lowest layer in the north to allow flow “out of the model,” which mimics flow toward the Yellowstone River.
Southwest Inflow (constant head)	Inflow from the southwest into the model area was simulated using constant head cells with an elevation equal to the top of the coal zone.
Coal Mines and CBM Wells	**Mine plans and locations**: Wyoming Department of Environmental Quality (WDEQ) and Office of Surface Mining (OSM) annual reports from mining companies; Gillette Area Groundwater Monitoring Organization (GAGMO) 15-year report, GAGMO 2000 Data. **CBM Wells:** Put in as drain nodes. Existing coal bed methane (CBM) wells taken from the Wyoming Oil and Gas Conservation Commission (WOGCC) database dated 7/20/01. Projected CBM wells developed by BLM, WOGCC, Greystone, Applied Hydrology Associates (AHA) with input from CBM industry representatives.
Solver	Steady-state: WHS (Waterloo hydrologic solver); Transient-state: WHS.
Rewetting	Set to rewet from the sides and below. Rewetting interval is 15 threshold is 5 m, increment is 0.1 m.

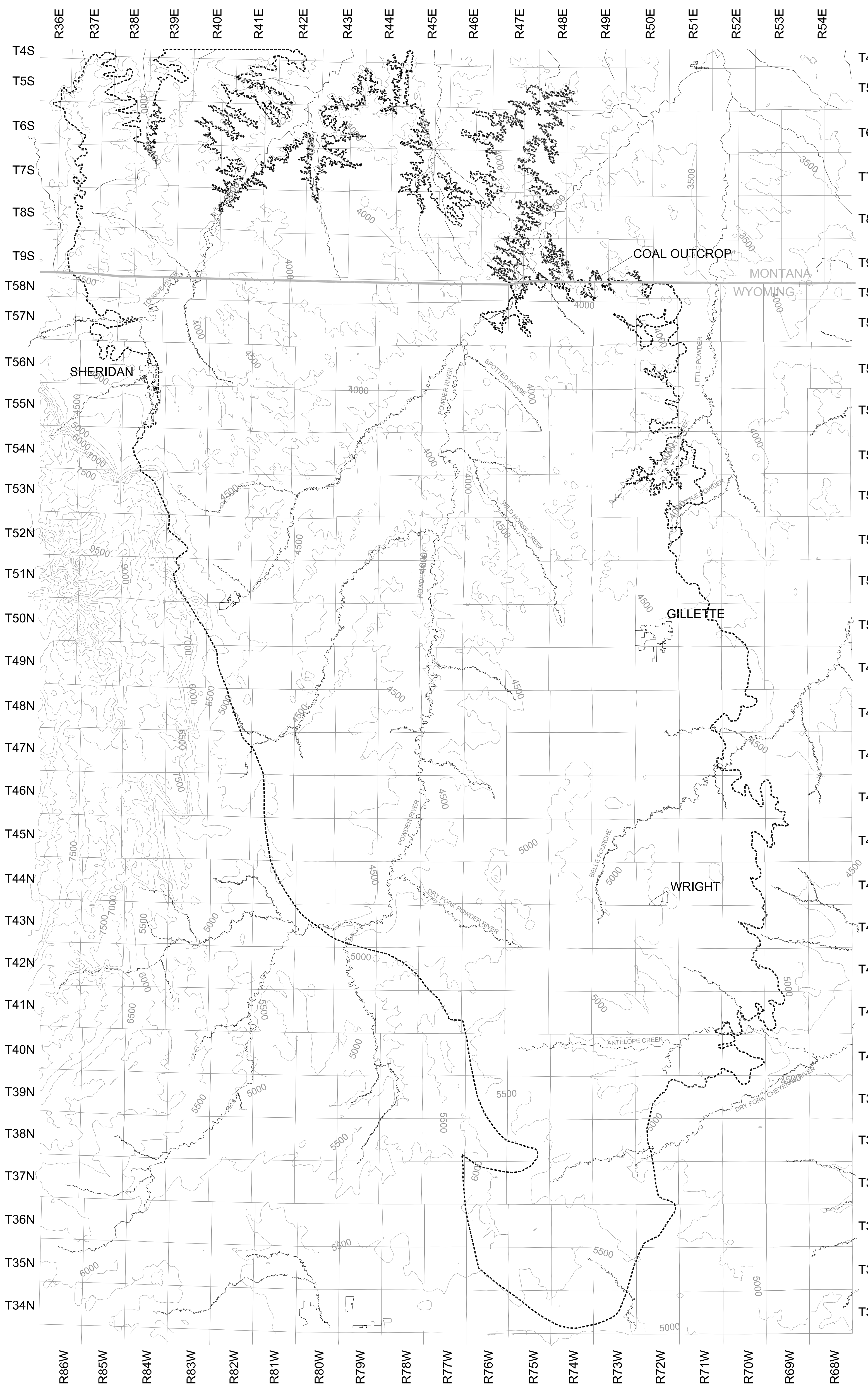
Table 4-2
Regional Model Layers

Model Layer	Geologic Formation/Member	Geologic Unit	Predominant Lithologies
1	Wasatch Formation	Upper Wasatch Formation and Alluvium	Sandstone, siltstone, claystone
2		Shallow Wasatch Sands	Sandstone, siltstone
3		Confining unit within Wasatch Formation	Siltstone, claystone
4		Intermediate Wasatch Sands	Sandstone, siltstone
5		Confining unit within Wasatch Formation	Siltstone, claystone
6		Deep Wasatch Sands	Sandstone, siltstone
7		Confining unit at base of Wasatch Formation	Siltstone, claystone
8	Fort Union Formation	Upper Fort Union Coal (Unit 1)	Coal (minor sandstone, siltstone)
9		Confining unit between coal units	Siltstone, claystone
10		Upper Fort Union Coal (Unit 2)	Coal (minor sandstone, siltstone)
11		Confining unit between coal units	Siltstone, claystone
12		Upper Fort Union Coal (Unit 3)	Coal (minor sandstone, siltstone)
13		Confining unit between coal units	Siltstone, claystone
14		Upper Fort Union Coal (Unit 4)	Coal (minor sandstone, siltstone)
15		Confining unit at base of coal units	Siltstone, claystone
16		Lower Fort Union Formation	Sandstone, siltstone, claystone
17		Lower Fort Union sand aquifer units	Sandstone, siltstone

The top and bottom surfaces of the four coal-bearing hydrogeologic units of the upper part of the Fort Union Formation, represented by Layers 8, 10, 12, and 14, were created from unpublished data compiled and consolidated by Goolsby, Finley, and Associates (2001) for the modeling effort. As the coal-bearing units split and merge in the PRB, the hydraulic properties assigned to the layers that represent both coal-bearing units and intervening units change accordingly. The coal-bearing units transition into clinker that is more highly permeable in outcrop areas.

Goolsby, Finley, and Associates (2001) provided the data for the Fort Union coal zone (such as for the top of unit and base of unit) for the entire basin at a density of one representative data point per township and up to four different coal units per point. Surfer was used to grid the data (which was provided in an Excel spreadsheet) at a one-half mile by one-half mile spacing, and the grid file was imported into VMODFLOW. The interpretation of the data shows only one distinct coal unit in some areas of the basin, while up to four distinct coal units may be found in other areas. The distribution of coal groupings is described in Chapter 2 and is illustrated in Figure 2-2.

In reality, there are more than four coal units in some parts of the basin, but, because of the limitations of the model, the maximum number of modeled coal units was held to four. Where coal units merged in the model, the total thickness of the coal was divided among the associated model layers. For example, coal units 1, 2, and 3 in the southern part of the basin (which have been arbitrarily named and are represented in the model by layers 8, 10, and 12) merge into one coal unit. In the model, the thickness of the coal unit was divided evenly among layers 8 through 12 and all of the layers were assigned coal properties. Dividing the thickness of the coal unit among all five layers provided better vertical discretization in the model. The alternative would be one very thick coal unit and four very thin underlying units, which could have led to numerical instability.



LEGEND

- Rivers
- Towns
- Surface Topography

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-2
TOPOGRAPHIC ELEVATION

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

Figure 4-2 continued (11x17)

Beyond the coal outcrop, the model layers that represent the coal units were assigned elevations equal to the surface topography. In this way, all coal and intervening layers were extended to the surface (less the minimum thickness). Surfer was used to combine the data for the Fort Union coal units within the coal outcrop and the topographic data outside the coal outcrop.

The lowermost three layers (layers 15, 16, and 17) represent the lower members of the Fort Union Formation and the claystone aquitard that separates these members from the overlying coals in the upper portion of the Fort Union Formation. The claystone aquitard (Layer 15) was set at a uniform thickness of 50 feet (15.5 meters) below the base of the Unit 4 coal group. The vertical permeability of this layer in any location reflects its ability to act as a confining unit between the upper Fort Union coal zone and the underlying sequence of the Fort Union Formation.

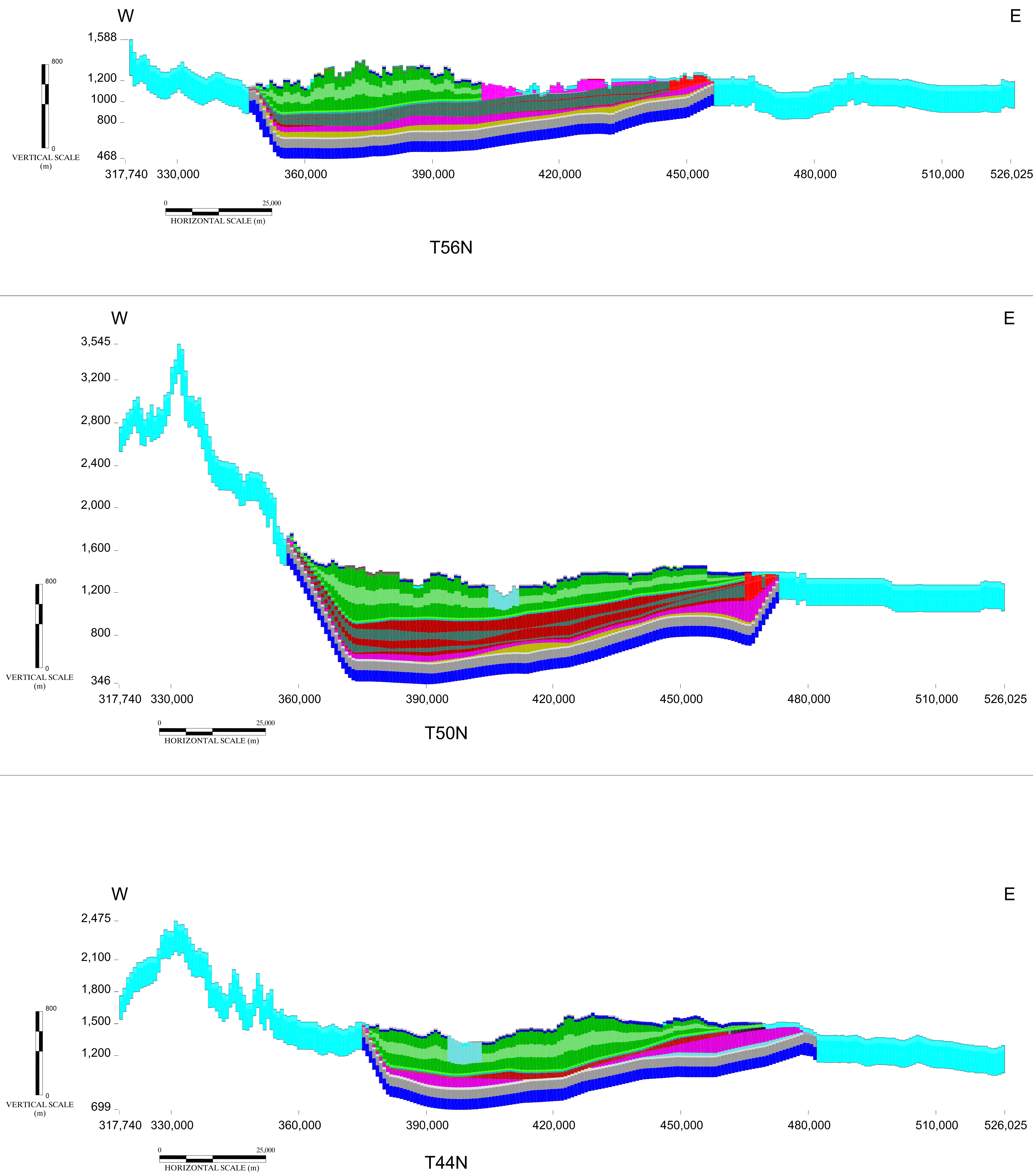
The sandstones in the lower portion of the Fort Union Formation form an aquifer that is tapped by many of the municipal supply wells in Campbell County. Layer 16 represents a transition zone, and layer 17 simulates the zone of relatively permeable sandstone units in the lower Tongue River/Lebo members of the Fort Union Formation. Layer 16 was set at a uniform thickness of 280 feet (85 meters), and layer 17 was set at a uniform thickness of 325 feet (100 meters). Claystones within the lower portion of the Fort Union Formation form the impermeable base of the model.

MODFLOW is a finite difference model and, consequently, every layer is continuous throughout the model. These continuous layers become problematic in modeling basin type structures (or non-continuous units) because, in reality, the geologic unit outcrops (terminates) while the layer that represents that unit must be continuous in the model. In addition, a minimum thickness must be associated with each node. At and beyond outcrop areas, the model will create an artificial thickness for the layer beyond the outcrops, and all layers below are displaced downward by that thickness. As more layers "outcrop," the magnitude of artificial thickness increases. For this model, the minimum thickness of each layer was set at 3 meters. The model layers above the coal near the outcrop (excluding the alluvium) were linearly decreased to a thickness of 3 meters using Surfer to minimize the effects of displacement on the coal units. However, it is impossible to avoid some displacement. At worst, the lowest coal might be displaced downwards by 46 meters (Layer 1 = 10 meters, Layers 2 through 13 = 3 meters). Inserting no-flow cells in the layers where the unit represented outcrops and applying recharge to the highest active cell further mitigates the effects of displacement.

Three typical cross-sections that show the setup of the model layers and the variability in the thickness of each layer are shown in Figure 4-3. The locations of the three cross-sections are shown in Figure 4-4. The different colors within individual layers indicate specific assigned hydraulic conductivities and no-flow zones that are described in subsequent sections.

4.6 Boundary Conditions and Model Stresses

Most of the PRB was encompassed by the model domain; however, no-flow boundaries were input within the outcrop of the Tullock member in the southwestern boundary of the model. Inflow to the model in this area was simulated using constant head cells. Outcrops (no-flow), perennial rivers (constant heads or drains), and ephemeral rivers (drains) were input into the model as boundary conditions based on physical features of the PRB. Stresses on the model included CBM wells (drains), coal mines (drains), municipal supply wells (wells), flowing artesian wells (drains), and spatial infiltration (recharge). These boundary conditions and model stresses are described in more detail in the following sections.



LEGEND

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

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

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

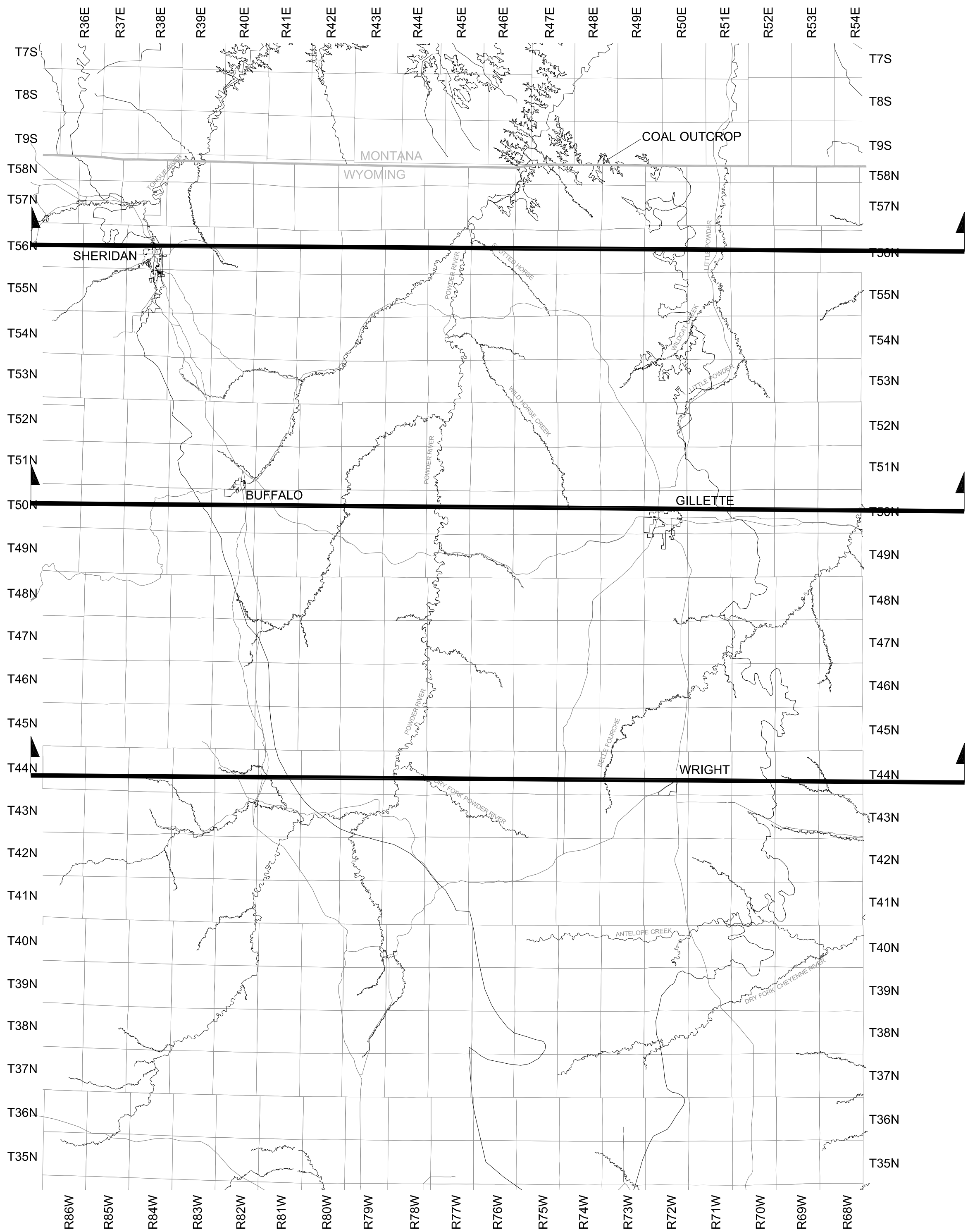
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-3
CROSS SECTIONS
OF MODELED LAYERS

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

Date: 09/04/02	Drawing File: Figure 4-3.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-3 continued (11x17)



LEGEND

- Rivers
- Roads
- Towns
- Cross Section Locations

N

0 11 22 44 Miles

POWDER RIVER BASIN
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TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-4
CROSS-SECTION
LOCATION MAP

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

Date: 09/04/02	Drawing File: Figure 4-4.dwg
Scale: As Noted	Drawn By: ETC

Different model boundary conditions were used to represent perennial and ephemeral surface flows, mining operations, CBM development, and zones of recharge. Boundary conditions are typically input into the model through the VMODFLOW graphical user interface (GUI). However, given the large number of boundary nodes needed for this model (more than 50,000 CBM wells, more than 15 mining operations, perennial and ephemeral rivers or streams, and different zones of recharge), it was necessary to streamline the process using other programs rather than enter all of the boundary conditions through standard entry routines provided by the VMODFLOW program.

ArcView, MS Access, Excel, PFE, Surfer, AutoCAD, and various FORTRAN programs were used to streamline the boundary input process. First, the model structure (i, j, k data of each node for each layer) was put into a file format that could be shared with other applications. A FORTRAN program was developed to extract this information from the MODFLOW boundary file (.bcf) and write it to a text file. A text file was created for each layer and was then imported into Access. Next, the corresponding X-Y coordinate was determined for each model node i, j using ArcView to define the node boundaries. Another FORTRAN program was developed to transform the model grid into a geo-referenced shape file. Using ArcView, coordinate information was imported and then changed into a shape file. This shape file was joined to the geo-referenced gird. Each boundary location was then assigned a corresponding model node i,j. The database file (.dbf) associated with the shape file (.shp) was then imported into the Access database.

Each model boundary was assigned an elevation using a series of queries in Access linked on layer-row-column. For example, CBM wells were input into the model as drain boundaries. A drain boundary requires a start time (in days), a stop time (in days), the elevation of the drain, and the conductance of the drain. The model accounts for more than 39,000 projected CBM wells and more than 12,000 existing wells. The locations of the projected wells were developed in ArcView. The well location shape file was spatially joined with the model grid shape file, and each well location was assigned a row-column. The .dbf file associated with the well location shape file was then imported into Access.

Using a query that was linked on layer-row-column, each projected well was assigned to a layer depending on where the well was placed within the basin and the number of developed coal seams at the location. For CBM wells, each drain boundary was assigned an elevation 16 feet (5 meters) above the top of the highest developed coal unit in that area. (This elevation was used because most CBM operators in the PRB depressurize wells with submersible pumps set close to the base of the well casing, with shut-off switches set above the pump. This system effectively limits depressurization to a level typically between 10 and 20 feet above the top of the coal.) The results of this query were then exported to Excel. The Excel file was formatted and used as input for another FORTRAN program that was developed to translate data from a spreadsheet format into the VMODFLOW boundary file (.vmb) format. The data were then copied to the existing .vmb file. Following is a summary of the process:

1. Create a shape file using an existing table that contains X-Y coordinates for each location.
2. Perform a spatial join on the new shape file to the model grid shape file.
3. Export the X-Y and i-j coordinates for each boundary location.
4. Import X,Y,i, j into Access.
5. Assign each boundary to a layer.
6. Query (linked on row-column-layer) to obtain the elevation at each point. Manipulate the elevation if necessary.
7. Export the data to an Excel spreadsheet.
8. Format the data.
9. Run the data through a FORTRAN program that translates them into the .vmb file format.

10. Copy the data to the .vmb file.

4.6.1 No-flow Cells

No-flow cells were assigned to areas outside the outcrop of the geologic units represented by the model layer. The extent of no-flow cells varies, depending on the layer represented. Using no-flow cells to represent outcrops helps mitigate the effects of displacement caused by minimum layer thickness. The no-flow cell configurations for some layers were identical, but in general, the deeper the layer, the fewer no-flow cells surrounded the active area. Recharge was applied to the highest active cell. In effect, the highest active cell acts as if it were at ground surface. The extent of no-flow cells for layer 14 (Lowermost Fort Union Coal Group) is shown in Figure 4-1.

No-flow cells were also designated in river areas where the river elevation was below the base of any layer. Some of the "fingers" along the coal outcrop were also set as no-flow cells because they contribute very little to the regional flow system, but can cause numerical convergence issues.

4.6.2 Recharge

The locations of recharge areas in the model are shown in Figure 4-5. With the exception of the largest rivers, most of the streams are intermittent or ephemeral. Recharge to groundwater aquifers occurs from infiltration of direct precipitation (rain and snowmelt), runoff in stream valleys, and standing water in playas, reservoirs, and stock ponds.

Recharge into the subsurface from precipitation is a small percentage of the total precipitation over most of the area because the climate and surface features restrict significant infiltration. The majority of precipitation runs off or evapotranspires. Given the large areal extent of the PRB, however, that small percentage of the available precipitation that infiltrates the surface does provide significant recharge to the subsurface. Average area-wide recharge, which includes recharge in stream valleys and ponds, expressed over the entire area is expected to be less than 1 percent of the total precipitation or equivalent to less than 0.1 to 0.15 inches per year. Steady-state calibration, described in Section 5, indicated that this amount of area-wide recharge appears realistic. A value of 0.03 inches per year was indicated by the steady-state calibration.

Infiltration rates are greater in areas that contain surface geologic units that are more permeable, such as the clinker that occurs along the eastern and northern outcrop areas of the upper Fort Union coal zone, and in the eastern portion of the PRB along the outcrop of Wasatch coals. The clinker areas are generally considered to form significant recharge areas for the coal However, as noted in Section 2.2, the rate of recharge to the coal may be limited by the presence of a low-permeability zone at the contact between the clinker and underlying coal or shale. Thick, clay-rich soils over flatter surfaces also may retard the downward movement of water (Heffern and Coates 1999.) Pre-mining potentiometric data and interpretations from many of the permit applications for the coal mines tend to support this assumption. The clinker provides a continuous source of recharge to the coal through ponding of water, albeit at a relatively slow rate because of the low-permeability transition zone. Recharge in the clinker areas is expected to be in the range of 5 to 10 percent of total precipitation or equivalent to between 0.5 to 1.5 inches per year. Steady-state calibration, described in Section 5, indicated that this range of recharge in the clinker areas appears realistic. Values of 0.1 inch per year for clinker associated with coals of the Wasatch Formation and 0.6 inch per year for clinker associated with the Fort Union coal zone were indicated by the steady-state calibration.

Infiltration of surface water in creek valleys and in impoundments is generally considered an important source of recharge to shallow aquifers, as discussed in Section 2.3. Additional water is available to infiltrate into the underlying alluvium and bedrock formations within valleys where discharge of CBM produced water into surface drainages has resulted in perennial flow conditions. Similarly, water stored in impoundments can leak into the underlying shallow groundwater.

The actual amount of recharge in any watershed depends on the distribution of water handling methods employed for managing CBM produced, water as described in Chapter 3. The effects of the various water handling methods were simulated in the model by applying additional recharge to each sub-watershed on a year-by-year basis during the production period. The amount of additional recharge was based on a combination of the amount of water produced, the projected percentage of water handled by the various methods, and the projected infiltration of the water handling method. The net recharge for each sub-watershed (shown as a percent of CBM water production for that sub-watershed) is summarized for each of the water handling scenarios in Tables 4-3 through 4-5.

The additional recharge was converted to a year-by-year infiltration rate based on the area of CBM development in each sub-watershed. For the model, the area of CBM development was considered to be the extent of CBM development plus a one-half mile buffer. The areas of enhanced recharge are shown in Figure 4-5.

4.6.3 Rivers

Rivers in the PRB may act as either recharge or discharge areas for shallow groundwater, depending on the elevation of water in the river compared with the head elevation in the adjacent shallow aquifer. The Powder River is interpreted to be a discharge area for groundwater in the PRB, particularly in the northern part of the basin, because upward vertical flow gradients generally prevail in the vicinity of the river. However, as explained in previous sections of this report, baseflow in the Powder River is not discernible because the small amount that occurs is lost through evapotranspiration. The Belle Fourche, Little Powder, and Cheyenne Rivers and their major tributaries are also considered to interact with shallow groundwater, although they may act as recharge areas along certain reaches, and discharge areas along other reaches.

The model simulates interactions between rivers and adjacent shallow aquifers using "constant head" nodes to represent major perennial streams and "drain" nodes to represent major ephemeral streams. Constant head nodes were input along the courses of the Powder River, Belle Fourche River, Crazy Woman Creek, Clear Creek and Tongue River and their major tributaries. The elevation set in the constant head nodes and the drain nodes was based on the topographic elevation of the river at each node location, trending in a linear manner downstream. The locations of the river constant head and drain nodes are shown on Figure 4-6. This figure consolidates the boundary conditions representing river cells from all of the model layers.

4.6.4 Drains (Mines)

The model simulates active surface coal mining by setting "drain" nodes in the target coal group layer at the appropriate locations. Groundwater will enter an active drain node from an adjacent node as long as the potentiometric level in the adjacent node is higher than the drain elevation. As the potentiometric elevation in the adjacent node is lowered by drainage, the rate of drainage decreases. Drain nodes can be made inactive by setting the drain elevation much higher than the adjacent node potentiometric elevation. Unlike constant head or general head nodes, drain nodes cannot add water to adjacent nodes. The use of drain nodes to simulate surface mining allows the water levels to recover when active mined areas are backfilled and reclaimed.

Table 4-3
Summary of the Net Recharge for Each Sub-Watershed – Alternatives 1 and 3

	Water Handling Method					Recharge to Groundwater (Fort Union coal zone and above)								
	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Land Application (percent)	Injection (percent)	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Injection (percent)	TOTAL (percent)	Runoff (percent)	Surface Discharge Evapotranspiration (percent)	Impoundment Storage and Evaporation (percent)	Consumptive Use (percent)
Upper Tongue River	35	45	10	0	10	7	26	0	0	33	34	2	23	0
Upper Powder River	75	15	5	0	5	13	9	0	0	22	62	3	9	0
Salt Creek	55	35	5	0	5	10	20	0	0	30	48	2	15	0
Crazy Woman Creek	70	5	5	15	5	12	3	0	0	15	57	3	6	15
Clear Creek	35	40	5	10	10	7	23	0	0	30	33	1	16	10
Middle Powder River	65	10	10	10	5	11	6	0	0	17	54	2	13	10
Little Powder River	65	10	10	10	5	11	6	0	0	17	54	2	13	10
Antelope Creek	55	35	5	0	5	10	20	0	0	30	48	2	15	0
Upper Cheyenne River	55	35	5	0	5	10	20	0	0	30	48	2	15	0
Upper Belle Fourche River	45	40	5	0	10	8	23	0	0	31	41	2	16	0

Note:
Injection zones would occur below the Fort Union coal zone and would not contribute to recharge of the coal zone aquifer

Totals may differ from 100 percent as a result of independent rounding

Table 4-4
Summary of the Net Recharge for Each Sub-Watershed – Alternative 2A

	Water Handling Method					Recharge to Groundwater (Fort Union coal zone and above)								
	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Land Application (percent)	Injection (percent)	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Injection (percent)	TOTAL (percent)	Runoff (percent)	Surface Discharge Evapotranspiration (percent)	Impoundment Storage and Evaporation (percent)	Consumptive Use (percent)
Upper Tongue River	5	65	5	15	10	2	37	0	0	39	12	1	23	15
Upper Powder River	30	60	0	5	5	6	34	0	0	40	31	1	17	5
Salt Creek	0	70	5	5	20	2	40	0	0	42	9	0	25	5
Crazy Woman Creek	5	70	5	10	10	3	40	0	0	43	13	1	25	10
Clear Creek	5	70	5	10	10	3	40	0	0	43	13	1	25	10
Middle Powder River	30	55	0	10	5	6	31	0	0	37	30	1	15	10
Little Powder River	40	45	0	10	5	8	26	0	0	34	38	2	13	10
Antelope Creek	60	30	0	5	5	11	17	0	0	28	52	2	8	5
Upper Cheyenne River	60	30	0	5	5	11	17	0	0	28	52	2	8	5
Upper Belle Fourche River	60	30	0	5	5	11	17	0	0	28	52	2	8	5

Note:
Injection zones would occur below the Fort Union coal zone and would not contribute to recharge of the coal zone aquifer

Totals may differ from 100 percent as a result of independent rounding

Table 4-5
Summary of the Net Recharge for Each Sub-Watershed – Alternative 2B

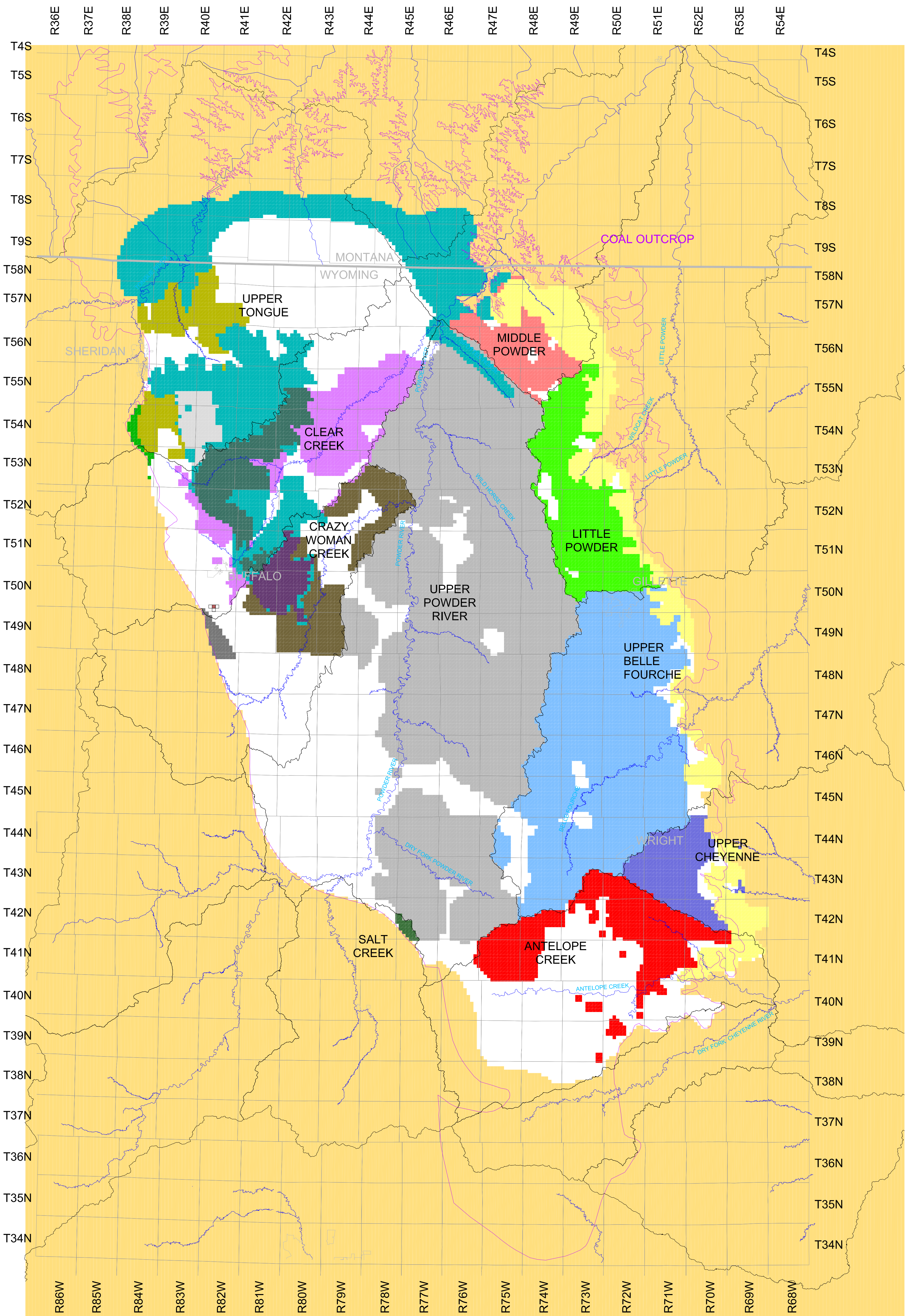
	Water Handling Method					Recharge to Groundwater (Fort Union coal zone and above)								
	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Land Application (percent)	Injection (percent)	Surface Discharge (percent)	Infiltration Impoundment (percent)	Containment Impoundment (percent)	Injection (percent)	TOTAL (percent)	Runoff (percent)	Surface Discharge Evapotranspiration (percent)	Impoundment Storage and Evaporation (percent)	Consumptive Use (percent)
Upper Tongue River	5	45	5	15	10	2	26	0	0	28	10	0	18	35
Upper Powder River	30	40	5	5	5	6	23	0	0	29	29	1	16	20
Salt Creek	0	50	10	5	20	1	28	0	0	29	6	0	24	20
Crazy Woman Creek	5	45	5	15	10	2	26	0	0	28	10	0	18	35
Clear Creek	5	50	5	10	10	2	28	0	0	30	10	0	19	30
Middle Powder River	30	40	5	10	5	6	23	0	0	29	29	1	16	20
Little Powder River	40	25	0	10	5	7	14	0	0	21	35	2	7	30
Antelope Creek	60	25	0	5	0	10	14	0	0	24	51	2	7	15
Upper Cheyenne River	60	25	0	5	0	10	14	0	0	24	51	2	7	15
Upper Belle Fourche River	60	30	0	5	5	11	17	0	0	28	52	2	8	5

Notes:

Injection zones would occur below the Fort Union coal zone and would not contribute to recharge of the coal zone aquifer

One hundred percent of the water handled by active treatment under Alternative 2B (reference FEIS Table 2-22) would be used consumptively

Totals may differ from 100 percent as a result of independent rounding



LEGEND

- Rivers
- Subwatershed
- Towns
- No Flow Cells
- Tongue River Watershed
- Clear Creek Watershed
- Crazy Woman Watershed
- Upper Powder Watershed
- Middle Powder Watershed
- Little Powder Watershed
- Upper Belle Fourche Watershed
- Upper Cheyenne Watershed
- Antelope Creek Watershed
- Scoria
- Upper Tongue Scoria
- Clear Creek Scoria
- Crazy Woman Scoria
- Wasatch Coal Clinker
- Clinker
- Areal Recharge
- Salt Creek Watershed

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-5
MODEL RECHARGE ZONES

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

Date: 09/04/02	Drawing File: Figure 4-5.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-5 continued (11x17)

Where mining occurs, the mining sequence was simulated from reasonably foreseeable mine plans as incremental impacts in 1-year stress periods from approximately 1975 (the earliest mining along the PRB outcrop areas, with the exception of the Wyodak mine east of Gillette) to 2033. Each drain node is turned on during the period of active mining in the area represented by the node, a 3-year period.. After this period, the drain node becomes inactive, which simulates backfilling and reclaiming of the pit area after active mining. The location and timing of drain nodes were based on historical mining records and life of mine plan maps included in mining permit applications and 5-year mining plan updates. It is understood that life-of-mine plans are dynamic and may change in future years, but they provide a general projection of likely coal removal sequences and mine progression. The mining permit areas and the extent of drain nodes representing these mine areas are shown in Figure 4-7. The drain node water level in an active mine area is set a few feet above the bottom elevation of the coal layer. Since the elevation of the coal bottom varies geographically, each drain node is input individually with a different elevation.

4.6.5 Drains (CBM Wells)

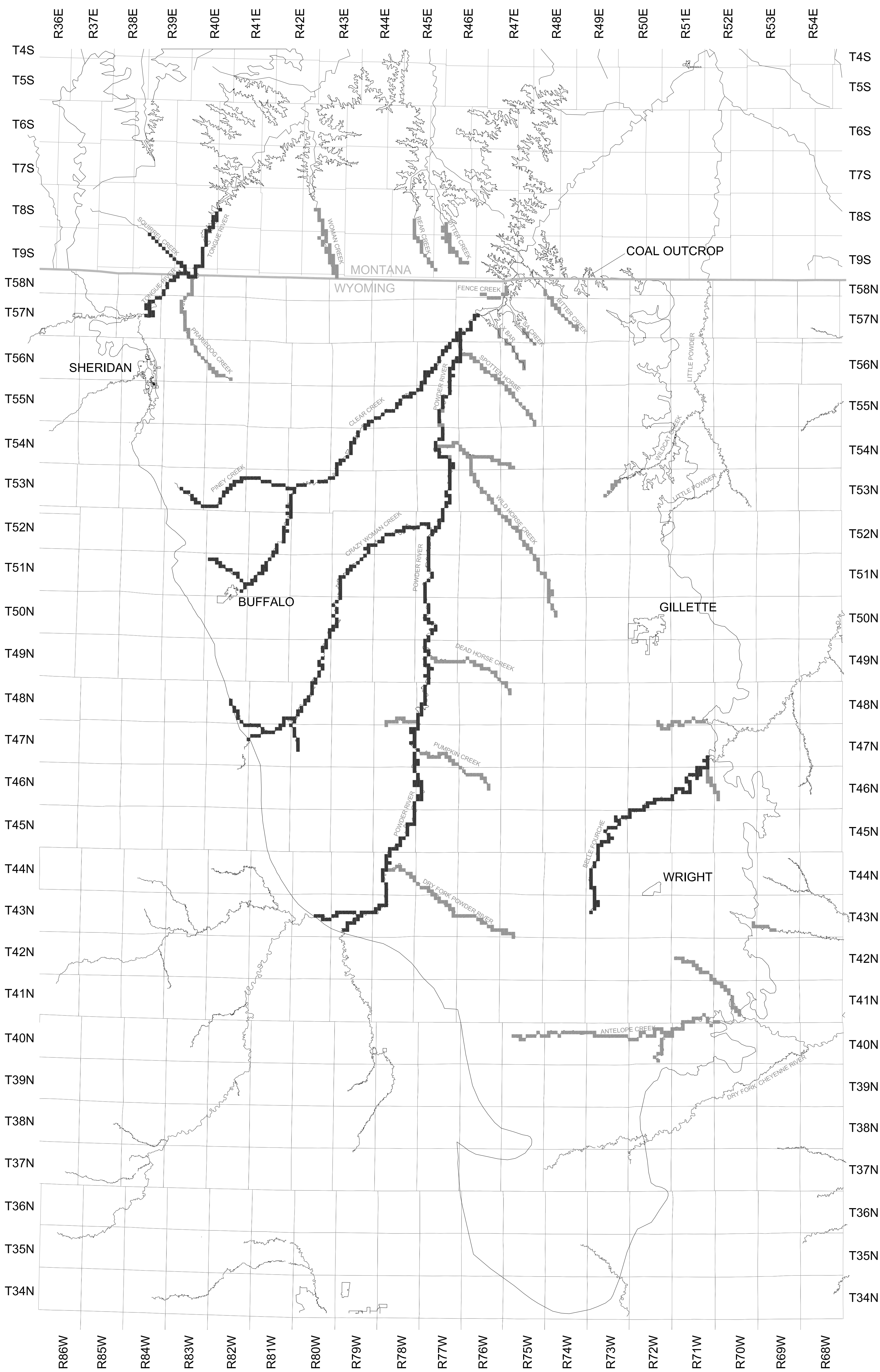
Active CBM wells are simulated in the model by setting "drain" nodes in the target coal group layer. Groundwater will enter an active drain node from an adjacent node as long as the potentiometric level in the adjacent node is higher than the drain elevation. Water flow to the drain declines as the potentiometric head declines in the model nodes surrounding the drain. This decline simulates the process that occurs during CBM production, where declines in water production over time typically are observed.

Depressurization of the coal zone aquifer was simulated as incremental impacts in 1-year stress periods from approximately 1989 (the earliest CBM production) to the presently anticipated end-of-CBM operations in 2018 for locations developed or projected to be developed. The location and timing of drain nodes representing existing CBM wells were based on data from WOGCC. Future CBM development is based on the Proposed Action development scenario described in Chapter 3.

Each drain node is activated during the period of active CBM operations in the area represented by the node. The water level in the drain node for an active CBM well is set about 16 feet above the top elevation of the highest coal unit being developed at that location. For example, if four coal units are being developed at a single location, drain nodes are placed in each of the coal layers, but the elevation of each drain is set at 16 feet above the highest active coal. The majority of drain boundaries representing CBM wells were placed in the lower coal layers of the model. After all CBM production ceases in the node, the drain node is made inactive by setting the drain elevation above ground surface, which allows the water level in the node to recover.

The model used water production data from WOGCC as the source for input of drains during the period from 1988 to March 2001. A total of 6,098 wells show some water production during this time. The productive life of wells that were still operating in March 2001was assumed to be 7 years from the start of production. A total of 3,677 permitted wells were assumed to begin production during March 2001 to March 2002. These wells were assigned a 7-year life span. It is assumed that future wells would be drilled over a 10-year period from March 2002 through March 2012. Each future well would have a 7-year life span, as described Chapter 2 of the FEIS. A total of 39,367 future wells were input into the model as drain nodes, with appropriate time schedules.

CBM wells in Montana were not included in the regional model for the following reasons. First, the regional model used to project impacts from CBM development in Wyoming requires some input parameters that could not be estimated for the proposed CBM wells in Montana. Detailed information on water handling methods that was not available would have been needed to account for infiltration and recharge in the model for the projected CBM wells in Montana.. In addition, the regional model was designed to provide a conservative estimate of the upper limits of water production in Wyoming. If CBM wells in Montana had been included in the regional model, the effect would have been to decrease water production from some nearby CBM wells in Wyoming. The exclusion of CBM wells in Montana from the regional model likely resulted in underestimation of the extent of impacts to the potentiometric surface in some areas near the state line between Wyoming and Montana while overestimating the amount of production from some CBM wells in Wyoming.



LEGEND

- Rivers
- Constant Head Node Representing a Perennial Stream or River
- Drain Node Representating an Ephemeral Stream
- Towns

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

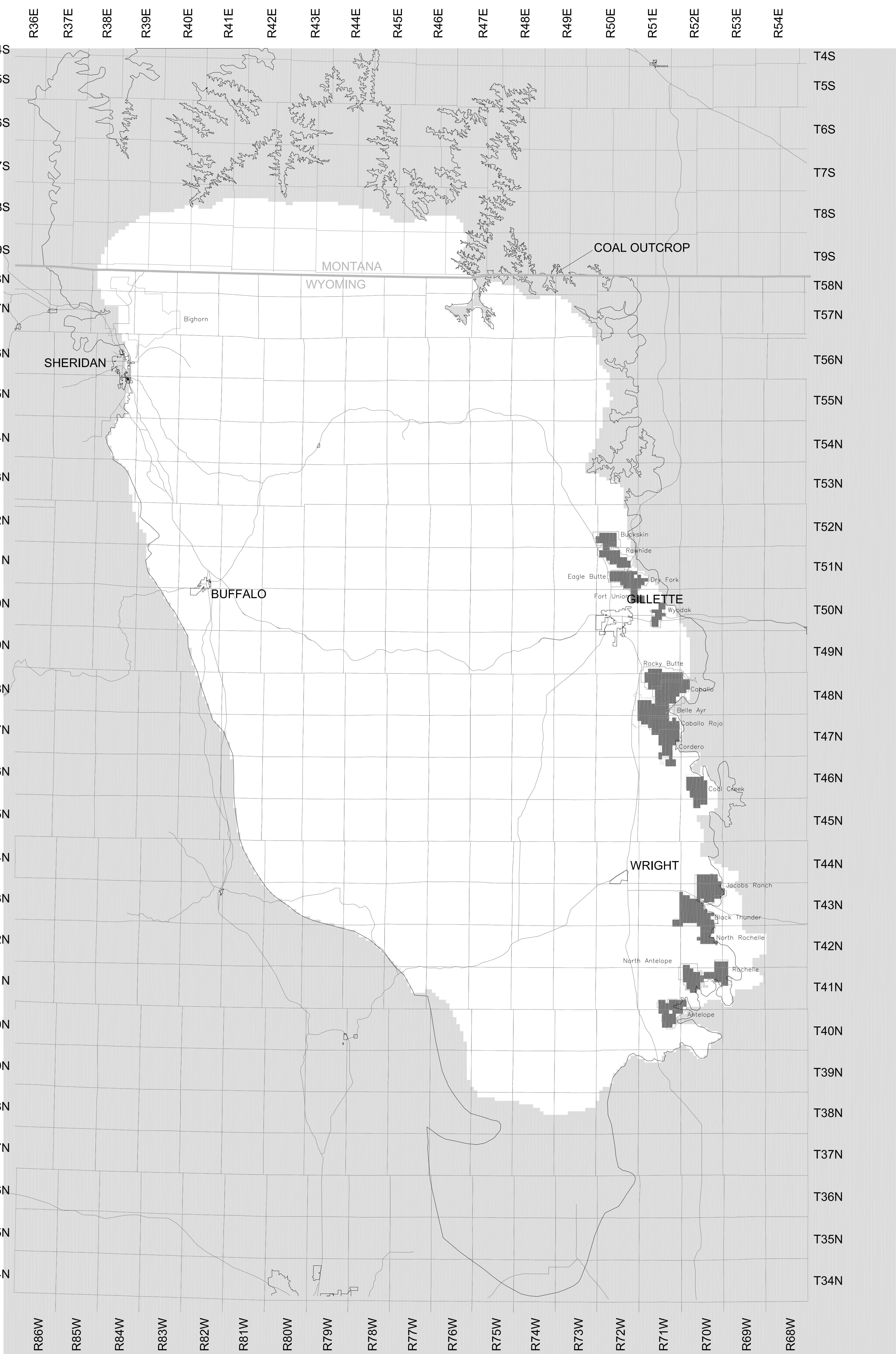
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-6
MODEL DRAIN NODES
REPRESENTING STREAMS OR RIVERS

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

Date: 09/04/02	Drawing File: Figure 4-6.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-6 continued (11x17)



LEGEND

- Towns
- Roads
- No Flow Cells
- Drain Node Representing Mining

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 4-7
MODEL DRAIN
(MINE) NODES

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

Date: 09/04/02	Drawing File: Figure 4-7.dwg
Scale: As Noted	Drawn By: ETC

Figure 4-7 continued (11x17)

The producing intervals of the wells were distributed among the four coal-bearing units (which are represented by layers in the model) based on existing production or the thickness and depths of the coals in any area. In many areas, more than one coal interval would be produced and this is reflected in the model where more than one well per well pad is projected. Input of the CBM wells as drain boundaries in the model was aided using ArcView, Access, and Fortran programs, as described earlier in this section. It is possible for several wells to produce from the same model grid node at the same time. Multiple CBM wells at the same grid node were represented by a single drain boundary. The number of operating wells simulated by the drain boundary was adjusted as production started and stopped. This was accomplished by adjusting the drain conductance proportionally to the number of wells operating during each year. Drain conductance was established from steady state and transient state calibration to production data at several wells in each watershed where data were available. Figure 4-8 shows the composite (all four coal layers) locations of CBM drain nodes that were input into the model.

4.6.6 Pumping from Municipal Water Supply Wells

The communities of Gillette and Wright, as well as many subdivisions that surround Gillette, obtain much of their municipal water supply from wells screened within the sands of the lower Tongue River, Lebo, and Tullock members of the Fort Union Formation (HKM 1994). Generally, these water supply wells are completed in aquifer units that underlie the upper Fort Union coal zone. Pumping wells were included in the model to represent municipal water supply wells for the City of Gillette, the community of Wright and several subdivisions around Gillette, including Antelope Valley, Crestview, and Sleepy Hollow. These wells were included in layer 17, representing the Fort Union Formation below the upper Fort Union coal zone. Well locations and average pumping rates were obtained from well completion reports (HKM 1993; Wester-Wetstein, 1994, 1999c, 1999e).

4.6.7 Flowing Artesian Wells

Numerous flowing artesian wells are present in the northern portion of the model area. These wells were operating before the start of the model simulation period (1975) and have continued to operate. The effect of these wells was incorporated into the model using low-conductivity drain cells located in the uppermost coal unit in areas where these wells are known to be present.

4.7 Aquifer Properties

A summary of the range of model input parameters assigned to the various geologic units in the model is given in Table 4-6.

4.7.1 Hydraulic Conductivity

The hydraulic conductivity of a material is a measure of the ease that water can pass through the material under a specified hydraulic gradient.A range of values for hydraulic conductivity was used for each layer for the regional PRB model. Values for hydraulic conductivity of the various geologic units were based on actual field data (results of pumping tests) and model calibration to both steady-state and transient-state conditions. The ranges of values used for various lithologies in the model layers are summarized in Table 4-6.Several lithologies or conditions may be represented within one layer. For example, values of hydraulic conductivity vary in the layers that represent the coal groups of the upper Fort Union Formation (layers 8, 10, 12 and 14), representing clinker at the outcrop and fracture zones within the coal.

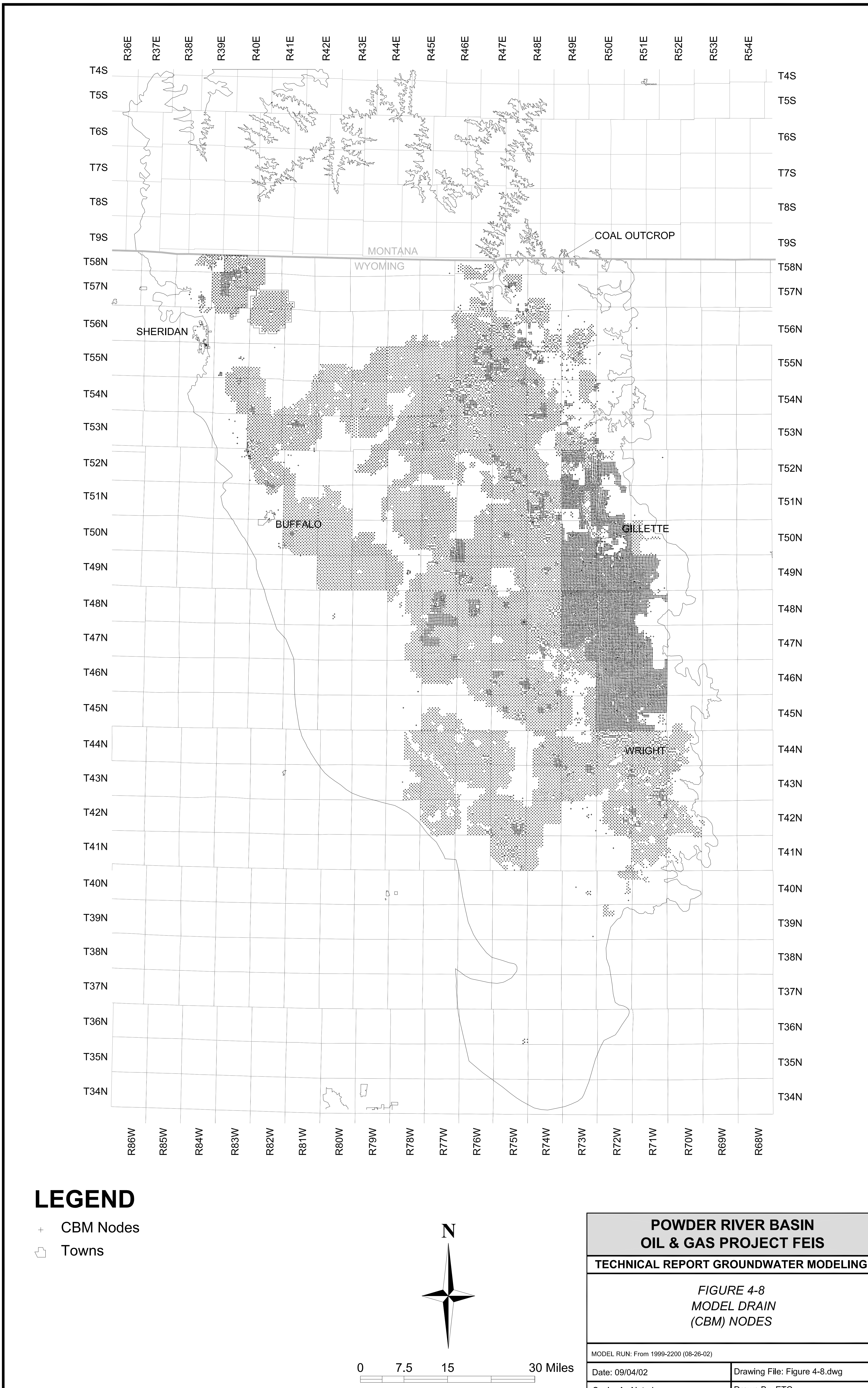

R36E R37E R38E R39E R40E R41E R42E R43E R44E R45E R46E R47E R48E R49E R50E R51E R52E R53E R54E
T4S T5S T6S T7S T8S T9S
T58N T57N T56N T55N T54N T53N T52N T51N T50N T49N T48N T47N T46N T45N T44N T43N T42N T41N T40N T39N T38N T37N T36N T35N T34N
R86W R85W R84W R83W R82W R81W R80W R79W R78W R77W R76W R75W R74W R73W R72W R71W R70W R69W R68W
MONTANA
WYOMING
COAL OUTCROP
SHERIDAN
BUFFALO
GILLETTE
WRIGHT
LEGEND
CBM Nodes
Towns
N
0 7.5 15 30 Miles
POWDER RIVER BASIN
OIL & GAS PROJECT FEIS
TECHNICAL REPORT GROUNDWATER MODELING
FIGURE 4-8
MODEL DRAIN
(CBM) NODES
MODEL RUN: From 1999-2200 (08-26-02)
Date: 09/04/02
Drawing File: Figure 4-8.dwg
Scale: As Noted
Drawn By: ETC

Figure 4-8 continued (11x17)

Table 4-6
Summary of Regional Model Input Parameters

Formation	Model Layer	$K_{x,y}$ (ft/s)	K_z (ft/s)	S_s (1/m)	S_Y (unitless)	Porosity (%)
Alluvium	1 - 7	1e-5	3e-6	1e-4	.2	25
Ancient Alluvium	1-4	1e-5	3e-6	5e-6	5e-4	10
Wasatch – Confining	1	1e-8	3e-9	5e-6	5e-4	10
Generalized Wasatch	2	1e-7	3e-8	1e-4	.02	10
Wasatch – Sand	4	2e-6	2e-7	1e-4	.02	10
Wasatch – Confining	3,5	2e-8	2e-10	5e-6	5e-4	10
Wasatch – Sand	6	2e-6	2e-7	1e-4	.02	10
Wasatch – Lower Confining	7	1e-8	6e-11	5e-6	5e-4	10
Upper Fort Union Coal Unit 1	8	1e-4 to 6e-5	1e-5	1e-6	1e-3	1
Upper Fort Union Confining	9	6e-8	6e-10	5e-6	5e-4	10
Upper Fort Union Coal Unit 2	10	6e-5	1e-5	1e-6	1e-3	1
Upper Fort Union Confining	11	6e-8	6e-10	5e-6	5e-4	10
Upper Fort Union Coal Unit 3	12	6e-5	1e-5	1e-6	1e-3	1
Upper Fort Union Confining	13	3e-9	6e-10	5e-6	5e-4	10
Upper Fort Union Coal Unit 4	14	1e-4 to 8e-5	8e-6	1e-6 to 2e-6	1e-3	1
Fort Union – Lower Confining	15	1e-8	5e-10	5e-6	5e-4	10
Middle Fort Union Lebo Shale	16	1e-8	1e-9	1e-4	0.02	10
Lower Fort Union Tullock	17	1e-7	3e-8	5e-4	0.01	25
Clinker	1 - 13	2e-5 to 6e-5	6e-5 to 2 e-6	0.01	0.1	25
Generalized Fort Union	8, 10, 12, 14	1e-6 to 3e-7	9e-8 to 2e-9	9e-5 to 5e-6	.0005 to 0.0125	10-25

$K_{x,y}$ = hydraulic conductivity (horizontal)
K_z = hydraulic conductivity (vertical)
S_s = specific storage
S_y = specific yield

The coal aquifers, particularly in the eastern PRB, have been subject to numerous field pumping tests. These tests have been evaluated in some detail in earlier studies (BLM 1994). A summary of hydrologic parameters derived from multi-well tests conducted in the PRB is included in Appendix B. Multiple well pumping tests, which rely on interpretation of observation wells that surround the pumping well, yield much more reliable and representative estimates of the hydraulic conductivity in an area. The values for hydraulic conductivity obtained from single-well pumping tests are less reliable because they tend to reflect the local conditions around the wellbore and so were not included in the summary of testing in Appendix B. The values for hydraulic conductivity derived from more reliable multi-well coal pumping tests fall within the range of 4.6×10^{-7} to 8.6×10^{-4} feet per second (ft/sec), with a median value of 2.3×10^{-5} ft/sec (Appendix B). Water yields from coal wells vary widely, from less than 1 gpm to more than 100 gpm. The wide range reflects the extent of fracturing and cleating in the vicinity of the well bore. Development and hydraulic fracturing of coal wells can significantly increase individual well yields.

The ranges of hydraulic conductivities derived from multi-well pumping tests were used as starting points for estimates of hydraulic conductivity in the regional model for any area. Even data from long-term multi-well coal pumping tests may not be representative of regional transmissivities, which tend to be dominated by major fracture zones in the coal. Accordingly, the range in values for hydraulic conductivity used in the model was based primarily on matching to steady-state and transient-state conditions.

The flatter, pre-mining potentiometric gradient in the southeastern part of the PRB (see Section 2.3) might suggest higher hydraulic conductivity for the coal in this area. Bloyd et al. (1986) suggest that this relatively flat potentiometric surface is questionable because it is based on very few data points, some of which are of suspect accuracy.

Hydraulic conductivity may be anisotropic, meaning that it changes depending on the direction of water movement. The MODFLOW model allows hydraulic conductivity to be input for each node in the three principal directions, corresponding to the three perpendicular axes of the model grid.The hydraulic conductivity in the horizontal direction (the x- and y- directions) was assumed to be uniform for the regional model. Although there is evidence to suggest that the coal exhibits some anisotropy caused by cleating and fracturing, studies show that the direction of anisotropy varies significantly over the PRB. In a regional sense, the simplification to isotropic conditions is believed to be a reasonable accommodation. The effect of fracturing on regional permeability was taken into account by assigning much higher hydraulic conductivities along the length of the major fracture traces or lineaments identified in the model area.

There is considerably less information on the hydraulic conductivity of the Wasatch sand aquifers. The nature of the Wasatch Formation, with discontinuous interbedded sands, silts, and clays, also results in considerable variability. Values derived from testing, summarized in Appendix B, range from 2.3×10^{-7} to 2.3×10^{-4} ft/sec, with a median value of 6.2×10^{-5} ft/sec. Accordingly, the range of values for hydraulic conductivity used in the model was based primarily on matching to steady-state and transient-state conditions. In general, the sandier Wasatch units will tend to dominate the overall horizontal conductivity, while the silt and clay units dominate the overall vertical conductivity. The assigned horizontal conductivity for most of the Wasatch Formation was representative of a fine- to medium-grained sand (2×10^{-6} ft/sec). The vertical conductivity was representative of silty clay (3×10^{-8} ft/sec). A small area close to the Powder River where the Wasatch Formation contains more sand was assigned a horizontal conductivity of 1×10^{-5} ft/sec.

The vertical hydraulic conductivity is typically one to two orders of magnitude lower than the horizontal value. The vertical hydraulic conductivity is an important parameter that controls the extent of influence in aquifer units above and below the pumped target coal seam. There are very little data from direct testing of this parameter. Vertical hydraulic conductivity of confining units was tested directly for the Ruby Ranch Project Permit Application (Power Resources, Inc. 1999) and is summarized in Appendix B. Measured values for claystone ranged from 2.8×10^{-10} ft/sec to 1.1×10^{-9} ft/sec. The range of vertical hydraulic conductivity values used in the model was based primarily on matching to steady-state and transient-state conditions. Modeling in the Caballo Creek area (Chapter 8) indicated that the vertical hydraulic conductivity of the claystone confining units above and below the coal zone (layers 7 and 15) ranges between 6×10^{-11} ft/sec and 5×10^{-10} ft/sec.

4.7.2 Storage Coefficient and Specific Storage

The range of values for storativity used for the various model layers are summarized in Table 4-7. There are relatively few reliable data on storage coefficients in the PRB. A compilation of values derived from multi-well pumping tests in the PRB is included in Appendix B. Storage coefficient values vary significantly, depending on whether the unit tested is under confined or unconfined conditions. Most pumping tests conducted in the coal are considered under confined conditions. Storage coefficients derived from these pumping tests are in the range of 10^{-3} to 10^{-5}. The specific storage (S_s, equivalent to the storage coefficient divided by the thickness) for these tests ranged between 2.1×10^{-7} ft^{-1} and

1.9×10^{-4} ft^{-1}, with a median value of 3.8×10^{-6} ft^{-1} Pumping tests conducted in the Wasatch sands may be under confined or unconfined conditions. Storage coefficients derived from these pumping tests are in the range of 10^{-2} to 10^{-6}. The specific storage derived from Wasatch sand tests averages 1.8×10^{-4} ft^{-1}.

4.8 Limitations of Model

4.8.1 Size of the Model

As indicated in Section 4.1, any regional model of this size will involve limitations caused by the size of the grid nodes and the simplification of a complex hydrogeologic system necessary for creating the model. The regional model was constructed using averaged and smoothed values so that localized conditions are typically not well refined. The size of each node in the model is one-half mile by one-half mile, so infiltration impoundments, small streams and rivers, and other smaller features cannot be represented exactly. Rather, smaller features are represented by the application of boundary conditions over the entire grid node. For example, infiltration of water from an impoundment is applied over an entire cell as a very small recharge rate. This assumption is less accurate for individual features, but this assumption improves as the density of features within a grid node increases. The primary purpose of modeling a hydrologic system on a regional, basin-wide scale is to project impacts and compare alternatives. A regional model also can be used to estimate the mass water balance so that long-term gain or loss can be evaluated. The regional model is an adequate tool for a comprehensive determination of the effects of CBM development. However, the results should be viewed in perspective with the scale, and a sub-regional or local area model should be used to help evaluate impacts on a smaller scale.

Two sub-area models, which are developed at a much smaller scale, complement the regional model and were used to demonstrate specific aspects of CBM development in the PRB. The Caballo Creek sub-area model, described in Chapter 8, was used to match transient water data in an area with a relatively long history of CBM development. This match allowed an evaluation of hydrologic parameters for confining zones that have a major influence on projections of shallow aquifer drawdown and coal recovery after CBM pumping ends. The LX-Bar sub-area model, described in Chapter 9, was developed specifically to examine the potential influences of impoundment infiltration and adjacent creek flows on groundwater levels in shallow Wasatch sands in an area where surface discharge would probably be limited by water quality considerations.

4.8.2 Lack of Geologic Data for the Wasatch Formation

The Fort Union coal units are reasonably well defined in the regional model, but the Wasatch units lack adequate definition. The Wasatch Formation is highly variable throughout the basin but, lacking sufficient geologic data, the Wasatch Formation was arbitrarily divided into six layers in the model. The primary reason for dividing the Wasatch Formation is to provide adequate vertical discretization, although not exact geologic definition, in the model. Greater vertical discretization improves the way MODFLOW handles the vertical movement of water. Hydraulic conductivities for each layer are set so that the overall conductivity of the Wasatch Formation is simulated.

4.8.3 Representation of CBM Wells as Drain Boundary Nodes

In the regional model, CBM wells were simulated using drain boundary nodes. Any node could encompass one to four actual CBM wells per layer and up to 16 wells per model column. The number of CBM wells represented per drain was accommodated by varying the drain conductance. Use of a drain boundary applied over the entire node to represent a CBM well, which is a single point within the node, will over-predict the water production of a single well during the early stages of production. As well density increases within a given node, however, the drain boundary becomes a better representation of CBM production.

4.8.4 Lack of Data in the Central and Western Parts of the Basin

There are a lack of data for observation wells, production, and geology for the Wasatch Formation away from established areas of development in the eastern portion of the basin. The model is limited and potentially skewed by the data that are available. Model results from areas of the basin that lack adequate calibration data should be considered only as a general indicator of potential impacts. The model should be updated and refined as new data become available.

4.8.5 Dry Cells

In MODFLOW, a cell is changed from an active cell to a dry cell when the head in that cell falls below the base of the cell. When a cell becomes dry, the model treats it as an inactive cell, and water cannot move through it. Also, if a cell becomes dry, any boundary conditions will effectively be removed from the model. For example, if a cell becomes dry in layer one, any recharge applied to that cell is lost unless it is specified that recharge be applied to the highest active cell within a column, as was the case in the PRB EIS model. If the entire column of cells becomes dry, however, the recharge will be lost to the system. Dry cells can severely affect the horizontal and vertical movement of water throughout the simulated aquifer system.

Cells can become dry for various reasons, such as simulated mining activity, CBM activity downdip, or steeply dipping beds. It is feasible for dry cells to occur as aquifers are dewatered, but dewatered areas would eventually repressurize and resaturate once development has stopped and water levels are allowed to recover. In the regional model, cells became dry because of mining and CBM development. The MODFLOW rewetting package was used to mitigate the impacts of the dry cells on the results. Rewetting parameters were set such that cells were allowed to rewet from adjacent cells and from cells directly below. The rewetting threshold was set at 5 meters, implying that if the head in an adjacent cell exceeded 5 meters, rewetting would occur, thus changing the dry cell to an active cell. The threshold was set at 0.1 meter, so the head in a dry cell that was activated would be set 0.1 meter above the base of the cell.

Rewetting has its own limitations, particularly with regard to solution convergence. If a cell is continually drying out and rewetting, the model will have difficulty converging. At times during the model run, it may be necessary to increase the solver convergence criteria to enable the model to converge.The convergence criteria were raised as high as 3 meters during some stress periods for the transient regional model. However, the water balance discrepancy for all stress periods was less than 1 percent, and typically was around 0.1 percent, indicating that the model did not converge until a reasonable solution was reached.

5.0 MODEL CALIBRATION AND SENSITIVITY ANALYSIS

5.1 Flow Model Calibration

Model calibration is achieved when the model reasonably simulates the interpreted groundwater flow conditions within the geologic units of interest using inputs that are within the range of measured or estimated values. The locations of pre-mining monitoring wells used in calibrating the steady-state model are shown in Figure 5-1. For transient-state calibration, modeled water levels were compared with water level monitoring data from the Gillette Area Groundwater Monitoring Organization (GAGMO) and BLM monitoring wells. In addition, modeled annual CBM water production rates were compared with reported annual water production for the sub-watersheds between 1987 and 2000. Calibration was performed iteratively between steady-state and transient-state model runs. All water level monitoring data were entered into the model so that this comparison could be made.

The following criteria were used in this study to calibrate the flow model:

1. Match actual steady-state groundwater elevations ("heads") for pre-mining (generally prior to 1975) with the heads predicted by the model.

2. Evaluate the overall global water balance to assess whether the model reasonably predicts flow into and out of the system by comparison with estimated groundwater discharges to surface drainages.

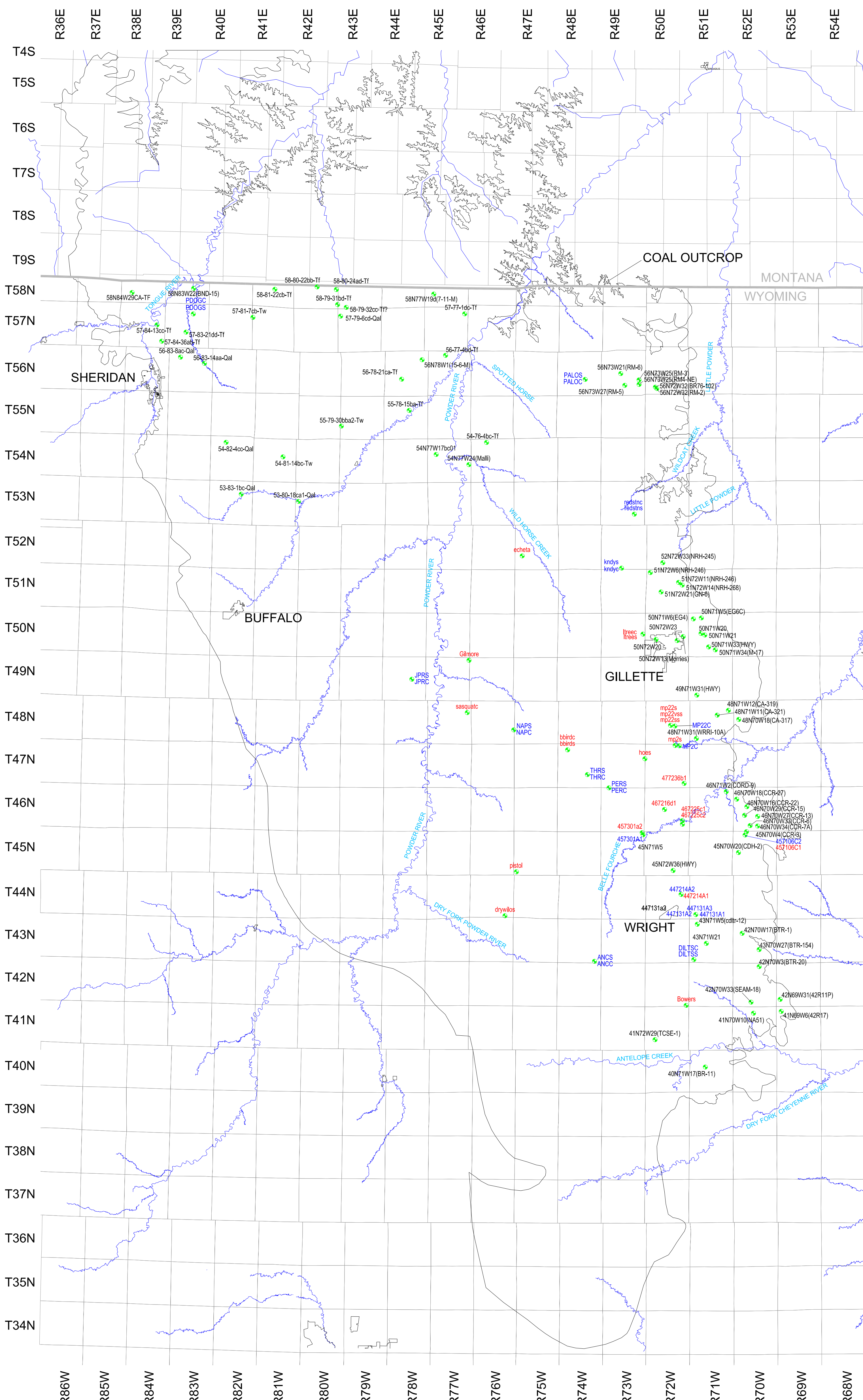
3. Match transient-state groundwater elevations ("heads") for post-mining and post-CBM development with the heads predicted by the model. Monitoring well data from GAGMO and BLM monitoring wells were used for this calibration. Interpreted potentiometric maps (areal comparison at different times) and individual monitoring well hydrographs (temporal comparison at different locations) were compared.

