Coalbed Methane Stream Depletion Assessment Study –

Piceance Basin, Colorado

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***In Conjunction with*:**

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EXECUTIVE SUMMARY

The Piceance Basin is one of the most productive natural gas basins in the U. S.; however, it is a frontier basin with regards to coalbed methane (CBM) production. Total CBM gas production through 2006 from wells perforated solely in coal seams and located outside of the CBM Exclusion Zone[1] was only approximately 22.4 billion cubic feet; corresponding CBM water production was slightly less than 1,200 acre-feet. Nonetheless, there are concerns that the production of water from CBM wells could be resulting in stream depletions or reductions in spring flows that could potentially impact water rights holders, the State of Colorado, and downstream water users not in Colorado. As such, this study evaluates the extent and impacts of CBM water production in the Piceance Basin and assesses the regulatory framework associated with the production of CBM water, the potential for beneficial uses of such water, and the interstate ramifications of the consumptive uses of such water.

The production of CBM in Colorado and disposal of associated exploration and production wastes, including produced water, is regulated by the Colorado Oil and Gas Conservation Commission (COGCC). The Colorado Division of Water Resources (DWR), meanwhile, has jurisdiction over the removal of groundwater that is put to beneficial use. Because of the joint interest of the COGCC and the DWR in ensuring efficient production of CBM and in protecting the state's water resources, the two agencies, in conjunction with the Colorado Geologic Survey, embarked on this study as a cooperative effort. The primary objectives of this CBM study were:

- To provide an overview of the geographic, geologic, hydrologic, water quality and regulatory setting in the Piceance Basin as it relates to the production of CBM and CBM produced water;

- To implement and evaluate the suitability of a stream depletion analytical tool, the Glover analysis (Glover and Balmer, 1954), to administer CBM water production in the Piceance Basin; and,

- To develop a quantitative assessment of the levels of stream depletion or reduction in formation outflows that may be occurring as a result of the removal of water by CBM wells.

As defined by the outcrop of the Late Cretaceous Mesaverde Group, the Piceance Basin covers an area of approximately 7,100 miles^2 in western Colorado. The basin is structurally complex, with dips along its east and northeast flank being very steep to overturned. While major faults along these boundaries have not been identified at the surface, it is believed that subsurface faulting is common. There are several major folds internal to the basin; some of which are associated with complex faulting. The strata along the west and south flanks of the

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[1] The CBM exclusion zone, originally delineated by the U. S. Geological Survey (2003), encompasses the central portion of the Piceance Basin and includes the area where the primary coal-bearing strata in the basin dip below 7,000 feet deep and are believed to be predominantly gas-saturated. It divides the basin into distinct areas between which hydraulic communication is limited. For this study the basin has been subdivided into six CBM subunits. Lateral hydraulic connection probably exists between some of the adjoining subunits, but hydraulic connection between subunits across the CBM exclusion zone is considered unlikely.

basin dip shallowly towards the basin interior. While both shallower and deeper coal beds exist, CBM in the Piceance Basin has been produced primarily from the Cameo-Fairfield coal group in the lower portion of the Mesaverde Group.

CBM exploration in the basin started in the early 1980s, driven by incentives provided under the Crude Oil Windfall Profits Tax Act of 1980; however, the first commercial-scale production of CBM gas did not occur until 1989. Attempts at economic CBM production in the basin continued into the early 1990s, but there has been only limited CBM resource development in the basin since 1995. Repeated attempts at economic CBM development overall have been lackluster due to low permeability, low gas yields from the coal beds (even in wells with little water production), and high water yields where permeability is enhanced by local fractures and faults. Nearly all Mesaverde gas production in the Piceance basin today is from fluvial sandstone layers higher in the Mesaverde Group that have likely been charged with gas from the coals, or is commingled production from thick zones spanning both coal-bearing intervals and the overlying sandstone intervals. Because of the variability of the CBM gas and water production, to evaluate depletion due to CBM water production, this study considers only wells located outside the CBM exclusion zone that are perforated solely in coal seams.

In most CBM-producing basins in North America, water production is normally greatest immediately after the well is brought on line. This pattern occurs because CBM is sorbed on the surfaces of the coal itself and is held in place by the hydrostatic pressure of the water that fills the fractures (known as cleats) of the coal. As water is pumped out of the coal-bearing formation and the pressure in the formation drops, the gas desorbs from the coal into the cleats and migrates into the well where it is captured at the ground surface. In only a few of the wells in the Piceance Basin is the production of gas from coal intervals accompanied by the production of water as described above; generally gas and water production in the basin varies widely, even between wells within a given field. For many CBM wells, gas and water production appear to begin near peak levels and decline rapidly over time.

Current and foreseeable future CBM development in the Piceance Basin is limited to the Cameo-Fairfield coal group, which is a low permeability hydrostratigraphic unit, confined both above and below by even less permeable strata. For use in the Glover analysis, the hydraulic conductivity of the Cameo-Fairfield coals was estimated from literature sources to be $2.7x10^{-3}$ ft/day and specific storage was estimated to be $1x10^{-6}$ ft^{-1}.

In the Piceance Basin there have been two brief periods when annual CBM water production rose quickly, peaked, and then dropped quickly. The larger peak, which occurred in 2004, resulted in the production of approximately 187 acre-feet of water from CBM wells. Based on the Glover analysis using the parameter values presented above, the total cumulative depletion to date for the Piceance Basin is estimated to be less than 1 acre-foot. The delineation of the statutory non-tributary area, wherein the withdrawal of groundwater by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than 0.1 percent of the annual rate of withdrawal, was calculated to be approximately 8.8 miles from the outcrop or stream/outcrop intersection using the Glover analysis.

In Colorado, CBM produced water, like water produced from any other type of oil or gas well, is handled as waste by COGCC Rule 907, and it remains under the jurisdiction of the COGCC. However, if CBM produced water is put to a beneficial use beyond the uses allowed under Rule 907, it is subject to DWR regulation through a permitting process and water users are subject to various controls to avoid injury to vested water rights. In some cases, augmentation of depletions to streams may be required. In the Piceance Basin, most CBM produced water has been disposed in evaporation ponds or into Class II UIC injection wells. Because of the poor quality of the water produced from the CBM wells in the basin (total dissolved concentrations much greater than 10,000 milligrams/liter), there are currently no active surface discharges or other beneficial use of the produced water. It is not known if such uses will become will be economically feasible in the basin in the near future.

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1.0 INTRODUCTION

1.1 Background

The Piceance Basin is one of the most productive natural gas basins in North America. However, despite the presence of gas-rich coal seams in the Late Cretaceous and Early Tertiary strata in the basin, the production of coalbed methane (CBM) gas is still at an early stage. Since the initial production of CBM in the late 1980s, approximately 22.4 billion cubic feet (Bcf) of gas have been produced from the approximately 110 wells perforated exclusively in coal seams in the basin. Estimated reserves in coalbeds and unconventional, tight gas reservoirs of the basin, which extends over an area of 7,100 square miles in western Colorado (Figure 1.1), are nearly 84 trillion cubic feet (Tcf) of gas-in-place (Tyler and McMurry, 1995). Much of the gas in this estimate lies in an area in the central portion of the basin in the CBM exclusion area where CBM production is not considered feasible (U. S. Geological Survey, 2003; see Section 4.3, below) and perforation of coals and production of coalbed gas has been incidental to production from other gas-charged strata. Johnson and Roberts (2003) estimate only about 0.4 Tcf of producible CBM exists in the Upper Cretaceous coal seams in the basin.

Concerns can arise in areas of CBM production because groundwater is produced in conjunction with CBM gas. In the two other major CBM-producing basins in Colorado, the San Juan Basin and the Raton Basin, there is current concern regarding the amount, quality, uses, and effects on streams due to CBM water production and how that production may be affecting CBM gas seepage at the surface. While concerns of this nature are not imminent in the Piceance Basin, if production of CBM increases in the future, such issues could arise. Of particular interest is future water production from CBM wells that could result in stream depletions that may be injurious to senior water rights.

The production of CBM in Colorado and disposal of associated exploration and production waste, including produced water, is regulated by the Colorado Oil and Gas Conservation Commission (COGCC). However, the Colorado Division of Water Resources (DWR) has jurisdiction over the production of groundwater that is put to beneficial use. Because of the joint interest of the COGCC and the DWR in both ensuring efficient production of CBM and in protecting the state’s water resources, the two agencies, in conjunction with the Colorado

Geological Survey (CGS), have commissioned this study to evaluate the magnitude of stream depletions from CBM water production in the Piceance Basin.

1.2 Objectives

The primary objectives of this CBM study are:

- To provide an overview of the geology, hydrology, water quality, and regulatory setting in the Piceance Basin as it relates to the production of CBM and CBM produced water;
- To evaluate the suitability of a stream depletion analytical tool, the Glover analysis (Glover and Balmer, 1954), to administer CBM water production in the Piceance Basin; and,
- To develop a quantitative assessment of the levels of stream depletion or reduction in formation outflows that may be occurring as a result of the removal of water by CBM wells.

1.3 Scope of Work

CBM in the Piceance Basin is produced primarily from the coals in the Late Cretaceous age Mesaverde Group. This study examined existing information relating to the geographic setting, geology, hydrogeology, CBM gas and water production, and water chemistry of these coal-bearing and adjacent formations. Existing information was obtained from the DWR, COGCC, CGS, United States Geological Survey (USGS), and other public domain sources.

A public meeting was advertised and held in Rifle on January 26, 2007, as part of this study. The meeting was held for the purpose of informing interested parties of the nature of the study and to solicit input and comments that might be of value to the study team. No written comments were received, although a technical meeting was subsequently held with EnCana Corporation personnel who provided a list of known CBM wells and a limited amount of formation pressure data.

Stream depletion analyses were conducted for portions of the basin to estimate current depletions of surface water due to CBM groundwater extraction. The results of the stream depletion analyses were considered in conjunction with statutory criteria for delineation of non-tributary areas, wherein the withdrawal of groundwater by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than 0.1 percent of the annual rate of withdrawal. The study further examined regulatory and other issues regarding use of CBM produced water.

The goal of this study was to provide background regarding CBM production and to evaluate stream depletions associated with CBM water production. As such, there are many related topics or analyses that fall beyond the scope of this study. Topics not evaluated as part of this study include:

- Reservoir optimization, i.e., production or well spacing issues;
- Dual-phase flow dynamics;
- Historical conditions and climatic influences on streams and springs;
- Impacts of other basin extraction activities on streams or water levels; and
- Evaluation of localized groundwater elevation changes at specific sites.

That the above topics are not evaluated in this study is not a reflection of their importance; rather, it is a reflection of the focus of this study on evaluation of stream depletion.

1.4 Report Organization

Chapter 2 summarizes available data and resources. Chapters 3, 4, and 5 describe the physical and geologic setting of the Piceance Basin, the nature of CBM gas and water production in the basin, and the hydrogeologic setting, respectively. Chapter 6 provides the stream depletion analysis. Chapter 7 provides a regulatory overview including a discussion of potential beneficial uses of CBM produced water and implications for CBM water production on interstate stream compacts. Chapter 8 summarizes results and conclusions and considers potential future depletion analysis in the Piceance Basin.

2.0 AVAILABLE DATA AND RESOURCES

This study draws on existing data and studies to provide an overview of conditions in the basin and to provide well information along with CBM and water production data. The key datasets reviewed are described below.

2.1 Geographic and Geologic Data

The Piceance Basin topographic, hydrographic and cultural details were obtained from public domain sources accessible by internet and from geographic information system (GIS) datasets maintained by the USGS, CGS, DWR and COGCC. The medium-resolution National Hydrography Datasets for the Upper Colorado, Gunnison, and White river basins, including tributaries present in the Piceance Basin, were obtained from the USGS. Coordinates of wells and other hydrologic measurement stations were obtained from the USGS National Water Information System (NWIS) online database (http://waterdata.usgs.gov/nwis/). Additionally, spatial layers supporting select USGS investigations in the Piceance Basin (USGS, 2003) were obtained. The CGS provided geologic cross-sections and generalized stratigraphic sections of the Piceance Basin in addition to spatial layers of geology, topography and administrative features, including detailed information for the geologic outcrops of the formations of interest. Coordinates were obtained for water supply and CBM production wells in the Piceance Basin from the DWR and COGCC, respectively.

2.2 Well Production Data

Oil, gas, and CBM well and production data are systematically collected by the COGCC. Much of their database is available for browsing on the internet at http://oil-gas.state.co.us. For this study, monthly oil and gas production data were assembled from pre-1999 lease production and post-1999 well production databases obtained from the COGCC. Production data were queried from the COGCC databases only for leases/wells determined to be perforated in and producing from the coal seams of the Mesaverde group outside of the CBM exclusion area. Common facility names that associate wells with specific leases which may include more than one well were used to merge the pre-1999 lease and post-1999 well production data. The water and gas production plots prepared for this study from the merged datasets do not demonstrate significant changes in production at the 1998 to 1999 transition, indicating that production data for the CBM wells in the basin are not significantly affected by aggregation of production by leases.

2.3 Water Level Data

Water level data for the Mesaverde Group, in general, and for the coalbeds, in particular, in the Piceance Basin are sparse. Water level data maintained by the USGS were obtained from the website http://waterdata.usgs.gov/nwis/gw. Data include discrete measurements from 203 wells located within the boundaries of the analysis areas and perforated in stratigraphic intervals including the Mesaverde Group, Green River and Wasatch Formations, and unconsolidated surficial deposits. These data represent water levels from the period 1960 through 1989. Sixty-nine wells in this dataset have more than two water level measurements. Additional well information includes screen depth and/or total well depth. A regional potentiometric surface map of the Mesaverde Formation is presented in Freethey and Cordy (1991). Water level data in the form of equivalent potentiometric head from shut-in pressure tests are available in USGS investigation reports (Teller and Chafin, 1986; Weigel, 1987). Several investigations of hydrology in relation to coal mining have been conducted in the east and south margins of the basin, and water levels and equivalent potentiometric heads have been reported for water supply and gas production wells in these reports. Shut-in pressure data in CBM wells was provided by EnCana Corporation for seven CBM production wells. No other operator data has been obtained.

2.4 Stream and Spring Flow Data

Stream and spring flow data in the Piceance Basin are available from several publications (Ackerman and Brooks, 1986; Brooks, 1983; Brooks, 1986; Brooks and Ackerman, 1985; Glover et al., 1998; and Lazear, 2006) and on-line sources. Stream and spring flow data maintained by the USGS were obtained from the website http://waterdata.usgs.gov/nwis/. Locations of 231 springs, originating from the Mesaverde Group, Wasatch and Green River Formations and unconsolidated, surficial deposits, were identified. Locations of 148 surface water monitoring stations were identified in the area.

2.5 Water Quality Data

Water quality data were obtained primarily from COGCC databases and USGS sources. COGCC produced water sample data were provided specifically for this study and for a study currently being conducted in the area of the Mamm Creek and Divide Creek natural gas fields. The USGS data for streams, springs, and various types of wells are available in publications from several regional hydrogeologic studies in the Piceance basin (Alley et al., 1978; Brooks, 1983 and 1986; Brooks and Ackerman, 1985; Ackerman and Brooks, 1986; Van Liew and Gesink, 1985); and, much of this data is accessible online at the USGS website http://waterdata.usgs.gov/nwis/. References to water quality data from near-outcrop areas are also available in other reports—most relating to coal mining permitting and operations—and were reviewed for this study (e.g., Williams and Clark, 1993; West Elk Mine Permit, 1995, 1999)

3.0 PICEANCE BASIN PHYSIOGRAPHIC AND GEOLOGIC SETTING

3.1 Regional Basin Setting

As defined by the outcrop of the Late Cretaceous Mesaverde Group (Figure 1.1), the Piceance Basin covers an area of approximately 7,100 $miles^2$ in western Colorado within the Colorado Plateau physiographic province as well as a small part of the Southern Rocky Mountains province at the basin's southeast end. This diverse area contains badlands, plateaus and mesas, sub-alpine and alpine peaks and highlands, as well as deep canyons and broad alluvial valleys. Much of the northeast side of the basin is marked by the Grand Hogback, one of Colorado's spectacular geographic features formed by erosion-resistant sandstone formations dipping steeply westward into the basin center. The impressive Book Cliffs, along with the west end of Grand Mesa, rise above the Grand Valley defining the southwest edge of the basin, while the southeastern end of the basin extends high into the West Elk Mountains. In the interior the Roan Plateau, Battlement Mesa, and Grand Mesa rise above the broad alluvial valleys of the Colorado River, Plateau Creek, and the North Fork Gunnison River. At the northwest end of the basin, the Cathedral Bluffs and Danforth Hills wrap around the high plateau country of the Piceance Creek drainage basin. Elevations in the West Elk Mountains reach heights of over 13,000 feet above mean sea level (MSL) at West Elk Peak, while the lowest point is at an elevation of approximately 4,700 feet above MSL near Palisade where the Colorado River leaves the Piceance Basin.

With its topographic diversity, the Piceance Basin is marked by widely varied precipitation patterns as shown in Figure 3.1. Average annual precipitation can exceed 40 inches, with much of that coming in the form of winter snowfall, in the interior highlands of the Elk Mountains, Grand Mesa, and Battlement Mesa, while in the lower alluvial valleys the average drops to less than 10 inches per year. Over much of the perimeter of the basin, where the coal-bearing Mesaverde Group is exposed, elevations are relatively low and annual precipitation is low. Because of this, direct recharge into the Mesaverde Group by precipitation at the outcrop is limited.

Three major river systems, sourced high in the Rocky Mountains to the east, flow across the Piceance Basin in a southwesterly direction (Figure 1.1). All are part of the Upper Colorado River Basin, and include the main-stem of the Colorado River that originates on the west side of the Front Range in Grand County well east of the Piceance Basin. The North Fork Gunnison River originates within the Piceance Basin in the highlands of Delta County, and joins the main stem of the Gunnison River a few miles downstream of Hotchkiss; the Gunnison River then flows into the Colorado River in Grand Junction. Originating just east of the Piceance Basin, the White River flows across the north end of the basin and joins the Green River, also a tributary of the Colorado, further to the west in Utah.

A number of tributaries to these major rivers are sourced from the high plateaus and mesas within the interior of the Piceance Basin. Many of these tributaries are either ephemeral or support very low base flow (on the order of 1 cubic foot per second or less).

3.2 Basin Stratigraphy

Formed during the Late Cretaceous and Early Tertiary Laramide Orogeny, the Piceance Basin is a deep structural downwarp that preserves a thick sequence of Paleozoic through Early Cenozoic era sedimentary rocks (Wilson et al., 2003). Figure 3.2 is a stratigraphic column for the basin summarizing this sequence which includes Cambrian through Mississippian period marine clastic and carbonate deposits; Pennsylvanian and Permian period marine and non-marine clastic deposits, carbonates, and evaporites; Triassic and Jurassic period non-marine clastic deposits and eolian deposits; and the marine and coastal non-marine deposits of the Cretaceous period Western Interior Seaway. Clastic sediments shed off the uplifts that rose adjacent to the basin during the Laramide Orogeny filled the basin as it evolved into the Early Tertiary period. In the final stages of its structural evolution, the basin area was inundated by Lake Uinta, a large inland body of water that deposited a thick sequence of lacustrian shale, oil-shale, limestone, evaporite accumulations, and sandstone (MacLachlan, 1987).

Subsequent to the structural development of the basin, the region has undergone uplift, erosion, and development of the Colorado River stream system forming the landscape as we see it today. In the southern part of the basin, Mid-Tertiary basalt flows followed ancient river valleys, and these ancient basalts, being more resistant to erosion, now form the cap-rock of Grand Mesa and Battlement Mesa. Alluvial deposits of unconsolidated sand, gravel, and silt fill the deep alluvial valleys along the modern stream drainages, while higher terrace deposits above the modern stream levels mark the gradual incision through the Late Tertiary and Quaternary periods.

The Mesaverde Group, consisting of non-marine coastal plain sediments deposited during the Late Cretaceous regression of the Western Interior Seaway, contains the coal from which CBM is produced today (Tyler et al., 1991). Following deposition, these coal-bearing sediments have undergone deep burial by as much of 12,000 feet of younger Early Tertiary sediments (Tyler, 1995) prior to uplift and erosion. Not only did deep burial during structural development of the basin provide a thermal blanket that enhanced methane generation from the coal-bearing source rocks (Tyler et al., 1991), but it probably also played an important role in establishing the hydrodynamic properties observed in the modern structural and geographic setting.

3.3 Basin Structural Geology

Trending northwest to southeast (Figure 3.3), the Piceance Basin is a Laramide structural basin of Late Cretaceous to Early Tertiary age that is asymmetrical in cross-sectional profile with its structural axis close to its northeast side (Figure 3.4). Following its structural axis from northwest to southeast, the basin is bounded along its steeply dipping northeast limb by the Uinta Mountain Uplift, Axial Arch, White River Uplift, and Elk Mountain Uplift. Along this limb, sedimentary layers dip steeply into the basin at angles often exceeding 60° and are sometimes overturned. Through much of its extent, the steep northeast limb expresses itself at the surface as the Grand Hogback, a striking topographic feature held up by erosion-resistant Late Paleozoic through Late Cretaceous sedimentary layers. Along the southwest limb of the basin, which is bounded on the southwest by the Uncompaghre Uplift, the sedimentary layers dip to the northeast into the basin at much lower angles, on the order of 5° to 10°. The west and northwest end of the basin is bounded by the Douglas Creek Arch, which separates the Piceance Basin from the larger Uinta Basin to the west. The southeast end of the basin is bounded by the Sawatch Uplift, while the southern end is bounded by the Gunnison Uplift.

The structurally complex basin interior is deformed by a number of folds and faults which display a primary northwest structural grain (Tyler, 1995). With relevance to CBM in the basin, the White River Dome, Rangely Anticline, and Divide Creek Anticline are believed to be underlain by west to southwest verging thrust faults (Tyler, 1995). Thrust faults with surface expression apparently do not cut Upper Cretaceous and younger strata with the exception of minor thrust faults along the Grand Hogback, although such faulting is postulated in the subsurface by several workers (e.g., Tweto, 1983; Johnson and Nuccio, 1986; Tyler, 1995) for most of the eastern basin boundary in association with the Grand Hogback. North-northwest to northwest trending strike-slip faults reportedly present in the basin interior display a simple geometry at depth but become more complex upward through the sedimentary section (Gunneson et al., 1994; Cumella and Ostby, 2003). These structures bifurcate and splay upward through the coal-bearing Mesaverde Group yet do not appear to offset upper Mesaverde and younger rocks. This geometry enhances gas reservoir characteristics in the otherwise low permeability strata while maintaining a top seal over much of the structural basin.

Many normal faults have been mapped in the basin interior and along the basin rim with the greatest number exposed on the Douglas Creek Arch where they trend primarily in a northeasterly direction (Tweto, 1979). Figure 3.5 shows the locations of these faults and others that have been mapped at a 1:500,000 scale. Many more faults are present within the region that have been documented by smaller scale mapping efforts and it is likely that there are many faults in the Tertiary strata in the basin that have not been recognized or documented. The faults mapped at 1:500,000 scale simply provide a sense of faulting fabric and intensity in the vicinity of the Piceance Basin. Readily apparent is the prevalence of mapped faults peripheral to the basin in older formations. Many of these faults may have been most active during the Laramide Orogeny, and therefore predate the Tertiary fill of the basin. If this is the case, the older faults are not likely to provide vertical hydraulic connection to the surface. These faults could provide horizontal hydraulic connection to the outcrop or, alternatively, may create barriers to flow between the basin interior and the outcrop.

Fracturing is pervasive in outcrop (Tremain and Tyler, 1995) and has been identified in the subsurface as a critical factor in gas production (Cumella and Ostby, 2003; Lorenz, 2003). Fracturing relevant to CBM development in the Piceance Basin can be categorized into three primary groups: 1) cleat systems in the coal seams, 2) regional fracture systems that evolved over time as the stress regimes across the basin have changed, and 3) local fracture sets associated with specific folds and faults (Tyler, 1991; Tremain and Tyler, 1995). Fracturing is better developed in the more brittle indurated sandstone, siltstone, and calcareous shale beds, yet is nearly absent in mudstones and shales (Lorenz, 2003). This relationship has ramifications in understanding gas migration and trapping mechanisms as well as potential groundwater flow pathways.

Fracture patterns throughout the basin are complex and show great variation due to gradual changes in stress regimes across the region over geologic time. Patterns relevant to CBM development and groundwater flow patterns will be discussed in more detail in later sections. East-west compressional stress accompanied deposition and burial of the coal-bearing Mesaverde group in the Late Cretaceous period. This was followed by north-south or northeast-southwest compression as the Laramide Orogeny evolved into the Tertiary (Tyler, 1995). Local structural heterogeneity such as the White River Uplift indenture is believed to have affected stress distribution, and hence, fracture patterns. Regional stress patterns changed dramatically following the Laramide Orogeny to an overall east-west extensional environment (Tremain and Tyler, 1995) and younger fracture patterns add a complexity to the regional fracture grain.

A series of Mid-Tertiary laccoliths and sills intrude the Mesozoic sedimentary rocks at the southeast end of the Piceance Basin (Figure 3.5). Concentrated in deeper marine shales, these granodiorite plutons have deformed the coal-bearing Mesaverde Group. In addition, the elevated geothermal gradient that accompanied their emplacement raised the rank of the coal (Streufert, 1999) and may have increased methane generation from the coals. Although the high methane content and possible increase in local fracturing could make this area a favorable CBM target, the area is structurally complex, topographically very rugged, and much of the surface area is managed as wilderness by the U. S. Forest Service. Net coal thicknesses also decrease in this direction such that total gas in-place probably also decreases.

3.4 Geology of the Mesaverde Group Coal-Bearing Intervals

3.4.1 Stratigraphy and Coal Bed Occurrence

Vast coal deposits have been preserved in the Late Cretaceous non-marine coastal plain sediments deposited during the gradual retreat of the Western Interior Seaway in the Late Cretaceous (Tyler et al., 1991). For almost 20 million years the Western Interior Seaway inundated the North American mid-continent, undergoing several episodes of advance and retreat before final withdrawal near the end of the Cretaceous period (Hettinger and Kirschbaum, 2002). Episodic shoreline progradation into the seaway was believed to be driven, in-part, by pulses of tectonism along the Sevier Orogenic belt active to the west. As shown in Figure 3.6, the ancient shoreline trended in a northeasterly direction across the area where the Piceance structural basin later developed. Primary geographic elements during this time consisted of a wave-dominated deltaic shoreline with a vast coastal plain extending westward to the Sevier Orogeny mountain chain in the distance.

Nomenclature for the many depositional sequences preserved during episodes of shoreline advance and retreat vary across the basin; however, this report will use the nomenclature summarized by Hettinger et al. (2002) for the southern Piceance Basin and shown in Figure 3.7. According to records at the COGCC, this nomenclature appears to be commonly used by industry throughout the Piceance Basin for the sedimentary sequence containing the CBM resources.

In short, the stratigraphic sequence consists of the non-marine Mesaverde Group overlying the marine Mancos Shale. The seaway retreated to the east-southeast across the Piceance Basin area preserving a time-transgressive sequence with the transition from marine sediments upward to non-marine sediments becoming younger to the east-southeast as shown in Figure 3.7. Since the retreat was episodic, with short periods of landward advance of the sea followed by shore-line progradation back into the sea, the sequence includes many intertongues of marine with non-marine sediments. This intertonguing nature of the strata has led to nomenclature confusion over the years.

It is interpreted that this ancient shoreline was part of a wave-dominated delta and consisted of barrier bars separating the seaway to the east and southeast from extensive swamps to the west and northwest (Cole et al., 2005). Streams originating in the highlands off to the west crossed the back-bar swamps and flowed into the seaway via distributary channels in the wave-dominated deltas. Shoreline progradation in a seaward direction tends to preserve each of the sedimentary facies found along the shoreline; and, hence, each time the shoreline advanced into the seaway, beach and delta sands buried the offshore marine shales. Peat deposits derived from coal-forming plant debris collected in the back-bar swamps followed, and buried, the beach deposited sands. Fluvial stream sands combined with over-bank silts and clays eventually buried the back-bar peat deposits. Because of this progression, basal coals deposited in the paludal back bar environment can be laterally continuous over many tens of miles. Other peat deposits were also formed in smaller swamps along the river systems further to the west; however, these fluvial coal deposits tend to have much less lateral continuity.

In the Piceance Basin the most widespread and continuous coal deposits are found in the Cameo-Wheeler coal zone just above the Rollins Sandstone Member of the Iles Formation (also called the Trout Creek Sandstone further north). The Cameo-Wheeler coal-zone is the basal portion of the non-marine Williams Fork Formation as recognized in most of the basin interior. To the east, the Cameo-Wheeler intertongues with the South Canyon and Coal Ridge coal zones where the entire interval is referred to as the Cameo-Fairfield coal group (Johnson and Roberts, 2003). The Williams Fork Formation above the Cameo-Fairfield coal group is considered “barren” of coal, although local discontinuous coal seams may be present anywhere in the basin. Much of this upper “barren” part of the Williams Fork Formation is the reservoir for the basin-centered gas accumulation in the CBM exclusion area. Potential also exists for CBM development in the deeper Black Diamond coal zone of the Cozzette and Corcoran Members of the Mesaverde Group; however, the coals are thinner and not as widespread. This evaluation will be limited primarily to the more widespread Cameo-Fairfield coal group.

Based on evaluations of geophysical logs from gas wells in the basin, a gross coal-bearing interval was identified that varies considerably in thickness across the basin with greater thicknesses observed on the east side of the basin (e.g. 930 feet at Divide Creek Anticline). This interval, interpreted to be the equivalent of the Cameo-Fairfield coal group, thins to the west and is approximately 300 feet thick where the coal seams of the South Canyon and Coal Ridge coal zones are no longer present. A basal coal interval, interpreted to consist primarily of the Cameo-Wheeler coal zone, is widespread across the basin and has a relatively uniform thickness that ranges between 130 feet and 300 feet, with the thickest section observed in the vicinity of the Divide Creek Anticline (Figure 3.3).

3.4.2 Structural Geology

The Piceance Basin displays great structural diversity. However, a number of primary structural elements may play important roles in controlling CBM production and groundwater flow in the coal-bearing interval of the Mesaverde Group. Perhaps the most important structural element is the pronounced downwarp of the basin which plunges the coal-bearing interval of the Mesaverde Group to depths exceeding over 12,000 feet along its structural axis (Tyler et al., 1991). Within the deeper parts of the basin, the strata are saturated with gas in what is referred to as a “gas-saturated basin-centered gas-accumulation” (USGS, 2003). Surrounding the gas-saturated basin center (identified by the USGS as the Mesaverde Group Coalbed Methane Exclusion Unit; see Figure 3.8) is a shallower area where gas and water co-exist and there is potential for CBM development (Johnson and Roberts, 2003). The gas-saturated basin center is believed to form a hydraulic barrier that serves to isolate flow between different regions in the basin. Other structural elements, discussed below, may have direct influence on groundwater flow. Although influence on groundwater flow may not be well understood or universally accepted, inferences can be made regarding each element to help understand the regional groundwater flow patterns in the basin.