4. Match year-by-year historical CBM production in various selected areas with water production predicted by the model.

5.1.1 Steady-State Calibration

Pre-mining potentiometric data are sparse. Available data are summarized in Table 2-2. Figure 2-3 shows the interpreted pre-mining (assumed steady state) potentiometric surface in the upper Fort Union Formation. Steady-state model runs were conducted and compared with actual water levels for pre-mining conditions. Steady-state calibration was conducted by varying model input parameters, primarily recharge rates and hydraulic conductivity. This calibration was iterative with the transient calibration discussed in Section 5.1.2.

Figure 5-2 shows the model-predicted steady state potentiometric surface for the upper Fort Union Formation. The comparison of actual observed heads to model-predicted heads at the pre-mining calibration points is shown in Table 5-1 and is graphically illustrated in Figure 5-3. Points above the line in Figure 5-3 represent heads over-predicted by the model.



LEGEND

- Rivers
- Towns
- Calibration Wells
- 56-78-21ca-Tf Steady State Calibration Well
- 45106C1 Transient Calibration Well
- drywilos Both Transient and Steady State Calibration Well

Note: Steady state calibration wells consist of wells from the Sheridan County well records (1966), Daddow's potentiometric-surface map of the Wyodak-Anderson coal (1986), and existing BLM wells. Transient calibration wells are BLM wells only.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

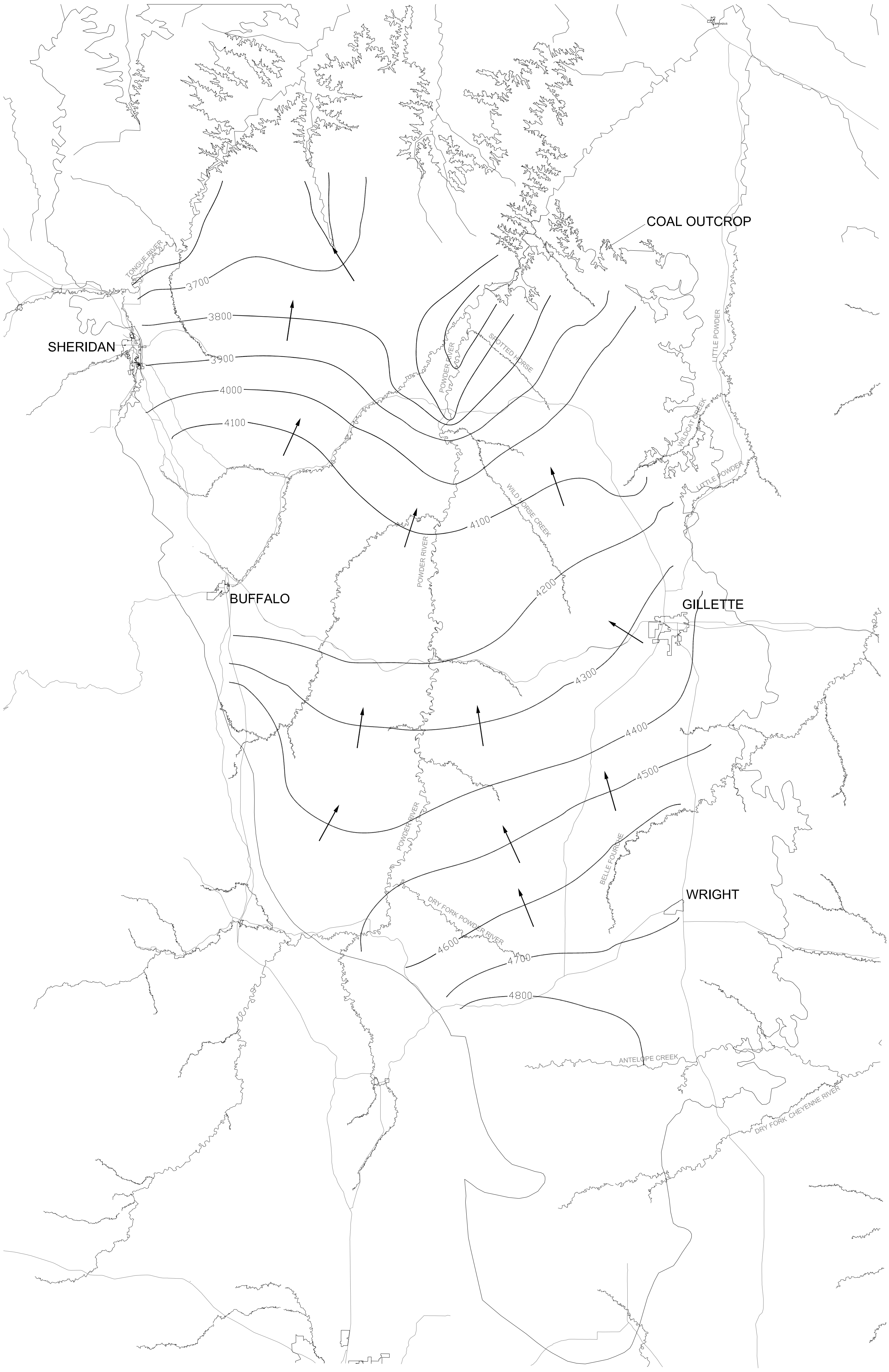
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 5-1
LOCATION OF CALIBRATION WELLS

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

Date: 09/04/02	Drawing File: Figure 5-1.dwg
Scale: As Noted	Drawn By: ETC

Figure 5-1 continued (11x17)



LEGEND

- Rivers
- Roads
- Towns
- Potentiometric Contour (ft)

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 5-2 MODELED PRE-MINING POTENTIOMETRIC HEADS (STEADY STATE)	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/04/02	Drawing File: Figure 5-2.dwg
Scale: As Noted	Drawn By: ETC

Figure 5-2 continued (11x17)

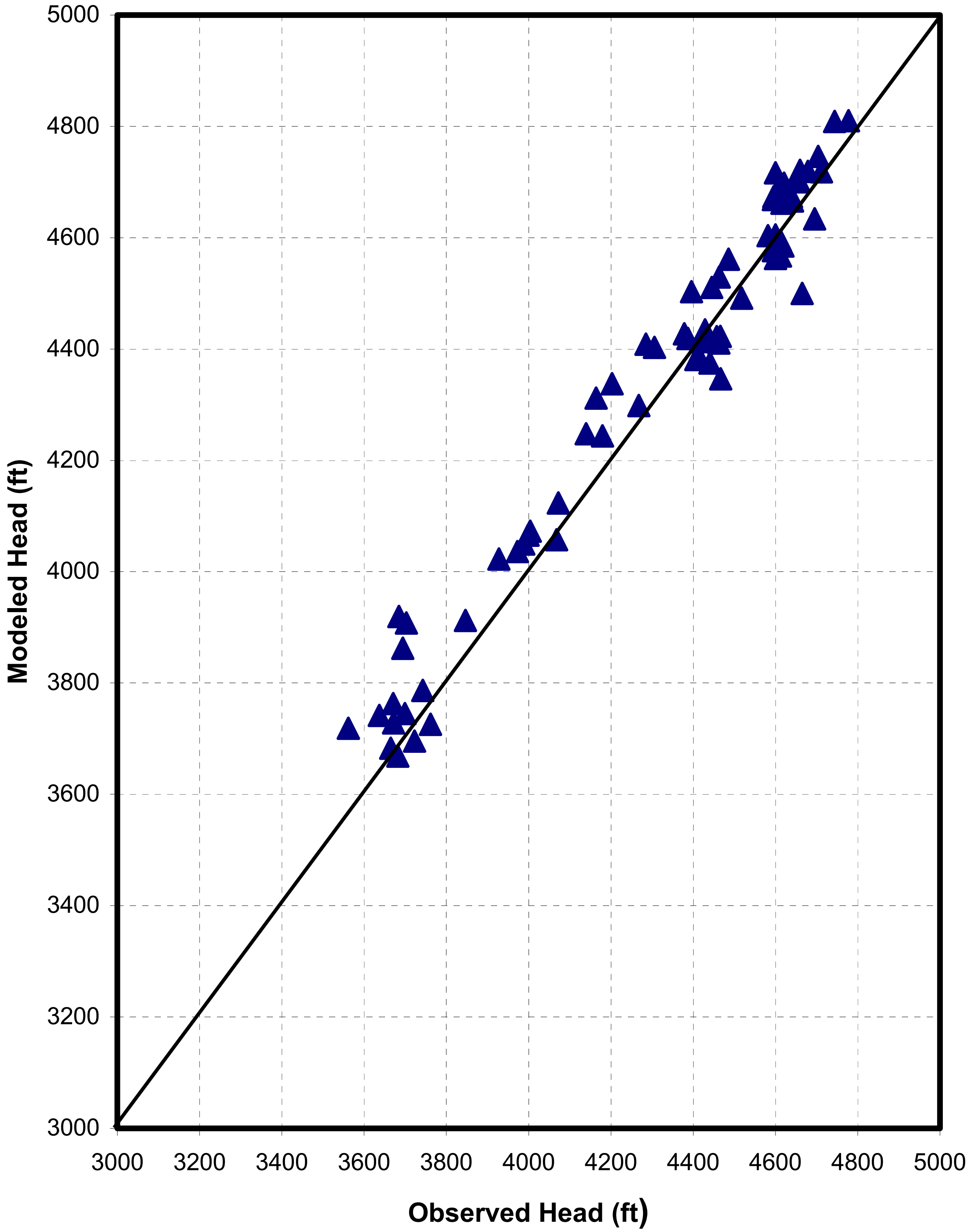
Table 5-1
Results of Steady-State Calibration for Observation Wells

Observation Well Name	Source of Data	Water Level Date	Observed Head (ft)	Modeled Head (ft)	Residual (observed -modeled)
40N71W17(BR-11)	Daddow	Oct-81	4695.0	4634.0	60.9
41N69W6(42R17)	Daddow	Dec-80	4778.0	4810.0	-32.0
41N70W10(NA51)	Daddow	Dec-80	4642.0	4665.9	-23.9
41N72W29(TCSE-1)	Daddow	Nov-82	4658.0	4700.4	-42.4
42N69W31(42R11P)	Daddow	Dec-80	4744.0	4808.9	-64.9
42N70W17(BTR-1)	Daddow	NA	4608.0	4688.9	-80.9
42N70W3(BTR-20)	Daddow	NA	4653.0	4705.6	-52.6
42N70W33(SEAM-18)	Daddow	Aug-78	4595.0	4668.6	-73.6
43N70W27(BTR-154)	Daddow	Oct-73	4621.0	4697.9	-77.0
43N71W21	Daddow	Jul-79	4605.0	4672.0	-67.0
43N71W5(CDLTR-12)	Daddow	Aug-78	4616.0	4662.0	-46.0
447131a1	BLM	NA	4679.3	4719.3	-40.0
447214a1	BLM	1998	4594.75	4634.75	-40.0
457106c1	BLM	1997	4576.87	4585.93	-9.1
457301a1	BLM	1997	4606.23	4550.31	55.9
457301a2	BLM	NA	4594.6	4576.9	17.7
45N70W20(CDH-2)	Daddow	Aug-78	4639.0	4673.4	-34.4
45N70W4(CCR-3)	Daddow	NA	4600.0	4716.3	-116.4
45N71W5	Daddow	May-77	4612.0	4594.4	17.6
45N72W36(HWY)	Daddow	NA	4600.0	4604.8	-4.9
467216d1	BLM	NA	4463.8	4529.5	-65.7
467225c1	BLM	1996	4600.2	4562.9	37.3
467225c2	BLM	NA	4618.0	4585.3	32.7
467236b1	BLM	NA	4612.6	4567.2	45.4
46N70W16(CCR-22)	Daddow	NA	4628.0	4667.9	-40.0
46N70W18(CCR-27)	Daddow	NA	4582.0	4603.6	-21.6
46N70W27(CCR-13)	Daddow	NA	4712.0	4718.3	-6.3
46N70W29(CCR-15)	Daddow	NA	4596.0	4673.7	-77.7
46N70W33(CCR-6)	Daddow	NA	4660.0	4720.9	-60.9
46N70W34(CCR-7A)	Daddow	NA	4704.0	4745.9	-42.0
46N71W2(CORD-9)	Daddow	NA	4486.0	4561.3	-75.3
477119c1	BLM	1995	4405.0	4502.8	-97.8
477236b1	BLM	1995	4445.2	4510.7	-65.6
48N70W18(CA-317)	Daddow	May-76	4665.0	4499.5	165.4
48N71W11(CA-321)	Daddow	May-76	4466.0	4422.7	43.3
48N71W12(CA-319)	Daddow	May-76	4518.0	4491.5	26.5
48N71W31(WRRI-10A)	Daddow	Nov-79	4457.0	4422.3	34.7
49N71W31(HWY)	Daddow	Dec-77	4463.0	4410.7	52.3
50N71W20	Daddow	Mar-77	4418.0	4413.6	4.4
50N71W21	Daddow	May-77	4387.0	4418.9	-32.0
50N71W33(HWY)	Daddow	Jun-74	4379.0	4427.2	-48.2
50N71W34(M-17)	Daddow	Aug-78	4429.0	4434.7	-5.7
50N71W5(EG6C)	Daddow	Oct-76	4285.0	4408.7	-123.7
50N71W6(EG4)	Daddow	Oct-76	4306.0	4403.2	-97.2
50N72W13(Morries)	Daddow	Jun-78	4414.0	4385.5	28.5
50N72W20	Daddow	NA	4467.0	4346.4	120.6
50N72W23	Daddow	NA	4441.0	4374.9	66.1

Table 5-1 (Continued)
Results of Steady-State Calibration for Observation Wells

Observation Well Name	Source of Data	Water Level Date	Observed Head (ft)	Modeled Head (ft)	Residual (observed -modeled)
51N72W14(NRH-268)	Daddow	NA	4203.0	4337.9	-134.9
51N72W21(GN-6)	Daddow	Feb-77	4268.0	4298.4	-30.4
51N72W6(NRH-246)	Daddow	NA	4140.0	4247.8	-107.8
52N72W33(NRH-245)	Daddow	NA	4180.0	4244.2	-64.3
53-80-18ca1-Qal	Sheridan	NA	4072.2	4123.2	-51.0
53-83-1bc-Qal	Sheridan	NA	4406.5	4381.1	25.4
54-76-4bc-Tf	Sheridan	NA	3846.8	3912.4	-65.6
54N77W17bc01	BLM	Aug-84	3694.0	3862.2	-168.2
54N77W24(Malli)	Daddow	Feb-79	3703.0	3907.7	-204.7
55-78-15ba-Tf	Sheridan	NA	3699.1	3745.1	-46.0
56-77-4bd-Tf	Sheridan	NA	3682.1	3668.7	13.3
56-78-21ca-Tf	Sheridan	NA	3742.1	3787.0	-44.9
56-83-14aa-Qal	Sheridan	NA	3664.7	3682.7	-18.0
56N72W32(BR76-102)	Daddow	Sep-76	4004.0	4072.8	-68.9
56N72W32(RM-2)	Daddow	Aug-75	3999.0	4065.9	-66.9
56N73W21(RM-6)	Daddow	Aug-75	3928.0	4022.5	-94.6
56N73W25(RM-3)	Daddow	Nov-79	3988.0	4049.7	-61.7
56N73W25(RM4-NE)	Daddow	May-76	4068.0	4057.4	10.6
56N73W27(RM-5)	Daddow	Sep-75	3973.0	4036.1	-63.1
56N78W1(15-6-M)	Daddow	Aug-84	3672.0	3728.2	-56.2
57-77-1dc-Tf	Sheridan	NA	3670.9	3762.8	-91.9
57-79-6cd-Qal	Sheridan	NA	3761.5	3726.0	35.4
57-81-7cb-Tw	Sheridan	NA	3637.1	3742.0	-104.9
57-84-13cc-Tf	Sheridan	NA	3562.0	3718.8	-156.8
58-79-31bd-Tf	Sheridan	NA	3722.4	3695.5	26.9
58-79-32cc-Tf?	Sheridan	NA	3716.9	3705.3	11.6
58-80-24ad-Tf	Sheridan	NA	3666.0	3665.4	0.6
58-81-22cb-Tf	Sheridan	NA	3858.6	3783.7	74.9
58N77W19d(7-11-M)	BLM	Aug-84	3802.0	3746.0	55.9
58N83W22(BND-15)	Daddow	Apr-84	3475.0	3698.2	-223.2
bbirdc	BLM	NA	4412.3	4375.3	37.0
bbirds	BLM	NA	4524.6	4452.7	72.0
Bowers	BLM	NA	4567.9	4670.0	-102.2
diltsc	BLM	NA	4590.1	4671.2	-81.0
diltss	BLM	NA	4810.7	4700.0	110.7
drywilos	BLM	NA	4852.7	4774.4	78.3
Echeta	BLM	Apr-84	4020.9	4157.7	-136.8
Gilmore	BLM	NA	4166.8	4191.5	-24.7
hoes	BLM	NA	4637.3	4580.8	56.6
ltreec	BLM	NA	4308.3	4310.6	-2.3
ltrees	BLM	NA	4445.4	4392.3	53.0
mp22s	BLM	NA	4474.3	4478.0	-3.8
mp22ss	BLM	NA	4520.9	4511.3	9.5
mp22vss	BLM	NA	4539.1	4541.3	-2.2
mp2s	BLM	NA	4490.6	4497.8	-7.2
Pistol	BLM	1997	4653.3	4535.1	118.2
Sasquatc	BLM	1997	4244.8	4261.7	-16.9

Figure 5-3 Modeled vs. Observed Heads for Pre-mining Calibration Wells



Overall, the calibrated model simulates pre-mining groundwater flow conditions fairly well, with about 75 percent of the modeled heads within plus or minus 70 feet of observed heads. The root-mean-square of all the model calibration points was 75 feet. Modeled and actual water levels may differ in a few areas by as much as plus or minus 200 feet. However, the pre-mining data from these wells are acknowledged to be questionable. The level of accuracy for calibration is believed to be reasonable in light of the regional nature of the model, with a grid spacing of one–half mile.

Pre-mining potentiometric heads predicted by the model in the coal will tend to be higher than actual (observed) heads because the model assumes 1975 as the pre-mining condition, while many of the observed heads assume 1980 as the pre-mining base year. Mining that occurred before 1980 presumably caused some level of drawdown, particularly in the coal, in the vicinity of active mines. Gradients simulated by the model were similar to observed gradients.

5.1.2 Steady-State Calibration to Powder River Baseflows

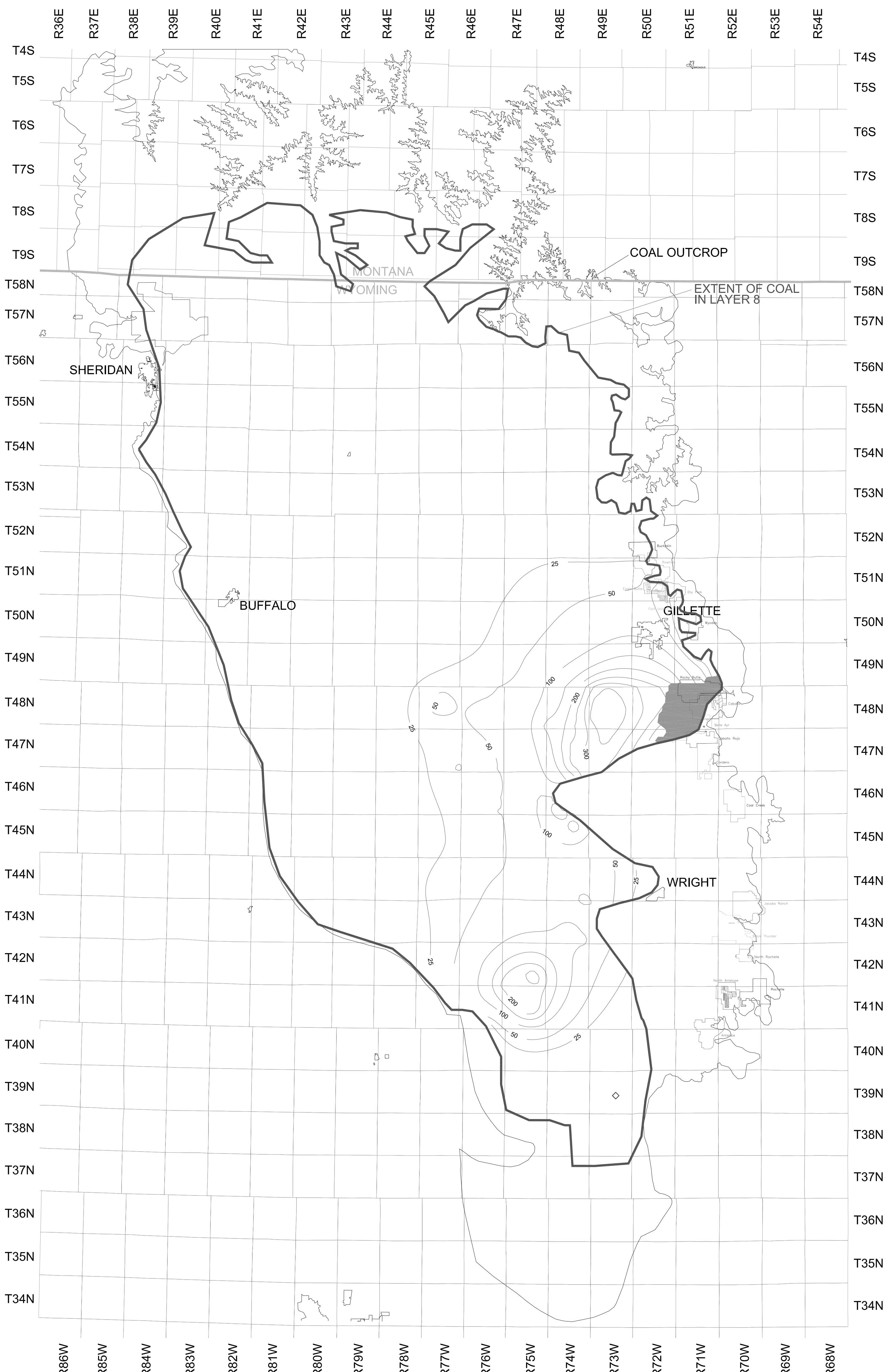
One consideration in model calibration is that modeled groundwater discharge rates must be consistent with observations of groundwater discharges to surface drainages. As discussed previously, the Powder River valley between Sussex, Wyoming, and Moorhead, Montana, has been interpreted as a significant groundwater discharge area (Hagmaier 1971), but Rankl and Lowry (1990) found no measurable effect of regional groundwater discharge on streamflow in this reach. A water balance analysis performed to estimate the potential baseflow to the Powder River in this reach was described in Section 2.3.2. This analysis, summarized in Table 2-3, concluded that regional groundwater discharge to the Powder River is in the range of 5 cfs to perhaps as high as 20 cfs. The water balance of the steady-state model indicates a net discharge of groundwater of approximately 15 cfs to the Powder River and its lower tributaries. This discharge is within the range of values estimated by the water balance analysis.

5.1.3 Transient-State Calibration to Water Levels

Transient model runs were conducted and compared with actual water levels for post-mining and post-CBM development conditions. Calibration was conducted iteratively with steady-state pre-mining conditions by adjusting the model input parameters, primarily: recharge rates, hydraulic conductivity, and storativity values. The final calibration for both steady-state and transient-state runs yielded consistent values for all hydrologic parameters.

Figures 5-4A, 5-4B, 5-4C, and 5-4D show the modeled changes in regional potentiometric surface for the model layers that represent coal deposits in the upper portion of the Fort Union Formation between 1975 and 2000. The extent and magnitude of modeled drawdown shown in these figures compare favorably with estimated actual drawdowns for selected BLM monitoring wells shown in Figure 2-4. The monitoring record for several of the BLM monitoring wells is relatively short, so that drawdown caused by earlier CBM or mining activity may not have been recorded in some areas. Interpreted drawdown in these wells, based on presumed initial static water levels that are already affected, would lead to underestimation of drawdown. This interpreted drawdown may account for some of the differences in modeled versus interpreted potentiometric drawdown.

Figures 5-5, 5-6, and 5-7 focus on three areas where there have been significant mining and CBM development, showing superimposed drawdown predicted by the model and drawdowns monitored near coal mines as of 1995 for comparison. The interpreted drawdown contours on these maps are from the 15-year drawdown report prepared for GAGMO. For all these maps, the modeled drawdown presented is of the model layer where the mines are located.



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

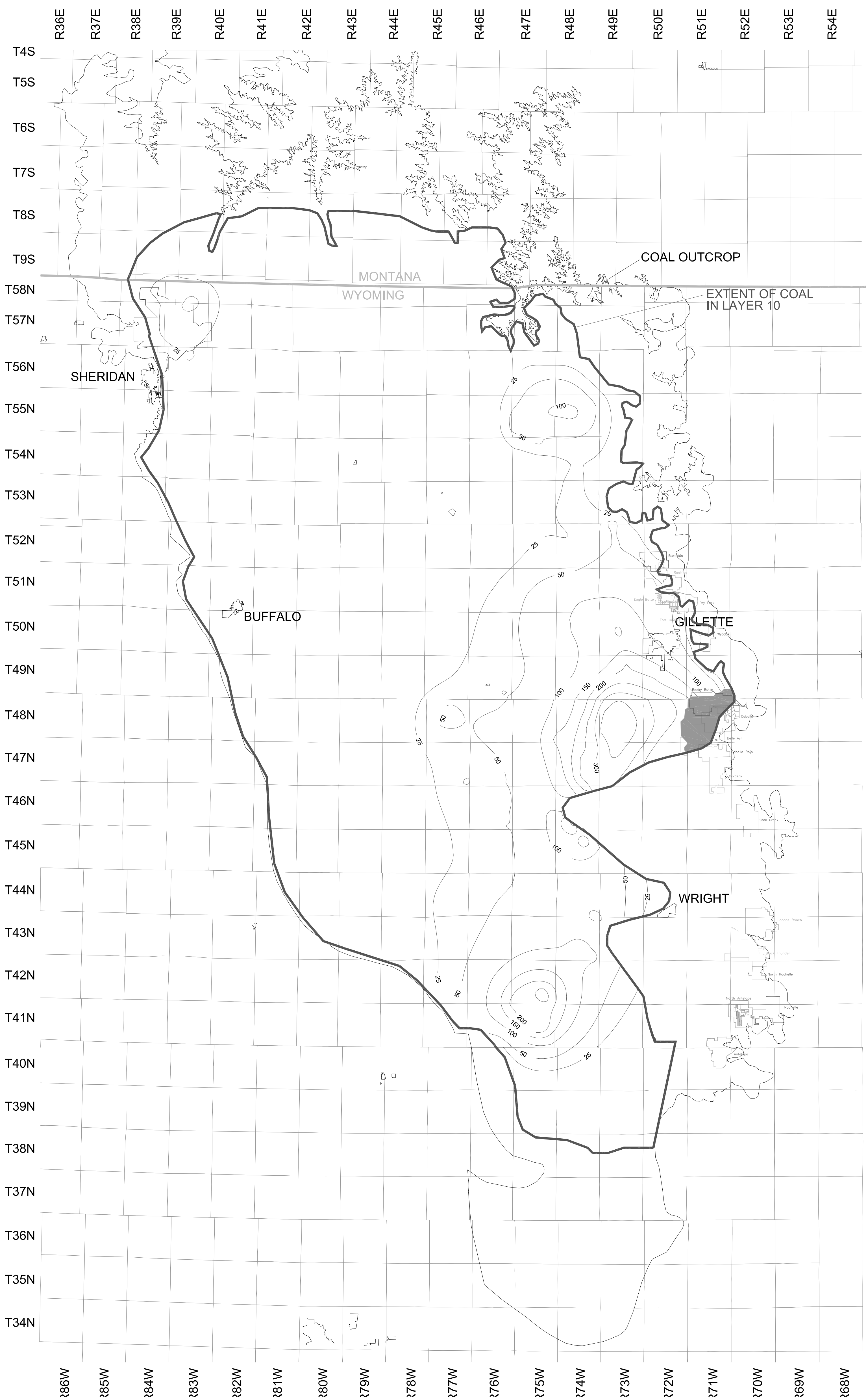
Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 5-4A MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2000	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/04/02	Drawing File: Figure 5-4 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 5-4A continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

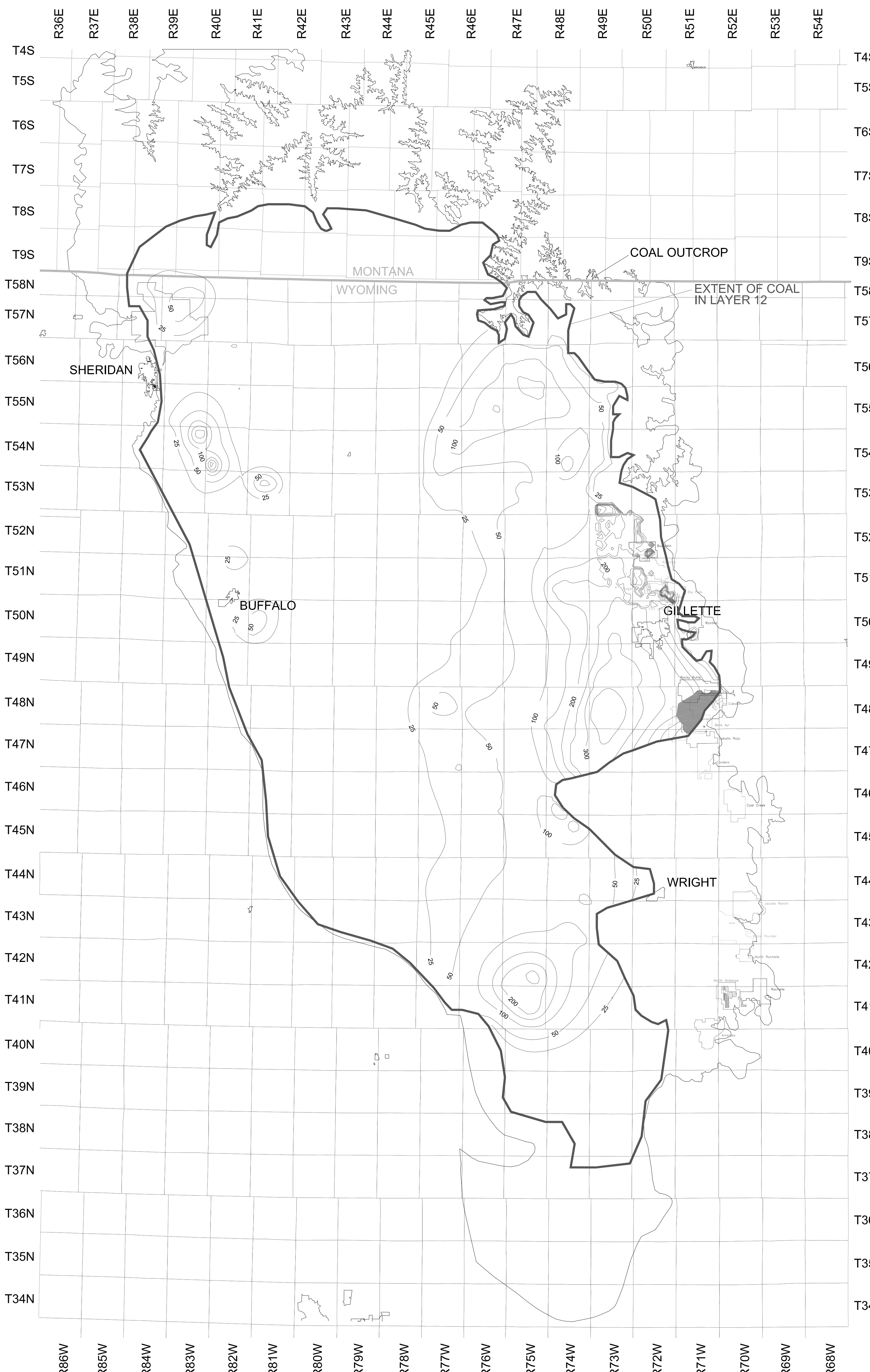
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 5-4B
MODELED DRAWDOWN
UPPER FORT UNION COALS
LAYER 10 YEAR 2000

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

Date: 09/04/02	Drawing File: Figure 5-4 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 5-4B continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

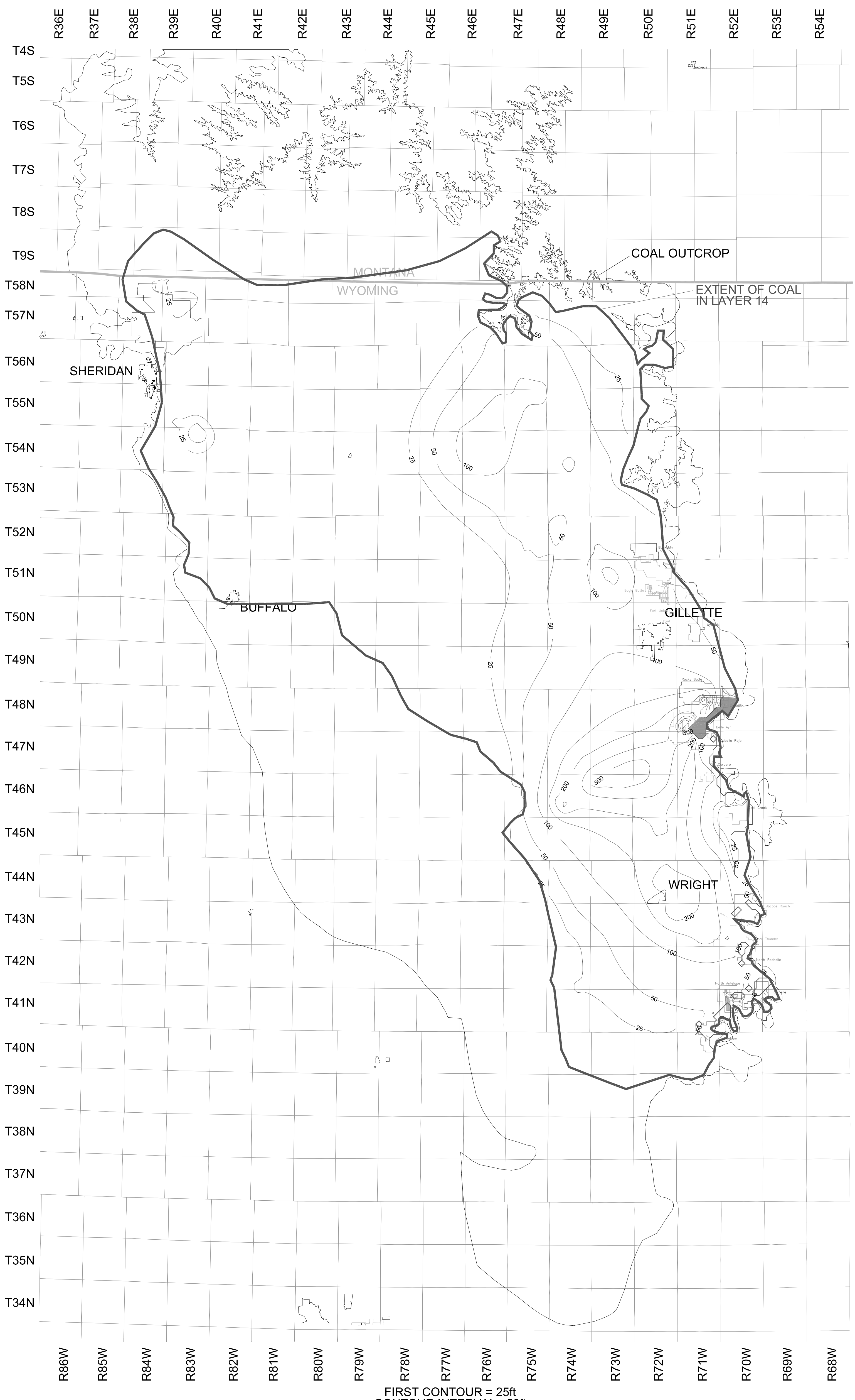
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 5-4C
MODELED DRAWDOWN
UPPER FORT UNION COALS
LAYER 12 YEAR 2000

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

Date: 09/04/02	Drawing File: Figure 5-4 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 5-4C continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 14
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

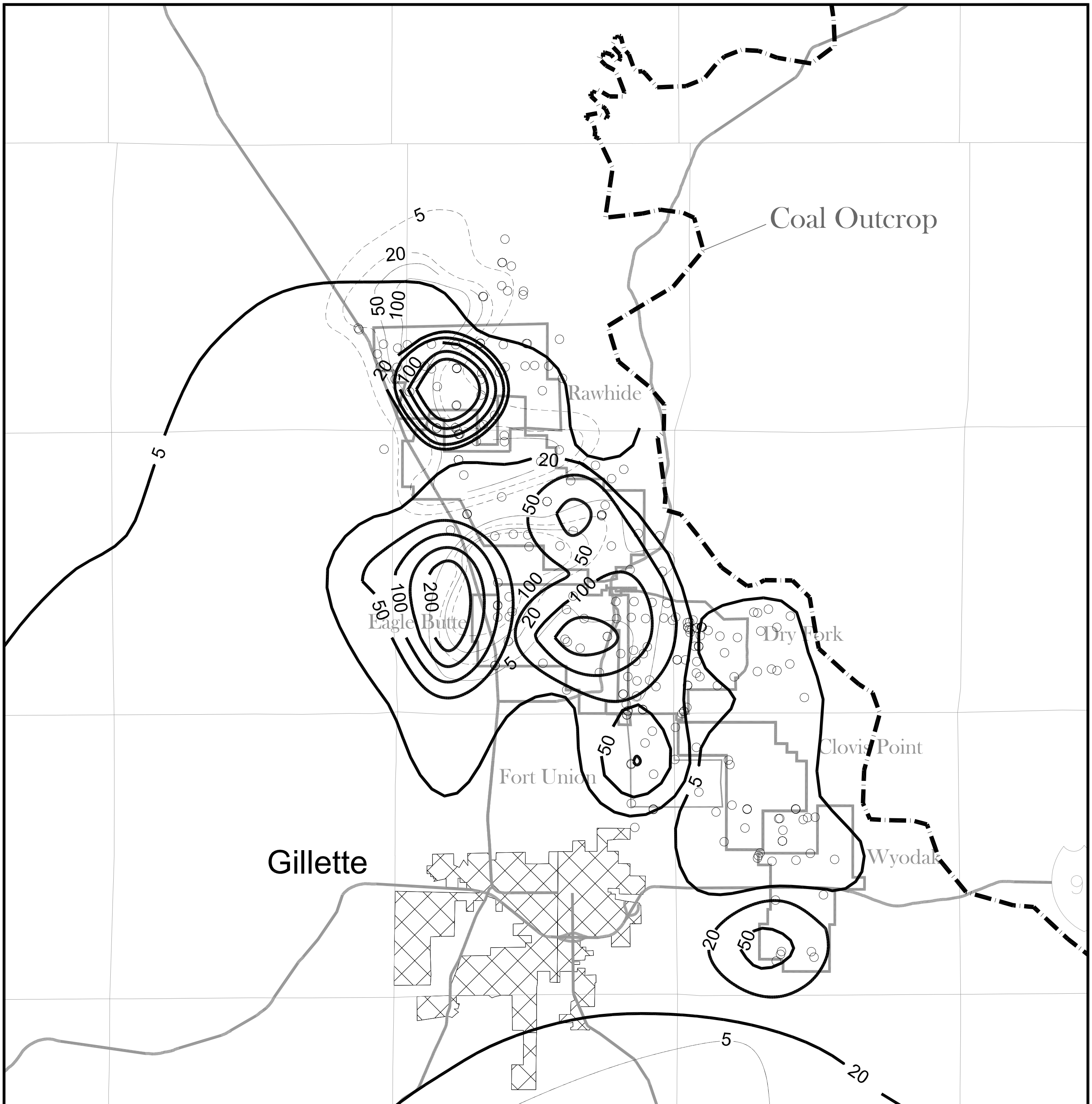
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 5-4D
MODELED DRAWDOWN
UPPER FORT UNION COALS
LAYER 14 YEAR 2000

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

Date: 09/04/02	Drawing File: Figure 5-4 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 5-4D continued (11x17)



LEGEND

- GAGMO Monitoring Wells
- Coal Lease Boundary
- Population Area
- GAGMO 15 Year Coal Seam Water Level Changes (Ft.)
- Modeled 1975-1995 Coal Seam Water Level Changes (Ft.)
- Coal Outcrop

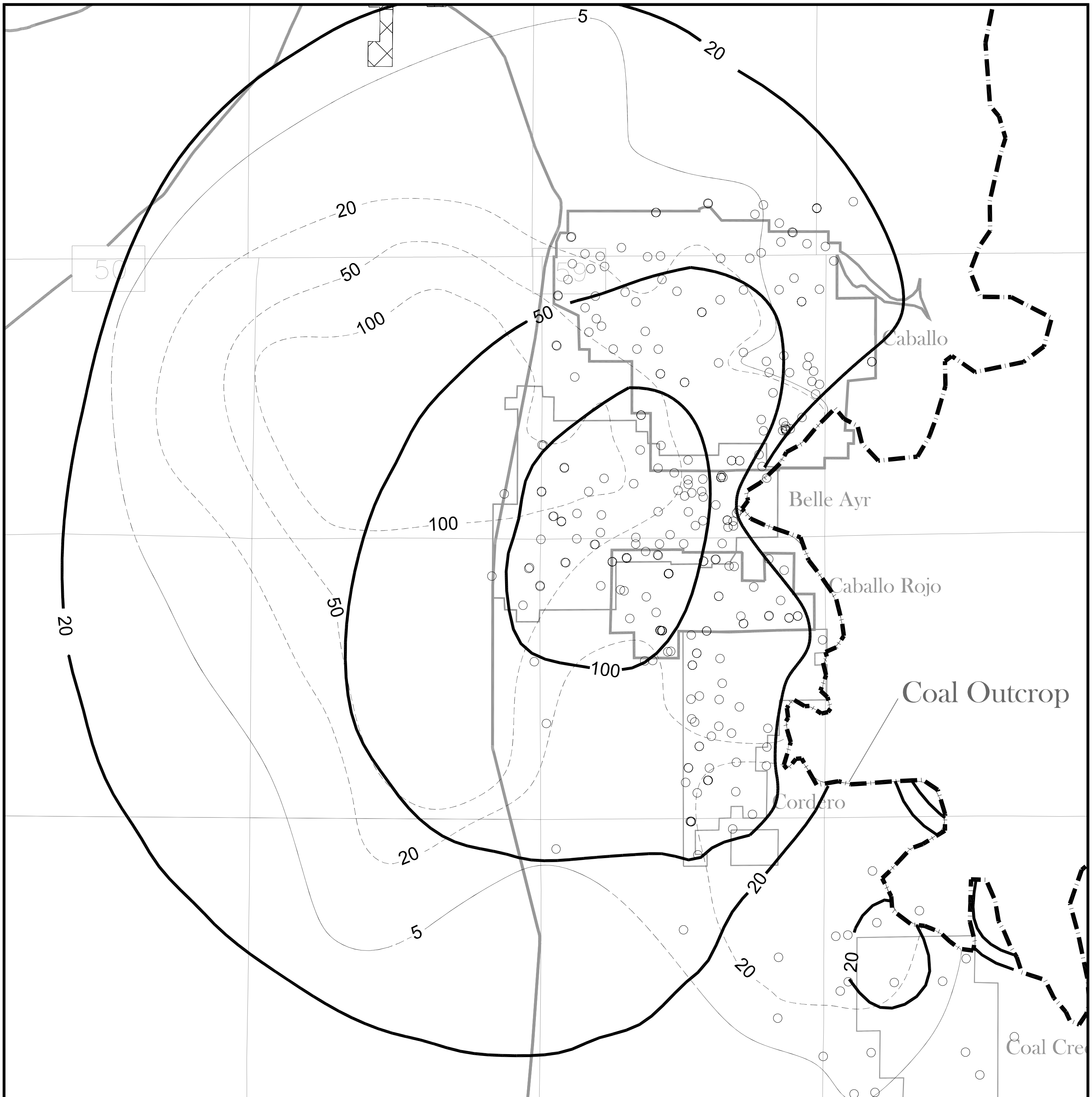
POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 5-5
MODELED vs ACTUAL DRAWDOWN IN UPPER FORT UNION COALS IN 1995
NORTHEAST AREA

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

Date: 09/04/02	Drawing File: Figure 5-5_5-7.dwg
Scale: As Noted	Drawn By: ETC



LEGEND

- GAGMO Monitoring Wells
- Coal Lease Boundary
- Population Area
- GAGMO 15 Year Coal Seam Water Level Changes (Ft.)
- Modeled 1975-1995 Coal Seam Water Level Changes (Ft.)
- Coal Outcrop

N

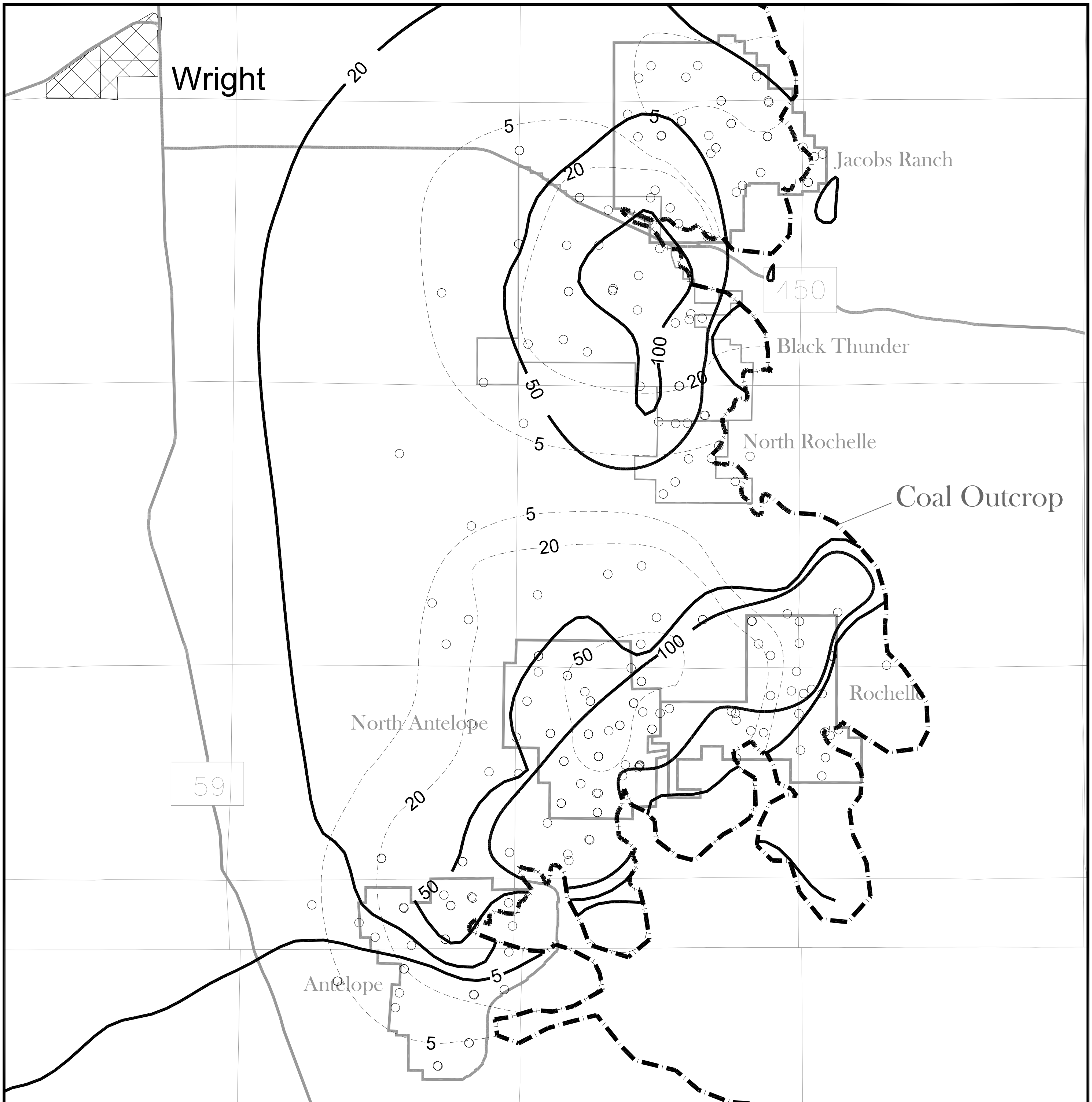
0 1.5 3 6 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 5-6
MODELED vs ACTUAL DRAWDOWN IN UPPER FORT UNION COALS IN 1995
CENTRAL-EAST AREA

MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/04/02	Drawing File: Figure 5-5_5-7.dwg
Scale: As Noted	Drawn By: ETC



LEGEND

- GAGMO Monitoring Wells
- Coal Lease Boundary
- Population Area
- GAGMO 15 Year Coal Seam Water Level Changes (Ft.)
- Modeled 1975-1995 Coal Seam Water Level Changes (Ft.)
- Coal Outcrop

0 1.5 3 6 Miles

N

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 5-7
MODELED vs ACTUAL DRAWDOWN IN UPPER FORT UNION COALS IN 1995 SOUTHEAST AREA

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

Date: 09/04/02	Drawing File: Figure 5-5_5-7.dwg
Scale: As Noted	Drawn By: ETC

Most of the mining in the PRB was initiated after 1977 (with the exception of the Wyodak and Belle Ayr mines), so that use of 1975 as the baseline year (pre-mining) is reasonable. It may, however, result in some overestimation of drawdown in the model compared with the GAGMO interpretation, for the reasons described in Section 5.1.1. The extent of drawdown predicted by the model in the three localized areas shown in Figures 5-5, 5-6, and 5-7 compares reasonably well with the drawdowns interpreted by GAGMO. The level of accuracy used for calibration is believed to be reasonable in light of the regional nature of the model with a grid spacing of about one-half mile. The model should not be expected to match water levels accurately at a smaller scale, such as a mine site.

The extent of drawdown projected by the model, represented by the 5-foot drawdown contour, tends to be more extensive than the GAGMO interpretation in the northeast and southeast areas (Figures 5-5 and 5-7). This larger extent may be caused in part because the drawdown projected by the model uses 1975 as the base year, while the GAGMO-interpreted drawdown uses 1980 as the base year. The model also accounts for drawdown in the coal that occurs as a result of pumping of the underlying Fort Union sands by the City of Gillette and the town of Wright, which began before 1980. The model's incorporation of drawdown has the effect of imposing a small amount of coal drawdown (5 to 10 feet) over an extended area above these well fields. The drawdown in the vicinity of the mines compares closely.

The extent of drawdown predicted by the model in the Marquiss area located west of the Belle Ayr Mine, represented by the 20-foot drawdown contour, is similar to the level actually observed, as shown in Figure 5-6. The extended drawdown area located west of the mine areas is caused by the initiation of CBM activity in 1992. Continued CBM development in the Marquiss field since 1995 has caused drawdowns in this area to increase to more than 250 feet. Overall, the calibrated model effectively simulates groundwater flow conditions in these local areas under the superimposed stresses of mining and CBM development.

Figures 5-8 through 5-11 show modeled versus actual drawdown over time in selected BLM monitoring wells where there is evidence of drawdown caused by CBM activity. The MP-22 and MP-2 wells (Figures 5-8 and 5-9) are located west of the Belle Ayr mine and south of Gillette. The Prairie Dog monitoring well (Figure 5-10) is located near Sheridan, and BLM well no. 447131 (Figure 5-11) is located in the southeastern part of the PRB. Generally, the graphs show reasonable agreement between modeled and actual drawdown over time, although the Prairie Dog monitoring well (Figure 5-10) shows considerably more drawdown than is predicted by the model. The regional nature of the model tends to smooth and average predicted drawdown effects attributed to depressurization. This effect tends to be most apparent in areas of relatively isolated CBM development, such as the Prairie Dog area.

5.1.4 Transient State Calibration to CBM Water Production

The CBM wells were simulated using "drain" nodes that turn on and off corresponding to actual pumping schedules for existing wells, and an assumed schedule of 7 years for proposed (future) wells. A single drain node may represent one or more wells because the node spacing in the model is one-half mile by one-half mile.

The rate of water production in an active drain will decline over time because the elevation of the water level in the drain cannot drop below a fixed elevation, assigned at 16 feet (5 meters) above the top of the highest coal seam being developed in that area. The water flow to the drain declines as the head declines in the model nodes that surround the drain. This decline simulates the process that occurs in CBM production wells.

The rate water flows toward a drain node from an adjacent node depends on:

1. The difference in head between the drain node and the adjacent node (time variable)
2. The hydraulic conductivity and thickness of the nodes (transmissivity)
3. The conductance assigned to the drain node

During calibration, the conductances of the drain nodes were varied to match historical production data reported to WOGCC at the CBM wells represented by the drain.

- A number of CBM well clusters with adequate production data were selected to represent individual drain nodes in the model for calibration. Criteria for selection included:

  - Wells with historical production data that spanned at least 10 months of any year were selected. Shorter production periods were considered only if wells with at least 10 months of data did not exist in a watershed.
  - Where possible, well clusters that covered the range of long-term CBM development areas as well as relatively "new" CBM development areas were selected.
  - Depending on the size of the watershed, three to five well clusters were selected.
  - Locations that covered the range of hydraulic conductivities and thicknesses assigned to the developed coal layers within the watershed were selected.
  - Well clusters that covered the range of well densities represented in the watershed were selected.
  - Well clusters where multiple and single coals are being developed were selected.

- Total production from these wells was normalized to a full 12 months for any years where the production data were less than 12 months.

- Individual "zone budget" areas were assigned for these calibration drain nodes. This zone budget allowed the model to track flows to the individual node.

- The drain node was calibrated by varying the drain conductance parameter to match the normalized historical production for the wells represented by the drain node.

- When a reasonable match was obtained for each watershed (within 20 percent), an average "drain conductance per well" was calculated based on the number of wells represented by each calibration drain in the watershed.

- A drain conductance was applied for existing and future drains in the model based on the average "drain conductance per well" for the watershed multiplied by the number of wells represented by the drain node.

Drain conductances per well was assumed to be similar to calibrated drains in other watersheds where coal thickness and hydraulic conductivity are similar for watersheds where little or no historical data on CBM production is available that can be used for calibration.

After the initial drain conductance was calibrated for the 2001 version of the model, BLM provided estimated production numbers for each watershed using representative production curves for each watershed, based on the updated WOGCC database. The CBM drain conductances in the model were modified to calibrate more closely to the watershed-wide estimates of produced water projected by the representative production curves provided by the BLM.

5.2 Sensitivity Analysis

A sensitivity analysis was used to evaluate the effects of changes in model parameters on model calibration. The "base" (calibrated) conditions reflect the most likely hydrogeologic conditions, as they were developed from site-specific field data.The most sensitive factors for both the steady-state and transient models were location and quantity of recharge, and permeability in both the horizontal and vertical directions. In the transient mode, storativity also was also a sensitive parameter.

It is necessary to use a vertical hydraulic conductivity for the intervening confining unit of between 2×10^{-9} to 6×10^{-11} ft/sec to match the fairly large difference in head observed between the overburden sands and the coal units under the current conditions. Similarly, the observed potentiometric drawdown induced by CBM operations within the coal could be matched only if a regional conductivity of between 1×10^{-4} and 6×10^{-5} ft/sec is assumed. This range of values is considerably less than might be expected from individual well testing. However, the existence of high amounts of released methane in the coal, induced by the lowered potentiometric pressures, will result in an effectively lower permeability to water.

One limitation of the MODFLOW code is that it does not allow hydraulic conductivity to vary as a function of pressure. Accordingly, the values for hydraulic conductivity that may be appropriate for steady-state calibration to pre-mining conditions may be over-estimated for transient calibration in areas of significant potentiometric drawdown.

A regional recharge rate of 0.03 inches per year must be assumed to achieve reasonable global water balance and match water levels in overburden sands. Increased recharge in the clinker of 0.1 to 0.6 inches per year was used to match the higher water levels found adjacent to these areas. The relatively low regional recharge rate appears inconsistent with the relatively high rates of infiltration seen in creek areas. However, the regional recharge rate is a representation of the recharge if it were to occur uniformly over the area. As the creeks constitute a small percentage of the total area (probably less than 1 percent), the equivalent areal recharge value is small. In addition, only a fraction (probably less than 20 percent) of the total precipitation falling on the land surface actually runs off into a creek drainage where it can then effectively infiltrate. It is likely that precipitation that does not become runoff makes no significant contribution to groundwater recharge (except in highly permeable zones such as clinker areas) because it is consumptively used by vegetation or evaporates (or sublimates) back to the atmosphere.

Figure 5-8 Modeled vs. Actual Drawdown Graphs for BLM MP-22 Monitoring Wells (West of Belle Ayr Mine South of Gillette)

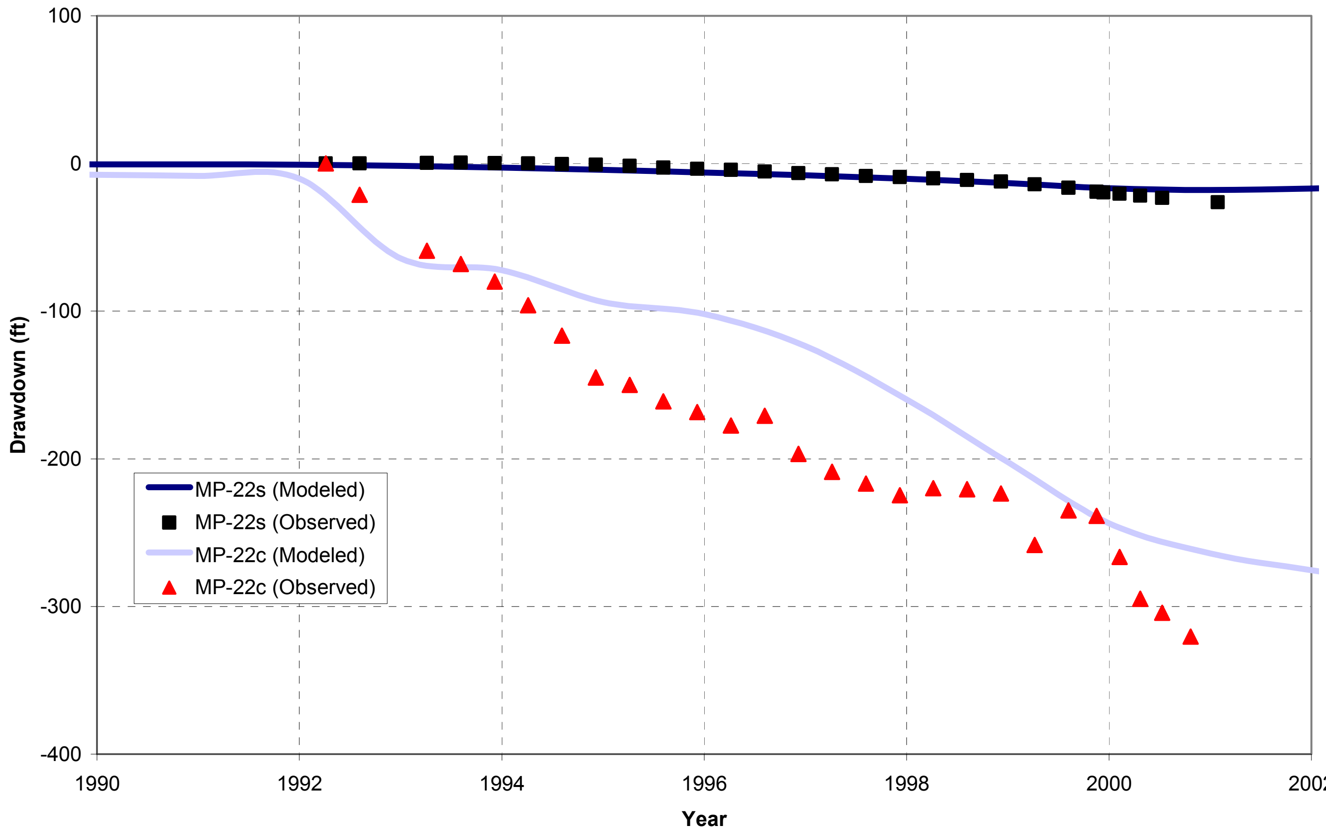


Figure 5-9 Modeled vs. Actual Drawdown Graphs for BLM MP-2 Monitoring Wells (West of Belle Ayr Mine South of Gillette)

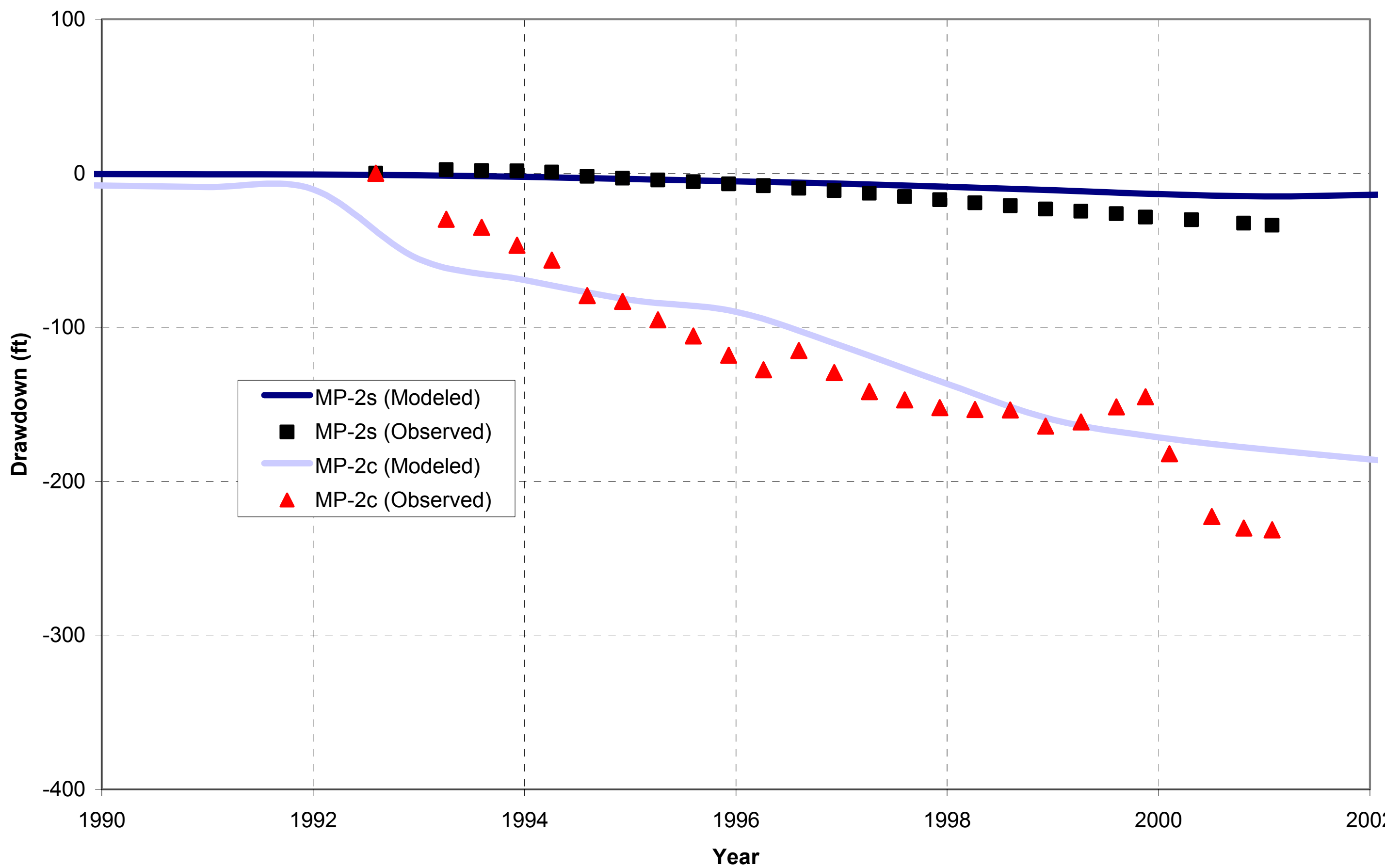


Figure 5-10 Modeled vs. Actual Drawdown Graphs for BLM Prairie Dog Monitoring Well (Near Sheridan)

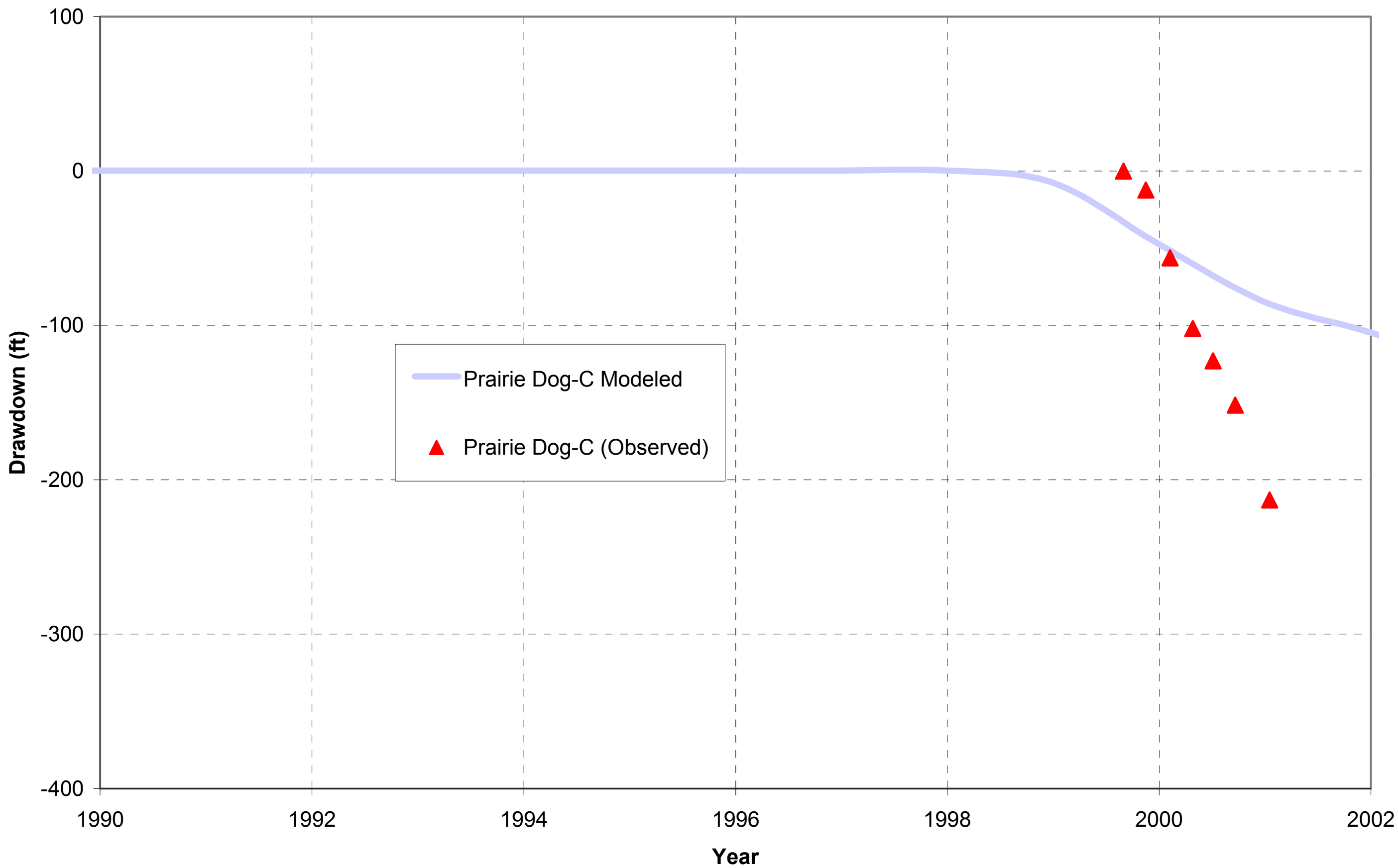
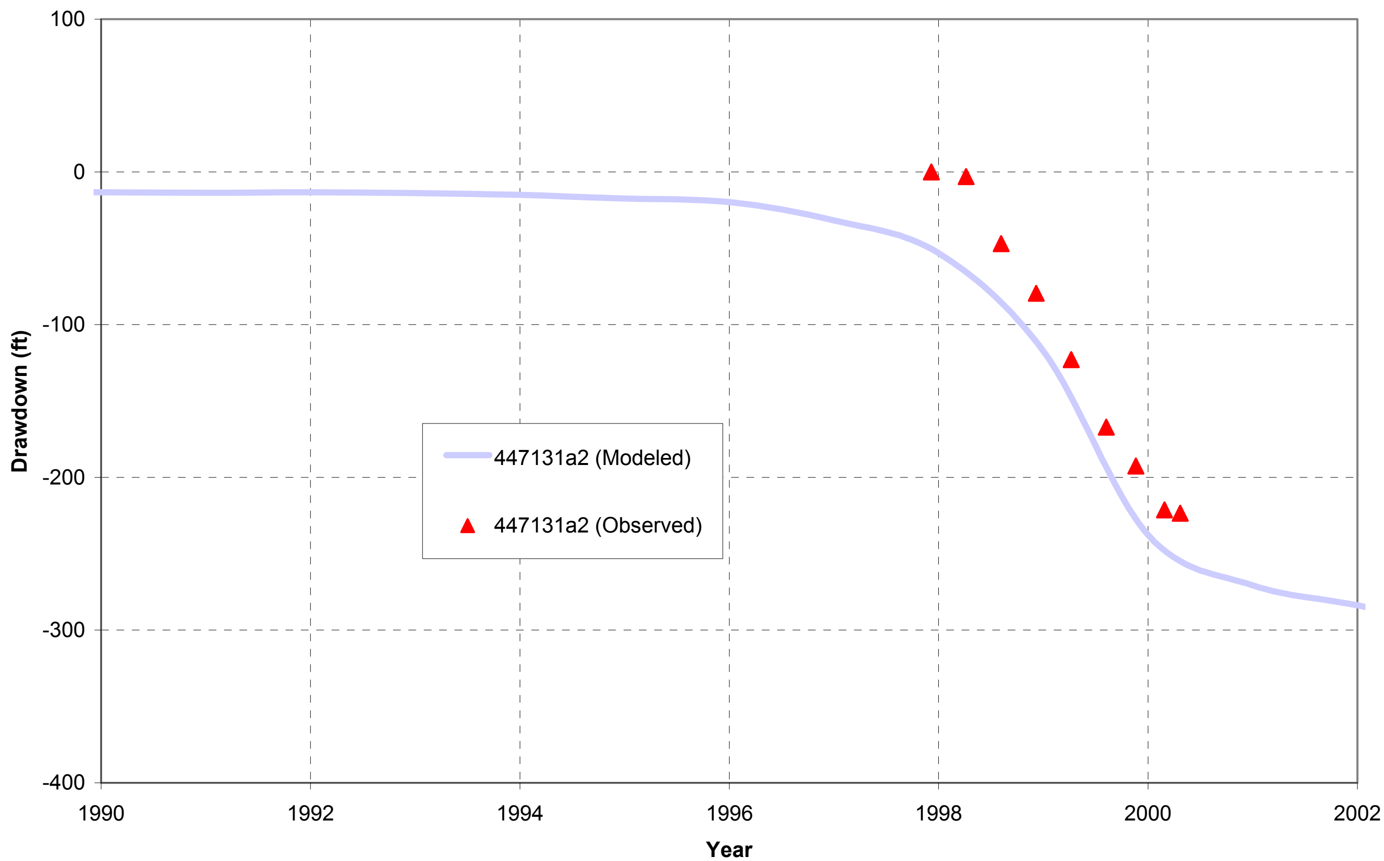


Figure 5-11 Modeled vs. Actual Drawdown Graphs for BLM 447131 Monitoring Well (Southeastern Powder River Basin)



6.0 IMPACTS PROJECTED BY THE MODEL UNDER ALTERNATIVE 1 (PROPOSED ACTION)

The primary effects of CBM development on groundwater resources are associated with the removal of groundwater stored within coal seams and the subsequent recharge of aquifers through infiltration or injection of produced water. The primary purpose of the numerical flow modeling was to project impacts to groundwater from CBM development in the PRB. The model also included the superimposed influences of surface coal mining operations. Modeling was necessary because of the large extent and variability of the cumulative stresses imposed by mining and CBM development on the aquifer units of the PRB. Modeling a hydrologic system on a regional, basin-wide scale allows a comparison of alternatives and a determination of the mass water balance so that long-term gain or loss can be forecast. The regional model is an adequate tool for analyzing the effects of CBM development, but the results should be used with caution when a sub-regional or local area is considered. The regional model is constructed using averaged and smoothed values so that localized conditions are typically not highly defined.