***Coalbed cleats*.** Cleats are natural systematic fractures in coal seams (Tremain and Tyler, 1995) believed to have formed soon after coalification. Typically oriented normal to the bedding, cleats are generally open-mode planar features found in sub-parallel sets with the earliest formed sets having more continuous length; hence, they are termed “face” cleats. Subsequent cleat sets that terminate against the face cleats are called “butt” cleats. Primary cleats extend across multiple coal-type layers and secondary or tertiary cleats are vertically discontinuous between layers. Spacing between cleats is believed to be a function of coal rank and type, coal seam thickness, structural setting, and stratigraphic position. In the Piceance Basin face cleats tend to be oriented east to northeast, orthogonal to the Laramide compressive deformation that formed the basin, although local variations exist and data are sparse in the northern part of the basin (Tremain and Tyler, 1995). Spacing values vary widely from 0.5 inch to more than 12 inches. In the deep interior part of the basin cleats may be annealed at depth (Gustafson, personal communication February 2007).

***Fracturing*.** Natural fractures have been well documented in the well-indurated sandstones of the Late Cretaceous through Early Tertiary strata across much of the Piceance Basin (Tremain and Tyler, 1995; Carroll, 2003). These fractures, believed to have tectonic origins, fall into three main categories: 1) regional joint sets, 2) enhanced fracturing over deeper folds and faults, and 3) conjugate shear sets. Multiple fracture networks characterize the region and at least five joint sets of post-Laramide origins have been identified. While fracturing may be common across the basin, not all may be relevant to this study. Furthermore, Lorenz (2003) recognized that most fractures occur mainly in the well-indurated sandstone layers and rarely, if ever, do they connect through bounding shales and mudstones; therefore, fractures observed at the surface in younger strata do not necessarily indicate vertical hydraulic connection with strata at depth. Many of the fracture sets identified in the Tertiary strata exposed at the surface in the interior of the basin likely provide little indication about fracture sets that potentially influence reservoir characteristics at depth and hydraulic connection with surface water. For this reason, this investigation will focus on fractures identified specifically in the Lower Mesaverde Group.

Natural extension fractures have been identified in the subsurface at great depths within the basin. Regional extension fractures present in the Mesaverde Group at depth and believed to have originated in response to west to southwest thrusting of the White River Uplift, tend to have a dominant west to northwest trend in the central and northern part of the basin but change to east-west and east to northeast in the western and southern part of the basin (Lorenz, 2003). The east to northeast trend was also recognized as a dominant set at the coal mines in the Somerset Coal Field (Carroll, 2003). Locally, enhanced fracturing related to deeper structures has been documented. For example, open fractures are recognized to enhance permeability on the White River Dome and have a northwest trend approximately parallel to the fold's axis (Olson, 2003).

Igneous Intrusions. The only significant igneous intrusions identified in the Piceance Basin are the Tertiary laccoliths and sills that dominate the geology of the southeast end of the basin (Figure 3.5). In addition to increasing the coal rank in this area, the plutons may also have influenced local fracture patterns observed at the Somerset Coal Field (Carroll, 2003) as well as modern horizontal stress fields (Agapito and Koontz, 2005). The Somerset Coal Field is also known for high methane content, which may also be due to an elevated geothermal gradient at the time of pluton emplacement. Cooper (2005) reports that intrusive bodies can stimulate methane generation from coal seams under favorable conditions.

Folding. Folding within the Piceance Basin is complex (Tyler et al., 1995); however, the structural fabric has an overall northwest trend sub-parallel to the main axis of the basin (Figure 3.3). Notable exceptions to the general northwest trend are the north to northeast trending Douglas Creek Arch, which forms the western edge of the Piceance Basin, and the northeast trending Grand Mesa Syncline that underlies Grand Mesa. Folds that have the greatest relevance to this investigation are the Grand Hogback Monocline; Divide Creek Anticline; White River Dome; and the paired Rangely Anticline and Red Wash Syncline to its north. The Grand Hogback brings the coal-bearing interval to the surface at high angles where recharge to groundwater may be locally enhanced; however, there may be thrust faulting at depth that could limit deep ground water flow pathways. Divide Creek Anticline, White River Dome, and Rangely Anticline form traps for the gas resources and have enhanced permeability resulting from fracturing along the crest of the folds.

Faulting. Large-scale faults displacing the Mesaverde Group do not appear to be present to a great extent at the outcrop around the perimeter of the basin (Figure 3.5), although local small scale faults have been mapped in many places. The greatest exceptions are a number of northeast trending faults that have been identified on the Douglas Creek Arch. It has also been noted that thrust faults that have splayed off of the main White River Uplift fault may be present at depth along the Grand Hogback (Lorenz, 2003). These faults could displace the coal-bearing interval of the Mesaverde (Tyler, et al., 1991) thereby limiting hydraulic connection between the surface and basin interior. Faults can act as barriers to groundwater flow as well as conduits for groundwater flow. Because of the relative lack of evidence for large scale faulting in outcrops, it is not certain that faulting is a significant factor overall in controlling regional groundwater flow, although faulting beneath the Grand Hogback that is related to the White River Uplift is a likely exception.

Cumella (2003) has suggested that deep seated wrench faults may be the reason for small-scale folding and fracture enhancement in the Williams Fork Formation of the Mesaverde Group. These faults do not appear to displace the coal-bearing interval in many places; where present, however, the deformation and fracturing has enhanced reservoir characteristics. It has been recognized that high water production is likely if a drill-hole directly intercepts one of these faults (Natali, 2006).

3.4.3 Outcrop Areas

The outcrop of the Mesaverde Group around the Piceance Basin forms an irregular oval shape that lies entirely within Colorado (Figure 3.5). Dips, topographic expression, and total thickness of the Mesaverde Group vary greatly along the perimeter of the basin; as such the width of the outcrop ranges from as little as 3,000 feet to almost 20 miles. Elevation ranges from almost 13,000 feet above MSL in the West Elk Mountains at the southeast end of the basin to approximately 4,700 feet above MSL at Palisade on the southwest edge of the basin. Exposure is generally good, allowing easy identification; however, details are often obscured by colluvium, landslide deposits, terrace deposits, glacial deposits, and alluvium along the main river drainages.

To date, detailed surface geologic mapping has not been completed over the entire length of the outcrop. Efforts by the USGS and CGS preparing detailed 1:24,000 scale geologic maps have focused along the Grand Hogback and the northwestern end of the basin. Elsewhere, mapping consists primarily of 1:250,000 scale maps by the USGS. Where fully exposed, the Williams Fork Formation, which contains the coal-bearing Cameo-Fairfield coal group, can form steep faces with cliffs and deep ravines due to the presence of many erosion-resistant sandstone bodies. The coal-bearing interval is often recognized at the surface by a reddish hue that owes its origin to the presence of klinker, or baked shale from natural coal bed fires.

3.4.4 Geologic Characteristics Bearing on Coalbed Methane Production

A number of geologic features suggest that the Cameo-Fairfield coals should be favorable for CBM development; however, to date, economic CBM production has been very limited (Johnson and Roberts, 2003). The basal coal seams can be quite thick and extensive and regionally, the coal-bearing interval is confined between relatively impermeable strata. Thermal maturation of the coals has been ideal for methanogenesis, and large-scale faulting has not fragmented the basin. Indeed, methane has been generated throughout the basin and is trapped in great volumes under tremendous pressure in the overlying stratigraphic sequence that is a major gas production play for the region. There are several geologic characteristics that may be limiting economic CBM development as summarized below:

- **Permeability.** In many of the production tests to date, gas production has been less than anticipated as permeability of the coal-bearing interval appears to be very low (Johnson and Roberts, 2003). A well developed cleat system in the coals may in effect have higher permeability than the enclosing sandstone and shale layers, yet the permeabilities are too low for economic gas production.
- **Depth of Burial.** Prior to Cenozoic uplift and erosion, the coal-bearing interval within the Piceance Basin was buried by as much as 12,000 feet of clastic and lacustrian deposits (Tyler, 1995). This deep burial may have limited permeability in the cleat system. In a few cases, exhumation has allowed the cleat-system permeability to open up as observed at White River Dome (Olson, 2003).
- **Regional Stress Fields**. Locally, there is evidence of high horizontal stress within the basin (Tremain and Tyler, 1995; Agapito and Koontz, 2005). Under certain conditions high horizontal stress fields could limit aperture width of natural fractures and cleats, thereby limiting permeability.
- **Formation Water.** Where permeabilities have been enhanced by fracturing, water production can be high (Johnson and Roberts, 2003). Overall, the produced water has high total dissolved solids (TDS) and disposal options are limited. This

can have a negative economic effect on developing CBM resources, often curtailing production of marginal wells.

4.0 COALBED METHANE PRODUCTION

Through 2006, the Piceance Basin has produced approximately 22.4 Bcf of CBM gas from wells completed exclusively in the coal bearing intervals of the Mesaverde Group outside of the CBM exclusion area. The annual gas production history for the basin is summarized on Figure 4.1. For comparison purposes, total CBM gas produced in the Piceance Basin is approximately 0.5 percent of the CBM produced in the Colorado portion of the San Juan Basin, and 4 percent of the CBM produced in the Colorado portion of the Raton Basin.

4.1 Piceance Basin CBM Gas and Water Production History

The Piceance Basin is well known for its economic energy resources that include conventional oil and gas, oil shale, and coal. CBM potential in the basin has long been recognized (Tremain, 1983; Tyler et al., 1991); however, economic CBM development to date has been limited. Conventional gas resources have been developed from sandstones within the Cretaceous Dakota Sandstone, Mancos Shale and Mesaverde Group as well as the Tertiary Wasatch Formation (USGS, 2003). Conventional oil has been developed from the Permian Weber Sandstone and, to a lesser extent, the Jurassic Entrada Sandstone and Morrison Formation. Sources for oil and conventional gas are believed to be the older marine Pennsylvanian Belden Shale and Minturn Formation, Permian Phosphoria Formation, and Cretaceous Mancos Shale. One of the primary sources for gas in the Upper Cretaceous and Lower Tertiary sandstone reservoirs is believed to be coal in the Upper Cretaceous Mesaverde Group.

Coal resources present in the Lower Mesaverde Group, in what is known as the Uinta Coal Region, have played an important role in the economic development of the region, particularly along the north edge of the basin in Moffat County and the southeast end of the basin in Gunnison and Delta Counties. The region has produced more than 350 million tons of coal from 300 mines. This equates to over 30% of Colorado's total coal production, making this the state's largest producing region (Carroll, 2004). As of 2004, there were six active coal mines producing from the Mesaverde Group coal beds around the perimeter of the Piceance Basin (Cappa et al., 2004). Methane has long been known to be present in the coals of the basin (Tremain, 1983) and has been a major hazard associated with historic underground coal mining. A methane gas explosion killed fifteen miners at a mine in the Carbondale Coal Field in 1981 prompting closure of underground mining in that area by 1991. Mines in the Somerset Coal Field require methane drains to bring underground seeps to acceptable levels.

Development of gas derived from the coal-bearing Mesaverde Group has early beginnings with possible early production at the north end of the basin going back to 1890 from the White River Dome (Olson, 2003). Elsewhere in the basin, early gas production was primarily from the marine Cozzette and Corcoran Sandstone reservoirs in the lower Mesaverde Group (Tremain, 1983). Actual CBM production, where coal beds are specifically targeted for production, started much later, with a reported first completion in 1978 (Johnson and Roberts, 2003). However, the first commercial large-scale production of CBM gas did not occur until 1989 with gas from Cameo-Fairfield coals (often commingled with gas from Mesaverde sandstones) in the Grand Valley and Parachute fields near the town of Parachute (Schwochow and Stevens, 1993). Attempts at economic CBM production in the basin targeting the Cameo-Fairfield coal group continued into the early 1990s driven by incentives provided under the Crude Oil Windfall Profits Tax Act of 1980. With the exception of drilling in the Mamm Creek field in the vicinity of the Divide Creek Anticline, there has been very little new CBM resource development in the basin since 1995. Repeated attempts at economic CBM development overall have been lackluster due to low permeability, low gas yields from the coal beds (even in wells with little water production), and high water yields where permeabilities are enhanced by local fractures and faults (Johnson and Roberts, 2003). Nearly all Mesaverde gas production in the Piceance basin today is either entirely from the fluvial sandstone layers higher in the Mesaverde Group that have likely been charged with gas from the coals, or is commingled production from thick zones spanning both coal-bearing intervals and the overlying sandstone dominant intervals.

In the Piceance Basin, because of the difficulty of producing gas from the low permeability coals and sandstones in the Mesaverde Group, all wells are stimulated by hydraulic fracturing to enhance gas production.

Because of the variable production of CBM gas and water in the basin, to evaluate depletion due to CBM water production, this study considers only wells with perforations in coals and not wells where the primary production is likely to be from sandstones even if it is commingled with gas from perforated coal intervals.

In contrast to traditional oil and gas wells where water is produced in highest quantities during the later portion of a well's life as the hydrocarbon production is falling off, in CBM wells water production is normally greatest immediately after the well is brought on line. In typical CBM wells, such as those in the San Juan Basin, as water production declines, CBM production increases and a well may have a long productive period with relatively high gas production and little to no water production. This pattern occurs because CBM is sorbed on the surfaces of the coal itself and is held in place by the hydrostatic pressure of the water that fills the fractures (i.e., cleats) of the coal. As water is pumped out of the coal-bearing formation and the pressure in the formation drops, the gas desorbs from the coal into the cleats and migrates into the well where it is captured at the ground surface.

In only a few CBM wells in the Piceance Basin is the production of gas from coal intervals accompanied by the production of water as described above. Overall, gas and water production in the basin varies widely, as is shown in Figure 4.2. Some wells have high water to gas ratios, while some wells produce little or no water over their lifetime. For many CBM wells, gas and water production both appear to peak shortly after production begins and then declines rapidly over time. In only a few Piceance CBM wells does gas production actually increase for an extended period after the well is brought online. Often it is difficult to evaluate what a well's long term production will be because of the discontinuous operation of many of the wells in the basin.

In addition to summarizing CBM gas production for the Piceance Basin, Figure 4.1 shows total annual water production from CBM wells for the period 1987 through 2006. As can be seen, annual CBM water production has experienced two short periods of relatively high production, from 1990 through 1994 and 2004 through 2005; between those two peaks there has been almost no production of water from CBM wells. The initial peak in gas and water production may have been motivated by the tax incentives discussed in the previous section; the latter peak is associated with the completion and operation of several wells in the Mamm Creek field along the crest of the Divide Creek Anticline.

Even considering the two peaks in water production, overall water production from CBM wells in the basin is very low. The first peak in 1992 resulted in the production of only 178 acre-feet (approximately 1.4 million barrels)[1] of water and the second peak in 2004 in only 187 acre-feet (1.45 million barrels) of water. Because most of the CBM wells in the Mamm Creek field have now been shut-in, water production has again declined rapidly, with approximately 39 acre-feet (300,000 barrels) of water being produced in 2006. For comparison purposes, in 2004, the year of highest CBM water production in the basin, the volume of water was less than 6 percent and 1.4 percent of 2004 water production from the Colorado portions of the San Juan and Raton Basins, respectively.

4.2 Well Densities and Distribution

The aerial distribution of CBM gas and produced water in the Piceance Basin in Colorado are illustrated in Figures 4.3 and 4.4, respectively[2]. As shown in Figure 4.3, the majority of gas production occurs in just a few gas fields spread over the basin. Successful gas fields include the White River Dome in the north, Divide Creek and Mamm Creek in the southeast, and South Shale Ridge and Bronco Flats in the southwest. The White River Dome, Mamm Creek, and Divide Creek fields together represent a large majority of water production from CBM operations in the basin.

4.3 Production Trends and Projections

The trend of future production of CBM gas and water in the Piceance Basin is based not only on the previous production history, but also on the technical and logistical hurdles that must be overcome simply to produce the gas (many of which relate to the great depth and low permeability of the coals in the basin), on the disposition of produced water, and on the complex intermixing of socio-economic factors that affect the development of all energy resources. The rapid rise in the price of natural gas in the past few years may spur continued efforts to develop CBM in the Piceance Basin, but the extent and pace remain unknown.

Estimates of CBM reserves have varied widely from a high of 77 Tcf of producible CBM gas-in-place by Tremain (1983) to a low of 0.4 Tcf of undiscovered producible CBM gas by Johnson and Roberts (2003). A primary reason for the wide range in estimates depends on the

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[1] An acre-foot is the amount of water that is required to cover an area of one acre (about the area of a football field) with one foot of water. One acre-foot equals 43,560 cu. ft. or approximately 326,000 gallons or 7,760 barrels of water.

[2] These figures depict relative gas and water production without regard to well completion date, production duration or other variables.

inclusion or exclusion of the central part of the basin. In the time since the early gas-in-place estimates were made, it has been recognized that much of the interior part of the basin is a "continuous" or "basin-centered" gas accumulation, where the majority of the reservoir is gas-saturated and over-pressurized (Johnson and Roberts, 2003; Cumella and Ostby, 2003). The evolution of this type of a gas accumulation stems in-part from overall very low permeabilities of the entire stratigraphic section. It is only as a result of rising gas prices and technological advances in hydraulic fracturing of the tight formation that the economic development of this resource has been made possible. When the area of the basin that is gas-saturated is removed, the total area with CBM potential decreases significantly. In its CBM assessment of the Mesaverde Group in the Uinta-Piceance province, the USGS recognized this distinction and defined a "Mesaverde Group Coalbed Methane Assessment Unit" which excluded the interior part of the basin (i.e., the Mesaverde Coalbed Methane Exclusion Unit in Figure 3.8) where depths to the base of the coal-bearing interval exceeded 7,000 feet (Johnson and Roberts, 2003).

This report, and the modeling efforts used to estimate possible depletion effects to surface water resources herein, will use the USGS Mesaverde Group Coalbed Methane Exclusion Unit, with a slight modification in the area of the Parachute and Grand Valley fields, for its initial designation of areas for CBM development. (This area is herein referred to as the "CBM exclusion area.") Due to the large size of the Piceance Basin, as well as geologic and probable hydrogeologic heterogeneity across the basin, the unit is further divided into six CBM subunits, which will be described in detail in Section 5.4, below. Delineation of these subunits is based on internal geologic structures as well as relationships between outcrops of the coal-bearing intervals with surface water drainage patterns to facilitate stream-depletion evaluations.

5.0 HYDROGEOLOGIC CONDITIONS

5.1 Piceance Basin Groundwater Flow Systems

Several aquifers have been recognized within the Piceance Basin, including the Quaternary alluvial aquifers associated with the main-stem of the Colorado River, North Fork Gunnison River, Plateau Creek, Surface Creek, and Tongue Creek; and the predominantly sandstone and marlstone bedrock aquifers of the Tertiary Uinta, Green River, and Wasatch Formations (Topper et al., 2003). The Cretaceous Mesaverde Group has been considered a regional aquifer; however, in the Piceance Basin proper, the overall hydrologic characteristics are poor (Freethey and Cordy, 1991) and present day use is limited mostly to the area of Delta County on the south flank of Grand Mesa (Topper et al., 2003).

With current and foreseeable future CBM development limited to the Cameo-Fairfield coal group, discussion of the regional groundwater flow systems in the Piceance Basin will focus on the lower Williams Fork Formation (hereafter referred to as the Cameo-Fairfield coal group hydrostratigraphic unit). Because of its very low permeability, this hydrostratigraphic unit is not referred to as an aquifer in this study, although in places the groundwater within it could potentially be produced at a quantity to be put to beneficial use.

5.2 Cameo-Fairfield Coal Group Hydrostratigraphic Unit Conceptual Model

In this conceptual model, the Cameo-Fairfield coal group behaves as a single hydrologic unit consisting of the entire package of coal seams and interbedded sandstone and shale layers. Principal elements of this model are discussed below.

5.2.1 Hydrostratigraphic Unit Geometry

The primary permeability of the Cameo-Fairfield coal group is in the cleat systems of the coal seams, and these coal seams are probably the most laterally continuous facies of the entire interval, particularly near the base. For the purposes of this study, the Cameo-Fairfield coal group is considered herein to be a hydrostratigraphic unit that is bound above by the upper Williams Fork Formation, which lacks continuous coal seams and is characterized by discontinuous lenticular fluvial sandstone bodies (Cole et al., 2005), and below by the Rollins/Trout Creek Sandstone, in which primary porosity decreases with depth due to increased clay content, decrease in grain size (Lorenz, 1983), and calcite and silica cementation (Wright

Water Engineers, 2003a). The Rollins/Trout Creek Sandstone is generally considered to be an aquitard (Tyler et al., 1991) and overlies the Mancos Shale. Basinward of its area of outcrop, the Cameo-Fairfield coal group behaves in a confined manner.

5.2.2 Recharge

Recharge to the hydrostratigraphic unit may occur through three primary pathways: 1) direct recharge of precipitation on the outcrop, 2) recharge by infiltration from intersecting stream-beds for losing streams, and 3) vertical inflow from overlying younger geologic formations or potentially, but less likely, from underlying formations in higher pressure regimes. Recharge to the Cameo-Fairfield coal group may be quite limited overall, regardless of the pathway due to the geologic and topographic characteristics of the basin.

Over the entire perimeter of the basin, the unit is exposed over a broad range of elevations (4,700 to almost 13,000 feet above MSL) and, accordingly, precipitation can vary greatly. Characteristics favoring recharge at the outcrop include weathering and the release of overburden pressure as overlying strata have been eroded away over the last 30 to 35 million years. However, over much of the outcrop, particularly at lower elevations, annual precipitation is low and evapotranspiration rates are high, so recharge is limited (Topper et al., 2003). It is only at the higher elevations, such as at Grand Mesa and near the West Elk Mountains, where direct recharge from precipitation is likely. In places, such as along the Grand Hogback and the Book Cliffs, the topographic relief of the outcrop is steep and rugged so that runoff is rapid and opportunity for direct recharge is limited.

Direct recharge from intersecting streams is possible under favorable potentiometric head conditions. Potentiometric head must be lower in the hydrostratigraphic unit than the intersecting stream for water to flow from the stream into the underlying formations. Of the major streams that flow into or out of the basin, the largest (the Colorado, North Fork of the Gunnison, and White Rivers) are all probably gaining streams and any exchange of water within the Cameo-Fairfield coal group would be flow out of the formation and into the stream. Site-specific data regarding stream recharge-discharge relationships were not obtained for this study.

Recharge by downward infiltration from overlying younger sedimentary formations is also possible within the basin. Although the permeabilities of the overlying formations may be very low, water will flow downward through them if the head differential exists to drive the flow. Downward flow through the low permeability confining layers could potentially contribute the largest component of recharge over much of the basin, particularly for areas where the overlying topography and precipitation are high such as Grand Mesa (Tyler et al., 1991). The potential for downward recharge may be facilitated where permeability is enhanced due to fracturing that cuts the Mesaverde and/or younger formations over structural features, such as at the White River Dome and the Divide Creek Anticline. In the center of the basin in the CBM exclusion area over-pressurized conditions exist and preclude downward infiltration of water into the Mesaverde Group coal-bearing intervals.

5.2.3 Groundwater Flow Pathways

The most permeable layers within the Cameo-Fairfield coal group are the coal seams themselves, where porosity and permeability are greatest within the cleats of the coal seams. While it may seem that the face cleat orientation may impose a preferred orientation for groundwater flow, and thus an anisotropic permeability distribution, the very close spacing of both face cleats and butt cleats creates a relatively isotropic hydrologic media. In addition to the coal seam permeability, fractures in the siltstone and sandstone layers that are adjacent to the coal seams are believed to provide local pathways for groundwater flow and may contribute to elevated water yields from some CBM wells (Johnson and Roberts, 2003). Individual coal seams can be laterally extensive, but over the extent of the basin, individual coal seams overlap each other in a shingled architecture with layers of shale, siltstone, and sandstone separating the coals. It may be argued that this shingled architecture would compartmentalize groundwater flow. However, Applied Hydrology Associates, Inc. (2000) evaluated this effect for the Fruitland Formation in the San Juan Basin using a two-dimensional numerical model and concluded that the large surface area of the shale intervals separating the shingled coal seams counteracts the relative low permeability of those separating layers and flow volumes did not appear to be diminished by the shingled layers. The shingled architecture of the basal coals in the Piceance Basin, therefore, may not significantly preclude the already small amount of lateral groundwater flow through the system.

One of the most significant characteristics contributing to the patterns of groundwater flow within the Piceance Basin is the basin-centered gas accumulation comprising the CBM exclusion area. This area, where the deeply buried Cameo-Fairfield coal group is believed to be gas-saturated, segregates the regional hydrostratigraphic unit into distinct areas between which hydraulic communication is limited. This is one reason that the basin has been subdivided into six CBM subunits (Figure 5.1). Lateral hydraulic connection probably exists between adjoining subunits, whereas hydraulic connection between subunits across the CBM exclusion area is highly unlikely. For example, under this interpretation, groundwater flow from the Hogback subunit to the Colorado River subunit would be impeded by the basin-centered gas accumulation in the CBM exclusion area.

Structural elements probably also impede groundwater flow within specific subunits. Along the Grand Hogback, Tyler et al. (1991) have suggested that possible offsets of coal seams along thrust faults basin-ward of the White River Uplift could limit groundwater flow into the basin. In the North Fork Gunnison River subunit the prevailing face cleat orientation is parallel to the outcrop. Locally, this could lower the effective permeability between the basin and the surface; however, normal faults observed offsetting the Mesaverde Group in this area trend to the north-northeast (Wright Water Engineers, 2003a) and could be pathways for preferred groundwater flow.

Tyler et al. (1991) suggested a groundwater flow model for much of the Piceance Basin wherein groundwater flows basin-ward following regional topographic gradients and structural dip. In this model, groundwater would discharge to the Colorado River where it crosses the basin at the lowest elevations. While not universally accepted (Wright Water Engineers, 2003b), certain elements of this model may have merit. There may be a component of recharge to the system along the Grand Hogback, particularly at higher elevations, as well as recharge by vertical infiltration through the younger overlying formations from areas receiving high annual precipitation. As previously described, the basin-centered gas accumulation probably precludes regional flow through the basin. There are insufficient quality public-domain data available to construct a potentiometric surface for the Cameo-Fairfield coal group over the basin, or over any of the CBM subunits for that matter. However, inferences can be made and generalized groundwater flow pathways inferred as shown in Figure 5.2. Several aspects of these inferred flow pathways are summarized below:

- **Outcrop flow patterns.** The greatest component of groundwater flow likely occurs very near the outcrop where the relatively impermeable geologic materials have been weathered and overburden pressures have been released. This has been suggested for the outcrop along the south flank of Grand Mesa (Wright Water Engineers, 2003a), and was identified as a key characteristic defining the hydrologic characteristics of the Fruitland-Pictured Cliffs aquifer in the northern San Juan Basin (S. S. Papadopulos & Associates, 2006). For this reason the flow lines depicted in Figure 5.2 cluster parallel to the outcrop.

- **Stagnation zones:** Because of the basin-centered gas accumulation in the CBM exclusion area and possible structural boundaries, there may be large areas where groundwater in the Cameo-Fairfield coal group is stagnant and flows at very low rates, if at all. This effect inhibits flow from the outcrop into deeper portions of the basin and may result in the presence of old connate waters have been identified in relatively shallow settings in certain areas. A large-scale area of down-dip groundwater stagnation may occur over much of the length of the Hogback subunit.
- **Unsaturated conditions.** In areas, the outcrop may be unsaturated such that there is no hydraulic connection between the outcrop and the basin interior and so there is little to no recharge to the coal bearing units from outcrop recharge. This condition probably exists over much of the length of the outcrop along the Book Cliffs in the Colorado River subunit. Coal mines along this reach of the outcrop are reported to be dry, as were the coals in three wells drilled into the Sego Formation near the outcrop (Tyler, et al., 1991; J. Burnell, personal communication). Further, almost all of the surface drainage is ephemeral.

5.3 Groundwater Chemistry

The COGCC dataset of produced water quality results provided for this study includes analyses of water from the Cameo-Fairfield coal group for 74 wells located across the basin. Additionally, Mesaverde/Williams Fork produced water analyses for 9 wells were obtained from a COGCC water quality data set for the Mamm Creek field. Most of the samples were analyzed for major ions and other primary water quality parameters, although several samples included analyses for radionuclides for wells located in the vicinity of the 1969 Project Rulison nuclear experiment in the Battlement Mesa area.

Additionally, groundwater chemistry analyses from Mesaverde Group wells in Delta County on the south flank of Grand Mesa, where the water is used for domestic supply purposes, are presented in Brooks and Ackerman (1985) and Ackerman and Brooks (1986). TDS concentrations in those wells ranged from 180 milligrams per liter (mg/L) to 3,400 mg/L and averaged approximately 1,000 mg/L. The waters had sodium-bicarbonate or sodium sulfate geochemical signatures based on major ion concentrations. A single sample from the Mesaverde aquifer in the Meeker area (Alley, et al., 1978) had very similar characteristics (TDS of 890 mg/L and a sodium-bicarbonate chemical signature).

Most of the produced water samples evaluated were from CBM wells spread throughout producing fields in Garfield County although there were also a few samples from Mesa and Rio Blanco Counties. The overarching characteristic of the samples is that the water had high TDS concentrations and strong sodium-chloride chemical signatures. For the 75 samples with useable major ion and other primary water quality analytical results, the TDS concentrations ranged from approximately 2,200 mg/L to 36,000 mg/L, with an average of 17,000 mg/L. Of those samples, only 13 had TDS concentrations below 10,000 mg/L, a value commonly used as an upper bound for beneficial use considerations. Of 64 samples evaluated, all but four had sodium-chloride chemical signatures. The other four wells had sodium-chloride-bicarbonate signatures; and of those wells, three had TDS concentrations less than 10,000 mg/L.

5.4 CBM Subunit descriptions

For purposes of this investigation the basin has been subdivided into CBM subunits as shown in Figure 5.1. The delineation of the CBM exclusion area in Figure 5.1 is modified from the original USGS delineation shown in Figure 3.8 such that many of the wells in the Parachute-Rulison-Rifle area are no longer included in the CBM assessment subunit. This modification was made after careful evaluation of completion intervals using COGCC completion data and geophysical logs, the results of which indicated that production in this area is predominantly from the overlying sandstone reservoirs commingled with the coal-bearing intervals.

This section summarizes key geologic and hydrogeologic characteristics for each subunit. Cross-sections for each of the subunits are presented in Figures 5.3 through 5.8[3]; cross-section locations are shown on Figure 5.1. Table 5.1 summarizes stratigraphic characteristics of the Cameo-Fairfield coal group obtained from select wells in each of the CBM subunits and provides a general assessment of what portion of the coal-bearing interval CBM is being produced from or has been tested for each subunit. Table 5.2 lists general information about structural elements interpreted to be relevant to CBM production and groundwater flow conditions in each subunit. Annual CBM gas and water production for each of the subunits with its production history is shown on Figure 4.1

[3] Large scale copies of the cross-sections may be obtained by contacting the CGS.

Colorado River Subunit

The Colorado River subunit, shown in Figure 5.1, extends from the Douglas Creek Arch on the west, in a southeasterly direction to the north end of Grand Mesa and spans much of the southwestern side of the basin where the sedimentary beds dip gently to the northeast into the basin. On its northeast side this subunit is bounded by the CBM exclusion area where the stratigraphic interval containing the coals is very deep and gas-saturated.

Along the outcrop, the coal-bearing interval consists primarily of the Cameo-Wheeler coal zone, as the upper coals of the South Canyon and Coal Ridge coal zones have pinched out mid-basin (Figure 5.3). The thickness of the coal-bearing interval is approximately 300 feet on the southwest side of the basin and the structural features are relatively simple; face cleats are orthogonal to the outcrop and primary fractures tend to be oblique, and faulting is minor and trends parallel to the outcrop trend.

CBM development has occurred primarily at the South Shale Ridge and Bronco Flats fields (Figure 4.3) in the middle part of the subunit. Completion data obtained from COGCC indicate that production is from the basal seams of the Cameo-Wheeler coal zone. Forty-two wells classified as “coal-gas” are reported to have been drilled in this subunit.

Much of the outcrop follows the high relief Book Cliffs escarpment where drainages are ephemeral. Perennial streams are limited to the main-stem of the Colorado River at Parachute and East Salt Creek and Big Salt Wash at the west end of the subunit. Recharge to the hydrostratigraphic unit is probably limited to elevated exposures on the Douglas Creek Arch and downward infiltration from overlying Tertiary strata, while discharge would be to the perennial streams crossing the outcrop. Many of the coal mines along the outcrop are reported to be dry, suggesting that much of the outcrop is unsaturated. Additionally, three wells drilled along the Mesa-Garfield County line near the Book Cliffs that were completed and perforated in Sego Formation coal beds (in the Mesaverde Group below the Cameo-Wheeler coal zone), produced modest amounts of dry gas prior to being shut in or abandoned.

North Fork Gunnison River Subunit

The North Fork Gunnison River subunit, shown in Figure 5.1, spans the south side of Grand Mesa and follows the North Fork Gunnison River to its headwaters in the West Elk

Mountains. This subunit covers much of the southern edge of the basin where the sedimentary beds dip gently to the north (Figure 5.4).

In this area, the coal-bearing interval consists of the entire Cameo-Fairfield coal group and is approximately 800 feet thick. The structure is relatively simple along the southern edge of the basin and face cleats and fractures tend to be parallel to the overall outcrop trend. North to northeast faulting has been identified that is orthogonal to the outcrop trend.

CBM development has been scattered across the subunit and there are seven wells classified as "coal-gas"; four of which have reported CBM production since 1999. Based on the limited data, it appears that production is from the entire Cameo-Fairfield coal group.

At the southeast end of the subunit, the North Fork Gunnison River follows, and is incised into, the coal-bearing interval. At the higher elevations annual precipitation over the outcrop is high, ranging to more than 32 inches per year, and a number of perennial streams sourced from the top of Grand Mesa where annual precipitation exceeds 40 inches per year, traverse the outcrop as they flow towards the North Fork Gunnison and Gunnison Rivers. Direct recharge at the outcrop is likely at the higher elevations and there may be limited recharge by vertical downward flow from younger water-bearing strata. Discharge is most likely directly to the perennial streams that cross the outcrop and most active groundwater flow probably occurs near the outcrop.

The structural Piceance Basin extends east-southeast from the North Fork Gunnison River subunit to where the Cretaceous section has been intruded and deformed by Mid-Tertiary granodiorite sills and laccoliths. Even though methane derived from the coals is known to be present in this area it is being excluded from this evaluation because the potential for CBM development is limited. Limitations to economic CBM development in this area include: 1) access in protected public lands, 2) rugged topography, 3) thinner net coal, and 4) probable structural complexity due to the numerous igneous intrusions.

Divide Creek Anticline Subunit

The Divide Creek Anticline subunit (Figure 5.1) is one of the smaller subunits and was delineated to include the northwest trending Divide Creek Anticline (Figure 3.3). Much of the anticline is surrounded by the CBM exclusion area and the outcrop on the east end of the subunit is limited to a short span of approximately 13 miles.

The coal-bearing interval consists of the entire Cameo-Fairfield coal group and is approximately 900 feet thick with the dominant structure being the Divide Creek Anticline. Fracturing along the crest of the anticline is believed to have enhanced permeability; however, while the anticline trends northwest, parallel to the outcrop at the Grand Hogback, it is separated from the outcrop by a steep-sided syncline that plunges the Cameo-Fairfield coal group into the CBM exclusion area, cutting off hydraulic connection between the anticline and the outcrop to the northeast. The structural geology between the crest of the Divide Creek Anticline and the southeastern end of the Grand Hogback monocline is complex with multiple folds and faults (Figure 5.5), including reverse faults within the anticline (Gunneson et al., 1994) and faults related to the White River-Elk Mountain Uplift at the south end Grand Hogback monocline (Tyler et al., 1991).

CBM development has occurred primarily at the Divide Creek and Mamm Creek Fields located above the crest of the Divide Creek Anticline (Figure 4.3). Completion data indicate that production is from the entire Cameo-Fairfield coal group. A total of 39 wells classified as "coal-gas" are reported to have been drilled in this subunit, including 13 in the Divide Creek field and 24 in the Mamm Creek field.

The Cameo-Fairfield outcrop is located in the Crystal River drainage basin, separated from the Divide Creek Anticline by the Wolf Creek Anticline in the subsurface (Figure 5.5) and by a drainage divide. However, the elevation of the outcrop area is high, with some stretches receiving precipitation well above 20 inches per year. Surface drainages crossing the outcrop consist mainly of small perennial streams tributary to Thompson Creek, which joins Crystal Creek just above Carbondale. Direct precipitation recharge to the coal-bearing interval is probable; but hydraulic connection with deeper zones away from the outcrop is questionable because of the complex structural geology in the area. Discharge most likely occurs at the Thompson Creek stream system.

Along the Divide Creek Anticline where it straddles the Garfield-Mesa county line, erosion has exposed the upper portion of the Mesaverde Group (Figure 3.5). This, combined with observations of enhanced permeabilities in the Mesaverde above the anticline, suggests the possibility of enhanced recharge to the lower portions of the Mesaverde, including the coal-bearing strata. However, the presence of recoverable gas trapped above the coal seams along the crest of the anticline argues that the degree of enhanced recharge to the Cameo-Fairfield coal group may be small at best. Finally, considering the geometric configuration relative to the CBM exclusion area, groundwater may be stalled within the structure itself.

Hogback Subunit

Extending approximately 90 miles in a southeast direction from the Danforth Hills to the Elk Mountains uplift, the Hogback subunit is a narrow strip delineating most of the steeply southwest dipping Grand Hogback monocline (Figure 5.1). At Danforth Hills at the north end of the subunit the outcrop takes on an irregular map pattern due to structural deformation and topographic relief. In this area, the western-most outcrop trace is the outcrop considered to be hydraulically connected with horizons that have CBM development in other areas within the Piceance Basin. There are four reported "coal-gas" wells within the subunit, but none have produced significant coalbed gas, and no CBM production has been reported since 1999.

The coal-bearing interval deepens considerably over a short horizontal distance because of the steep dip along the northeast limb of the basin and the CBM exclusion area is close to the edge of the basin (Figure 5.6). Over its length, the coal-bearing interval consists of the entire Cameo-Fairfield coal group and has a thickness of approximately 800 feet. As previously discussed, the coal-bearing interval could be offset by thrust faults related to the White River uplift (Tyler et al., 1991). Face cleats in the coal seams mostly trend orthogonally to the outcrop, while fractures tend to be oblique.

Much of the coal-bearing interval is found on steep slopes at intermediate elevations where precipitation on the outcrop ranges between 10 and 16 inches per year. Because of the steep topography, runoff may be high and direct infiltration into the coal-bearing interval may be limited. However, the hogback is interrupted by a number of water-gaps where perennial streams intersect, and are probably in direct hydraulic connection with, the coal-bearing interval. Examples of this relationship are the Colorado River at New Castle, Rifle Creek at Rifle Gap, and the White River near Meeker. Some direct recharge may come from the more elevated portions of the outcrop; however, most groundwater flow probably occurs very near the surface and discharge is probably directly to the rivers and streams at the water gaps since groundwater deeper in the basin may be stalled down-dip against the basin-centered gas accumulation.

White River Dome Subunit

Located at the northern end of the basin, the White River Dome subunit (Figure 5.1) is defined by a northwest trending anticline that plunges to the north. Because of deformation over the anticline and topographic relief, the outcrop follows a sinuous pattern in map view.

Within the White River Dome subunit the coal-bearing interval consists primarily of the entire Cameo-Fairfield coal group and is approximately 800 feet thick. Strike directions along the outcrop vary and the bedding planes dip into the basin between 10° and 50° (Figure 5.7). It has been recognized that fracturing along the anticline enhances permeability (Olson, 2003) and the predominant northwest strike of the fractures is orthogonal to the outcrop trend which may enhance hydraulic connection with the outcrop. The CBM exclusion area nearly completely bounds the subunit except at the outcrop. This, in conjunction with regional scale faulting related to the uplifts to the north and east of the subunit (Figures 3.3 and 3.5), likely limits hydraulic connection with any of the other subunits in the basin.

CBM development has occurred primarily along the crest of the anticline. Seventeen wells classified as “coal-gas” and not in the CBM exclusion area are reported to have been drilled in this subunit. The wells are from two fields: 1) the Pinyon Ridge Field, with 7 CBM completions, all of which have now been abandoned, and 2) the White River Field, located at the southeast end of the subunit, with 10 completions (Figure 4.3). In the White River Field, several other wells have been completed in Cameo-Fairfield coals, but all are located within the CBM exclusion area, which surrounds the field on all sides but the west.

At the north end of the basin, outcrop elevations are relatively low and annual precipitation ranges between 10 and 14 inches per year. The main-stem of the White River crosses the outcrop where it dips steeply to the southeast and then flows parallel to it and north of it over a distance of approximately four miles before crossing back to the south in the Rangely Anticline subunit (see below). Elsewhere in the White River Dome subunit, the outcrop is crossed by a number of ephemeral tributaries to White River. Recharge at the outcrop of the coal-bearing interval from precipitation is probably very limited, but there may be recharge by downward flow from shallower water-bearing strata. Discharge probably occurs where the

Cameo-Fairfield coal group intersects with the White River alluvium. As with the Colorado River subunit, there may be significant portions of the outcrop that are not saturated.

Rangely Anticline Subunit

Located at the west end of the Piceance Basin (Figure 5.1), the Rangely Anticline subunit extends from the northwest trending Rangely Anticline south to Douglas Pass which is situated on the topographic divide between the White River and Colorado River drainage basins. Similar to the White River Dome, the coal-bearing interval outcrop takes on a sinuous pattern because of structural deformation and topographic relief. At the south end of the subunit along its western boundary, the coal-bearing interval does not extend to the surface, remaining buried beneath younger Cretaceous and Tertiary strata.

Within the Rangely Anticline subunit the coal-bearing interval consists primarily of the entire Cameo-Fairfield coal group and is approximately 400 feet thick (Figure 5.8). Strike directions along the outcrop vary and the bedding planes dip into the basin at angles less than 10°. Published data on face cleats and fractures are sparse, but orientations probably trend to the north-northwest. Normal faulting observed on the Douglas Creek Arch is orthogonal to the overall outcrop trend.

There is only one well, located on Calamity Ridge approximately 8 miles east-southeast of Rangely, that is designated as "coal-gas." The well was drilled and shut-in in 2004; it has not produced any gas or water through early 2007. Based on the stratigraphy at the west end of the basin, production in this area would most likely be from the basal coals of the Cameo-Fairfield coal group.

North of Douglas Pass the elevation of the outcrop area is relatively low and annual precipitation ranges between 8 and 14 inches per year. Surface drainages coming into contact with the outcrop of the coal-bearing interval include the main stem of the White River at the north end and portions of Douglas Creek, which flows northward from Douglas Pass to join the White River at Rangely. Ephemeral tributaries to Douglas Creek cross the outcrop over much of its extent. Limited direct recharge to the coal-bearing interval from precipitation on the outcrop is possible and there may be recharge by downward flow from shallower water-bearing strata. Discharge probably occurs where the outcrop intersects with the perennial streams. As with the Colorado River subunit, there may be portions of the outcrop that are not saturated.

6.0 STREAM DEPLETION ANALYSIS

6.1 CBM Produced Water Stream Depletion Analysis

A stream depletion analysis was conducted to evaluate the potential impacts of CBM water production on flow in streams traversing the Piceance Basin. For this analysis, the DWR directed that the study team apply a specific method, the "Glover-Balmer" (or "Glover") analysis (Glover and Balmer, 1954), because of its ease of application and utility in administrative processes. However, the DWR also instructed the study team to evaluate the suitability of the Glover analysis for use as an administrative tool in the Piceance Basin.

Pursuant to C.R.S. 37-90-103(10.5) and 37-92-103(11), non-tributary groundwater is defined as groundwater withdrawn by a well which will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than 0.1 percent of the annual rate of withdrawal. In Colorado, CBM produced water, like water produced from any other type of oil or gas well, is considered a waste under COGCC Rule 907 and remains under the jurisdiction of the COGCC. However, if the produced water is applied to a *beneficial use*[4] beyond those allowed under COGCC Rule 907, it is regulated by DWR through a permitting process and water users are subject to various controls to avoid injury to decreed and vested water rights. In most cases, replacement of depletions to streams will be required. Because of the potential for groundwater withdrawn from the CBM wells in the Piceance Basin to be tributary to the streams that cross the aquifer, the DWR is interested in a first order identification of the area within which pumping may result in stream depletion exceeding 0.1 percent of the pumped quantity within 100 years of pumping.

6.2 Glover Depletion Analysis

The analytical Glover methodology is premised on a number of simplifying assumptions, among them, that the flow system is dominated by a single phase (i.e., water). This and other simplifying assumptions are examined in the analysis.

[4] "Beneficial use" means those uses for water that have been recognized as beneficial by DWR (e.g., domestic or municipal water supply, irrigation, minimum stream flow, etc.)

6.2.1 Description of Method

In 1954, Glover and Balmer developed an analytical solution for the ratio of stream depletion to total pumping at any given time for a well pumping from an aquifer fully penetrated by a stream. The basic form of the Glover-Balmer equation (hereafter simplified to Glover) is:

$$q/Q = erfc\left(\sqrt{\frac{a^2 S}{4tT}}\right)$$

where ***q/Q*** is the ratio of the quantity of stream depletion to pumping rate for time ***t***, ***a*** is the distance of the pumping well from the stream, and ***T*** and ***S*** are the aquifer transmissivity and storativity, respectively. The complementary error function, ***erfc***, is a probability function that returns a proportion (between 0 and 1) for the input value $\sqrt{\frac{a^2 S}{4tT}}$. Note that *q/Q* is a ratio of rates, and therefore independent of the pumping rate.

Because of the flexibility inherent in the solution and the ease of its application, the Glover analysis has been adopted for use in administering water rights law in a number of stream-connected basins of the western United States, including Colorado.

6.2.2 Assumptions and Limitations

The Glover analysis is premised on several idealizations (or simplifying assumptions) regarding aquifer conditions and geometry. There exist few natural environments that fully satisfy idealizations such as these; however, through careful configuration and application of the model, the error associated with divergence from the ideal case can be minimized and useful information for planning and management can be obtained. The idealizations inherent in the Glover analysis and comments regarding the application of the method to the Piceance Basin are provided below:

- *The aquifer is homogeneous*. The Cameo-Fairfield coal group hydrostratigraphic unit is heterogeneous, containing both strata of variable lithologies and faults and fractures that may inhibit or enhance aquifer permeabilities. Groundwater movement through a heterogeneous aquifer can be modeled as flow in a homogeneous media through the identification of "effective average parameters" that will reasonably characterize the aggregate properties of the aquifer. Ideally, effective average parameters are determined through examination of system-scale stress-response data, for example, wellfield production and fluid pressure data that allow regional pressure regimes or potentiometric surfaces to be delineated.

Where such operational data are not available, best estimates must be developed from localized or site-specific test data. The latter method is applied in this study to derive best-estimate hydraulic parameters that will reasonably incorporate the heterogeneity known to exist in the Cameo-Fairfield coal group.

- *The aquifer is semi-infinite in extent.* In the Piceance Basin, the CBM exclusion area may behave as a regional boundary that inhibits groundwater flow in Cameo-Fairfield coal group into the deep basin. Similarly, the presence of regional faulting may also form hydraulic barriers. For wells close to the CBM exclusion area and/or regional fault boundaries, over a long enough period of time, this would result in a measurable increase in stream depletion above what would occur in a semi-infinite aquifer over the same time period. There are analytical methods that allow these boundaries to be incorporated into depletion assessments (McWhorter and Sunada, 1977; Bear, 1979; Miller et al., 2007), and the effects of aquifer boundaries were tested for this study in areas where they were likely to be the greatest.
- *The boundary at which depletions are calculated is a linear stream that fully penetrates the aquifer, where the streambed is in hydraulic connection with the aquifer*. The model geometry must be set up in a manner that best approximates this assumption, given the physical configuration of the basin. With respect to the stream location, the key element is identification of the nearest stream location that intersects the modeled formation. Regarding the assumption of a fully penetrating stream, the fundamental element of the assumption is that hydraulic communication between the producing interval of the formation and the stream is not impeded beyond what is implied by the aquifer hydraulic properties. Typically, in the Piceance Basin, the aquifer is traversed by the stream where it outcrops. As such, the stream is in contact with all horizons of the aquifer, thus, partial penetration concerns are minimal. Geometrically, that the stream crosses the aquifer perpendicular to the outcrop, and constitutes a finite rather than an infinite boundary, will cause some overestimation of early stage depletions to the stream; however, this is not likely to be significant in the context of the 100-year time frame used in this evaluation.
- *Flow within the aquifer is horizontal*. On a regional scale, wherein most wells are located at distances many times the thickness of the aquifer away from the stream, the flow can be treated as horizontal without introducing significant error. The violation of this assumption at wells located very close to the stream will result in some over-estimation of stream depletion impacts, particularly in early years. For this study, the overall results of this study are not sensitive to this approximation. Given that the majority of flow is constrained within the Cameo-Fairfield hydrostratigraphic unit, use of the Glover solution will provide a reasonable approximation to stream depletion.
- *Flow is dominated by one phase*. This method only considers single-phase flow. Where water extraction and pressure changes dominate the flow regime, this assumption is acceptable. For the Piceance Basin, outside of the CBM exclusion area, the presence of flowing gas will have the effect of reducing permeability in the vicinity of a producing CBM well. However, it is unlikely that quantities of

gas would be sufficient to affect the overall permeability on a regional scale. The calculation of stream depletion impacts will be driven by effective average regional parameters (rather than by transient, localized, permeability changes in the vicinity of a CBM production well) and by timing and quantity of water production in the well, which is typically most significant in the early stages of operation of a CBM well.

The implementation of the Glover analysis has been structured to conform to these idealizations to the extent possible, as described in the following sections.

6.2.3 Parameter Estimation

6.2.3.1 Permeability and Transmissivity

Relatively few public domain data are available concerning aquifer characteristics within the Cameo-Fairfield coal group, or indeed within the Mesaverde Group as a whole. Table 6.1 provides a tabulation of transmissivity, hydraulic conductivity, and permeability data available in the literature for the Mesaverde Group and the Mesaverde coals. As shown, measured or estimated coalbed hydraulic conductivity values range from 1.6×10^{-4} to 0.6 ft/day (approximately equal to permeabilities of 0.06 to 227 millidarcies [mD]). These data are primarily from near-outcrop locations, where secondary permeability due to fractures is likely to be significantly greater than for locations at depth. More general estimates suggest that Mesaverde coal hydraulic conductivities range from 2.7×10^{-4} ft/day or less to 2.7×10^{-3} ft/day (0.1 mD or less to 1 mD), with values above 2.7×10^{-3} ft/day (1 mD) occurring only locally (Tyler et al., 1991; Olson, 2003). As shown in Table 6.1 permeabilities in the Mesaverde sandstones and shales tend to be lower than in the coal beds.

In the absence of more definitive data for the Cameo-Fairfield coal group, and lacking observation well pressure data required to determine best-fit values for transmissivity, for the Glover analysis, the hydraulic conductivity away from the outcrop is estimated to be 2.7×10^{-3} ft/day (1 mD).

Because the Glover analysis is being applied only for wells perforated in coal seams and not for those wells where coal seam production is commingled with production from sandstones, the effective transmissivities for the Cameo-Fairfield coals in the different subunits are determined by utilizing the mean coal thickness provided in Table 5.1 for each subunit. The use of this adjusted aquifer thickness is justified by the fact that the coals are both the most permeable strata in the formation and the most continuous, and therefore, the flow of water through the formation will be primarily horizontal and constrained to the coals. Assuming a hydraulic conductivity of 2.7×10^{-3} ft/day (1 mD) for the Cameo-Fairfield coals and the mean coal thicknesses for all the subunits as presented in Table 5.1, this represents a range of transmissivities of 0.14 to 0.25 ft^2/day.

6.2.3.2 Storage Properties

Several parameters are used to describe storage properties in aquifers. These include porosity, specific storage, storativity, and specific yield. Porosity is the proportion of open space in any solid media. Specific storage and storativity relate primarily to storage within confined portions of aquifers, while specific yield relates to water released by gravity drainage in unconfined aquifers. These parameters are discussed below as they relate to the study area.

Specific storage (S_s) is the volume of water that a unit volume of a saturated confined aquifer will release from storage under a unit decline in pressure in the aquifer. Confined aquifers release water due to the compaction of the aquifer materials and expansion of the water as the pressure drops; therefore the quantity of water released is small. The total amount of water released from an aquifer of a certain thickness due to the decline in head is called storativity (S, where $S = S_s$ x thickness). Storativity relates the volume of water released to the volume of the aquifer and is a dimensionless ratio. Common values of storativity range between 5×10^{-5} and 5×10^{-3} (Freeze and Cherry, 1979).

Specific yield (S_y) is the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline of the water table. Because water is released primarily by gravity drainage, specific yield of an unconfined aquifer is usually several orders of magnitude higher than storativity of a confined aquifer. Specific yield differs from the total porosity of the aquifer by the amount of water that is held in the pore spaces after the decline in the water table.

Only two estimates of storativity were found in the literature for the Mesaverde Group: 2×10^{-6} to 7×10^{-3} for the Mesaverde Formation (Freethey and Cordy, 1991), and 1.97×10^{-3} for Rollins Sandstone (Mayo and Koontz, 2000). No values for storativity have been found in the literature for the Cameo-Fairfield coals. Assuming a specific storage of 1×10^{-6} ft^{-1} for the

Cameo-Fairfield coals and the mean coal thickness for all the subunits as presented in Table 5.1, this represents a range of storativities of $5x10^{-5}$ to $1x10^{-4}$.

6.2.4 Geometry and Problem Configuration

Based on evaluation of lithologic characteristics, streamflow conditions, shallow groundwater elevations, presence of springs, and other information provided in earlier sections of this report, stream depletion from water production by CBM wells may potentially occur within the Colorado River subunit to the Colorado River, within the North Fork Gunnison subunit to the Gunnison River, and within the White River Dome subunit and the Rangely Anticline subunit to the White River.

Water production within the Divide Creek and Hogback subunits is not considered in this analysis on the basis of stratigraphic and structural geologic considerations and supporting evidence. In both subunits, there is little evidence of connection between the Cameo-Fairfield coal group within the basin and the outcrop. Along the Grand Hogback it is believed that faulting related to the White River Uplift may isolate the areas of CBM production from surface outcrops and areas where perennial streams cross the outcrop. Additionally, along the Grand Hogback, neither documentation of methane seeps nor methane in the shallow groundwater were identified for this study. Within Divide Creek, though methane has been documented in wells and streams along the axis of the Divide Creek Anticline (URS, 2006), it is not known if the source of the methane is due to natural upward migration from depth or from drilling and gas production-related activities or both. Further, the areas of CBM production (the Divide Creek and Mamm Creek fields) are structurally complex and appear to be isolated from the Cameo-Fairfield coal group outcrop more than 10 miles to the east by faulting related to the formation of the anticline itself or present beneath the Grand Hogback. Calculating potential depletions due to vertical flow beneath Divide Creek where it traverses the Divide Creek Anticline was not performed because data supporting and quantifying a vertical connection between the ground surface and the Cameo-Fairfield coal group is not available.

Within the Colorado River, Rangely Anticline, and White River Dome subunits, the timing and location of stream depletion impacts to the respective rivers is a function of distance from the pumping horizon to the stream where it traverses the outcrop, and the hydraulic conductivity and storage properties of the Cameo-Fairfield coal group. Within the North Fork of the Gunnison subunit, distance to the outcrop along the stretch of the subunit between its western end and where it is traversed by the North Fork of the Gunnison River, is the region evaluated for depletion. This approach is used because the outcrop of the Cameo-Fairfield coal group in this subunit is along the south slopes of Grand Mesa in an area that receives in excess of 20 inches of precipitation each year and is cut by several perennial streams that are tributary to the North Fork Gunnison and Gunnison Rivers. It is expected, therefore, that the outcrop is hydraulically connected to the CBM-producing interval at depth in the subunit.

Based on the information reviewed in this study, the following conditions and constraints were taken into account in deriving stream depletions estimates:

1. The Cameo-Fairfield coal group is not generally present at land surface in the immediate vicinity of existing or potential CBM wells within the subunits. The assumed distance from a well to the potentially impacted stream was taken as the distance to the stream where it transects the outcrop of the Cameo-Fairfield coal group. This approach neglected the potential for impacts to propagate vertically through overlying formations, but assumed that reasonable hydraulic connection occurs within a formation to the outcrop of that formation where it is traversed by a stream.
2. The Glover analysis was run for wells at a range of distances from the outcrop-stream intersections to establish location of the boundary where stream depletion would exceed 0.1 percent after 100 years of pumping for each affected subunit (the tributary/non-tributary boundary). As described above, for the North Fork Gunnison subunit, the distance to the outcrop between the western end of the subunit and the North Fork of the Gunnison River was used.
3. All of the subunits are bounded on at least one side by the CBM exclusion area; therefore, it was necessary to consider the potential effects of this boundary. Using the image well method described in McWhorter and Sunada (1977) allowed more accurate calculation of depletion for pumping wells sufficiently close to the boundary. Sensitivity analyses incorporating the geometry of the basin and the CBM exclusion area showed that, given the aquifer parameters provided above, in most areas the amount of depletion and the location of the tributary/non-tributary boundary were not affected significantly. (The exceptions to this conclusion are discussed further in the following section.)
4. There is no apparent active development of CBM gas solely from coal seams anywhere in the Piceance Basin. As such, due to the very small amount of CBM water production, both historically and currently, no attempts are made to estimate stream depletion in the basin based on possible future CBM development scenarios.

6.3 Results of Glover Stream Depletion Analysis

6.3.1 Characterization of Percentage Depletions

For the Colorado River, North Fork of the Gunnison River, Rangely Anticline, and White River Dome subunits, Figure 6.1 shows where the depletion ratio (i.e., percentage of pumping impacting the stream) is greater than 0.1 percent after 100 years of pumping as a function of distance from the outcrop-stream intersection. The basinward edge of this demarcation, identified as the tributary/non-tributary boundary, is approximately 8.8 miles from the Cameo-Fairfield hydrostratigraphic unit outcrop or from the intersection of the outcrop with the stream within the Piceance Basin. The boundary is applicable only for water produced from coal beds in the Cameo-Fairfield coal group.

For all four subunits where the boundary is identified, the Glover analysis calculations are made using an S/T value of 3.6×10^{-4} day/ft^2. This ratio reflects the assumed hydraulic conductivity of 2.7×10^{-3} ft/day (1 mD), a specific storage of 1×10^{-6} ft^{-1}, and subunit estimates of total coal thickness as discussed in Section 5.

Because hydraulic parameters for the Cameo-Fairfield coal group are not well constrained, the effects of modifying S/T were evaluated in a cursory manner. If S/T is assumed first to be 1×10^{-3} and then to be 1×10^{-4} (equivalent to holding storativity constant while changing hydraulic conductivity from 2.7×10^{-3} feet/day [1 mD] to 1×10^{-3} feet/day [0.37 mD] and then to 1×10^{-2} feet/day [3.7 mD]) then the tributary/non-tributary boundary is seen to change from 8.8 miles to 5.3 miles for the smaller permeability value and to 16.8 miles for the larger permeability value[5].

The depiction of the tributary/non-tributary boundaries shown in Figure 6.1, neglects boundary influences that may occur in some subunits due to the presence of the CBM exclusion area or to regional scale faulting along the north side of the Rangely Anticline subunit and the south and northeast sides of the White River Dome subunit (Johnson and Nuccio, 1986; Tyler, 1995). Sensitivity analyses indicate that consideration of these boundaries does not significantly affect depletion except in the White River Dome subunit. In this subunit, if it is assumed that the effects of pumping are not transmitted across these boundaries, then the distance from the

[5] Similarly, the same reduction and increase in distance to the tributary/non-tributary boundary results from changing specific storage to 2.1×10^{-4} ft^{-1} and then to 2.1×10^{-5} ft^{-1}, respectively.

stream-outcrop intersection to the tributary/non-tributary boundary is increased. While more closely studying the conditions in the White River Dome subunit to evaluate the validity of the possible barriers to flow is beyond the scope of this project, a sense of the change the barriers could cause can be estimated. Using the method provided by Bear (1979), for a hypothetical well located at the interior corner of a wedge shaped aquifer where the outcrop represents the outer face of the triangle whose interior angle is approximately 30 degrees, the tributary/non-tributary boundary extends to a distance of approximately 12 miles from the stream-outcrop intersection. While not all of the White River Dome subunit would be tributary under this scenario, the majority of it would be.

6.3.2 Current Extent and Magnitude of Depletions

CBM water production in the Piceance Basin is very small compared to water production in other Colorado CBM basins. As discussed in Section 4.1 and shown on Figure 4.1, there have been two brief periods when annual CBM water production rose quickly, peaked, and then dropped quickly. The second peak, which occurred in 2004, resulted in the production of approximately 187 acre-feet of water from CBM wells. To date cumulative CBM water production in the basin is less than 1,200 acre-feet, which is considerably less than the 2005 single year CBM produced water quantities for either the San Juan or Raton Basins. Current depletions at the outcrop are a fraction of this. Based on the Glover analysis with parameters as described above, the total cumulative depletion to date for the Piceance basin is estimated to be less than one acre-foot, all from the Colorado River subunit.

Although over 80 percent of the CBM water production in the Piceance Basin has come from the Divide Creek Anticline subunit, initially from wells in the Divide Creek field and more recently from wells in the Mamm Creek field, it is not believed that depletion at the outcrop has occurred due to production from these wells since they are both greater than 8.8 miles from the outcrop and likely not hydraulically connected to the outcrop. Outside of the Divide Creek subunit, most of the CBM water production has come from wells in the White River Dome subunit. Wells in this subunit have produced a total of approximately 195 acre-feet of water, the majority prior to 1995. These wells are assumed to be in connection with the Cameo-Fairfield coal group outcrop where it is intersected by the White River; however, they are all more than 8.8 miles from the river and calculations indicate that there has been no depletion by these wells, except potentially as has been discussed above due to flow barriers within the hydrostratigraphic unit.

7.0 PICEANCE BASIN CBM WATER PRODUCTION AND REGULATORY IMPLICATIONS

Depletions to surface water streams from CBM groundwater production have potential implications to water rights holders, the State of Colorado, and to downstream water users not in Colorado. For these reasons it is necessary to evaluate the current regulatory framework associated with the production of CBM water, the potential for beneficial uses of such water, and the interstate ramifications of the consumptive uses of such water.

7.1 Regulatory Framework and Potential Beneficial Uses of CBM Produced Water

COGCC has regulatory jurisdiction over all CBM operations, including the generation, transportation, storage, and treatment or disposal of exploration and production wastes. This includes water produced during CBM operations unless that water is put to beneficial use in accordance with Colorado Revised Statutes and DWR regulations. The jurisdictional framework is illustrated in Figure 7.1. A summary of DWR authorities regarding groundwater administration and CBM water production is provided by Wolfe and Graham (2002) and is included in Appendix A of this report.