The effects of groundwater extraction during CBM development on groundwater resources would be seen as a drop in the water level (potentiometric drawdown) in nearby water wells completed in the developed coals of the upper portion of the Fort Union Formation and underlying or overlying sandstone aquifers. Drawdown is observed when a loss in hydraulic pressure head occurs in the developed coals or in the overlying and underlying sand aquifers. Other potential effects on existing water wells include changes in water yield, quality, or methane emissions. Potentiometric drawdown may also change the nature of groundwater discharge to the surface in the form of reduced spring flows, seeps, or base flows to surface drainages.

Surface discharge of extracted groundwater from CBM operations into surface drainages, flow-through stock reservoirs, or infiltration impoundments would enhance recharge of shallow aquifers below creeks and impoundments. Injection of CBM-produced water would recharge the aquifer units in whichthe injection wells are completed.

6.1 Water Yield (CBM-Produced Water)

Table 6-1 shows the quantity of water projected by the model that would be removed during CBM development from 2002 through 2017. The projected discharge is summarized by sub-watershed. The Salt Creek sub-watershed is in a boundary area of the model that does not remain saturated for the transient simulation and therefore showed extremely low production volumes. Water removal (modeled) is projected to peak during 2007 at a rate 277,000 acre-feet per year (2,148,600 thousand barrels [Mbbls] per year).

CBM produced water is derived primarily from storage within the developed coals and leakage of groundwater contained in sand units into the coals as a result of coal depressurization. Over the life of a CBM well, most of the produced water may come from leakage into the coal from above and below. Storage in the coal is removed early in the life of a CBM well.

An example illustrates this concept and explains declines in production that are typically seen in the PRB. Consider a 50-foot thick coal seam at a depth of 1,000 feet that is bounded above and below by 40-foot thick claystones that separate the coal from overlying and underlying sandstone units. Assume that CBM development is occurring on an 80-acre well spacing and depressurization of the coal causes an average drop in potentiometric head of 500 feet.

If the coal is not dewatered (in other words, water is removed from confined storage only by depressurization), then the contribution of the coal to well water production depends on the drop in head and the confined storativity. Using a typical storativity for the coal of $5x10^{-6}$ ft^{-1}, the confined storage contribution from the coal would be about 2 acre-feet for every 100 feet of head drop, or 10 acre-feet in this example.Additional water in unconfined storage would be released to the well if the coal were completely dewatered. The unconfined storage in the coal depends on the thickness of the coal and the specific yield. Assuming a specific yield for the coal of 0.4 percent (Section 2.3.3), the amount of unconfined storage in the coal in the 80-acre-feet area of one production well would be 16 acre-feet. The contribution from confined storage therefore becomes comparable with the contribution from unconfined storage in the deeper parts of the basin where drops in head of between 500 to 1,000 feet may be encountered. The total volume of storage in coal (from confined and unconfined storage) of 26 acre-feet (about 8.5 million gallons) is equivalent to a well pumping at 10 gpm for 1.6 years.

Removal of water from storage in coal is concurrent with leakage into the coal from above and below so, depending on the rate of leakage, the coal does not necessarily become dewatered in the short time frames noted above. The contribution from leakage would increase over the life of a well as water stored in the coal is removed. Leakage rates under high induced vertical gradients can be significant. For this example, a 500-foot drop in head would result in a vertical hydraulic gradient across the claystones of 12.5 feet per foot. Assuming a very low vertical hydraulic conductivity for the claystone confining units of $6x10^{-11}$ ft/sec (derived from field data for the Marquiss area) results in a vertical leakage over the 80-acre area of 1.2 gpm from both above and below (for a total of 2.4 gpm). Higher drops in head, higher vertical hydraulic conductivities, or thinner claystone units would lead to higher leakage rates. The leakage rates for this example are typical of the pumping rates for CBM wells during the latter portions of their productive life.

The example above illustrates that most of the water produced by a CBM well likely would come from leakage after about the first 2 years of pumping,. The higher storativity and specific yields in the sandstones result in relatively less observable drawdown in these units compared with the coal (as actually observed in nested monitoring wells) while still providing a large source of water for leakage into the coal.

A review of Table 2-4 indicates that the majority of recoverable groundwater in the PRB is contained in the sandstones of the Fort Union and Wasatch Formations. The total projected CBM water production from 2002 to 2017 shown in Table 6-1 (about 2.93 million acre-feet) exceeds the estimated recoverable water within the coal units of the Wasatch and Fort Union Formations, but is less than 1 percent of the total recoverable groundwater (about 745.6 million acre-feet) in these formations.

Depending on the water handling practices used within each sub-watershed under Alternative 1, an estimated 15 to 33 percent of the pumped water would be recharged to the groundwater system as a result of infiltration along creeks and below impoundments (Table 3-1). Table 4-3 summarizes assumptions for groundwater and the fate of the CBM-produced water under Alternative 1.

Table 6-1
Regional Model Projection of Water Production from CBM Wells under Alternatives 1, 2A, and 2B

(Average volume of water produced from CBM development [in 1,000 barrels])

Sub-watershed	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	TOTAL
Upper Tongue River	49,900	70,900	95,600	110,400	118,800	126,900	129,900	140,800	140,200	135,400	120,000	107,800	84,200	65,900	44,800	23,900	1,565,400
Upper Powder River	573,000	774,300	922,900	1,022,900	1,100,200	1,140,600	1,134,100	1,015,400	899,400	776,500	643,800	492,500	309,900	140,000	75,300	28,900	11,049,700
Salt Creek	29	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54
Crazy Woman Creek	47,800	83,900	111,500	133,200	147,900	161,400	168,700	150,900	131,400	116,900	95,000	76,700	56,400	36,000	23,800	12,700	1,554,200
Clear Creek	46,200	73,500	99,900	126,500	150,100	170,000	177,000	179,400	177,400	175,500	150,200	125,800	99,400	76,400	52,700	28,000	1,908,000
Middle Powder River[1]	53,300	56,600	59,700	62,100	60,600	51,800	40,700	45,100	46,300	47,000	42,700	37,600	31,600	25,300	18,300	9,000	687,700
Little Powder River	125,000	123,700	120,700	122,800	111,500	101,200	77,300	78,900	81,000	81,000	70,800	62,500	50,000	38,500	26,100	15,100	1,286,100
Antelope Creek	54,400	61,100	70,400	75,600	81,400	83,000	82,000	77,400	74,200	68,700	60,800	51,900	39,400	25,400	18,700	11,100	935,500
Upper Cheyenne River	39,200	36,500	34,100	30,800	28,700	24,300	24,000	22,100	19,500	16,400	15,400	8,800	5,500	100	0	0	305,400
Upper Belle Fourche River	349,400	336,500	324,400	318,200	312,600	289,400	242,700	231,400	218,500	209,100	188,600	163,100	130,900	70,800	53,600	36,900	3,476,100
TOTAL	1,338,200	1,617,000	1,839,200	2,002,500	2,111,800	2,148,600	2,076,400	1,941,400	1,787,900	1,626,500	1,387,300	1,126,700	807,300	478,400	313,300	165,600	22,768,100

Note: Volumes shown include produced water from pre-2002 wells, as well as new CBM wells.
Assumes all pre-2002 wells have their first year of water production prior to 2002, and water production for the last pre-2002 wells ends after 2007.
Sub-watersheds where no new CBM development is proposed are excluded.

6.2 Projection of of Changes in Water Level for Upper Fort Union Formation

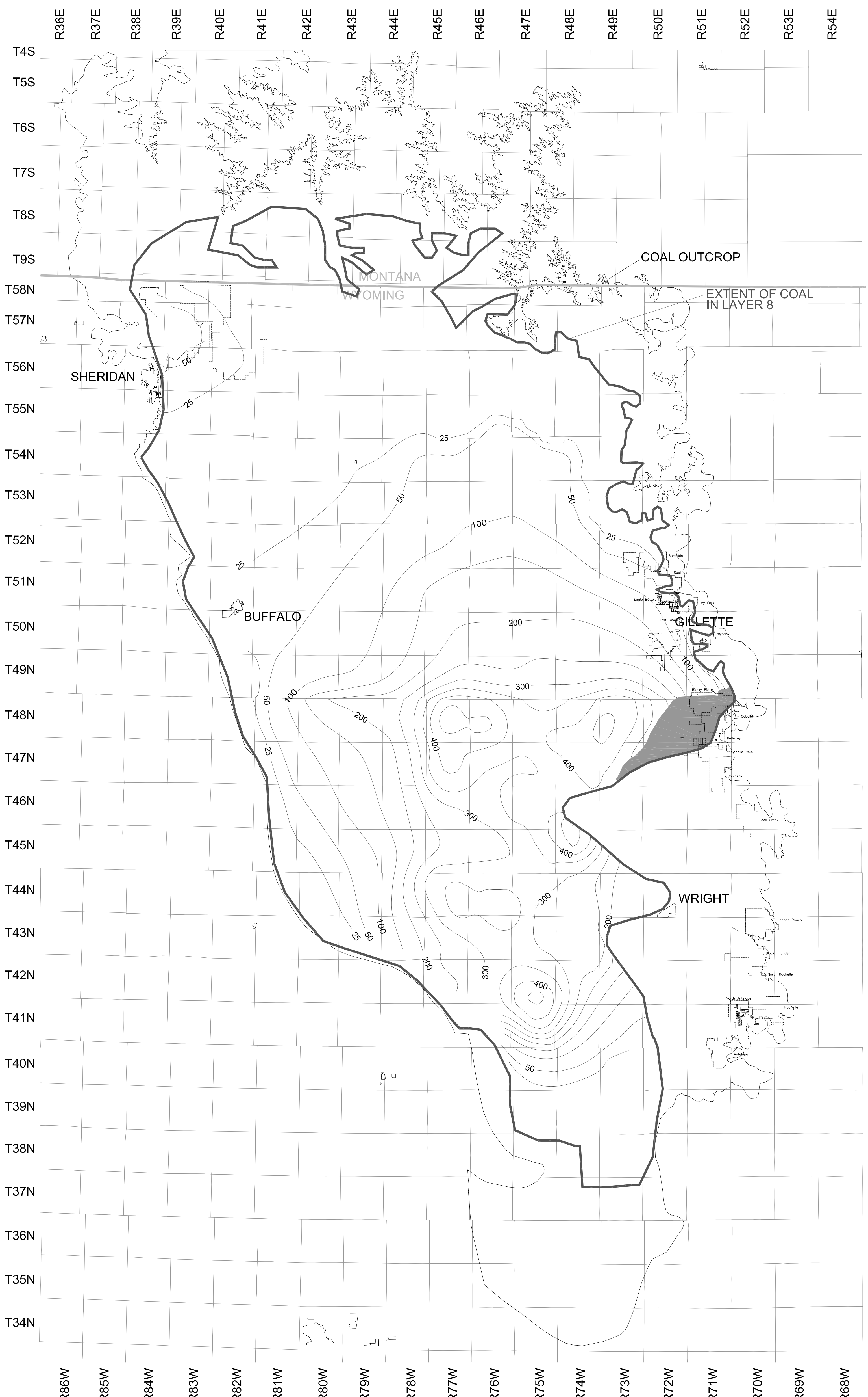
The ability of the model to reasonably project the extent and magnitude of changes in water level caused by coal mining and CBM development may be judged by comparing results projected by the model with actual trends in water levels. As described in Section 5.1.2, drawdown projected by the model for the year 2000 compares favorably with actual drawdowns where they have been measured (Figures 5-4 and 2-4). Drawdown projected by the model versus time compares well with actual drawdown measured at several monitoring wells with monitoring histories of several years (Figure 5-8 through 5-11). These results lend credibility to the model's projections of future changes in water level under the superimposed stresses of coal mining and CBM development.

6.2.1 Drawdown

Under Alternative 1, the model-projected drawdowns in the model layers representing the coal-bearing units of the upper portion of the Fort Union Formation are shown in a series of maps for the model years 2003, 2006, 2009, 2012, 2015, and 2018 (Figures 6-1A, B, C, and D through 6-6A, B, C, and D). The series of maps shows how the extent and magnitude of drawdown in the upper portion of the Fort Union Formation changes over time as CBM development spreads through the PRB. Because the mining and CBM operations are dynamic, the maximum areal extent of drawdown changes over time and may increase in some areas of the PRB while it recovers in others. Total CBM water production projected by the model in the Project Area under Alternative 1 peaks in year 2007 (Table 6-1). Peak production in the individual watersheds varies from 2002 to 2009 in the model, resulting in maximum drawdowns in these areas that occur at different times. The maximum drawdown in a sub-watershed generally coincides or closely follows the period of peak water production. The maximum drawdown projected by the model in the central area of the PRB, where the Big George coal would be developed, is projected to occur around 2009 under Alternative 1.

Maximum drawdowns occur in the vicinity of active mining operations and in the centers of CBM development. Because the numerical model is subdivided into discrete cells and CBM water production is simulated using drain nodes, the drawdowns caused by CBM well pumping are averaged over the area of a cell (about 160 acres). Consequently, model simulations are representative for areas located more than 200 to 300 feet from a pumping well. The drawdown at a pumping well would be more than is represented by the model. Maximum model-projected drawdowns exceed 700 feet in the deeper parts of the basin, such as in the northwestern portion. In shallower areas of the basin, such as the southeastern portion of the Project Area, modeled drawdowns would be 200 to 400 feet over most of the active CBM well fields.

Projections of maximum drawdown and the extent of drawdown are based on the projected locations of CBM development. Actual drilling locations and density of drilling may result in shifts of drawdown contours from the projections illustrated in Figures 6-1A, B, C, and D through 6-6A, B, C, and D.



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

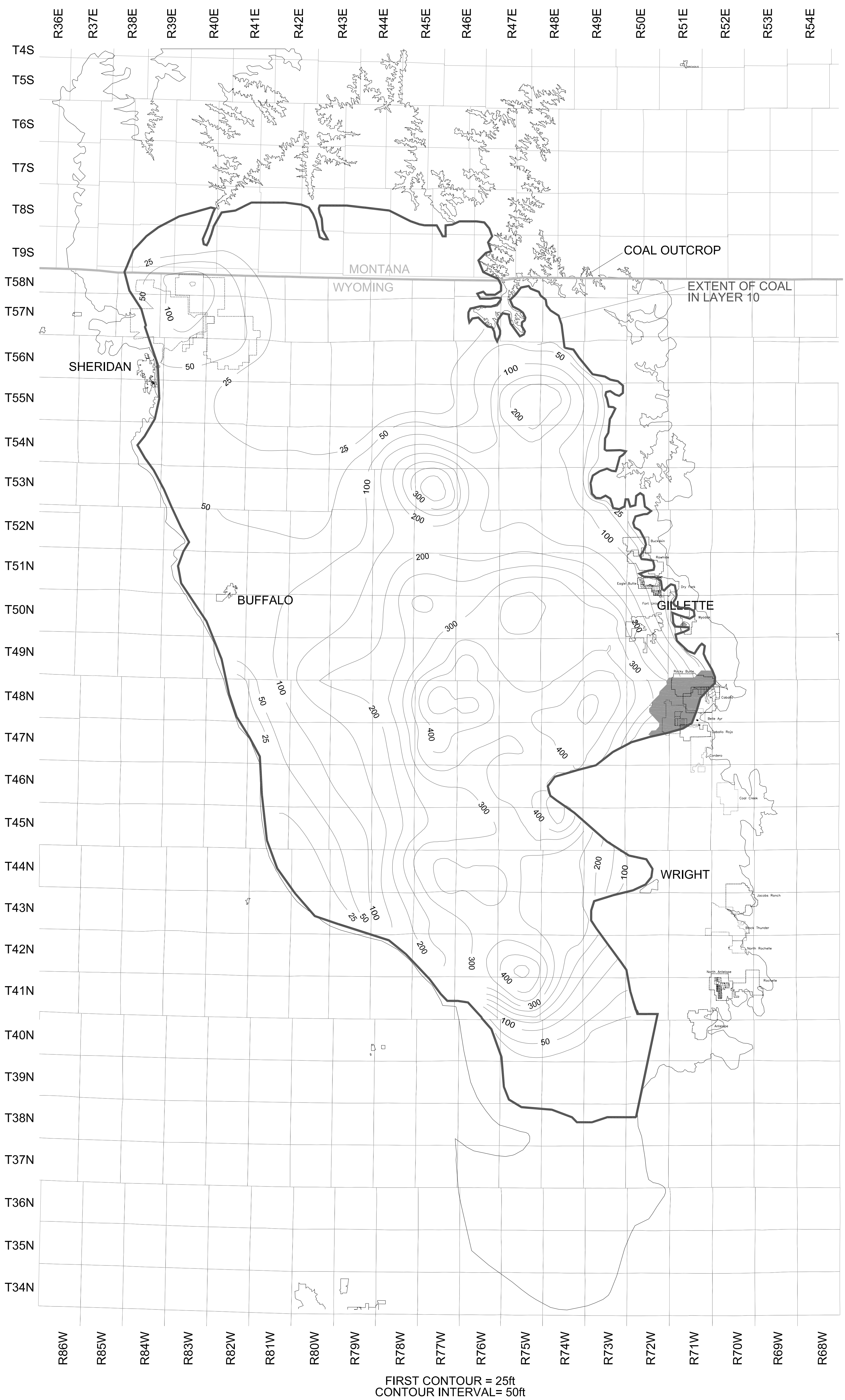
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-1A
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2003

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

Date: 09/05/02	Drawing File: Figure 6-1 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-1A continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

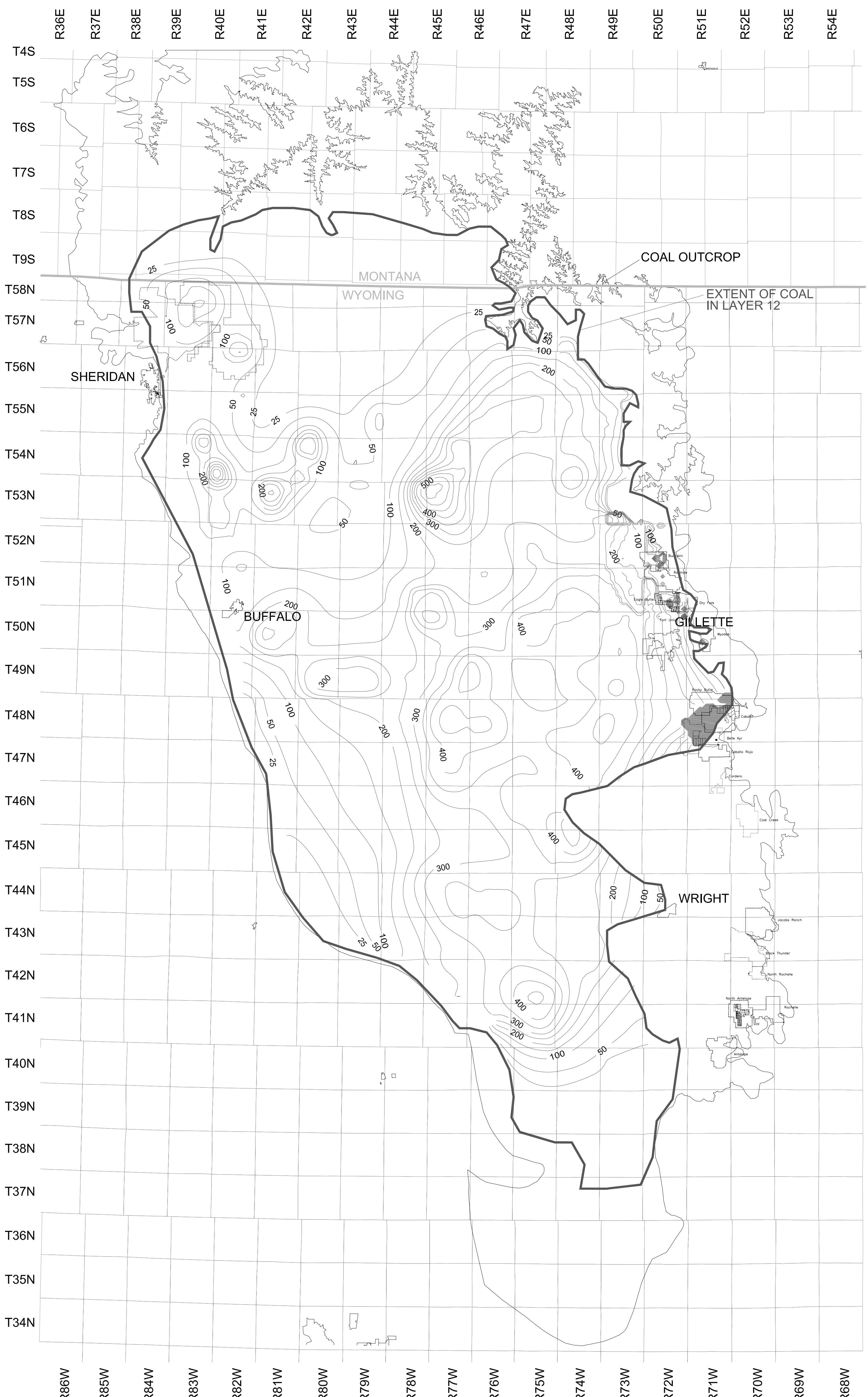
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-1B
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 10 YEAR 2003

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

Date: 09/05/02	Drawing File: Figure 6-1 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-1B continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

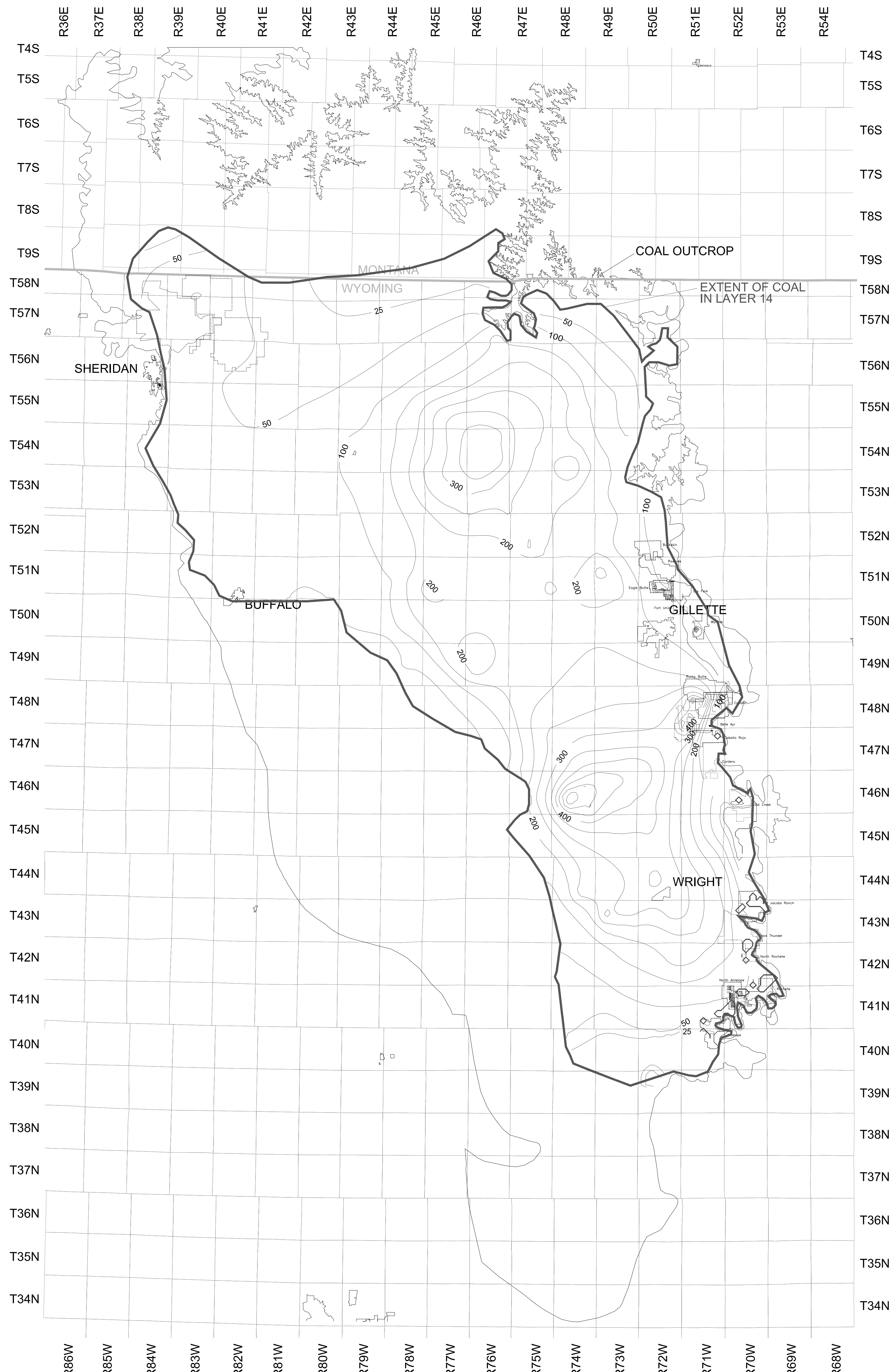
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-1C
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 12 YEAR 2003

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

Date: 09/05/02	Drawing File: Figure 6-1 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-1C continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 14
- Dry Cell
- Towns
- Mine Boundary

N

0 7.5 15 30 Miles

Note: Contours are not closed due to insufficient data.

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

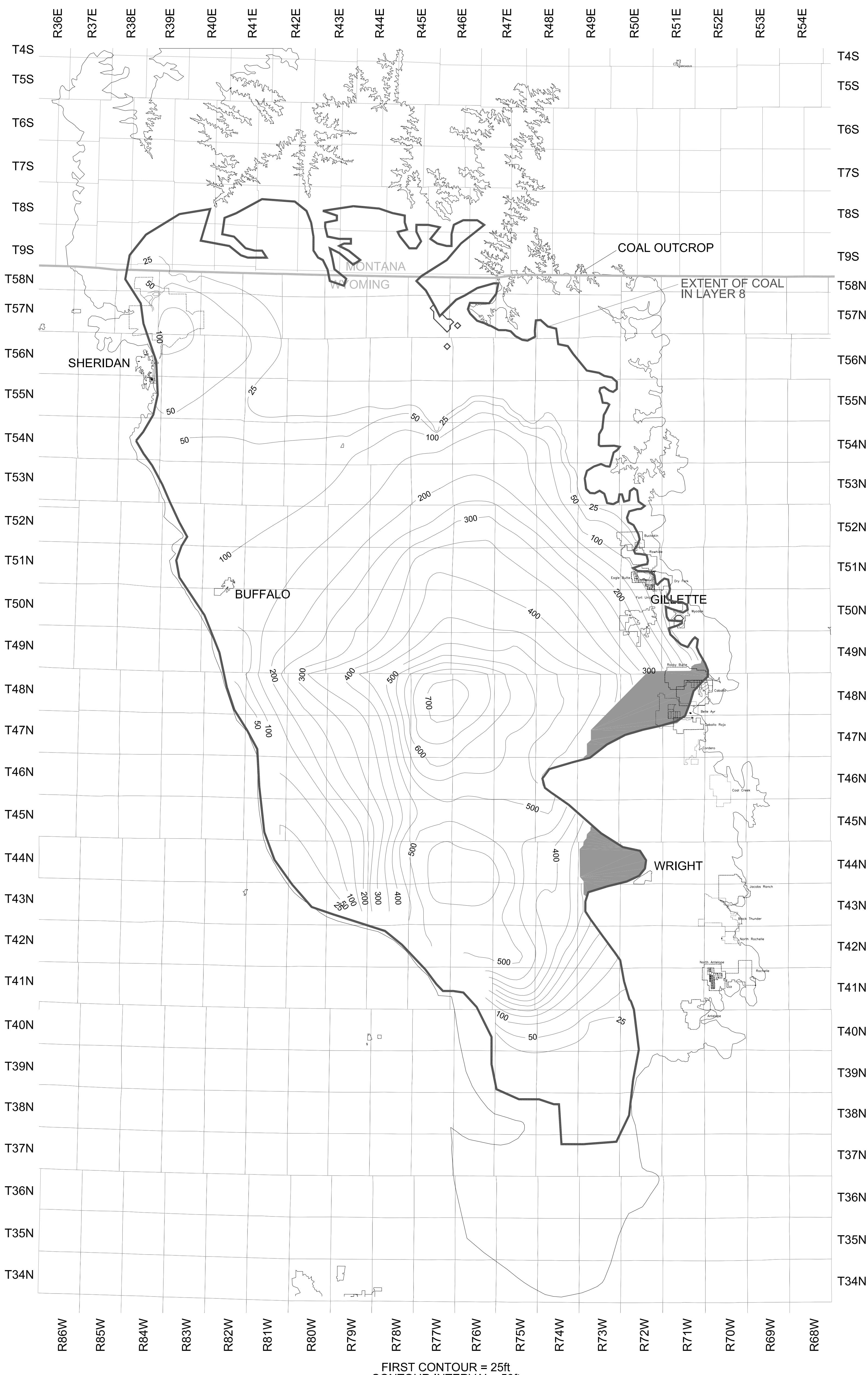
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-1D
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 14 YEAR 2003

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

Date: 09/05/02	Drawing File: Figure 6-1 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-1D continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

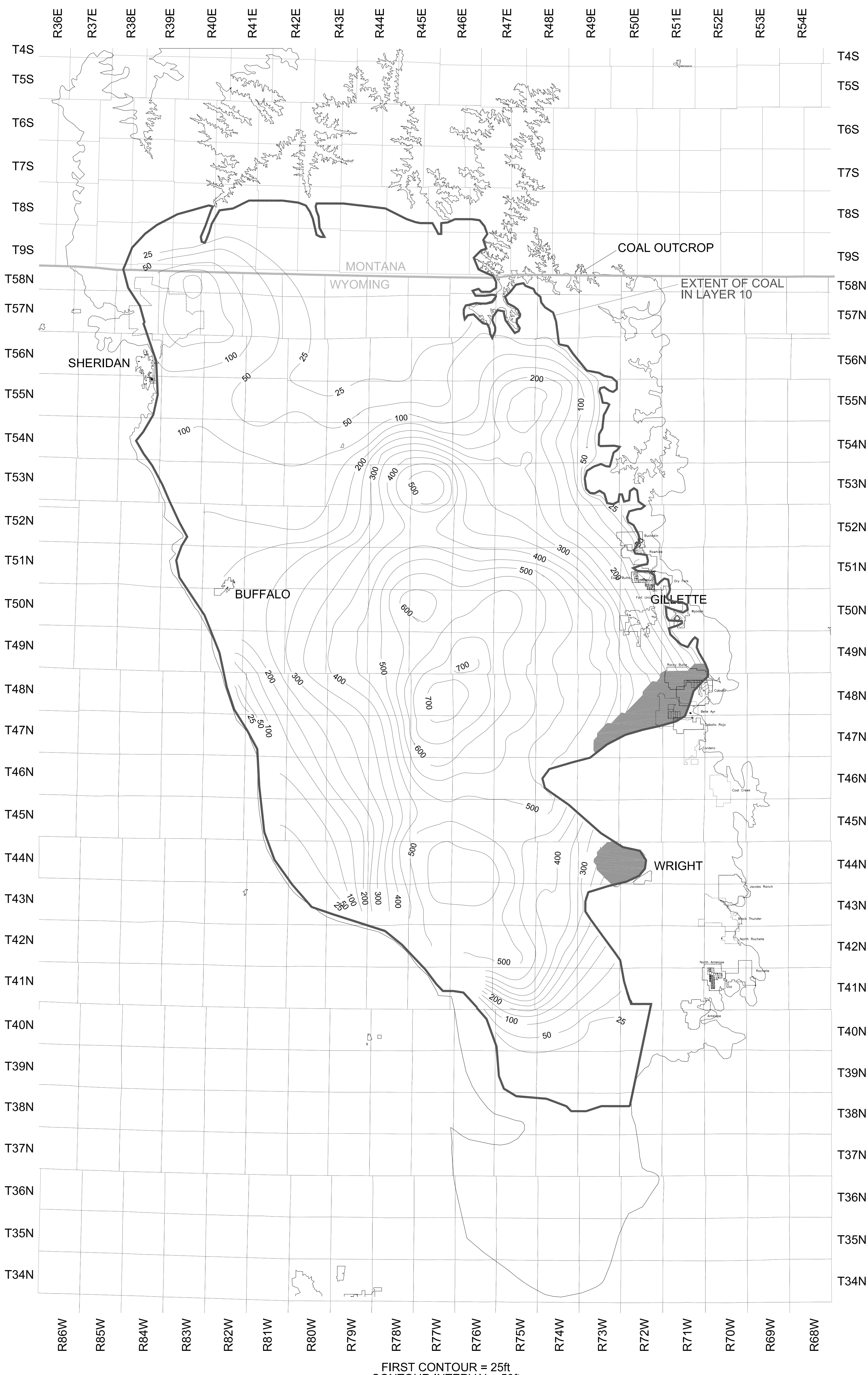
N

0 7.5 15 30 Miles

Note: Contours are not closed due to insufficient data.

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-2A MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2006	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-2 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-2A continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

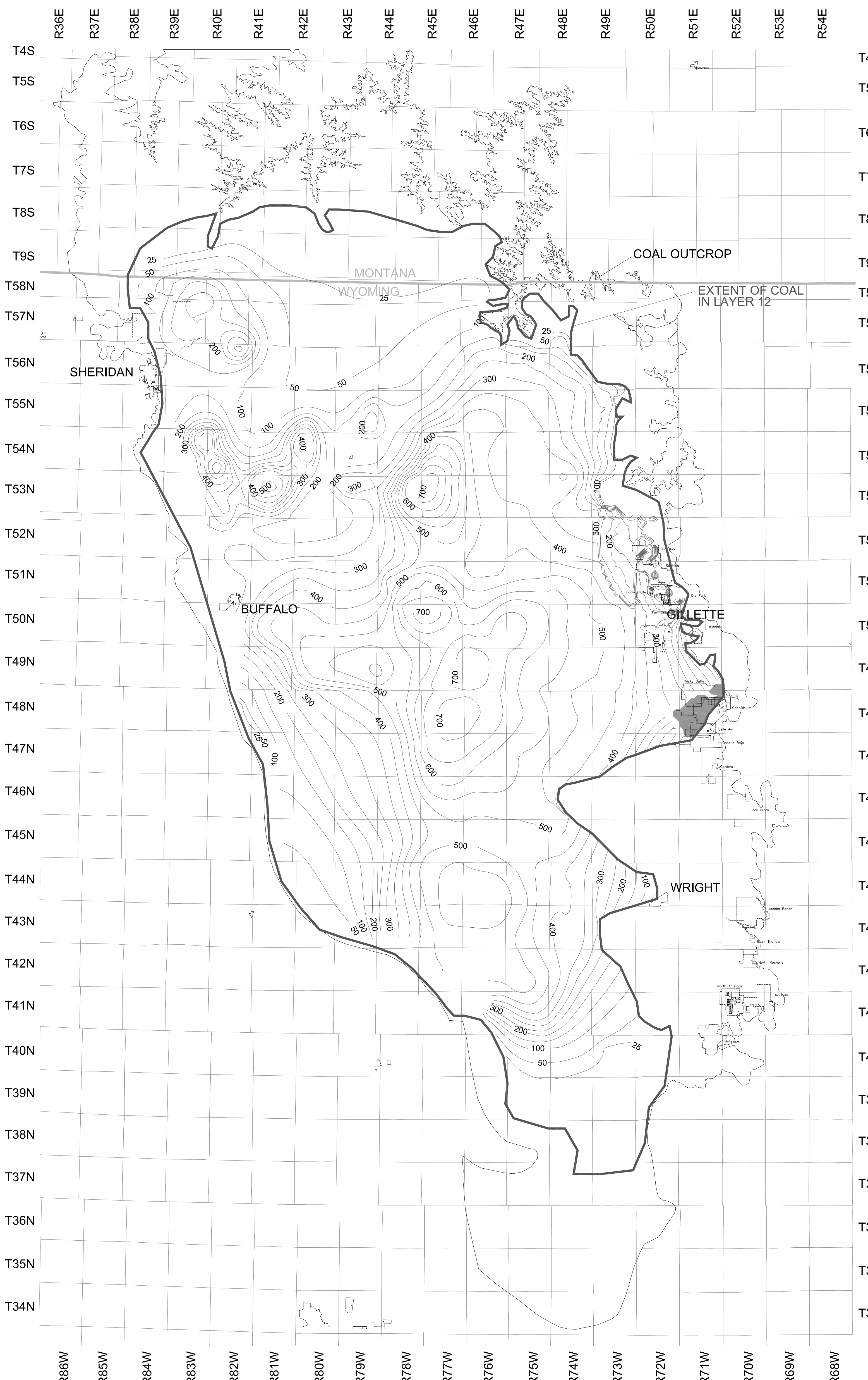
N

0 7.5 15 30 Miles

Note: Contours are not closed due to insufficient data.

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-2B MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 10 YEAR 2006	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-2 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-2B continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

N

0 7.5 15 30 Miles

Note: Contours are not closed due to insufficient data.

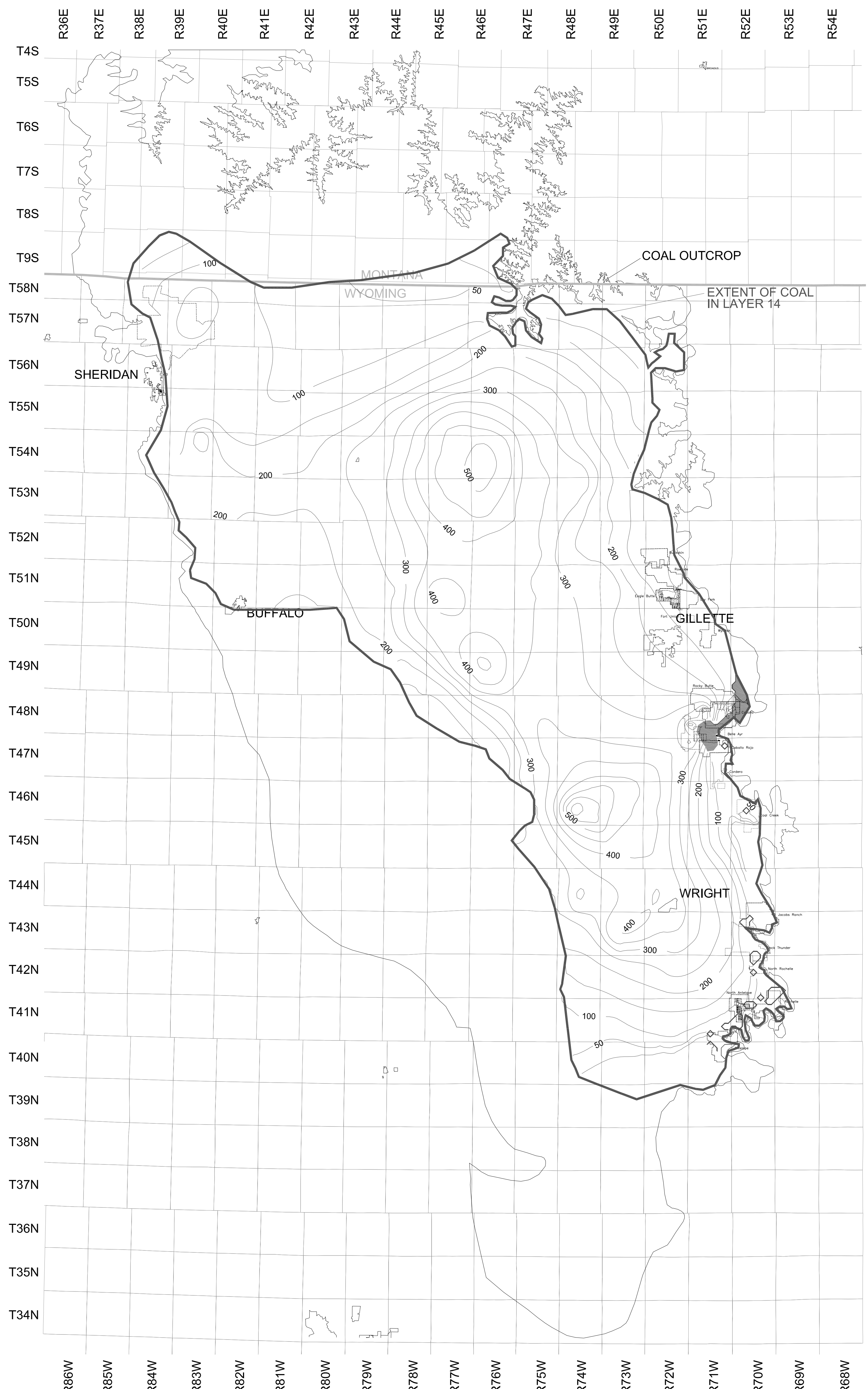
POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-2C
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 12 YEAR 2006

MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-2 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-2C continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 14
- Dry Cell
- Towns
- Mine Boundary

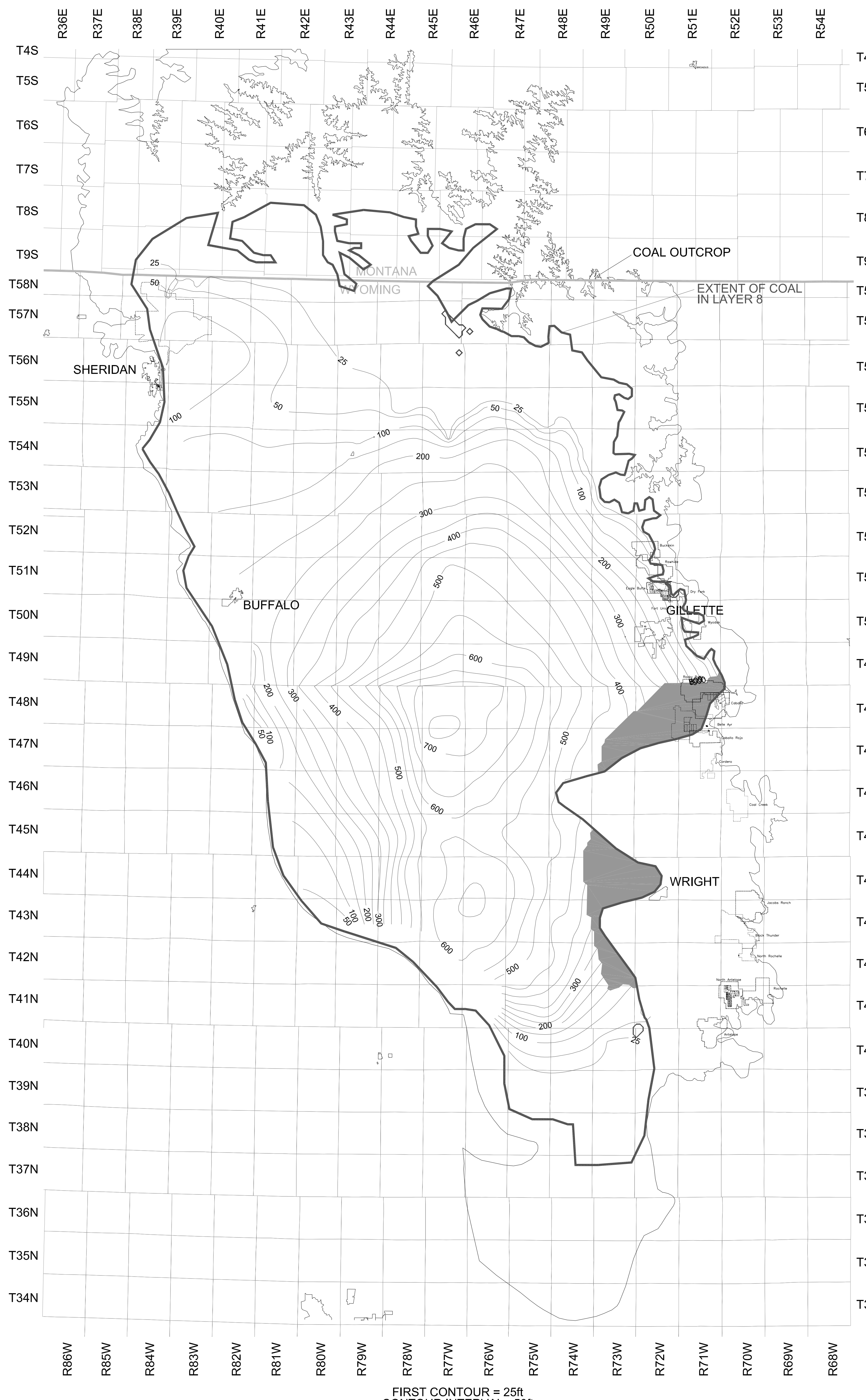
Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-2D MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 14 YEAR 2006	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-2 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-2D continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

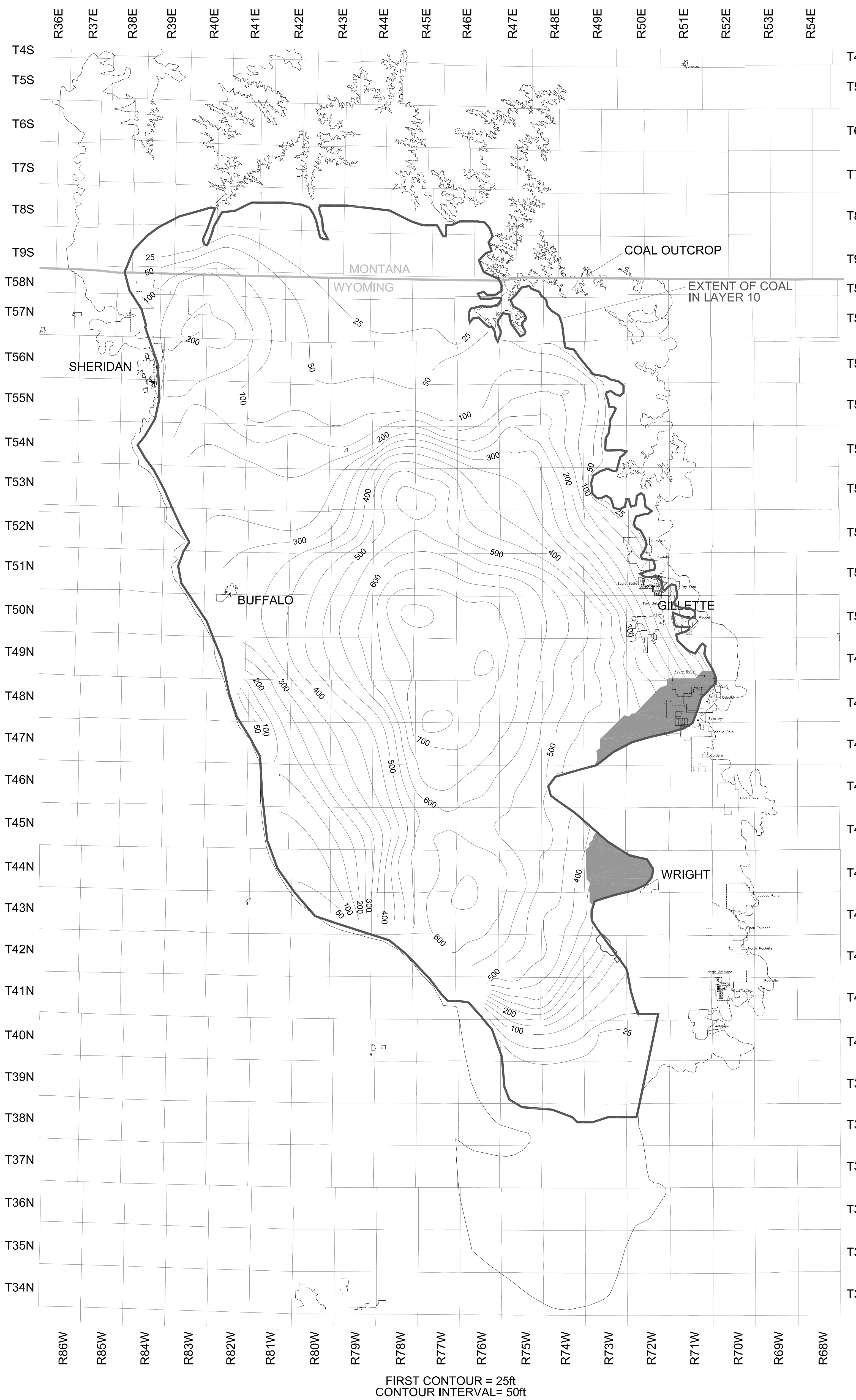
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-3A
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2009

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

Date: 09/05/02	Drawing File: Figure 6-3 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-3A continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

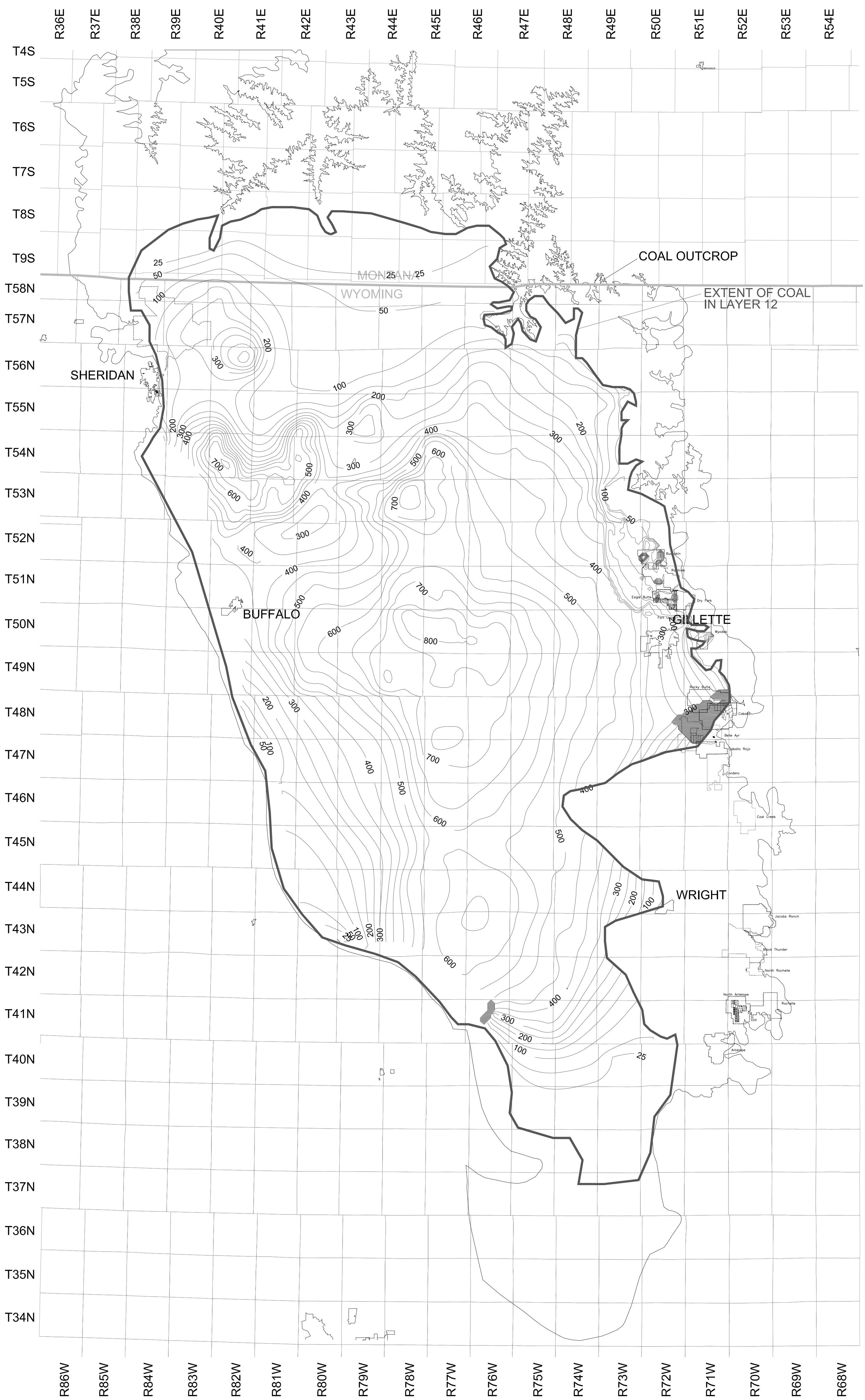
POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-3B
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 10 YEAR 2009

MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-3 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-3B continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

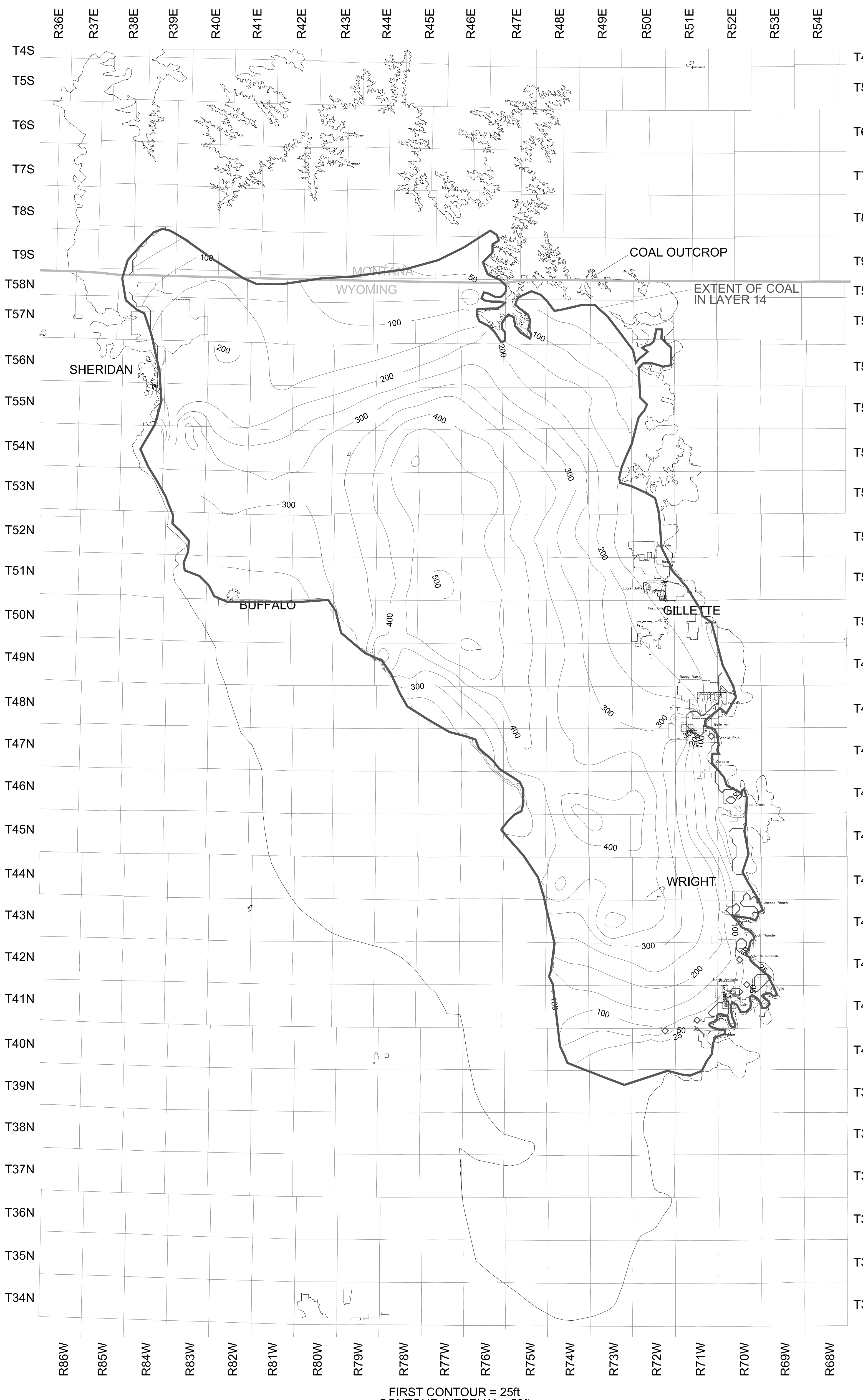
Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-3C MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 12 YEAR 2009	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-3 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-3C continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 14
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN
OIL & GAS PROJECT FEIS

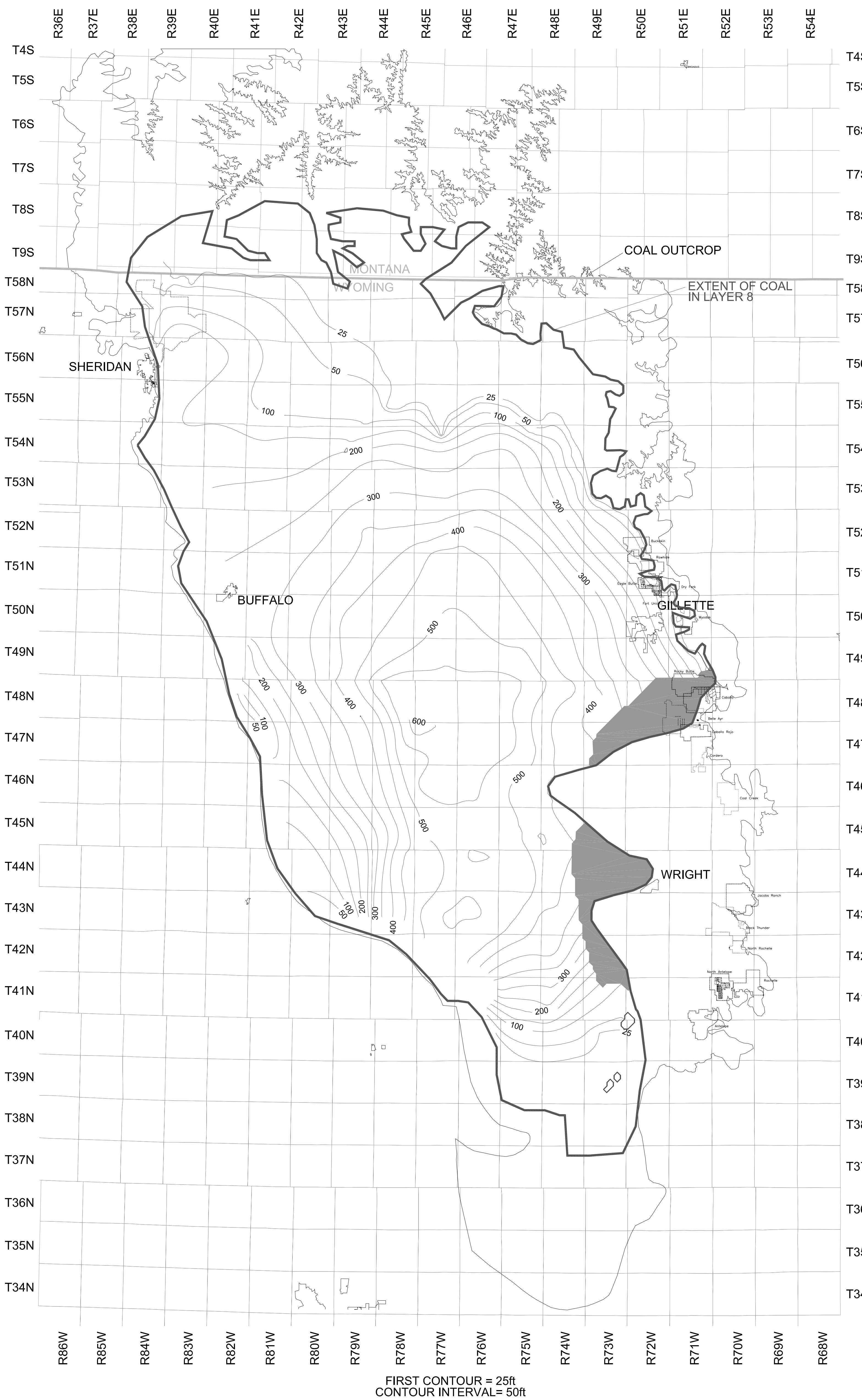
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-3D
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 14 YEAR 2009

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

Date: 09/05/02	Drawing File: Figure 6-3 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-3D continued (11x17)



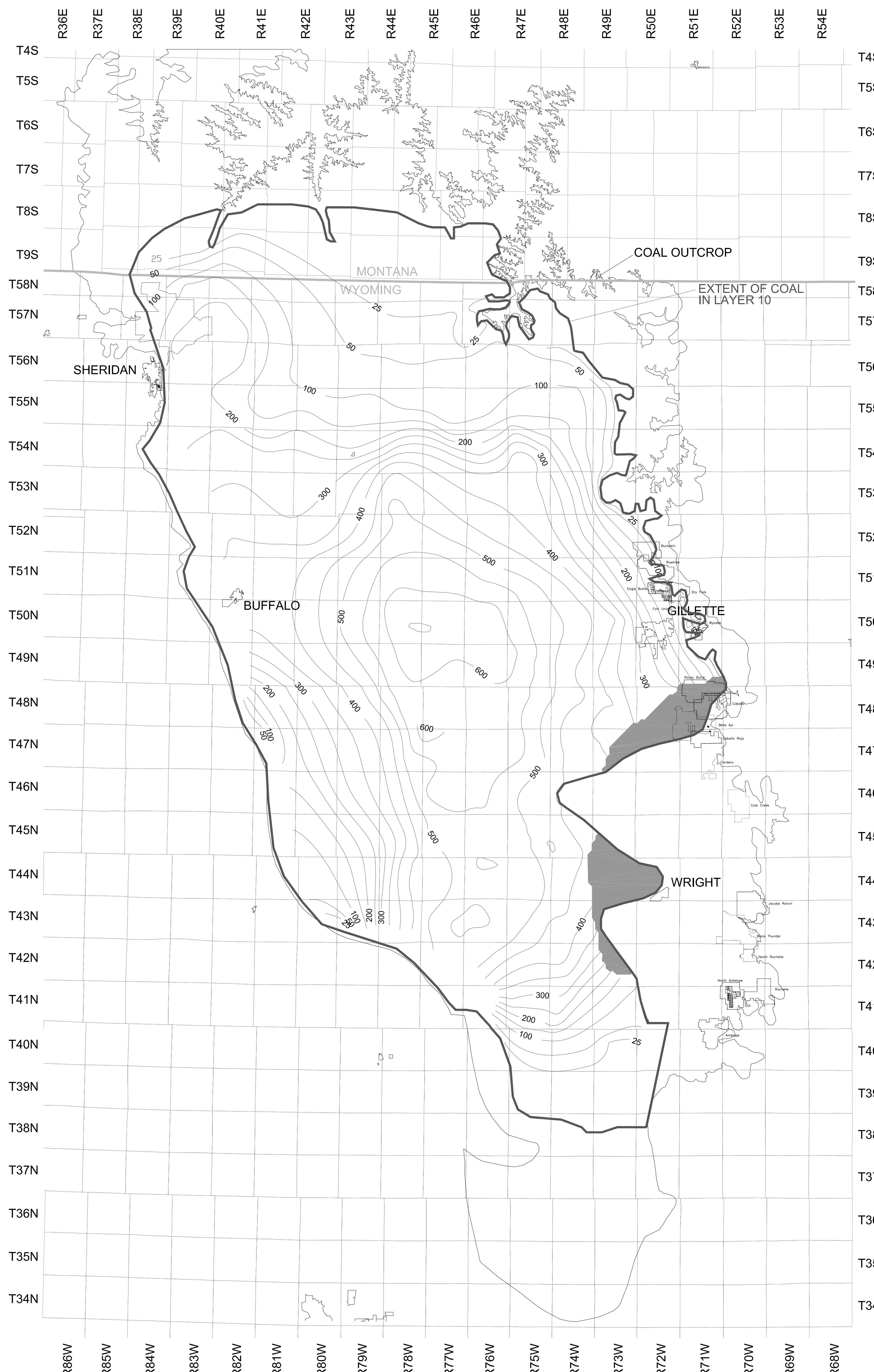
LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-4A MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2012	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-4 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-4A continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

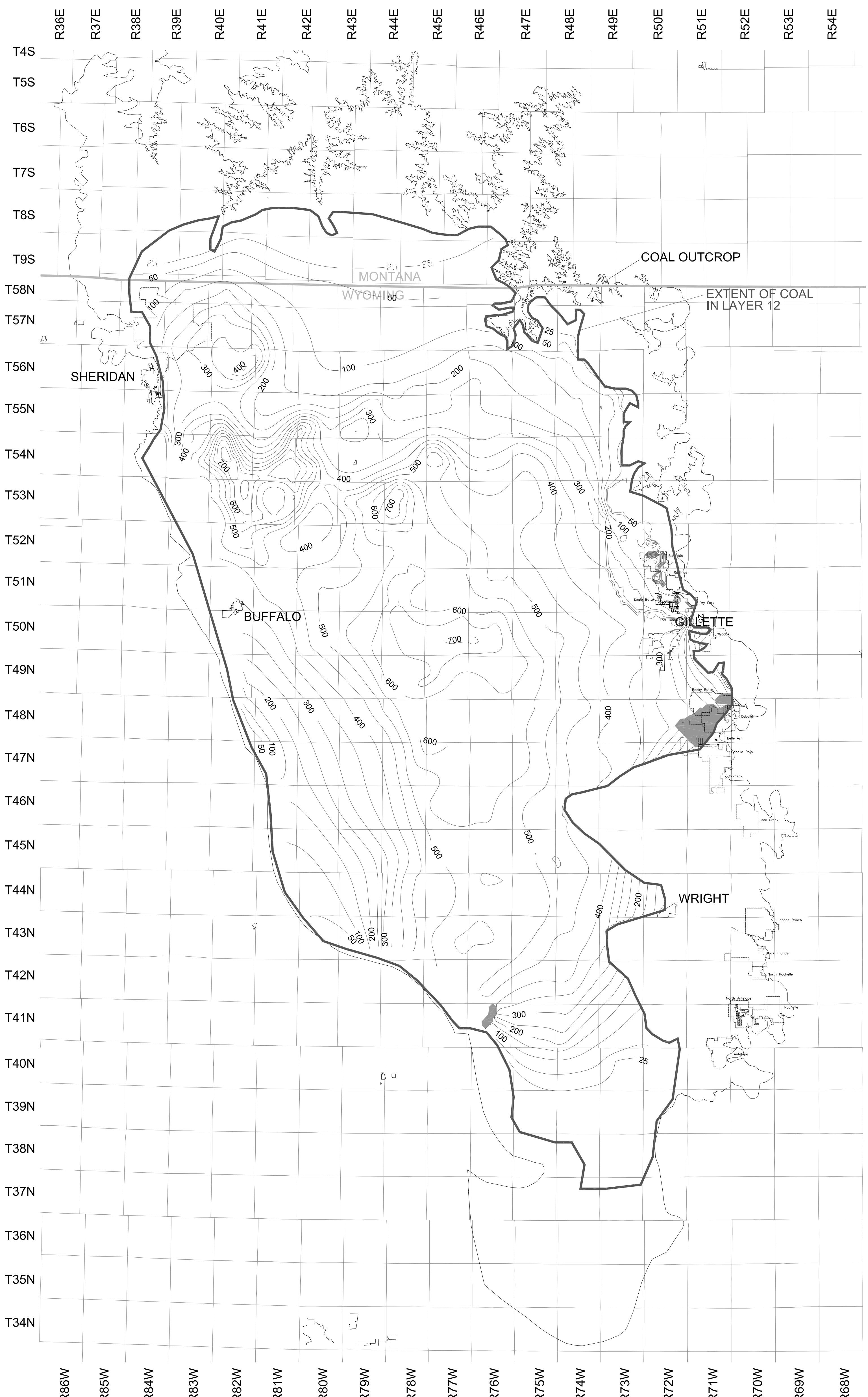
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-4B
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 10 YEAR 2012

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

Date: 09/05/02	Drawing File: Figure 6-4 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-4B continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

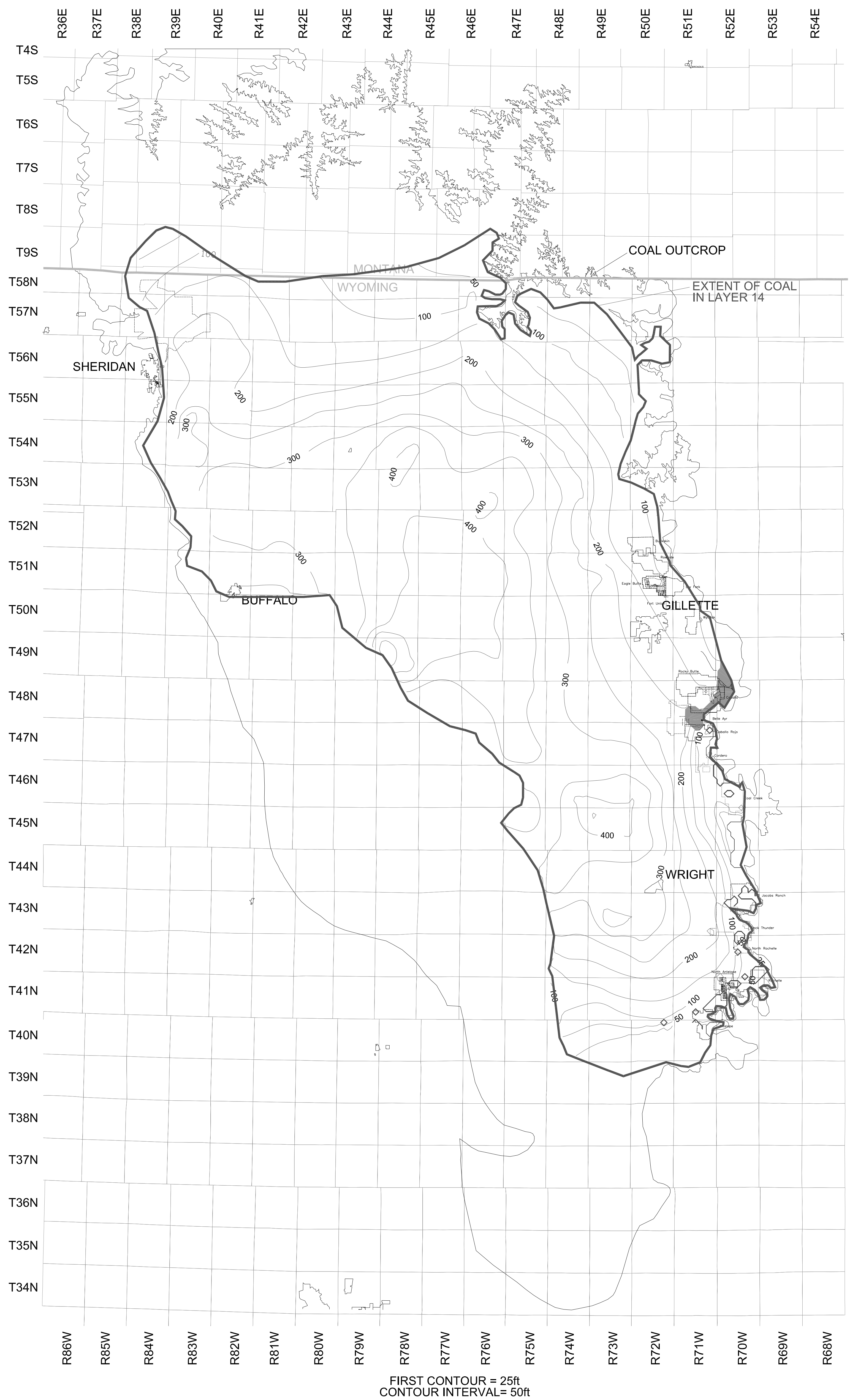
Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-4C MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 12 YEAR 2012	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-4 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-4C continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 14
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

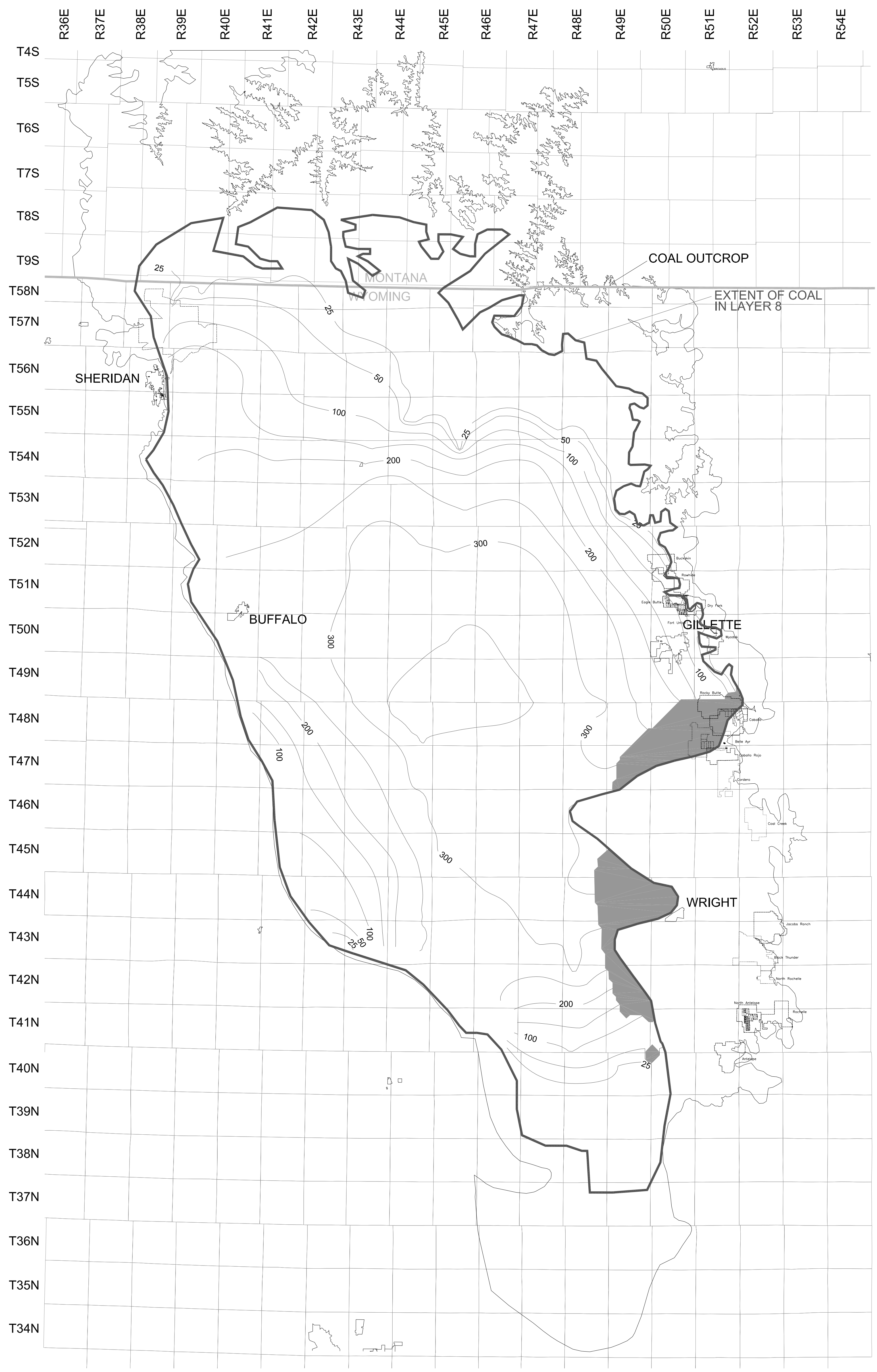
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-4D
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 14 YEAR 2012

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

Date: 09/05/02	Drawing File: Figure 6-4 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-4D continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

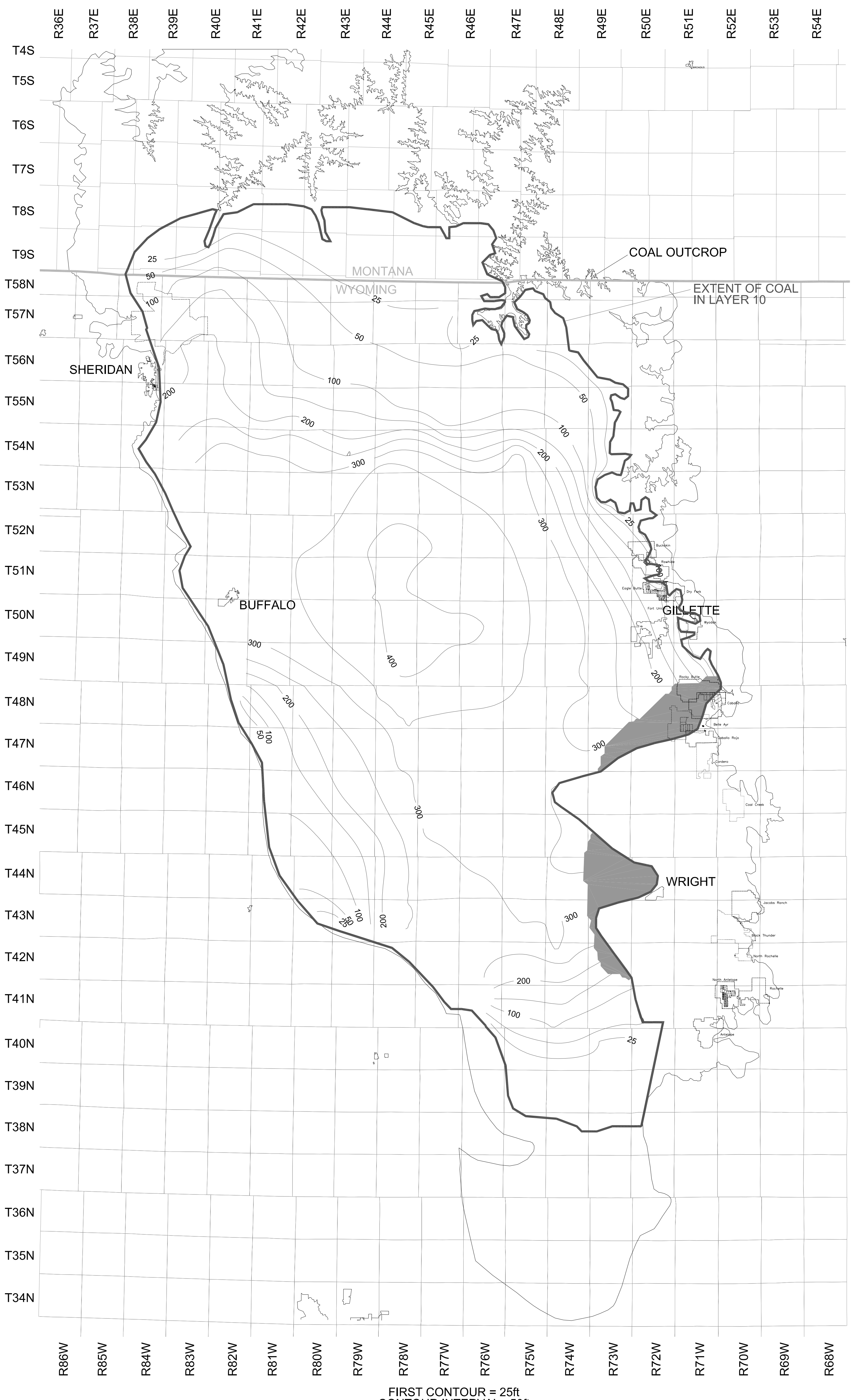
Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-5A MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2015	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-5 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-5A continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

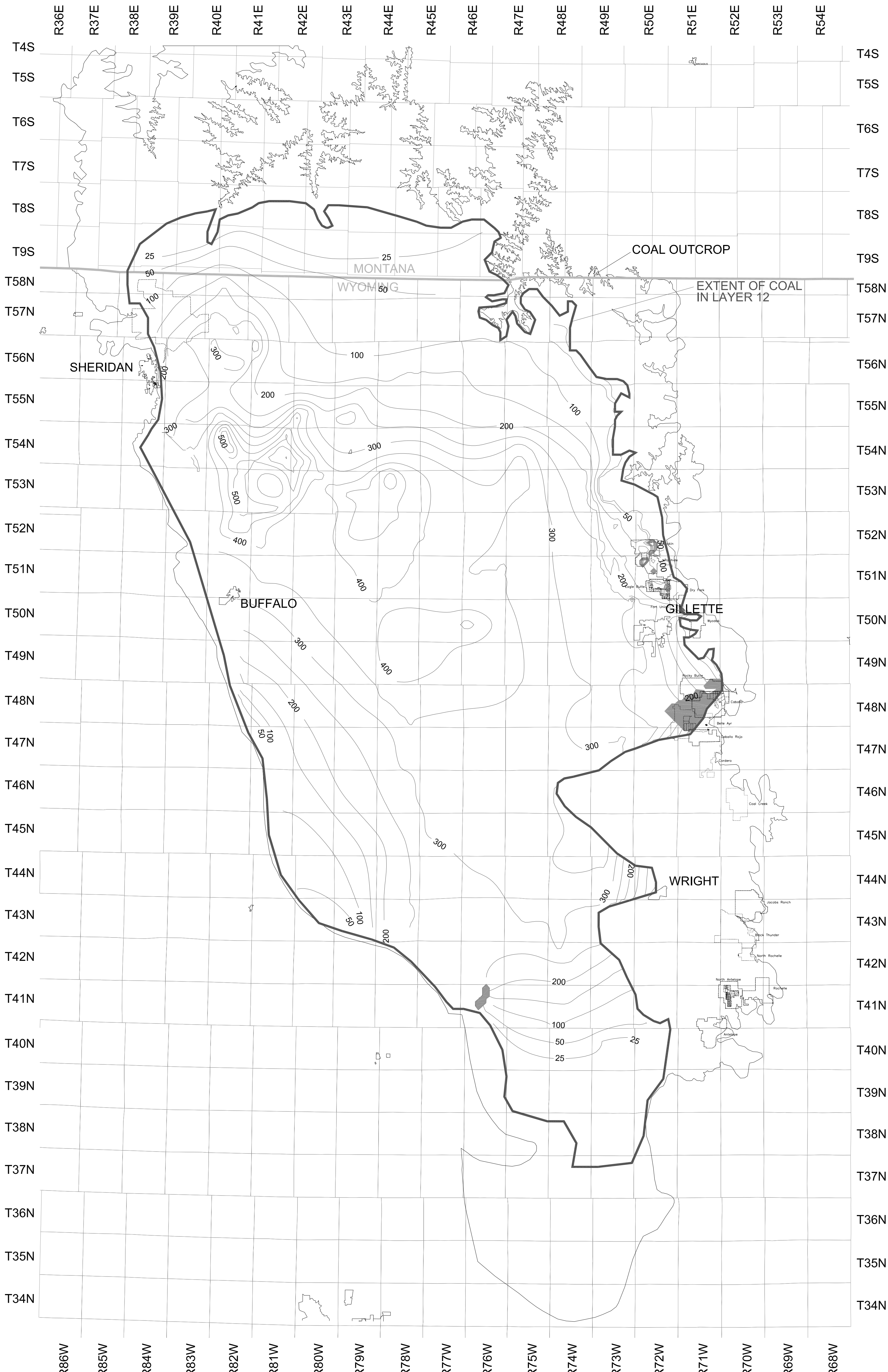
N

0 7.5 15 30 Miles

Note: Contours are not closed due to insufficient data.