Under existing regulations in Colorado, CBM produced water, like water produced from any other type of oil or gas well, is considered a waste. As long as CBM produced water is handled as waste under COGCC Rule 907, it remains under the jurisdiction of the COGCC. However, if CBM produced water is put to a beneficial use beyond the uses allowed under Rule 907, it is subject to DWR regulation. There are several beneficial uses for waters of the state recognized by DWR, including domestic and municipal water supply, irrigation, livestock watering, manufacturing and industry, fire protection, dust suppression, minimum stream flows, and augmentation. Based on the designation of the groundwater where extraction for beneficial use is occurring, several of these uses may require a permit from DWR. Furthermore, if CBM produced water is discharged to the waters of the state[6], a permit must be obtained from the Colorado Department of Public Health and Environment, Water Quality Control Division (CDPHE-WQCD). The regulatory framework may appear complicated, but the authority and guidance to put CBM water to beneficial use are well established.

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[6] "Waters of the state" refers to all surface and underground waters that are tributary to natural streams, except designated groundwater as specified in C.R.S. 37-90-103(6)(a) and related statutes.

In the Piceance Basin, there has been very little CBM water produced, and production has been highly variable. Historically, most CBM produced water has been disposed in evaporation ponds or into Class II UIC injection wells. Because of the poor quality of the water produced from the CBM wells in the basin (TDS much greater than 10,000mg/L), there are currently no active surface discharges or other beneficial uses of the produced water. Currently, a significant number of the CBM wells in the basin (especially in the Mamm Creek field) that are not abandoned, are shut-in and possibly may be waiting on completion of a system that will allow efficient produced water disposal or beneficial use. It is not known if beneficial uses will become economically feasible in the basin in the near future.

7.2 Interstate Stream Compact Ramifications

Interstate stream compacts relating to surface waters from the Piceance Basin in Colorado (where the border of the basin is defined by the Mesaverde Formation outcrop) to other states include the Colorado River Compact (C.R.S. 37-61-101) and the Upper Colorado River Compact (C.R.S. 37-62-101).

Article III(a) of the Colorado River Compact apportions 7.5 million acre-feet/year of water both to the states of the "Upper Basin", of which Colorado is one, and to the states of the "Lower Basin". In accordance with the compact, surface waters that flow from the Piceance Basin in streams tributary to the Colorado River constitute a portion of the 7.5 million acre-feet/year of water that must be delivered to the lower basin at Lee Ferry in northern Arizona. The Upper Colorado River Compact further apportions the waters of the upper basin of the Colorado River among the states of Colorado, New Mexico, Utah, and Wyoming. In accordance with Article III(a)(2) of the compact, Colorado is apportioned 51.75 percent of the water that is available for consumptive use from the Colorado River and its tributaries in the upper basin. Whether Colorado over-appropriates water under this compact depends on total consumptive use from all the streams in the upper basin in Colorado, not on consumptive use from any single stream. The Colorado Department of Natural Resources must evaluate whether current regulation of the depletions resulting from CBM produced water is appropriate in the context of the Upper Colorado River Compact.

8.0 SUMMARY OF CONCLUSIONS

For this study, information was reviewed to provide background on the hydrogeologic setting related to CBM production in the Piceance Basin; literature and existing data were reviewed to obtain reasonable estimates of aquifer parameters for a stream depletion analysis; and, stream depletion due to the production of groundwater from CBM wells was evaluated. Primary study findings include:

- ***Gas and water production***: Approximately 22.4 Bcf of gas and 1,200 acre-feet (9.2 million barrels) of water have been produced from Piceance Basin CBM wells—not including wells in the CBM exclusion area or with production that is commingled with non-coal horizons. Gas production has declined steadily since peaking at approximately 2.8 Bcf in 1992. In 2006 total CBM gas production was 0.21 Bcf. Water production similarly peaked in 1992 at nearly 180 acre-feet and then declined sharply. However, in 2004 and 2005, water production rose relatively sharply from 11 acre-feet in 2003 to 187 and 163 acre-feet, respectively. The rise was driven by drilling and production in the Mamm Creek field in the Divide Creek Anticline subunit; the sharp reduction in water production in 2006 to 39 acre-feet was a result of the Mamm Creek wells being shut-in. While the increase in CBM water production in the early 1990s was accompanied by an associated increase in gas production, the increase in water production in 2004 and 2005 was not accompanied by a significant increase in gas production.

  Past CBM gas and water production trends in individual wells in the Piceance Basin differs from trends common in other basins, such as the San Juan Basin, in that both gas and water production in Piceance Basin wells frequently peaked within a year or two of initial production and then fell off quickly. To date, only a few wells in the White River field in the White River Anticline subunit and the Divide Creek field in the Divide Creek Anticline subunit have had significant sustained production of CBM.

- ***Hydrogeologic setting***: CBM is produced primarily from coal seams in the Williams Fork Formation of the late Cretaceous Mesaverde Group. The coal seams are interbedded with laterally discontinuous fine-grained sandstone and shale layers and the sequence is collectively known as the Cameo-Fairfield coal group. The Cameo-Fairfield coal group extends to an outcrop area that almost completely encircles the Piceance Basin. The region is traversed by three major streams (the Colorado, White, and North Fork Gunnison Rivers) and several smaller perennial streams, most of which are located along the south and southeast edge of the basin in the near Grand Mesa and the West Elk Mountains.

  Groundwater flow occurs through coal cleats and fractures, although the unit transmissivity is very low and areas of deep subsurface fracturing and faulting are present in several areas. In four of the six delineated subunits (Colorado River, North Fork of the Gunnison River, Rangely Anticline, and White River Dome), no significant barriers between the CBM wells and the outcrop were identified that would negate an assumption of hydraulic connection from the wells to the streams at the outcrop. The two other subunits (Divide Creek and the Hogback) appear to be fault-bounded to a sufficient extent to preclude widespread hydraulic connection between productive portions of the Cameo-Fairfield coal group and the outcrop.

- ***Estimation of aquifer parameters***: Little published data regarding aquifer parameters exists for the Cameo Fairfield coal group except in shallow near-outcrop areas (generally near coal mining regions). One set of aquifer parameters (specific storage and permeability/hydraulic conductivity) was developed to represent the Cameo-Fairfield coal group based on literature review of estimated and measured parameters, and evaluation of supporting evidence. Transmissivity and storativity for individual sub-areas were calculated based on sub-area estimates of total coal thickness.
- ***Stream depletion analysis***: The Glover analysis was applied for the four subunits identified above where communication with perennial streams traversing the Cameo-Fairfield Coal Group outcrop could reasonably be justified. Using the estimated average transmissivity and storativity values given above, the distance to the tributary/non-tributary boundary was calculated to be approximately 9 miles. The total stream depletion for the Piceance Basin from CBM water production is estimated to be less than one acre foot.
- ***Suitability of the Glover method:*** Considering the geologic and hydrogeologic characteristics of the Piceance Basin and the nature of the aquifer hydraulic data available to estimate input parameters, the Glover analysis is an appropriate tool for evaluating stream depletion effects for areas where hydraulic connection between gas producing coal seams and the outcrop can be reasonably argued. Uncertainty exists in the projected depletions due to lack of sufficient data to fully characterize aquifer properties. However, absent data on formation thickness and fluid pressures at individual CBM production and observation wells, it is not possible to structure and parameterize a more detailed or complex model; nor is it possible to conclude that a more detailed or complex model (such as MODFLOW) would necessarily yield more accurate results.
- ***Regulatory framework and possibilities for beneficial use of CBM produced water:*** When produced water is disposed as a waste, regulatory authority lies with COGCC under Rule 907. If water is beneficially used beyond those uses allowed under Rule 907, regulatory authority for use lies with the DWR; if water is discharged to waters of the state, the discharge must be permitted by the CDPHE-WQCD. The Agencies' roles in these situations are clear; even though the process of obtaining approval to put CBM produced water to beneficial use may require multiple permits.

  Beneficial use of produced water in the Piceance Basin is limited due to the high TDS values of the water, and the lack of economic drivers to justify expensive treatment and conveyance systems from points of production to points of use.

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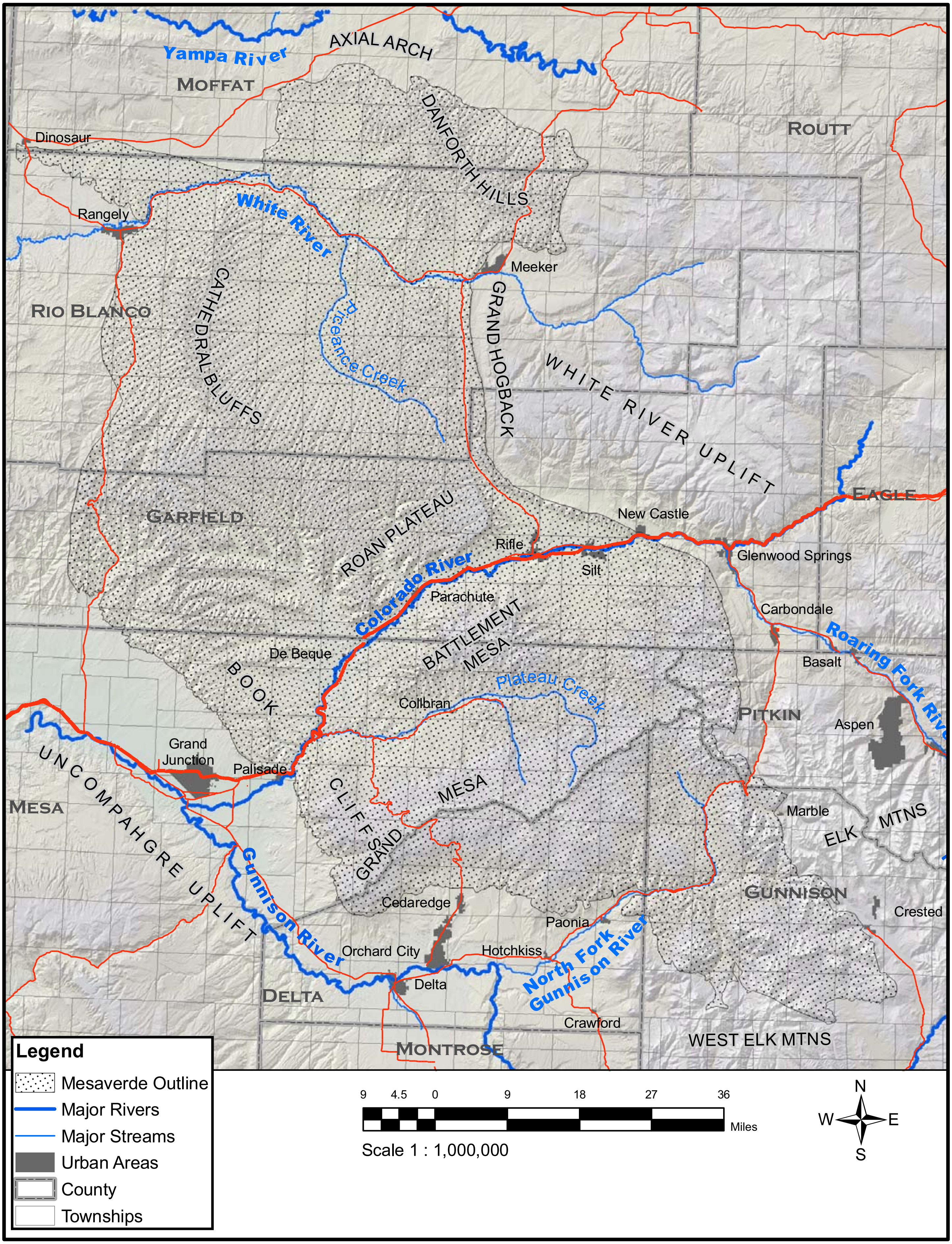


Figure 1.1 Geographic Reference Map for the Piceance Basin

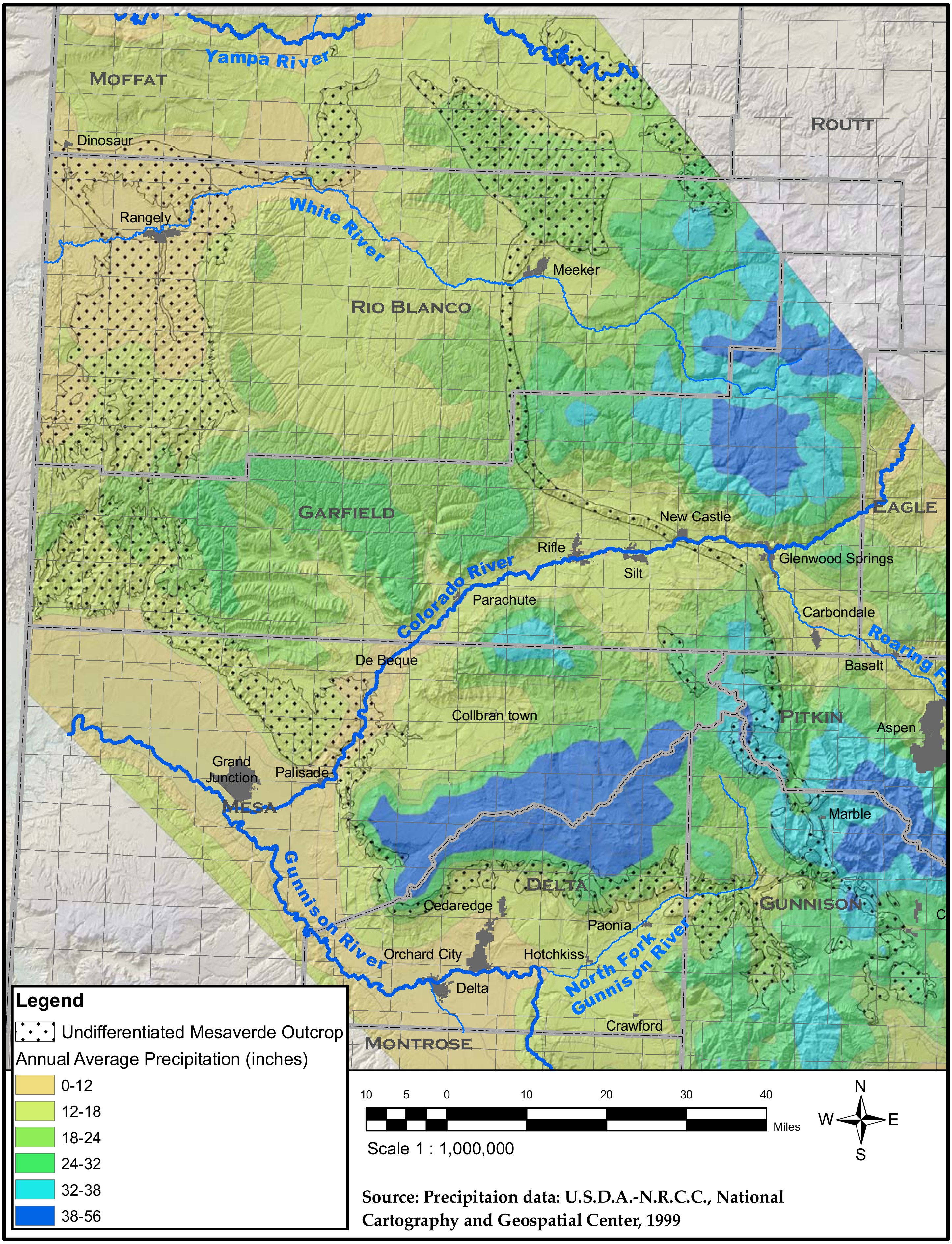
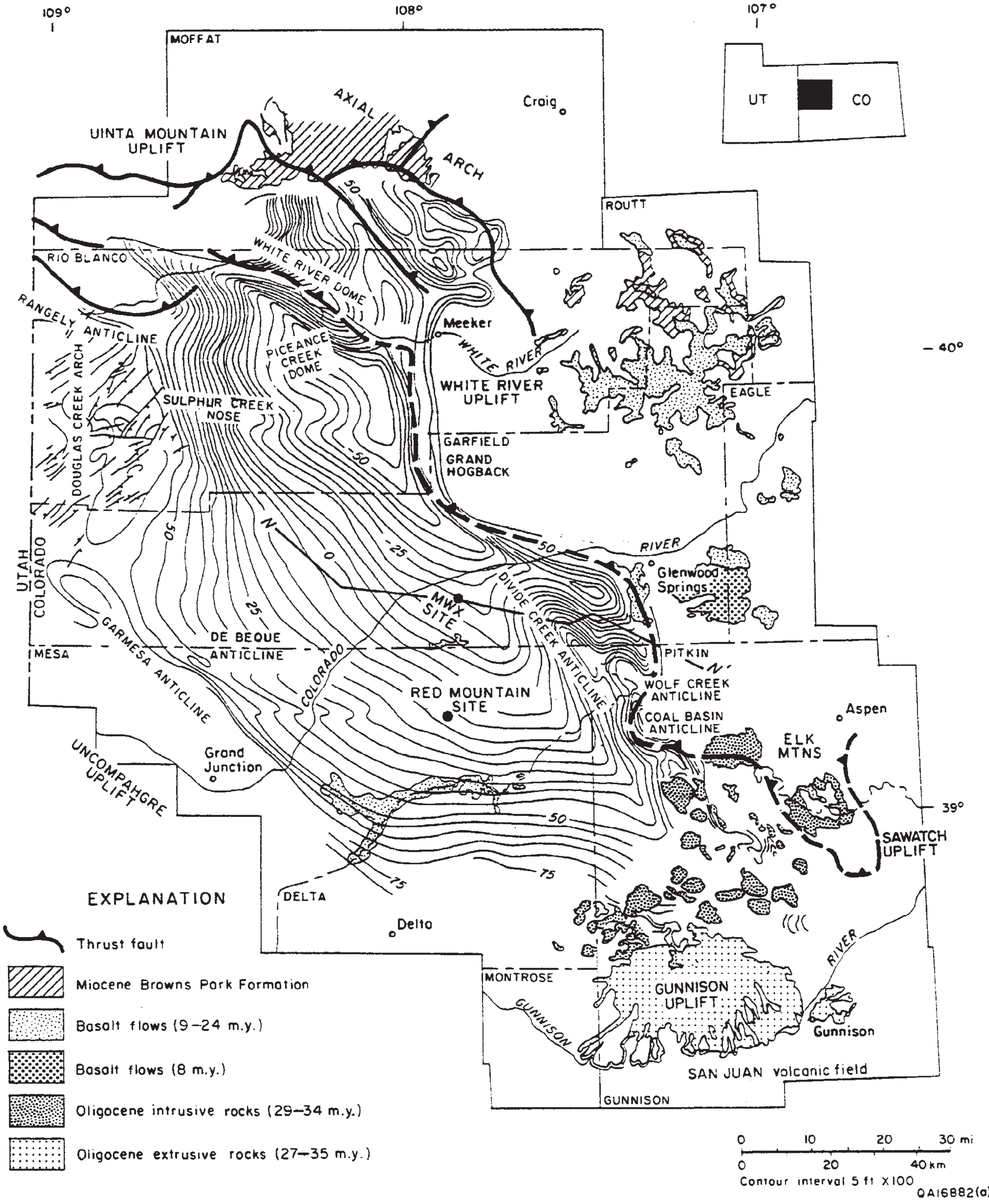


Figure 3.1. Annual Precipitation within the Piceance Basin

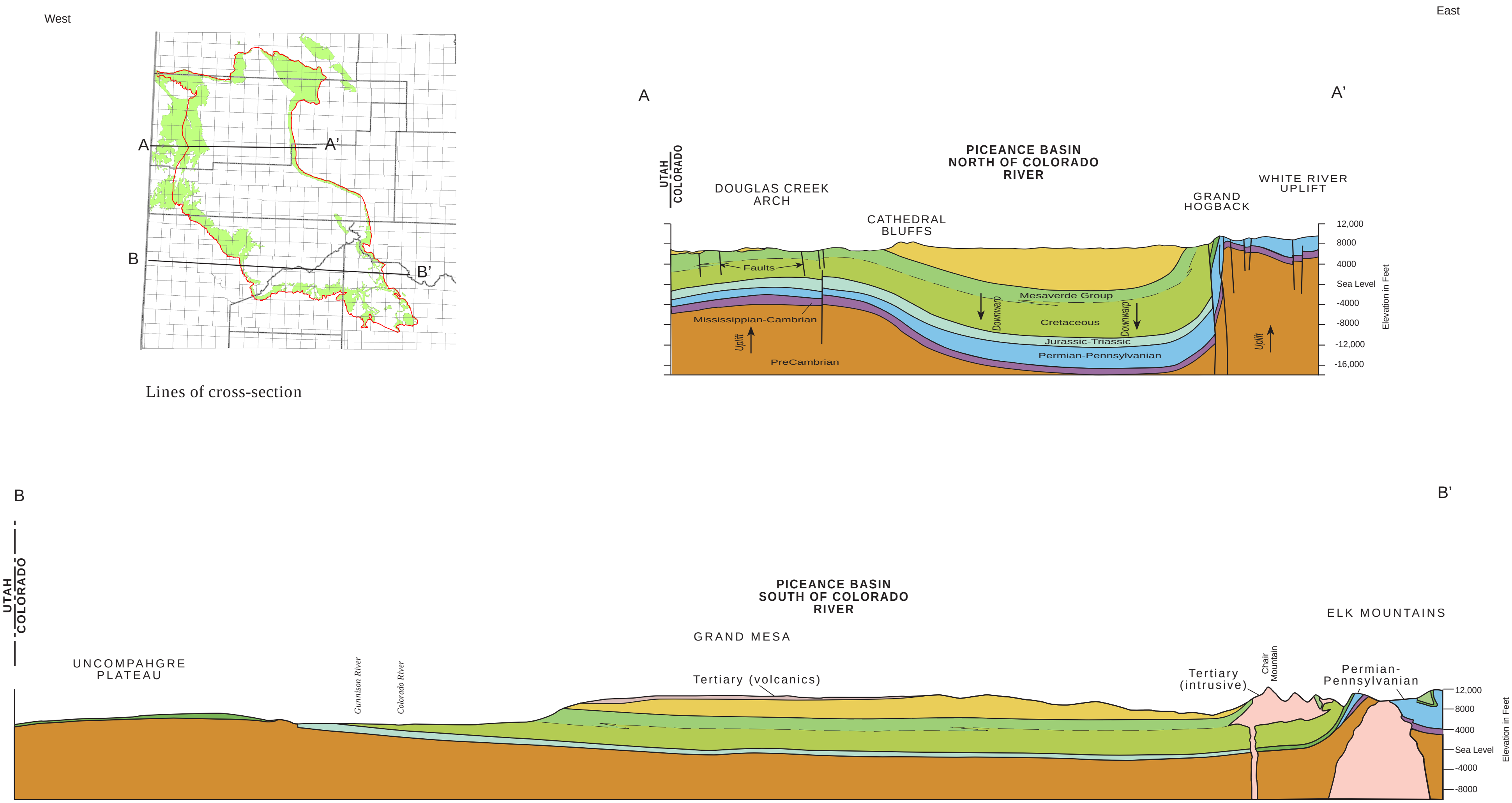
Stratigraphic Units and Principal Tectonic Events of the Piceance Basin						
Era	Period	Epoch	Age (ma)	Events, environments	Formations	CBM Evolution
CENOZOIC	Quaternary	Holocene	0.01	Regional uplift, erosion, development of Colorado River System	Alluvial, glacial, eolian deposits	Modern groundwater systems
		Pleistocene	1.8			
	Tertiary	Pliocene	5.3			
		Miocene	23	Rio Grande rift extensional tectonics, basalt volcanism, erosion	Basalt flows	Uplift, erosion, develop fracture patterns
		Oligocene	34	Intermediate and silicic volcanism, intrusions, erosion	West Elk volcanic field, lacoliths	
		Eocene	55	Uplift of White River Plateau and Axial Arch, erosion, Lake Uinta	Uinta Fm. Green River Fm.	Deep burial, gas generation, deformation, develop fracture patterns
		Paleocene	65	Laramide Orogeny, subsidence of Piceance Basin, bordering uplifts, deep weathering of erosional surfaces	Wasatch Fm. Ft. Union Fm.	
MESOZOIC	Cretaceous	Upper	99	Withdrawal of Interior Seaway, start of Laramide Orogeny	Mesaverde Grp Mancos Sh.	Source Rock coals deposited
		Lower	145	Development of Interior Seaway	Dakota Grp.	
	Jurassic		200	Fluvial and lacustrine environment Eolian environment	Morrison Fm. Entrada Ss.	
	Triassic		253	Fluvial and lacustrine environment	Chinle Fm. Moenkope Fm.	
PALEOZOIC	Permian		300	Fluvial sandstone, Carbonates and shale Eolian dunes	State Bridge Fm. Phosphoria Fm. Weber Ss.	
	Pennsyl-vanian		318	Ancestral Rocky Mountains, basin fill, restricted marine basins, evaporite deposits	Maroon Fm. Minturn Fm. Eagle Valley Fm. Belden Fm. Molas Fm.	
	Missis-sippian		360	Regional uplift, erosion		
				Shallow carbonate shelf	Leadville Ls.	
	Devonian		418	Shallow carbonate and clastic shelf	Gilman Ss. Dyer Fm Parting Fm.	
	Silurian		443	Non-deposition, erosion		
	Ordovician		489	Shallow carbonate and clastic shelf	Manitou Fm.	
	Cambrian		544	Marine transgression	Peerless Fm. Sawatch Ss.	
PRE CAMBRIAN	Proterozoic		2,500	Uinta Aulacogen	Uinta Mt. Grp.	
				Regional metamorphism and plutonism	Igneous and Metamorphic Basement	

Figure 3.2. Stratigraphic Column of the Piceance Basin (Adapted from Wilson et al., 2003 and Johnson and Roberts, 2003.)



Source: From Tyler (1995).

Figure 3.3 Structural Map of the Piceance Basin (contours on the top of the Upper Cretaceous Rollins-Trout Creek Sandstone)



Source: Modified from Tweto, 1983

Figure 3.4 Generalized Cross-Sections Across the Piceance Basin

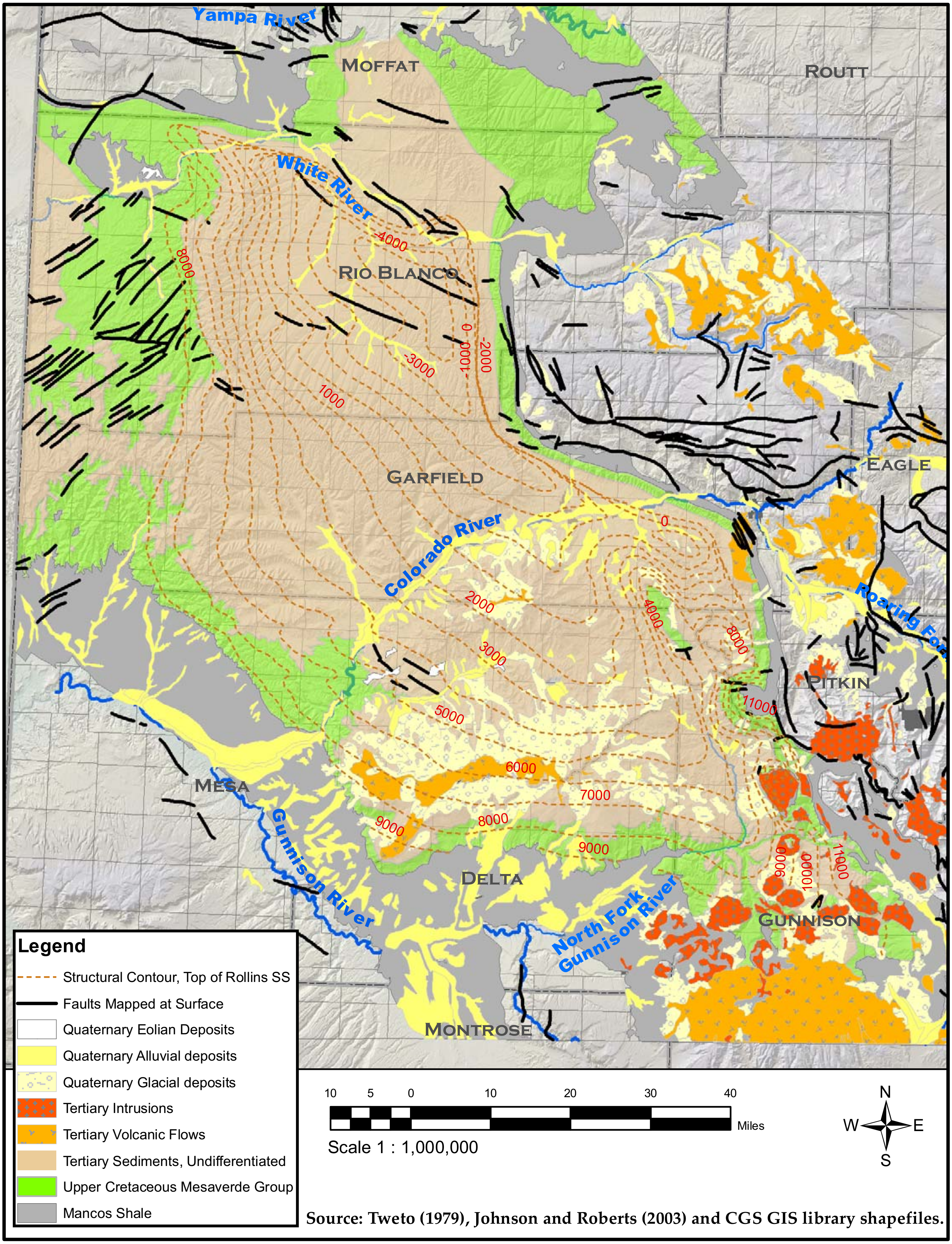
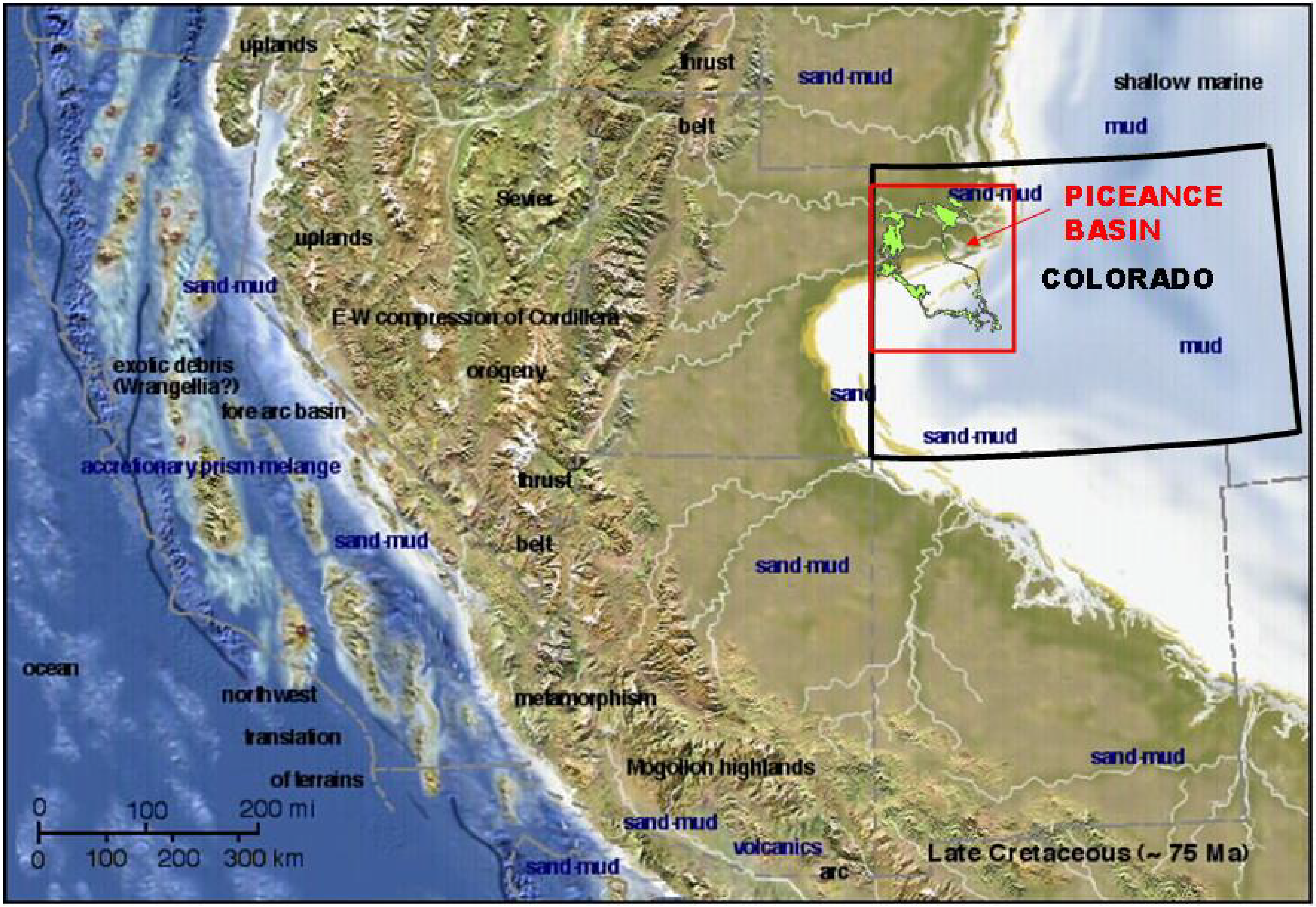
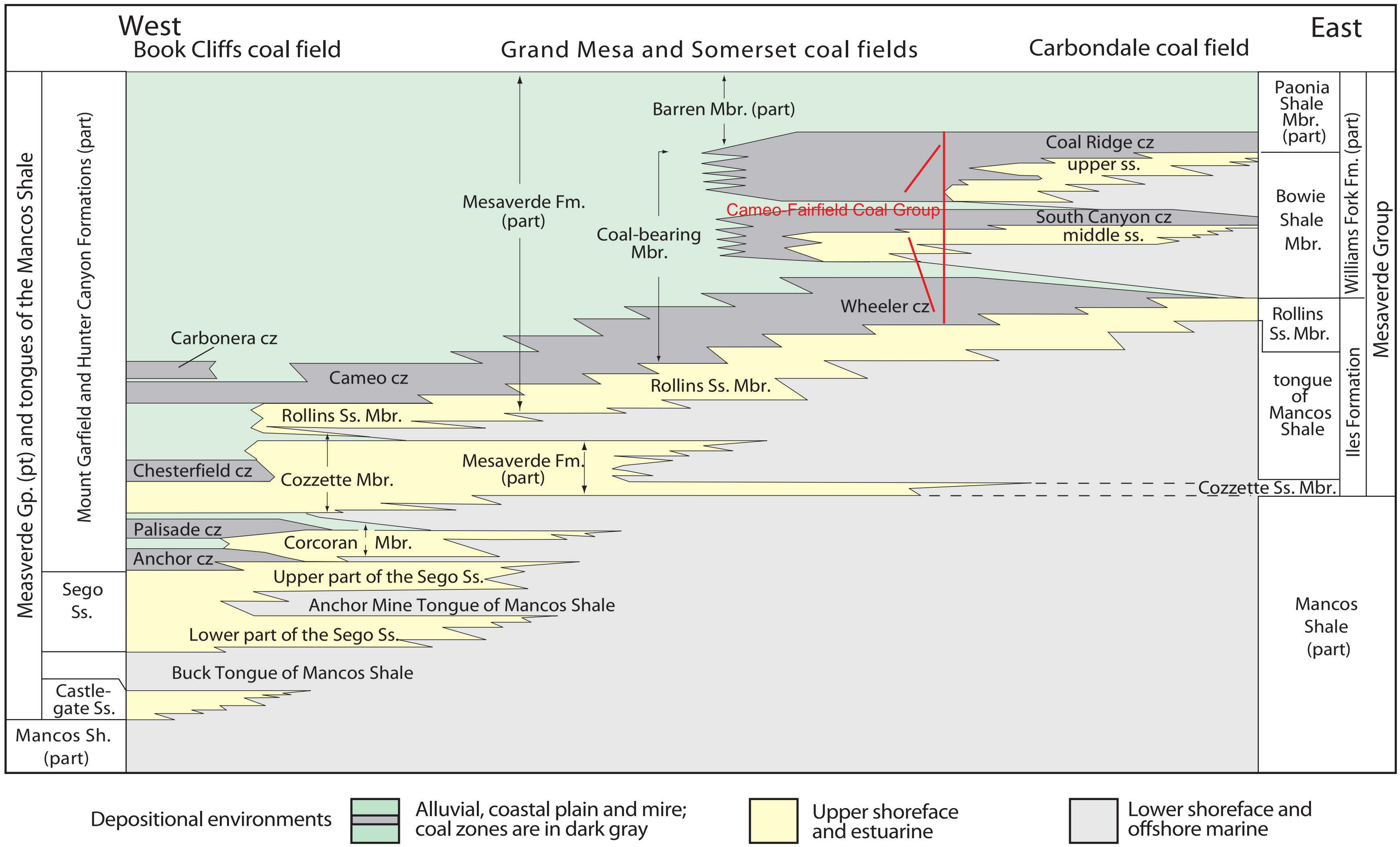


Figure 3.5 Geologic Map of Piceance Basin Showing Faults Mapped at 1:500,000 Scale



Source: Modified from Blakey (2007).

Figure 3.6 Late Cretaceous Western Interior Seaway



Source: From Carroll, 2003; modified after Hettinger et al., 2000.

Figure 3.7 Stratigraphic Correlations and Facies Relationships in the Mesaverde Group, Southern Piceance Basin

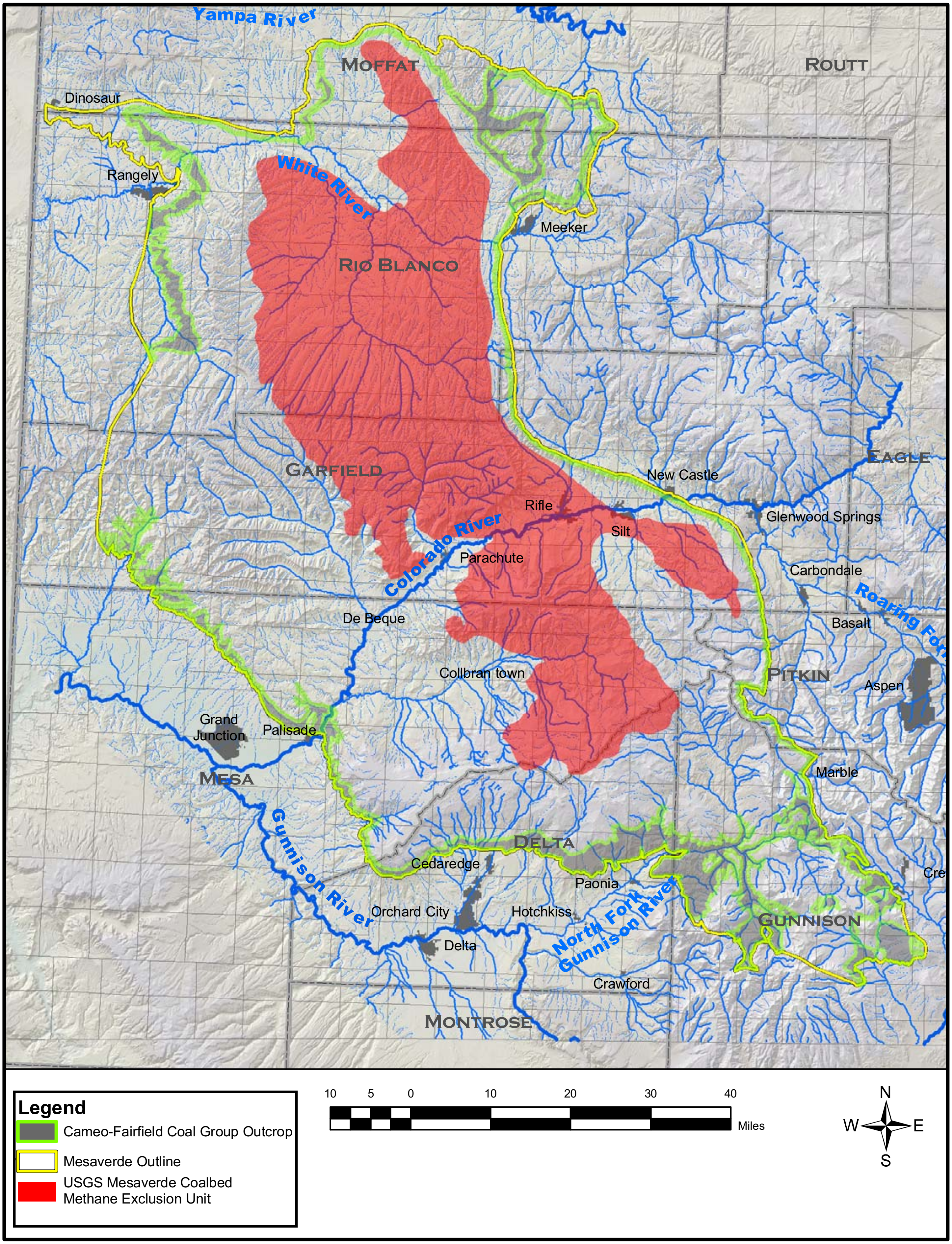
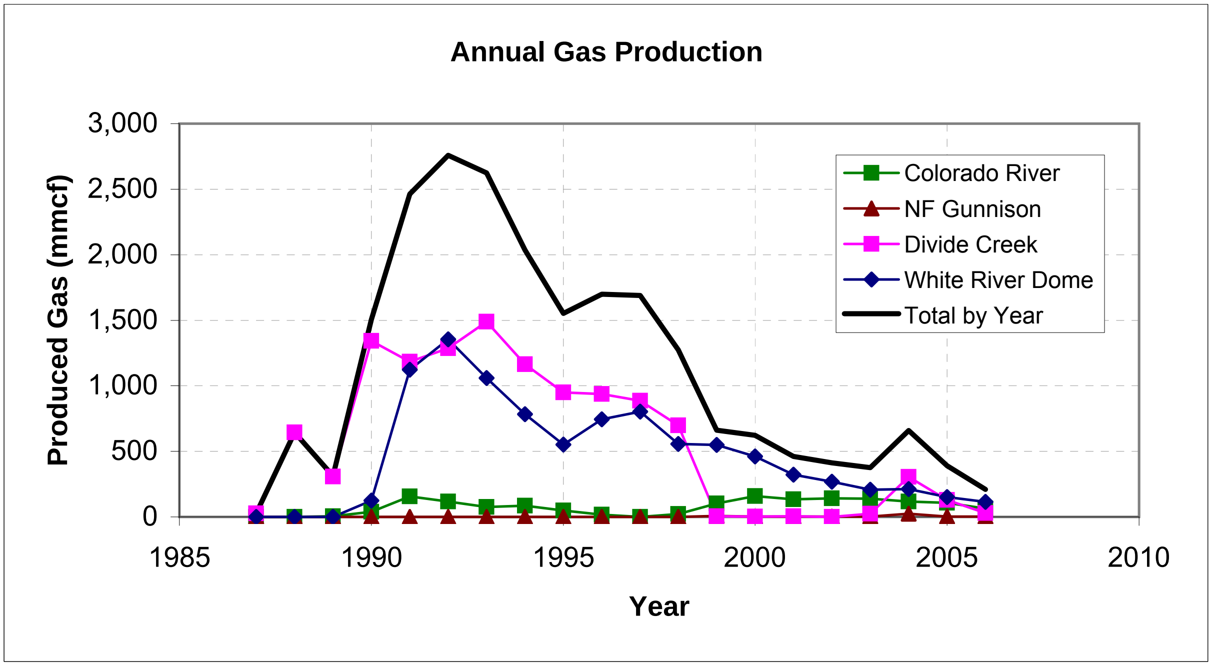


Figure 3.8 USGS Mesaverde Coalbed Methane Exclusion Unit for the Piceance Basin



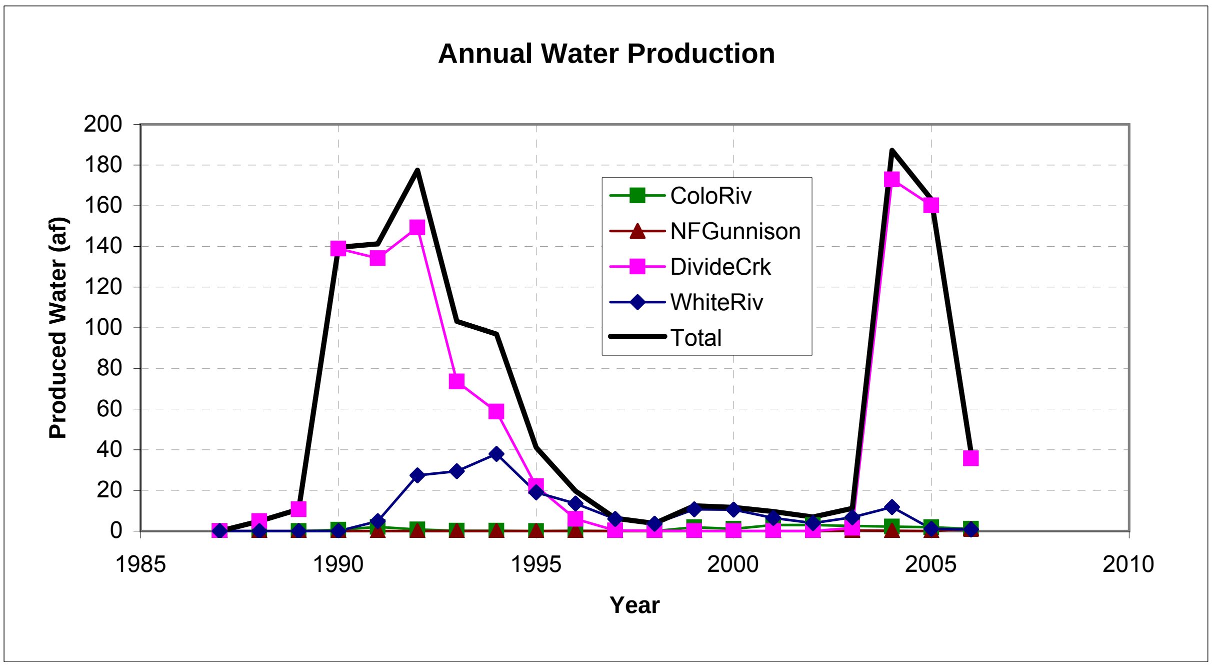


Figure 4.1 Annual Piceance Basin CBM Gas and Water Production, 1987-2006

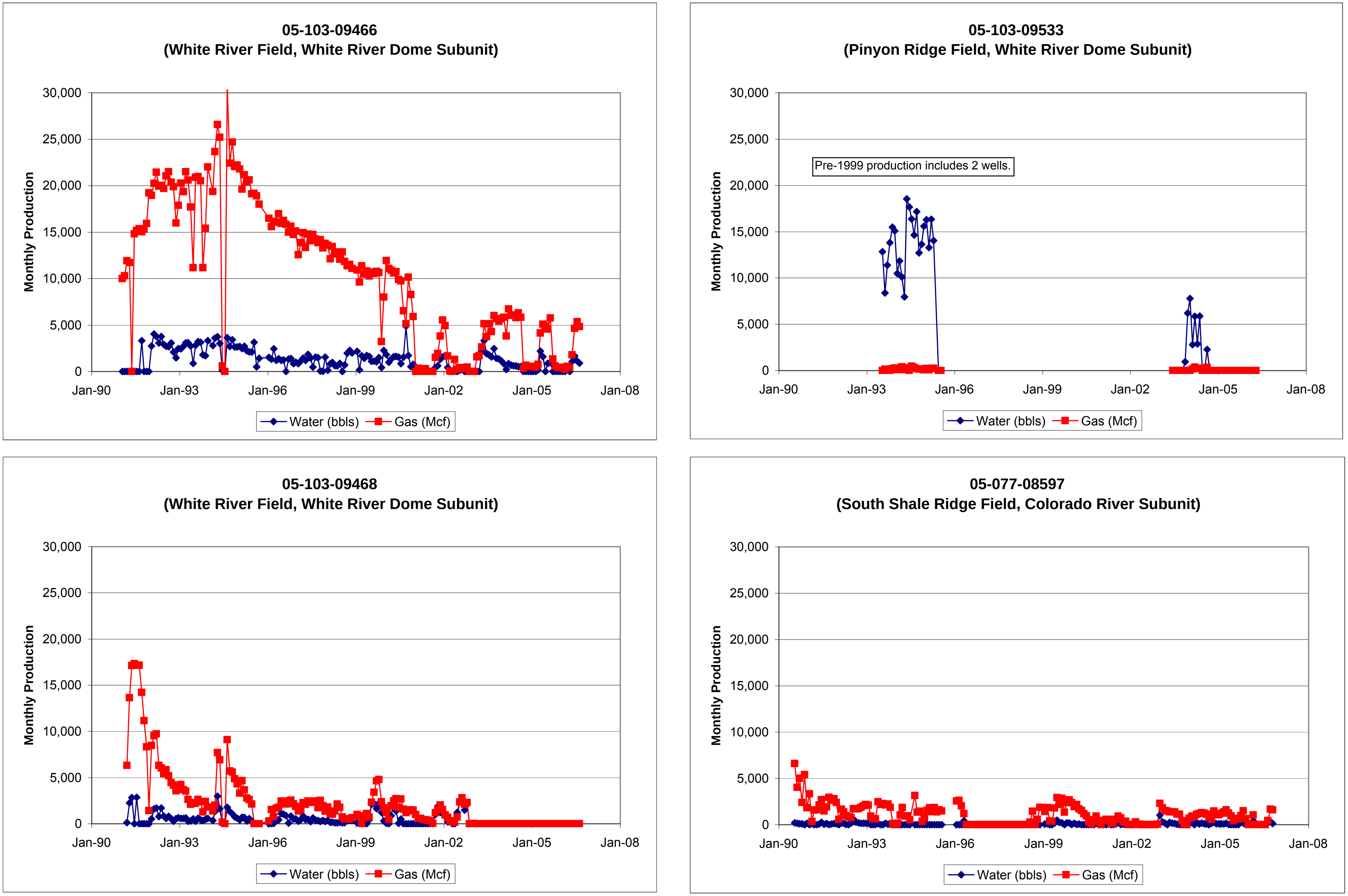
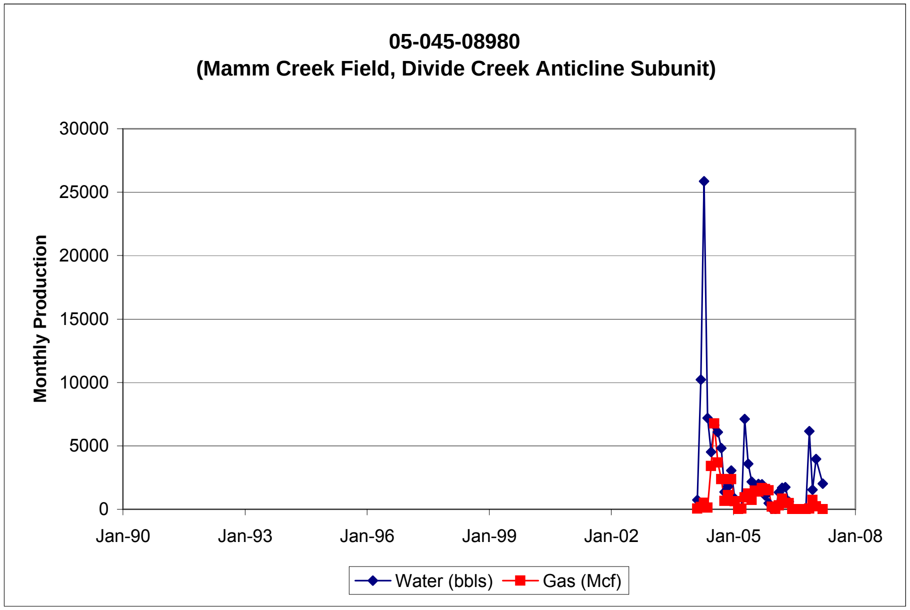
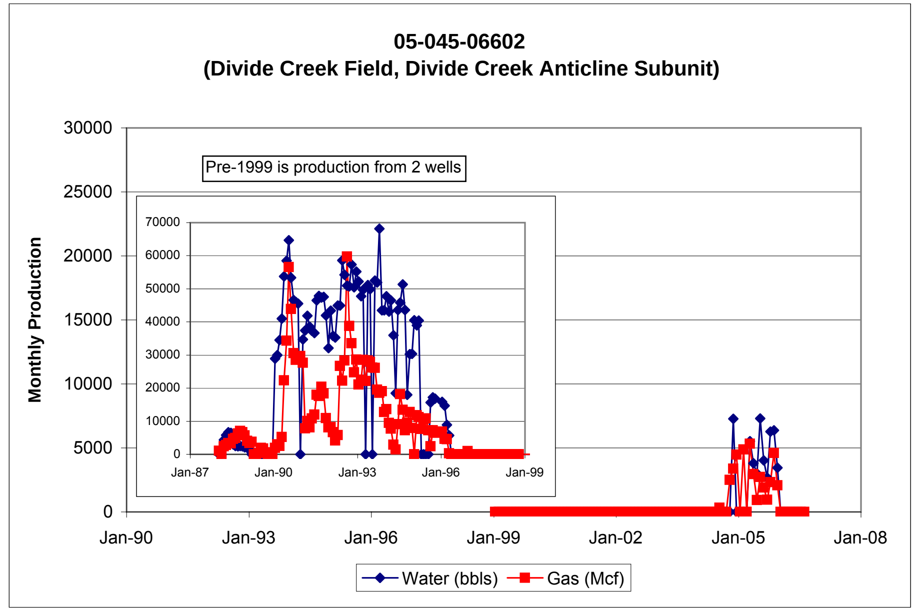
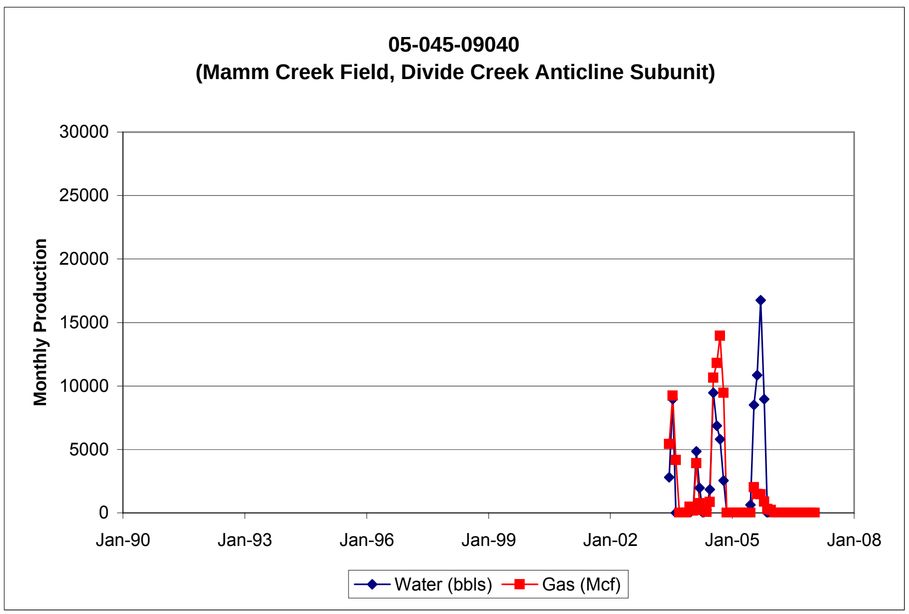