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-5B MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 10 YEAR 2015	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-5 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-5B continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

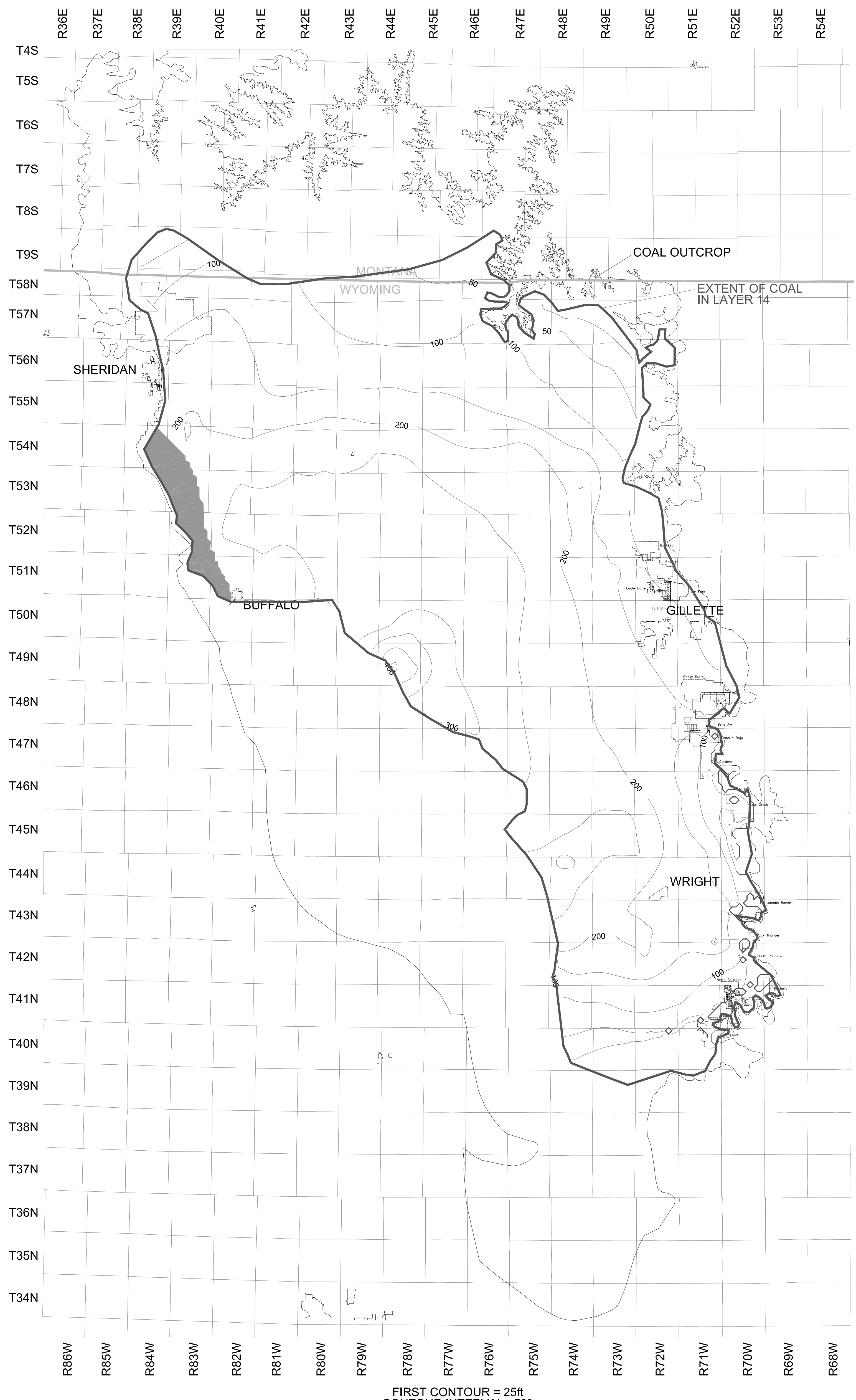
Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-5C MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 12 YEAR 2015	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-5 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-5C continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 14
- Dry Cell
- Towns
- Mine Boundary

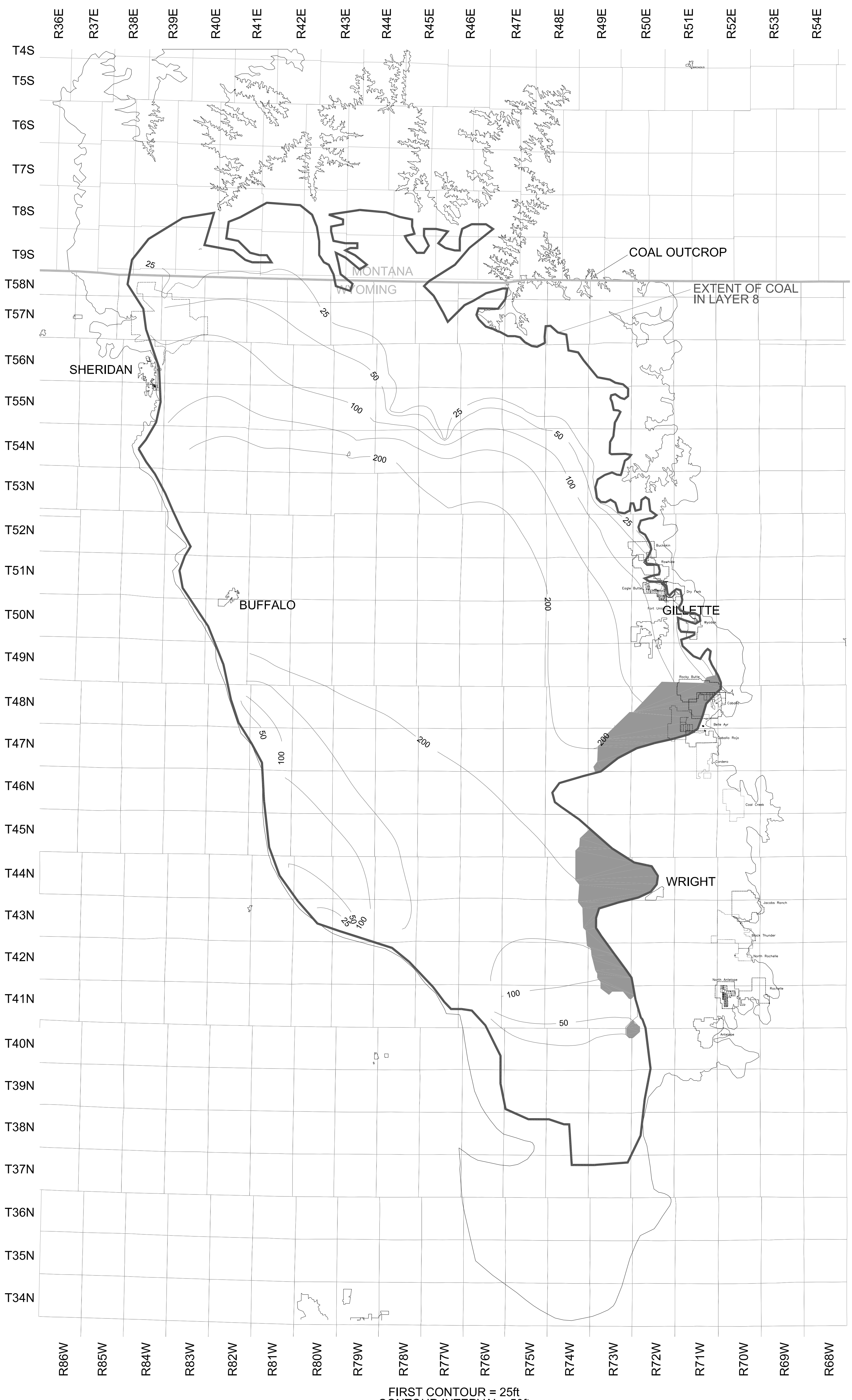
Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS	
TECHNICAL REPORT GROUNDWATER MODELING	
FIGURE 6-5D MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 14 YEAR 2015	
MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-5 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-5D continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

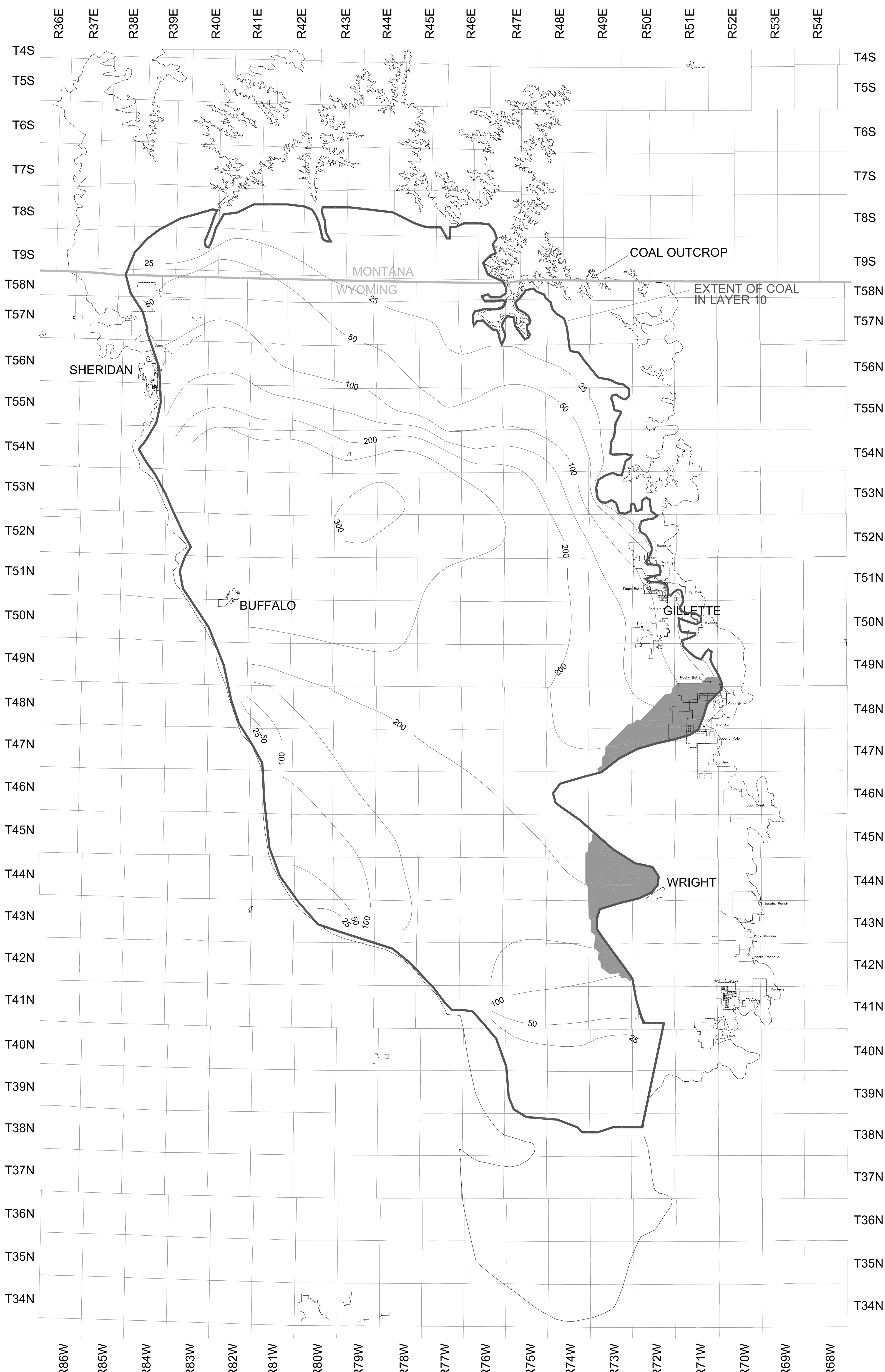
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-6A
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2018

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

Date: 09/05/02	Drawing File: Figure 6-6 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-6A continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

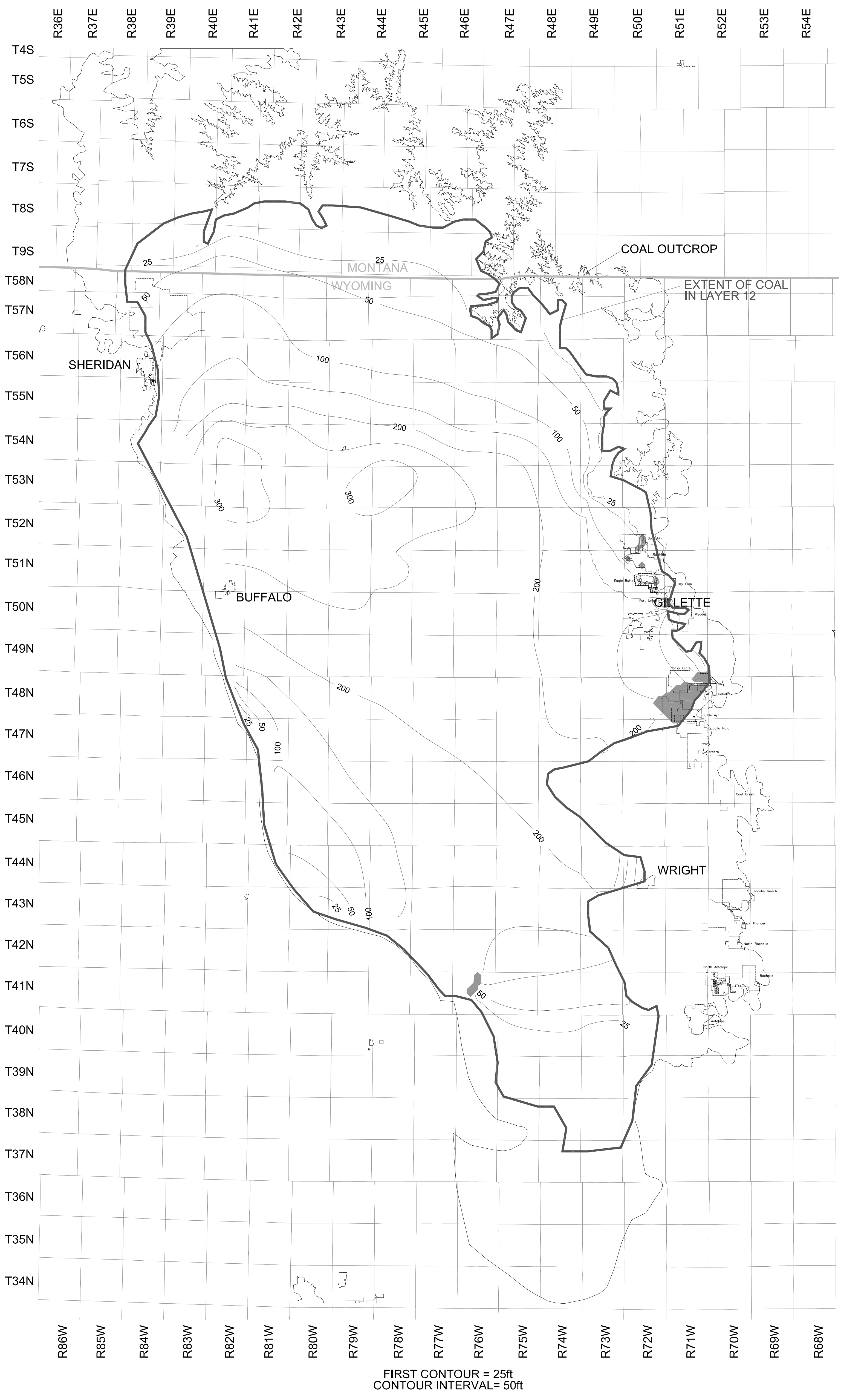
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-6B
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 10 YEAR 2018

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

Date: 09/05/02	Drawing File: Figure 6-6 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-6B continued (11x17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

N

Note: Contours are not closed due to insufficient data.

0 7.5 15 30 Miles

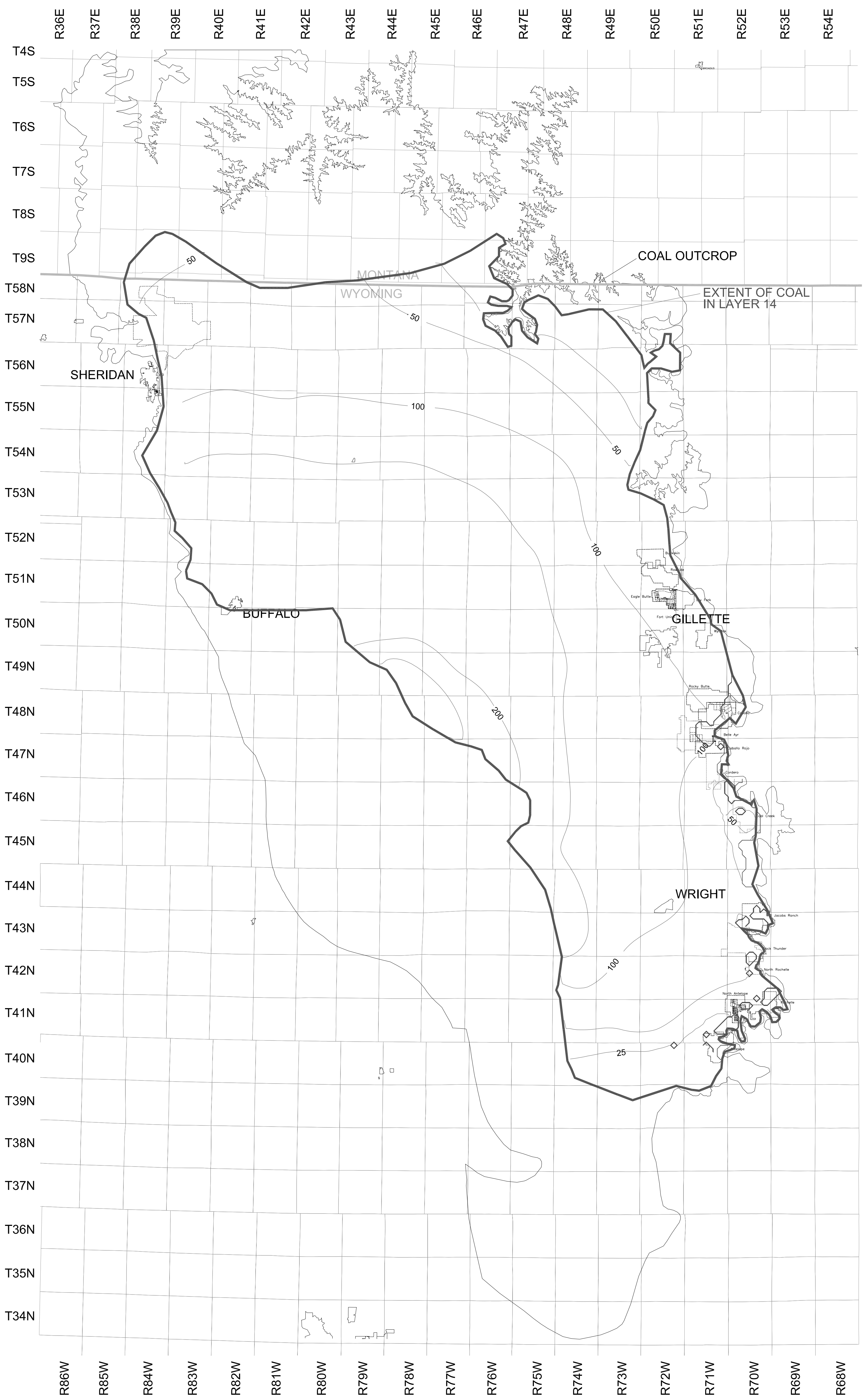
POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-6C
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 12 YEAR 2018

MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-6 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-6C continued (11x17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 14
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-6D
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 14 YEAR 2018

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

Date: 09/05/02	Drawing File: Figure 6-6 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-6D continued (11x17)

The projected rate of drawdown in the coal aquifer is presented by graphs of modeled drawdown versus time at selected locations in the model (Figure 6-7). The locations of the monitoring points are shown on Figure 5-1. The graphs show that water level changes in the coal aquifer that would be induced by CBM development tend to be rapid.

Initial hydraulic head in the coal, as measured by the water level in a well completed in the coal, may be several hundred feet above the top of the coal, particularly in the deep portions of the PRB, where the depth to the coal may exceed 1,300 feet. Removal of water from the coal in these areas during CBM development could result in drawdown of the hydraulic head to the top of the coal at the location of the pumping wells. For reference, an initial hydraulic head of 800 feet would exist where the depth to the coal is 1,200 feet and the depth to water in a well tapping the coal is 400 feet. Even though the thickness of the coal itself may only be 100 feet, maximum drawdown in this example could be as much as 800 feet.

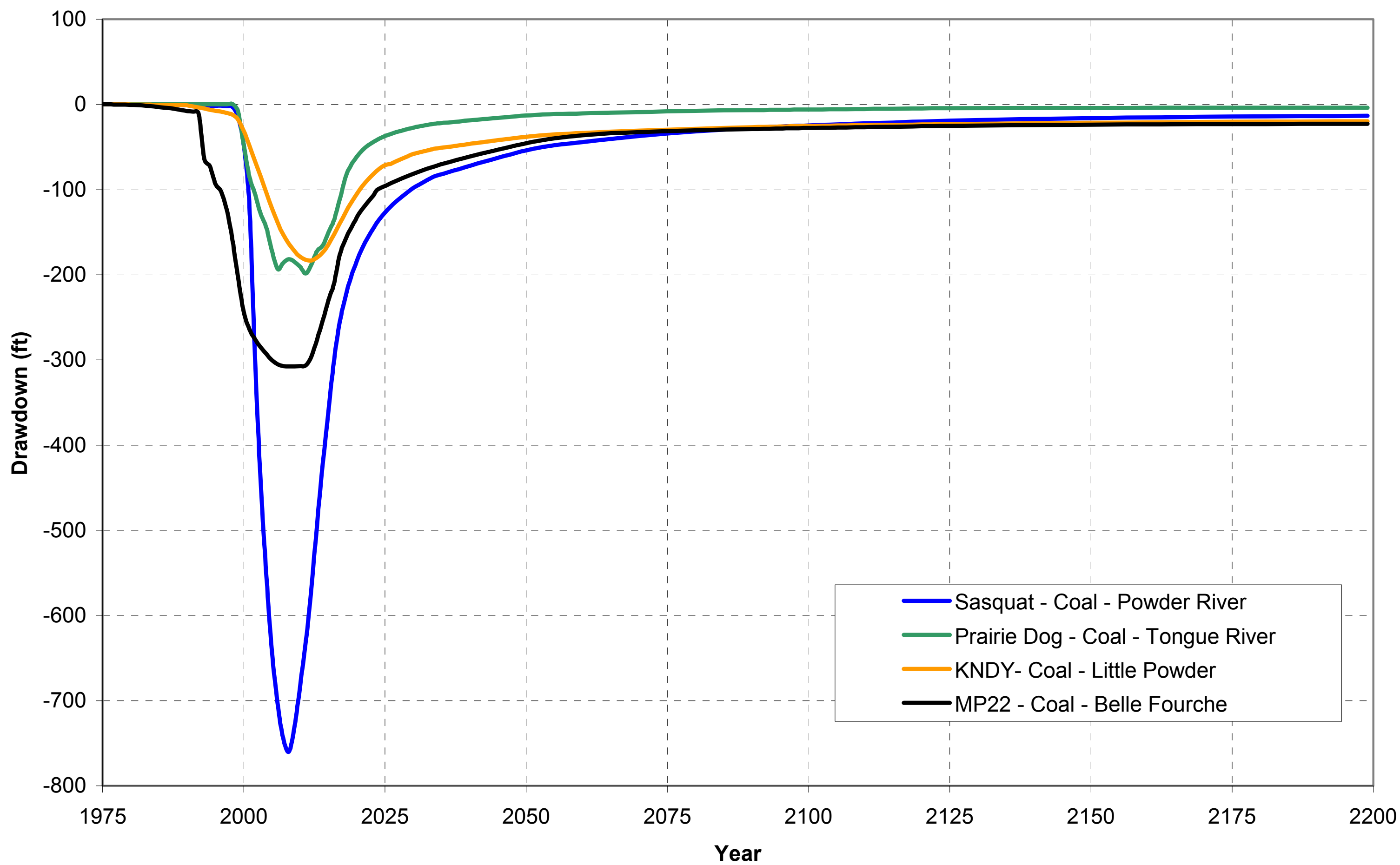
6.2.2 Recovery

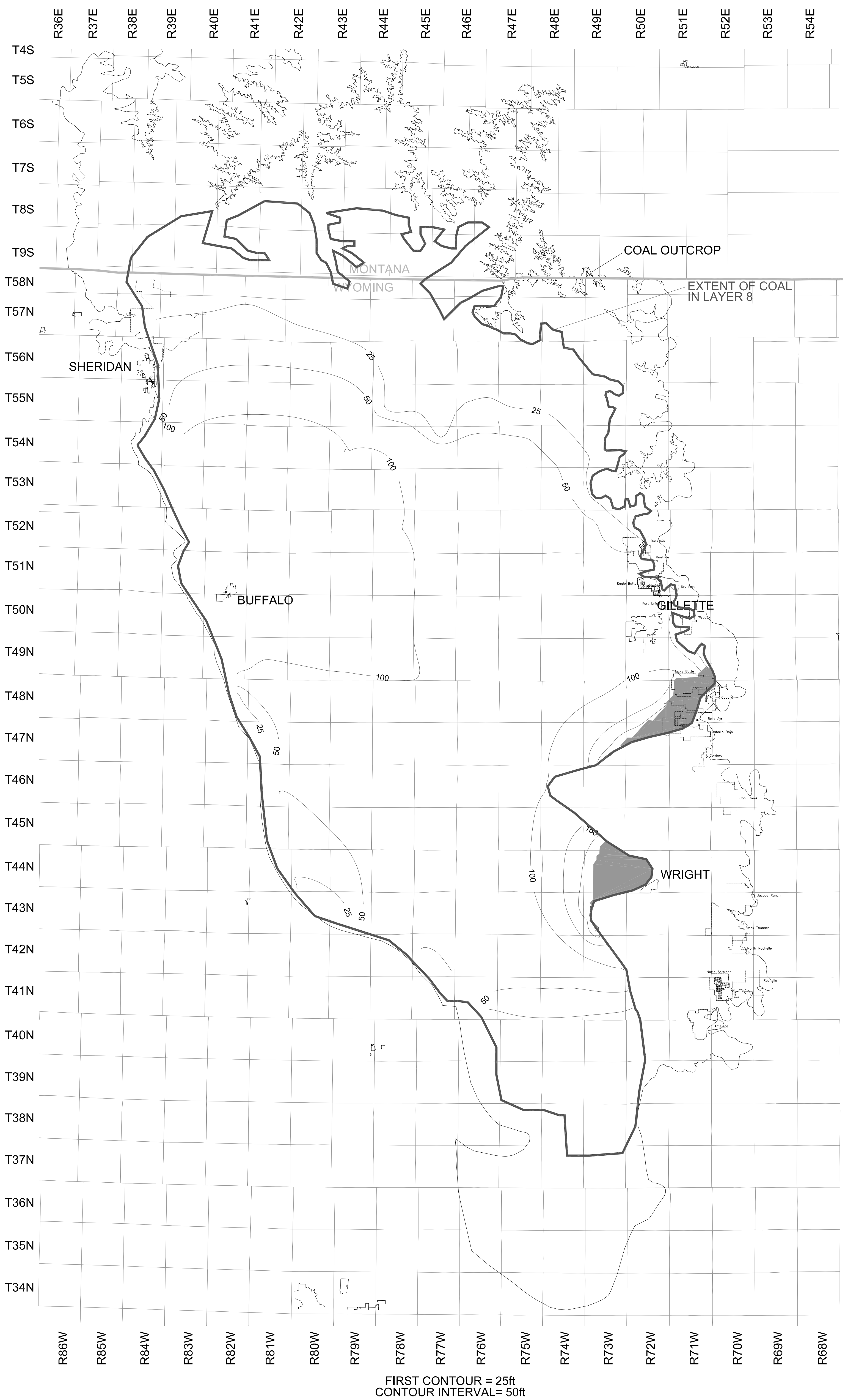
Recovery of water levels in the coal would become apparent after water production began to decline. As modeled, water production is expected to begin to decline about 2008 and end about 2018. Initial recovery would be primarily caused by redistribution of groundwater stored in the surrounding coal. When the stresses of pumping are removed, the groundwater in storage outside the CBM development areas would resaturate and repressurize the areas that were partially depressurized during operations. Longer-term recovery would occur through continued slow leakage from overlying sand aquifers in the Wasatch Formation and sand aquifers in the underlying Fort Union Formation. The amount of groundwater storage within the coal and within the sand units above and below the coal is enormous (Section 2.3.3 and Table 2-4). Almost 750 million acre-feet of recoverable groundwater are stored within the Wasatch-Tongue River sands and coals (Table 2-4). Redistribution would be projected to result in a rapid initial recovery of water levels in the coal. By 2030, 100 feet of drawdown would still exist in most of the coal seams in the basin. Drawdowns of 50 to 200 feet would be typical within portions of the Project Area that have undergone CBM development (Figure 6-8A, B, C, and D).

Complete recovery of the water level would be a long-term process because recharge to the coal aquifer would need to replace groundwater removed from storage during CBM operations. Most of this recharge would come from leakage from overlying and underlying sand and undeveloped coal units. These units would, in turn, be recharged from surface infiltration. Recharge rates would increase temporarily as a result of infiltration of CBM produced water discharged to impoundments and streams. However, based on modeling and information from nested wells, tens of years would be required before these surface recharge influences would appear in the coal. Recharge to the coal in the central part of the PRB through surface infiltration at the outcrop areas would take even longer. The drawdowns projected by the model in 2060 for each of the coal layers are shown in Figures 6-9A, B, C, and D. The drawdowns projected in the model from initial conditions are recovered to less than 50 feet except for localized areas of the basin.

Coal mining along the eastern and northwestern subcrop would result in minimal recharge to the coal from the outcrop areas while the mines are active as a result of the groundwater sink caused by pit dewatering. As mines are reclaimed and eventually shut down, the backfilled areas would become long-term recharge zones for the coal aquifer. Infiltration through backfill areas may be significant because the permeability of the backfill materials tends to be much higher than in the original, unmined materials. In addition, most of the creeks would be diverted over these backfilled areas, providing an important source of recharge water.

Figure 6-7 Modeled Drawdown vs. Time for Selected Upper Fort Union Monitoring Locations





LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

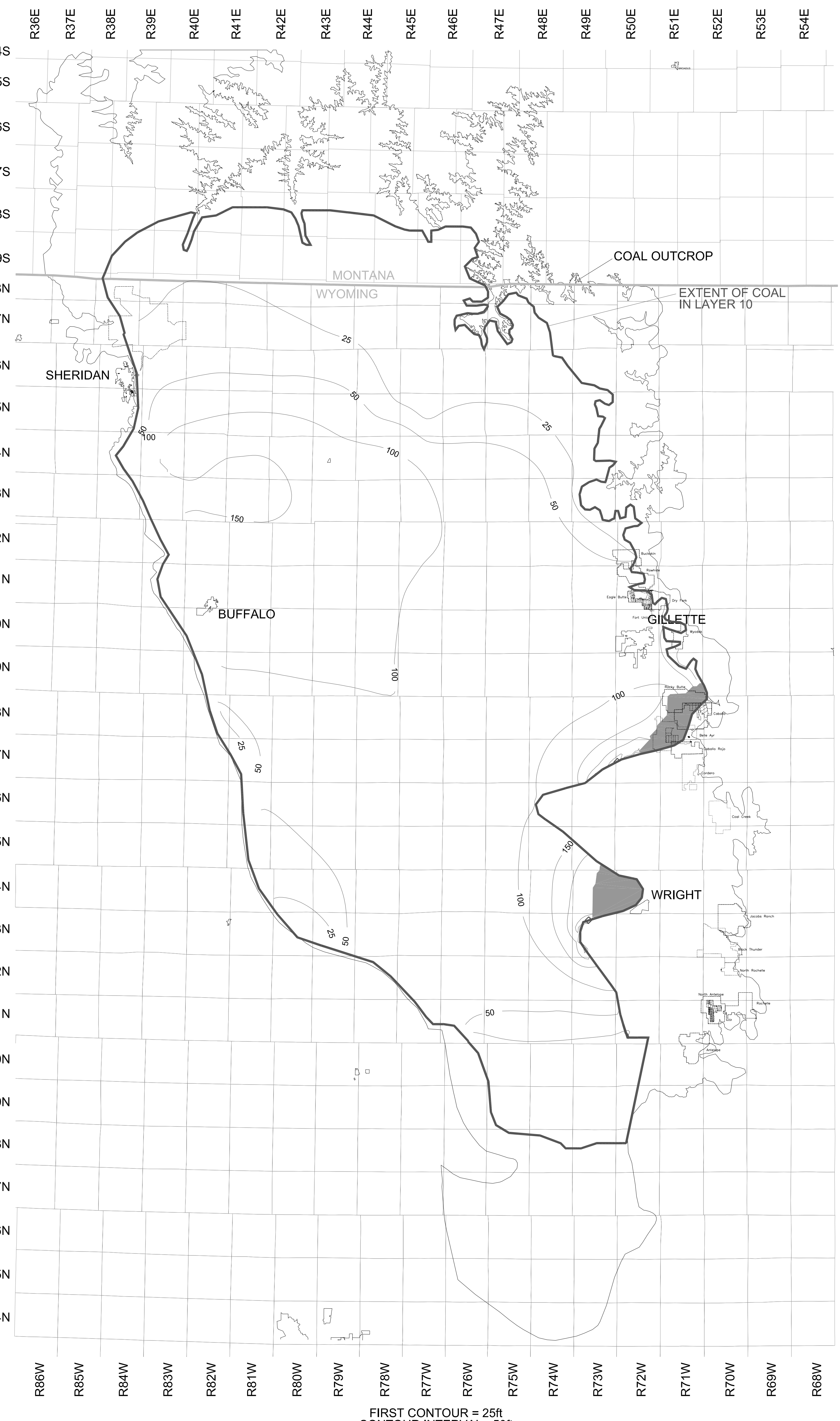
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-8A
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2030

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

Date: 09/05/02	Drawing File: Figure 6-8 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-8A continued (11 x 17)



LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

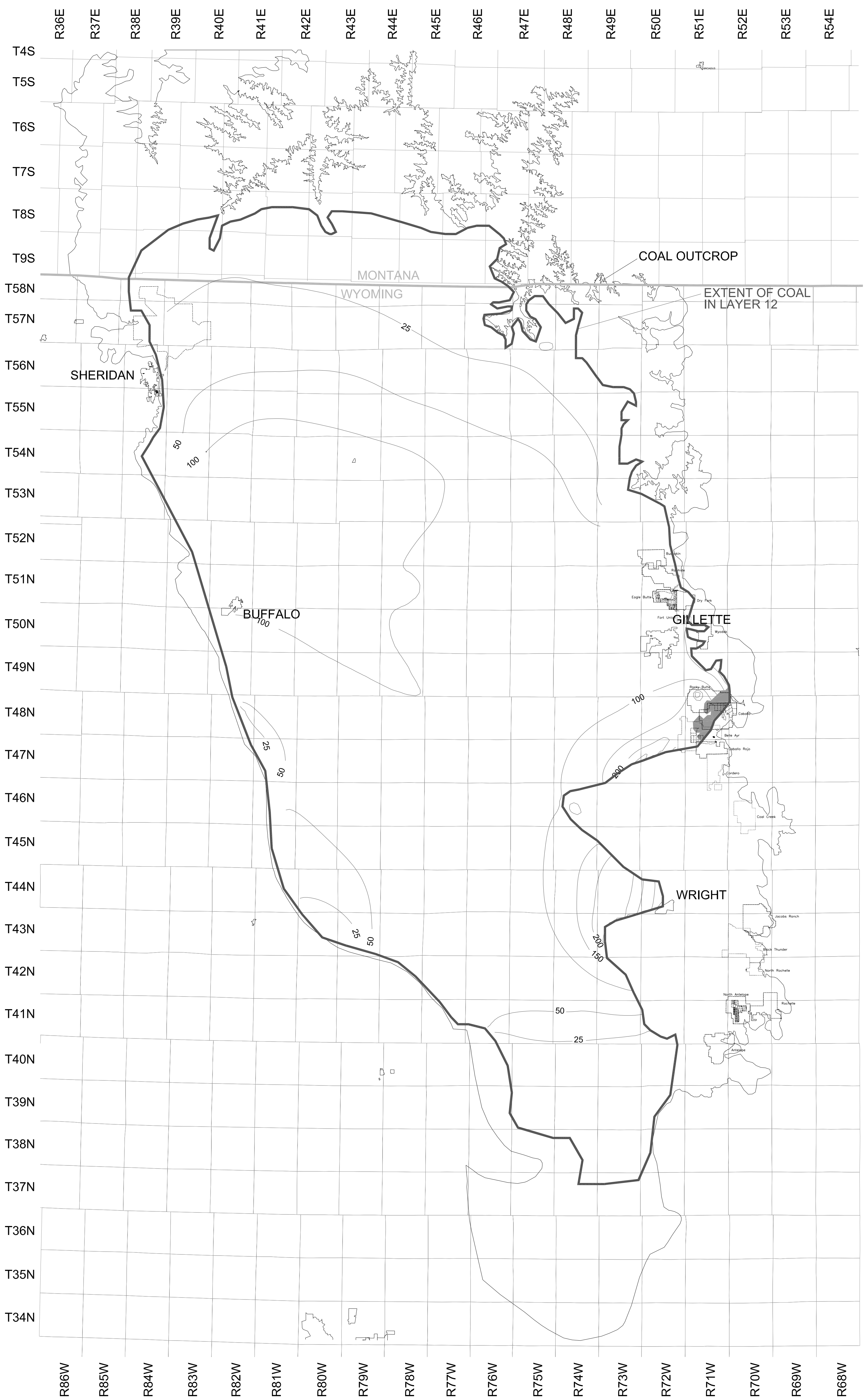
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-8B
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 10 YEAR 2030

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

Date: 09/05/02	Drawing File: Figure 6-8 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-8B continued (11 x 17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

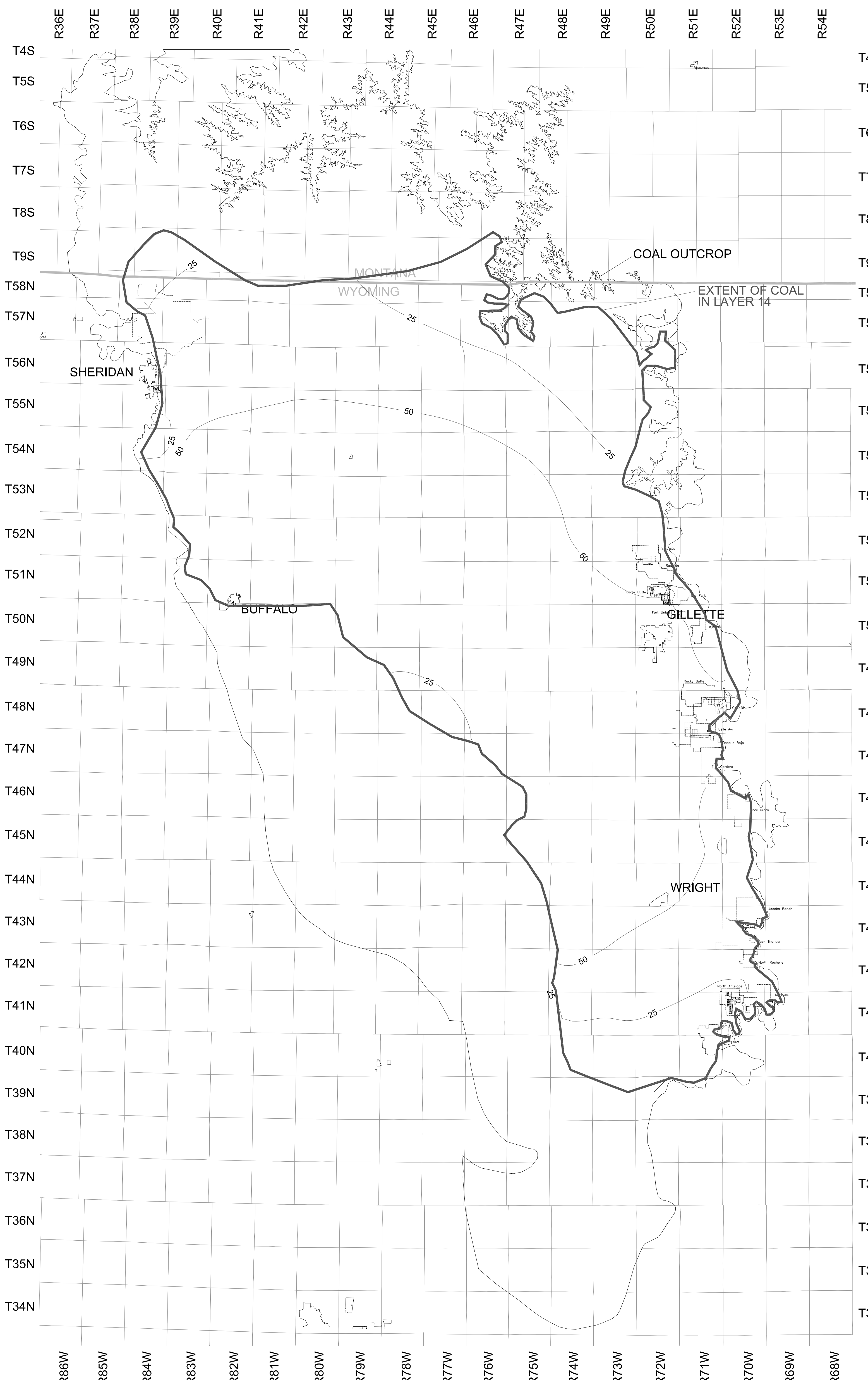
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-8C
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 12 YEAR 2030

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

Date: 09/05/02	Drawing File: Figure 6-8 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-8C continued (11 x 17)



FIRST CONTOUR = 25ft
CONTOUR INTERVAL= 50ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 14
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

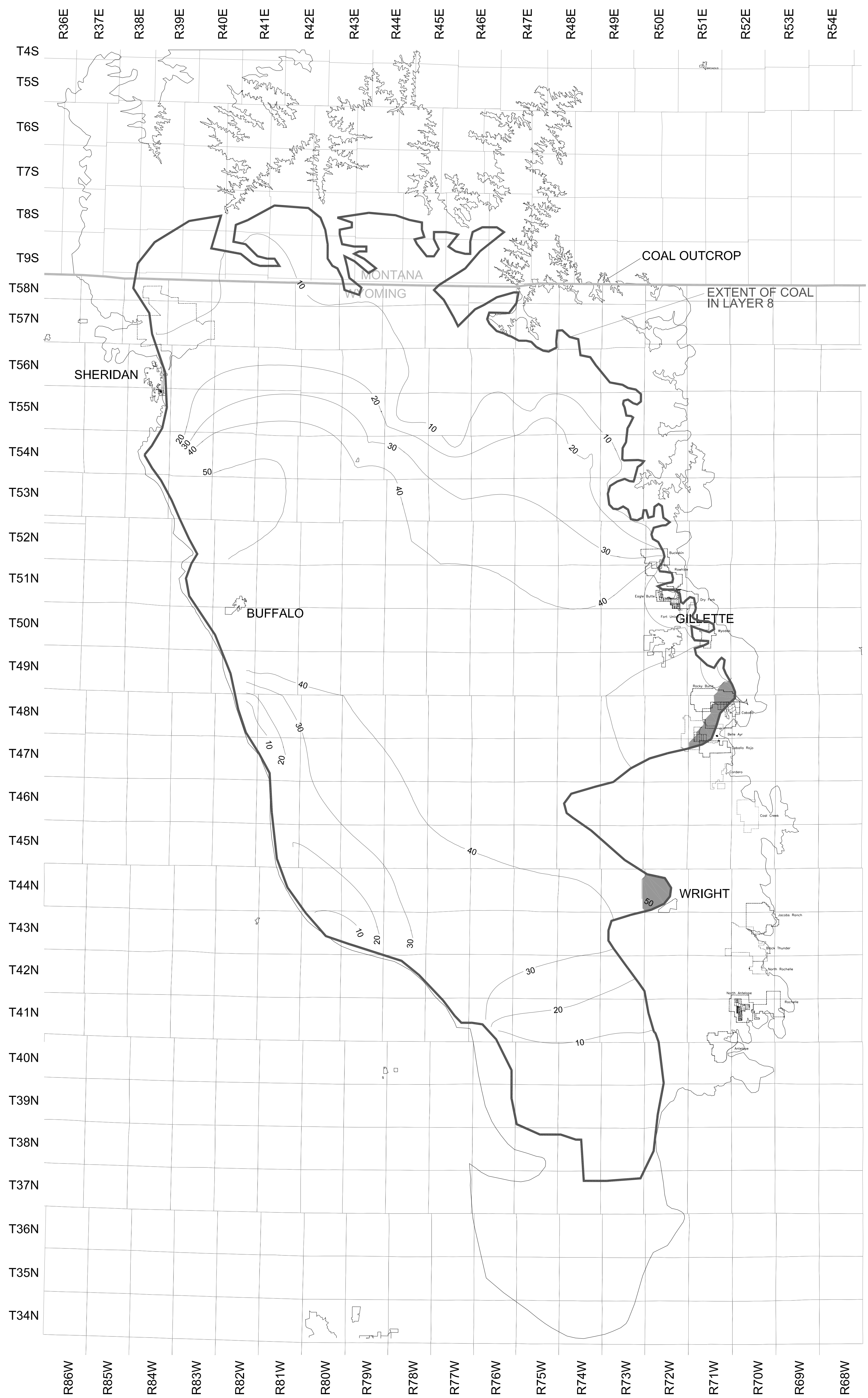
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-8D
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 14 YEAR 2030

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

Date: 09/05/02	Drawing File: Figure 6-8 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-8D continued (11 x 17)



CONTOUR INTERVAL= 10ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 8
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

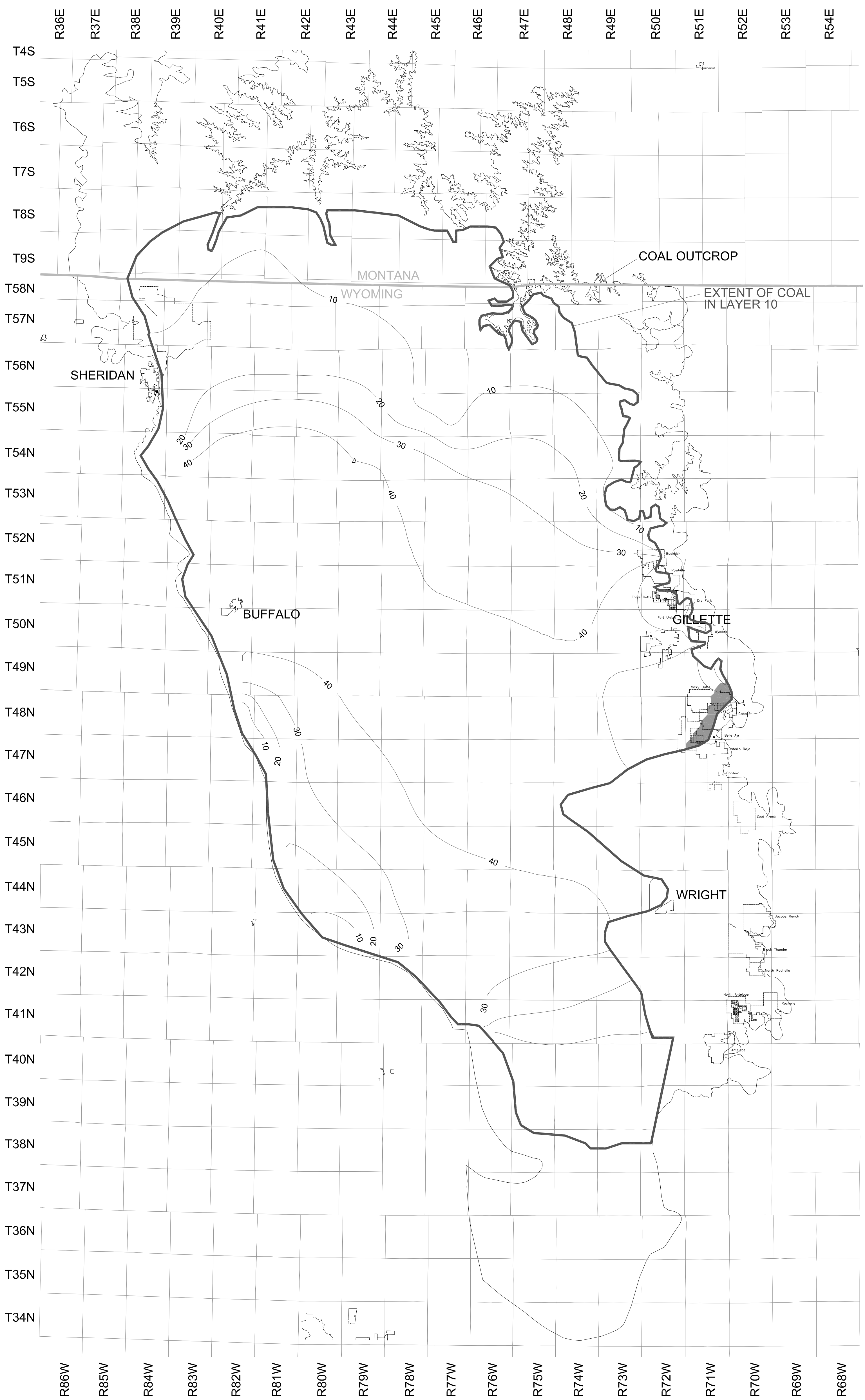
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-9A
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 8 YEAR 2060

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

Date: 09/05/02	Drawing File: Figure 6-9 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-9A continued (11 x 17)



CONTOUR INTERVAL= 10ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 10
- Dry Cell
- Towns
- Mine Boundary

N

0 7.5 15 30 Miles

Note: Contours are not closed due to insufficient data.

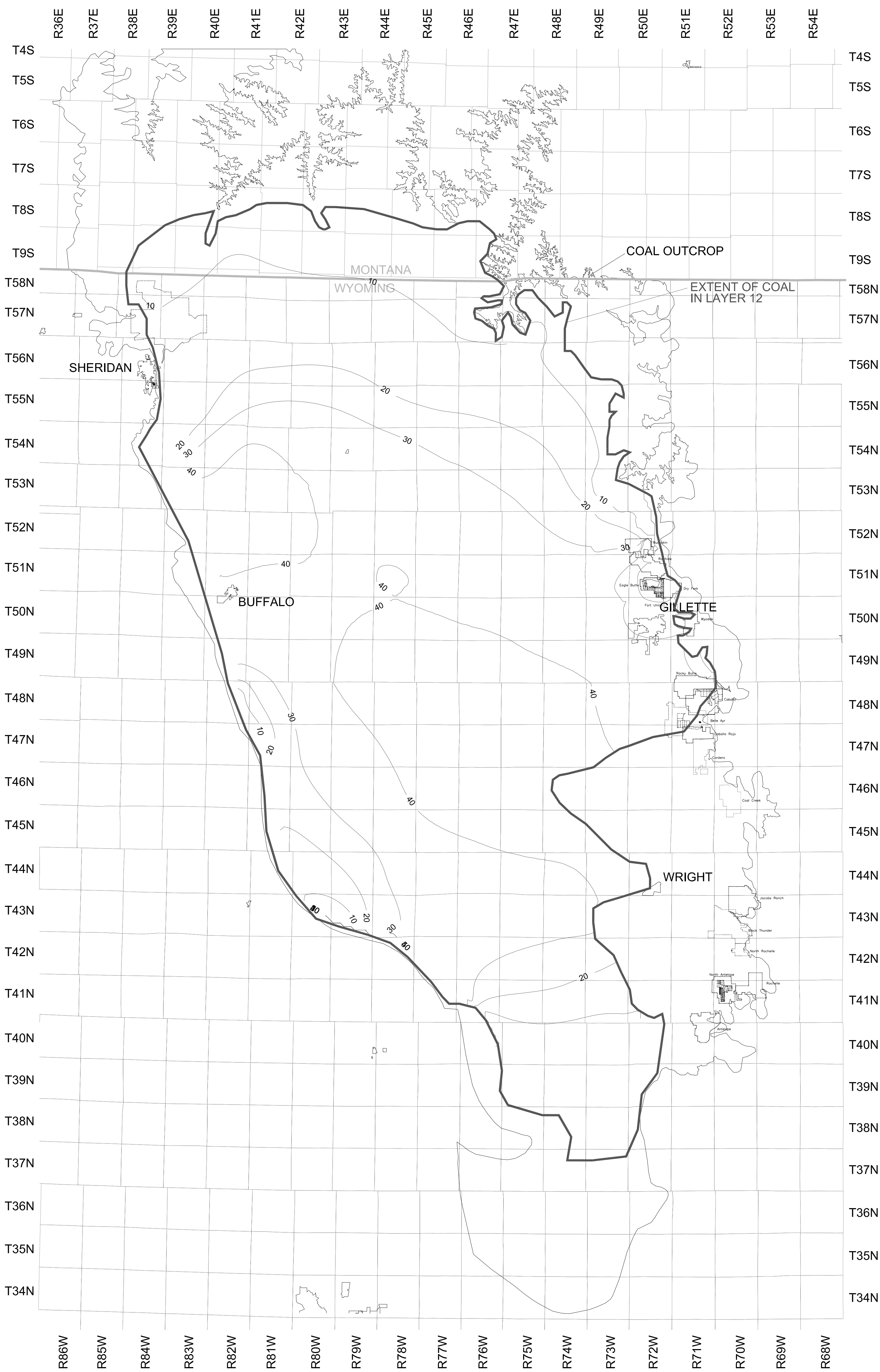
POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-9B
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 10 YEAR 2060

MODEL RUN: From 1999-2200 (08-26-02)	
Date: 09/05/02	Drawing File: Figure 6-9 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-9B continued (11 x 17)



CONTOUR INTERVAL= 10ft

LEGEND

- Drawdown (ft) Upper Ft. Union Coals
- Extent of Coal in Layer 12
- Dry Cell
- Towns
- Mine Boundary

Note: Contours are not closed due to insufficient data.

N

0 7.5 15 30 Miles

POWDER RIVER BASIN OIL & GAS PROJECT FEIS

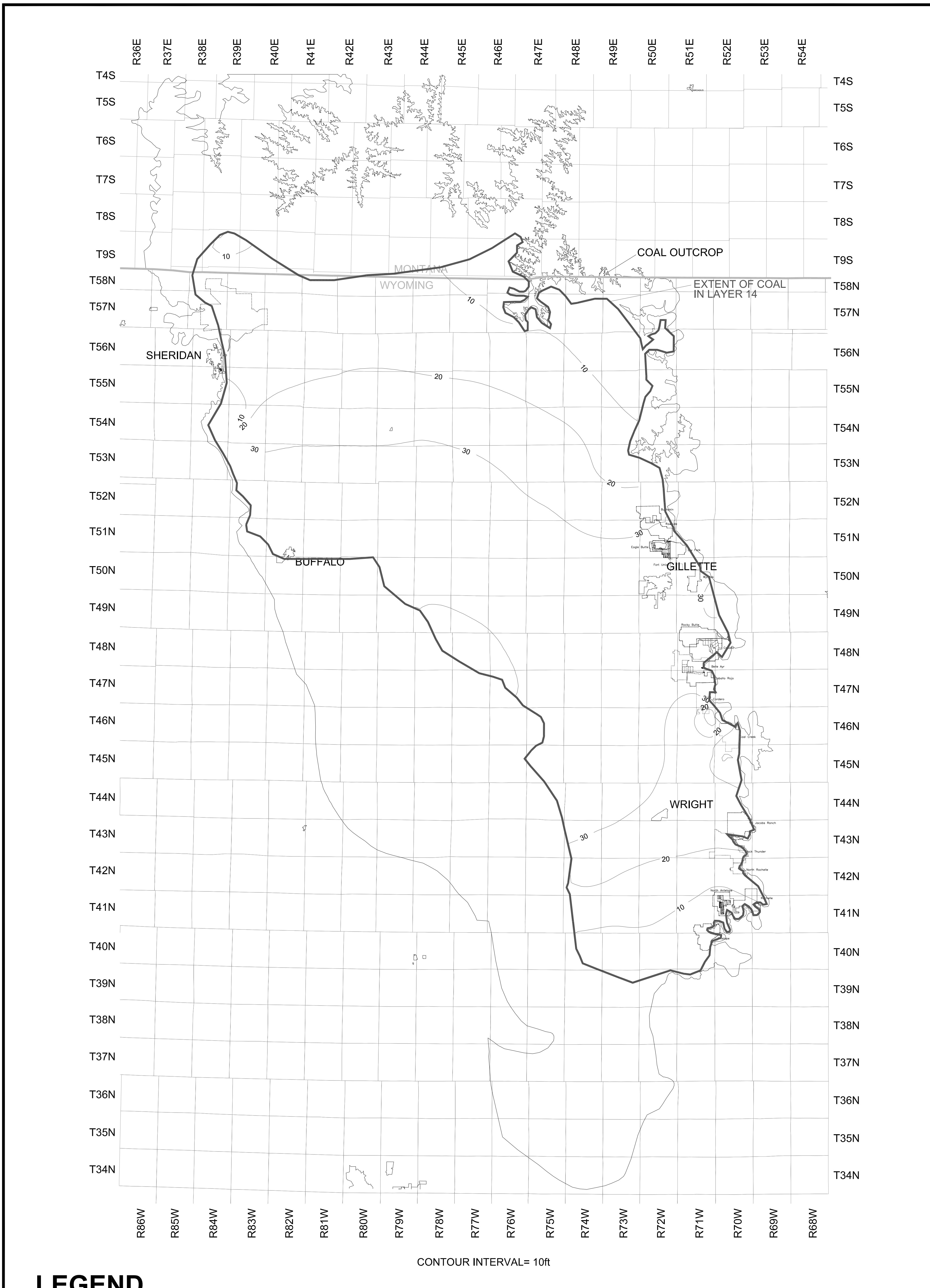
TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-9C
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 12 YEAR 2060

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

Date: 09/05/02	Drawing File: Figure 6-9 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-9C continued (11 x 17)



POWDER RIVER BASIN OIL & GAS PROJECT FEIS

TECHNICAL REPORT GROUNDWATER MODELING

FIGURE 6-9D
MODELED DRAWDOWN UPPER FORT UNION COALS LAYER 14 YEAR 2060

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

Date: 09/05/02	Drawing File: Figure 6-9 a-d.dwg
Scale: As Noted	Drawn By: ETC

Figure 6-9D continued (11 x 17)

The projected recovery of water levels after CBM development and coal mining operations end is illustrated in the hydrographs for selected locations in the model (Figure 6-7). The graphs show water levels recovering to within 55 to 65 feet (75 to 80 percent) of pre-operational conditions approximately 25 years after CBM operations end. However, the rate of recovery would slow dramatically after this initial period, eventually recovering to within less than 20 feet (95 percent) of pre-operational conditions over the next 100 years or so.

Drawdown and recovery within the shallow and deep sands of the Wasatch Formation cannot be accurately projected by the regional model because of the variability of the sand units and the general lack of data available to calibrate the model layers that represent the Wasatch Formation.

6.3.2 Recharge

Some of the extracted groundwater released to surface drainages and impoundments would recharge shallow bedrock (the Wasatch Formation). A portion of the released water would recharge the alluvium. In turn, the alluvium along many of the creek valleys would recharge the underlying Wasatch sands. Several studies of losses in water flow along creeks during dry weather have shown that a considerable portion of the discharged water infiltrates the alluvium within a few miles of the surface discharge outfall. Shallow bedrock monitoring wells located close to areas where CBM produced water is discharging into creeks or impoundments have shown increases in water level, indicating that recharge is occurring. The nature of recharge in any area is directly related to the permeability of the surface exposures of the Wasatch Formation under creeks and ponds.

The recharge effect was evaluated in this analysis by examining the area of affected surface drainages and the probable range of vertical infiltration rates into the Wasatch Formation below the creeks and ponds. The total discharge from CBM operations was obtained from the model output for each of the affected sub-watersheds(Table 6-1). This projected water production would be managed according to the water handling options identified for each sub-watershed under Alternative 1 (Table 2-9 of the FEIS). The projected net recharge is calculated based on the percentage of the produced water handled by each method and the projected loss through infiltration (Tables 3-1 and 4-3). This infiltration has been characterized as an area recharge, considering the scale and limited detail in the regional model.

The calculated net recharge volume, on a year-by-year basis, was divided by the projected area of CBM development within each sub-watershed to obtain an equivalent recharge rate for the area, in inches per year (Table 6-2). This additional recharge was then input into the model for the area of CBM development within each sub-watershed during the period when CBM operations are expected to be active.

Table 6-2
Annual Recharge Rate Projected in the Model by Sub-Watershed (2002 to 2017) Under Alternative 1

(Recharge rate applied to developed CBM areas [inches per year])

Sub-watershed	Developed Area (acres)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Upper Tongue River	10,246,277	0.192	0.260	0.340	0.388	0.414	0.440	0.450	0.486	0.484	0.468	0.419	0.379	0.303	0.243	0.175	0.107
Upper Powder River	78,184,723	0.191	0.247	0.289	0.317	0.338	0.350	0.348	0.315	0.282	0.248	0.210	0.168	0.117	0.069	0.051	0.038
Salt Creek	298,848	0.033	0.033	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Crazy Woman Creek	11,776,274	0.091	0.137	0.173	0.200	0.219	0.237	0.246	0.223	0.198	0.180	0.152	0.128	0.102	0.076	0.060	0.046
Clear Creek	17,828,989	0.108	0.154	0.198	0.243	0.283	0.316	0.328	0.332	0.329	0.326	0.283	0.242	0.197	0.159	0.119	0.077
Middle Powder River	6,818,630	0.165	0.174	0.182	0.188	0.184	0.161	0.133	0.144	0.147	0.149	0.138	0.125	0.110	0.094	0.076	0.053
Little Powder River	13,350,050	0.192	0.190	0.186	0.189	0.174	0.161	0.130	0.132	0.135	0.135	0.122	0.111	0.095	0.080	0.064	0.050
Antelope Creek	11,399,624	0.176	0.193	0.218	0.233	0.249	0.253	0.250	0.238	0.229	0.214	0.193	0.169	0.135	0.098	0.080	0.060
Upper Cheyenne River	5,660,490	0.241	0.226	0.214	0.196	0.185	0.161	0.159	0.149	0.135	0.118	0.113	0.077	0.060	0.030	0.030	0.030
Upper Belle Fourche River	35,874,382	0.340	0.329	0.318	0.312	0.307	0.286	0.245	0.235	0.224	0.215	0.197	0.175	0.146	0.093	0.078	0.063

Note: Recharge rates shown include average recharge of 0.03 inches per year from precipitation and projected recharge resulting from water handling methods.