Figure 4.2 Piceance Basin CBM Gas and Water Production Plots







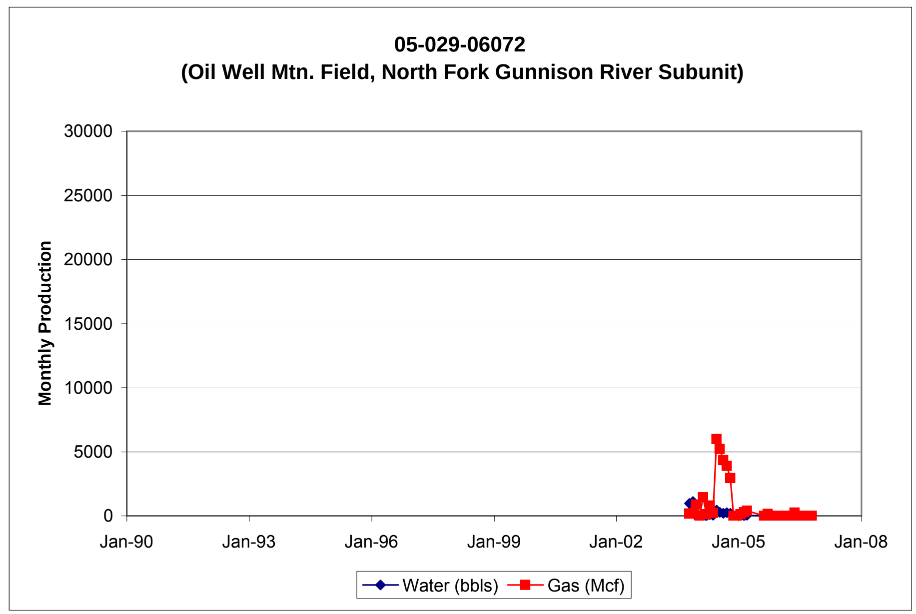


Figure 4.2 (cont.) Piceance Basin CBM Gas and Water Production Plots

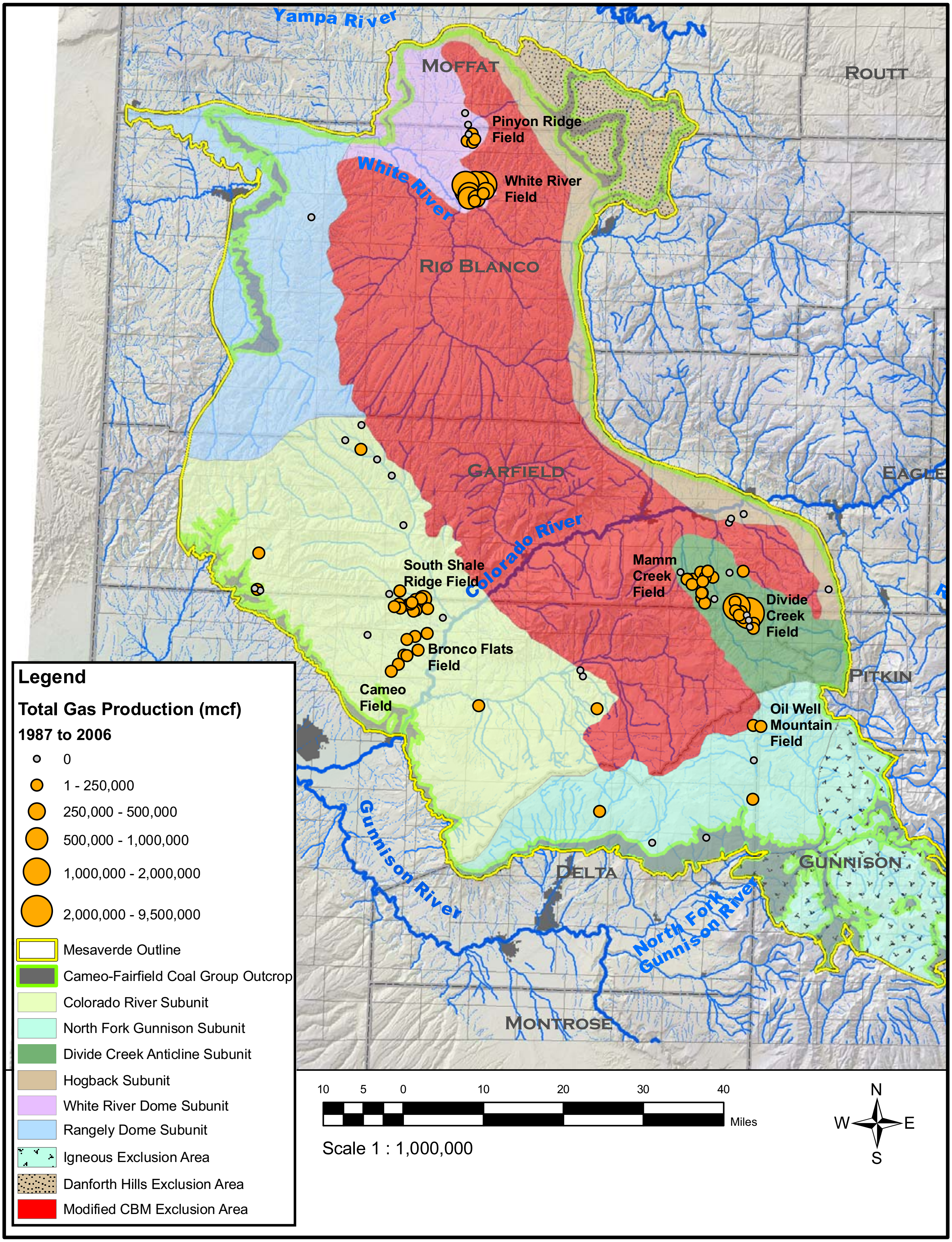


Figure 4.3. Areal Distribution of CBM Gas Production in the Piceance Basin

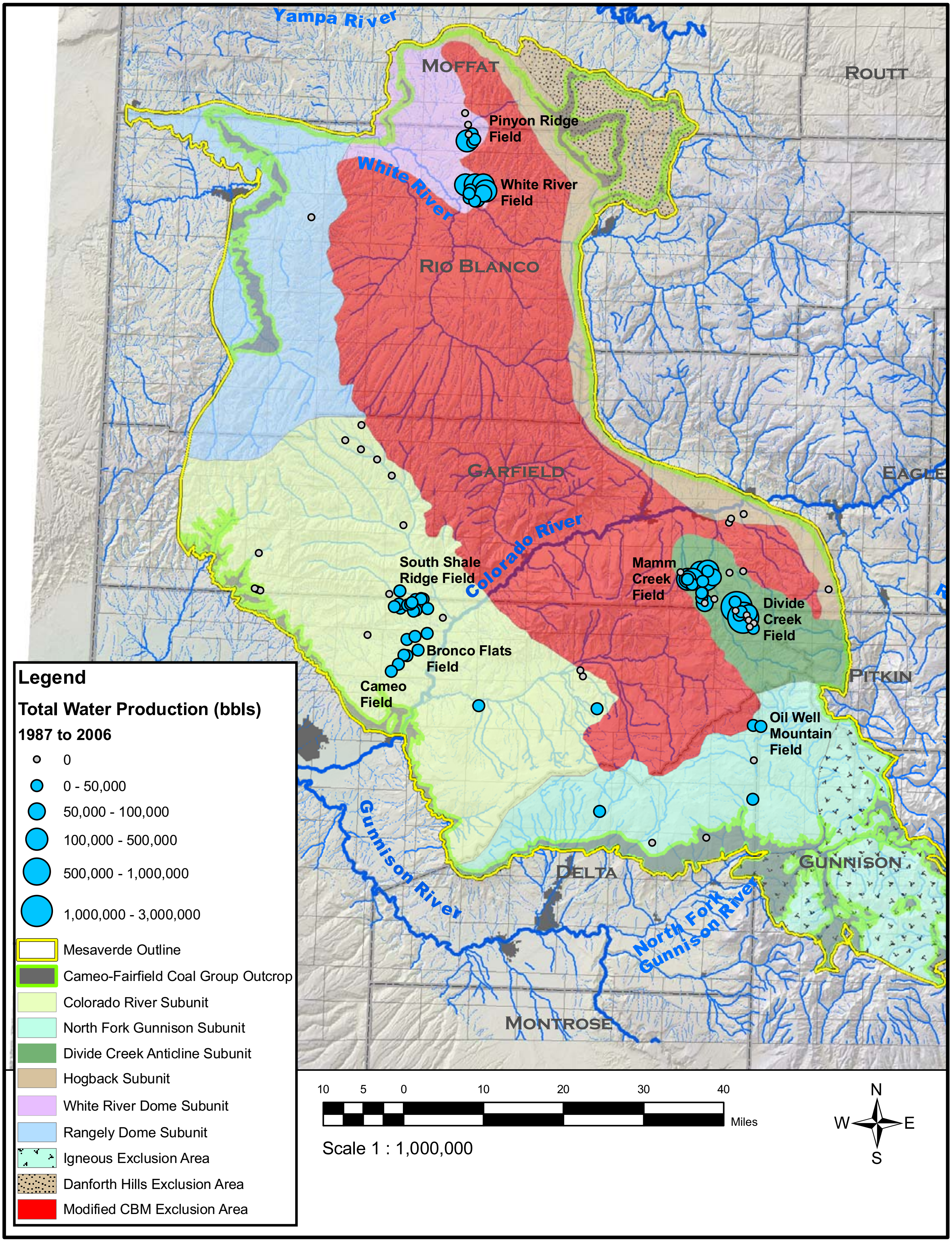
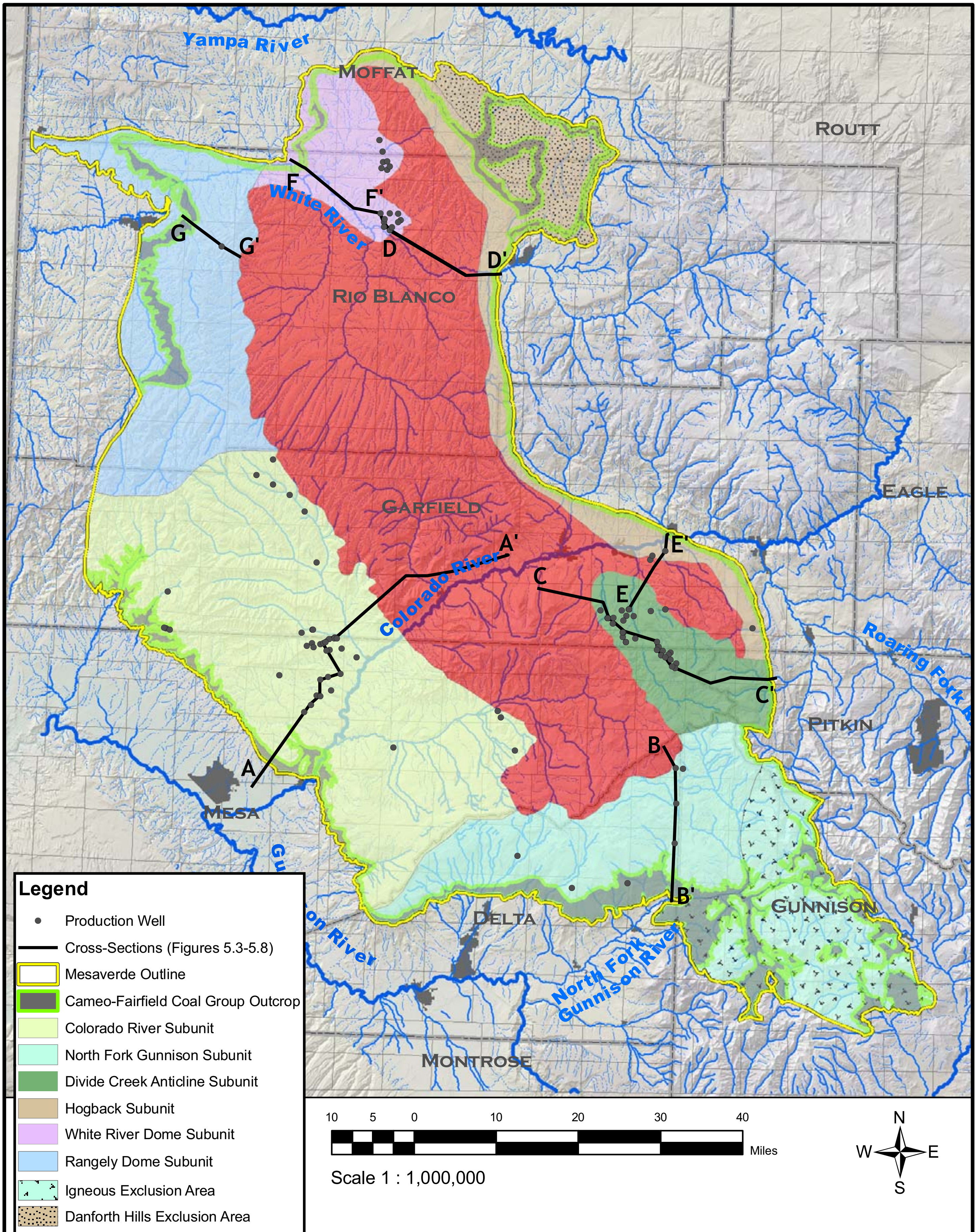


Figure 4.4 Areal Distribution of CBM Water Production in the Piceance Basin



Source: CGS GIS Library shapefiles.

Figure 5.1 Piceance Basin CBM Subunits

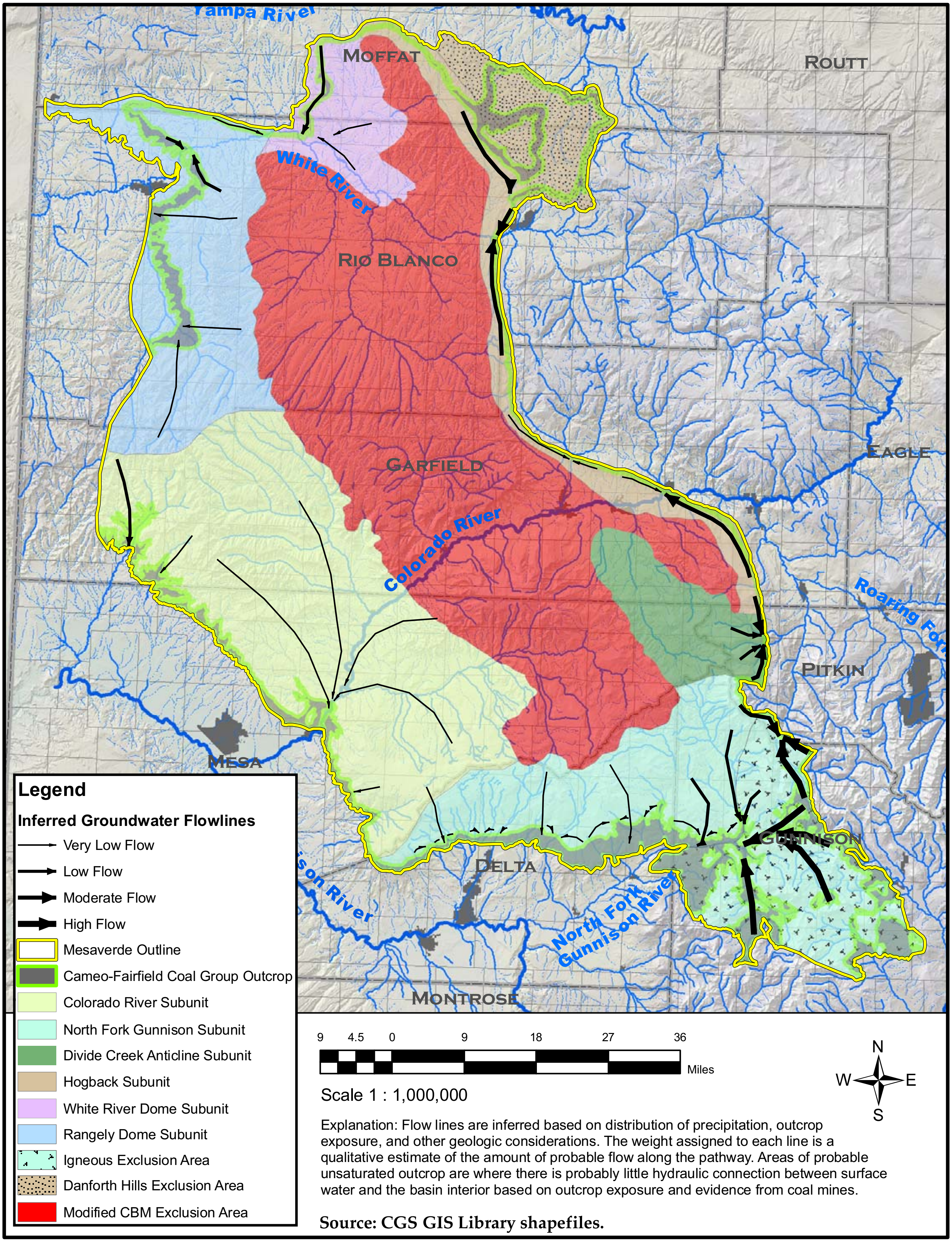
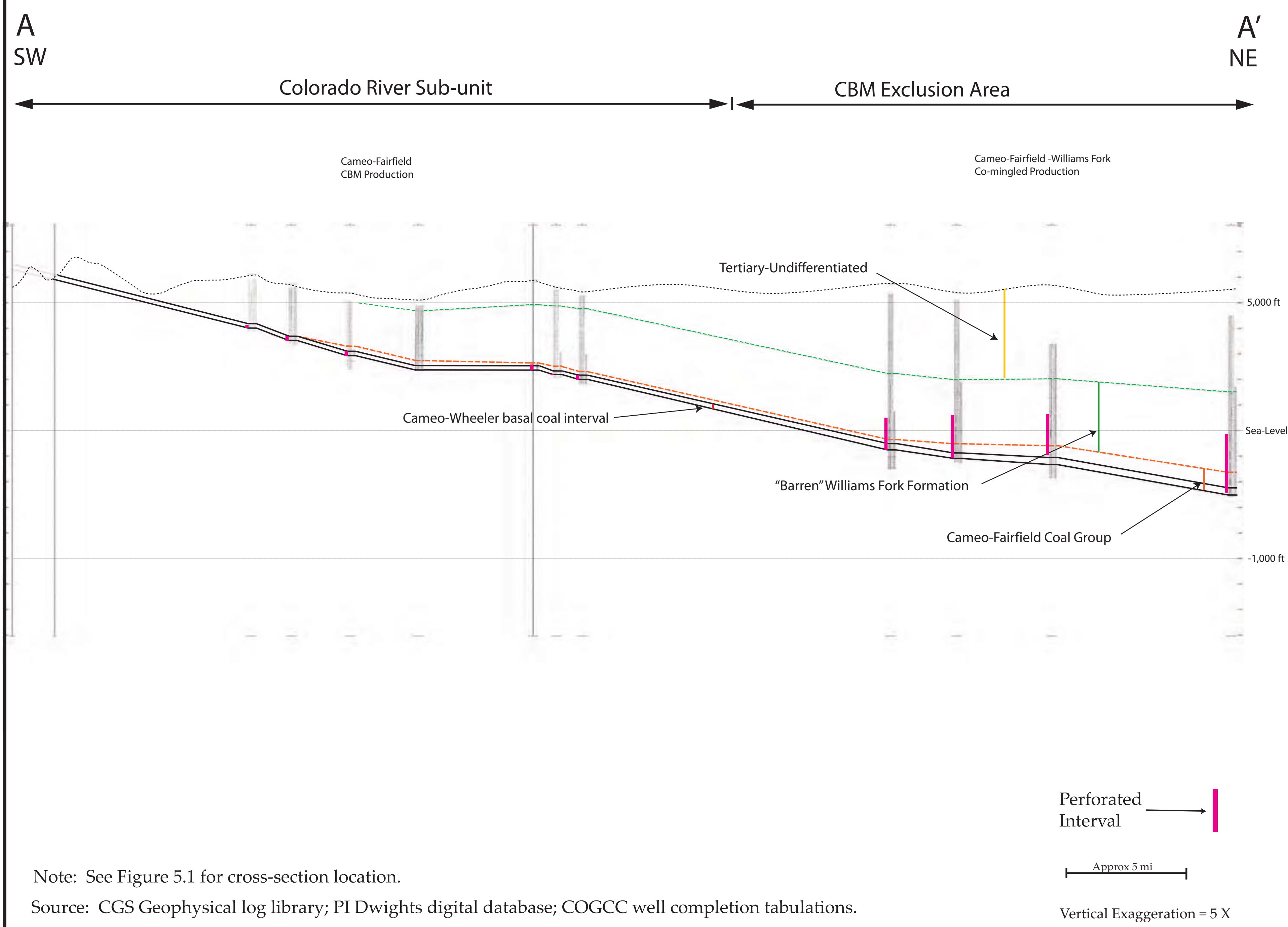


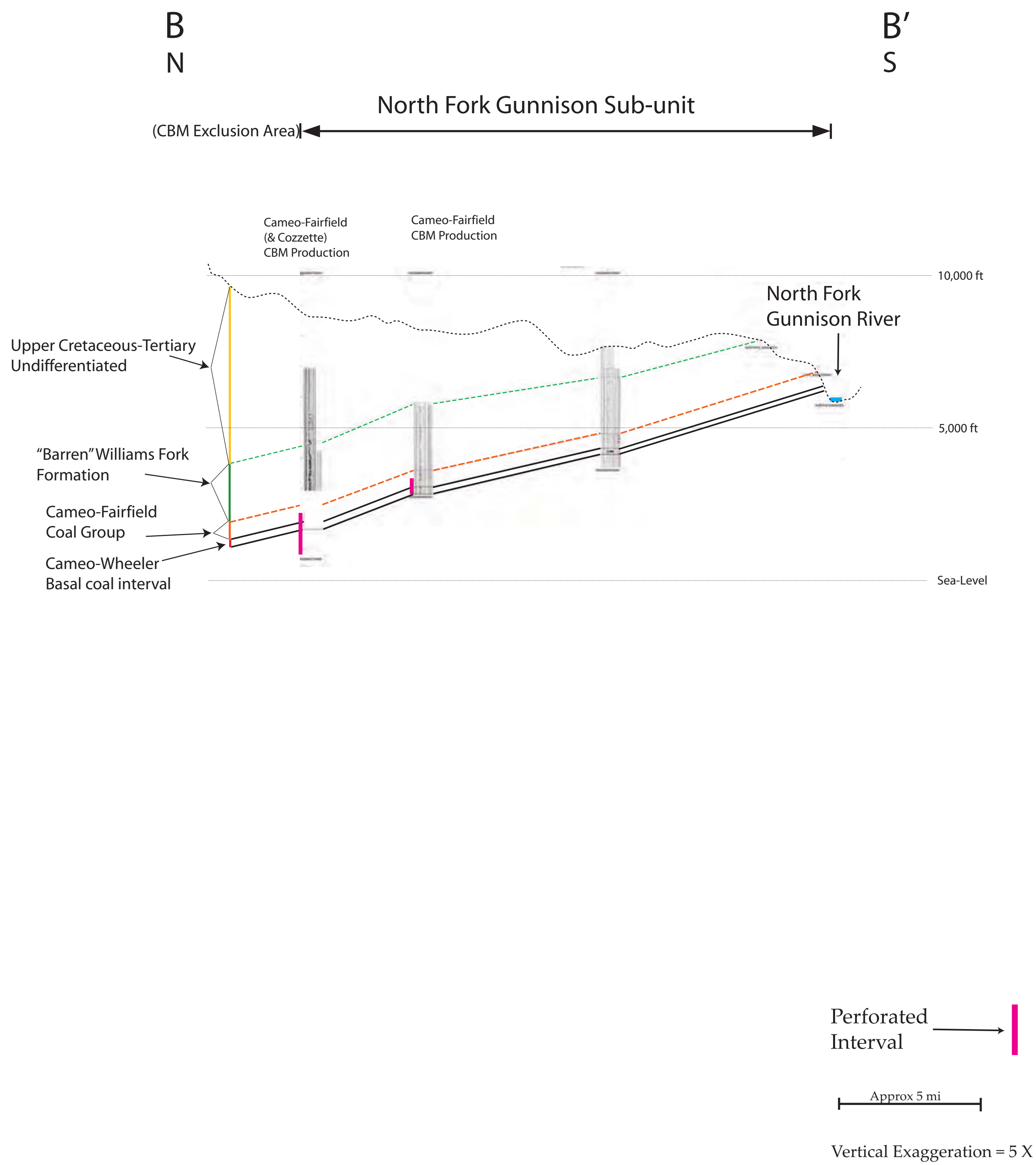
Figure 5.2. Inferred Groundwater Flow Patterns in the Piceance Basin



Note: See Figure 5.1 for cross-section location.

Source: CGS Geophysical log library; PI Dwights digital database; COGCC well completion tabulations.

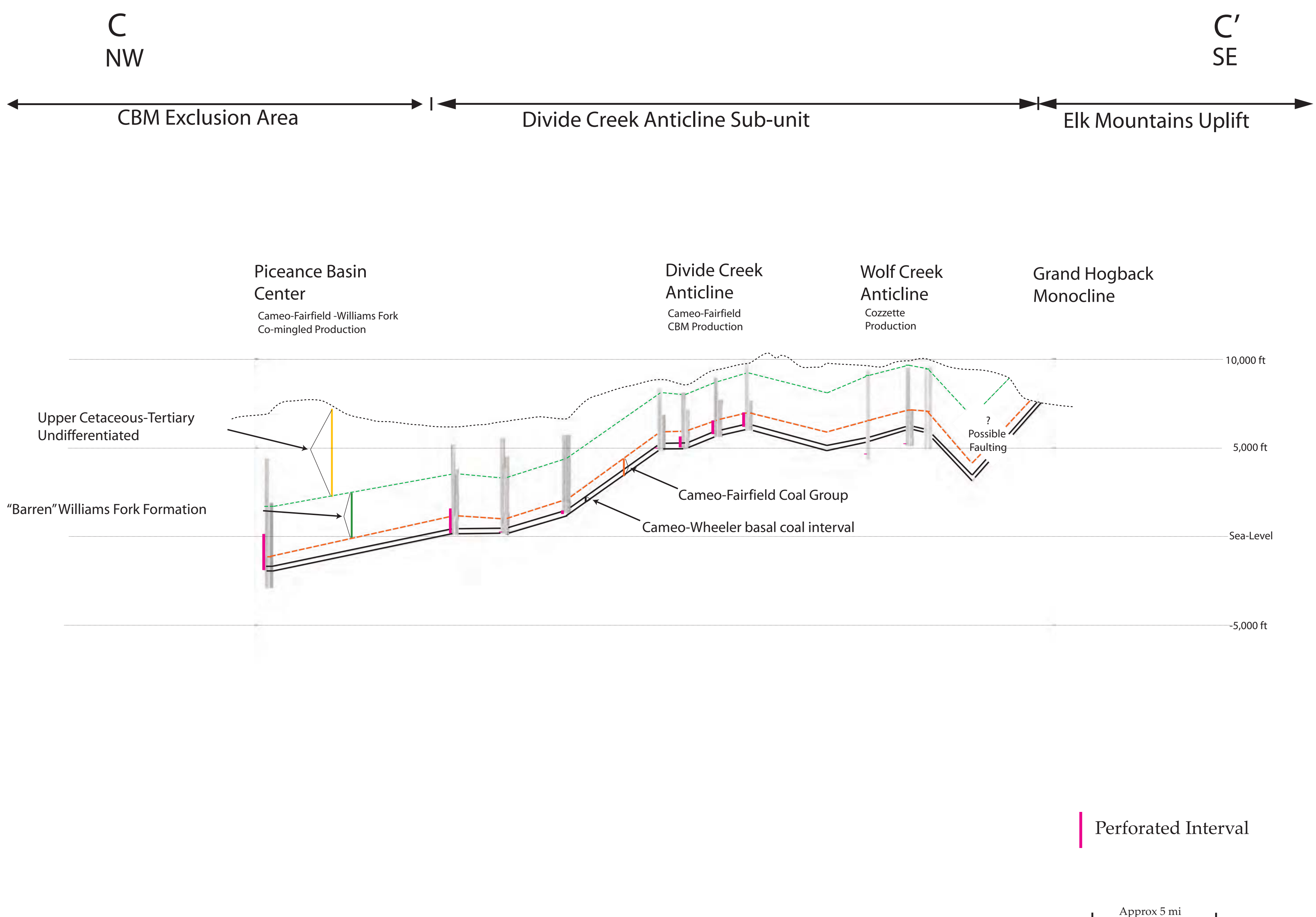
Figure 5.3. Colorado River Subunit Cross-Section



Note: See Figure 5.1 for cross-section location.

Source: CGS Geophysical log library; PI Dwights digital database; COGCC well completion tabulations.

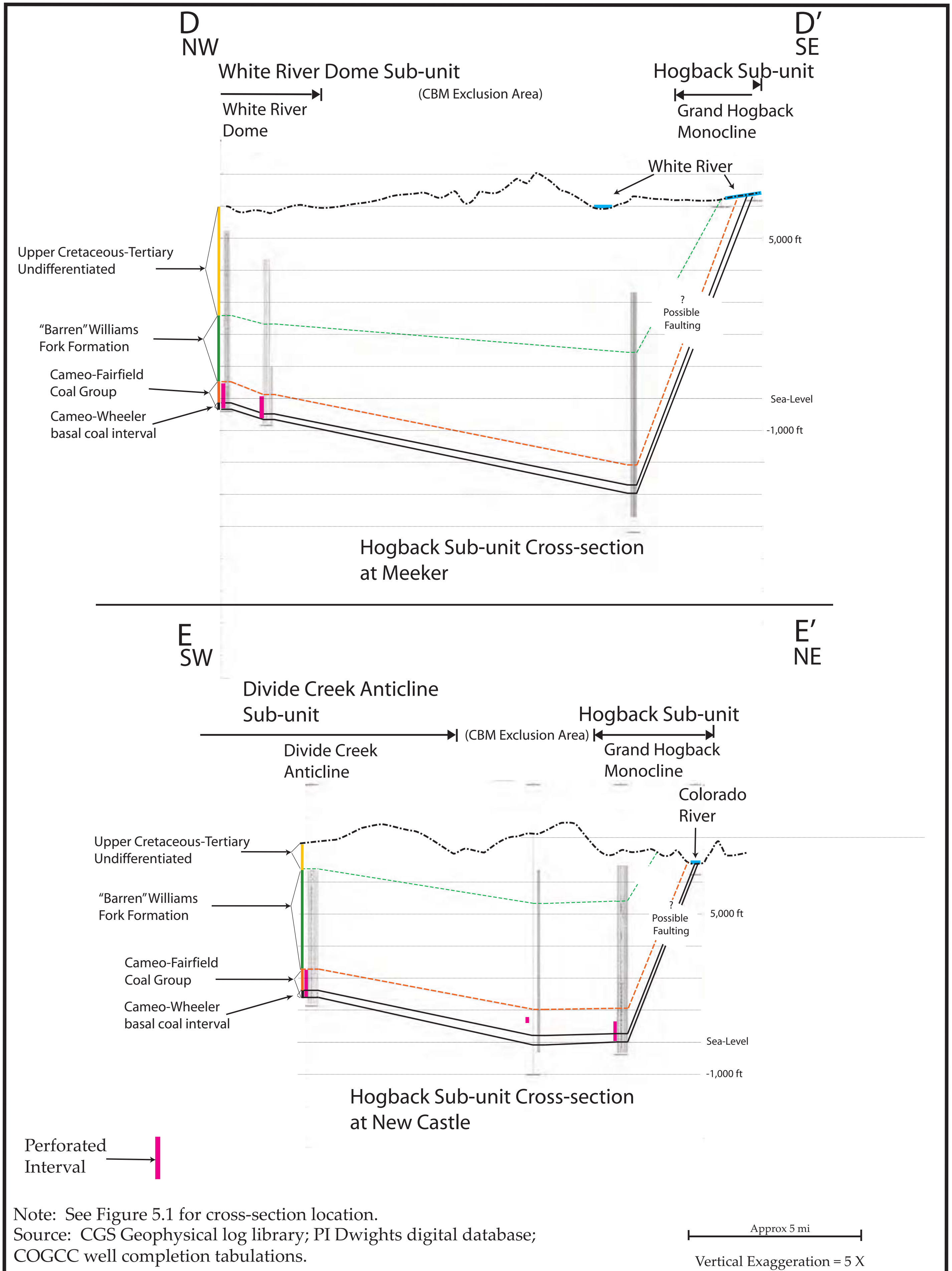
Figure 5.4. North Fork Gunnison Sub-unit Cross-Section



Note: See Figure 5.1 for cross-section location.
Source: CGS Geophysical log library; PI Dwights digital database; COGCC well completion tabulations.

Vertical Exaggeration = 5 X

Figure 5.5. Divide Creek Anticline Subunit Cross-Section



Note: See Figure 5.1 for cross-section location.
Source: CGS Geophysical log library; PI Dwights digital database; COGCC well completion tabulations.

Figure 5.6. Hogback Subunit Cross-Sections

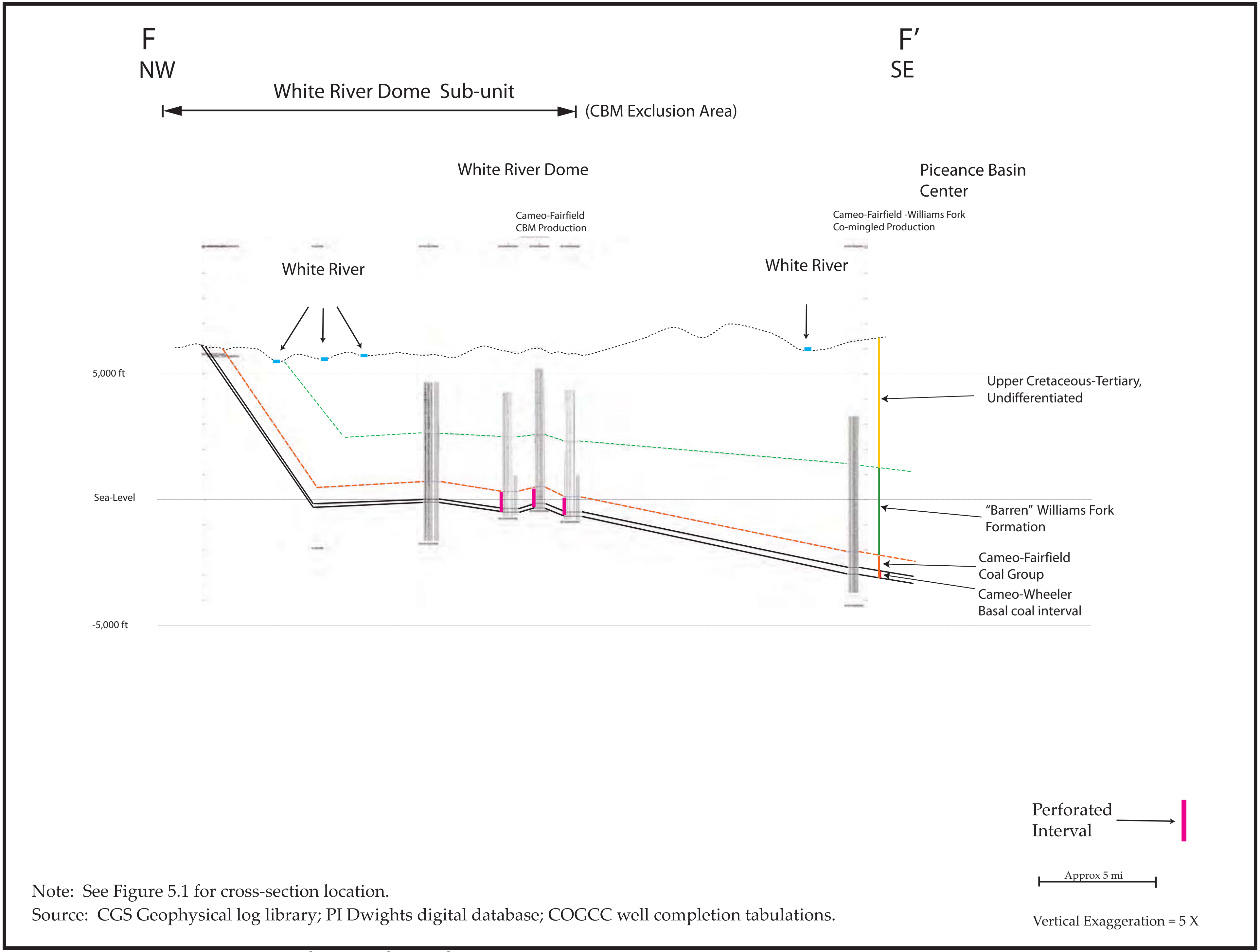
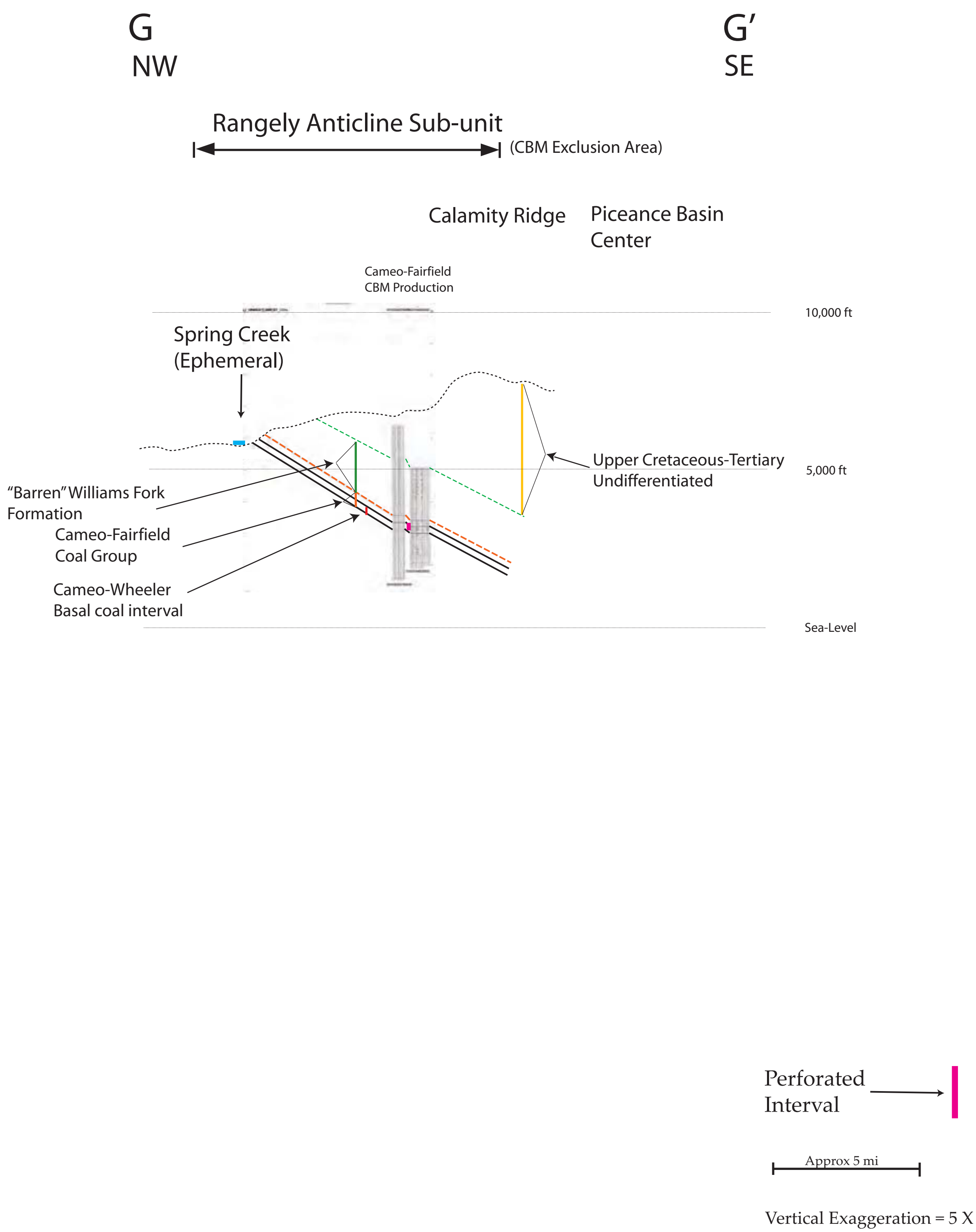


Figure 5.7. White River Dome Subunit Cross-Section



Note: See Figure 5.1 for cross-section location.
Source: CGS Geophysical log library; PI Dwights digital database; COGCC well completion tabulations.