6.4 Potential Impacts to Groundwater Use

6.4.1 Water Wells

Impacts to individual water wells completed within the coal and in sands above the coal would depend on proximity to CBM production wells, depth, completion interval, and the yield required to maintain it as a usable source. Drawdown of water levels in coal aquifers caused by CBM development may affect individual well users by reducing well yield and inducing methane emissions.

Under Alternative 1, the model projects more than 800 feet of coal aquifer drawdown near the centers of active CBM development. (Figures 6-1A, B, C, and D through 6-6A, B, C, and D). The maximum available drawdown (the hydraulic pressure head) in the coal aquifer in the affected areas ranges from 300 to 1,400 feet. Most individual water supply wells in the coal seam do not exceed 600 feet in depth and have up to 300 feet of available drawdown. Pumps typically are set between 50 and 200 feet below the static water level in the well.

Impacts, in terms of well yield or availability, are likely to be an issue only if the drawdown exceeds about 20 to 30 percent of the amount available at any location. This area would tend to coincide with the area of drawdown in excess of approximately 100 feet. The decreased head may cause the pump discharge to decrease. However, yield may be restored by installing a larger pump if sufficient available drawdown remains in the well. In cases where the drawdown causes the water level in a well to drop below the intake of the pump, the pump may be lowered in the well.

Changes in water level in wells are not expected to be as significant in the aquifers above or below the coal because the coal is confined both above and below by low-permeability claystone layers over most of the PRB. This claystone unit restricts hydraulic communication between the coal and the overlying Wasatch sands. The response of existing monitoring wells located in sands above developed coals indicates that a significant period of time (typically several years) likely would pass before drawdown effects caused by pumping groundwater from the coal are apparent in the overlying Wasatch sands. The integrity of the confining layer may be compromised locally by water supply wells screened through both the coal and the overlying sands, deteriorating well casings, or poorly plugged oil and gas wells or exploratory drill holes. However, these isolated local influences would not affect regional results.

Artesian flow has been reported in wells located near the Powder River, where the hydraulic head from the deep coal aquifer extends to the surface. Groundwater has been discharging in this area, in part to artesian wells. Reductions in hydraulic head projected by the model within the coal aquifer likely would reduce or eliminate artesian flow in water wells. Artesian flow in wells likely would not recover until hydraulic head in the coal aquifer recovers sufficiently after CBM development ends.

6.4.2 Methane Emissions

Withdrawal of water from the coal aquifer during CBM development can depressurize the coal aquifer and induce the release of methane into nearby water wells completed in the coal aquifer. Individual users of wells completed in the coal aquifer may experience increased methane emissions if the wells fall within an area that experiences noticeable depressurization in the aquifer.

Records of first indications of methane production in monitoring wells that have experienced drops in water level caused by mining indicate that methane emission from the coal can occur with as little as 50 feet of head drop (Belle Ayr Mine groundwater monitoring data). Consequently, coal wells within the predicted 50-foot drawdown area may be susceptible to this impact. Methane emissions by a well pose a potential explosive safety hazard, particularly if gases can build up in an enclosed space. Well houses and basements located within the potential 50-foot drawdown area associated with operational CBM fields should be well ventilated and periodically checked for methane gas.

6.5 Potential Impacts to Groundwater Flow Systems

The groundwater resources of the PRB are vast (Table 2-4), and regional flow within and out of the PRB would not be noticeably affected under Alternative 1. Nearly 1.4 billion acre-feet of recoverable groundwater have been estimated to exist within the Wasatch and Fort Union Formations (FEIS, Table 3-5). The projected CBM water production from 2002 to 2017, about 3 million acre-feet (FEIS, Table 2-8), represents only about 0.2 percent of the recoverable groundwater. The modeled removal of water during coal mining through 2033, about 1 million acre-feet (Table 6-3), represents less than 0.1 percent of the recoverable groundwater. Any noticeable effects on local groundwater flow systems would be expressed as effects on existing springs or groundwater discharge areas.

Table 6-3
Water Removed During Coal Mining

Year	Rates [m^3/day]	MBBL/yr	AC-FT/yr
1975	0	-	
1976	2277.1	5,200	670
1977	48863	112,200	14,461
1978	45614	104,700	13,495
1979	37335	85,700	11,046
1980	14362	33,000	4,253
1981	16846	38,700	4,988
1982	45496	104,400	13,456
1983	45744	105,000	13,533
1984	47764	109,600	14,126
1985	28001	64,300	8,288
1986	45554	104,600	13,482
1987	28993	66,600	8,584
1988	95765	219,800	28,330
1989	78023	179,100	23,084
1990	130840	300,300	38,706
1991	144000	330,500	42,598
1992	175320	402,400	51,865
1993	121210	278,200	35,857
1994	50370	115,600	14,900
1995	92510	212,400	27,376
1996	150080	344,500	44,403
1997	129430	297,100	38,293
1998	70322	161,400	20,803
1999	61942	142,200	18,328
2000	74081	170,100	21,924
2001	149980	344,300	44,377
2002	114840	263,600	33,975
2003	124370	285,500	36,798
2004	80608	185,000	23,845
2005	74875	171,900	22,156
2006	53963	123,900	15,969

Table 6-3
Water Removed During Coal Mining

Year	Rates [m^3/day]	MBBL/yr	AC-FT/yr
2007	100790	231,400	29,825
2008	80434	184,600	23,793
2009	95921	220,200	28,382
2010	46071	105,800	13,637
2011	71810	164,800	21,241
2012	49608	113,900	14,681
2013	43931	100,800	12,992
2014	24576	56,400	7,269
2015	36217	83,100	10,711
2016	27771	63,700	8,210
2017	28954	66,500	8,571
2018	21195	48,700	6,277
2019	34745	79,800	10,285
2020	39740	91,200	11,755
2021	32770	75,200	9,693
2022	16613	38,100	4,911
2023	782.55	1,800	232
2024	36631	84,100	10,840
2025	26448	60,700	7,824
2026	46554	106,900	13,778
2027	30013	68,900	8,881
2028	62759	144,100	18,573
2029	29652	68,100	8,777
2030	27563	63,300	8,159
2031	5419.9	12,400	1,598
2032	4877.4	11,200	1,444
2033	3027.9	7,000	902
2034	0	-	
2050	0	-	
2060	0	-	
2070	0	-	
2080	0	-	
2090	0	-	
2100	0	-	
2125	0	-	
2150	0	-	
2175	0	-	
2199	0	-	
		7,814,500	1,007,211

Source: Regional Model

6.5.1 Existing Springs

The public has expressed concern over the potential effects of CBM development on springs that issue from clinker outcrops, such as the Moyer Springs located north of Gillette in Section 30, T51N R71W. Moyer Springs is located at the base of an exposed clinker deposit in the outcrop area of the Roland-Smith coal seam. The springs recharge through surface infiltration and lateral movement of water from adjacent clinker and alluvium. The springs issue along a low-permeability zone at the contact between the clinker and the coal. Large areas of clinker are exposed northeast and southeast of Moyer Springs

(Williams 1978). This exposure allows a large amount of recharge to the clinker by infiltration of rainfall and snowmelt. Hodson et al. (1973) reported a flow of 200 gallons per minute from Moyer Springs.

No decrease in spring flows would be anticipated under Alternative 1 where the springs result from flow along a near-surface zone of low permeability intercepting the surface. Many springs in the Project Area, including Moyer Springs, represent this type. A contact of low permeability inhibits flow between the clinker and the coal. The presence of a low-permeability zone between the clinker and the coal channels water in the clinker to the spring rather than recharging the coal. A decrease in recharge to the spring (which is not projected to occur under Alternative 1) could reduce flow for this type of spring.

The natural discharge of springs in the Project Area could be affected by a reduction in the hydraulic head in an aquifer unit, if the aquifer that experiences the reduction in hydraulic head were the spring's source aquifer. Spring flow could decrease or stop under these conditions. Spring flow likely would not recover until the hydraulic head in the coal aquifer recovers sufficiently after CBM development ends. Springs that issue from the Wasatch sands into surface drainages may experience increased flows during the period that CBM produced water is recharging shallow aquifers.

The use of infiltration impoundments or flow-through stock reservoirs during surface discharge associated with CBM development could increase existing spring flows where a near-surface zone of low permeability intercepts the surface. This increase in spring flow would not occur if these water handling facilities are sited to minimize this potential effect. Avoidance of sites where a zone of low permeability intercepts the surface downhill or downgradient from an area where considerable infiltration of CBM-produced water is occurring would minimize the potential for shallow infiltrated water to increase the recharge or flow of existing springs.

Negligible infiltration would be anticipated where containment ponds or reservoirs constructed in upland areas would be used to handle CBM produced water. It is unlikely that existing spring flows would be affected near properly engineered and constructed containment impoundments.

6.5.2 Groundwater Discharge Areas

Groundwater has been discharging to the surface in many areas near the Powder River where the hydraulic head from the deep coal aquifer intercepts the surface and flow along the natural groundwater gradient is toward the river. A reduction in hydraulic head within the coal aquifer, projected to occur during CBM development under Alternative 1, likely would reduce groundwater discharge and base flows in surface drainages within the Powder River's drainage basin. Groundwater discharge likely would not recover until the hydraulic head in the coal aquifer recovers sufficiently after CBM development ends.

Negligible infiltration would be anticipated where containment ponds or reservoirs constructed in upland areas would be used to handle CBM-produced water. It is unlikely that new springs would develop or that shallow infiltrated water would resurface near properly engineered and constructed containment impoundments.

The use of infiltration impoundments or flow-through stock reservoirs during surface discharge associated with CBM development could cause new springs to develop where a near-surface zone of low permeability intercepts the surface. This increase in spring flow would not occur if these water handling facilities are sited to minimize this potential effect. Siting in accordance with applicable WDEQ and WSEO requirements and avoidance of sites where a zone of low permeability intercepts the surface downhill or downgradient from an area where considerable infiltration of CBM-produced water is occurring would minimize the potential for shallow infiltrated water to resurface.

The detailed model study for the LX Bar drainage (Chapter 9) focused on the potential contributions to surface flows from increased groundwater discharge associated with rising water tables that would result from infiltration ponds. This modeling study assumed that all CBM-produced water in the LX Bar drainage was discharged to infiltration impoundments. The model indicated that the resulting rise in groundwater levels within shallow Wasatch sands would occur regionally, up to 10 feet, and locally near the impoundments up to 50 feet. The net increase in surface water flows would be less than 0.1 cfs or 45 gpm.

The current water table may be shallow in many areas where infiltration impoundments could be constructed.Groundwater discharge may occur if infiltration causes the water table to rise above the surface. In these areas, the increase in water level may be exhibited as standing water in areas that did not previously display this condition or as wetland development, unless the percentage of CBM wells where produced water held in infiltration impoundments is carefully controlled. The effects of impoundment and infiltration of CBM-produced water would need to be analyzed on a site-specific basis to ensure that water table and groundwater discharge effects are carefully balanced or mitigated during CBM development.

7.0 IMPACTS PROJECTED UNDER OTHER ALTERNATIVES

Projected impacts for Alternatives 2A, 2B, and 3 (No Action) are described in relation to Alternative 1, (Proposed Action), which was discussed in Section 6.0.

7.1 Projected Impacts Under Alternative 2A

Under Alternative 2A, the same number of CBM wells and the same volume of water production would be projected as under Alternative 1. Except for the differences in recharge that would occur based on differences in water handling options, (discussed below), the effects on groundwater resources would be similar to Alternative 1.

The recharge effect was evaluated in this analysis by examining the area of affected surface drainages and the probable range of vertical infiltration rates into the Wasatch Formation below the creeks and ponds. The total discharge from CBM operations would be managed according to the water handling options identified for each sub-watershed under Alternative 2A. Depending on the water handling practices used within each sub-watershed under Alternative 2A, an estimated 28 to 43 percent of the water pumped would be recharged to the shallow groundwater system as a result of infiltration along creeks and below impoundments.

The net recharge is calculated based on the percentage of the produced water handled by each method and its associated estimated percentage recharge (Section 4.5.2 and Table 4-4). The calculated net recharge volume, on a year-by-year basis, was divided by the projected CBM development area within each sub-watershed to obtain an equivalent recharge rate in inches per year (Table 7-1). This infiltration has been characterized as areal recharge, considering the scale and limited detail in the analysis. This recharge under Alternative 2A is compared below with the values input into the model under Alternative 1.

Alternative 2A involves different methods of handling the water produced by CBM operations in certain sub-watersheds. The proportion of water handled by infiltration impoundments and injection would be emphasized under Alternative 2A. Under Alternative 2A, a smaller amount CBM produced water would be discharged to surface drainages than under Alternative 1. More CBM produced water would be handled using infiltration impoundments, containment impoundments, land application disposal (LAD), and injection than under Alternative 1. In addition, there would be a 5 percent reduction from Alternative 1 under Alternative 2A in the produced water handled using LAD in the Crazy Woman Creek sub-watershed, with a corresponding increase in the produced water handled by infiltration impoundments and injection. In the Salt Creek sub-watershed, surface discharge would be eliminated and replaced by increased use of other water handling methods — in particular, infiltration impoundments and injection.

The difference in water handling methods generally results in an increase in infiltration at the ground surface compared with Alternative 1. This increase would be small, with some sub-watersheds (Antelope Creek, Upper Cheyenne River, and Upper Belle Fourche River) showing small decreases. Increases in infiltration of between 12 and 28 percent would occur in the Salt Creek, Upper Powder River, Crazy Woman Creek, Clear Creek, Middle Powder River, and Little Powder River sub-watersheds compared with Alternative 1. Under Alternative 2A, this projected increase in surface infiltration would

Table 7-1
Annual Recharge Rate Projected by Sub-Watershed (2002 to 2017) Under Alternative 2A

(Recharge rate applied to developed CBM areas [inches per year])

Sub-watershed	Developed Area (acres)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Upper Tongue River	10,246,277	0.231	0.315	0.415	0.474	0.507	0.539	0.552	0.596	0.594	0.574	0.513	0.464	0.369	0.295	0.210	0.126
Upper Powder River	78,184,723	0.339	0.447	0.527	0.581	0.623	0.645	0.641	0.577	0.515	0.448	0.377	0.295	0.197	0.105	0.071	0.046
Salt Creek	298,848	0.034	0.034	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Crazy Woman Creek	11,776,274	0.214	0.353	0.459	0.543	0.599	0.651	0.679	0.610	0.536	0.480	0.396	0.325	0.247	0.168	0.122	0.079
Clear Creek	17,828,989	0.147	0.217	0.284	0.352	0.412	0.462	0.480	0.486	0.481	0.476	0.412	0.350	0.283	0.224	0.164	0.101
Middle Powder River	6,818,630	0.335	0.354	0.372	0.385	0.377	0.327	0.263	0.288	0.295	0.299	0.274	0.245	0.211	0.175	0.134	0.082
Little Powder River	13,350,050	0.366	0.362	0.354	0.360	0.329	0.301	0.238	0.242	0.247	0.247	0.220	0.198	0.164	0.133	0.100	0.071
Antelope Creek	11,399,624	0.171	0.188	0.212	0.226	0.241	0.245	0.243	0.231	0.222	0.208	0.187	0.164	0.132	0.096	0.078	0.059
Upper Cheyenne River	5,660,490	0.234	0.220	0.207	0.190	0.179	0.156	0.155	0.145	0.131	0.115	0.110	0.076	0.059	0.030	0.030	0.030
Upper Belle Fourche River	35,874,382	0.317	0.307	0.297	0.292	0.287	0.267	0.230	0.220	0.210	0.202	0.185	0.164	0.137	0.088	0.074	0.060

Note: Recharge rates shown include average recharge from precipitation of 0.03 inches per year and projected recharge resulting from water handling methods.

be a small fraction of an inch per year in the various sub-watersheds. These small changes would have a negligible effect on groundwater conditions within these drainages. The percentage of water managed by injection into aquifer units below the coal zone would increase in the Crazy Woman Creek and Salt Creek sub-watersheds..

7.2 Projected Impacts Under Alternative 2B

Under Alternative 2B, the same number of CBM wells and the same volume of water production would be projected as under Alternative 1. Except for the differences in recharge that would occur based on differences in water handling options, (discussed below), the effects on groundwater resources would be similar to Alternative 1.

The recharge effect was evaluated in this analysis by examining the area of affected surface drainages and the probable range of vertical infiltration rates into the Wasatch Formation below the creeks and ponds. The total discharge from CBM operations would be managed according to the water handling options identified for each sub-watershed under Alternative 2B. Depending on the water handling practices used in each sub-watershed under Alternative 2B, an estimated 21 to 30 percent of the pumped water would be recharged to the shallow groundwater system as a result of infiltration along creeks and below impoundments.

The net recharge is calculated based on the percentage of the produced water handled by each method and its associated estimated percentage recharge, as described in Section 4.5.2 and summarized in Table 4-5. The calculated net recharge volume, on a year-by-year basis, was divided by the projected CBM development area within each sub-watershed to obtain an equivalent recharge rate, in inches per year (Table 7-2). This infiltration has been characterized as areal recharge, considering the scale and limited detail in the analysis. This recharge under Alternative 2B is compared below with the values input into the model under Alternative 1.

Alternative 2B involves different handling of the water produced by CBM operations in certain sub-watersheds. An upper limit would be set for the proportion of water handled by infiltration impoundments under Alternative 2B, and active treatment for CBM-produced water would be included as a water handling method. Under Alternative 2B, a smaller amount of CBM produced water would be discharged to surface drainages than under Alternative 1. More CBM produced water would be handled using infiltration impoundments, containment impoundments, LAD, and injection than under Alternative 1. In addition, there would be a 5 percent reduction under Alternative 2B from Alternative 1 in the produced water handled using LAD in the Crazy Woman Creek sub-watershed, with a corresponding increase in the produced water handled by infiltration impoundments and injection. In the Salt Creek sub-watershed, surface discharge would be eliminated and replaced by increased use of other water handling methods — in particular, infiltration impoundments and injection.

The difference in water handling methods for Alternative 2B generally results in a small change in infiltration at the ground surface compared with Alternative 1. The changes in infiltration associated with Alternative 2B are generally small, with the largest increases in infiltration occurring in the Crazy Woman Creek, and Middle Powder River sub-watersheds. The Upper Tongue River, Salt Creek, Antelope Creek, Upper Cheyenne River, and Upper Belle Fourche River sub-watersheds show small decreases in infiltration of up to 6 percent. Under Alternative 2B, this projected increase in infiltration would

Table 7-2
Annual Recharge Rate Projected by Sub-Watershed (2002 to 2017) Under Alternative 2B

(Recharge rate applied to developed CBM areas [inches per year])

Sub-watershed	Developed Area (acres)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Upper Tongue River	10,246,277	0.174	0.235	0.306	0.349	0.373	0.395	0.405	0.436	0.435	0.421	0.376	0.341	0.273	0.220	0.159	0.099
Upper Powder River	78,184,723	0.254	0.333	0.391	0.430	0.460	0.476	0.473	0.427	0.381	0.333	0.281	0.222	0.151	0.085	0.059	0.041
Salt Creek	298,848	0.033	0.033	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Crazy Woman Creek	11,776,274	0.150	0.240	0.309	0.364	0.401	0.435	0.453	0.408	0.359	0.323	0.268	0.222	0.171	0.120	0.090	0.062
Clear Creek	17,828,989	0.112	0.160	0.207	0.254	0.296	0.331	0.344	0.348	0.345	0.341	0.296	0.253	0.206	0.166	0.123	0.080
Middle Powder River	6,818,630	0.269	0.284	0.298	0.309	0.302	0.263	0.212	0.232	0.237	0.240	0.221	0.199	0.172	0.143	0.112	0.071
Little Powder River	13,350,050	0.237	0.235	0.230	0.234	0.215	0.197	0.158	0.161	0.164	0.164	0.147	0.134	0.113	0.094	0.073	0.055
Antelope Creek	11,399,624	0.150	0.165	0.186	0.198	0.211	0.215	0.212	0.202	0.195	0.182	0.165	0.145	0.117	0.086	0.071	0.054
Upper Cheyenne River	5,660,490	0.205	0.193	0.182	0.167	0.158	0.138	0.137	0.128	0.117	0.103	0.098	0.069	0.054	0.030	0.030	0.030
Upper Belle Fourche River	35,874,382	0.317	0.307	0.297	0.292	0.287	0.267	0.230	0.220	0.210	0.202	0.185	0.164	0.137	0.088	0.074	0.060

Note: Recharge rates shown include average recharge from precipitation of 0.03 inches per year and projected recharge resulting from water handling methods.

average a small fraction of an inch per year in the various sub-watersheds. These small changes would have a negligible effect on groundwater conditions within these drainages. The percentage of water managed by injection into aquifer units below the coal zone would increase in the Crazy Woman and Salt Creek sub-watersheds.

7.3 Projected Impacts Under Alternative 3

Alternative 3 (No Action) assumes that no new federal CBM wells would be completed, except for in areas of potential drainage. Water handling options would be same as under Alternative 1 and would result in a substantial reduction in projected new CBM wells, from 39,367 to 15,458. Except for the differences discussed below, the effects on groundwater resources would be similar to Alternative 1.

Under Alternative 1, the largest numbers of new federal CBM wells would be drilled in the Upper Powder River and Upper Belle Fourche River sub-watersheds (24,898 of 39,367 projected wells under Alternative 1). The exclusion of federal wells from these sub-watersheds under Alternative 3, represents a 77 percent reduction in the Upper Powder River sub-watershed (14,531 wells) and a 43 percent reduction in the Upper Belle Fourche River sub-watershed (2,531 wells). The percentage reduction in wells also would be great in the Middle Powder River sub-watershed, where the reduction would be 79 percent (or 757 wells). More than 1,000 wells also would be eliminated in each of the following sub-watersheds: Crazy Woman Creek (1,986 wells); Clear Creek (1,265 wells); Little Powder River (1,076 wells); and Antelope Creek (1,041 wells). Relatively lower percentage reductions in wells would occur in the Upper Tongue River sub-watershed (17 percent) and in the Clear Creek sub-watershed (34 percent).

Water handling options would be the same as under Alternative 1. Depending on the water handling practices used within each sub-watershed, an estimated 15 to 33 percent of the groundwater produced from CBM operations would recharge the coal zone aquifer or higher aquifer units (Table 4-1).

Although water production would decline substantially in all sub-watersheds under Alternative 3, the percentage reduction in water production would be less than the percentage reduction in wells, compared with Alternative 1. Under Alternative 3, individual wells would yield more water to maintain sufficient drawdown and allow methane to be produced. Water produced was not modeled under Alternative 3.

The extent of drawdown in the coal units would also change. The greatest change would occur in the sub-watersheds with the largest percentages of federal wells. The areal extent of the 25-foot drawdown contour would tend to decrease in areas where large concentrations of federal wells were projected to be drilled under Alternative 1, for example in the Upper Powder River and Upper Belle Fourche River sub-watersheds. It is less likely that state and fee wells would be completed around the large undeveloped federal blocks unless there would be enough wells to maintain adequate drawdown and produce methane.

The volume of produced water that would recharge shallow bedrock and alluvium would diminish proportionately with the decline in water production. The areal extent of recharge would be reduced to exclude areas that would have contained new federal CBM wells, such as in the Upper Powder River, Upper Belle Fourche River, and Crazy Woman Creek sub-watersheds.The extent of drawdown in the coals would be considerably less as a result of the lack of development under Alternative 3, resulting in less drawdown in the overlying Wasatch sands within areas that would have contained high concentrations of federal wells under Alternative 1.

8.0 CABALLO CREEK SUB-AREA MODEL

The Caballo Creek sub-area model was constructed to aid in establishing criteria for the regional model and to evaluate the potential impacts of CBM development that are more reasonably assessed at a smaller scale than the regional model. As with the regional model, the VMODFLOW program (v.3.0) was used to complete pre-processing, modeling, and post-processing, including zone water budgets.

The Caballo Creek area has been extensively developed for coal and coalbed methane and has a long history of groundwater monitoring that extends back to the late 1970s. Mining started in 1974 at the Belle Ayr mine and was followed closely by the Caballo, Cordero, and Rojo Caballo mines in the late 1970s and early 1980s. The Cordero and Rojo Caballo mining operations have since been merged. CBM operations have been active in this area since about 1992, when the Marquiss field was initially developed by Martens and Peck. Groundwater level data have been collected in the vicinity of these CBM operations at several nested BLM monitoring wells since early 1993. Earlier groundwater monitoring data are available from the Belle Ayr, Caballo, and Cordero mines. As a result, the Caballo Creek area provides a unique opportunity to model the influences of nearly complete CBM development where sufficient monitoring well data provide good calibration points.

8.1 Model Grid and Layering

The area of the Caballo Creek sub-area model is shown in Figure 8-1. Table 8-1 summarizes the model setup and assumptions. The model grid (Figure 8-1) consists of 62 cells in the north-south direction (rows) and 108 cells in the east-west direction (columns), for a total of 6,696 cells per layer. The grid spacing is uniform throughout the model and is one-quarter mile (about 400 meters) in both the north-south and east-west directions. The uniform grid spacing allows for easier manipulation of the model in ArcView, Surfer, and Access, while maintaining the integrity of the model. The model grid was set up in the NAD27 UTM Zone 13 meters coordinate system.

The model was constructed with 11 layers, as summarized in Table 8-2. Model layers 1 through 6 represent the Wasatch Formation, and layers 7 through 11 represent the upper part of the Fort Union Formation. A typical cross-section through the model is shown in Figure 8-2.

The top of the uppermost layer (layer 1) is the topographic surface. This surface was constructed from downloaded 1:250,000 USGS DEMs for the Caballo Creek area. The x,y,z data from the DEMs were extracted into a .dat file using Surfer software. The extracted .dat files were combined, and the coordinates were converted from Lat/Long to the NAD27 UTM Zone 13 meters coordinate system using Tralaine software. Surfer was used to grid this file at one-quarter mile spacing using the "Natural Neighbor" algorithm. The grid file was then imported into VMODFLOW as the surface of layer 1 (Figure 8-2).

The uppermost layer (layer 1) represents the surface geologic units that include shallow Wasatch geologic units (claystone, siltstone and sandstone) and unconsolidated alluvial sands within creek valleys. This layer was assigned a uniform thickness of 30 feet (10 meters). The hydrologic properties within this layer were varied to reflect the different characteristics of the geologic units within this layer (Table 8-1).

Table 8-1
Summary of Caballo Creek Model Setup and Assumptions

Project	Powder River Basin (PRB) Oil& Gas Environmental Impact Statement (EIS) - Powder River Basin Groundwater Impacts
Area	Caballo Creek Drainage Basin, Powder River Basin in northeast Wyoming
Code	MODFLOW-96. Pre- and post-processor: VMODFLOW v.3.0
Time modeled	Steady State: 1975 (Pre-mining); Transient State: 1975 to 2200
Dimensions	X = 43.2 Km, Y = 24.8 Km (10,713.6 Km^2, 4,131.3 sq. miles)
X coords	437,711 – 480,911 meters
Y coords	4,871,087 – 4,895,887 meters
Coordinates	North American Datum (NAD)27 Universal Transverse Mercator (UTM) Zone 13, meters
Rows, columns	No. of rows: 62 No. of columns: 108 (6,696 cells/layer)
Grid spacing	400 meters x 400 meters (¼ mile x ¼ mile) for the entire model
Layers/type	No. of layers: 11. Layer 1: Unconfined: Layers 2-11 Variable T, S
Surfaces	**Coal surfaces and isopachs:** Goolsby, Finley, and Associates: 2001 **Steady-state potentiometric surface:** Modified after Daddow 1986, BLM Well Data, RAG Belle Ayr Mine Monitoring well data **Surface topography:** U.S. Geological Survey (USGS) Digital Elevation Models
Geology	**Coal Units:** Goolsby, Finley, and Associates (2001) **Surface Geology:** USGS: "National Coal Resource Assessment, 1999 Resource Assessment of Selected Tertiary Coal Beds and Zones in the Northern Rocky Mountains and Great Plains Region" (USGS 1999a)
No-flow Boundaries	Each layer has a different no-flow boundary area that is determined by the formation the layer represents.
Drains	Regional groundwater flow to discharge areas beyond the model boundaries, such as the Powder River, was simulated using drain nodes in layers 7 through 11 at the northwestern "no-flow" boundary.
Recharge	Basin-wide infiltration: 0.025 inches per year Clinker infiltration: 0.21 inches per year
Rivers (constant head)	**Intermittent Rivers**: The lower part of Caballo Creek was set as drain nodes with the surface elevation minus 3m as the drain node elevation.
Coal Mines and CBM Wells	**Mine plans and locations**: Wyoming Department of Environmental Quality (WDEQ) and Office of Surface Mining (OSM) annual reports from mining companies; Gillette Area Groundwater Monitoring Organization (GAGMO) 15-year report. **CBM Wells:** Input as drain nodes. Existing CBM wells taken from the Wyoming Oil and Gas Conservation Commission (WOGCC) database dated 7/20/01. Projected coal bed methane (CBM) wells were developed by the Bureau of Land Management (BLM), WOGCC, Greystone, and Applied Hydrology Associates (AHA) with input from CBM industry representatives.
Solver	Steady-state: WHS (Waterloo hydrologic solver); Transient-state: WHS.

Table 8-2
Caballo Creek Model Layers

Model Layer	Geologic Formation/Member	Geologic Unit	Predominant Lithologies
1	Wasatch Formation	Upper Wasatch Formation and Alluvium	Sandstone, siltstone, claystone
2, 3		Shallow Wasatch Unit	Sandstone, siltstone, claystone
4		Intermediate Wasatch Unit	Sandstone, siltstone, claystone
5		Deep Wasatch Unit	Sandstone, siltstone, claystone
6		Confining unit at base of Wasatch Formation	Siltstone, claystone
7	Fort Union Formation	Upper Fort Union Coal (Unit 1)	Coal (minor sandstone, siltstone)
8		Confining unit between coal units	Siltstone, claystone
9		Upper Fort Union Coal (Unit 2)	Coal (minor sandstone, siltstone)
10		Confining unit at base of coal units	Siltstone, claystone
11		Lower Fort Union sand aquifer units	Sandstone, siltstone

Layers 2 through 5 represent zones of the Wasatch Formation where discontinuous sandstone units occur. The discontinuous nature of the sandstone units is difficult to accurately simulate. However, this simulation was attempted by assigning hydrologic parameters to these layers that represent mixed sandstones and siltstone/claystone.

The lowermost layer (layer 6) within the Wasatch Formation represents claystones that act as a confining unit between the underlying coal zone of the Fort Union Formation and the discontinuous sandstones within the Wasatch Formation. This layer was set at a uniform thickness of 30 feet (10 meters) above the top of the upper Fort Union Formation coal zone. The vertical permeability of this layer in any location reflects its ability to act as a confining unit between the Fort Union coal zone and the overlying deep Wasatch sandstones. The assigned thickness of this unit influences the rate of leakage from the discontinuous sandstone unit layers (primarily layer 5). However, varying the vertical permeability assigned to the layer in any area can effectively be used to compensate for variations in thickness since the leakage is proportional to the product of the thickness and the vertical hydraulic conductivity.

Layers 7 through 11 represent the upper part of the Fort Union Formation. The top and bottom surfaces of the two coal-bearing hydrogeologic units of the upper Fort Union Formation that occur in this area, represented by layers 7 and 9, were created from unpublished data compiled and consolidated by Goolsby, Finley and Associates for the modeling effort. As the coal-bearing units split and merge, the hydraulic properties assigned to the layers representing coal-bearing units and intervening units change accordingly. The coal-bearing units transition into more highly permeable clinker in outcrop areas.

The east-west cross-section in Figure 8-2 shows the model layer setup and the variability in the thickness of model layers. The different colors within individual layers indicate specific hydraulic conductivities assigned and no-flow zones that are described in subsequent sections.

Figure 8-1 Caballo Creek Model Area and Grid

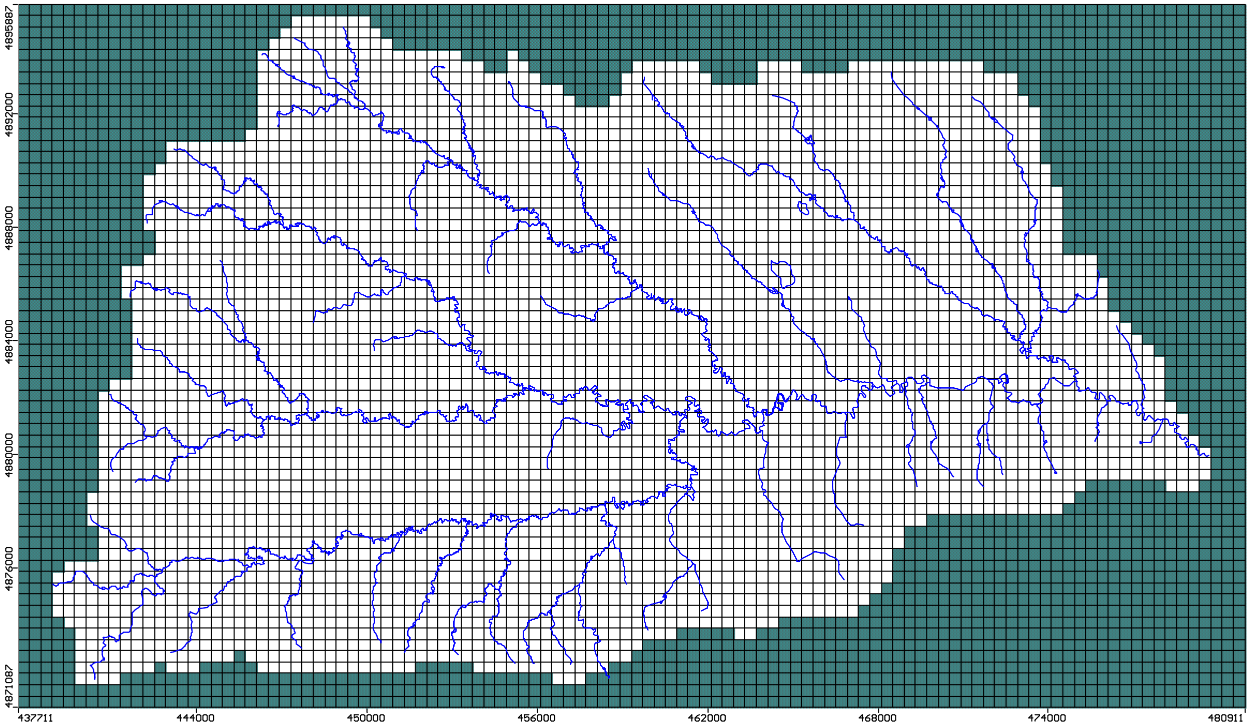
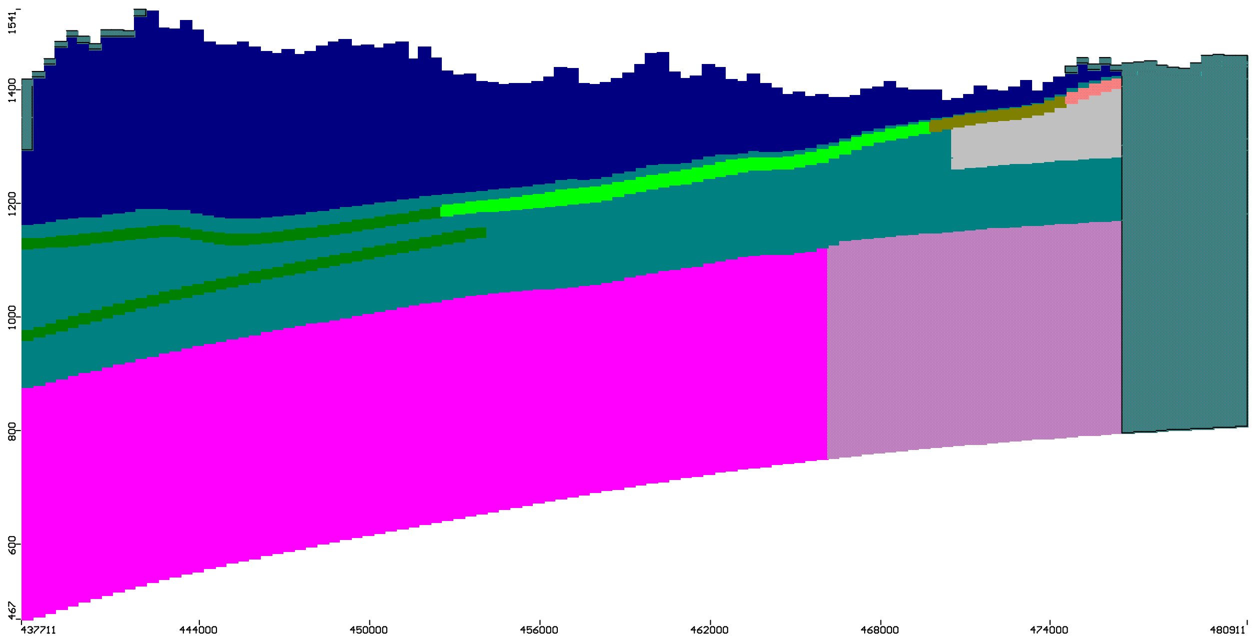


Figure 8-2
Caballo Creek Model - Typical East-West Cross-Section



8.2 Boundary Conditions

Boundary conditions used in the Caballo Creek model include no-flow and drains (rivers, mines, CBM wells, and model outflow).

No-flow cells were assigned to the model grid that was outside the area of the outcrop for the geologic units represented by each model layer. The extent of no-flow cells varies for each layer. Use of no-flow cells helps mitigate the effects of layer displacement caused by minimum thickness. The no-flow cell configuration was identical for some layers, but in general, fewer no-flow cells surrounded the active area with increasing depth of the layer. Recharge was applied to the highest active cell so, in effect, the highest active cell acts as if it were at ground surface. The extent of no-flow cells is shown in Figure 8-1.

No-flow cells were also designated in river areas where the river elevation was below the base of any given layer. Some of the fingers along the coal outcrop were also set as no-flow because they contribute little to the regional flow system but can cause considerable difficulty when attempting to achieve convergence of the model.

Interaction between rivers and adjacent shallow aquifers is simulated in the model by drain nodes along the lower portion of Caballo Creek. The head set in the drain nodes was based on the topographic elevation of the river at each node location.

Active surface coal mining is simulated in the model by setting drain nodes in the coal layer at appropriate locations. Groundwater will enter an active drain node from an adjacent node as long as the potentiometric level in the adjacent node is higher than the elevation of the drain.The rate of drainage decreases as the potentiometric elevation in the adjacent node is lowered by drainage. Drain nodes can be made inactive by setting the drain elevation much higher than the potentiometric elevation of the adjacent node. Unlike constant head nodes or general head nodes, drain nodes will not add water to adjacent nodes in this condition. The use of drain nodes to simulate surface mining allows the water levels to recover when active mined areas are backfilled and reclaimed.

The mining sequence was simulated from reasonably foreseeable mine plans for geographic locations projected to be mined as incremental impacts in 1-year stress periods from approximately 1975 (the earliest mining along the PRB outcrop in this area) to 2021. Each drain node is activated only during the period of active mining in the area represented by the node, typically set at 3 years. After this period, the drain node is made inactive, which simulates backfilling and reclamation of a pit area after active mining ends. The location and timing of drain nodes simulate past and future mining based on historical mining records and life of mine plan maps included in mining permit applications and 5-year mining plan updates. The water level in a drain node in an active mine area is set a few feet above the bottom elevation of the coal layer.Each drain node is input individually because the elevation of the coal bottom varies.

Drain nodes were also set along the western and northern boundaries of the model to allow regional groundwater flow to continue to the northwest if prevailing head gradients indicate that this flow would occur. Drain elevations were set based on steady-state, pre-development calibration data.

8.3 Recharge

The Caballo Creek area receives between 10 and 12 inches of precipitation per year (USDC/NOAA, 1979). The Caballo Creek drainage is naturally ephemeral. Groundwater aquifers recharge from infiltration of direct precipitation (rain and snowmelt), runoff in creek valleys, and standing water in playas, reservoirs, and stock ponds.

Precipitation provides a minimal source of recharge over most of the area because the climate and surface features restrict significant infiltration. Only a small percentage of the available precipitation infiltrates, while the majority runs off. Area-wide recharge, which includes recharge in creek valleys and ponds, expressed over the entire area, is expected to be less than 1 percent of the total precipitation, on average. This rate would be equivalent to less than 0.12 inches per year. Steady-state calibration indicated that this amount of area-wide recharge appears to be realistic. A value of 0.025 inches per year was indicated by the steady-state calibration. This value is similar to the recharge rate of 0.03 inches per year established from steady-state calibration of the regional model.

Infiltration is significant where surface geologic units are more permeable, such as in alluvial valleys and clinker that occur along the eastern outcrop area of the upper Fort Union coal zone. The clinker areas are generally considered to form recharge areas for the coal. However, although the clinker provides good potential for infiltration, the rate of recharge to the coal may be limited by the presence of a low-permeability zone at the contact between the clinker and the underlying coal or shale. Thick, clay-rich soils over flatter surfaces also may retain the downward movement of water (Heffern and Coates 1999).

Pre-mining potentiometric data and interpretations from many of the permit applications for coal mines tend to support the potential for clinker recharge to the coal, but the rate of recharge is relatively low. Recharge in the clinker areas is expected to be between 2 and 5 percent of the total precipitation, or equivalent to between 0.2 to 0.5 inches per year. Steady-state calibration indicated that this amount of recharge in the clinker areas appears to be realistic. A value of 0.21 inches per year was indicated by the steady-state calibration.

8.4 CBM Wells

The model simulates active CBM wells by setting pumping wells in the appropriate coal layer at the well locations. The location and reported pumping rates of existing CBM wells over time were downloaded from the WOGCC database and were imported into the model. Future CBM operations are based on an assumed well life of 7 years.

8.5 Hydrologic Parameters

Several lithologies or conditions may be represented within any layer. A summary of the model input parameters assigned to the various geologic units in the model is shown in Table 8-3.For example, areas of different hydraulic conductivity representing clinker areas along the outcrop and fracture zones within the coal appear in the layers that represent the zone of the upper Fort Union Formation (layers 7 and 9). The results of multi-well pumping tests in the Caballo Creek area (Appendix B) were generally used as starting points for estimates of permeability in any area. Data for pumping tests in the coal, particularly single-well or short-term tests, may not represent regional permeabilities, which tend to be dominated by major fracture zones in the coal. Accordingly, the range of permeability values used in the model was based primarily on matching to steady-state and transient-state conditions.

Table 8-3
Summary of Model Input Parameters for Caballo Creek

Formation	Model Layer	$K_{x,y}$ (ft/s)	K_z (ft/s)	S_s (1/ft)	S_Y (unitless)	Porosity (%)
Alluvium	1,2,3,4,5,6,7	.0003	3E-5	0.00003	0.2	25
Wasatch Discontinuous sands	2,3,4,5	1E-6 to 3E-6	2.5E-9 to 3E-7	2.4E-5	0.15	20
Wasatch Confining	6	3E-10	6E-11	1.5E-5	0.005	10
Upper Fort Union Coals	7,9	5E-6 to 1E-4	5E-7 to 4E-5	2.1E-6 to 7.9E-5	0.0005 to 0.004	1
Upper Fort Union Confining	8,9,10	3E-10	6E-11 to 1E-10	1.5E-5	0.005	10
Lower Fort Union Tullock	11	1E-6 to 2E-5	1E-7 to 2E-7	1.5E-5	0.01	20
Scoria	2,3,4,5,6	8E-5	1E-6	0.003	0.1	25

$K_{x,y}$ = hydraulic conductivity (horizontal)
K_z = hydraulic conductivity (vertical)
S_s = specific storage
S_y = specific yield

There are relatively few reliable data on storage coefficients in the PRB, but a compilation of values derived from multi-well pumping tests is included in Appendix B. The values for storativity used for the various model layers are summarized in Table 8-3. Storage coefficient values vary considerably, depending on whether the unit being tested is under confined or unconfined conditions. Most pumping tests conducted in the coal are considered to be under confined conditions. Storage coefficients derived from these pumping tests are in the range of 10^{-3} to 10^{-5}. The specific storage (S_s) (equivalent to the storage coefficient divided by the thickness) used for the coal ranged between $3.2x10^{-6}$ ft^{-1} and $6.4x10^{-6}$ ft^{-1}. Pumping tests conducted in the Wasatch sands may be under confined or unconfined conditions. Storage coefficients derived from these pumping tests are generally in the range of 10^{-2} to 10^{-4}. The specific storage derived from Wasatch sand tests averages $1.8x10^{-4}$ ft^{-1}.

8.6 Impacts of CBM and Mining on Groundwater Levels

The primary purpose of the Caballo Creek sub-area model was to provide good calibration data for the regional model within an area that has a long history of CBM development. The groundwater level drawdown in the developed coal unit (layer 7) for the year 2000 is shown in Figure 8-3. The modeled drawdown is reasonably consistent with actual drawdowns observed in BLM monitoring wells. Figure 8-4 shows the drawdown in the year 2000 for the deep Wasatch sandstone unit that overlies the developed coal. The sandstone is separated from the coal by as little as 40 feet of claystone.

A hydrograph that shows the modeled and actual drawdown in the developed coal and the overlying sandstone is shown in Figure 8-5. There has been extensive drawdown of more than 250 feet in the coal in the area of the BLM MP-22 monitoring well nest as a result of CBM pumping over the past 8 years. Drawdown in the sandstone has been apparent only in the past 3 to 4 years and is currently about 20 feet. Matching of model-projected drawdowns to actual drawdowns over an extended period provided the best information on the vertical permeability of the claystone confining layer that separates the coal from the overlying sandstone.

Figure 8-3 Drawdown of Groundwater Levels in Coal – Year 2000

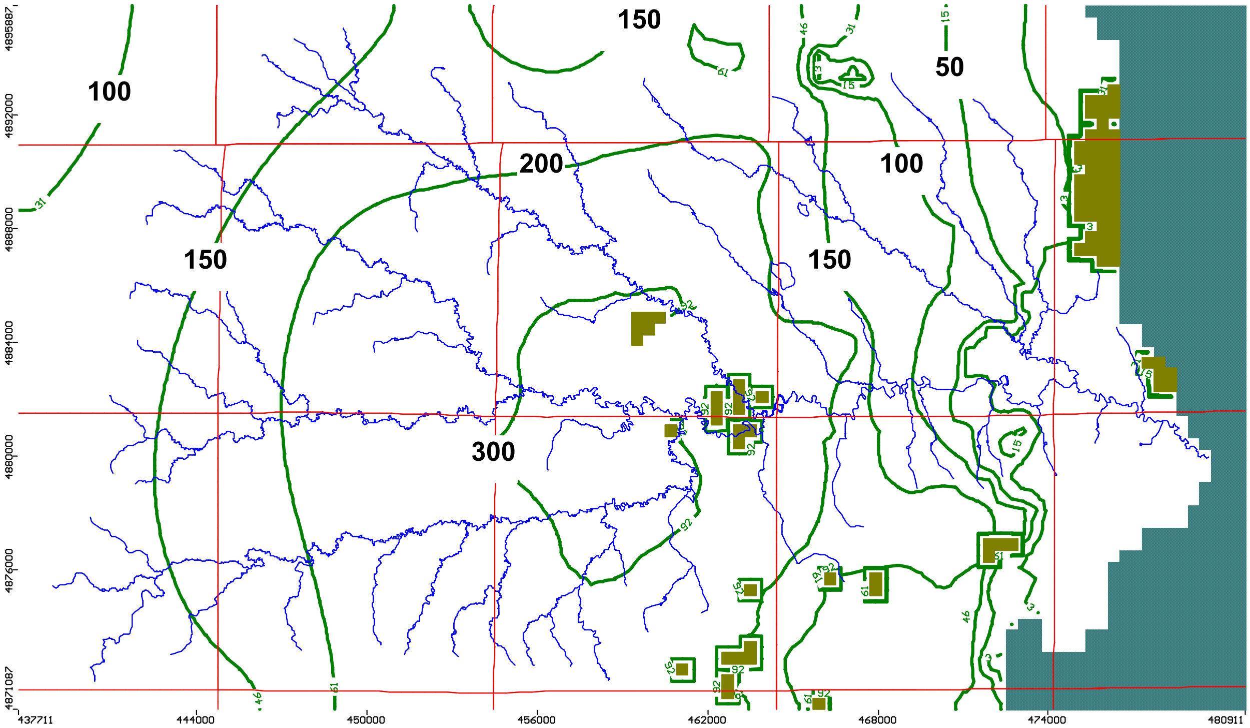


Figure 8-4 Drawdown of Groundwater Levels in Deep Wasatch Sandstone – Year 2000

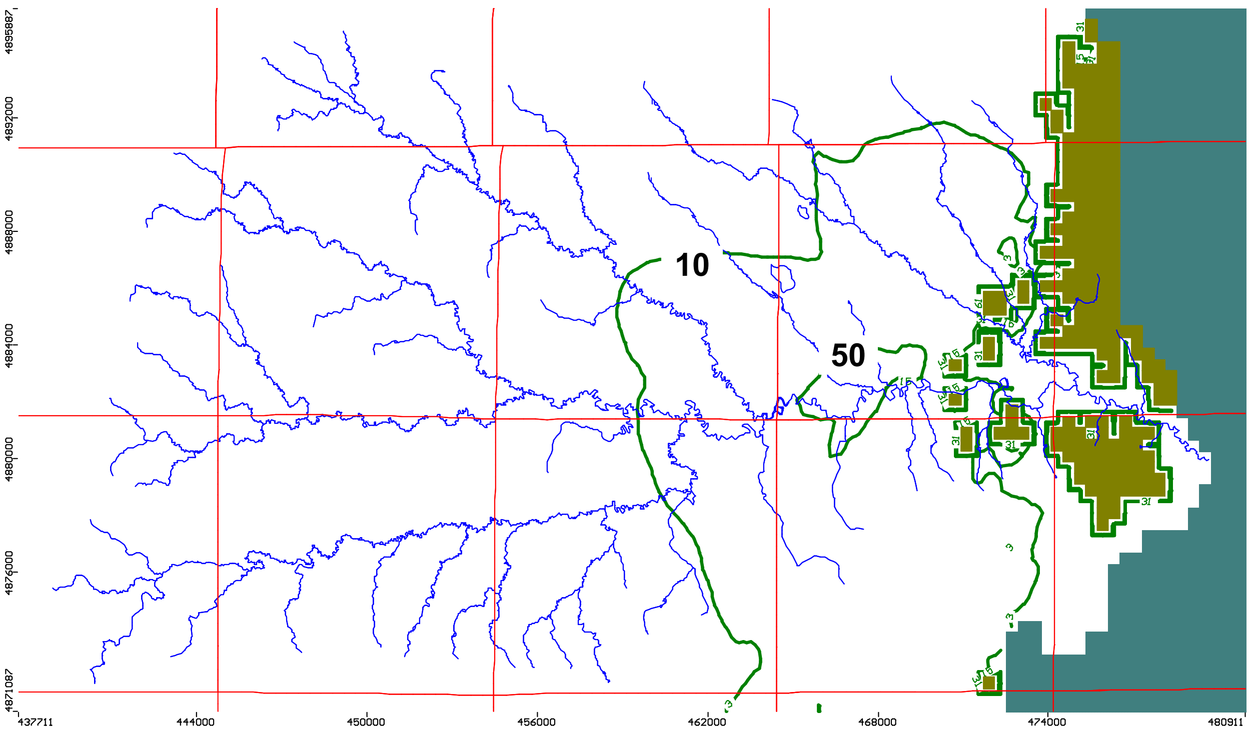
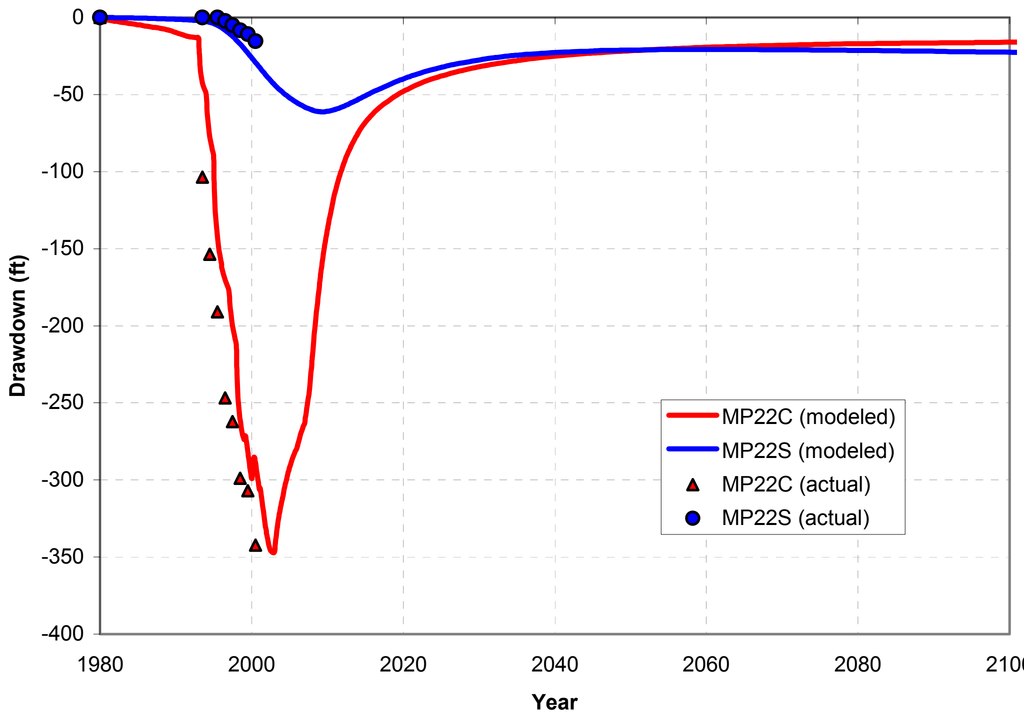


Figure 8-5 Modeled and Actual Hydrographs of Groundwater Levels in Coal and Sandstone



9.0 LX BAR SUB-AREA MODEL

The LX Bar sub-area model was constructed primarily to evaluate the potential issues associated with extensive use of infiltration impoundments rather than direct discharge to handle CBM produced water. This type of impact analysis is more reasonably conducted at a smaller scale than the regional model. As with the regional model, the VMODFLOW program (v.3.0) was used to complete pre-processing, modeling, and post-processing, including zone water budgets.

Impoundments have seen increased use as a method of water handling in areas where direct discharge into creeks is discouraged, mainly as a result of concerns with the quality of CBM produced water that may affect downstream use for irrigation. Impoundments are used extensively for CBM discharges in the sub-watersheds of the Powder, Little Powder, and Tongue Rivers. Infiltration impoundments provide water for livestock and wildlife use and for artificial recharge of groundwater. Infiltration impoundments are designed to accommodate all the CBM produced water by infiltration to groundwater or evaporation with little or no discharge to surface waters. Some infiltration impoundments may be designed to allow surface discharge during storm water runoff events, however.

The major concerns regarding the use of infiltration impoundments are release of water that leaks from these impoundments into adjacent creeks, increasing flows in creeks that are downgradient of impoundments. This leakage could occur as seeps above low-permeability subsurface geologic units that may cause perched groundwater conditions. Alternatively, infiltration may increase shallow groundwater levels that may, in turn, cause increased discharge to adjacent creeks. The shallow groundwater table in ephemeral drainages is typically below the bottom of the creek bed, so that groundwater does not discharge to the creek and, in fact, creek flows recharge the groundwater.

The LX Bar drainage basin is an ephemeral system that is tributary to the Powder River in Townships 56 and 57 North and Ranges 75, 76 and 77 West. The area has not been extensively developed for coal bed methane, but CBM operators in the area likely would not be allowed to discharge to LX Bar Creek because of concerns that involve water quality. This area was selected for modeling because it is typical of a drainage basin that will likely see complete CBM development (assumed 80-acre spacing for two coal seams) and will use infiltration impoundments as its primary water handling method.

9.1 Leakage Rates for Infiltration Impoundments

The rate of leakage from an impoundment is largely controlled by the permeability of the soils and shallow geologic materials that directly underlie the impoundment, and by the amount of head in the impoundment. The proportion of water that infiltrates versus the proportion that evaporates is site-specific and varies seasonally. It is expected that most impoundments would be constructed in fine-textured soils ranging from clay loam to sandy loam. Infiltration impoundments would not be constructed on shale or clay soils where clay content is greater than 40 percent and infiltration rates would be low. Most infiltration impoundments would be constructed in upland areas that are not within alluvial deposits, within headwater drainages, and on valley terraces. Some infiltration impoundments may, however, be constructed in valley bottoms where the depths to groundwater are shallow.

Infiltration rates have been estimated at two impoundments within the PRB using water balance considerations.

The BLM completed a water balance study of Brown Reservoir (Meyer 2000b), which is located within the Dry Fork of Willow Creek. The water balance was performed between April 1 and July 31, 2000. The study found that infiltration rates during this 4-month period were essentially constant and averaged 0.077 feet per day (ft/day) or 27.6 feet per year (ft/yr). Evaporation increased from April through July, with an equivalent rate of approximately 0.015 ft/day or 5.5 ft/yr. Infiltration represented 84 percent of water loss from the reservoir during the study period, while evaporation accounted for 16 percent. Since this average is somewhat larger than estimates of annual lake evaporation rates in the vicinity, it is thought that the actual infiltration rate would average more than 84 percent over an entire year.

A seepage rate of 26.5 feet per year has been estimated for the K-Bar closed basin, located in Section 25, T44N R74W, based on water balance measurements taken over a 10-month period from January 1 through October 31, 1999 (NPDES Permit WY0037435). The water balance over this period indicates 90 percent seepage loss and 10 percent evaporation loss. The soils at the K-Bar closed basin are classified as an Ulm clay loam. The K-Bar seepage estimates were confirmed using a one-dimensional unsaturated flow model for a clay loam soil. The unsaturated flow parameters for the clay loam soil were obtained from the U.S. Soil Salinity Laboratory, Rosetta database. The results of the model projected that a steady-state seepage rate of 33 to 34 ft/yr could be sustained in a typical clay loam soil with a surface impoundment head of 4.92 feet.

9.2 Model Grid and Layering

The area of the LX Bar model is shown in Figure 9-1. A summary of the model setup and assumptions is provided in Table 9-1. The model grid consists of 146 cells in the north-south direction (rows) and 177 cells in the east-west direction (columns), for a total of 25,842 cells per layer. The grid spacing is uniform throughout the model and is 500 feet in both north-south and east-west directions within the active area of the model. The model grid was set up in the NAD27 UTM Zone 13 meters coordinate system. The active model area is shown in Figure 9-2.

Figure 9-1 Location of LX Bar Model Study Area

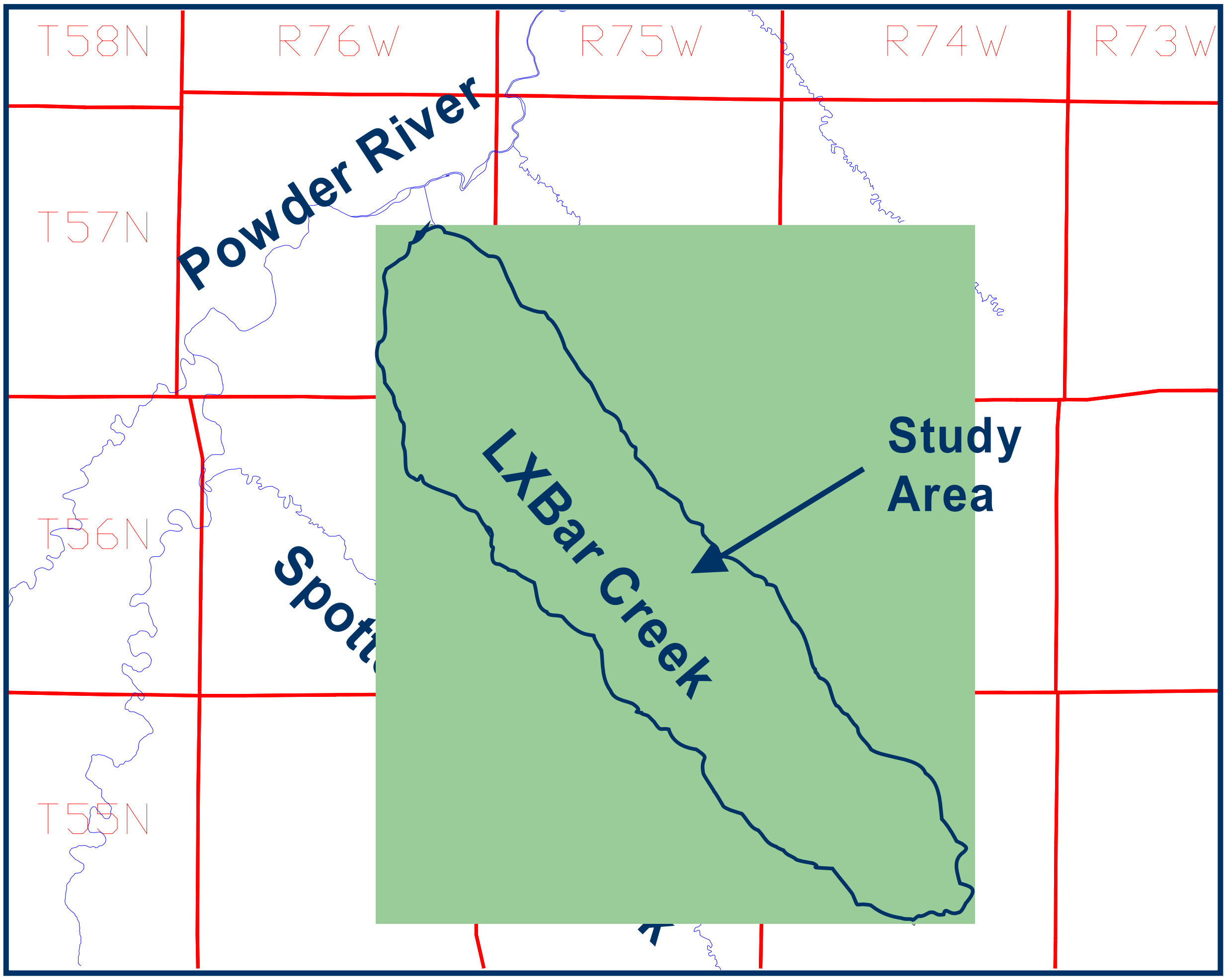


Table 9-1
Summary of LX Bar Model Setup and Assumptions

Project	Powder River Basin (PRB) Oil& Gas Environmental Impact Statement (EIS) - Powder River Basin Groundwater Impacts
Area	LX Bar Drainage Basin, Powder River Basin in northeast Wyoming
Code	MODFLOW-96. Pre- and post-processor: VMODFLOW v.3.0
Time modeled	Steady State: (Pre-development); Transient State: 40 years
Dimensions	X = 140,000 ft, Y = 120,000 ft (602.6 sq. miles)
X coords	0 – 140,000 ft
Y coords	0 – 120,000 ft
Coordinates	North American Datum (NAD)27 Universal Transverse Mercator (UTM) Zone 13, meters
Rows, columns	No. of rows: 177 No. of columns: 146 (25,842 cells/layer)
Grid spacing	500 ft x 500 ft (~0.1 mile x 0.1 mile) within the active area of the model
Layers/type	No. of layers: 13. Layer 1: Unconfined: Layers 2-13 Variable T, S
Surfaces	**Coal surfaces and isopachs:** Forney, 2001; Goolsby, Finley, and Assoc. 2001; WOGCC: 2001; Olive, 1957. **Surface topography:** U.S. Geological Survey (USGS) Digital Elevation Models (DEMs)
Geology	**Coal Units:** Forney 2001; Goolsby, Finley, and Associates (2001); Olive, 1957. **Surface Geology:** USGS: "National Coal Resource Assessment, 1999 Resource Assessment of Selected Tertiary Coal Beds and Zones in the Northern Rocky Mountains and Great Plains Region" (USGS 1999a)
No-flow Boundaries	The LX Bar Creek drainage basin, and a two-mile reach of the Powder River opposite the confluence with LX Bar Creek, is the active area for the model
General Head	Regional groundwater flow to discharge areas beyond the model boundaries, such as the Yellowstone River, were simulated using general head nodes in layers 7, 11, and 13 at the northern "no-flow" boundary.
Recharge	Basin-wide infiltration: 0.04 inches per year LX Bar Creek infiltration: 0.6 inches per year Infiltration Impoundments: 72 inches per year for 10 yrs (max. life of CBM well)
Rivers (drain nodes)	Discharge of groundwater to the Powder River and the main channel of LX Bar Creek; Rivers were simulated by drain nodes with an elevation of the surface elevation minus about 5ft.
CBM Wells (drains)	**CBM Wells:** Input as drain nodes in the Canyon Coal (Layer 7). Projected CBM wells based on 80-acre spacing. Full development over the entire drainage area.
Solver	Steady-state: WHS (Waterloo hydrologic solver); Transient-state: WHS.

Table 9-2
LX Bar Model Layers

Model Layer	Geologic Formation/Member	Geologic Unit	Predominant Lithologies
1	Wasatch Formation	Upper Wasatch Formation	Sandstone, siltstone, claystone
2		Confining unit at base of Wasatch Formation	Siltstone, claystone
3	Fort Union Formation	Anderson Coal	Coal
4		Confining unit between coal units	Siltstone, claystone
5		Fort Union Sandstone	Sandstone, siltstone
6		Confining unit between coal units	Siltstone, claystone
7		Canyon Coal	Coal
8		Confining unit between coal units	Siltstone, claystone
9		Fort Union Sandstone	Sandstone, siltstone
10		Confining unit between coal units	Siltstone, claystone
11		Cook Coal	Coal
12		Confining unit between coal units	Siltstone, claystone
13		Wall Coal	Sandstone, siltstone

Figure 9-2 LX Bar Model Area and Grid

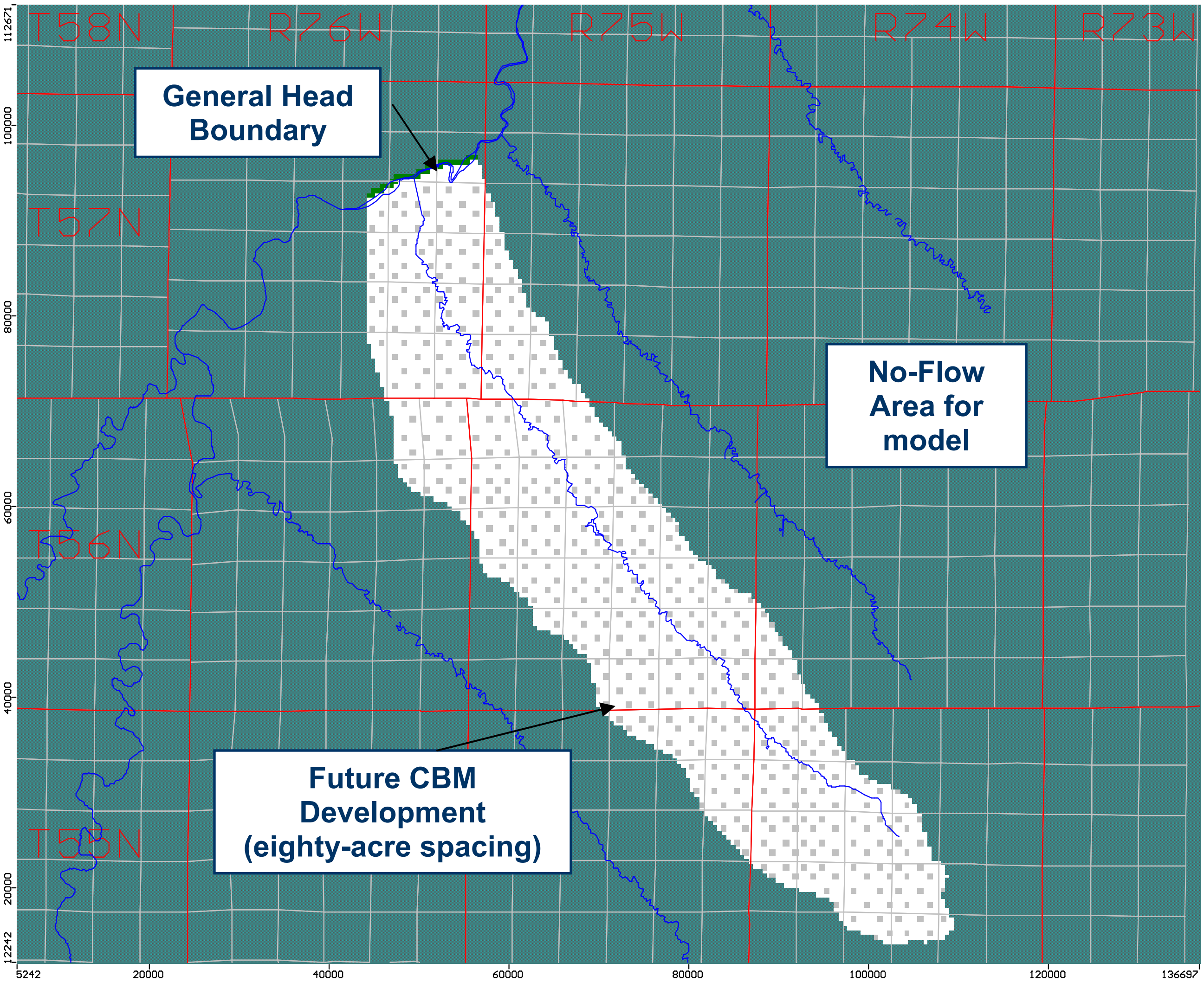
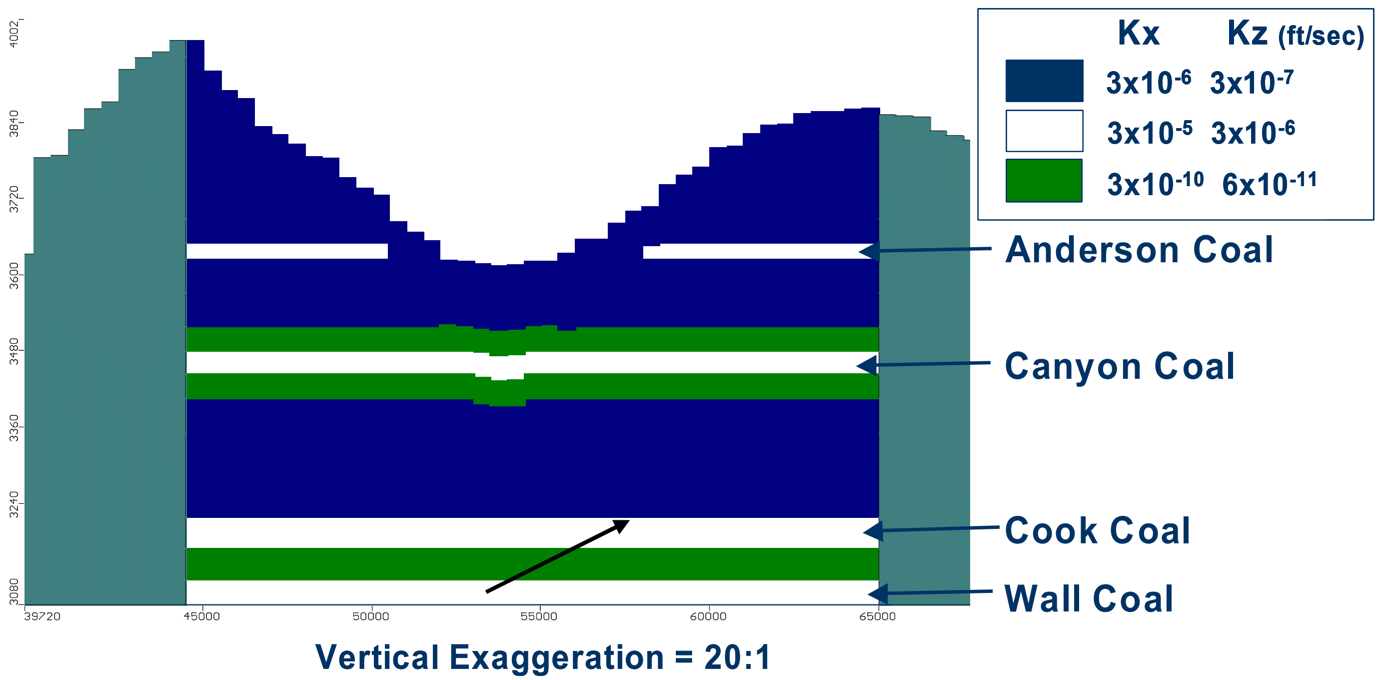


Figure 9-3 LX Bar Model - Typical East-West Cross-Section



Model layers 1 and 2 represent the shallow geologic units that are in the Wasatch Formation in the southeast part of the model area but represent the upper part of the Fort Union Formation in the northwestern part of the area. This distinction occurs because the valleys of LX Bar Creek and the Powder River cut down into the Fort Union Formation to the northwest. The uppermost layer (layer 1) represents the surface geologic units that include claystone, siltstone, and sandstone. This layer was assigned a variable thickness that ranged from 30 feet to 150 feet. The hydrologic properties within this layer were varied to reflect the different characteristics of the geologic units within this layer (Table 9-3). The discontinuous nature of the sandstone units within this layer is difficult to accurately simulate in a model, even at a drainage basin scale. However, this simulation was attempted by assigning hydrologic parameters to these layers that are representative of mixed sandstones and siltstone/claystone.