Figure 5.8. Rangely Anticline Subunit Cross-Ssection

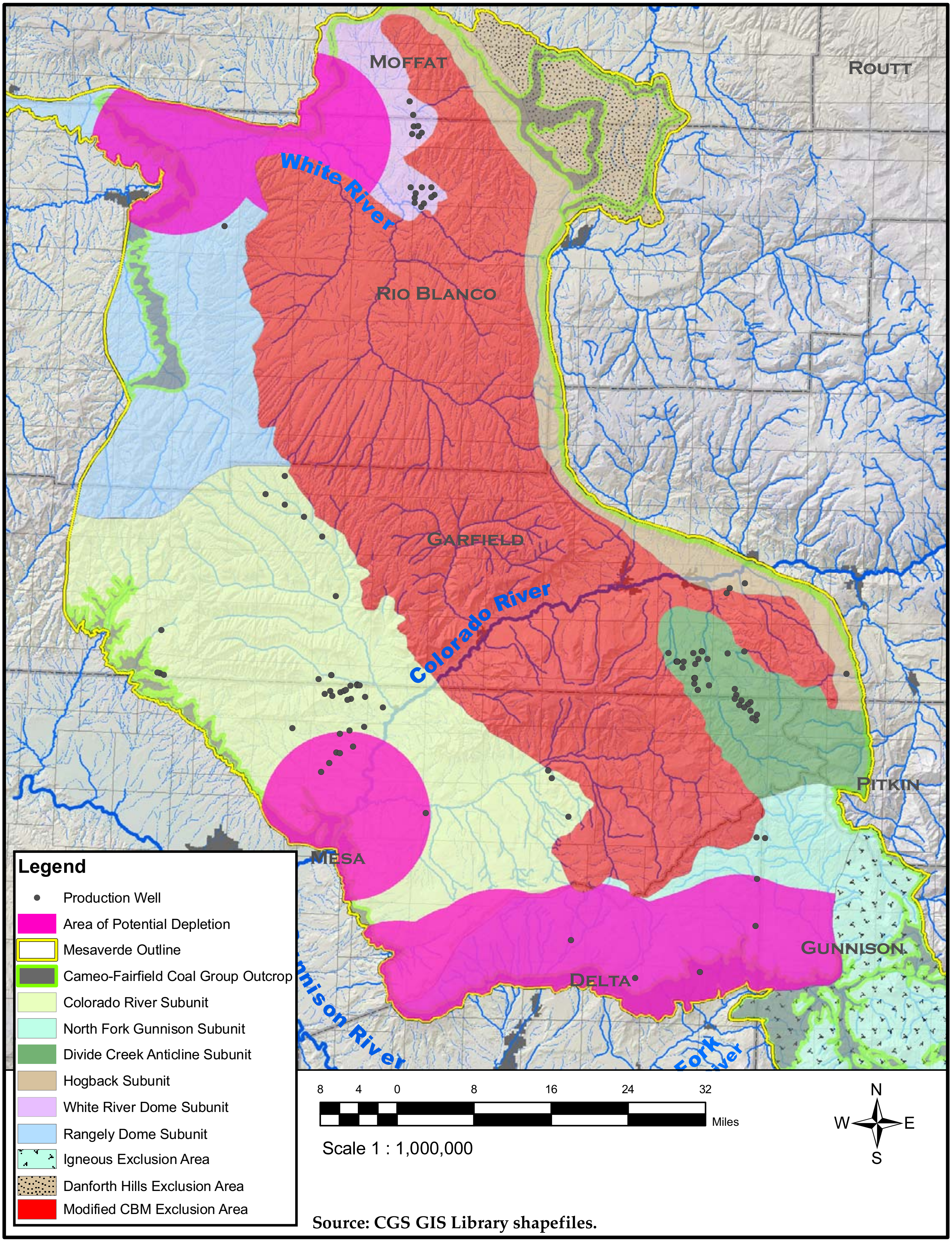
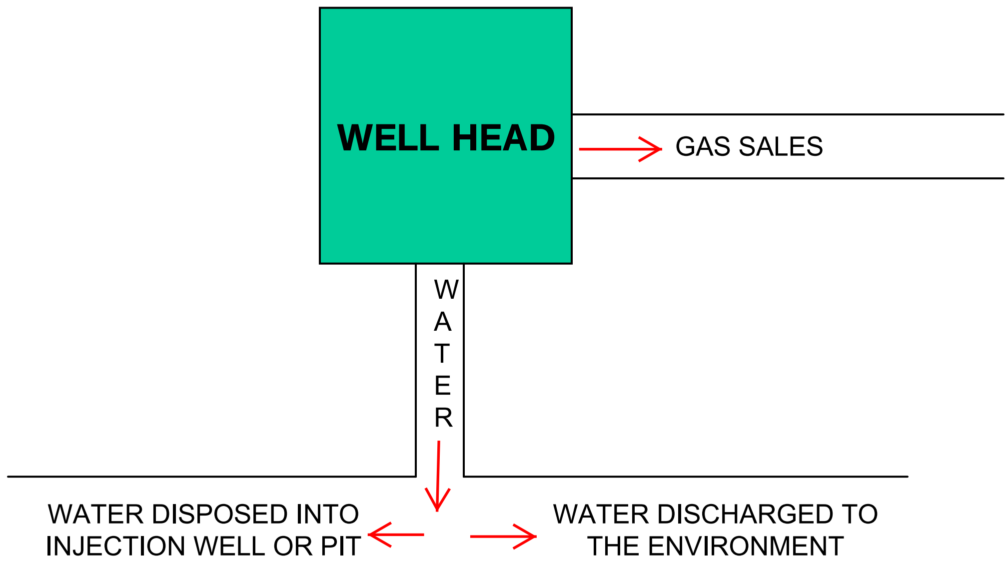


Figure 6.1 Area with Potential for Depletion to Exceed 0.1% in 100 Years



These water disposal methods are under the jurisdiction of the **OGCC**.

This method of water disposal is under the jurisdiction of the **CDPHE-WQCD** for approval to discharge water. After the water is discharged it is under the jurisdiction of the **DWR** for issues concerning water rights.

Figure 7.1 Regulation of Water from CBM Wells

Table 5.1
Cameo-Fairfield Coal Group CBM Subunit
Physical Characteristics and Completion Summary

Subunit[1]	Well Census			Coal-bearing Interval Characteristics[4]		Basal Coal Interval Characteristics[4]		Completion Characteristics[5]			
	Number of "Coal-gas" Wells[2]	Number of Producing CBM Wells[3]	Number of Wells Reviewed for Characterization and Completion	Coal-bearing Interval Median Thickness (ft)	Coal-bearing Interval Net Coal Median Thickness (ft)	Basal-coal Interval Median Thickness (ft)	Basal-coal Interval Net Coal Median Thickness (ft)	Number of Wells Perforated in Basal Coals	Number of Wells Perforated in Coal-bearing Intervals	Number of Wells Co-Mingled with upper Williams Fork	Generalization About Production
Colorado River	42	27	16	322	52	172	44	11	3	0	CBM in basal coal interval
North Fork Gunnison River	7	4	6	769	95	188	46	1	2	1	CBM in entire coal-bearing interval
Divide Creek Anticline	39	31	10	930	95	300	57	4	4	2	CBM in entire coal-bearing interval
Hogback	4	0	7	782	71	132	40	0	1	0	Insufficient data
White River Dome	17	12	8	782	71	132	40	0	6	1	CBM in entire coal-bearing interval
Rangely Anticline	1	0	3	433	51	131	28	0	1	0	Insufficient data, basal coal most probable

1. See Figure 5.1 for sub-unit locations.
2. "Coal gas" designation from review of COGCC database.
3. "Producing CBM Wells" are wells that have reported production since 1999.
4. The "coal-bearing interval" is interpreted to be equivalent to the Cameo-Fairfield coal group and the "basal coal interval" is interpreted to be equivalent to the Cameo-Wheeler coal zone (Figure 3.7).
5. Based on details on record in PI-Dwights data base, and obtained from COGCC.

Table 5.2
Cameo-Fairfield Coal Group CBM Subunit
Primary Structural Elements Summary

Subunit[1]	Coalbed cleats		Fractures		Folds			Faults		
	Face Cleat strike direction[2]	Orientation to outcrop	Fracture strike direction[4,5,6]	Orientation to outcrop	Type	Axis strike direction[7]	Orientation to outcrop	Type[8]	Fault strike direction	Orientation to outcrop
Colorado River	E-NE	Orthogonal	W-NW	Oblique	Monocline	NW	Gentle dip into basin away from outcrop	Normal	NW	Parallel
North Fork Gunnison River	E-NE	Parallel	E-NE	Parallel	Monocline	E-W	Gentle dip into basin away from outcrop	Normal	N-NW	Orthogonal
Divide Creek Anticline	E-NE	Orthogonal	Prob. NW[3]	Parallel	Anticline	NW	Parallel	Thrusts at depth	NW	Parallel
								Normal at crest	NE	Orthogonal
Hogback	E-NE[3]	Orthogonal	W-NW	Oblique	Monocline	NW	Steep dip into basin away from outcrop	Inferred Thrusts	NW	Parallel
White River Dome	NW[3]	Orthogonal	NW[3]	Orthogonal	Anticline	NW	Orthogonal	Thrusts at depth	NW	Orthogonal
								Normal at crest	NW	Orthogonal
Rangely Anticline	N[3]	Oblique	Prob. NW[3]	Variable	Anticline/ with syncline	NW	Outcrop wraps around the paired anticline and syncline	Thrusts at depth	NW	Variable
								Normal at crest	NE	Variable

1. See Figure 5.1 for subunit locations.
2. Tremain and Tyler, (1995)
3. Sparse data
4. Lorenz (2003)
5. Carroll (2003)
6. Olsen (2003)
7. Tyler (1995)
8. Tweto (1979)

Table 6.1
Summary of Mesaverde Formation Hydraulic Property Data Reported in the Literature

Location	Strata	Transmissivity	Estimated Thickness (ft)	Permeability	Coal Permeability Range (mD)		Hydraulic Conductivity (K; ft/day)	Coal K Range (ft/day)		Source	Comments
Delta County	MVG coal beds	1.5 to 16.7 ft^2/day	50?		11?	124?		0.03?	0.33?	Brooks, 1983	Consistent with Book Cliff area aquifer tests in Northern Mesa County
Delta County	MVG upper sandstones	0.33 ft^2/day					minimal			Brooks, 1983	
Lower Gunnison River Basin	MVG sandstones	0.3 to 16.7 ft^2/day								Brooks and Ackerman, 1985	Transmissivity for unfractured rock
Moffat County, Upper Colorado River Basin				0.08 to 110 mD			0.0002 to 0.27			Teller and Chafin, 1986	Drill stem tests
Bookcliff Coal Field	coal				41		0.11	0.11		Brooks, 1986	Slug-type aquifer tests conducted by JF Sato & Associates, Inc., 1983
Bookcliff Coal Field	shale and sandstone above coal			2.6 mD			0.007			Brooks, 1986	
Bookcliff Coal Field	fractured sandstone			6.2 Darcy			16.63			Brooks, 1986	
Bookcliff Coal Field	shale and sandstone above coal			0.03 mD			Kv=0.00007			Brooks, 1986	
North Fork of the Gunnison River Basin	sandstone and shale			smaller than for coal						Ackerman and Brooks, 1986	
Upper Colorado River Basin: Rio Blanco, Mesa, Routt, Moffat Counties	MVG	0.0015 to 6.1 ft^2/day	Various				0.00019 to 0.5			Weigel, 1987	Horner's graphical analysis or limited-data analysis, drill stem tests
Upper Colorado River Basin: Delta County	MVG	11 to 450 ft^2/day	Various				0.07 to 30			Weigel, 1987	Confined aquifer, specific capacity tests at water well sites
Upper Colorado River Basin: Rio Blanco, Garfield, Mesa Counties	MVG			0.02 to 28 mD			0.00005 to 0.068			Weigel, 1987	Lab core tests; determined horizontal permeability to air and converted to K
Upper Colorado River Basin	MVG						< 0.01 where deeply buried; higher where outcrops			Glover, Naftz, Martin, 1998	Map of K assuming formation is water saturated
Upper Colorado River Basin	MVG	< 50 or unknown; local areas up to 500 ft^2/day		5-23 mD; mean 15 mD			0.00001 to 0.001 in SE; 0.01 to 0.1 in W			Freethey and Cordy, 1991	T, perm, K based on mapped values, Figures 37, 44, 54
East Divide Creek	Cameo Coal				16			0.043		Tyler etal, 1991	Permeability considered to be structurally enhanced.
West Elk Mine	F seam	0.028 to 61 gpd/ft	Various	1.0 to 4.1 gpd/ft^2	52	200		0.14	0.54	West Elk Permit, 1995 and 1999	Slug test data
West Elk Mine	B seam	3.3 gpd/ft	Various	0.042 to 0.083 gpd/ft^2	2	4		0.006	0.011	West Elk Permit, 1995 and 1999	Slug test data
West Elk Mine	Rollins Sandstone	0.18 m/s		< 0.1 to 11 mD						Mayo and Koontz, 2000	DH-1 aquifer test transmissivity; drill core permeability
Delta County	Lower and Upper Coal			0.001 to 0.022 Darcy	1	22		0.0027	0.06	Cordilleran, 2002	Porosities 4-12%
Cedaredge, Delta County	MVG	156 ft^2/day								Lazear, 2002	Based on 6 wells with drawdown measurements
White River Dome Field	productive sandstone			0.01 to 0.1 mD; in-situ permeability of 0.02 mD						Olson, 2003	
White River Dome Field	coals				0.2			0.0005		Olson, 2003	
Grand Mesa	Williams Fork Formation, MVG			<0.1 mD						Law (Pangea), 2003 for WWE	
Grand Valley/Rulison, Garfield County	Cameo Coal Group			very low						Nance and Kaiser, 1995	"There appears to be structural control on production"; suggest permeability may be fracture enhnaced along the fold axis

MVG is Mesa Verde Group

Appendix A

Water Rights and Beneficial Use of Coal Bed Methane Produced Water in Colorado

(Source: Colorado Division of Water Resources, October 2002)

Water Rights and Beneficial Use of Coal Bed Methane Produced Water in Colorado

By

Dick Wolfe, P.E.
&
Glenn Graham, P.G.

COLORADO DIVISION OF WATER RESOURCES
DEPARTMENT OF NATURAL RESOURCES

Denver, Colorado

October 2002

1.0 Objective

Water is a scarce and valuable resource in Colorado. Any activity that appears to waste it or that may waste it creates challenges as well as potential opportunities. The beneficial use of produced water from coal bed methane (CBM) wells is one such potential opportunity that also raises challenges. This paper explores the state laws and regulations in Colorado governing the use of produced water. This paper does not attempt to address county or local laws and regulations, which are beyond its scope.

2.0 Types of Ground Water

In Colorado, there are basically five types of ground water that are administered by the Colorado Division of Water Resources (CDWR) and the Colorado Ground Water Commission (CGWC). The CGWC has primary authority over the administration of designated ground water. The five types are as follows:

Tributary

Ground water that is hydrologically connected to a natural stream system either by surface or underground flows.

Nontributary

Ground water located outside the boundaries of any designated ground water basin. The withdrawal of this ground water by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal.

Not-nontributary

Ground water located within those portions of the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers that are outside of any designated ground water basin in existence on January 1, 1985, the withdrawal of which will, within 100 years, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal.

Designated

Ground water that, in its natural course, is not available to or required for the fulfillment of decreed surface rights, or ground water in areas not adjacent to a continuously flowing natural stream, wherein ground water withdrawals have constituted the principal water usage for at least 15 years preceding the date of the first hearing on the proposed designation of the basin, and which is within the geographic boundaries of a designated ground water basin.

Geothermal

Ground water that contains geothermal energy.

3.0 Geologic Factors Affecting Water Production

CBM gas in Colorado is produced from coal seams that were created by the deposition of large amounts of organic material in fluvial and marginal marine environments adjacent to the western margin of the Western Interior Cretaceous Seaway during late Cretaceous and early Tertiary time.

The coals are interbedded with mudstones or claystones and sandstones, and are predominately lenticular in cross section and laterally discontinuous. These coal seams vary in thickness from a fraction of an inch to several feet. In a few limited areas, individual beds may be more than 10 feet thick. The individual beds may be spread vertically over several hundred feet of stratigraphic section. The coal bearing sequences are found cropping out on the surface or as deep as 5,000 feet below the surface. At this time, most CBM production in Colorado is from coal seams that are less than about 3,000 feet below the surface.

Some of the geologic formations containing existing or potential CBM resources in Colorado are the Raton and Vermejo formations in the Raton Basin; the Denver and Laramie formations in the Denver Basin; and formations within the Mesa Verde Group, found in several basins on the western slope of the state.

CBM gas is molecularly adsorbed on crystal surfaces of the coal, and is held there under the hydrostatic pressure of the water contained in the coal beds and the adjacent sandstones. In order for the CBM gas to be liberated or desorbed from the crystalline structure of the coal, the hydrostatic head, or the reservoir pressure in the coal seam, must first be reduced. This pressure reduction is accomplished by dewatering the coal seams. To further enhance the productive ability of the coals, hydraulic fracturing techniques are used to increase the permeability of the coal seams.

A typical CBM well is drilled and cased through the potential productive interval. Selected intervals containing the coal seams are perforated and hydraulically fractured, and a down-hole pump designed to remove large quantities of water is installed. When first placed on-line, a CBM well will produce significant amounts of water with little or no gas production. Ideally, within a month or two of being placed on-line gas production will start to increase and water production will start to decrease as the coal seams become dewatered. After a year or two of production, water production rates can fall to as little as a few barrels of water per day for individual wells, while daily gas production rates will increase from essentially nothing to several hundred thousand cubic feet or more per day.

Ideally, the water produced by the CBM extraction process is water that was contained in only the coal seams, and not water contained in other parts of the stratigraphic column. Because of the highly layered or interbedded and lenticular nature of the geologic formations that contain CBM resources, there are significant barriers to the vertical movement of water. Given the amount of water being produced during the early life of a CBM well, there has been some concern that there may be some impact to water bearing zones that might be of suitable quality to be a source of water for residential, stock watering or irrigation purposes. At this point in time in Colorado, no documented incidents of direct impact on existing water wells from nearby production of CBM gas have been reported to CDWR.

Another concern identified is the possible effect on stream systems that flow across the outcrop areas of coal-bearing formations. Again, the highly interbedded and lenticular nature of these geologic formations may limit or effectively disconnect the stream systems from the zones from which the water is being produced. This is an area where further study is certainly warranted.

Historically, CBM produced water in Colorado has typically not been of suitable quality for any beneficial use, and only recently has some of this produced water been of good enough quality for some limited beneficial uses. For the most part, beneficial use of produced water in the San Juan Basin has not been proposed, because the quality of produced water in that area is too poor for most uses, but some concerns have been raised regarding potential effects on surface water flows. In the Raton Basin of southern Colorado, approximately 5 Mgal/day of ground water is produced from CBM wells. Of this amount, approximately 30% is discharged to natural streams, 30% is reinjected and 40% is discharged to evaporation pits. The 1.5 Mgal/day that is discharged to the natural streams is done under discharge permits issued by the Colorado Water Quality Control Division (CWQCD) of the Colorado Department of Public Health and Environment (CDPHE) via approximately 40 discharge points (equal to approximately 26 gpm on average per discharge point). Proponents of the use of this produced water should keep in mind that the volume of water being produced will typically decline quite rapidly during the first year or so of production, and may approach nothing after a few years. Further, the economic life of a CBM well may not exceed 10 years.

Other basins in the state are being evaluated for CBM potential, but no development has occurred to this point in time. Those basins are the southeast part of the Piceance Basin in Delta County, the southeast part of the Greater Green River Basin, and the Denver Basin.

In addition to the physical limitations described above, there presently are significant legal and institutional barriers to the beneficial use of CBM produced water.

4.0 Jurisdiction Over Produced Ground Water

4.1 Historical Perspective

The desire to use water from CBM wells has only recently surfaced because the quality of water from CBM wells has never been good enough for most uses. Multiple agencies regulate and monitor various aspects of produced ground water, yet no agency oversees and integrates all aspects. Each agency has its own jurisdiction as established by enabling laws. At least three different agencies (the Colorado Oil and Gas Conservation Commission (COGCC), CDWR, and CWQCD) have authority as it relates to the withdrawal, use, and/or disposal of water from a CBM well, and the relationships between the constitutional provisions, statutory language, and various rules are extremely complex.

CDWR is aware of overlapping jurisdictional issues between the COGCC and CWQCD. COGCC has authority over all oil and gas operations, including the generation, transportation, storage, treatment, or disposal of exploration and production wastes. Water removed from a CBM well is considered a waste product. The CDPHE rules provide that no person shall discharge CBM produced water into waters of the state without first having obtained a permit from CWQCD for such discharge.

4.2 Allowed Beneficial Uses and Restrictions of Ground Water

Whether a use is beneficial is a question of fact and depends on the circumstances of each case. However, the following uses have been recognized as beneficial uses by CDWR: agriculture, mining, domestic, manufacturing, stock watering, wildlife watering, irrigation, industrial, mechanical, commercial, municipal, recreation, minimum stream flows, fire protection, and dust suppression.

CDWR has jurisdiction over appropriations of water. An appropriation is defined as the application of a specified portion of the waters of the state to a beneficial use pursuant to the procedures prescribed by law. Waters of the state in this context means all surface and underground water tributary to natural streams, except designated ground water as designated by the CGWC. The statutory and case law vests CDWR with jurisdiction over water withdrawn from a CBM well that is beneficially used.

If an operator or another person wants to beneficially use water from a CBM well, that operator or person must comply with the Water Right Determination and Administration Act and the Ground Water Management Act (Water Rights Acts). The person could apply for a water right in water court and/or file for a well permit. If the person applies for a well permit for water from a CBM well, that water is presumed tributary, but the person may submit evidence such as engineering documentation that the water is nontributary. Regardless of whether the water withdrawn from a CBM well is nontributary or tributary, there are certain statutory requirements that the water user must meet before obtaining a well permit and/or a water court decree. Any water discharged into waters of the state (as defined by the Water Quality Control Act) is subject to appropriation under the Water Rights Acts.

CBM wells are not "wells" as defined in the Water Rights Acts, and operators do not need to obtain a permit from CDWR to withdraw water from these wells as part of the CBM extraction process. However, if water from a CBM well is put to beneficial use other than those uses allowed under COGCC Rule 907 (see below), then CDWR has certain jurisdiction over the water and the well, and the well is subject to the *Rules and Regulations for Water Well Construction, Pump Installation, and Monitoring and Observation Hole/Well Construction (2CCR 402-2).*

4.2.1 COGCC Rule 907

The COGCC statute (COGCC Act) grants certain authority to COGCC to promote oil and gas conservation, and rescinds any authority of any other agency as it relates to the conservation of oil and gas. CBM produced water is considered a waste product by operators and must be properly disposed of to prevent adverse environmental impacts. Pursuant to COGCC rules, an operator may dispose of water from a CBM well in any of the following ways: 1) inject into a disposal well; 2) place it in a properly permitted lined or unlined pit for evaporation and or percolation; 3) dispose the water at a permitted commercial facility; 4) dispose of the water by road spreading on lease roads outside sensitive areas for produced waters; 5) discharge the water into waters of the state in accordance with the Water Quality Control Act and the rules and regulations promulgated thereunder; 6) reuse the water for enhanced recovery, recycling, and drilling; or 7) mitigation to provide an alternate domestic water supply to surface owners within the oil and gas field.

4.2.2 Ground Water Permitting by CDWR

Under Colorado law, CBM operators are not required to obtain a permit from the State Engineer when withdrawing nontributary water unless the produced water is put to a beneficial use. The State Engineer has authority to issue permits outside designated basins in accordance with section 37-90-137(7), CRS (2002), which is restated as follows:

In the case of dewatering of geologic formations by removing nontributary ground water to facilitate or permit mining of minerals: (a) No well permit shall be required unless the nontributary ground water being removed will be beneficially used; and, (b) In the issuance of any well permit pursuant to this subsection (7), the provisions of subsection (4) of this section shall not apply. The provisions of subsections (1), (2), and (3) of this section shall apply; except that, in considering whether the permit shall issue, the requirement that the state engineer find that there is unappropriated water available for withdrawal and the six-hundred-foot spacing requirement in subsection (2) of this section shall not apply. The state engineer shall allow the rate of withdrawal stated by the applicant to be necessary to dewater the mine; except that, if the state engineer finds that the proposed dewatering will cause material injury to the vested water rights of others, the applicant may propose, and the permit shall contain, terms and conditions which will prevent such injury. The reduction of hydrostatic pressure level or water level alone does not constitute material injury.

In the context of this section, the State Engineer considers CBM gas a mineral. As stated above, if ground water produced from a CBM well is determined to be nontributary, the amount of water claimed is not based on overlying land ownership. If nontributary ground water is produced to the surface and discharged, it may be subject to CWQCD regulation.

For water rights purposes, all ground water in Colorado is presumed to be tributary unless there has been a ruling by the water court or a permit issued by the State Engineer that ground water from a certain aquifer in a specific area is declared nontributary. Any beneficial use of tributary ground water is subject to section 37-90-137(1) and (2), CRS (2002). Any use of tributary ground water requires a well permit and a determination by the State Engineer as to whether or not the exercise of the requested permit will materially injure the vested water rights of others. Also, the requirement that the State Engineer find that there is unappropriated water available for withdrawal and the six-hundred-foot spacing requirement in subsection (2) of this section shall apply.

5.0 Conclusions

A rough assessment of the opportunities to use produced water from CBM wells is that they are limited at best. Much of the water is too poor in quality to be legally discharged. Because most basins are over-appropriated, senior water rights claims complicate the issue. Because water production rates from CBM wells decline as gas is produced, CBM wells are unreliable as long-term sources of water. In limited areas where produced water quality is sufficient and vested water rights owners would not be injured, there may be some opportunities for beneficially using water produced from CBM wells in the short term. Such opportunities are not without cost or legal and technical complication.

Due to the complex and overlapping regulatory authority of state agencies, many companies are collaboratively working with local residents, concerned citizens, and state agencies to mitigate and minimize impacts of CBM production. It has been only recently that the CDPHE, COGCC, and the CDWR have coordinated efforts to understand and minimize the conflicts in regulatory authority and decision-making. These efforts have resulted in many public awareness meetings with both the general public and legislative committees on oil and gas. New rules and regulations were adopted by the COGCC to clarify jurisdictional uses of CBM produced water. The state must continue to educate and communicate with citizens and industry representatives to understand the impacts of CBM development and the statutory and regulatory environment in which it occurs.

Appendix B

Responses to Public Comments on the Draft Piceance Basin CBM Report, April 9,

STATE OF COLORADO

COLORADO GEOLOGICAL SURVEY— *serving the people of Colorado*

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COLORADO
DEPARTMENT OF
NATURAL
RESOURCES

MEMORANDUM

TO: **Colorado Geological Survey, Oil and Gas Conservation Commission, and Division of Water Resources**

FROM: **Peter Barkmann, Colorado Geological Survey**
Bryan Grigsby, S.S. Papadopulos & Associates, Inc.

DATE: **April 9, 2008**

SUBJECT: **Public Comments on the Draft Coalbed Methane Stream Depletion Assessment Study-Piceance Basin, Colorado**

On January 8, 2008 the Colorado Geological Survey (CGS) published on its website the draft report *Coalbed Methane Stream Depletion Assessment Study – Piceance Basin, Colorado* prepared by S.S. Papadopulos & Associates, Inc. (SSPA). At the same time, all interested parties including those who had attended the kick-off public meeting held in Rifle on January 26, 2007 were notified via email. Subsequently, on January 22, 2008, a public meeting was held again in Rifle to present results of the study. The public was then invited to provide comments about the report to the CGS or SSPA by January 31, 2008. This memo addresses all comments related to the Piceance Basin coalbed methane (CBM) stream depletion assessment study report following publication of the draft on January 8, 2008.

Only one set of written comments have been received and those were submitted via Email on February 8, 2008 by Wright Water Engineers (WWE) on behalf of Gunnison Energy Corporation (GEC). WWE had requested, and were granted, an extension of the comment deadline. The first set of comments by WWE, under the heading "General Comments", addressed general concepts used in the study or aspects of report content whereas the second set, under the heading "Detail Comments", addressed specific items in the text, tables or figures that appeared to be problematic. Each of WWE's comments are reproduced below with responses by CGS and SSPA following in italics

General Comments

1. WWE applauds the Study authors for recognition and inclusion of the concept that the point of impact to surface flow is where the surface streams cross the outcrop and not at all locations along the exposed outcrop (North Fork Gunnison River subunit apparently excluded and discussed below).

Response: This concept was driven by the hydrogeologic framework of the CBM producing interval of the Mesa Verde Formation and how it outcrops around the basin perimeter.