Overlying the Fort Union coal zone is a layer (layer 2) that represents claystones that act as a confining unit between the coal zone and the shallower discontinuous sandstones. This layer was set at a uniform thickness of 40 feet above the top of the coal zone in the upper portion of the Fort Union Formation. The vertical permeability and thickness of this layer in any location reflect its ability to act as a confining unit and influence the rate of leakage from the shallow discontinuous sandstone units in layer 1.

The major coal seams in the Fort Union Formation in this area are the Anderson, Canyon, Cook, and Wall, represented by layers 3, 7, 11, and 13. The average thicknesses of these seams, based on examination of drilling logs in this area, are 25 feet for layer 3, 45 feet for layer 7, 50 feet for layer 11,and 40 feet for layer13 (Table 9-3). The appropriate layers were assigned these thicknesses and representative coal properties. Similarly, the thicknesses of the intervals between the coal seams were averaged, and the model layers that represent these intervals reflect these values. In some cases, the interval between two coals was represented by several model layers (Table 9-3).

9.3 Boundary Conditions

Boundary conditions used in the LX Bar model include no-flow, general head (model outflow), and drains (Powder River, LX Bar Creek, and CBM wells). No-flow cells were assigned to the model grid that was outside the area of the outcrop for the geologic units represented by each model layer. The no-flow cell configuration was identical for all layers. The extent of no-flow cells is shown in Figure 9-2.

Interaction between rivers and shallow Wasatch sands is simulated in the model by drain nodes along the reach of the Powder River that cuts through the northwest corner of the model and the main channel of LX Bar Creek. The head set in the drain nodes was based on the topographic elevation of the river at each node location. Drain nodes were also used to simulate CBM wells. These are described in Section 9.4.

General head nodes were designated along the western and northern boundaries of the model to allow regional groundwater flow to continue to the northwest if prevailing head gradients indicate that this flow would occur. General head elevations were set based on steady-state, pre-development conditions.

Table 9-3
Summary of Input Parameters for LX Bar Model

Formation	Model Layer	Thickness (ft)	$K_{x,y}$ (ft/s)	K_z (ft/s)	S_s (1/ft)	S_Y (unitless)
Wasatch Discontinuous sandstone	1	30 to 150	3×10^{-6}	3×10^{-7}	5×10^{-5}	0.1
Wasatch Discontinuous siltstone	1	30 to 150	3×10^{-7}	3×10^{-8}	5×10^{-5}	0.1
Wasatch Confining	2	40	3×10^{-10}	6×10^{-11}	3×10^{-6}	0.03
Upper Fort Union Anderson Coal	3	25	1×10^{-4}	3×10^{-6}	2×10^{-5}	0.005
Upper Fort Union Confining	4	55	3×10^{-10}	6×10^{-11}	3×10^{-6}	0.03
Upper Fort Union Discontinuous sandstone	5	50	3×10^{-6}	3×10^{-6}	5×10^{-5}	0.1
Upper Fort Union Confining	6	40	3×10^{-10}	6×10^{-11}	3×10^{-6}	0.03
Upper Fort Union Canyon Coal	7	35	1×10^{-4}	3×10^{-6}	2×10^{-5}	0.005
Upper Fort Union Confining	8	40	3×10^{-10}	6×10^{-11}	3×10^{-6}	0.03
Upper Fort Union Discontinuous sandstone	9,10	185	3×10^{-6}	3×10^{-6}	5×10^{-5}	0.1
Upper Fort Union Cook Coal	11	50	1×10^{-4}	3×10^{-6}	2×10^{-5}	0.005
Upper Fort Union Confining	12	50	3×10^{-10}	6×10^{-11}	3×10^{-6}	0.03
Upper Fort Union Wall Coal	13	40	1×10^{-4}	3×10^{-6}	2×10^{-5}	0.005

$K_{x,y}$ = hydraulic conductivity (horizontal)
K_z = hydraulic conductivity (vertical)
S_s = specific storage
S_y = specific yield

9.4 CBM Wells

Active CBM wells are simulated in the model by setting drain nodes at appropriate locations in the Canyon and Cook coal seams (layers 7 and 11). A CBM development scenario on an 80-acre spacing pattern was assumed for both coal seams (Figure 9-2). For simplicity, the CBM development was assumed to occur simultaneously and would last for 10 years. Groundwater will enter an active drain node from an adjacent node as long as the potentiometric level in the adjacent node is higher than the drain elevation.The water flow to the drain declines as the potentiometric head declines in the model nodes surrounding the drain to simulate the process that occurs in CBM production wells, where declines in production over time are typically observed.

Each drain node is activated for a 10-year period to simulate the period of active CBM operations. The water level in a drain node for an active CBM development area is set 16 feet above the top elevation of the highest coal unit being developed in that area. After all CBM production ceases in the node, the drain node is made inactive by setting the drain elevation above ground level, which allows the water level in the node to recover. The reported pumping rates of existing CBM wells over time were downloaded from the WOGCC database and were used to calibrate the drains that represent these wells in the model. The limited production data in this area suggest that the average pumping rate for a CBM well is equivalent to about 4 to 6 gpm.

9.5 Recharge

The LX Bar area receives between 10 and 12 inches of precipitation per year (USDC/NOAA 1979). The LX Bar drainage is naturally ephemeral. Groundwater aquifers recharge from infiltration of direct precipitation (rain and snowmelt), runoff in creek valleys, and standing water in playas, reservoirs, and stock ponds.

Precipitation provides a minimal source of recharge over most of the area because the climate and surface features restrict significant infiltration. Only a small percentage of the available precipitation infiltrates, while the majority runs off. Recharge during the short period when LX Bar Creek flows is probably significant but would be restricted to the area of the main creek channel. A value for infiltration of 0.6 inches per year was assigned to this restricted area. Area-wide recharge, which includes recharge in ponds and side tributaries to LX Bar Creek, expressed over the entire area, is expected to be less than 1 percent of the total precipitation, on average or equivalent to less than 0.12 inches per year. A value of 0.04 inches per year was assigned to this area. The assigned recharge value yielded a reasonable water table configuration when the model was run in steady state, reflecting conditions that existed before CBM development began.

It is assumed that infiltration impoundments would be used to accommodate the CBM produced water during the 10-year active life of the CBM development. Two infiltration impoundments per section, each with a surface area of 5.74 acres (500 feet by 500 feet) were assumed to be adequate to accommodate the average production from 16 CBM wells (8 wells per section in two coal seams). The impoundments were assumed to recharge the shallow groundwater at a rate of 72 inches per year over the entire 10-year period of CBM development. In addition to infiltration, evaporation from the impoundments would average about 42 inches per year. Neglecting storage within the reservoir, total infiltration and evaporation from each reservoir would be equivalent to about 34 gpm, or eight wells pumping an average of 4.2 gpm over the entire 10-year period of CBM development. In actuality, pumping rates from an individual well will probably be higher than the average at the beginning of its life cycle and will decline to rates much lower than the average after a few years of operation.

9.6 Hydrologic Parameters

A summary of the model input parameters assigned to the various geologic units in the model is shown in Table 9-3.Several lithologies or conditions may be represented within any layer. The range of permeability values used in the model was based primarily on typical values derived from pumping test data and the model calibration performed for the Caballo Creek area and the regional model (Appendix B).

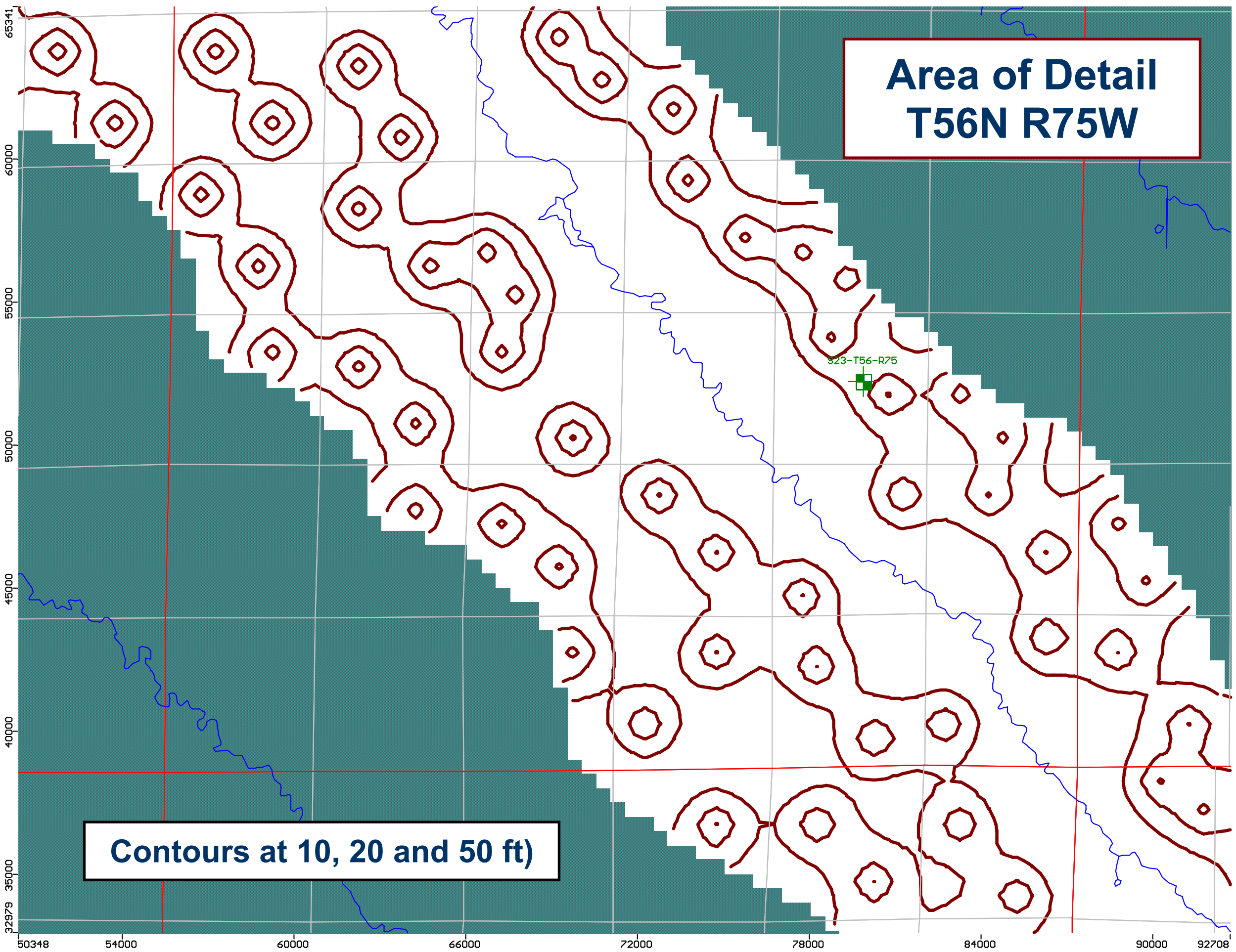
The values for storativity used for the various model layers are also summarized in Table 9-3. There are relatively few reliable data on storage coefficients in the PRB. Storage coefficient values vary considerably, depending on whether the unit tested is under confined or unconfined conditions. Most pumping tests conducted in the coal are considered to be under confined conditions. Storage coefficients derived from these pumping tests are in the range of 10^{-3} to 10^{-5}. The specific storage (S_s, equivalent to the storage coefficient divided by the thickness) used for the coal ranged between 2 x 10^{-5} ft^{-1} and 5 x 10^{-6} ft^{-1}. Pumping tests conducted in the Wasatch sands may be under confined or unconfined conditions. Storage coefficients derived from these pumping tests are in the range of 10^{-2} to 10^{-4}. The specific storage derived from Wasatch sand tests averages 1.8x10^{-4} ft^{-1}. The specific yield of the unconfined geologic units in the uppermost layer is assumed to be about 0.1, reflecting typical poorly consolidated sandstones and siltstones.

9.7 Effects of Infiltration Impoundments on Water Levels

A major focus of this modeling work was to assess the influence of continuous recharge from infiltration impoundments on groundwater levels in shallow Wasatch sands. Figure 9-4 shows the peak water level rise (build-up) in the shallow geologic units (layer 1) at the end of the 10-year development period. The recharge from the impoundments (at a rate of 6 ft/yr) results in a groundwater rise below ponds ranging from 20 to 50 feet for the case of impoundments that are built on sandy loam soils ($K_{x,y}$ = 3 x 10^{-6} ft/sec. K_z =3 x 10^{-7} ft/sec.). The storage within the pore spaces of the previously unsaturated geologic units accommodates much of the infiltrated water. However, the model results illustrate that infiltration impoundments that overlie Wasatch sands should preferably be sited in upland areas where the groundwater table is more than 50 feet below the land surface.

Higher recharge rates or lower vertical permeabilities could result in higher rises in the groundwater level. However, the recharge rate is linked to the permeability of the underlying soils, so that the rise in water level is self-limiting to some extent.

Figure 9-4 Projected Groundwater Rise in Shallow Wasatch Sands after 10 Years Caused by Recharge from Infiltration Impoundments



Notes:

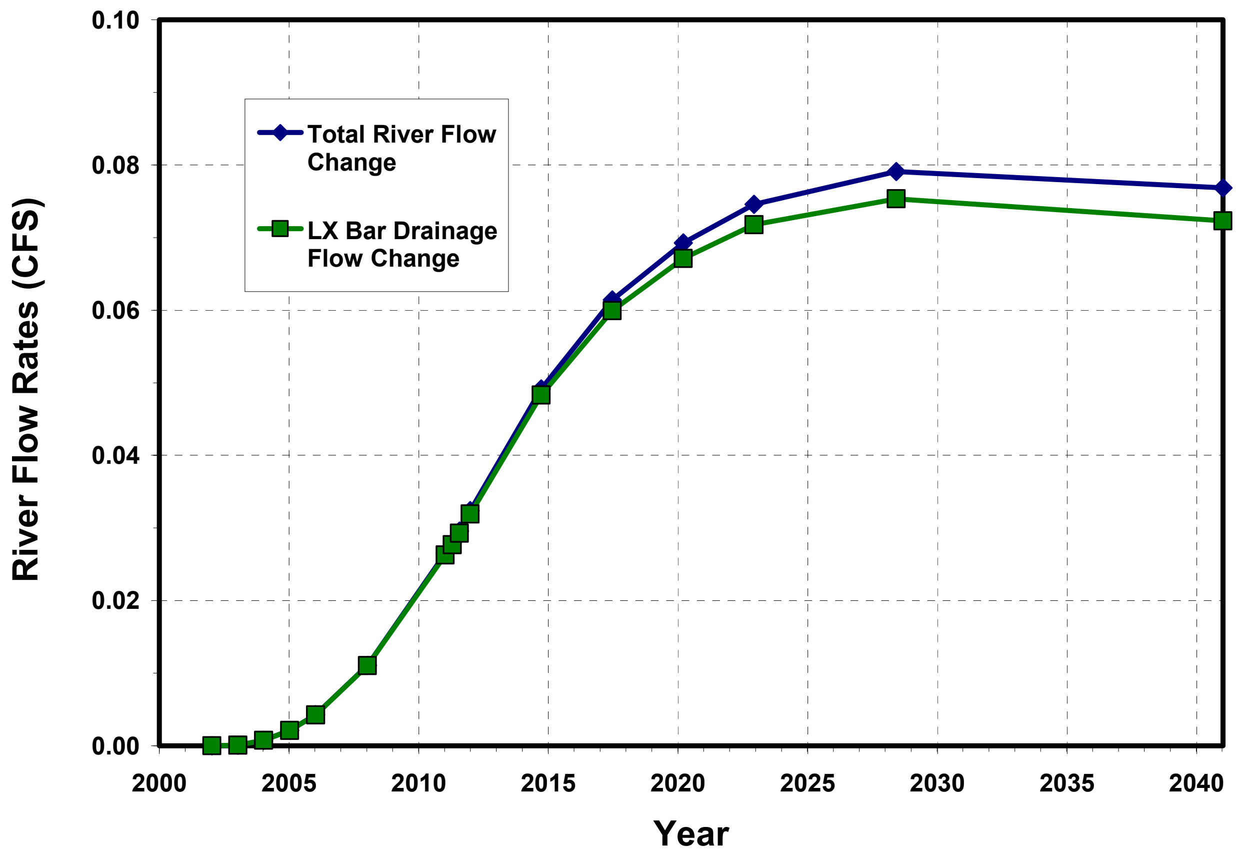
Sandy Loam Soils ($K_{x,y} = 3 \times 10^{-6}$ ft/sec. $K_z = 3 \times 10^{-7}$ ft/sec.)
Recharge from Impoundments (infiltration rate = 6 ft/yr)
(groundwater rise in shallow Wasatch sands below ponds ranges from 20 to 50 feet.

9.8 Effects of Infiltration Impoundments on Surface Flows

A second objective of this modeling was to assess the influence of continuous recharge from infiltration impoundments on surface flows in LX Bar Creek and the Powder River. Figure 9-5 shows that the increase in groundwater discharge to total surface flows (Powder River and LX Bar Creek) will peak at 0.08 cfs, equivalent to about 36 gpm. This increase in surface flow is almost entirely attributable to projected increased flows in the upper part of the LX Bar drainage as a result of higher groundwater levels. The increase in surface flows would be negligible compared with total flows in the Powder River.

Groundwater levels would subside slowly after infiltration from the impoundments ceases. As a result, the increases to surface flows peak some years after the CBM development period and slowly subside, as shown in Figure 9-5.

Figure 9-5 Projected Changes in River Flows Caused by Recharge from Infiltration Impoundments



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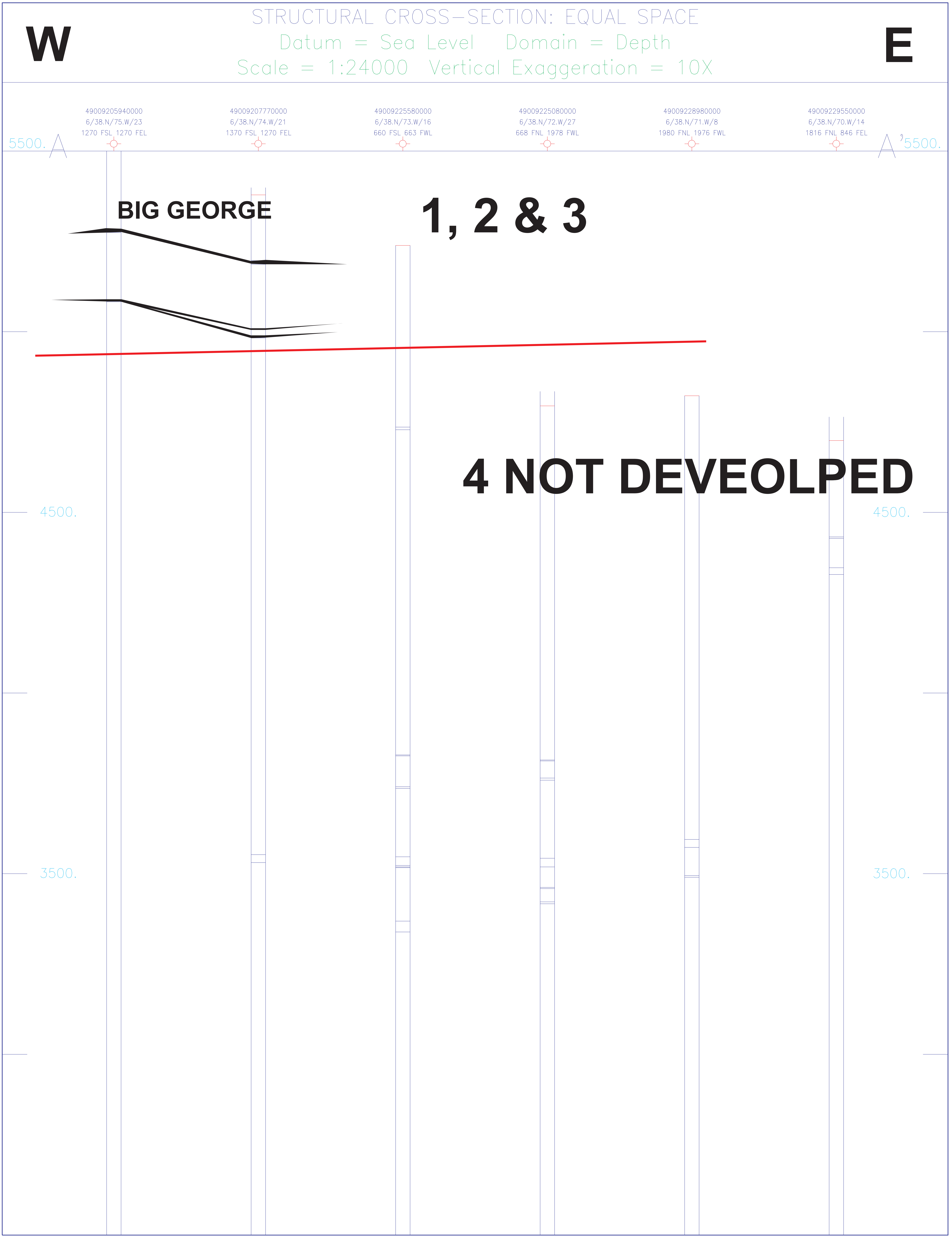
APPENDIX A

Powder River Basin Geologic Cross-Sections (Goolsby, Finley and Associates 2001)

Legend

Fort Union Formation Hydrogeological Groups (refer to Figure 2-2)

1 or Unit 1	**Group 1**
2 or Unit 2	**Group 2**
3 of Unit 3	**Group 3**
4 or Unit 4	**Group 4**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STRUCTURAL CROSS-SECTION: EQUAL SPACE
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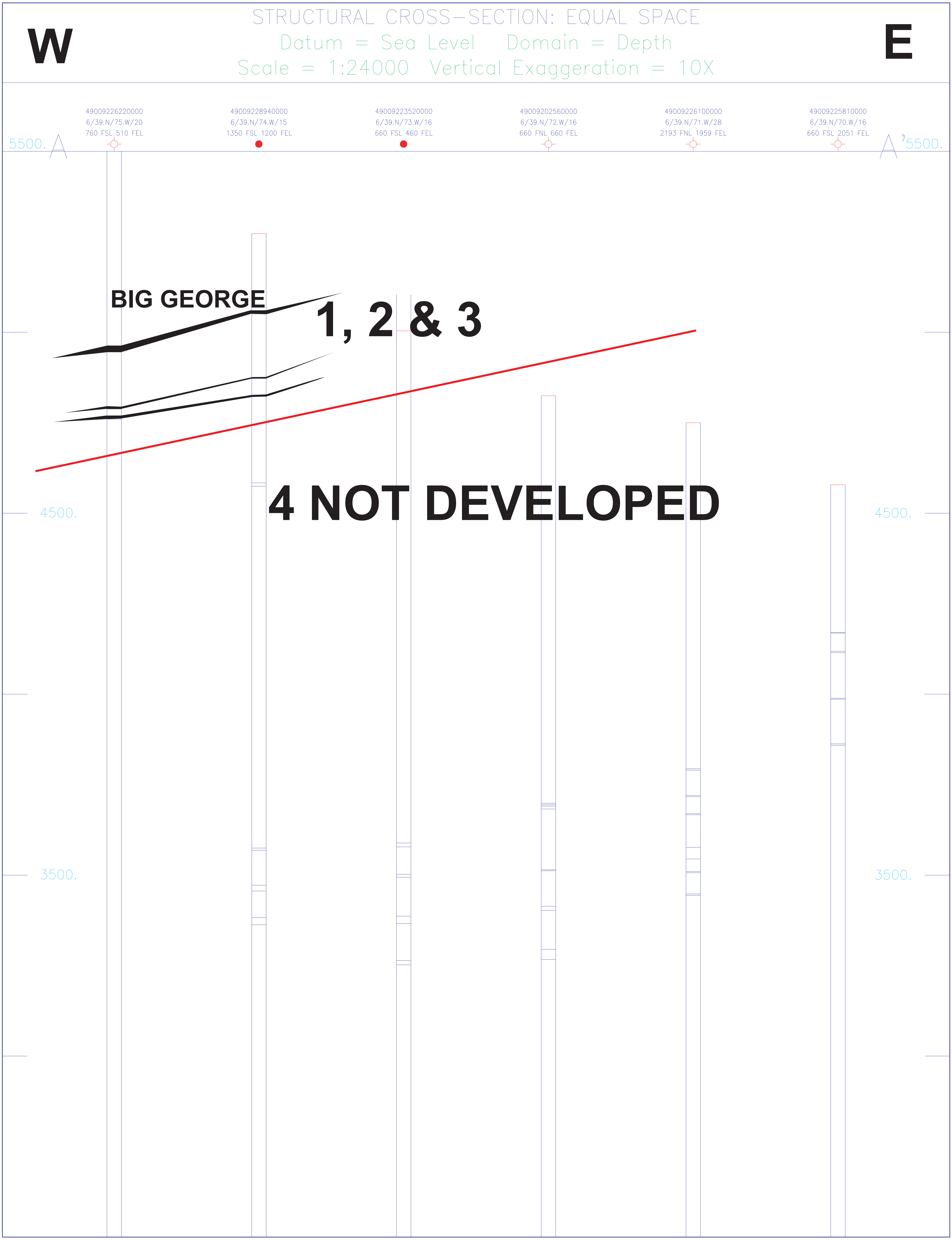
1270 FSL 1270 FEL
49009207770000
6/38.N/74.W/21
1370 FSL 1270 FEL
49009225580000
6/38.N/73.W/16
660 FSL 663 FWL
49009225080000
6/38.N/72.W/27
668 FNL 1978 FWL
49009228980000
6/38.N/71.W/8
1980 FNL 1976 FWL
49009229550000
6/38.N/70.W/14
1816 FNL 846 FEL
5500.
A
A'
5500.
BIG GEORGE
1, 2 & 3
4 NOT DEVEOLPED
4500.
4500.
3500.
3500.



W
E
STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
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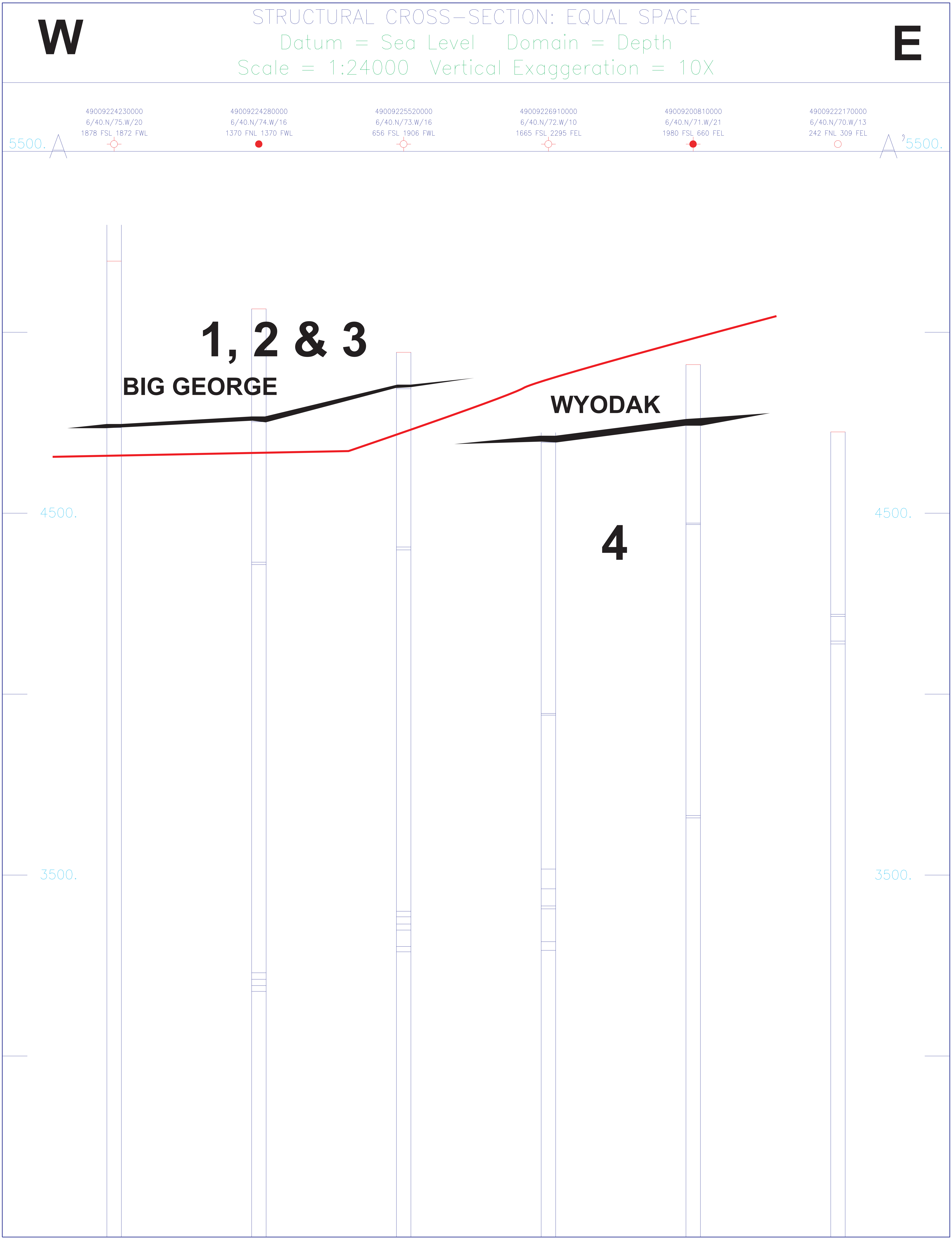
6/39.N/75.W/20
760 FSL 510 FEL
49009228940000
6/39.N/74.W/15
1350 FSL 1200 FEL
49009223520000
6/39.N/73.W/16
660 FSL 460 FEL
49009202560000
6/39.N/72.W/16
660 FNL 660 FEL
49009226100000
6/39.N/71.W/28
2193 FNL 1959 FEL
49009225810000
6/39.N/70.W/16
660 FSL 2051 FEL
5500.
A
A'
5500.
BIG GEORGE
1, 2 & 3
4 NOT DEVELOPED
4500.
4500.
3500.
3500.


W
STRUCTURAL CROSS—SECTION: EQUAL SPACE
Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
E
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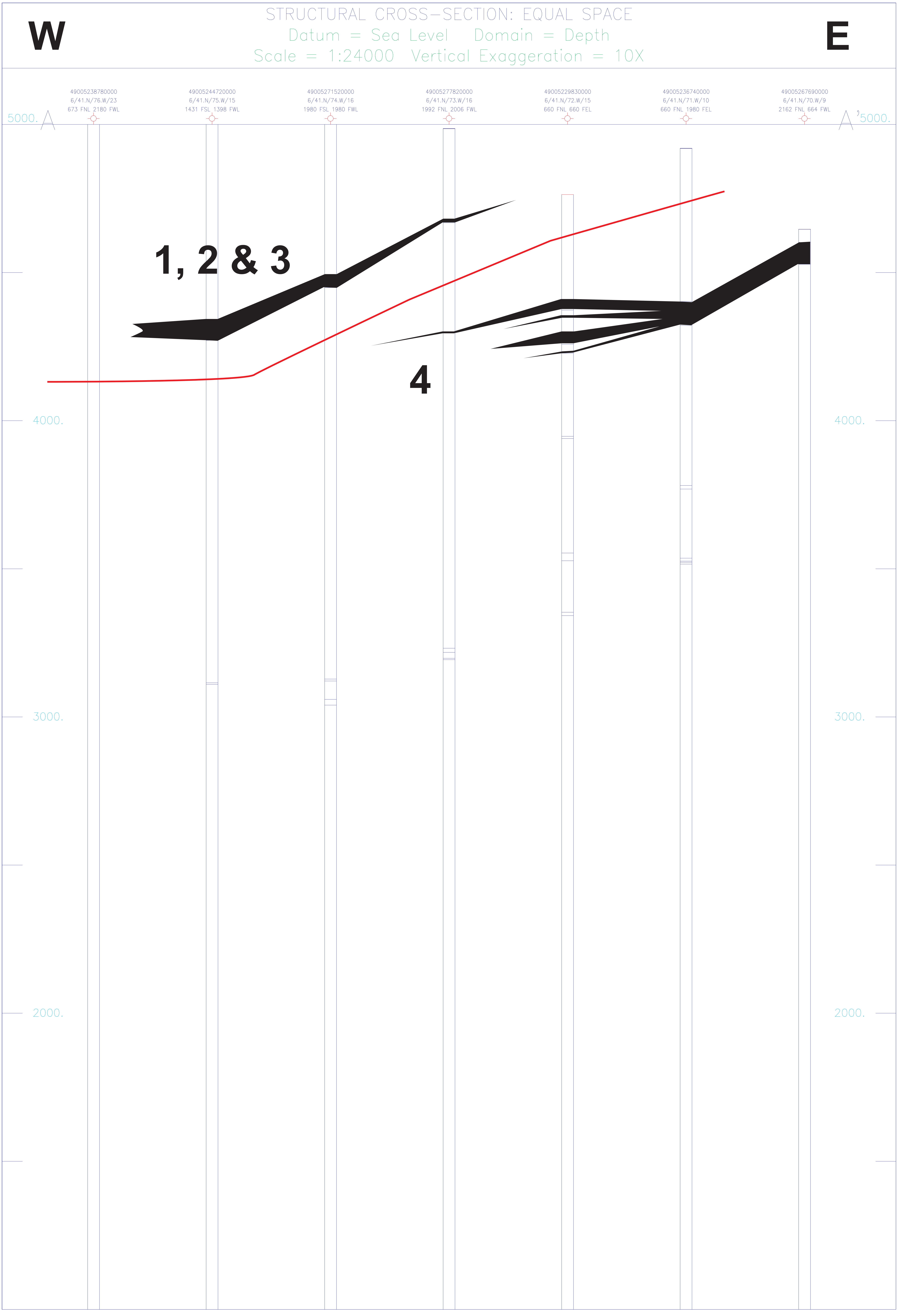
1878 FSL 1872 FWL
49009224280000
6/40.N/74.W/16
1370 FNL 1370 FWL
49009225520000
6/40.N/73.W/16
656 FSL 1906 FWL
49009226910000
6/40.N/72.W/10
1665 FSL 2295 FEL
49009200810000
6/40.N/71.W/21
1980 FSL 660 FEL
49009222170000
6/40.N/70.W/13
242 FNL 309 FEL
5500.
A
A'
5500.
1, 2 & 3
BIG GEORGE
WYODAK
4
4500.
4500.
3500.
3500.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673 FNL 2180 FWL
49005244720000
6/41.N/75.W/15
1431 FSL 1398 FWL
49005271520000
6/41.N/74.W/16
1980 FSL 1980 FWL
49005277820000
6/41.N/73.W/16
1992 FNL 2006 FWL
49005229830000
6/41.N/72.W/15
660 FNL 660 FEL
49005236740000
6/41.N/71.W/10
660 FNL 1980 FEL
49005267690000
6/41.N/70.W/9
2162 FNL 664 FWL
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A
A'
5000.
1, 2 & 3
4
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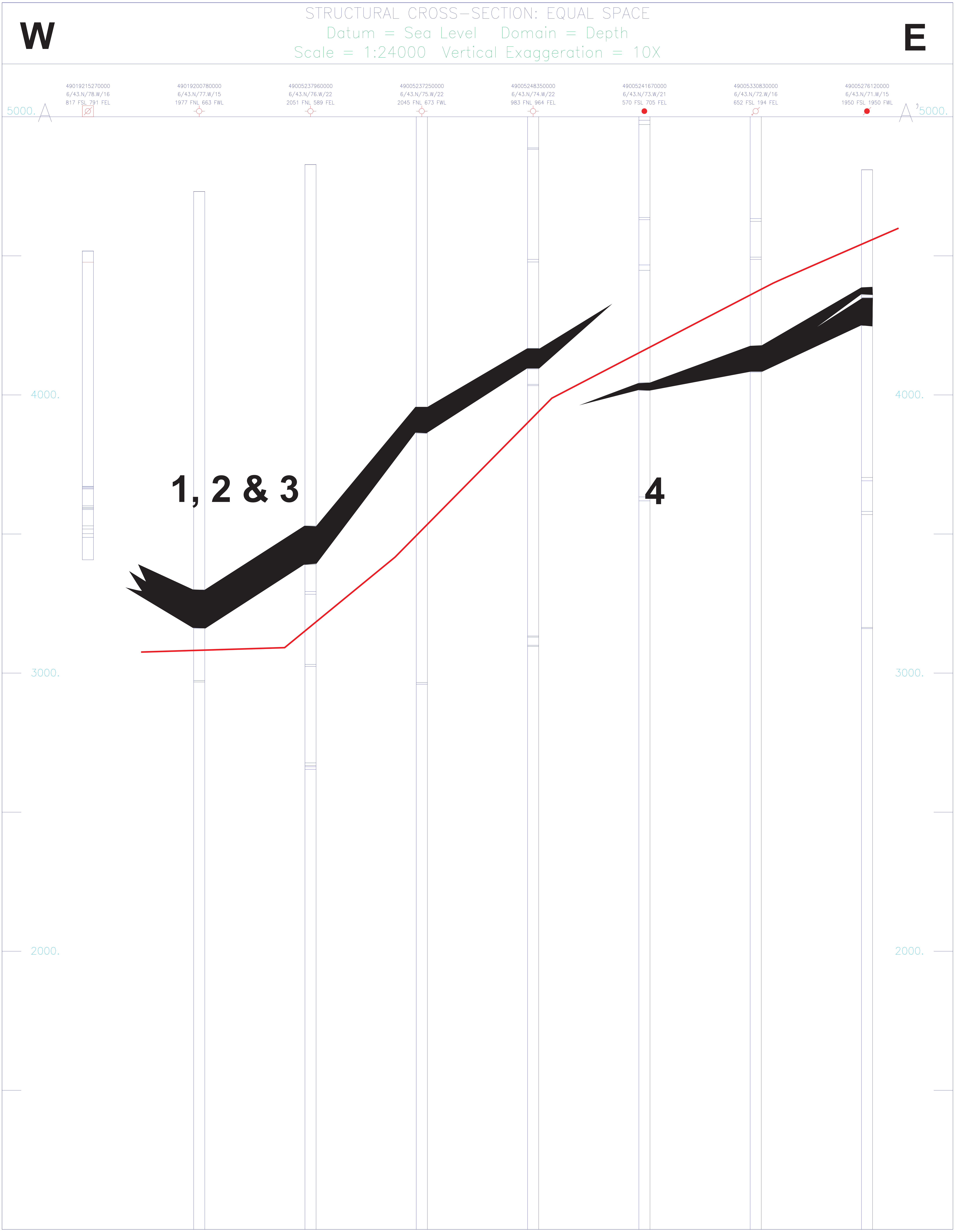
2000.
2000.



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Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
49019215270000
6/43.N/78.W/16
817 FSL 791 FEL
49019200780000
6/43.N/77.W/15
1977 FNL 663 FWL
49005237960000
6/43.N/76.W/22
2051 FNL 589 FEL
49005237250000
6/43.N/75.W/22
2045 FNL 673 FWL
49005248350000
6/43.N/74.W/22
983 FNL 964 FEL
49005241670000
6/43.N/73.W/21
570 FSL 705 FEL
49005330830000
6/43.N/72.W/16
652 FSL 194 FEL
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1950 FSL 1950 FWL
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A'
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1, 2 & 3
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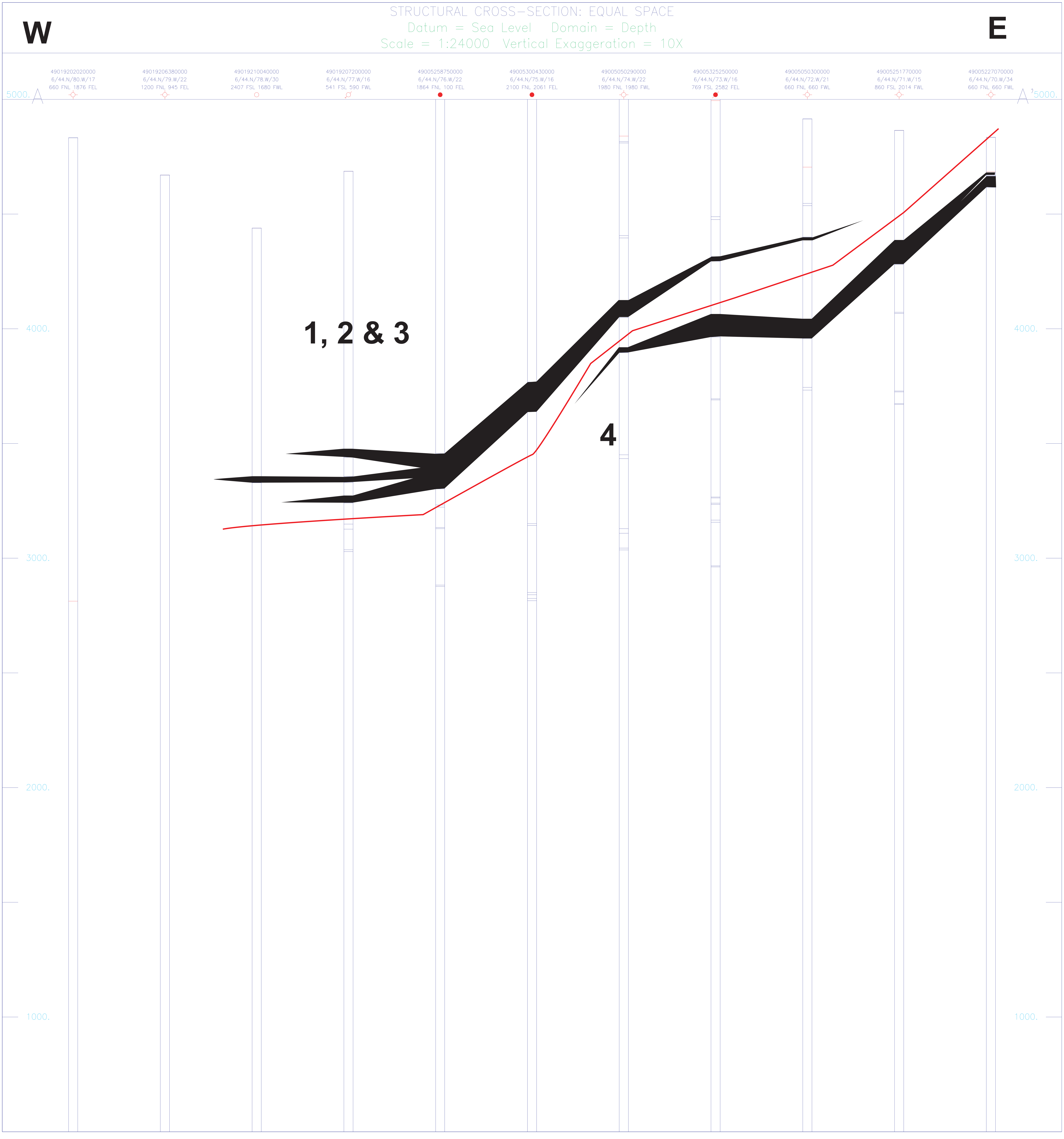
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660 FNL 1876 FEL
49019206380000
6/44.N/79.W/22
1200 FNL 945 FEL
49019210040000
6/44.N/78.W/30
2407 FSL 1680 FWL
49019207200000
6/44.N/77.W/16
541 FSL 590 FWL
49005258750000
6/44.N/76.W/22
1864 FNL 100 FEL
49005300430000
6/44.N/75.W/16
2100 FNL 2061 FEL
49005050290000
6/44.N/74.W/22
1980 FNL 1980 FWL
49005325250000
6/44.N/73.W/16
769 FSL 2582 FEL
49005050300000
6/44.N/72.W/21
660 FNL 660 FWL
49005251770000
6/44.N/71.W/15
860 FSL 2014 FWL
49005227070000
6/44.N/70.W/34
660 FNL 660 FWL
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A'
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3000.
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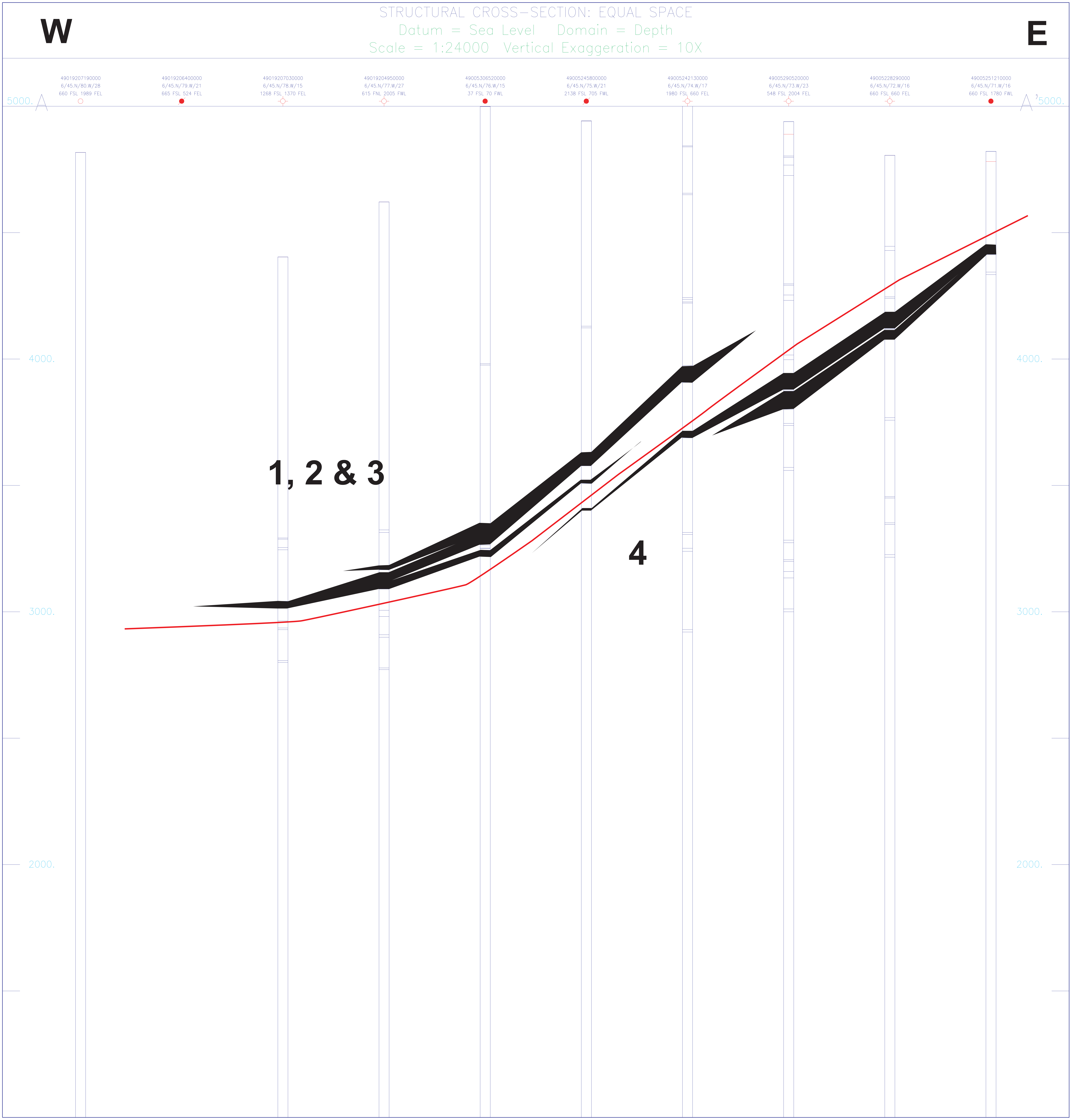
1000.
1, 2 & 3
4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STRUCTURAL CROSS-SECTION: EQUAL SPACE
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Scale = 1:24000 Vertical Exaggeration = 10X
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660 FSL 1989 FEL
49019206400000
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665 FSL 524 FEL
49019207030000
6/45.N/78.W/15
1268 FSL 1370 FEL
49019204950000
6/45.N/77.W/27
615 FNL 2005 FWL
49005306520000
6/45.N/76.W/15
37 FSL 70 FWL
49005245800000
6/45.N/75.W/21
2138 FSL 705 FWL
49005242130000
6/45.N/74.W/17
1980 FSL 660 FEL
49005290520000
6/45.N/73.W/23
548 FSL 2004 FEL
49005228290000
6/45.N/72.W/16
660 FSL 660 FEL
49005251210000
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660 FSL 1780 FWL
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A'
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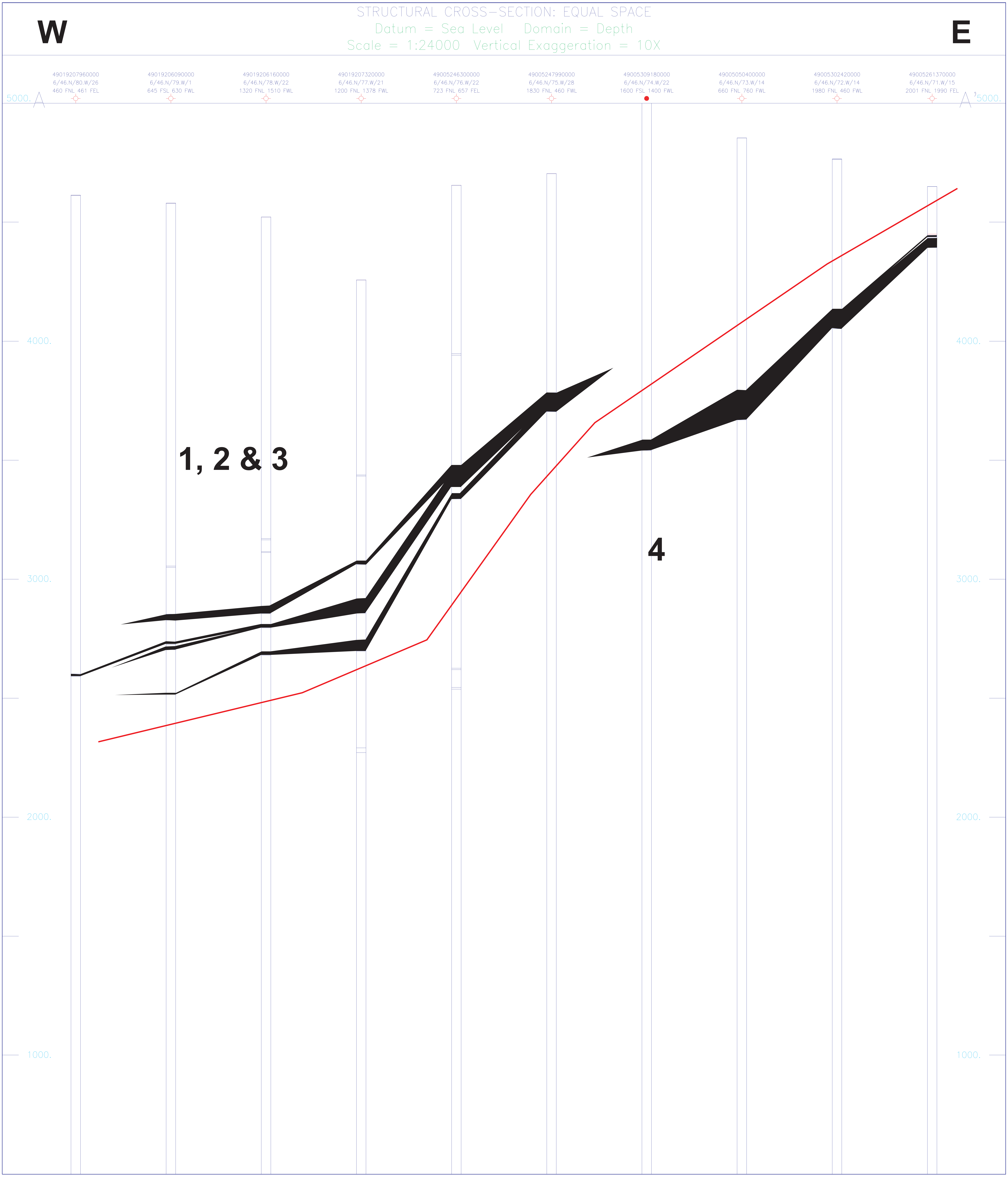
4000.
3000.
2000.
1, 2 & 3
4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E
STRUCTURAL CROSS-SECTION: EQUAL SPACE
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Scale = 1:24000 Vertical Exaggeration = 10X
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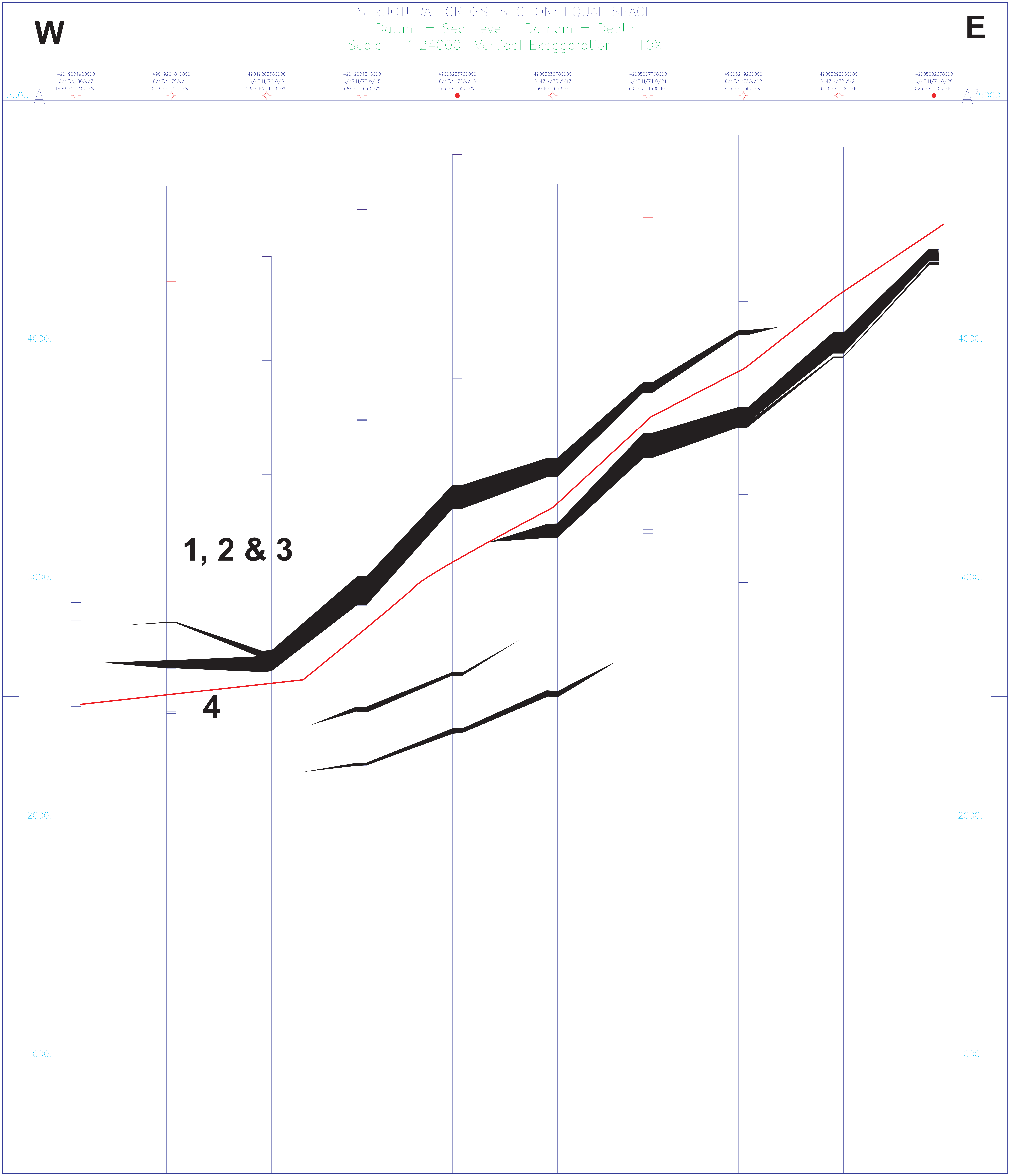
460 FNL 461 FEL
49019206090000
6/46.N/79.W/1
645 FSL 630 FWL
49019206160000
6/46.N/78.W/22
1320 FNL 1510 FWL
49019207320000
6/46.N/77.W/21
1200 FNL 1378 FWL
49005246300000
6/46.N/76.W/22
723 FNL 657 FEL
49005247990000
6/46.N/75.W/28
1830 FNL 460 FWL
49005309180000
6/46.N/74.W/22
1600 FSL 1400 FWL
49005050400000
6/46.N/73.W/14
660 FNL 760 FWL
49005302420000
6/46.N/72.W/14
1980 FNL 460 FWL
49005261370000
6/46.N/71.W/15
2001 FNL 1990 FEL
A
A'
5000.
4000.
3000.
2000.
1000.
1, 2 & 3
4



W
STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
E
49019201920000
6/47.N/80.W/7
1980 FNL 490 FWL
49019201010000
6/47.N/79.W/11
560 FNL 460 FWL
49019205580000
6/47.N/78.W/3
1937 FNL 658 FWL
49019201310000
6/47.N/77.W/15
990 FSL 990 FWL
49005235720000
6/47.N/76.W/15
463 FSL 652 FWL
49005232700000
6/47.N/75.W/17
660 FSL 660 FEL
49005267760000
6/47.N/74.W/21
660 FNL 1988 FEL
49005219220000
6/47.N/73.W/22
745 FNL 660 FWL
49005298060000
6/47.N/72.W/21
1958 FSL 621 FEL
49005282230000
6/47.N/71.W/20
825 FSL 750 FEL
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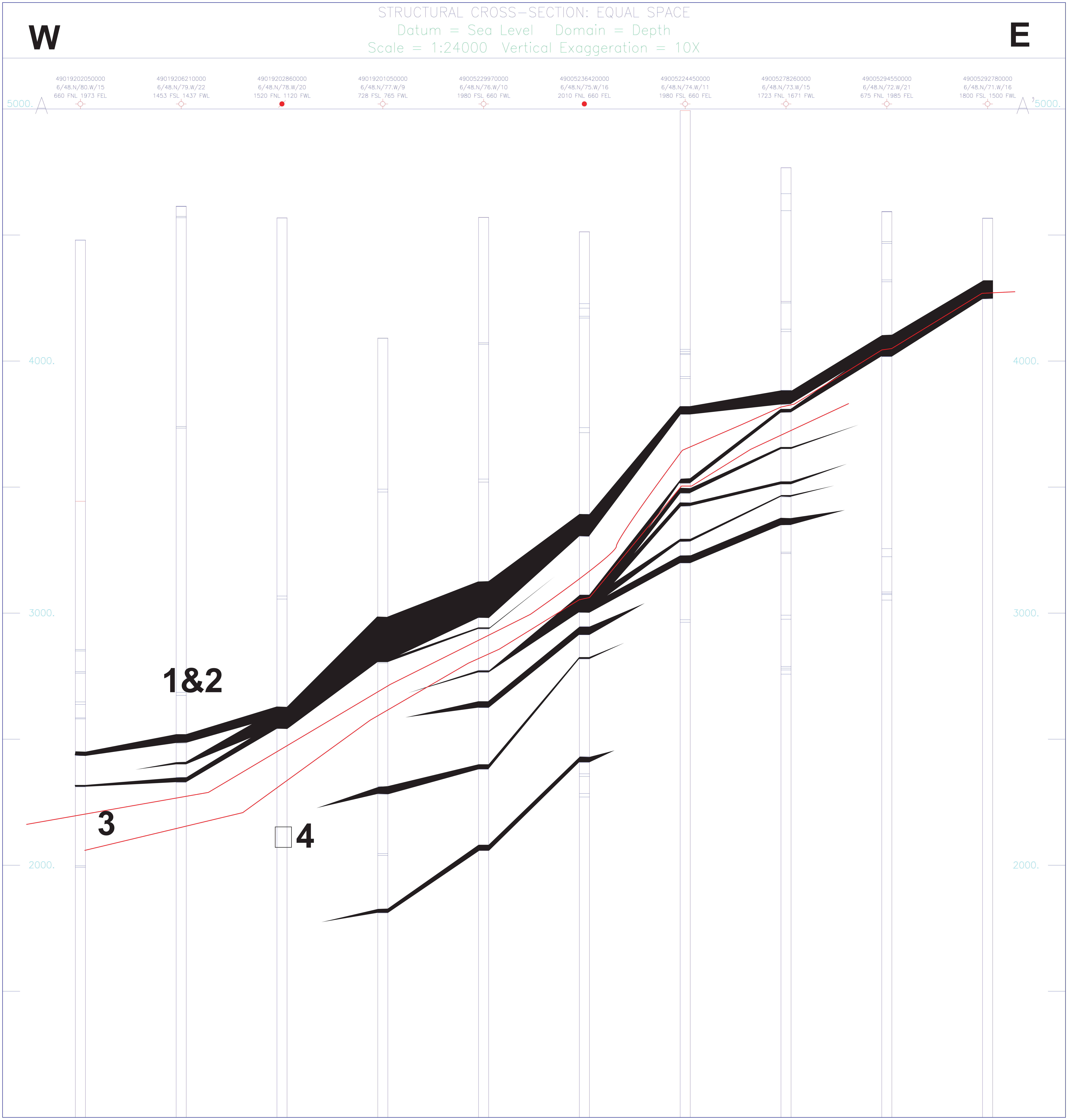
A
A'
5000.
4000.
4000.
3000.
3000.
2000.
2000.
1000.
1000.
1, 2 & 3
4


STRUCTURAL CROSS-SECTION: EQUAL SPACE
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Scale = 1:24000 Vertical Exaggeration = 10X
W
E
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660 FNL 1973 FEL
49019206210000
6/48.N/79.W/22
1453 FSL 1437 FWL
49019202860000
6/48.N/78.W/20
1520 FNL 1120 FWL
49019201050000
6/48.N/77.W/9
728 FSL 765 FWL
49005229970000
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1980 FSL 660 FWL
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2010 FNL 660 FEL
49005224450000
6/48.N/74.W/11
1980 FSL 660 FEL
49005278260000
6/48.N/73.W/15
1723 FNL 1671 FWL
49005294550000
6/48.N/72.W/21
675 FNL 1985 FEL
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6/48.N/71.W/16
1800 FSL 1500 FWL
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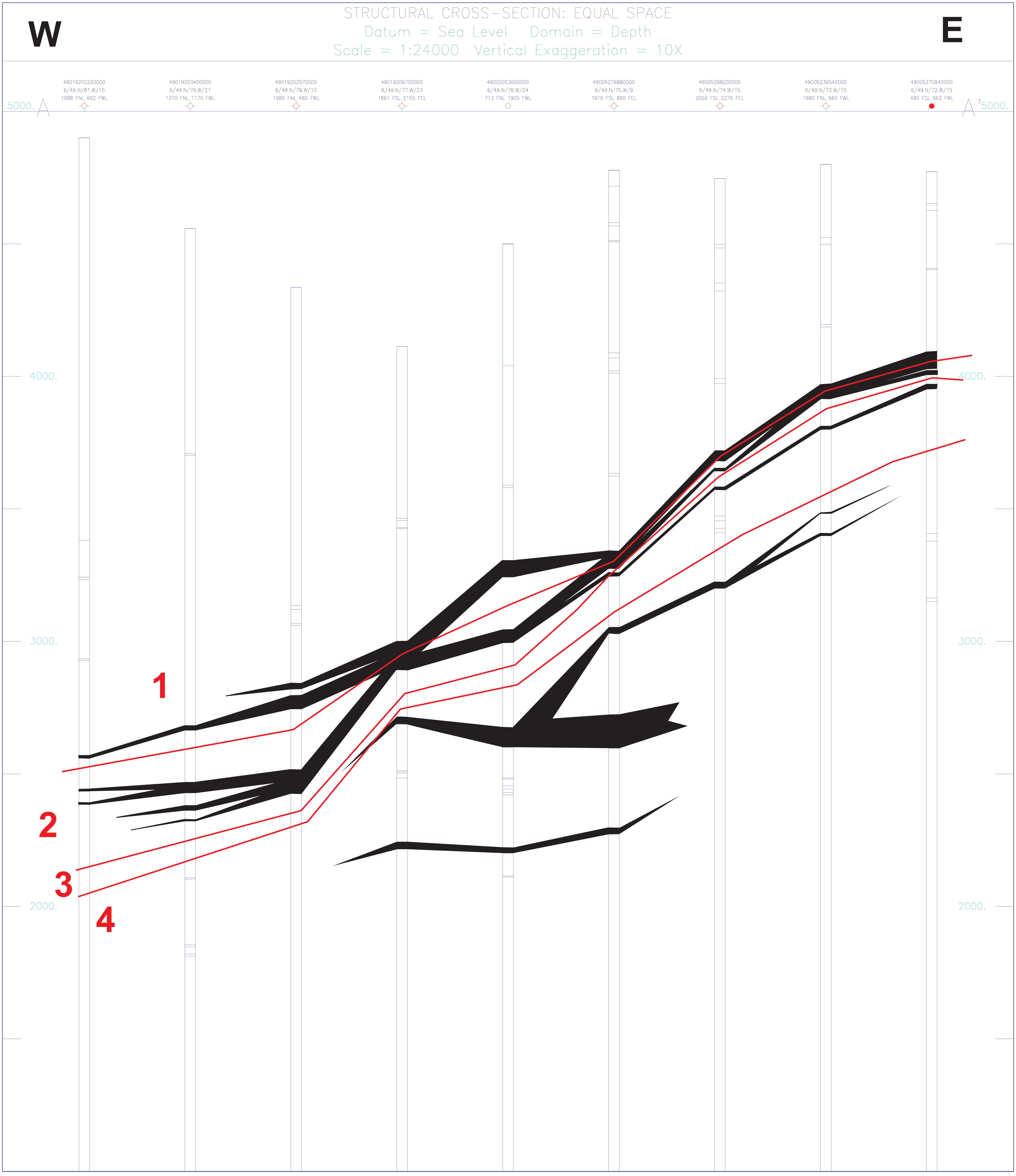
4000.
3000.
2000.
1&2
3
4


W
STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
E
49019202220000
6/49.N/81.W/15
1988 FNL 662 FWL
49019203400000
6/49.N/79.W/21
1370 FNL 1170 FWL
49019202570000
6/49.N/78.W/10
1980 FNL 460 FWL
49019206700000
6/49.N/77.W/23
1861 FSL 2155 FEL
49005053600000
6/49.N/76.W/24
713 FNL 1905 FWL
49005276880000
6/49.N/75.W/9
1916 FSL 860 FEL
49005268200000
6/49.N/74.W/15
2050 FSL 2275 FEL
49005236540000
6/49.N/73.W/15
1980 FNL 660 FWL
49005270940000
6/49.N/72.W/15
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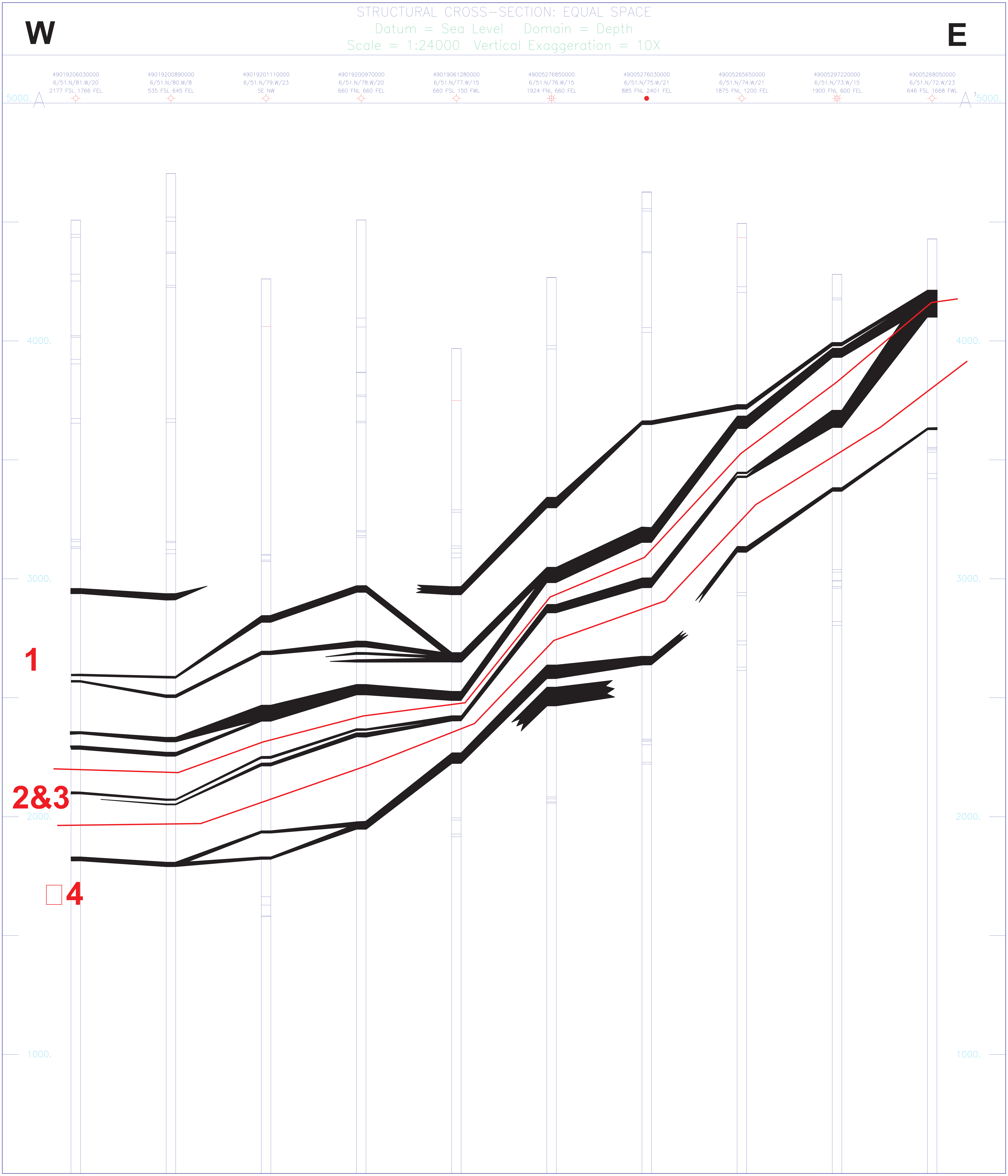
2000.
1
2
3
4



W
STRUCTURAL CROSS–SECTION: EQUAL SPACE
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Scale = 1:24000 Vertical Exaggeration = 10X
E
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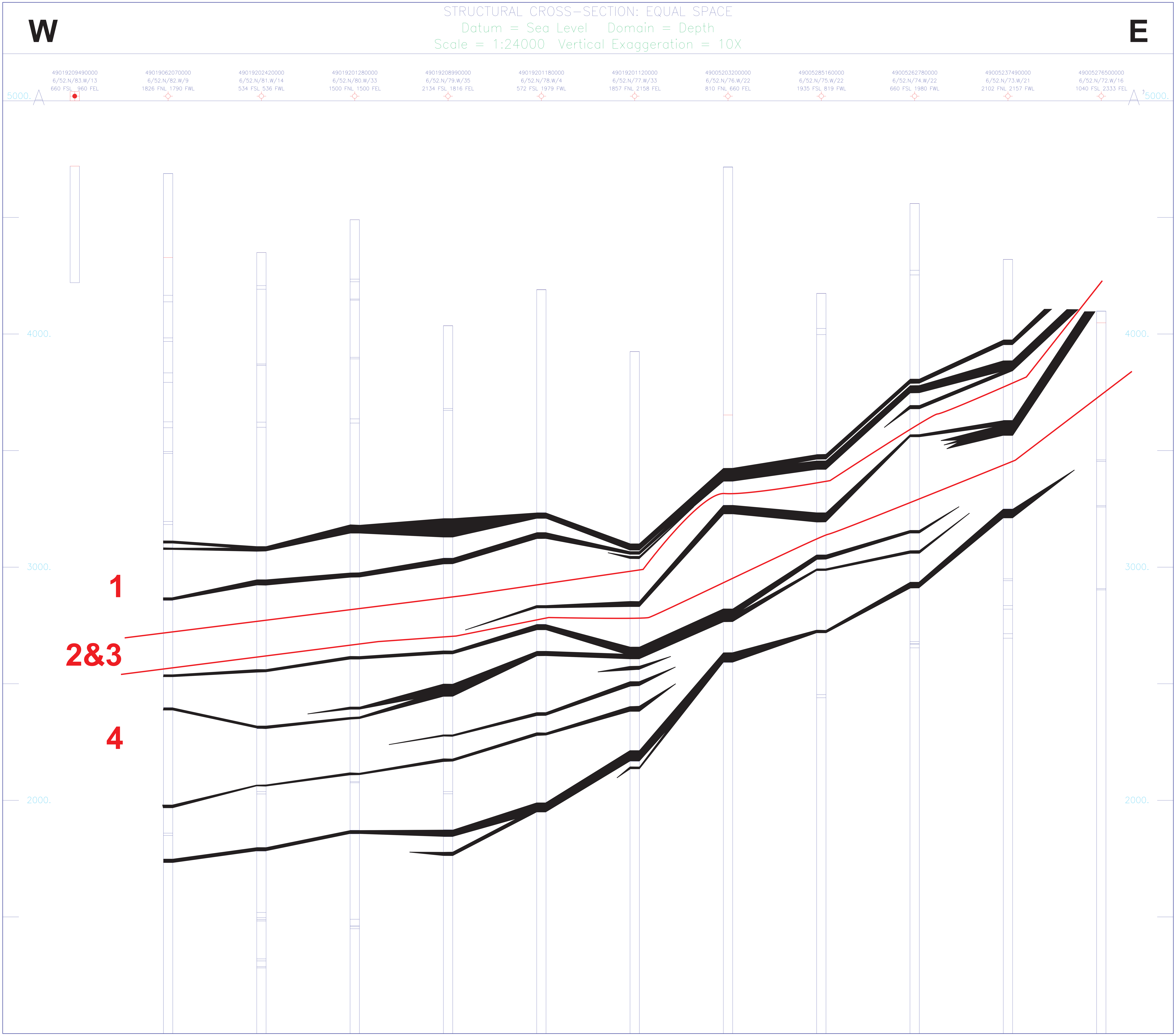
2177 FSL 1766 FEL
49019200890000
6/51.N/80.W/8
535 FSL 645 FEL
49019201110000
6/51.N/79.W/23
SE NW
49019200970000
6/51.N/78.W/20
660 FNL 660 FEL
49019061280000
6/51.N/77.W/15
660 FSL 150 FWL
49005276850000
6/51.N/76.W/15
1924 FNL 660 FEL
49005276030000
6/51.N/75.W/21
885 FNL 2401 FEL
49005265650000
6/51.N/74.W/21
1875 FNL 1200 FEL
49005297220000
6/51.N/73.W/15
1900 FNL 600 FEL
49005268050000
6/51.N/72.W/23
646 FSL 1668 FWL
5000.
4000.
3000.
2000.
1000.
A
A'
1
2&3
4



W
E
STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level
Domain = Depth
Scale = 1:24000
Vertical Exaggeration = 10X
49019209490000
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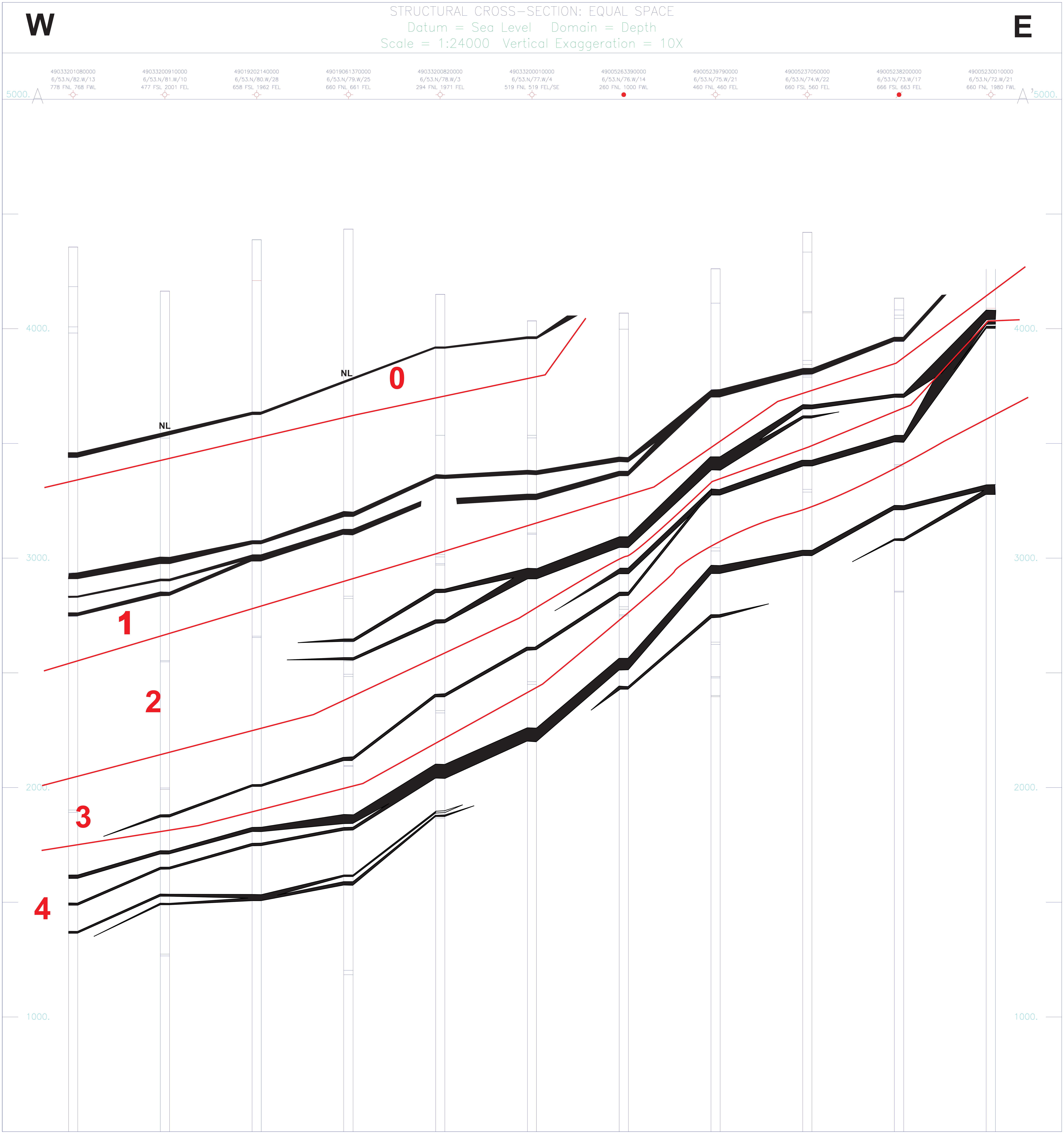
49019062070000
6/52.N/82.W/9
1826 FNL 1790 FWL
49019202420000
6/52.N/81.W/14
534 FSL 536 FWL
49019201280000
6/52.N/80.W/33
1500 FNL 1500 FEL
49019208990000
6/52.N/79.W/35
2134 FSL 1816 FEL
49019201180000
6/52.N/78.W/4
572 FSL 1979 FWL
49019201120000
6/52.N/77.W/33
1857 FNL 2158 FEL
49005203200000
6/52.N/76.W/22
810 FNL 660 FEL
49005285160000
6/52.N/75.W/22
1935 FSL 819 FWL
49005262780000
6/52.N/74.W/22
660 FSL 1980 FWL
49005237490000
6/52.N/73.W/21
2102 FNL 2157 FWL
49005276500000
6/52.N/72.W/16
1040 FSL 2333 FEL
A
A'
5000.
4000.
3000.
2000.
1
2&3
4



W
E
STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
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6/53.N/82.W/13
778 FNL 768 FWL
49033200910000
6/53.N/81.W/10
477 FSL 2001 FEL
49019202140000
6/53.N/80.W/28
658 FSL 1962 FEL
49019061370000
6/53.N/79.W/25
660 FNL 661 FEL
49033200820000
6/53.N/78.W/3
294 FNL 1971 FEL
49033200010000
6/53.N/77.W/4
519 FNL 519 FEL/SE
49005263390000
6/53.N/76.W/14
260 FNL 1000 FWL
49005239790000
6/53.N/75.W/21
460 FNL 460 FEL
49005237050000
6/53.N/74.W/22
660 FSL 560 FEL
49005238200000
6/53.N/73.W/17
666 FSL 663 FEL
49005230010000
6/53.N/72.W/21
660 FNL 1980 FWL
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4000.
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2000.
1000.
NL
NL
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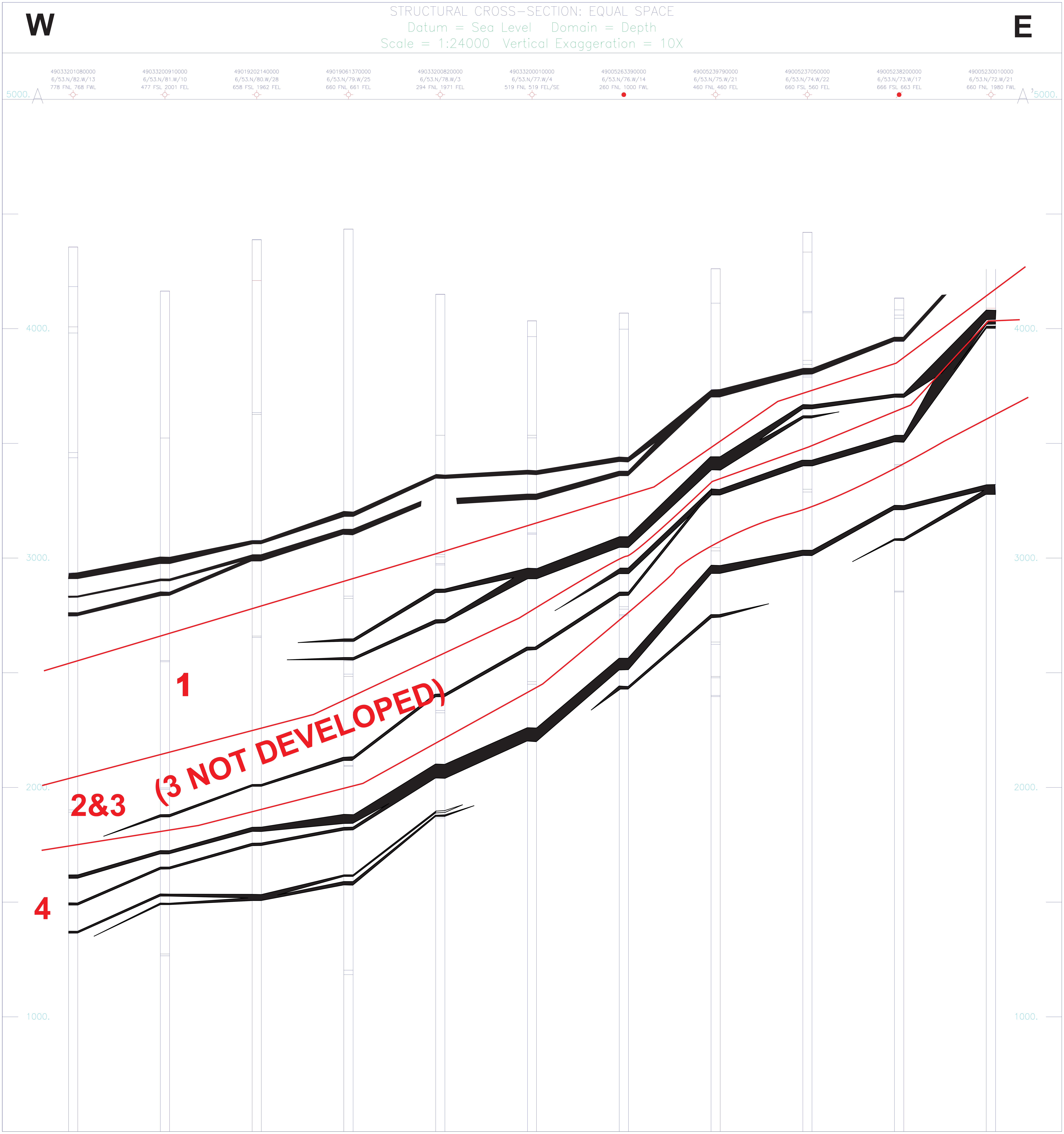
1
2
3
4



W
E
STRUCTURAL CROSS–SECTION: EQUAL SPACE
Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
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6/53.N/82.W/13
778 FNL 768 FWL
49033200910000
6/53.N/81.W/10
477 FSL 2001 FEL
49019202140000
6/53.N/80.W/28
658 FSL 1962 FEL
49019061370000
6/53.N/79.W/25
660 FNL 661 FEL
49033200820000
6/53.N/78.W/3
294 FNL 1971 FEL
49033200010000
6/53.N/77.W/4
519 FNL 519 FEL/SE
49005263390000
6/53.N/76.W/14
260 FNL 1000 FWL
49005239790000
6/53.N/75.W/21
460 FNL 460 FEL
49005237050000
6/53.N/74.W/22
660 FSL 560 FEL
49005238200000
6/53.N/73.W/17
666 FSL 663 FEL
49005230010000
6/53.N/72.W/21
660 FNL 1980 FWL
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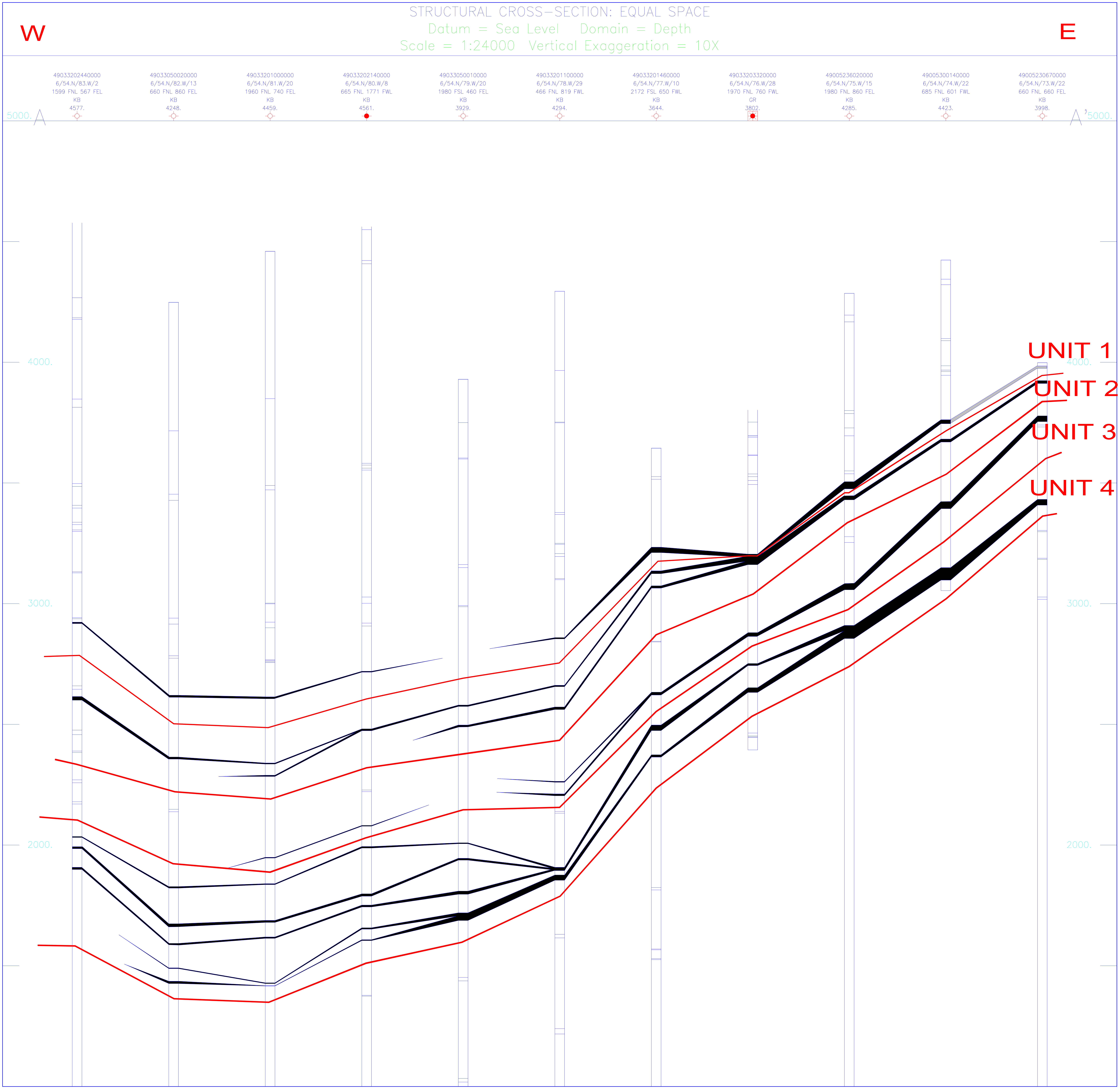
A
A'
4000.
3000.
2000.
1000.
1
2&3
(3 NOT DEVELOPED)
4



STRUCTURAL CROSS-SECTION: EQUAL SPACE
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Scale = 1:24000 Vertical Exaggeration = 10X
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E
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KB
4577.
49033050020000
6/54.N/82.W/13
660 FNL 860 FEL
KB
4248.
49033201000000
6/54.N/81.W/20
1960 FNL 740 FEL
KB
4459.
49033202140000
6/54.N/80.W/8
665 FNL 1771 FWL
KB
4561.
49033050010000
6/54.N/79.W/20
1980 FSL 460 FEL
KB
3929.
49033201100000
6/54.N/78.W/29
466 FNL 819 FWL
KB
4294.
49033201460000
6/54.N/77.W/10
2172 FSL 650 FWL
KB
3644.
49033203320000
6/54.N/76.W/28
1970 FNL 760 FWL
GR
3802.
49005236020000
6/54.N/75.W/15
1980 FNL 860 FEL
KB
4285.
49005300140000
6/54.N/74.W/22
685 FNL 601 FWL
KB
4423.
49005230670000
6/54.N/73.W/22
660 FNL 660 FEL
KB
3998.
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A'
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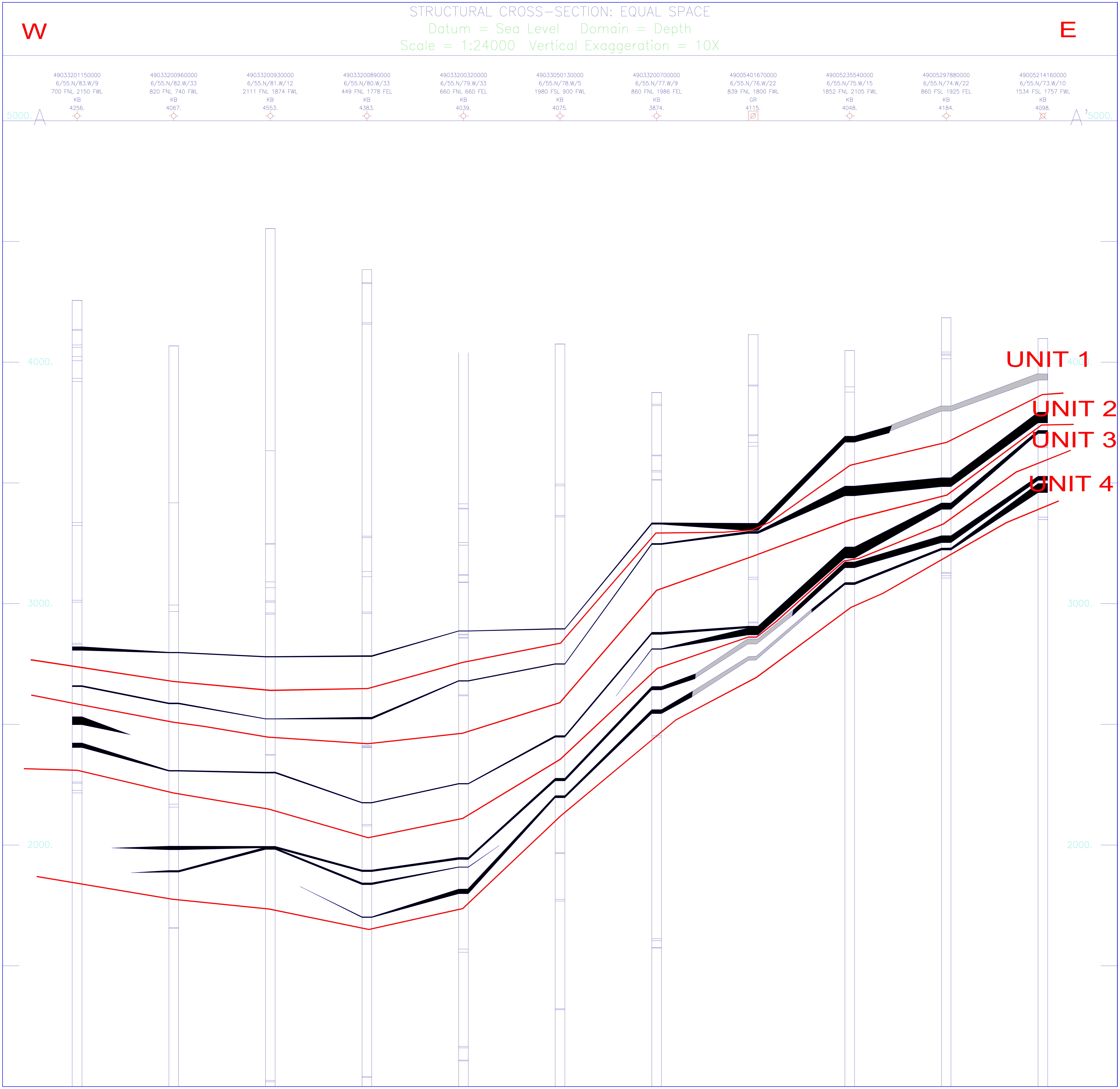
4000.
3000.
2000.
UNIT 1
UNIT 2
UNIT 3
UNIT 4


STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
W
E
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49033200960000 6/55.N/82.W/33 820 FNL 740 FWL KB 4067.
49033200930000 6/55.N/81.W/12 2111 FNL 1874 FWL KB 4553.
49033200890000 6/55.N/80.W/33 449 FNL 1778 FEL KB 4383.
49033200320000 6/55.N/79.W/33 660 FNL 660 FEL KB 4039.
49033050130000 6/55.N/78.W/5 1980 FSL 900 FWL KB 4075.
49033200700000 6/55.N/77.W/9 860 FNL 1986 FEL KB 3874.
49005401670000 6/55.N/76.W/22 839 FNL 1800 FWL GR 4115.
49005235540000 6/55.N/75.W/15 1852 FNL 2105 FWL KB 4048.
49005297880000 6/55.N/74.W/22 860 FSL 1925 FEL KB 4184.
49005214160000 6/55.N/73.W/10 1534 FSL 1757 FWL KB 4098.
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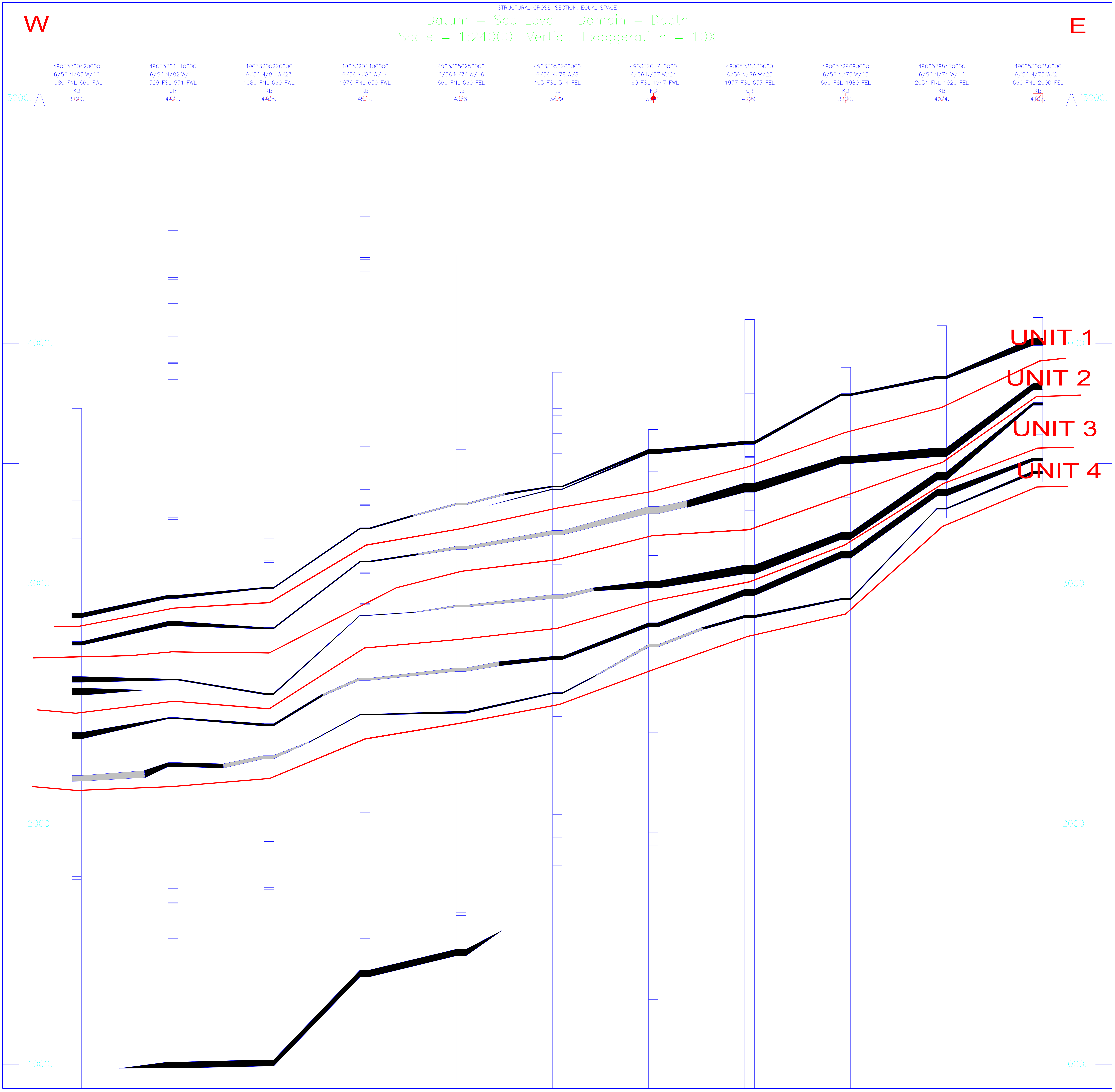
A
A'
4000.
3000.
2000.
UNIT 1
UNIT 2
UNIT 3
UNIT 4



W
E
STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level   Domain = Depth
Scale = 1:24000   Vertical Exaggeration = 10X
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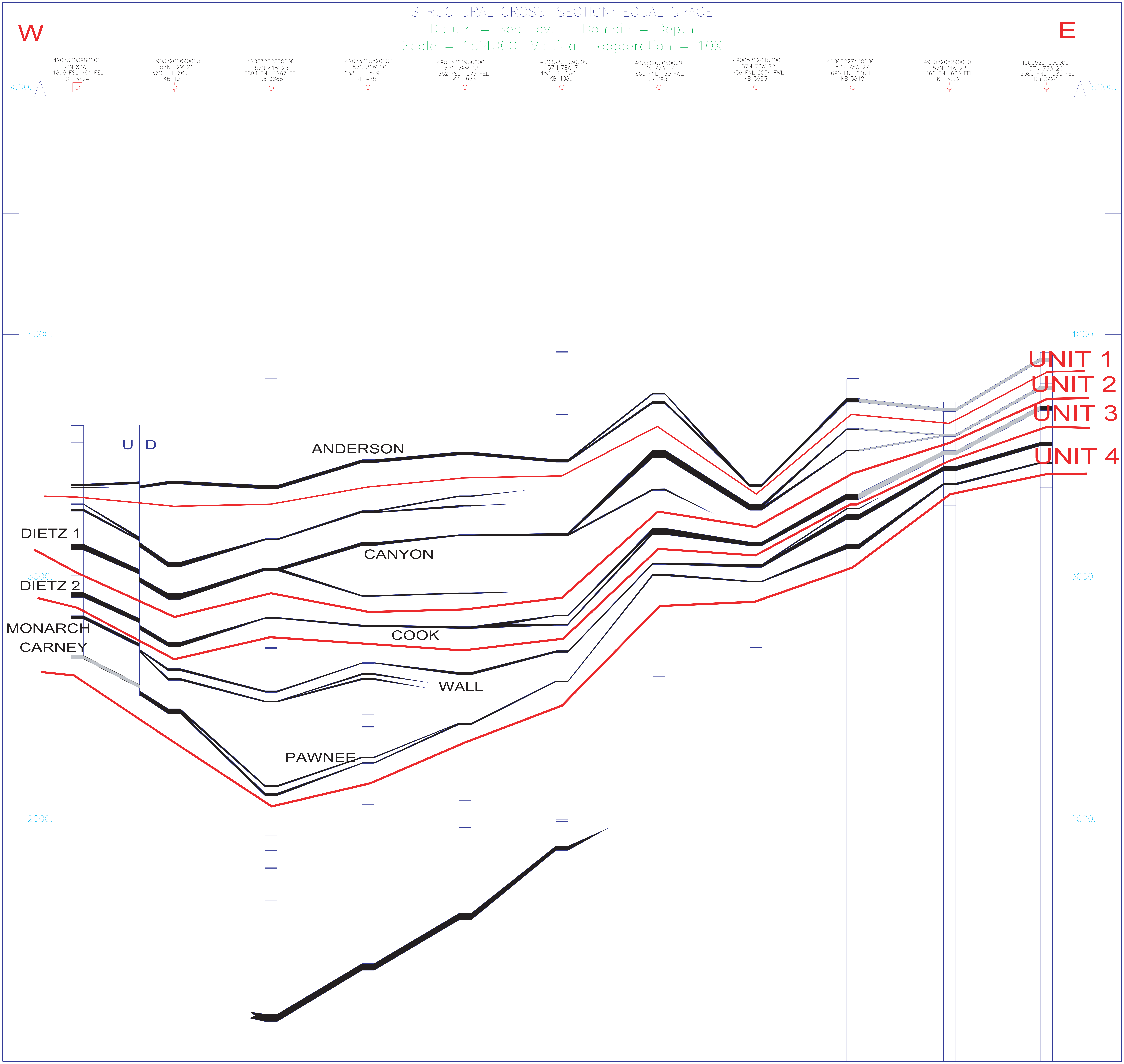
KB
3729.
49033201110000
6/56.N/82.W/11
529 FSL 571 FWL
GR
4470.
49033200220000
6/56.N/81.W/23
1980 FNL 660 FWL
KB
4408.
49033201400000
6/56.N/80.W/14
1976 FNL 659 FWL
KB
4527.
49033050250000
6/56.N/79.W/16
660 FNL 660 FEL
KB
4368.
49033050260000
6/56.N/78.W/8
403 FSL 314 FEL
KB
3879.
49033201710000
6/56.N/77.W/24
160 FSL 1947 FWL
KB
49005288180000
6/56.N/76.W/23
1977 FSL 657 FEL
GR
4099.
49005229690000
6/56.N/75.W/15
660 FSL 1980 FEL
KB
3900.
49005298470000
6/56.N/74.W/16
2054 FNL 1920 FEL
KB
4074.
49005300880000
6/56.N/73.W/21
660 FNL 2000 FEL
KB
4107.
A
A'
5000.
4000.
3000.
2000.
1000.
UNIT 1
UNIT 2
UNIT 3
UNIT 4


STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level
Domain = Depth
Scale = 1:24000
Vertical Exaggeration = 10X
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E
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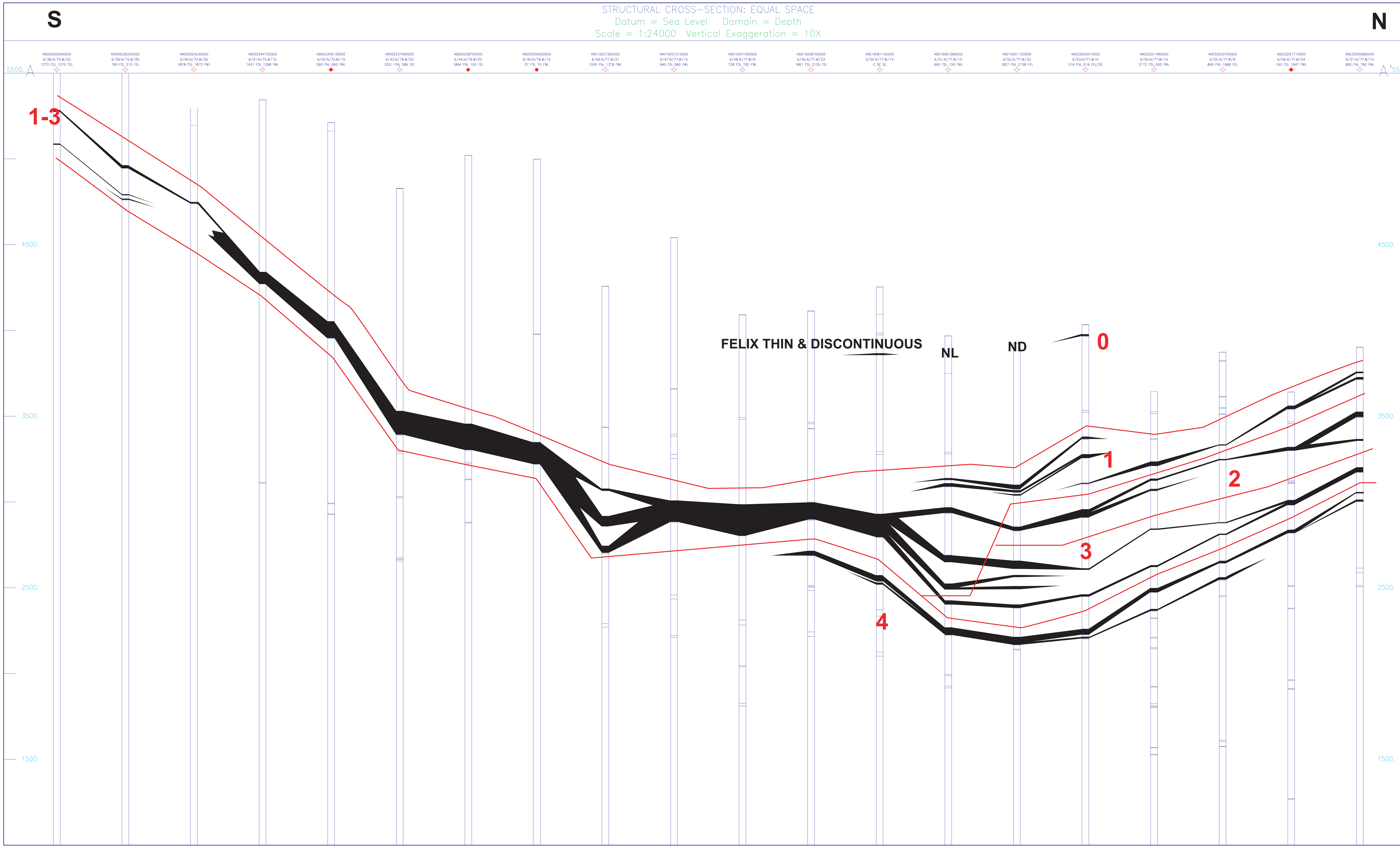
1899 FSL 664 FEL
GR 3624
49033200690000
57N 82W 21
660 FNL 660 FEL
KB 4011
49033202370000
57N 81W 25
3884 FNL 1967 FEL
KB 3888
49033200520000
57N 80W 20
638 FSL 549 FEL
KB 4352
49033201960000
57N 79W 18
662 FSL 1977 FEL
KB 3875
49033201980000
57N 78W 7
453 FSL 666 FEL
KB 4089
49033200680000
57N 77W 14
660 FNL 760 FWL
KB 3903
49005262610000
57N 76W 22
656 FNL 2074 FWL
KB 3683
49005227440000
57N 75W 27
690 FNL 640 FEL
KB 3818
49005205290000
57N 74W 22
660 FNL 660 FEL
KB 3722
49005291090000
57N 73W 29
2080 FNL 1980 FEL
KB 3926
A
A'
5000.
4000.
3000.
2000.
U
D
ANDERSON
DIETZ 1
CANYON
DIETZ 2
COOK
MONARCH
CARNEY
WALL
PAWNEE
UNIT 1
UNIT 2
UNIT 3
UNIT 4



S
N
STRUCTURAL CROSS-SECTION: EQUAL SPACE
Datum = Sea Level Domain = Depth
Scale = 1:24000 Vertical Exaggeration = 10X
5500.
4500.
3500.
2500.
1500.
1-3
FELIX THIN & DISCONTINUOUS
NL
ND
0
1
2
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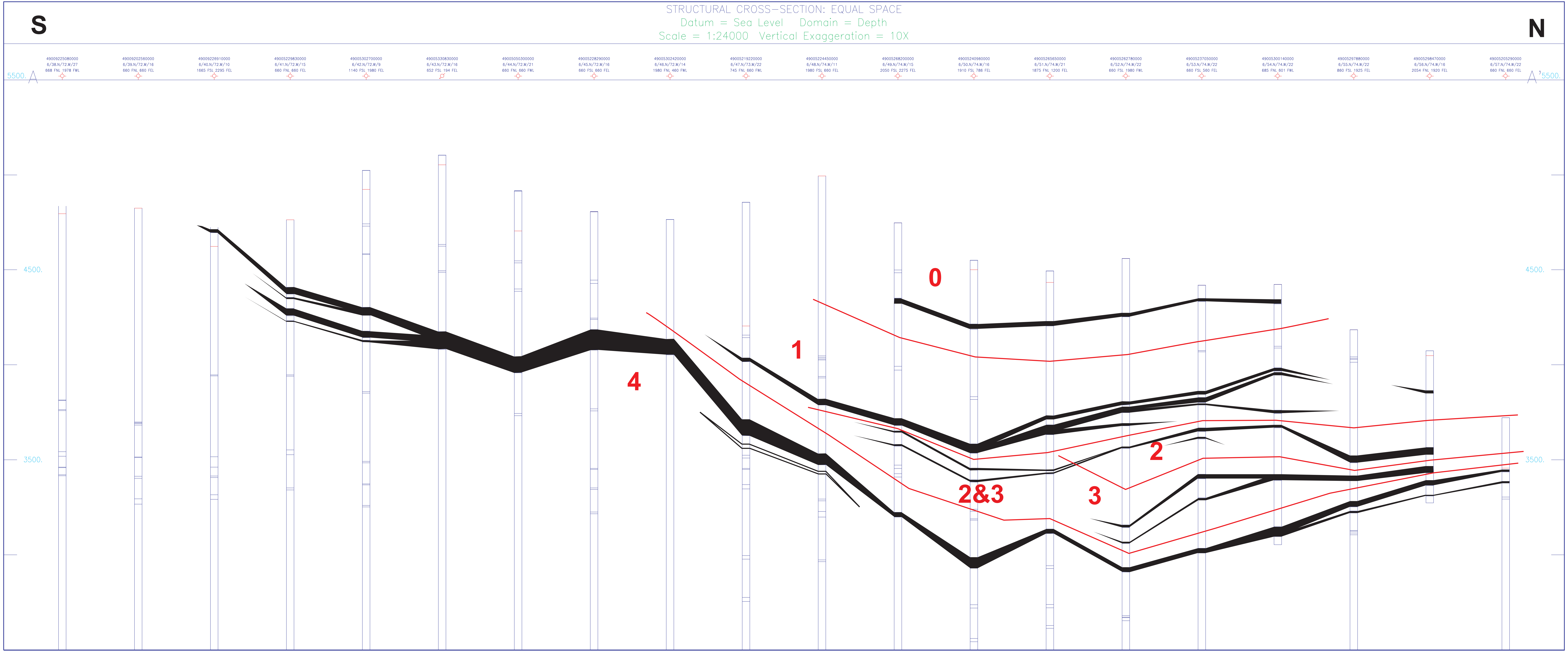

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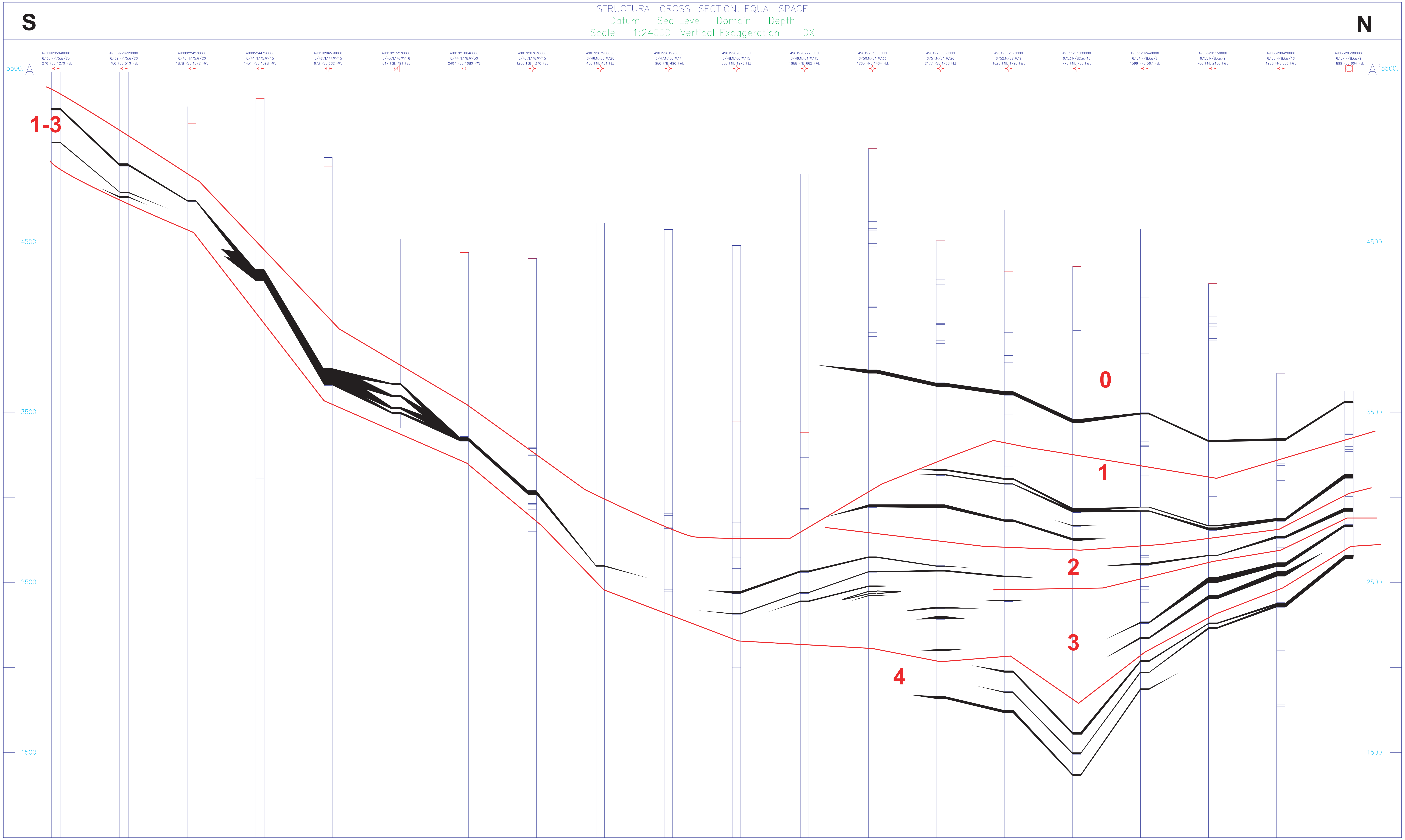
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APPENDIX B

Summary of Pumping Test Analyses Performed in the Powder River Basin (compiled by Applied Hydrology and Associates, Inc.)

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
Alluvium																		
cmc1, wwrc1	Alluvium:	Caballo Mine T48N, R71W, Sec 21	200	1/27/82	3240	112-168	41	90.0	40.0	5.6	Jacob	429	10.4	2.7E-04	6.6E-06	N/A	confined	assumed confined based on reported saturated thicknesses Caballo Rojo Permit to Mine Application; well completion data on CD accompanying wwrc1
cmc1, wwrc1	Alluvium:	Caballo Mine T48N, R71W, Sec 21	50	1/27/82	3240	109-165	39	83.0	40.0	11.5	Jacob	429	8.2	1.3E-04	3.3E-06	N/A	confined	assumed confined based on reported saturated thicknesses Caballo Rojo Permit to Mine Application; well completion data on CD accompanying wwrc1
tcc1	Alluvium: Wasatch	Buckskin Mine; T52N, R72W	25	12/20/78	1470	12.0-16.0	15		5.0		Theis	148	9.8	2.4E-03	N/A	0.00240	unconfined	assumed unconfined based on shallow completion in alluvium
tcc1	Alluvium: Wasatch	Buckskin Mine; T52N, R72W	76	12/20/78	1470	12.0-16.0	15		5.0		Theis	313	20.9	5.1E-03	N/A	0.00510	unconfined	assumed unconfined based on shallow completion in alluvium
tcc1	Alluvium: Wasatch	Buckskin Mine; T52N, R72W	176	12/20/78	1470	12.0-16.0	15		5.0		Theis	768	51.2	1.2E-02	N/A	0.01200	unconfined	assumed unconfined based on shallow completion in alluvium
tcc1	Alluvium: Wasatch	Buckskin Mine; T52N, R72W	48	1/14/81	294	6.0-19.5	15		2.7		Jacob	868	59.9	1.2E-03	N/A	0.00120	unconfined	assumed unconfined based on shallow completion in alluvium
tcc1	Alluvium: Wasatch	Buckskin Mine; T52N, R72W	53	1/14/81	420	11.0-35.0	15		11.1		Jacob	1079	72.0	2.5E-02	N/A	0.02500	unconfined	assumed unconfined based on shallow completion in alluvium
hitt1 (a)	Alluvium:	Buckskin Mine T52N, R72W, Sec. 32					20					1126	56.3	5.6E-02	N/A	0.05600	unconfined	assumed unconfined based on completion in alluvium; no well names or specific locations given
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 10	33	5/17/83	1410		3		6.9	0.5	Theis	201	17.4	2.3E-01	N/A	0.23000	unconfined	assumed unconfined due to shallow completion in alluvium; partial penetration
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 3	220	5/24/83	1200	5.0-18.0	12		14.4	0.3	Theis	2010	190.3	8.0E-03	N/A	0.00800	unconfined	assumed unconfined due to shallow completion in alluvium; static w.l.. after drilling = 13.0 ft

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 3	167	5/24/83	1200	6.0-15.0	12		14.4	0.2	Theis	4253	349.7	1.4E-02	N/A	0.01400	unconfined	assumed unconfined due to shallow completion in alluvium; static w.l.. after drilling = 3.1 ft
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 4	91	5/22/83	720	5.0-20.0	16		6.5	3.7	Boulton	391	24.1	1.5E-02	N/A	0.01500	unconfined	assumed unconfined due to shallow completion in alluvium; static w.l.. after drilling = 10.8 ft
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 6	73	5/13/83	1410	6.5-16.5	6		1.1	0.1	Theis	316	57.6	3.3E-02	N/A	0.03300	unconfined	assumed unconfined due to shallow completion in alluvium
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 6	62	5/13/83	1410	5.0-20.0	10		1.1	0.1	Theis	588	63.0	2.2E-02	N/A	0.02200	unconfined	assumed unconfined due to shallow completion in alluvium
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 6	52	5/10/83	1518	5.0-17.0	10		1.0	0.1	Boulton	52	5.5	6.0E-02	N/A	0.06000	unconfined	assumed unconfined due to shallow completion in alluvium
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 6	3.6	5/10/83	1518	8.0-20.0	3		1.0	0.6	Boulton	216	25.5	2.1E-02	N/A	0.02100	unconfined	assumed unconfined due to shallow completion in alluvium
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 9	43	5/17/83	1410	7.5-12.5	10		6.9	0.7	Theis	584	61.6	2.1E-02	N/A	0.02100	unconfined	assumed unconfined due to shallow completion in alluvium; static w.l.. after drilling = 2.9 ft
cmc2	Alluvium:	Rawhide Mine; T51N, R72W, Sec. 9	45	5/17/83	1410	6.0-11.0	11		6.9	0.9	Theis	478	41.5	1.2E-02	N/A	0.01200	unconfined	assumed unconfined due to shallow completion in alluvium
fump1	Alluvium: Channel sand	Fort Union Mine T50N, R71W, Sec.7		Not reported	Not reported	202-260	160	88.0	Not reported		Theis	1.3	0.01	7.9E-05	4.9E-07	N/A	confined	static w.l.. > top of aquifer
fump1	Alluvium: Channel sand	Fort Union Mine T50N, R72W, Sec.1		Not reported	Not reported	108-306	200	93.0	1.5	2.7	Cooper-Jacob	15	0.07	1.1E-04	5.5E-07	N/A	confined	static w.l.. > top of aquifer
											MIN	**1.34**	**0.01**	**7.9E-05**	**4.9E-07**	**0.00120**		
											MAX	**4253.16**	**349.74**	**2.3E-01**	**6.6E-06**	**0.23000**		
											MEDIAN	**428.80**	**33.50**	**1.3E-02**	**1.9E-06**	**0.01800**		
											ARITH MEAN	**713.31**	**56.25**	**2.7E-02**	**2.7E-06**	**0.03361**		

Upper Ft. Union Coals

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
hitt1 (b)	Fort Union/ Roland Coal	Rawhide Mine T51N, R72W, Sec. 11					25					7	0.0	2.8E-04	1.1E-05	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
hitt1 (b)	Fort Union/ Roland Coal	Rawhide Mine T51N, R72W, Sec. 11					25					15	0.6	1.6E-04	6.4E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
hitt1 (b)	Fort Union/ Roland Coal	Rawhide Mine T51N, R72W, Sec. 11					25					15	0.6	1.7E-04	6.8E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
hitt1 (b)	Fort Union/ Roland Coal	Rawhide Mine T51N, R72W, Sec. 11					25					16	0.6	1.7E-04	6.8E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
hitt1 (b)	Fort Union/ Roland Coal	Rawhide Mine T51N, R72W, Sec. 11					25					15	0.6	2.0E-04	8.0E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
hitt1 (b)	Fort Union/ Smith Coal	Rawhide Mine T51N, R72W, Sec. 11					80					67	0.8	1.6E-03	2.0E-05	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
hitt1 (b)	Fort Union/ Smith Coal	Rawhide Mine T51N, R72W, Sec. 11					80					57	0.7	2.1E-04	2.6E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations given.
hitt1 (b)	Fort Union/ Smith Coal	Rawhide Mine T51N, R72W, Sec. 11					80					42	0.5	3.0E-04	3.8E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y= S)	Confined/ Unconfined (see comments)	Comments
																		or specific locations.
hitt1 (b)	Fort Union/ Smith Coal	Rawhide Mine T51N, R72W, Sec. 11					80					43	0.5	3.0E-04	3.8E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
hitt1 (b)	Fort Union/ Smith Coal	Rawhide Mine T51N, R72W, Sec. 11					80					44	0.6	2.8E-04	3.5E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
hitt1 (b)	Fort Union/ Smith Coal	Rawhide Mine T51N, R72W, Sec. 11					80					42	0.5	3.0E-04	3.8E-06	N/A	confined	Assumed confined based on low S value. K value based on presented T & b values. No well names or specific locations.
cmc2	Fort Union/ Smith Coal	Rawhide Mine; T51N, R72W, Sec. 10	150	5/30/05		202-204	5		22.0		Theis	87	17.4	1.9E-04	3.8E-05	N/A	confined	Assumed confined based on low S value. Boundaries present
acc1	Ft. Union/ Canyon Coal	Antelope Mine		6/1/05	1440	204-240	31		12.0		Theis	256	8.3	2.7E-05	8.7E-07	N/A	confined	Assumed confined based on low S value. Assumed K value based on presented T & b values.
acc1	Ft. Union/ Canyon Coal	Antelope Mine		6/1/05	1440	205-240	29		12.0		Theis	318	11.0	2.6E-05	9.0E-07	N/A	confined	Assumed confined based on low S value. Assumed K value based on presented T & b values.
tcc1	Ft. Union/ Canyon Coal	Buckskin Mine; T52N, R 73W, Sec. 25, CA	97.3	10/13/88	264	437-511	70		3.2	1.3	Theis & Jacob	64	0.9	3.0E-04	4.3E-06	N/A	confined	Assumed confined based on low S value.
tcc1	Ft. Union/ Canyon Coal	Buckskin Mine; T52N, R 73W, Sec. 25, CA	21	8/11/88	1440	250-280	62		1.1	1.0	Theis & Jacob	42	0.7	1.2E-02	1.9E-04	N/A	confined	Assumed confined based on 250 ft of overburden.
tcc1	Ft. Union/ Anderson & Canyon	Buckskin Mine; T52N, R72W	199	7/22/76	2850		116		18.2		Theis	576	5.0	2.3E-04	2.0E-06	N/A	confined	Assumed confined based on low S value. Well completed in

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y= S)	Confined/ Unconfined (see comments)	Comments
	Coals																	multiple coals
tcc1	Ft. Union/ Anderson & Canyon Coals	Buckskin Mine; T52N, R72W	100	7/22/76	2850	70-205	117		18.2		Theis	549	4.7	5.1E-04	4.4E-06	N/A	confined	Assumed confined based on low S value. Well completed in multiple coals
tcc1	Ft. Union/ Anderson & Canyon Coals	Buckskin Mine; T52N, R72W	51	7/22/76	2850	70-200	122		18.2		Theis	560	4.6	1.6E-03	1.3E-05	N/A	confined	Assumed confined based on low S value. Well completed in multiple coals
tcc1	Ft. Union/ Anderson & Canyon Coals	Buckskin Mine; T52N, R72W	335	6/6/79	4386	40-80	49		25.7		Theis	68	1.3	1.9E-03	3.9E-05	N/A	confined	Assumed confined based on low S value. Well completed in multiple coals
tcc1	Ft. Union/ Anderson & Canyon Coals	Buckskin Mine; T52N, R72W	807	6/6/79	4386	65-170	80		25.7		Theis	107	1.3	6.6E-04	8.3E-06	N/A	confined	Assumed confined based on low S value. Well completed in multiple coals
tcc1	Ft. Union/ Anderson & Canyon Coals	Buckskin Mine; T52N, R72W	52	1/6/81	222	74-190	64		18.1		Jacob	716	11.3	3.0E-03	4.7E-05	N/A	confined	Assumed confined based on low S value. Well completed in multiple coals
aha9	Ft. Union/ Big George	Johnson County	139	7/6/01	5760	1626-1756	139	173.7	30.0		Theis	22	0.53	2.1E-04	1.51E-06	0.000209	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	118	7/6/01	5760	1701-1804	118	215.4	30.0		Theis	23	0.63	3.0E-04	2.54E-06	0.000299	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	112	7/6/01	5760	1717-1822	112	219.4	30.0		Theis	39	1.13	3.7E-04	3.32E-06	0.000372	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	124	7/6/01	5760	1738-1855	124	259.1	30.0		Theis	34	0.89	2.8E-04	2.29E-06	0.000284	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	119	7/6/01	5760	1772-1860	119	259.1	30.0		Theis	47	1.29	3.0E-04	2.54E-06	0.000302	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	165	7/6/01	5760	1575-1730	166	159.3	30.0		Theis	20	0.4	1.9E-04	1.16E-06	0.000191	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	150	7/6/01	5760	-	150	173.0	30.0		Theis	31	0.68	2.4E-04	1.62E-06	0.000243	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	150	7/6/01	5760	1640-1784	153	203.3	30.0		Theis	50	1.11	2.7E-04	1.83E-06	0.000274	confined	static w.l.. > top of aquifer

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
aha9	Ft. Union/ Big George	Johnson County	180	7/6/01	5760	1539-1710	180		30.0		Theis	13	0.24	1.8E-04	9.91E-07	0.000178	confined	Assumed confined based on low S value and conditions existing in area around well
aha9	Ft. Union/ Big George	Johnson County	139	7/16/01	5760	1626-1756	139	178.1	45.0		Theis		0.48	2.7E-04	1.95E-06	0.000271	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	118	7/16/01	5760	1701-1804	118	213.4	45.0		Theis		0.66	3.2E-04	2.68E-06	0.000317	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	112	7/16/01	5760	1717-1822	112	223.6	45.0		Theis		0.96	4.5E-04	4.04E-06	0.000453	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	124	7/16/01	5760	1738-1855	124	222.1	45.0		Theis		0.99	3.1E-04	2.49E-06	0.000309	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	119	7/16/01	5760	1772-1860	119	261.3	45.0		Theis		0.94	3.3E-04	2.73E-06	0.000325	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	165	7/16/01	5760	1575-1730	166	245.6	45.0		Theis		0.45	2.3E-04	1.39E-06	0.000229	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	150	7/16/01	5760	-	150	204.5	45.0		Theis		0.68	2.6E-04	1.74E-06	0.00026	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	150	7/16/01	5760	1640-1784	153	153.0	45.0		Theis		0.93	3.3E-04	2.17E-06	0.000325	confined	static w.l.. > top of aquifer
aha9	Ft. Union/ Big George	Johnson County	180	7/16/01	5760	1539-1710	180	163.0	45.0		Theis		0.32	2.2E-04	1.23E-06	0.000221	confined	static w.l.. > top of aquifer
aha4	Ft. Union/ Big George	Campbell County	2613	5/7/99	4320	753-803	52	252.6	61.2	4.2	Theis	75	1.4	1.2E-04	2.3E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1890	5/7/99	4320	787-850	56	265.1	61.2	5.4	Theis	122	2.2	1.9E-04	3.4E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1299	5/7/99	4320	797-850	56	266.0	61.2	13.8	Theis	101	1.8	9.9E-05	1.8E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1742	5/7/99	4320	828-888	52	279.4	61.2	10.3	Theis	115	2.1	8.3E-05	1.6E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1980	5/7/99	4320	971-1037	59	363.8	61.2	4.3	Theis	115	2.1	2.2E-04	3.7E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big	Campbell County	1245	5/7/99	4320	798-863	51	263.4	61.2	12.2	Theis	108	2.0	1.4E-04	2.7E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y= S)	Confined/ Unconfined (see comments)	Comments
	George																	thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1232	5/7/99	4320	889-951	58	318.3	61.2	11.5	Theis	115	2.1	1.4E-04	2.4E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1867	5/7/99	4320	880-?	63	265.4	61.2	10.8	Theis	109	2.0	6.9E-05	1.1E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1320	5/7/99	4320	?	61	310.5	61.2	14.3	Theis	94	1.7	1.0E-04	1.6E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1838	5/6/99	360	753-803	52	252.6	64.1		Theis	144	2.6	2.1E-04	4.0E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1838	5/6/99	360	840-898	60	290.4	64.1		Theis	130	2.3	6.7E-05	1.1E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1300	5/6/99	360	797-850	56	266.0	64.1		Theis	86	1.6	1.2E-04	2.1E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
aha4	Ft. Union/ Big George	Campbell County	1300	5/6/99	360	889-951	58	318.3	64.1		Theis	86	1.6	7.3E-05	1.3E-06	N/A	confined	w.l.. > top of aquifer. K & S_s based on avg coal thickness = 55 ft
kmcc2, hitt2, wwrc1	Ft. Union/ Wyodak-Anderson	Jacob's Ranch Mine T43N, R70W, Sec. 11	50	3/20/74	4000	25-52	25	17.7	1.0	4.2	Theis	5	0.2	6.9E-04	2.8E-05	N/A	confined	static w.l.. > top of aquifer. Assumed K value based on presented T & b values.
cri1, wwrc1	Ft. Union/ Wyodak-Anderson	Caballo Rojo Mine	61	11/7/78	243	138-198	71		6.9	0.4	Jacob	1353	19.0	5.0E-04	7.0E-06	N/A	confined	Assumed confined based on low S value. From Caballo Rojo Permit to Mine Application; well completion data from CD accompanying wwrc1
wwrc1	Ft. Union/ Wyodak-Anderson	Caballo Rojo Mine	30.5	11/7/78	243	186-236	72	122.0	6.9	0.6	Jacob	1112	15.6	7.0E-04	9.7E-06	N/A	confined	Static w.l.. >aq. thickness; well completion data from CD accompanying wwrc1
wwrc1	Ft. Union/ Wyodak-Anderson	Caballo Rojo Mine	73	11/7/78	2885	198-268	71	173.0	10.6	2.3	Theis	482	6.8	3.0E-04	4.2E-06	N/A	confined	Static w.l.. >aq. thickness; well completion data from CD accompanying wwrc1
wwrc1	Ft. Union/ Wyodak-	Caballo Rojo Mine	41.7	11/7/78	2885	188-263	71	171.0	11.0	3.0	Theis	402	5.7	5.0E-04	7.0E-06	N/A	confined	Static w.l.. >aq. thickness; well

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
	Anderson																	completion data from CD accompanying wwrc1
hitt2, wwrc1	Ft. Union/ Wyodak-Anderson	Coal Creek Mine T46N, R70W, Sec. 17, BB	31.4	6/13/75	300	109-145	37	71.3	3.6	4.0	Theis	46	1.5	1.0E-03	2.7E-05	N/A	confined	static w.l.. > top of aquifer
hitt2, wwrc1	Ft. Union/ Wyodak-Anderson	Coal Creek Mine T46N, R70W, Sec. 19, AC	80	5/17/75	240	46-90	34	15.1	43.6	2.9	Theis	1113	32.7	5.6E-04	1.6E-05	N/A	confined	static w.l.. > top of aquifer
tbcc2, hitt2	Ft. Union/ Wyodak-Anderson	Coal Creek Mine T46N, R70W, Sec. 29, CC	61.4	5/15/75	240	119-139	35	48.1	19.3	2.5	Theis	569	7.3	3.2E-04	9.1E-06	N/A	confined	static w.l.. > top of aquifer
tbcc2, hitt2, wwrc1	Ft. Union/ Wyodak-Anderson	Coal Creek Mine T46N, R70W, Sec. 32, CA	77.9	6/11/75	240	148-175	35	94.0	16.2	3.5	Theis	256	7.4	4.7E-04	1.3E-05	N/A	confined	static w.l.. > top of aquifer
kmcc1	Ft. Union/ Wyodak-Anderson	East Gillette/Clovis Mine T40N, R71W, Sec. 29	74	8/7/79	1440	195-275	104		22.0	8.5		218	2.1	6.4E-04	6.2E-06	N/A	confined	Assumed confined based on low S value.
kmcc1	Ft. Union/ Wyodak-Anderson	East Gillette/Clovis Mine T50N, R71W, Sec. 20	50	10/22/76	486	217-237	100		3.4	4.6		33	0.3	5.2E-04	5.2E-06	N/A	confined	Assumed confined based on low S value.
kmcc1	Ft. Union/ Wyodak-Anderson	East Gillette/Clovis Mine T50N, R71W, Sec. 29	99	8/7/79	1440	200-190	119		22.0	6.4		178	1.5	7.1E-04	6.0E-06	N/A	confined	Assumed confined based on low S value.
kmcc1	Ft. Union/ Wyodak-Anderson	East Gillette/Clovis Mine T50N, R71W, Sec. 29	164	8/7/79	1440	170-190	55		22.0	8.2		119	2.2	6.5E-04	1.2E-05	N/A	confined	Assumed confined based on low S value.
kmcc1	Ft. Union/ Wyodak-Anderson	East Gillette/Clovis Mine T50N, R71W, Sec. 29	101	11/3/76	816	135-155	99		7.7	2.0		84	0.9	3.2E-03	3.2E-05	N/A	confined	Assumed confined based on low S value.
hitt2	Ft. Union/ Wyodak-Anderson	East Gillette/Clovis Mine T50N, R71W, Sec.			1956							517		1.1E-01	N/A	0.11000	unconfined	Assumed unconfined based on high S value.

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
		29, AD																
soc1, wwrc1	Ft. Union/ Wyodak-Anderson	North Rochelle Mine T42N, R70W Sec. 9	38	7/5/80	2866	290-350	62	227.0	3.0	1.3	Boulton	188	3.0	2.9E-04	4.7E-06	N/A	confined	assumed confined based on saturated thicknesses reported in analysis from North Rochelle Permit to Mine Application & well completion data from CD accompanying wwrc1
hitt2	Ft. Union/ Wyodak-Anderson	T47N, R72W, Sec. 7			600							9		1.1E-02	N/A	0.01100	unconfined	Assumed unconfined based on high S value.
hitt2	Ft. Union/ Wyodak-Anderson	T47N, R72W, Sec. 7			600							19		1.0E-02	N/A	0.01000	unconfined	Assumed unconfined based on high S value.
wrdc1	Ft. Union/ Wyodak-Anderson	Wyodak Mine; T50N, R71W, Sec 33, BB	10	4/21/83	1440	119-178	58	89.0	19.2	12.3	Theis & Jacob	48	1.0	4.0E-03	6.9E-05	N/A	confined	static w.l.. > top of aquifer
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	415	3/25/00	864	291-361	93	242.3	25.6		Theis	1512.0	20.2	8.6E-04	9.2E-06	0.00086	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	750	3/25/00	864	307-377	70		25.6		Theis	2044.8	27.3	4.2E-04	5.9E-06	0.00042	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	750	3/25/00	864	307-377	70	257.2	25.6		Theis	2476.8	33.0	1.9E-04	2.7E-06	0.00019	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	360	3/25/00	864	296-366	70	261.4	25.6		Theis	1684.8	22.5	1.3E-04	1.9E-06	0.00013	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	860	3/25/00	864	375-445	70	259.3	25.6		Theis pumping & recovery	1584.0	21.1	1.5E-04	2.1E-06	0.00015	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	470	3/25/00	864	302-362	60	249.2	25.6		Theis pumping & recovery	2736.0	36.5	4.1E-05	6.8E-07	0.00004	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	390	3/25/00	864	302-362	74	256.0	25.6		Theis	1440.0	19.2	1.3E-04	1.8E-06	0.00013	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	750	3/28/00	720	291-361	93	242.4	22.5		Theis	1324.8	17.7	2.7E-04	2.9E-06	0.00027	confined	assumed confined based on low S value
aha8	Wyodak	Belle Ayr	720	3/28/00	720	307-377	70		22.5		Theis	1440.0	19.2	3.4E-04	4.9E-06	0.00034	confined	assumed confined

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
	Coal	Mine T47N, R72W																based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	720	3/28/00	720	307-377	70	258.5	22.5		Theis	1105.9	14.7	2.7E-04	3.9E-06	0.00027	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	170	3/28/00	720	296-366	70	260.8	22.5		Theis	779.0	10.4	6.2E-04	8.9E-06	0.00062	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	460	3/28/00	720	375-445	70	260.0	22.5		Theis pumping & recovery	1081.4	14.4	3.1E-04	4.4E-06	0.00031	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	500	3/28/00	720	302-362	60	249.2	22.5		Theis pumping & recovery	1113.1	14.8	2.3E-04	3.8E-06	0.00023	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	390	3/28/00	720	304-364	60	250.9	22.5		Theis	1009.4	13.5	2.8E-04	4.7E-06	0.00028	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	980	3/31/00	360	291-361	93	243.1	16.1		Theis pumping & recovery	1828.8	24.4	3.6E-04	3.9E-06	0.00036	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	530	3/31/00	360	307-377	70		16.1		Theis pumping & recovery	951.8	12.7	3.9E-04	5.6E-06	0.00039	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	530	3/31/00	360	307-377	70	259.1	16.1		Theis	590.4	7.9	3.3E-04	4.7E-06	0.00033	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	420	3/31/00	360	296-366	70	260.9	16.1		Theis	766.1	10.2	4.2E-04	6.0E-06	0.00042	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	480	3/31/00	360	302-362	74	256.0	16.1		Theis	256.3	3.4	9.0E-05	1.2E-06	0.00009	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	515	3/31/00	360	302-362	60	250.3	16.1		Theis pumping & recovery	1201.0	16.0	3.0E-04	5.0E-06	0.00030	confined	assumed confined based on low S value
aha8	Wyodak Coal	Belle Ayr Mine T47N, R72W	780	3/31/00	360	304-364	60	251.4	16.1		Theis pumping & recovery	1620.0	21.6	1.4E-04	2.3E-06	0.00014	confined	assumed confined based on low S value
aha5	Wyodak Coal	Belle Ayr Mine T47N, R72W, Sec 1, DA							13.0			1400.0		5.6E-04		0.00056	confined	assumed confined based on low S value
aha5	Wyodak Coal	Belle Ayr Mine T47N, R72W, Sec 1, DA							13.0			1540.0		5.4E-04		0.00054	confined	assumed confined based on low S value
aha5	Wyodak Coal	Belle Ayr Mine T47N,							13.0			1400.0		6.0E-04		0.00060	confined	assumed confined based on low S value

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
		R72W, Sec 1, DA																
aha5	Wyodak Coal	Belle Ayr Mine T47N, R72W, Sec 1, DA							13.0			1430.0		3.4E-04		0.00034	confined	assumed confined based on low S value
tbcc1, wwrc1	Wyodak Coal	Black Thunder Mine T43N, R70W, Sec.22	N/A	8/9/73	470	37-97	Assumed 60	96.5	50.0	1.2	Cooper-Jacob	2674	74	1.0E-02	N/A	0.01000	unconfined	Assume coal unconf. by 37 ft overburden and gravity drainage complete; sat. thick. < coal thickness
tbcc1, wwrc1	Wyodak Coal	Black Thunder Mine T43N, R70W, Sec.27	30	6/8/73	210	42-117	Assumed 75		4.6	5.7	Cooper-Jacob	80	2	2.0E-03	N/A	0.00200	unconfined	Assume coal unconf. by 42 ft overburden and gravity drainage complete; sat. thick. < coal thickness, stated unconfined in original analysis
tbcc1	Wyodak Coal	Black Thunder Mine T43N, R70W, Sec.27	24.5	6/8/73	210	42-112	Assumed 70		4.6	5.8	Cooper-Jacob	109	2	1.9E-03	N/A	0.00190	unconfined	Assume coal unconf. by 37 ft overburden and gravity drainage complete; sat. thick. < coal thickness, stated unconfined in original analysis
tbcc1, wwrc1	Wyodak Coal	Black Thunder Mine T43N, R70W, Sec.27	39.5	6/12/73	300	assumed 42-116	Assumed 74		13.0	62.0	Cooper-Jacob	61	2.5	6.9E-04	N/A	0.00069	unconfined	Assume coal unconf.; sat. thickness < assumed coal thickness; overburden 42 ft based on wells BTR-12 and BTR-12B, stated unconfined in original analysis
fump1	Wyodak Coal	Fort Union Mine T50N, R71W, Sec.7		Not reported	Not reported	218-290	80	200.0	Not reported	6.0	Theis	92	1.15	3.2E-04	4.0E-06	N/A	confined	Static w.l.. >depth to top of aquifer
fump1	Wyodak Coal	Fort Union Mine T50N, R71W, Sec.7		Not reported	Not reported	240-310	80	210.0	Not reported	1.0	Theis	92	1.15	4.6E-04	5.8E-06	N/A	confined	Static w.l.. >depth to top of aquifer
fump1	Wyodak Coal	Fort Union Mine T50N, R71W, Sec.7		Not reported	Not reported	260-315	65	203.0	Not reported	2.0	Theis	45	0.71	1.0E-04	1.5E-06	N/A	confined	Static w.l.. >depth to top of aquifer
fump1	Wyodak Coal	Fort Union Mine T50N, R71W, Sec.7		Not reported	Not reported	211-288	65	178.0	Not reported	3.0	Theis	92	1.43	6.1E-04	9.4E-06	N/A	confined	Static w.l.. >depth to top of aquifer
prcc1	Wyodak Coal	N. Antelope Mine T42N, R70W, Sec.	54.4	8/22/95	252	340-400	60		16.5			1472	25	2.3E-04	3.8E-06	N/A	confined	Assume coal confined by 340 ft of overburden.