2. Given the much more significant amount of natural gas production within the Piceance Basin from more "conventional" or basin-centered development methods (i.e., from non-coal-bearing intervals and without the removal of groundwater to reduce the hydrostatic pressure on the formation), a comparison of the analyses employed in this report to the other types of gas development in the basin should be included. While it is specifically stated that the impact of other basin extraction activities on streams or water levels were not evaluated as part of this study, WWE considers this exclusion to be highly significant, given the magnitude of the other extraction methods and the potential correlation between the two as it relates to produced water effects. A general discussion of the basin-centered gas accumulation was included in the report text but not in the context of the potential effects on surface streams and the location of the tributary/nontributary line in those areas where CBM development is not occurring.

WWE recommends that the Study authors provide additional text to put this report and its findings in perspective with the other gas production activities in the basin.

Response: Concern has arisen from the public (in particular, from potentially affected water rights holders) that there could be injury due to non-CBM water production. However, the scope of this study was specifically limited to the CBM producing intervals because of the initial concern with the normal method of CBM development, wherein water is intentionally removed from the coal-bearing intervals in order to release the methane gas.

Additionally, limiting the assessment of water production to the CBM production interval is not based solely on the original paradigm and scope of the study. In evaluating the hydrologic characteristics of the sedimentary sequences hosting the CBM resources, it became apparent that the coal-bearing intervals where CBM is being withdrawn directly are the most laterally continuous hydro-stratigraphic units within this part of the basin. This interval consists of laterally extensive coal seams where the primary permeability is in the natural fracture, or "cleat" systems. Elsewhere in the stratigraphic sequence, where "conventional" gas development is occurring, the sediments consist of discontinuous sand bodies bound by relatively impermeable silt and shale which limits lateral hydraulic continuity.

3. As stated in the background portion of this letter (Page 1, 2nd Paragraph, Last Sentence), the Study authors suggest that future water production from CBM wells is of particular interest relative to stream depletions that may be injurious to senior water rights. This appears to be inconsistent with the results of the Glover Stream Depletion Analysis (Section 6.3, Page 43-44) where there is no discussion or apparent indication that any future projections of

depletions were assessed. In fact, the Section 6.3.2 (1st Paragraph, Last sentence) states that "…the total cumulative depletion to **date** [emphasis added] for the Piceance basin is estimated to be less than one (1.0) acre-foot, all from the Colorado River subunit." This sentence suggests that there will be potential future depletions that were not assessed. While not stated in the same way in the Conclusions, it appears that the one acre-foot of estimated depletions is representative of current conditions. The Study authors need to provide some discussion of the anticipated future impacts even if no significant increase in CBM development occurs.

Response: We cannot predict future production of water from CBM wells based on current water production patterns; however, it is our opinion that the current 1 acre-foot of depletion will NOT increase significantly, if at all, in the future. For that reason, we did not attempt to project future depletions. (As of late 2007 there were only 6 wells in the Colorado River subunit actively producing water from coalbeds, and in most of these cases, production was less than in the past.). Regarding future development of CBM in the subunit, no new wells have been drilled and completed as CBM wells since 2003.

4. A likely interpretation of Figure 6.1 is that water produced from CBM development anywhere in the Piceance Basin other than those identified in pink as "Areas of Potential Depletion" is nontributary. It is unclear if that was the intent of this figure; nonetheless, that has been the interpretation of at least one operator who contacted WWE regarding the relevancy of this report to their operations. WWE recommends that the authors supplement the report text to address the significance of this figure as it relates to potential future nontributary groundwater claims.

Response: Such a position in this document is beyond the scope of this study. This assessment, and the supporting modeling efforts, were designed to provide a first-order estimate of CBM-producing areas that may be tributary or non-tributary based on data made available for the study. At present, any operator claiming a non-tributary designation for beneficial use of CBM water in the Piceance Basin will be required to submit a technically defensible validation for that claim to DWR.

The report text has been modified to clarify this situation.

5. Four specific areas of Potential Depletions are identified in the Study and specifically represented on Figure 6.1. It appears as if the 8.8-mile offset to the tributary/nontributary line is based upon the point at which the surface stream crosses the coal-bearing portion of the Mesaverde Formation in the White River Dome, Rangely Dome and Colorado River subunits but not in the North Fork Gunnison River subunit. In the latter case, it appears that the 8.8-mile offset is from the exposed outcrop. What is the explanation for this difference? Particularly in light of the statement in the *North Fork Gunnison River Subunit* Section (Page 31, 4th Paragraph, 2nd Sentence) stating that "Even though methane derived from the coals is known to be present in this area, it is being excluded from this evaluation because the potential for CBM development is limited."

GEC is presently working to demonstrate a conclusion contrary to that by the Study authors; however, it remains to be seen to what extent the production of gas from this area is specific to the coal-bearing section or the stratigraphic intervals overlying the coals. Nonetheless, inclusion of this subunit in Figure 6.1 as an area of potential depletion while excluding it from the quantitative assessment of stream impacts requires further explanation.

Response: The inclusion of the entire outcrop within this subunit was based on several factors related primarily to the elevated precipitation upslope from the outcrop on Grand Mesa. A number of perennial streams transverse the outcrop and it is probable that the upper weathered face of the outcrop bears water in most areas. This condition was explained in detail in a report prepared by WWE for GEC describing the hydrologic conditions of the region (Wright Water Engineers, 2003a).

The statement in the 4th Paragraph on Page 31 refers specifically to the southeast extension of the basin where the Cretaceous section has been deformed and intruded by Mid-Tertiary sills and laccoliths. This statement does not pertain to the rest of the North Fork Gunnison River subunit.

Production from this subunit was included in the quantitative assessment, however, because of the limited production, there has not been any significant depletion to date.

6. Use of the 8.8-mile offset to the tributary/nontributary line in the southern end of the Piceance Basin is not carried elsewhere. The application of this approach in the North Fork Gunnison River subunit should be either dropped (given its limited potential CBM development as stated on Page 31 and discussed above) or carried to other locations in the basin with similar limited CBM potential (i.e., along the Hogback subunit; particularly in the areas of the Colorado and White rivers). Conversely, should the 8.8- mile depletion area be eliminated from the North Fork Gunnison River subunit given that the available data suggests limited, if any, depletive effects.

Response: The Hogback and Divide Creek Anticline subunits were excluded from the assessment due to theorized structural barriers. It is also likely that the geometry of the potential CBM production interval along the Hogback limits the size of any CBM reservoir, thus limiting potential future production. Also see response to comment 5 above.

7. Absent from the Study's discussion of regulatory implications (Section 7.0) is how a CBM operator might use the findings and conclusions of this Study to move toward potential beneficial use of the CBM-produced water from a water rights perspective. It is naïve to believe that some method of treatment will not ultimately be developed (given enough time and available funding) which will allow this water to be beneficially used.

WWE recommends that the Study authors provide additional text in this section of the report that addresses issues of whether CBM-produced water is tributary or nontributary throughout the basin (see above) and what might be the expected magnitude and location (both present and future) of depletions if the produced water is considered to be tributary.

Response: As with produced water from any hydrocarbon production, eventual application of the water for various beneficial uses will be driven by economic/technological considerations. At present, as explained above in the response to question 4, if claims for beneficial use of non-tributary water are made the applicant will be required to submit a technically defensible validation for that claim to DWR.

8. Section 5.4 (Page 29, 1st Paragraph, 2nd Sentence) – Figure 5.1 includes a modified representation of the USGS' CBM exclusion area. Specific reference is made to the Study.

Response: The depiction of the USGS Mesaverde Group Coalbed Methane Exclusion Unit and the modified CBM exclusion area used in this study are reversed in Figure 3.8, Figure 5.1, and several other figures in the report. These figures will be corrected.

9. Modified CBM Exclusion Area – WWE requests that the authors provide additional text to better explain their interpretation of this area, particularly with regard to stream depletions and its effects, if any, on the tributary/nontributary boundary.

Response: This is adequately described in Section 5.2.3 in the text. Water in the production interval is believed to be relatively minor, as this area is believed to be gas-saturated (Roberts and Johnson, 2003). Accordingly, hydrologic connection to the outcrop is likely to be very limited and water specifically produced from the CBM production interval within the exclusion area would probably be non-tributary.

10. Section 6.3.1 (2nd Paragraph) – Implicit in this sensitivity analysis is an assumption that the hydraulic conductivity value is the parameter with the most uncertainty and the greatest potential to change the location of the tributary/nontributary boundary. While its represented range of values in the Study is greatest, it by no means implies that there is any more confidence in the assumed storativity value used. WWE suggests that a sensitivity analysis be conducted on each parameter, the results presented and discussed; particularly in the context of the uncertainty associated with the values cited in the Study.

The second paragraph of Section 6.3.1 is worded as it is precisely so that the reader understands that the important variable is the storativity/transmissivity (S/T) ratio. The parenthetical discussion of holding storativity constant while varying hydraulic conductivity is provided as an example of how S/T could change; implicit in the text is that hydraulic conductivity could be changed while storativity is held constant to result in an identical change in S/T. To clarify this point for the reader, the text will be added to show the alternative variation.

Detailed Comments

1. Section 2.1 (Page 4, 1st Paragraph, Last Sentence) - This sentence states that coordinates were obtained for water supply and CBM production wells within the Piceance Basin from the DWR and COGCC, respectively. For what purpose was the water supply well data collected and what impact, if any, did the production from water supply wells have on the outcome of the analysis?

Response: There was no impact to production from water wells on the study. The data came as part of the process…There were very few Mesaverde wells and so there were no attempts to map potentiometric surfaces.

SECTION 3.0
RFP PIA-707
SCOPE OF WORK

3.1 Introduction

This document outlines a scope of work for carrying out analyses relating to current and potential future levels of stream depletion generated by removal of water by coalbed methane ("CBM") production wells. This study is a joint effort by the Colorado Oil and Gas Conservation Commission ("OGCC"), the Colorado Geological Survey ("CGS") and the State Engineer's Office Division of Water Resources ("DWR"). These agencies are part of the Colorado Department of Natural Resources ("DNR"). Note that while most of the tasks described below are in narrative format, there are a few items that are assumed to be self-explanatory in nature and not requiring narrative discussion. These items are simply listed by heading and enumerated in accord with the overall structure of this scope.

3.2 Purpose and Goals

The purpose of this study is to develop a quantitative assessment of the levels of stream depletion or reduction in formation outflows (spring flows or flowing stream systems gaining from contact with formations) that may be occurring as a result of the removal of water by coalbed methane wells. This water historically has been disposed by one or more methods, including re-injection into deep formations, discharge to the surface stream system, and ponding/evaporation. The concern has been raised that the removal of significant volumes of water from aquifers that may be tributary to the surface stream system could be resulting in stream depletions or a reduction in spring flows and/or formation outflows (accretions) that are of a magnitude sufficient to cause injury to senior water rights holders on over-appropriated stream systems throughout Colorado. This study seeks to develop a reliable assessment as to the levels of depletion, definition of the areas where CBM is ongoing that might be classified as nontributary, definition of any potential correlations of water quality, geology, aquifer geometry, or formation/well depth that could lead to general guidelines about the potential for stream depletion that would be useful in either prompting or avoiding more detailed studies, and development of recommendations for further data collection or investigations.

3.3 Scope/Focus Area

The analysis carried out under this scope of work will focus in the Raton and Piceance Basins of Colorado (see attached map). The overall analysis tasks to be included in this study are outlined in sections V through X below. The work product will be a comprehensive report presenting all analyses carried out, methods applied, assumptions, results, conclusions, and recommendations.

Sources of data that will be useful in carrying out the tasks involved in this study include, but are not limited to the following: OGCC website, databases, and library; DWR maps, publications and data bases; USGS maps, reports and other publications; Colorado Geological Survey maps and publications; Bureau of Land Management maps and publications; and Colorado Department of Public Health and Environment data. A similar study of stream depletions from CBM production titled, "Coalbed Methane Stream Depletion Assessment Study

– Northern San Juan Basin, Colorado" was completed in May 2006 (http://www.water.state.co.us/pubs/pdf/CMSDA_Study.pdf). It's content may be instructive for the present study. It is likely that other useful information will be available from other sources, but those listed herein are considered as being most applicable and are expected to significantly reduce the amount of additional data development necessary to conduct the needed analyses. As part of the work on this project, the data sufficiency and quality and the need, if any, for additional data to effectively carry out the study will be clearly assessed and described.

At this time, an analysis of a two-phase (i.e., gas and water) system will not be considered. Depending on the results of this study, it may be recommended that an additional study be performed using a two-phase model.

Please note that some of the following sections will be completed by CGS and should not be included in the contractor's bid for this project. Also, the consultant will complete some sections with assistance from CGS. The contractor should consider the cost of this arrangement in his bid for this project. All sections affected by the above statements are duly noted. Please see the summary table in section 3.14.

3.4 Communication/Outreach

DNR strives to promote an open and honest communication that builds trust and respect with those we serve. This fosters continuous improvements and innovative thought, learning and shared leadership. The success of this study depends on the involvement of people in the water resources community, oil and gas industry, environmental organizations, and of Colorado citizens with DNR and its respective agencies. The consultant who is selected for this study will need to successfully plan and coordinate public meetings between the industry and the respective agencies of DNR including any required presentations. There will be a minimum of two coordinated meetings, one at the beginning and one at the end of the study period, for each basin prior to the completion of this study.

3.5 Methodology

The depletion determination methodology applied to these analyses will be the analytical "Glover" methodology available in several formats. While it is recognized that the Glover methodology was developed for alluvial applications, it is considered to be the most easily applied tool for the level of study contemplated. The IDS "AWAS" program developed by Colorado State University is one acceptable tool for this analysis. If the hydrogeologic setting is appropriate, the methodology developed by S.S. Papadopulos and Associates for the DNR study, "Coalbed Methane Stream Depletion Assessment Study – Northern San Juan Basin, Colorado" may also be useful. The report generated for this study will include a discussion of the assumptions and limitations of the Glover methodology and the applicable programs as applied to the determinations that are the subject of this study. A comparison of these assumptions and limitations to the actual conditions and geometries encountered will be required.

3.6 Basin Analysis

This section of the scope details the analyses that will be required for the Raton and Piceance Basins in Colorado. The study report will document the analysis, presenting the data utilized, the limitations of such data, if any, the methodologies applied, the results, and a thorough discussion of any problems or issues encountered during the analysis that would have a bearing on the outcome of the analysis.

The analysis will include as a minimum the following items.

3.6 A. CBM Gas Production

The levels of CBM production will be researched and assessed. This will include the following specific aspects:

3.6 A.1. Current Levels
- a. Gas and Water Production
- b. Development of Correlations between Gas and Water Production

3.6 A.2. Estimated Future Production Levels
- a. Recent Production Trends and Projections

3.6 A.3. Well Densities and Distribution

3.6 B. Geology

The geology will be adequately characterized to facilitate the depletion analyses for as many wells as will be required to sufficiently determine the overall levels of depletion in rate and annual volume and the location or locations of nontributary areas within the basin. As a minimum the following items will be addressed and summarized in the report:

3.6 B.1. Basin Stratigraphy ***(to be completed by CGS)***

3.6 B.2. Target Producing Formations ***(to be completed by CGS)***

3.6 B.3. Formation Gas Pressures and Areas of Gas Discharge

It is recognized that the existence of higher gas pressure in the formations and gas discharge from the formation water can have an impact on the ability of water to infiltrate into the formation in any such areas. Accordingly, the study will require identification of any such areas and an assessment of the potential for elevated gas pressures or gas discharge to reduce or eliminate stream depletion where it otherwise might be occurring, based on all other factors.

3.6 B.4. Basin Geologic Structure ***(to be completed by CGS)***

3.6 B.5. Formation Outcrop Areas and Configuration ***(to be completed by CGS)***

3.6 B.6. Spatial Variation in Lithologies or Characteristics Bearing on CBM Production **(to be completed by CGS)**

3.6 C. Hydrogeology

The hydrogeologic characteristics pertinent to the depletion analyses will be thoroughly assessed for each differing hydrologic regime so that reliable depletion analyses can be carried out within the basin. With respect to the aquifer characteristics noted below, it is required that, assuming a range of values is developed, the values utilized in the actual depletion analyses runs, and ultimately applied be assessed for reasonableness and appropriateness. In addition, there will be required sensitivity analyses on each characteristic used in the analyses so that the level of potential variation in the results can be understood. The work under this category will include assessments, at a minimum, of the following items:

3.6 C.1 Identification of Regional Ground Water Flow Systems ***(to be***

completed by consultant with assistance from CGS)

3.6 C.1.a Characterize Regional Ground Water Flow Systems ***(to be completed by CGS)***

3.6 C.1.b Identify Target Intervals to be De-watered in Relation to Regional Ground Water Flow Systems ***(to be completed by CGS)***

3.6 C.1.c Identify Potential Flow Pathways Between Target Intervals and Aquifers or Tributary Surface Water Systems ***(to be completed by consultant with assistance from CGS)***

3.6 C.1.d Rank Potential Flow Pathways according to Potential to Impact to Tributary Water Within Regulatory Time Constraints ***(to be completed by consultant with assistance from CGS)***

3.6 C.2. Aquifer (or identified pathway) Characteristics

3.6 C.2.a. Hydraulic Conductivities

3.6 C.2.b. Saturated Thicknesses

3.6 C.2.c. Porosities and Specific Yield

3.6 C.3. Aquifer Extent and Boundary Conditions

3.6 C.3.a. Lateral and Spatial Extent

3.6 C.3.b. Nature of the Boundary, e.g., Outcropping at Surface or Fault Truncated, Etc.

3.6 C.3.c. Discharge Areas (springs or streams gaining via formation contact)

1. Rate
2. Volume

3.6 C.4. Water-Level Conditions

3.6C.4.a. Confined/unconfined

3.6 C.4.b. Pre-CBM flow conditions

3.6C.4.c. Surface Discharge

1. Location
2. Amount
   a. Rate
   b. Annual Volume

3.6 C.5 Evaluate Regional Ground Water Flow Systems for Implications of Ground Water Age Dates (from existing studies and literature) ***(to be completed by CGS)***

3.6 C.5 a. Estimate pre-CBM Travel Times Through Ground Water Flow Pathways

3.6 C.6. Surface Drainage Basins

The surface hydrology shall be characterized with respect to identification of the streams involved and the drainage basins associated with any such streams. The nature of the streams and their associated alluvial aquifers will be assessed with respect to flow conditions (perennial or intermittent), the nature, thickness and extent of the associated alluvial aquifer, the losing or gaining nature of the stream, and the alluvial water table. This work will also include identification of the administrative stream basins and whether or not these basins are considered by the Division of Water Resources as over- or under-appropriated. Discussion of whether any of the stream administration basins identified as under-appropriated might be reclassified as over-appropriated in the reasonable future is required.

3.6 C.7. Stream-aquifer Contact Areas

To carry out the depletion analyses, it is required that the stream-aquifer contact areas be accurately and thoroughly delineated. This work will also include determination as to whether any stream reaches may exhibit hydraulic break conditions. It is possible that at some locations the water table or potentiometric head within the aquifer (from which the water associated with CBM production is being removed) may currently be below the bottom of the streams and/or their associated alluvium at any points of contact with the target formation. In these instances, a hydraulic break has occurred and no subsequent CBM gas production-induced change in the water table or head in the formation can affect the stream flow or alluvial conditions. The existence of any areas where such a break has occurred can bear strongly on the identification of nontributary areas of the basin. (Note: Even though the water level has dropped below the alluvial system there will still be flow from the alluvial system to the underlying aquifer as long as there is hydraulic conductivity in the separating interval. If there is still a hydraulic connection the lowered water level just implies that there is a gradient to drive that flow. It certainly does not imply that the connection between the alluvial system and the deeper aquifer has been severed. What needs to be defined are areas where there is separation between the alluvial system and the underlying aquifer –or identified pathway-formed by strata with sufficiently low hydraulic conductivity that, even though there is a steep gradient, there is little potential for flow)

3.6 C.8. Water Quality

Water quality is a factor with respect to any current or future discharge to the stream system and with respect to the potential for utilizing water quality parameters, and total dissolved solids ("TDS") in particular, as an indicator of possible recharge to the target formations from surface waters. Accordingly, this study will include characterization of the CBM production water quality and the water quality of the local stream systems identified as being in contact with the target formations. The data will be assessed with respect to any similarities or differences and with respect to whether the data indicates a potential recharge interconnection between the two sources.

3.6 D. Topographic Constraints/Considerations

The study will assess the impacts, if any, of topographic conditions on the potential for stream depletions and the impacts if any on the Glover depletion analyses carried out.

3.6 E. Glover Analyses

The Glover depletions analyses shall include sufficient number of runs to adequately characterize the current and estimated future levels of depletions to the surface stream system and to identify, as appropriate, any areas within the target formations that could be considered to be nontributary. The analyses and report will identify and fully describe the following items:

3.6 E.1. Geometry and Setup

3.6 E.2. The Aquifer Parameters Applied in Each Run

3.6 E.3. Magnitude of Depletions - Current Levels of Production
3.6.E.3.a. Depletions vs. Reduction in Accretion (Outflow)

3.6 E.4. Magnitude of Depletions - Estimated Future levels of Production

3.6 E.5. Estimate of Post-Pumping Depletions and Estimate of Recovery Time to Pre-CBM Conditions

3.6 E.6. Definition of Nontributary Areas

The assessment of areas determined to be nontributary under current conditions will also examine the possibility that such areas will be enlarged over time or that additional areas may in the future be designated as nontributary due to the influence of hydraulic breaks or other changes in the system having a bearing on the depletions.

3.6 E.7. Correlations

There is a possibility that the depletion analyses may allow for identification of correlations between certain geologic or hydrogeologic characteristics of the formations. Such correlations could provide valuable tools to simplify depletion assessments in similar areas or under future conditions. These possible correlations could include depletion vs. well producing zone/formation depth, depletions vs. aquifer transmissivity, depletions vs. the stream contact area, depletions vs. distance to the outcrop, or others, either singly or in combination. The study will thus require an assessment as to whether any such correlations appear to exist and discussion as to whether and how they might be applied.

3.6 F. Conclusions

The report generated for this study will include a summary of results, including maps of the geology, geologic structure, aquifer outcrop and stream contact areas, identified stream basins, Glover geometries and distances, locations of areas defined as nontributary, tables of depletions, water quality data for both the target formations and the surface stream waters, and any other data that would be useful and pertinent to the narrative discussions. The report shall also include discussions of changes to the systems as a result of water table or potentiometric head lowering, including ultimate limits to depletions as a result of hydraulic breaks and the potential for reductions in spring flows and any potential for water-quality related impacts on the surface stream system. Finally, the report shall also include for each basin a discussion of the potential impacts, if any, of formation gas pressure and/or gas discharge on the levels of stream depletions calculated.

3.7 Post-Pumping Ramifications

As part of this study, an assessment will be made as to the potential useful production life of the CBM wells and the estimated volume, rate and duration of post-pumping stream depletions or reductions in spring flow accretions. This determination will be presented and discussed in the report along with an assessment of the estimated collective impacts of the active and post-pumping depletions on the surface stream system.

3.8 Regulatory Framework

This task will involve an assessment of the current regulatory framework applicable to CBM wells and the production and disposal of water produced from these wells. Specifically, this section will address the roles of the OGCC and the DWR and the laws and rules governing the disposition of water produced by the CBM wells and the laws and rules relating to augmentation of stream depletions in over-appropriated basins. This work will also include an assessment as to how the roles of the various agencies might be changed if stream depletions are determined to be of a magnitude that could be resulting in injury to other water rights. As part of this work, the question of post-pumping depletions shall also be addressed with respect to the regulatory framework. Finally, this work will assess the role of CDPHE with respect to water quality and the potential impacts with respect to drinking water standards, stream standards or other applicable CDPHE rules or standards.

3.9 Potential Beneficial Uses of Discharged Wastewater

As part of this study the potential for beneficial use of the water produced by the CBM wells will be investigated. This assessment will address water quantity, water quality, the current disposition of water, the potential beneficial uses, both local and via stream conveyance, potential for exchange or use as augmentation water, and an overview of the potential positive and negative aspects of any such use, including economic considerations.

3.10 Interstate Ramifications

This task will involve a review and discussion of the various interstate compacts that could be affected by stream depletions and/or by changes in water quality as a result of CBM production, at both current and future estimated levels. This would include, but may not be limited to, the Arkansas River Compact, the Colorado River Compact, and the Upper Colorado River Compact. The analyses should reflect consideration of both water quantity and quality and how the current and estimated future levels of CBM production and calculated stream depletions could impact the provisions and restrictions of the compacts.

3.11 Rep ort: Results, Conclusions and Recommendations *(to be completed by consultant with assistance from CGS)*

The final report generated for this study will include a comprehensive assessment of all results and conclusions and will present recommendations as to the need for additional future data collection and /or depletion analyses. The consultant is responsible for producing 20 copies of the final report accompanied by data files created or compiled (e.g., Access, GIS, etc.) and any maps generated from these files.

3.12 Agency Review (to be completed by consultant with assistance from CGS, COGCC, DWR)

All draft reports will be reviewed by the CGS, OGCC, and the DWR prior to the final report being published. At a minimum, the first draft report must be prepared for agency review **by May 31, 2007** to allow for agency review, and subsequently, editing and correction by the contractor by June 30, 2007.

3.13 Timeline

This project and all work including the final report must be completed by June 30, 2007. The delivery location is 1313 Sherman Street, Denver, CO 80203.

3.14 Summary of Responsibilities

The table below summarizes the entity responsible for completing each task area of the study:

Task & Description	**Responsibility**
3.6 Basin Analyses	

3.6 A. CBM Gas Production	
3.6 A.1. Current Levels	Consultant
a. Gas and Water Production	Consultant
b. Development of Correlations between Gas and Water Production	Consultant
3.6 A.2. Estimated Future Production Levels	Consultant
a. Recent Production Trends and Projections	Consultant
3.6 A.3. Well Densities and Distribution	Consultant
3.6 B. Geology	
3.6 B.1. Basin Stratigraphy	CGS
3.6 B.2. Target Producing Formations	CGS
3.6 B.3. Formation Gas Pressures and Areas of Gas Discharge	Consultant
3.6 B.4. Basin Geologic Structure	CGS
3.6 B.5. Formation Outcrop Areas and Configuration	CGS
3.6 B.6. Spatial Variation in Lithologies or Characteristics Bearing on CBM Production	CGS
3.6 C. Hydrogeology	
3.6 C.1 Identification of Regional Ground Water Flow Systems	Primarily Consultant with CGS assistance
a. Characterize Regional Ground Water Flow Systems	CGS
b. Identify Target Intervals to be De-watered in Relation to Regional Ground Water Flow Systems	CGS
c. Identify Potential Flow Pathways Between Target Intervals and Aquifers or Tributary Surface Water Systems	Primarily Consultant with CGS assistance
d. Rank Potential Flow Pathways according to Potential to Impact to Tributary Water Within Regulatory Time Constraints	Primarily Consultant with CGS assistance
3.6 C.2. Aquifer (or identified pathway) Characteristics	Consultant
a. Hydraulic Conductivities	Consultant
b. Saturated Thicknesses	Consultant
c. Porosities and Specific Yield	Consultant
3.6 C.3. Aquifer Extent and Boundary Conditions	Primarily Consultant with CGS assistance
a. Lateral and Spatial Extent	Primarily Consultant with CGS assistance
b. Nature of the Boundary, e.g., Outcropping at Surface or Fault Truncated, Etc.	Primarily Consultant with CGS assistance
c. Discharge Areas (springs or streams gaining via formation contact)	Consultant
1. Rate	Consultant
2. Volume	Consultant
3.6 C.4. Water-Level Conditions	Consultant
a. Confined/unconfined	Consultant
b. Pre-CBM flow conditions	Consultant

c. Surface Discharge	Consultant
1. Location	Consultant
2. Amount	Consultant
a. Rate	Consultant
b. Annual Volume	Consultant
3.6 C.5 Evaluate Regional Ground Water Flow Systems for Implications of Ground Water Age Dates (from existing studies and literature)	CGS
a. Estimate pre-CBM Travel Times Through Ground Water Flow Pathways	Consultant
3.6 C.6. Surface Drainage Basins	Consultant
3.6 C.7. Stream-aquifer Contact Areas	Consultant
3.6 C.8. Water Quality	Consultant
3.6 D. Topographic Constraints/Considerations	Consultant
3.6 E. Glover Analyses	Consultant
3.6 E.1. Geometry and Setup	Consultant
3.6 E.2. The Aquifer Parameters Applied in Each Run	Consultant
3.6 E.3. Magnitude of Depletions - Current Levels of Production	Consultant
a. Depletions vs. Reduction in Accretion (Outflow)	Consultant
3.6 E.4. Magnitude of Depletions - Estimated Future levels of Production	Consultant
3.6 E.5. Estimate of Post-Pumping Depletions and Estimate of Recovery Time to Pre-CBM Conditions	Consultant
3.6 E.6. Definition of Nontributary Areas	Consultant
3.6 E.7. Correlations	Consultant
3.6 F. Conclusions	Consultant
3.7. Post-Pumping Ramifications	Consultant
3.8. Regulatory Framework	Consultant
3.9. Potential Beneficial Uses of Discharged Wastewater	Consultant
3.10. Interstate Ramifications	Consultant
3.11. Report: Results, Conclusions and Recommendations	Completed by Consultant with CGS, COGCC, DWR assistance
3.12. Agency Review	Completed by Consultant with CGS, COGCC, DWR assistance

2. Top of Page 10 (First full sentence) – The first word “Northwest” occurs twice in this sentence. Might the first word actually be “West”?

Response: The report text will be revised.

3. Section 3.4.2 (***Folding***, Page 15, 1st Paragraph, 2nd Sentence) - What is the source information for the identification of the northeast-trending Grand Mesa Syncline under Grand Mesa?

Response: The axis of the syncline beneath Grand Mesa is shown in Figure 7 on page 11 of Tyler (1995) ***Tectonic evolution and stratigraphic setting of the Piceance Basin, Colorado: A Review.*** *This structure is not addressed in particular in the text by Tyler and is not evident in the structure map contoured on the top of the Rollins-Trout Creek Sandstone (Figure 4, page 5 of the same report).*

4. Section 4.3 (Page 23, Last Paragraph, 1st Sentence) – There is inconsistency with the base unit defined by the USGS in recognition of the decreased potential for CBM development in the gas-saturated portion of the basin (i.e., “Mesaverde Group Coalbed Gas Assessment Unit” vs. “Mesaverde Group Coalbed Methane Exclusion Unit”). Please correct or provide further explanation.

Response: “Mesaverde Group Coalbed Gas Assessment Unit” will be changed to “Mesaverde Group Coalbed Methane Assessment Unit.” This is the area where there is potential for CBM development. “Mesaverde Group Coalbed Methane Exclusion Unit” is the term used in this report for the deep gas-saturated area in the center of the basin. While the USGS used a depth of 7,000 feet as the cut-off in order to include methane production in the Grand Valley and Parachute fields. The area was modified to exclude these fields as most wells in this field appear to have completions co-mingling the coal-bearing interval with overlying sandstone reservoirs.

5. Figures 5.3 through 5.8 – These cross sections appear to include geophysical logs from wells constructed throughout the basin. While likely provided as a basis to support the information contained in Table 5.1, the scale of the published figures render them useless in attempting to corroborate physical geologic data for the coal section.

Response: “The figures were published at this scale to fit on 8.5” X 11” pages in a printed report. The figures are available at a larger scale upon request from CGS.