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
		28																
prcc1	Wyodak Coal	N. Antelope Mine T42N, R70W, Sec. 30	48.6	8/31/95	315	330-390	60		14.5			3980	66	9.9E-04	1.7E-05	N/A	confined	Assume coal confined by 330 ft of overburden.
prcc1	Wyodak Coal	N. Antelope Mine T42N, R71W, Sec. 26	41.7	9/6/95	240	336-396	60		7.3			2824	47	5.8E-04	9.7E-06	N/A	confined	Assume coal confined by 336 ft of overburden.
aha7	Wyodak Coal	T46N, R72W, Sec. 16, AC	75	6/15/87	240	870-868			3.7		Cooper-Jacob	125	1.3	1.9E-04			confined	Static w.l.. >depth to top of aquifer
aha7	Wyodak Coal	T46N, R72W, Sec. 16, AC	99	6/15/87	240	860-888			3.7		Cooper-Jacob	99	1.0	2.4E-04			confined	Static w.l.. >depth to top of aquifer
aha7	Wyodak Coal	T46N, R72W, Sec. 16, AC	65.5	6/15/87	240	861-892	96		3.7		Cooper-Jacob	114	1.2	2.1E-04	2.1E-06		confined	Static w.l.. >depth to top of aquifer
aha7	Wyodak Coal	T46N, R72W, Sec. 16, AC	75	6/13/87	240	795-849	96		5.2		Cooper-Jacob	116	1.2	2.7E-04	2.8E-06		confined	Static w.l.. >depth to top of aquifer
aha7	Wyodak Coal	T46N, R72W, Sec. 16, AC	75	7/18/80	900	795-849	96	338.2	3.0	1.8	Cooper-Jacob	154	1.6	1.6E-04	1.7E-06		confined	Static w.l.. >depth to top of aquifer
aha7	Wyodak Coal	T46N, R72W, Sec. 16, AC	70	7/18/80	900	860-888	76	333.1	3.0	1.8	Cooper-Jacob	3	0.04	1.7E-05	2.2E-07		confined	Static w.l.. >depth to top of aquifer, K assumed from given T and aq thickness
aha7	Wyodak Coal	T46N, R72W, Sec. 16, AC	70	7/16/80	1080	870-868	75	337.1	3.2	1.8	Cooper-Jacob	3	0.04	1.6E-05	2.1E-07		confined	Static w.l.. >depth to top of aquifer, K assumed from given T and aq thickness
aha7	Wyodak Coal	T47N, R72W, Sec. 16		8/9/80	20	665-695		197.0	8.2		Cooper-Jacob	286		7.9E-04			confined	Static w.l.. >depth to top of aquifer
hitt1 (a)	Coal	Buckskin Mine T52N, R72W, Sec. 32					120					584	4.9	2.3E-04	1.9E-06	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
hitt1 (a)	Coal:	Buckskin Mine T52N, R72W, Sec. 32					120					701	5.8	4.8E-04	4.0E-06	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
hitt1 (a)	Coal:	Buckskin Mine T52N, R72W, Sec. 32					120					619	5.2	1.7E-03	1.4E-05	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
hitt1 (a)	Coal:	Buckskin Mine T52N, R72W, Sec. 32					120					568	4.7	2.4E-04	2.0E-06	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
hitt1 (a)	Coal:	Buckskin Mine T52N, R72W, Sec. 32					120					536	4.5	5.8E-04	4.8E-06	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
hitt1 (a)	Coal:	Buckskin Mine T52N, R72W, Sec. 32					120					473	3.9	1.8E-03	1.5E-05	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
hitt1 (a)	Coal:	Buckskin Mine T52N, R72W, Sec. 32					90					1233	13.7	4.9E-04	5.4E-06	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
aha3	Coal:	Caballo Mine; T48N, R71W, Sec. 24	10	7/15/85	1400	63-83	38	51.8	2.3	8.7	Jacob	22.0	0.7	7.0E-04	N/A	0.00070	unconfined	static w.l.. < top of aquifer; Assumed K value based on presented T & b values.
aha3	Coal:	Caballo Mine; T48N, R71W, Sec. 24	10	7/15/85	1400	63-83	32	53.0	2.3	11.8	Jacob	12.5	0.5	4.0E-03	N/A	0.00400	unconfined	static w.l.. < top of aquifer; Assumed K value based on presented T & b values.
hitt1 (a)	Coal & Sandstone	Buckskin Mine T52N, R72W, Sec. 32					140					898	35.9	4.8E-04	3.4E-06	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
hitt1 (a)	Coal & Sandstone	Buckskin Mine T52N, R72W, Sec. 32					140					898	35.9	3.8E-04	2.7E-06	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
hitt1 (a)	Coal & Sandstone	Buckskin Mine T52N, R72W, Sec. 32					140					898	35.9	8.5E-04	6.1E-06	N/A	confined	Assumed K value based on presented T & b values. No well names or specific locations given.
											MIN	2.99	0.04	1.6E-05	2.1E-07	4.1E-05		

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
											MAX	**3980.00**	**74.27**	**1.1E-01**	**1.9E-04**	**1.1E-01**		
											MEDIAN	**129.60**	**1.99**	**3.0E-04**	**3.8E-06**	**3.1E-04**		
											ARITH MEAN	**557.27**	**8.17**	**1.7E-03**	**8.5E-06**	**3.1E-03**		
Wasatch Coals																		
hitt1 (c)	Wasatch/ Felix #1	T47N, R72W, Sec. 7					9					32		2.0E-02	N/A	0.02000	unconfined	Assumed unconfined based on high S value. No well names or specific locations given.
hitt1 (c)	Wasatch/ Felix #1	T47N, R72W, Sec. 7					9					96		2.0E-02	N/A	0.02000	unconfined	Assumed unconfined based on high S value. No well names or specific locations given
hitt1 (c)	Wasatch/ Felix #1	T47N, R72W, Sec. 7					9					57		2.0E-02	N/A	0.02000	unconfined	Assumed unconfined based on high S value. No well names or specific locations given.
hitt1 (c)	Wasatch/ Felix #1	T47N, R72W, Sec. 7					25					88		1.6E-02	N/A	0.01600	unconfined	Assumed unconfined based on high S value. No well names or specific locations given

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
											MIN	**31.9**	**N/A**	**1.6E-02**	**N/A**	**0.01600**		
											MAX	**96.1**	**N/A**	**2.0E-02**	**N/A**	**0.02000**		
											MEDIAN	**72.5**	**N/A**	**2.0E-02**	**N/A**	**0.02000**		
											ARITH MEAN	**68.2**	**N/A**	**1.9E-02**	**N/A**	**0.01900**		

Wasatch Sands

aha6	Wasatch: sand	Ruby Ranch Project Area				285-305	35	189.1				328	9.4	1.3E-04	3.7E-06	0.00013	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					40					246	6.1	8.2E-05	2.0E-06	0.00008	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					45					426	9.5	1.7E-04	3.8E-06	0.00017	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					45					457	10.2	1.7E-05	3.8E-07	0.00002	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					40					222	5.6	2.8E-05	7.0E-07	0.00003	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					57			1.0		361	0.0	1.1E-04	1.9E-06	0.00011	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					36					199	5.5	3.0E-02	8.3E-04	0.03000	confined	not consistent w/ previously reported T
aha6	Wasatch: sand	Ruby Ranch Project Area					48					747	15.6	9.0E-04	1.9E-05	0.00090	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					35					524	15.0	4.0E-05	1.2E-06	0.00004	confined	Assumed confined in analysis

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
aha6	Wasatch: sand	Ruby Ranch Project Area					55					892	16.2	1.7E-04	3.1E-06	0.00017	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					33					665	20.2	2.3E-06	7.1E-08	0.00000	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					44					487	11.1	5.0E-05	1.1E-06	0.00005	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					42					129	3.1	2.3E-04	5.5E-06	0.00023	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					36					137	3.8	7.8E-05	2.2E-06	0.00008	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					50					340	6.8	7.6E-05	1.5E-06	0.00008	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					50					269	5.4	8.6E-05	1.7E-06	0.00009	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					50					270	5.4	1.1E-04	2.2E-06	0.00011	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					37					238	6.4	5.9E-05	1.6E-06	0.00006	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					55					348	6.3	3.5E-03	6.4E-05	0.00350	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area				273-318	38	193.2				143	3.8	8.3E-05	2.2E-06	0.00008	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					33					207	6.3	6.1E-05	1.8E-06	0.00006	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					39					87	2.2	5.3E-03	1.4E-04	0.00530	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					35					116	3.3	7.3E-04	2.1E-05	0.00073	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					24					76	3.2	6.8E-04	2.8E-05	0.00068	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					44					100	2.3	1.4E-04	3.1E-06	0.00014	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					20					106	5.3	7.2E-05	3.6E-06	0.00007	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					20					61	3.1	2.5E-04	1.2E-05	0.00025	confined	Assumed confined in analysis
aha6	Wasatch: sand	Ruby Ranch Project Area					20					95	4.7	3.3E-05	1.7E-06	0.00003	confined	Assumed confined in analysis
prcc1	Wasatch pumped; obs coal	N. Antelope Mine T41N, R71W, Sec. 5		4/24/90	320	113-173	80		0.5		Wither-spoon	1	0.02	4.1E-03	N/A	0.00410	unconfined	Coal had drawdown during overburden pumping, assume coal communicates with and is unconfined by leaky overburden and gravity drainage complete.
fump1	Wasatch:	Fort Union Mine T50N,		Not reported	Not reported	87-207	120	76.0	Not reported	23.0	Theis recovery	485	4.032	7.0E-04	5.8E-06	N/A	confined	Static w.l.. > top of aquifer

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
		R72W, Sec.13																
fump1	Wasatch:	Fort Union Mine T50N, R72W, Sec.13		Not reported	Not reported	97-217	115	78.0	Not reported	20.0	Theis recovery	432	3.744	1.6E-04	1.4E-06	N/A	confined	Static w.l.. > top of aquifer
fump1	Wasatch:	Fort Union Mine T50N, R72W, Sec.13		Not reported	Not reported	89-209	120	76.0	Not reported	14.0	Theis recovery	598	4.896	3.9E-04	3.3E-06	N/A	confined	Static w.l.. > top of aquifer
fump1	Wasatch:	Fort Union Mine T50N, R72W, Sec.13		Not reported	Not reported	92-248	80	87.0	Not reported		Theis recovery	1214	14.4	4.0E-04	5.0E-06	N/A	confined	Static w.l.. > top of aquifer
cmc2	Wasatch:	Rawhide Mine; T51N, R72W, Sec. 11	40	7/7/83	9900	167-187	44		16.5	4.2	Neuman	178		1.3E-01	N/A	0.13000	unconfined	Assume unconfined based on high S value.
cmc2	Wasatch:	Rawhide Mine; T51N, R72W, Sec. 11	120	7/7/83	9900	162-182	45		16.5	1.3	Neuman	106		1.9E-01	N/A	0.19000	unconfined	Assume unconfined based on high S value. Static w.l.. after drilling = 133.5 ft
mel1	Wasatch: Ft. Un ss	Sheridan County T4N, R84W, Sec.5		6/61?	1440		12	15.0	Not reported		Theis & Cooper-Jacob	13	1.1	3.5E-04	2.9E-05	N/A	confined	Assume confined based on low S value.
mel1	Overburd. Ft. Union ss	Sheridan County T55N, R84W, Sec.27		6/61?	80		4		Not reported		Theis recovery	1	0.3	9.0E-05	2.3E-05	N/A	confined	Assume confined based on low S value.
hitt2	Overburd. Wyodak-Anderson Coal	T41N, R70W, Sec. 17			1260				86.0		Hantush, Jacob	200		7.9E-05	2.0E-05	N/A	confined	Assume confined based on low S value. Antelope Creek; test employed pumping well & 3 obs wells at varying unspecified distances; data presented is averaged
hitt2	Overburd. Wyodak-Anderson Coal	T44N, R71E, Sec. 34			960				85.0		Theis, Jacob	352		1.4E-04	3.5E-05	N/A	confined	Assume confined based on low S value. Stewart; test employed pumping well & 1 obs wells at an unspecified distance; data presented is averaged
hitt2	Overburd. Wyodak-Anderson Coal	T44N, R71W, Sec. 34, DA			900							352		1.4E-04	3.5E-05	N/A	confined	Assume confined based on low S value.

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
tcc1	Intbrdn between Anderson & Rider Coals	Buckskin Mine; T52N, R 73W, Sec. 25, BA	50	7/27/88	720	293-335	23		2.7	5.7	Theis & Jacob	38	3.1	8.0E-05	2.0E-05	N/A	confined	Assume confined based on low S value and 293 ft overburden.
cri1, wwrc1	Wasatch:	Caballo Rojo Mine	43.75	11/8/78	75	55-155	57	49.0	7.0	0.6	Theis	182	3.2	2.1E-02	5.3E-03	N/A	confined	Static w.l.. >aq. thickness; well completion data from CD accompanying wwrc1
cri1, wwrc1	Wasatch:	Caballo Rojo Mine	22.6	11/8/78	75	70-120	57	53.8	7.0	2.6	Jacob	117	2.0	3.2E-03	8.0E-04	N/A	confined	Static w.l.. >aq. thickness; well completion data from CD accompanying wwrc1
											MIN	**1.3**	**0.0**	**2.3E-06**	**7.1E-08**	**0.00000**		
											MAX	**1213.9**	**20.2**	**1.9E-01**	**5.3E-03**	**0.19000**		
											MEDIAN	**222.5**	**5.1**	**1.4E-04**	**3.7E-06**	**0.00011**		
											ARITH MEAN	**291.8**	**6.1**	**9.2E-03**	**1.8E-04**	**0.01185**		

Wasatch Clay Confining Units

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
aha6	upper confining unit for sand	Ruby Ranch Project Area									Neuman-Wither-spoon		9.5E-05		5.3E-05			Reported hydraulic conductivity is Kz,, t=4600
aha6	upper confining unit for sand	Ruby Ranch Project Area									Neuman-Wither-spoon		5.5E-05		2.1E-05			Reported hydraulic conductivity is Kz, t=6215
aha6	upper confining unit for sand	Ruby Ranch Project Area									Neuman-Wither-spoon		5.5E-05		1.3E-05			Reported hydraulic conductivity is Kz, t=6215
aha6	upper confining unit for sand	Ruby Ranch Project Area									Neuman-Wither-spoon		4.4E-05		1.3E-05			Reported hydraulic conductivity is Kz, t=6215
aha6	upper confining unit for sand	Ruby Ranch Project Area									Neuman-Wither-spoon		7.7E-05					Reported hydraulic conductivity is Kz, t=2850

PRB Hydrogeologic Data from Pumping Tests

Ref No.	Aquifer	Location	Observ. Dist. from Test Well (ft)	Date Tested	Test Period (min)	Screened Interval (ft)	Reported Aquifer Thickness (ft)	Static W.L. (fbgs)	Pump Rate (gpm)	Final Draw-down (ft)	Analysis Method	T (ft^2/day)	K (ft/day)	Reported Storage Coef. (S)	Specific Storage (ft-1)	Specific Yield (S_y = S)	Confined/ Unconfined (see comments)	Comments
aha6	upper confining unit for sand	Ruby Ranch Project Area									Neuman-Wither-spoon		3.1E-02		6.2E-05			Reported hydraulic conductivity is Kz, t=68
aha6	upper confining unit for sand	Ruby Ranch Project Area									Flexible-wall permeability		2.4E-05					Reported hydraulic conductivity is Kz
aha6	upper confining unit for sand	Ruby Ranch Project Area									Neuman-Wither-spoon		7.7E-05					Reported hydraulic conductivity is Kz
											MIN		**2.4E-05**		**5.3E-05**			
											MAX		**3.1E-02**		**6.2E-05**			
											MEDIAN		**6.6E-05**		**2.1E-05**			
											ARITH MEAN		**4.0E-03**		**2.4E-03**			

REFERENCES - PRB PUMPING TESTS

Ref No.	Reference	Area	Aquifer Data
aha1	Project files (PR 120) containing PRB depositional environment study. Author and date unknown.	PRB, Campbell Co	Summary table of well test results including T & S. 8 wells in Anderson Coal, 4 wells in overburden.
aha4	Applied Hydrology Associates. October 1999. Proprietary technical report.	PRB, Campbell Co	Multiple obs well test results for numerous pumping tests in Big George coal; T, S, Ss, K, k. Good data.
aha3	Applied Hydrology Associates. 1985. Project files (PR 85 003) for Carter Mining Company Caballo Mine south of Gillette.	PRB, Gillette, WY	Raw test data and analysis plots for multiple-well pumping test in July 1985. T & S (shallow, unconfined Wyodak coal)
aha2	Applied Hydrology Associates. 1985. Project files (RH-12-14) for summary of hydrologic testing at Rocky hill No. 1 Site.	PRB, Rocky Hill	Well construction data, stratigraphy and injection test analysis (T, K values)
aha5	Applied Hydrology Associates. 1998. Project files for hydrologic testing at the Belle Ayr Mine.	PRB, Belle Ayr Mine	T, S values derived for 4 wells during a multi-well pumping test
aha6	Hydrologic testing at the Ruby Ranch Project. 1999. From U.S. NRC and WDEQ Application, Appendix D6.	PRB, Ruby Ranch	Well construction data, aquifer test results for single-well and multi-well pumping tests in sands. Includes some vertical hydraulic conductivity data.
aha7	Applied Hydrology Associates. 1987. Project files for hydrologic testing of Lindsey (T46N, R72W, Sec. 16) and Red Top (T47N, R72W, Sec. 16) sections, Campbell County, WY.	PRB, Campbell Co	Well construction data, aquifer test results for multiple-well pumping tests.
aha8	Applied Hydrology Associates. 2000. Project files for hydrologic testing at the Belle Ayr Mine, Campbell County, WY.	PRB, Belle Ayr Mine	Well construction data, aquifer test results for multiple-well pumping tests.
aha9	Applied Hydrology Associates. December 2001. Proprietary technical report.	PRB, Johnson County	Multiple obs well test results for numerous pumping tests in Big George coal; T, S, Ss, K, k. Good data.
ak1	Anderson & Kelly. [date and report title unknown]. Wright Water & Sewer District RJ-4 well strat. & as-built, diagram and test data.	PRB, Wright, WY	RJ-4 well test data - drawdown & recovery tests results; ave T for composite of 13 Fort Union ss beds open to 13 screened intervals. [includes S from Theis type-curve method -invalid for single well test]
cmc1	Carter Mining Company. March 1982 (rev October 1982). Caballo Mine permit application 433-T3. Appendix D-6, Addendum E.	PRB, Caballo mine, south of Gillette	Appendix D-6. Well and aq test text and data for ovbd sand. Pumped well and 5 obs wells. T& S.

REFERENCES - PRB PUMPING TESTS

Ref No.	Reference	Area	Aquifer Data
cmc2	Carter Mining Company. November 1993. Rawhide Mine 240-T3 permit application. Appendix D6.	PRB, Rawhide Mine north of Gillette	Appendix D-6. 25-30 well test results. Coal, alluvium, ovrb, and clinker tests
df1	Dry Fork Coal Company. March 2000. Permit No. 599.	PRB, Dry Fork Mine	Appendix D-6, Table D-6-2. Summary of 44 aquifer test results. Mostly single well tests; 5 S results
fump1	Fort Union Mine Partnership. December 1990. Fort Union Mine permit application. Appendix D6	PRB, Fort Union Mine, Gillette	Appendix D-6 info prepared by Western Water Consultants and Hydro-Engineering. Well and aq data for 2 pit areas, Tables D6-3 and D6-4; alluv, clinker, coal, ovrb, sands,
hitt1	Hittman Associates. February 1978. Monitoring and modeling of the shallow groundwater in the Powder River Basin, Annual Technical Report. Prepared for U.S. Bur. Mines. Hittman Associates, Inc., Englewood, Colorado.	PRB	Listing of private and coal company monitoring wells in MT and WY. Summary of aquifer test data (T & S) obtained from 4 sources in 4 different townships (Table IV-3, pp. IV-6 & IV-7) in WYO (3) and MT (Decker). (a) "Analysis of Constant Yield Tests of Wells CT-1, CT-2 and OT-2B Buckskin Mine Property, Campbell Co., WY" for Shell Oil Co. (b) "Report on Aquifer Tests for U.S. Coal Lease W-5036 Near Gillette, WY" for Carter Oil Co. (c) "Evaluation of Native Hydraulic Characteristics of the Felix Coal and Associated Strata" for U.S. Energy Research & Development Administration by Lawrence Livermore Lab.
hitt2	Hittman Associates. July 1982. Monitoring and modeling of shallow Ground Water Systems in the Powder River Basin. (Report and Appendices in sep volumes). Prepared for U.S. Bur. Mines. Hittman Associates, Inc., Englewood, Colorado.	PRB	Summary of pumping test results (4 sites, T & S, Table III-1, p. III-9); Appendix E includes 5 page summary of PRB aquifer test data (T & S) for ovbd and coal, which IDs mining company source.
mdsl1	Montana Department of State Lands and U.S. Office of Surface Mining. April 1985. Draft EIS, Consolidation Coal Company CX Ranch Mine, Big Horn County, Montana.	PRB, west of Decker, MT	Limited to summary. Table 2-3, ch 31. Provides T and S ranges for alluvium, ovbrdn, Anderson/Dietz and Canyon coals. Fig. 2-5, p. 33 is potentiometric surface map of Anderson-Dietz coal seam for July 1980 levels.

REFERENCES - PRB PUMPING TESTS

Ref No.	Reference	Area	Aquifer Data
mel1	Lowry, M.E. and T. R. Cummings. 1966. Ground-water resources of Sheridan County, Wyoming. U.S. Geological Survey Water-Supply Paper 1807.	Sheridan Co., WY	Table 2 lists pumping test results for 6 wells; 3 ss aqs., 1 Wasatch coal, and 2 alluv. Log for coal well 54-81-14bc on p. 68
osmre1	Office of Surface Mining Reclamation and Enforcement. March 1989. Proposed mining plan, Dry Fork Mine, Campbell County, Wyoming. Final environmental impact statement OSMRE-EIS-24.	PRB, Dry Fork Mine	Appendix D includes hydraulic parameter summary tables (pp. D-8 & D-9) for several mines in Dry Fork Mine area.
prcc1	Powder River Coal Company. June 1998. North Antelope/Rochelle Complex mine permit 569-T5. Appendix D-6	PRB, N. Antelope/ Rochelle mines, Wright	Appendix D-6. Well and aq data Tables D6-4 and D6-5; ovrb, coal, alluv
rehm1	Rehm, B.W., G. H. Groenewold, and K.A. Morin. 1980. Hydraulic properties of coal and related materials, Northern Great Plains. Ground Water, v. 18, no.6, Nov-Dec.	ne WY, e MT,, ND, Alberta	No well-specific data. Ave hydraulic parameters for coal and other materials by State and Province mine sites.
sno1	Snoebeerger, D. F. January 1977. Field hydrology tests of explosively fractured coal. Lawrence Livermore Laboratory, Livermore, CA.B6	PRB, Hoe Ck, sw of Gillette	Tested explosively fract. Felix No. 2 coal for in-situ coal gasification experiment. Gives k ranges by distance from shot holes. Summary, individual well results limited.
sto1	Stone, R. and D. F. Snoeberger. February 1977. Cleat orientation and areal hydraulic anisotropy of a Wyoming coal aquifer. (preprint of paper). Lawrence Livermore Laboratory, Livermore, CA	PRB, Hoe Ck, sw of Gillette	Gives summary results of anisotropic k of Felix No. 2 coal using 1 pumping well and 3 obs wells; constant rate test.
tbcc1	Thunder Basin Coal Company. July 1999. Black Thunder Mine permit 233. Appendix D-6.	PRB, Black Thunder Mine, Wright	Appendix D-6. Well and aq data Tables D-6.1.1 and D-6.1.2; ovrb, Wyodak-Anderson coal, shale, scoria, Wasatch Sand
tbcc2	Thunder Basin Coal Company. 1990. Coal Creek Mine permit update. Water Rights & Ground Water Hydrology Sections II.F.1, II.F.2, and II.F.3	PRB, Coal Creek Mine	Table II.F-2.4 summarizes pumping test results and calculated aquifer coefficients. Table II.F-2.1 summarizes well completions. Table II.F-2.1.11 shows tabulated aquifer test data and data plots.

REFERENCES - PRB PUMPING TESTS

Ref No.	Reference	Area	Aquifer Data
tcc1	Triton Coal Company. December 1989. Buckskin Mine T-3 permit application.	PRB, Buckskin Mine north of Gillette	Appendix D-6. Anderson and Canyon coals combined hydraulic data for 10 tests; ovrb and clinker tests. 79 monitoring wells in current mine database
wrdc1	Wyodak Resources Development Corp. 1983. Wyodak Mine permit 232-T5. Appendix D-6	PRB, Wyodak Mine, Gillette	Appendix D-6, Table 1, p. D6.3-91 includes test results for M-26 and M-27 in 1983 report by Western Water Consultants. Also result for M-3, M-4, M-5, M-13, M-14, M-15M-18, M-19
wvv1	Van Voast., W.A. and R.B. Hedges. December 1975. Hydrogeologic aspects of existing and proposed strip coal mines near Decker, southeastern Montana. Montana Bureau of Mines and Geology Bulletin 97.	PRB, Decker, MT	Limited. Table 1, p. 5; 5 T&K values. No S or S_y values. Table 2 lists USGS & MBMG water-well data for Decker area. Plates include piezometric maps for D-1 and D-2 coals
wwa1	Wester-Wetstein & Associates. July 1999. Transmittal letter and file folder of selected figures and data for water supply wells in Gillette area provided by Larry Wester.	PRB, Gillette, WY	Location map, lithologic log, as-built drawing, and composite Fort Union ss data for City of Gillette S-series wells, Antelope Valley, Am Rd, Sleepy Hollow, and Bell Knob supply wells.
wwc1	Western Water Consultants. June 1983. Results of aquifer pumping tests of monitoring wells M-26 and M-27 at the Wyodak mine, Gillette, Wyoming. *In* Wyodak Mine permit 232-T5. For Wyodak Resources Development Corp., Gillette, WY. Western Water Consultants, Inc., Sheridan, Wy.	PRB, Wyodak Mine, Gillette	Appendix D-6 of permit application. Table 1, p. D6.3-91 includes test results for M-26 and M-27 in 1983. Pumping test data pulled from Permit to Mine Application for applicable mines.
wwrc1	Wyoming Water Resources Center. November 1997. A study of techniques to assess surface and groundwater impacts associated with coal bed methane and surface coal mining, Little thunder Creek Drainage, Wyoming. Wyoming Water Resources Center, University of Wyoming, Laramie	PRB, Little Thunder Creek, Wright	Appendix F. Pumping test results summarized for several Wright area mines. Accompanying CD includes basic well and water level data.
hag1	Hagmaier, J.L. August 1971. Groundwater flow, hydrochemistry, and uranium deposition in the Powder River Basin, Wyoming. PhD dissertation, University of North Dakota, Grand Forks.	PRB	Appendix B. Water level & chemistry data for 208 wells in Ft. Union & Wasatch Formations in 1970.

REFERENCES - PRB PUMPING TESTS

Ref No.	Reference	Area	Aquifer Data
kmcc1	Kerr-McGee Coal Corporation. 1981. East Gillette Federal Mine permit. Appendix D-6.	PRB, East Gillette/Clovis Mine	Appendix D-6. Table D6.1-1 summarizes well completions. Table D6.1-6 summarizes pumping test results and calculated aquifer coefficients.
acc1	Antelope Coal Company.1999. Antelope Coal Mine permit revision. Appendix D6.	PRB, Antelope Mine	Appendix D6. Table V-1 summarizes pumping test results and calculated aquifer coefficients. Section 2 contains lithologic logs of observation wells.
kmcc2	Kerr-McGee Coal Corporation. 1982. Jacob's Ranch Mine permit. Appendix D-6.	PRB, Jacob's Ranch Mine	Appendix D-6. Table D6.1-1 summarizes well completions. Table D6.1-4 summarizes pumping test results and calculated aquifer coefficients. Addendum D6A contains pumping test data plots and analyses.
amax1	Amax Coal Company. 1998. Belle Ayr Mine permit 214. Volume 5, Section 2.6.2	PRB, Belle Ayr Mine	Table 2.6.2-1 summarizes monitoring well completion data. Table 2.6.2-2 summarizes pumping test data and analysis.
cri1	Caballo Rojo, Inc. 2000. Revised Caballo Rojo Mine permit 511. Appendix D-6.	PRB, Caballo Rojo Mine	Table 2.6-2 summarizes well completion data. Table 2.6-3 summarizes monitoring well status. Table 2.6-4 summarizes pumping test data and analysis.
soc1	Shell Oil Company Mining. 1982. Revised North Rochelle Mining Permit Application. Appendix D-6 & Addendum D-6C.	PRB, North Rochelle Mine	Table D-6-2 summarizes well completion data. Table D-6-3 summarizes pumping test data and analysis. Addendum D-6C includes tabulated aquifer test data and data plots.

APPENDIX C
List of Electronic Files Used for Groundwater Model (compiled by Applied Hydrology and Associates, Inc.) and Instructions for Running the Model

Electronic Files Used for Groundwater Model

File Name	File Type	Description
		Model Support Files
99PITAR1	AutoCAD (.dwg)	GAGMO outline of mine pit and backfill in Area 1
99PITAR2	AutoCAD (.dwg)	GAGMO outline of mine pit and backfill in Area 2
99PITAR3	AutoCAD (.dwg)	GAGMO outline of mine pit and backfill in Area 3
99PITAR4	AutoCAD (.dwg)	GAGMO outline of mine pit and backfill in Area 4
99PITAR5	AutoCAD (.dwg)	GAGMO outline of mine pit and backfill in Area 5
AllUnits	Excel	Goolsby data modified by AHA to create model layer elevations
alluvium	DXF	Alluvium in the PRB
alluvium_cropped	DXF	Alluvium in the PRB - used for the Caballo Creek Model
Allwellspre2000_8-14-02	DBF	DBF for associated .shp listing allo f the pre Year 2000 wells
AllWellsPre2002	DXF	Locations of all pre-2002 model wells
APPHYD 3847	Excel	Goolsby, Finley, and Assoc. coal seam elevations for Townships 38 through 47
APPHYD 38N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 38N
APPHYD 39N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 39N
APPHYD 40N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 40N
APPHYD 41N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 41N
APPHYD 43N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 43N
APPHYD 44N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 44N
APPHYD 45N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 45N
APPHYD 46N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 46N
APPHYD 47N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 47N
APPHYD 4853	Excel	Goolsby, Finley, and Assoc. coal seam elevations for Townships 48 through 53
APPHYD 48N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 48N
APPHYD 49N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 49N
APPHYD 51N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 51N
APPHYD 52N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 52N
APPHYD 53N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 53N
APPHYD 53N2	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 53N
APPHYD 54N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 54N
APPHYD 55N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 55N
APPHYD 56N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 56N
APPHYD 57N	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units at 57N
APPHYD MONT	Excel	Goolsby, Finley, and Assoc. coal seam elevations for the first township in Montana across the border
APPHYD NS CENTRAL	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units North to South in central part of PRB
APPHYD NS EAST	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units North to South in east part of PRB
APPHYD NS WEST	Acrobat PDF	Goolsby, Finley, and Assoc. geologic cross-section showing coal units North to South in west part of PRB
APPLIED HYROLOGY 54-57n	Excel	Goolsby, Finley, and Assoc. coal seam elevations for Townships 54 through 57
AREA1	AutoCAD (.dwg)	GAGMO drawdown contours for Area 1
Area1_DD	AutoCAD (.dwg)	Areal drawdown
AREA1-95DD_UTM	AutoCAD (.dwg)	GAGMO drawdown contours for Area 1 in UTM Z13m NAD 27 coordinates
AREA2	AutoCAD (.dwg)	GAGMO drawdown contours for Area 2
AREA3	AutoCAD (.dwg)	GAGMO drawdown contours for Area 3
AREA4	AutoCAD (.dwg)	GAGMO drawdown contours for Area 4
AREA5	AutoCAD (.dwg)	GAGMO drawdown contours for Area 5
Areas and Mines	DXF	Active mine pit outlines and GAGMO 15 Year drawdown (1980 to 1995)
Assign_Layer_macro	Excel	Excel Macro used to assign model layers to wells
BLM_monitoring_wel ldata_arp_02	Excel	BLM monitoring well data up to April 2002
buff_projwells_24sept	DBF	DBF for associated .shp file used to create area of development

Electronic Files Used for Groundwater Model

File Name	File Type	Description
01		
buff_projwells_24sept01	SHX	SHX for associated .shp file used to create area of development
buffwells_exist_permitted_all_merge_17oct	DBF	DBF for associated .shp file used to create area of development
buffwells_exist_permitted_all_merge_17oct	SHX	SHX for associated .shp file used to create area of development
Calibration Nodes and Layer	DXF	Model Nodes used to calibrate transient model to reported production
CBM_Drain_Nodes	DXF	Locations of existing, permitted, and proposed CBM wells represented as drain boundaries in the model.
cbm_pads_existing	DBF	DBF for associated .shp file used to locate existing CBM well pads
cbm_pads_existing	DXF	DXF file create from .shp file
cbm_pads_existing	SBN	SBN file for associated .shp file used to locate existing CBM well pads
cbm_pads_existing	SBX	SBX file for associated .shp file used to locate existing CBM well pads
cbm_pads_existing	SHX	SHX file for associated .shp file used to locate existing CBM well pads
cbm_wells_prop_2002_v2	DBF	DBF for associated .shp file used to locate proposed CBM well pads
cbm_wells_prop_2002_v2	SBN	SBN for associated .shp file used to locate proposed CBM well pads
cbm_wells_prop_2002_v2	SBX	SBX for associated .shp file used to locate proposed CBM well pads
cbm_wells_prop_2002_v2	SHX	SHX for associated .shp file used to locate proposed CBM well pads
cbmdrns3	Fortran Executable	Program used to create drain boundary shchedules for input into MODFLOW
CBMWells-Access2000--7-20-2001	Access (.mdb)	WOGCC CBM database from 7-20-2001. Contains additional tables and queries created by AHA and updated WOGC information edited by Joe Meyer of the BLM
Constratined PRB Aq Tests Results083002	Excel	Summary of aquifer test data within PRB.
Counties	DXF	Counties of the PRB
Daddow Water Level Data Wyodak Anderson Coal Bed	Excel	Table of Daddow (1986) data some which was used for steady state calibration.
Drains	Access (.mdb)	AHA created database used to place CBM wells and coal mines in the model as drain boundaries
edit_elevations3	Excel	Goolsby data modified by AHA to create model layer elevations
EIS_Outline	DXF	Outline of the PRB EIS area
EIS_Watersheds	DXF	Sub-watersheds in the PRB
ExistingCBMWells	DXF	Flowing artesian wells in Sheridan County
FlowingWells	DXF	Locatoins of flowing artesian wells in Sheridan County
FlowingWellsand Rates	DXF	Locations and flow rate of flowing artesian wells in Sheridan County.
greystone 1 well per pad	DBF	DBF for associated .shp file showing the locations of well pads with one well
greystone 1 well per pad	SBN	SBN for associated .shp file showing the locations of well pads with one well
greystone 1 well per pad	SBX	SBX for associated .shp file showing the locations of well pads with one well
greystone 1 well per pad	SHX	SHX for associated .shp file showing the locations of well pads with one well
greystone 2 well per pad	DBF	DBF for associated .shp file showing the locations of well pads with two well
greystone 2 well per pad	SBN	SBN for associated .shp file showing the locations of well pads with two well

Electronic Files Used for Groundwater Model

File Name	File Type	Description
greystone 2 well per pad	SBX	SBX for associated .shp file showing the locations of well pads with just one well
greystone 2 well per pad	SHX	SHX for associated .shp file showing the locations of well pads with just one well
greystone 3 well per pad	DBF	DBF for associated .shp file showing the locations of well pads with just one well
greystone 3 well per pad	SBN	SBN for associated .shp file showing the locations of well pads with just one well
greystone 3 well per pad	SBX	SBX for associated .shp file showing the locations of well pads with just one well
greystone 3 well per pad	SHX	SHX for associated .shp file showing the locations of well pads with just one well
gridextract	Fortran Executable	Program used to extract the row, column, and elevation of each grid node for each layer from the model .bcf file and put the data into i,j,z .txt format.
Kl_Wells	DXF	Lebo wells in Sheridan County
LAKES	DXF	Lakes in the PRB
LXBAR_BOUNDARY_feet	DXF	LX Bar groundwater model boundary
LXBAR_RIVERNAMES_feet	DXF	LX Bar groundwater model river names
LXBAR_RIVERS_feet2	DXF	LX Bar groundwater model rivers
LXBAR_SECTIONS_feet	DXF	LX Bar groundwater model sections
LXBAR_TOWNSHIPS_feet	DXF	LX Bar groundwater model townhips
LXBAR_WATERSHED_feet	DXF	LX Bar groundwater model watershed
merged coals	DBF	DBF for associated .shp showing the areal extent of the coals
merged coals	SHX	SHX for associated .shp showing the areal extent of the coals
mine_drains	Fortran Executable	Program used to change mine progression data form .txt (i,j,z) into a .vmb compatible format.
mines_progression	DXF	Shows all mines and mine plans in the PRB
ModelGrid	DXF	Map of the model grid (1/4 mile x 1/4 mile)
MunicipalPumpingWells	DXF	Locations of the municipal pumping wells on the eastern half of the PRB
MunicipalPumpingWells	Excel	Locations and pumping schedules for the municipal wells
ObservationWell	Access (.mdb)	AHA created database used to place BLM observation well data in the model.
prb coal seam development	DBF	DBF for associated .shp file
prb coal seam development	SHX	SHX for associated .shp file
PRB_Topo_UTM	Text	Text file (X,Y,Z) created from translated USGS DEM 1:250,000 files to create to model surface topo.
PRBOutcropPlus	DXF	Wyodak-Anderson outcrop (inferred where data does not exist on the Crow reservation)
PRBOutcropPlus_cropped	DXF	Wyodak-Anderson outcrop (inferred where data does not exist on the Crow reservation) - used for the Caballo Creek Model
Production Per Watershed Per Year	Excel	Model predicted produced water per year per wathershed

Electronic Files Used for Groundwater Model

File Name	File Type	Description
Qal_Wells	DXF	Alluvial wells in Sheridan County
Qt_Wells	DXF	Tongue Fm wells in Sheridan County
Reinfiltration_FromPRBEIS_OneModel	Excel	Model predicted production turned into an equivalent recharge rate
Rivers	DXF	Rivers in the PRB
Rivers_cropped	DXF	Rivers in the PRB - used for the Caballo Creek Model
Roads	DXF	Roads in the PRB
Scoria	DXF	Scoria in the PRB
SECTIONS	DXF	Section lines for the PRB
Sheridan County Well Records	Excel	Table compiling data from the "Ground-Water Resources of Sheridan County, Wyoming (1966) some of which was used for steady state calibration
STATE LINE	DXF	The Wyoming-Montana state line
Tf_Wells	DXF	Fort Union Fm wells in Sheridan County
TopoSurface	DXF	Topographic contours of the surface of the PRB
Towns	DXF	Major towns in the PRB
Tw_Wells	DXF	Wasatch Fm wells in Sheridan County
TWP	DXF	Township and Range
WasatchOutcrop	DXF	Outcrop of the Wasatch formation
WasatchOutcrop_cropped	DXF	Outcrop of the Wasatch formation - used for the Caballo Creek Model
watershed_cropped	DXF	Major watersheds in the PRB - used for the Caballo Creek Model
watersheds	DXF	Major watersheds in the PRB
wells_cbm_exist_watershed	DBF	DBF for associated .shp file
wells_cbm_exist_watershed	SHX	SHX for associated .shp file
Readme-rm	TXT	Readme file with directions on how to run the regional transient model.
Readme-srm	TXT	Readme file describing the sub area model files.

List of Shape Files Used for Groundwater Model

File	Type	Comment
buff_projwells_24sep01	Arcview (.shp)	1/2 mile buffer around projected wells
buffwells_exist_permitted_all_merge_17oct	Arcview (.shp)	1/2 mile buffer around existing and permitted wells
cbm_pads_existing	Arcview (.shp)	All pre 2002 CBM well pad locations. Provided by Greystone.
Cbm_wells_prop_2002_v2	Arcview (.shp)	Proposed CBM well locations. Includes moved wells. Provided by Greystone.
greystone 1 well per pad	Arcview (.shp)	Locations of well pads with one well per pad
greystone 2 well per pad	Arcview (.shp)	Locations of well pads with two wells per pad
greystone 3 well per pad	Arcview (.shp)	Locations of well pads with three wells per pad
merged coals	Arcview (.shp)	Areal extent of coals
prb coal seam development	Arcview (.shp)	Areal extent of development in the PRB
prb_modflow_model2	Arcview (.shp)	Arcview shape file of the model grid. The shape file has the x,y and row, column for each node
Wells_cbm_exist_watershed	Arcview (.shp)	All pre 2002 CBM well locations and watershed designation. Provided by Greystone

List of Groundwater Models and Associated Files

File	Type	Comment
PRBEIS_oneModel_modK.vmf	**Vmodflow**	**Region groundwater transient model with results for years 1975-2220. Run date 8/26/02**

Model Files Associated With PRBEIS_oneModel_modK.vmf

Prbeis_onemodel_modk.vmt	VMT File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.$STRG	$STRG File	Visual MODFLOW modeling file
fort.456	456 File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.ov...	BACKUP File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.vm...	BACKUP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.bcf	BCF File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mo...	BF File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.BGT	BGT File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.ch	CH File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.clb	CLB File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.En...	Configuratio...	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.ini	Configuratio...	Visual MODFLOW modeling file
Schema.ini	Configuratio...	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.DDN	DDN File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.drn	DRN File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.DVT	DVT File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.HDS	HDS File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.HVT	HVT File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mo...	IN File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.zo...	IN File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.vm...	LOCK File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.LST	LST File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.ah...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.al...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.an...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.be...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.cb...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.ex...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.ex...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.ex...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.fl...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.fl...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.li...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.mi...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.mi...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.mi...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.ov...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.po...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.pr...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.ri...	MAP File	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
Prbeis_onemodel_modk.sa...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.sc...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.st...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.to...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.tw...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.up...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.wa...	MAP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.wa...	MAP File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.MBT	MBT File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.Co...	MCP File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mfi	MFI File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mdb	Microsoft Ac...	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.vm...	Microsoft Pr...	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.vm...	Microsoft Sc...	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mps	MPS File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mrk	MRK File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.bat	MS-DOS Batch...	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.MSS	MSS File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mtd	MTD File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mth	MTH File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.Co...	MTI File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mtn	MTN File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mts	MTS File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mtt	MTT File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mtv	MTV File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.ndc	NDC File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.oc	OC File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.ovmf	OVMF File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.rch	RCH File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.mo...	RPT File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.bas	BAS File	Visual MODFLOW modeling file
TCObservations.txt	Text Document	Visual MODFLOW modeling file
TCPoints.txt	Text Document	Visual MODFLOW modeling file
TCWells.txt	Text Document	Visual MODFLOW modeling file
test.TXT	Text Document	Visual MODFLOW modeling file
TFObservations.txt	Text Document	Visual MODFLOW modeling file
TFPoints.txt	Text Document	Visual MODFLOW modeling file
TFWells.txt	Text Document	Visual MODFLOW modeling file
TGroupPoints.txt	Text Document	Visual MODFLOW modeling file
TGroups.txt	Text Document	Visual MODFLOW modeling file
TPumpingSchedules.txt	Text Document	Visual MODFLOW modeling file
Twells.txt	Text Document	Visual MODFLOW modeling file
TWellScreens.txt	Text Document	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vih	VIH File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vma	VMA File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmb	VMB File	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
PRBEIS_oneModel_modK.vmf	VMF File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmg	VMG File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmn	VMN File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmo	VMO File	Visual MODFLOW modeling file
PRBEIS_ONEMODEL_MODKOld...	VMO File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmp	VMP File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmr	VMR File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.$CND	$CND File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmv	VMV File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmw	VMW File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vmz	VMZ File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vor	VOR File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.vrt	VRT File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.wel	WEL File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.WHS	WHS File	Visual MODFLOW modeling file
Prbeis_onemodel_modk.zbi	ZBI File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.zni	ZNI File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.Zo...	ZONEBUDGET File	Visual MODFLOW modeling file
PRBEIS_oneModel_modK.ZOT	ZOT File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10	**Vmodflow**	**Regional groundwater steady state model with results for year 1975. Run date 8/26/02**

Model Files Associated With PRBEIS_SS802_mod10

File	Type	Comment
Prbeis_ss802_mod10.vor	VOR File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.$STRG	$STRG File	Visual MODFLOW modeling file
fort.456	456 File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.vmf....	BACKUP File	Visual MODFLOW modeling file
PRBEIS_SS802_MOD10.VMB.bak	BAK File	Visual MODFLOW modeling file
PRBEIS_SS802_MOD10.VMP.bak	BAK File	Visual MODFLOW modeling file
PRBEIS_SS802_MOD10.VMW.bak	BAK File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.modf...	BF File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.BGT	BGT File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.clb	CLB File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.Engi...	Configuratio...	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.ini	Configuratio...	Visual MODFLOW modeling file
Schema.ini	Configuratio...	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.DDN	DDN File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.drn	DRN File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.DVT	DVT File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.HDS	HDS File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.HVT	HVT File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.modf...	IN File	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
PRBEIS_SS802_mod10.zone...	IN File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.vmf....	LOCK File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.LST	LST File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.aha ...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.allu...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.ante...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.bell...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.cbm_...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.deve...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.flow...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.flow...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.litt...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.midd...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.midd...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.mine...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.over...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.pots...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.prbo...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.rive...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.salt...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.scor...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.stat...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.town...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.uppe...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.wasa...	MAP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.wate...	MAP File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.MBT	MBT File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.mfi	MFI File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.mdb	Microsoft Ac...	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.mps	MPS File	Visual MODFLOW modeling file
		Visual MODFLOW modeling file
PRBEIS_SS802_mod10.bat	MS-DOS Batch...	
PRBEIS_SS802_mod10.MSS	MSS File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.ndc	NDC File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.oc	OC File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.modb...	RPT File	Visual MODFLOW modeling file
TCObservations.txt	Text Document	Visual MODFLOW modeling file
TCPoints.txt	Text Document	Visual MODFLOW modeling file
TCWells.txt	Text Document	Visual MODFLOW modeling file
TFObservations.txt	Text Document	Visual MODFLOW modeling file
TFPoints.txt	Text Document	Visual MODFLOW modeling file
TFWells.txt	Text Document	Visual MODFLOW modeling file
TGroupPoints.txt	Text Document	Visual MODFLOW modeling file
TGroups.txt	Text Document	Visual MODFLOW modeling file
TPumpingSchedules.txt	Text Document	Visual MODFLOW modeling file
Twells.txt	Text Document	Visual MODFLOW modeling file
TWellScreens.txt	Text Document	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
Prbeis_ss802_mod10.vih	VIH File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vma	VMA File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmb	VMB File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.vmf	VMF File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmg	VMG File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmn	VMN File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmo	VMO File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmp	VMP File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmr	VMR File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmt	VMT File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmv	VMV File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmw	VMW File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vmz	VMZ File	Visual MODFLOW modeling file
PRBEIS_SS802_mod10.$CND	$CND File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.vrt	VRT File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.wel	WEL File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.whs	WHS File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.zbi	ZBI File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.zni	ZNI File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.zone...	ZONEBUDGET File	Visual MODFLOW modeling file
Prbeis_ss802_mod10.zot	ZOT File	Visual MODFLOW modeling file
LXBar-flat-04.vmf	**Vmodflow**	**LX Bar groundwater model**

Model Files Associated With LXBar-flat-04

FOR097	File	Visual MODFLOW modeling file
FOR098	File	Visual MODFLOW modeling file
IMFlow	MS-DOS Batch File	Visual MODFLOW modeling file
IZBud	MS-DOS Batch File	Visual MODFLOW modeling file
LXBar-boundaries	EMF	Visual MODFLOW modeling file
LXBar-buildup	EMF	Visual MODFLOW modeling file
LXBar-flat-04	MS-DOS Batch File	Visual MODFLOW modeling file
LXBar-flat-04	Configuration Settings	Visual MODFLOW modeling file
LXBar-flat-04	Microsoft Access	Visual MODFLOW modeling file
LXBar-flat-04.BAS	BAS	Visual MODFLOW modeling file
LXBar-flat-04.BCF	BCF	Visual MODFLOW modeling file
LXBar-flat-04.BF	BF	Visual MODFLOW modeling file
LXBar-flat-04.BGT	BGT	Visual MODFLOW modeling file
LXBar-flat-04.CH	CH	Visual MODFLOW modeling file
LXBar-flat-04.CLB	CLB	Visual MODFLOW modeling file
LXBar-flat-04.CONC001.MCP	MCP	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
LXBar-flat-04.CONC001.MTI	MTI	Visual MODFLOW modeling file
LXBar-flat-04.DDN	DDN	Visual MODFLOW modeling file
LXBar-flat-04.DRN	DRN	Visual MODFLOW modeling file
LXBar-flat-04.DVT	DVT	Visual MODFLOW modeling file
LXBar-flat-04.ENGINS	Configuration Settings	Visual MODFLOW modeling file
LXBar-flat-04.GHB	GHB	Visual MODFLOW modeling file
LXBar-flat-04.HDS	HDS	Visual MODFLOW modeling file
LXBar-flat-04.HVT	HVT	Visual MODFLOW modeling file
LXBar-flat-04.LST	LST	Visual MODFLOW modeling file
LXBar-flat-04.MBT	MBT	Visual MODFLOW modeling file
LXBar-flat-04.MFI	MFI	Visual MODFLOW modeling file
LXBar-flat-04.MPEG	MPEG	Visual MODFLOW modeling file
LXBar-flat-04.MRK	MRK	Visual MODFLOW modeling file
LXBar-flat-04.MSS	MSS	Visual MODFLOW modeling file
LXBar-flat-04.MTD	MTD	Visual MODFLOW modeling file
LXBar-flat-04.MTH	MTH	Visual MODFLOW modeling file
LXBar-flat-04.MTN	MTN	Visual MODFLOW modeling file
LXBar-flat-04.MTS	MTS	Visual MODFLOW modeling file
LXBar-flat-04.MTT	MTT	Visual MODFLOW modeling file
LXBar-flat-04.MTV	MTV	Visual MODFLOW modeling file
LXBar-flat-04.NDC	NDC	Visual MODFLOW modeling file
LXBar-flat-04.OC	OC	Visual MODFLOW modeling file
LXBar-flat-04.RCH	RCH	Visual MODFLOW modeling file
LXBar-flat-04.VIH	VIH	Visual MODFLOW modeling file
LXBar-flat-04.VMA	VMA	Visual MODFLOW modeling file
LXBar-flat-04.VMB	VMB	Visual MODFLOW modeling file
LXBar-flat-04.vmf.backup	BACKUP File	Visual MODFLOW modeling file
LXBar-flat-04.VMG	VMG	Visual MODFLOW modeling file
LXBar-flat-04.VMN	VMN	Visual MODFLOW modeling file
LXBar-flat-04.VMO	VMO	Visual MODFLOW modeling file
LXBar-flat-04.VMO	Microsoft Program Group	Visual MODFLOW modeling file
LXBar-flat-04.VMP	VMP	Visual MODFLOW modeling file
LXBar-flat-04.VMR	VMR	Visual MODFLOW modeling file
LXBar-flat-04.VMT	VMT	Visual MODFLOW modeling file
LXBar-flat-04.VMT	Microsoft Program Group	Visual MODFLOW modeling file
LXBar-flat-04.VMV	VMV	Visual MODFLOW modeling file
LXBar-flat-04.VMW	VMW	Visual MODFLOW modeling file
LXBar-flat-04.VMZ	VMZ	Visual MODFLOW modeling file
LXBar-flat-04.VOI	VOI	Visual MODFLOW modeling file
LXBar-flat-04.VOO	VOO	Visual MODFLOW modeling file
LXBar-flat-04.WEL	WEL	Visual MODFLOW modeling file
LXBar-flat-04.WHS	WHS	Visual MODFLOW modeling file
LXBar-flat-04.ZBI	ZBI	Visual MODFLOW modeling file
LXBar-flat-04.ZNI	ZNI	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
LXBar-flat-04.ZONEBUDGET	ZONEBUDGET	Visual MODFLOW modeling file
LXBar-flat-04.ZOT	ZOT	Visual MODFLOW modeling file
LXBar-flat-04ss	MS-DOS Batch File	Visual MODFLOW modeling file
LXBar-flat-04ss	Configuration Settings	Visual MODFLOW modeling file
LXBar-flat-04ss	Microsoft Access	Visual MODFLOW modeling file
LXBar-flat-04ss.BAS	BAS	Visual MODFLOW modeling file
LXBar-flat-04ss.BCF	BCF	Visual MODFLOW modeling file
LXBar-flat-04ss.BF	BF	Visual MODFLOW modeling file
LXBar-flat-04ss.BGT	BGT	Visual MODFLOW modeling file
LXBar-flat-04ss.CH	CH	Visual MODFLOW modeling file
LXBar-flat-04ss.CLB	CLB	Visual MODFLOW modeling file
LXBar-flat-04ss.CONC001.MCP	MCP	Visual MODFLOW modeling file
LXBar-flat-04ss.CONC001.MTI	MTI	Visual MODFLOW modeling file
LXBar-flat-04ss.DDN	DDN	Visual MODFLOW modeling file
LXBar-flat-04ss.DRN	DRN	Visual MODFLOW modeling file
LXBar-flat-04ss.DVT	DVT	Visual MODFLOW modeling file
LXBar-flat-04ss.ENGINS	Configuration Settings	Visual MODFLOW modeling file
LXBar-flat-04ss.GHB	GHB	Visual MODFLOW modeling file
LXBar-flat-04ss.HDS	HDS	Visual MODFLOW modeling file
LXBar-flat-04ss.HVT	HVT	Visual MODFLOW modeling file
LXBar-flat-04ss.LST	LST	Visual MODFLOW modeling file
LXBar-flat-04ss.MBT	MBT	Visual MODFLOW modeling file
LXBar-flat-04ss.MFI	MFI	Visual MODFLOW modeling file
LXBar-flat-04ss.MODFLOW	MODFLOW	Visual MODFLOW modeling file
LXBar-flat-04ss.MPS	MPS	Visual MODFLOW modeling file
LXBar-flat-04ss.MRK	MRK	Visual MODFLOW modeling file
LXBar-flat-04ss.MSS	MSS	Visual MODFLOW modeling file
LXBar-flat-04ss.MTD	MTD	Visual MODFLOW modeling file
LXBar-flat-04ss.MTH	MTH	Visual MODFLOW modeling file
LXBar-flat-04ss.MTN	MTN	Visual MODFLOW modeling file
LXBar-flat-04ss.MTS	MTS	Visual MODFLOW modeling file
LXBar-flat-04ss.MTT	MTT	Visual MODFLOW modeling file
LXBar-flat-04ss.MTV	MTV	Visual MODFLOW modeling file
LXBar-flat-04ss.NDC	NDC	Visual MODFLOW modeling file
LXBar-flat-04ss.OC	OC	Visual MODFLOW modeling file
LXBar-flat-04ss.RCH	RCH	Visual MODFLOW modeling file
LXBar-flat-04ss.VIH	VIH	Visual MODFLOW modeling file
LXBar-flat-04ss.VMA	VMA	Visual MODFLOW modeling file
LXBar-flat-04ss.VMB	VMB	Visual MODFLOW modeling file
LXBar-flat-04ss.vmf	vmf	Visual MODFLOW modeling file
LXBar-flat-04ss.vmf.backup	BACKUP File	Visual MODFLOW modeling file
LXBar-flat-04ss.VMG	VMG	Visual MODFLOW modeling file
LXBar-flat-04ss.VMN	VMN	Visual MODFLOW modeling file
LXBar-flat-04ss.VMO	VMO	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
LXBar-flat-04ss.VMO	Microsoft Program Group	Visual MODFLOW modeling file
LXBar-flat-04ss.VMP	VMP	Visual MODFLOW modeling file
LXBar-flat-04ss.VMR	VMR	Visual MODFLOW modeling file
LXBar-flat-04ss.VMT	VMT	Visual MODFLOW modeling file
LXBar-flat-04ss.VMT	Microsoft Program Group	Visual MODFLOW modeling file
LXBar-flat-04ss.VMV	VMV	Visual MODFLOW modeling file
LXBar-flat-04ss.VMW	VMW	Visual MODFLOW modeling file
LXBar-flat-04ss.VMZ	VMZ	Visual MODFLOW modeling file
LXBar-flat-04ss.VOI	VOI	Visual MODFLOW modeling file
LXBar-flat-04ss.VOO	VOO	Visual MODFLOW modeling file
LXBar-flat-04ss.WEL	WEL	Visual MODFLOW modeling file
LXBar-flat-04ss.WHS	WHS	Visual MODFLOW modeling file
LXBar-flat-04ss.ZBI	ZBI	Visual MODFLOW modeling file
LXBar-flat-04ss.ZNI	ZNI	Visual MODFLOW modeling file
LXBar-flat-04ss.ZONEBUDGET	ZONEBUDGET	Visual MODFLOW modeling file
LXBar-flat-04ss.ZOT	ZOT	Visual MODFLOW modeling file
modbatch.rpt	RPT	Visual MODFLOW modeling file
modflow.bf	BF	Visual MODFLOW modeling file
modflow.in	IN	Visual MODFLOW modeling file
SCHEMA	Configuration Settings	Visual MODFLOW modeling file
TCObservations	text document	Visual MODFLOW modeling file
TCPoints	text document	Visual MODFLOW modeling file
TCWells	text document	Visual MODFLOW modeling file
TFObservations	text document	Visual MODFLOW modeling file
TFPoints	text document	Visual MODFLOW modeling file
TFWells	text document	Visual MODFLOW modeling file
TGroupPoints	text document	Visual MODFLOW modeling file
TGroups	text document	Visual MODFLOW modeling file
TPumpingSchedules	text document	Visual MODFLOW modeling file
TWells	text document	Visual MODFLOW modeling file
TWellScreens	text document	Visual MODFLOW modeling file
zonebud.in	IN	Visual MODFLOW modeling file
LXBAR	DXF	Visual MODFLOW modeling file
LXBAR_BOUNDARY_feet	DXF	Visual MODFLOW modeling file
LXBAR_BOUNDARY_feet	EXT	Visual MODFLOW modeling file
LXBAR_BOUNDARY_feet	MAP	Visual MODFLOW modeling file
LXBAR_R12	DXF	Visual MODFLOW modeling file
LXBAR_RIVERNAMES_feet	DXF	Visual MODFLOW modeling file
LXBAR_RIVERNAMES_feet	EXT	Visual MODFLOW modeling file
LXBAR_RIVERNAMES_feet	MAP	Visual MODFLOW modeling file
LXBAR_RIVERS_feet2	DXF	Visual MODFLOW modeling file
LXBAR_RIVERS_feet2	EXT	Visual MODFLOW modeling file
LXBAR_RIVERS_feet2	MAP	Visual MODFLOW modeling file
LXBAR_SECTIONS_feet	DXF	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
LXBAR_SECTIONS_feet	EXT	Visual MODFLOW modeling file
LXBAR_SECTIONS_feet	MAP	Visual MODFLOW modeling file
Lxbar_Topo_feet	DXF	Visual MODFLOW modeling file
Lxbar_Topo_feet	EXT	Visual MODFLOW modeling file
Lxbar_Topo_feet	MAP	Visual MODFLOW modeling file
LXBAR_TOWNSHIPS_feet	DXF	Visual MODFLOW modeling file
LXBAR_TOWNSHIPS_feet	EXT	Visual MODFLOW modeling file
LXBAR_TOWNSHIPS_feet	MAP	Visual MODFLOW modeling file
LXBAR_WATERSHED_feet	DXF	Visual MODFLOW modeling file
LXBAR_WATERSHED_feet	EXT	Visual MODFLOW modeling file
LXBAR_WATERSHED_feet	MAP	Visual MODFLOW modeling file
Sstate9.vmf	**Vmodflow**	**Caballo Creek steady state groundwater model**
	Model Files Associated With Sstate9	
sstate9.APR	APR	Visual MODFLOW modeling file
sstate9.vmf.backup	BACKUP File	Visual MODFLOW modeling file
sstate9.BAK	BAK	Visual MODFLOW modeling file
sstate9.BAS	BAS	Visual MODFLOW modeling file
sstate9.BCF	BCF	Visual MODFLOW modeling file
sstate9.BF	BF	Visual MODFLOW modeling file
sstate9.BGT	BGT	Visual MODFLOW modeling file
sstate9.CLB	CLB	Visual MODFLOW modeling file
sstate9	Configuration Settings	Visual MODFLOW modeling file
sstate9.ENGINS	Configuration Settings	Visual MODFLOW modeling file
sstate9.PESTPLOT	Configuration Settings	Visual MODFLOW modeling file
sstate9.DDN	DDN	Visual MODFLOW modeling file
sstate9.DRN	DRN	Visual MODFLOW modeling file
sstate9.DVT	DVT	Visual MODFLOW modeling file
sstate9.HDS	HDS	Visual MODFLOW modeling file
sstate9.HVT	HVT	Visual MODFLOW modeling file
sstate9.INH	INH	Visual MODFLOW modeling file
sstate9.JST	JST	Visual MODFLOW modeling file
sstate9.LST	LST	Visual MODFLOW modeling file
sstate9.MBT	MBT	Visual MODFLOW modeling file
sstate9.CONC001.MCP	MCP	Visual MODFLOW modeling file
sstate9.MFI	MFI	Visual MODFLOW modeling file
sstate9	Microsoft Access	Visual MODFLOW modeling file
sstate9.VMO	Microsoft Program Group	Visual MODFLOW modeling file
sstate9.VMT	Microsoft Program Group	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
sstate9.MPS	MPS	Visual MODFLOW modeling file
sstate9.MRK	MRK	Visual MODFLOW modeling file
sstate9	MS-DOS Batch File	Visual MODFLOW modeling file
sstate9.MSS	MSS	Visual MODFLOW modeling file
sstate9.MTD	MTD	Visual MODFLOW modeling file
sstate9.MTH	MTH	Visual MODFLOW modeling file
sstate9.CONC001.MTI	MTI	Visual MODFLOW modeling file
sstate9.MTN	MTN	Visual MODFLOW modeling file
sstate9.MTS	MTS	Visual MODFLOW modeling file
sstate9.MTT	MTT	Visual MODFLOW modeling file
sstate9.MTV	MTV	Visual MODFLOW modeling file
sstate9.OC	OC	Visual MODFLOW modeling file
sstate9	Office Data File	Visual MODFLOW modeling file
sstate9.PAR	PAR	Visual MODFLOW modeling file
sstate9	PKCS #7 Certificates	Visual MODFLOW modeling file
sstate9.RCH	RCH	Visual MODFLOW modeling file
sstate9.REC	REC	Visual MODFLOW modeling file
sstate9.RST	RST	Visual MODFLOW modeling file
sstate9.SEN	SEN	Visual MODFLOW modeling file
sstate9.BCF.SRC	SRC	Visual MODFLOW modeling file
sstate9	text document	Visual MODFLOW modeling file
sstate9.VMW	text document	Visual MODFLOW modeling file
sstate9.MF.TPL	TPL	Visual MODFLOW modeling file
sstate9.VBB	VBB	Visual MODFLOW modeling file
sstate9.VBH	VBH	Visual MODFLOW modeling file
sstate9.VBT	VBT	Visual MODFLOW modeling file
sstate9.VIH	VIH	Visual MODFLOW modeling file
sstate9.VMA	VMA	Visual MODFLOW modeling file
sstate9.VMB	VMB	Visual MODFLOW modeling file
sstate9.VMG	VMG	Visual MODFLOW modeling file
sstate9.VMN	VMN	Visual MODFLOW modeling file
sstate9.VMO	VMO	Visual MODFLOW modeling file
sstate9.VMP	VMP	Visual MODFLOW modeling file
sstate9.VMR	VMR	Visual MODFLOW modeling file
sstate9.VMT	VMT	Visual MODFLOW modeling file
sstate9.VMV	VMV	Visual MODFLOW modeling file
sstate9.VMW	VMW	Visual MODFLOW modeling file
sstate9.VMZ	VMZ	Visual MODFLOW modeling file
sstate9.VOI	VOI	Visual MODFLOW modeling file
sstate9.VOO	VOO	Visual MODFLOW modeling file
sstate9.VOR	VOR	Visual MODFLOW modeling file
sstate9.WEL	WEL	Visual MODFLOW modeling file
sstate9.WHS	WHS	Visual MODFLOW modeling file
sstate9.ZBI	ZBI	Visual MODFLOW modeling file
sstate9.ZNI	ZNI	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
sstate9.ZONEBUDGET	ZONEBUDGET	Visual MODFLOW modeling file
sstate9.ZOT	ZOT	Visual MODFLOW modeling file
tran23.vmf	**Vmodflow**	**Caballo Creek transient groundwater model**

Model Files Associated With tran23

File	Type	Comment
tran23.APR	APR	Visual MODFLOW modeling file
tran23.vmf.backup	BACKUP File	Visual MODFLOW modeling file
tran23.BAK	BAK	Visual MODFLOW modeling file
tran23.BAS	BAS	Visual MODFLOW modeling file
tran23.BCF	BCF	Visual MODFLOW modeling file
tran23.BF	BF	Visual MODFLOW modeling file
tran23.BGT	BGT	Visual MODFLOW modeling file
tran23.CLB	CLB	Visual MODFLOW modeling file
tran23	Configuration Settings	Visual MODFLOW modeling file
tran23.ENGINS	Configuration Settings	Visual MODFLOW modeling file
tran23.PESTPLOT	Configuration Settings	Visual MODFLOW modeling file
tran23.DDN	DDN	Visual MODFLOW modeling file
tran23.DRN	DRN	Visual MODFLOW modeling file
tran23.DVT	DVT	Visual MODFLOW modeling file
tran23	File	Visual MODFLOW modeling file
tran23.HDS	HDS	Visual MODFLOW modeling file
tran23ss.HDS	HDS	Visual MODFLOW modeling file
tran23.HVT	HVT	Visual MODFLOW modeling file
tran23.INH	INH	Visual MODFLOW modeling file
tran23.JST	JST	Visual MODFLOW modeling file
tran23.LST	LST	Visual MODFLOW modeling file
tran23.MBT	MBT	Visual MODFLOW modeling file
tran23.CONC001.MCP	MCP	Visual MODFLOW modeling file
tran23.MFI	MFI	Visual MODFLOW modeling file
tran23	Microsoft Access	Visual MODFLOW modeling file
tran23	Microsoft Excel	Visual MODFLOW modeling file
tran23	Microsoft Program Group	Visual MODFLOW modeling file
tran23	Microsoft Program Group	Visual MODFLOW modeling file
tran23.MPS	MPS	Visual MODFLOW modeling file
tran23.MRK	MRK	Visual MODFLOW modeling file
tran23	MS-DOS Batch File	Visual MODFLOW modeling file
tran23.MSS	MSS	Visual MODFLOW modeling file
tran23.MTD	MTD	Visual MODFLOW modeling file

List of Groundwater Models and Associated Files

File	Type	Comment
tran23.MTH	MTH	Visual MODFLOW modeling file
tran23.MTI	MTI	Visual MODFLOW modeling file
tran23.MTN	MTN	Visual MODFLOW modeling file
tran23.MTS	MTS	Visual MODFLOW modeling file
tran23.MTT	MTT	Visual MODFLOW modeling file
tran23.MTV	MTV	Visual MODFLOW modeling file
tran23.NDC	NDC	Visual MODFLOW modeling file
tran23.OC	OC	Visual MODFLOW modeling file
tran23	Office Data File	Visual MODFLOW modeling file
tran23.PAR	PAR	Visual MODFLOW modeling file
tran23	PKCS #7 Certificates	Visual MODFLOW modeling file
tran23.RCH	RCH	Visual MODFLOW modeling file
tran23.REC	REC	Visual MODFLOW modeling file
tran23.RST	RST	Visual MODFLOW modeling file
tran23.SEN	SEN	Visual MODFLOW modeling file
tran23.SOR	SOR	Visual MODFLOW modeling file
tran23.BCF.SRC	SRC	Visual MODFLOW modeling file
tran23	text document	Visual MODFLOW modeling file
tran23.VMW	text document	Visual MODFLOW modeling file
tran23.MF.TPL	TPL	Visual MODFLOW modeling file
tran23.VBB	VBB	Visual MODFLOW modeling file
tran23.VBH	VBH	Visual MODFLOW modeling file
tran23.VBT	VBT	Visual MODFLOW modeling file
tran23.VIH	VIH	Visual MODFLOW modeling file
tran23.VMA	VMA	Visual MODFLOW modeling file
tran23.VMB	VMB	Visual MODFLOW modeling file
tran23.VMG	VMG	Visual MODFLOW modeling file
tran23.VMN	VMN	Visual MODFLOW modeling file
tran23.VMO	VMO	Visual MODFLOW modeling file
tran23.VMP	VMP	Visual MODFLOW modeling file
tran23.VMR	VMR	Visual MODFLOW modeling file
tran23.VMT	VMT	Visual MODFLOW modeling file
tran23.VMV	VMV	Visual MODFLOW modeling file
tran23.VMW	VMW	Visual MODFLOW modeling file
tran23.VMZ	VMZ	Visual MODFLOW modeling file
tran23.VOI	VOI	Visual MODFLOW modeling file
tran23.VOO	VOO	Visual MODFLOW modeling file
tran23.VOR	VOR	Visual MODFLOW modeling file
tran23.WEL	WEL	Visual MODFLOW modeling file
tran23.WHS	WHS	Visual MODFLOW modeling file
tran23.ZBI	ZBI	Visual MODFLOW modeling file
tran23.ZNI	ZNI	Visual MODFLOW modeling file
tran23.ZONEBUDGET	ZONEBUDGET	Visual MODFLOW modeling file
tran23.ZOT	ZOT	Visual MODFLOW modeling file

How to Run the Regional Transient Model

This readme file provides instructions on how to run the PRB EIS regional model in Transient mode. This readme file shows at which stress periods the model might stall, and how to change the run parameters, particularly the damp factor and/or the convergence criteria, for the WHS solver in order to get the model to converge. This model utilizes rewetting which makes it more difficult to get the model to converge. This readme file assumes that the user is familiar with Visual MODFLOW and the WHS solver. It should be noted that there are any number of combinations of changes that can be made to the run parameters. Each combination can yield slightly different results in the output. In a quick check between successive model runs using slightly different run parameters, model predicted production changed by at most 0.2% for a given stress period. The mass balance did not change at all between the two runs. This model was run using Visual MODFLOW v. 3.0 build 175. For more details on how the model was designed and to see output, please review the Groundwater Model Technical Report.

Starting the model run:

1. In the main Visual MODFLOW menu, go to **Setup**, then select *Numeric Engines*, then select *Flow*. Specify "USGS MODFLOW 96 from WHI".
2. Go to the **Run** menu.
3. Select *Transient Run*
4. Under **Modflow96**:
   a. **Timesteps** – do not make any changes
   b. **Initial Heads** – select "Previous Visual MODFLOW Run", make sure that "PRBEIS_SS802_mod10.hds" is the specified file. Select the only available time step for the initial heads.
   c. **Solver** – select WHS: Max Outer = 50000, Max Inner = 25000, Head Change (HCLOSE) = 0.01, Head Change (RCLOSE) = 0.01, Damp = 0.9. Leave everything else as the default.
   d. **Recharge** – set to "Highest Active Cell"
   e. **Layers** – Layer 1 is set as "Type 1 Unconfined", Layers 2-17 are set as "Type 3 Confined/Unconfined variable S/T"
   f. **Rewetting** – Select "Activate". Wetting Threshold = 5, Wetting Interval = 15, select "From Sides and Below" and select "Calculated from Threshold", set WETFCT = 0.1. Leave everything else as default.
   g. Leave everything else as default.
5. Hit **Run**
6. Check the box next to "MODFLOW 96" and "Zonebudge"
7. Select "Run "

At this point it will take the model some time to compile – 20 to 60 minutes depending on your computer. Once the model starts running, make the following adjustments during the run at the specified stress period and time step in order to get the model to converge. Simply make the change to the run parameter and hit "Apply", and the new settings will take effect. Do not hit the stop button or the model will restart. Once the change is made leave it until the next stress period. For example, at stress period 8 time step 9, change the damp factor to 0.8, and don't change it again until stress period 23, time step 9.

Stress Period	Time Step	Damp	HCLOSE
8	9	0.8	1.0
23	9	0.7	5.0
25	1	0.8	1.0
27	1	0.8	3.0
37	8	0.8	2.0
44	1	0.8	0.1
44	8	0.8	0.5
44	9	0.8	3.0

If you want rewetting to activate at any given stress period, reduce HCLOSE so that it takes more than 15 outer iterations to converge. Every 15th outer iteration, rewetting is invoked.

Note also that the first time the model is opened, it will look for overlays that are no longer needed for the model. These overlays were used at one point in time, but have been superseded by newer dxf's. The old files are:

PotSurf__Coal.dxf
Overburden Potsurf(m).dxf
CBM_Existing_To2002_Doubled.dxf
SaltCreekCBMLocs.dxf
MiddlePowderNonCBMCondLocs.dxf
BelleFourcheWellMapKeys.dxf
AntelopeCreekWellMapKeys.dxf
Township Range PRB.dxf
UpperCheyenneWellMapkeys.dxf
MiddlePowderWellMapKeys.dxf
LittlePowderWellMapkeys.dxf
Ahawatersheds.dxf
CBMWElls_Y2000.dxf
ExistingCBMWells_Y2000.L14.dxf
ExistingCBMWells_Y2000.L10

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