

Chapter 5

Summary of Coalbed Methane Basin Descriptions

As part of the Phase I study EPA conducted an extensive literature review to collect information regarding the major coal basins in the United States. Eleven major coal basins were identified in the United States and are shown in Figure 5-1 at the end of the chapter (those basins shaded in red have the highest coalbed methane production volumes). The goals of this review were to assess the following for each of the 11 major coal basins:

- The physical relationship between the coalbeds and the USDWs.
- Whether hydraulic fracturing is or has been used to stimulate coalbed methane wells in production basins.
- The types of fluids used to create the fractures.
- If possible, whether the potential for contaminants to enter a USDW exists.

This information is necessary to evaluate whether hydraulic fracturing is practiced within a basin and the types of fluids used in the fracturing process. More importantly, this information establishes whether the coal formations lie within a USDW, creating the potential for hydraulic fracturing fluid injection to threaten USDWs. A USDW is not necessarily currently used for drinking water and may contain groundwater unsuitable for drinking without treatment. In some cases, very little information was uncovered by EPA regarding certain topics for some of the basins.

Each of the 11 major basins is described in this chapter and in Table 5-1 (immediately following section 5.12 of this chapter). In addition, a more comprehensive description of the geology, hydrology, and coalbed methane production activity for each basin is provided in Attachments 1 through 11 of this report.

5.1 The San Juan Basin

The San Juan Basin covers an area of about 7,500 square miles straddling the Colorado-New Mexico state line in the Four Corners region (Figure 5-1). It measures roughly 100 miles long north to south and 90 miles wide. The Continental Divide trends north to south along the east side of the basin.

The major coal-bearing unit in the San Juan Basin is known as the Fruitland Formation. Coalbed methane production occurs primarily in coals of the Fruitland Formation, but some coalbed methane is trapped in the underlying and adjacent Pictured Cliffs sandstone. Many wells are completed in both zones. The coals of the Fruitland Formation are very thick compared to

coalbeds in eastern basins: the thickest coals range from 20 to over 40 feet. Total net thickness of all coalbeds ranges from 20 to over 80 feet throughout the San Juan Basin, compared to 5 to 15 feet in eastern basins.

Coalbed methane wells in the San Juan Basin range from 550 to 4,000 feet in depth, and about 2,550 wells were operating in 2001 (Colorado Oil and Gas Conservation Commission and New Mexico Oil Conservation Division, 2001). The San Juan Basin is the most productive coalbed methane basin in North America. In 1996, coalbed methane production there averaged about 800 thousand cubic feet per day per well and totaled over 800 billion cubic feet (Bcf) for that year (Stevens et al., 1996). This total rose to 925 Bcf in 2000 (GTI, 2002)).

The majority of coalbed methane development and hydraulic fracturing in the northern portion of the San Juan Basin takes place within a USDW. The waters in parts of the Fruitland Formation usually contain less than 10,000 mg/L TDS, which is the water quality criterion for a USDW. In the northern half of the formation, most waters contain less than 3,000 mg/L, and wells near the outcrop produce water that contains less than 500 mg/L TDS.

Fracturing fluids used in the San Juan Basin include hydrochloric acid; slick water (water mixed with solvent); linear and crosslinked gels; and, since 1992, nitrogen- or carbon dioxide-based foams (Harper et al., 1985; Jeu et al., 1988; Holditch et al., 1988; Palmer et al., 1993b; Choate et al., 1993). Data are not readily available concerning fracture growth and height within the Fruitland Formation.

5.2 The Black Warrior Basin

The Black Warrior Basin is the southernmost of the three basins that compose the Appalachian Coal Region of the eastern United States. The basin covers about 23,000 square miles in Alabama and Mississippi. It is approximately 230 miles long from west to east and approximately 188 miles wide from north to south (Figure 5-1). Basin coalbed methane production is limited to the bituminous coalfields of west-central Alabama, primarily in Jefferson and Tuscaloosa Counties.

Coalbed methane production in the Black Warrior Basin is confined to the Pennsylvanian-aged Pottsville Formation. The ancient coastline of prehistoric Alabama was characterized by 8 to 10 “coal-deposition cycles” of rising and falling sea levels. Each cycle features mudstone at the base of the cycle (deeper water) and coalbeds at the top (emergence). Most coalbed methane wells tap the Black Creek/Mary Lee/Pratt cycles and range from 350 to 2,500 feet deep (Holditch, 1990).

Coalbed methane production in the Black Warrior Basin is among the highest in the United States. In 1996, about 5,000 coalbed methane wells were permitted in Alabama. In 2000, this number increased to over 5,800 wells (Alabama Oil and Gas Board, 2002). Coalbed methane wells have production rates that range from less than 20 to more than 1 million cubic feet (Mcf) per day per well (Alabama Oil and Gas Board, 2002). Between 1980 and 2000, coalbed methane

wells in Alabama produced roughly 1.2 trillion cubic feet (Tcf) of gas. According to GTI, annual gas production was 112 Bcf in 2000 (GTI, 2002).

Some portions of the Pottsville Formation contain waters that meet the quality criterion of less than 10,000 mg/L TDS for a USDW. According to the Alabama Oil and Gas Board, some waters in the Pottsville Formation do not meet the definition of a USDW and have TDS levels considerably higher than 10,000 mg/L.

Early literature indicates that most of the wells in production in the early 1990s have been hydraulically fractured an average of two to six times to achieve acceptable production rates (Holditch et al., 1988; Holditch, 1990; Palmer et al., 1993a and 1993b).

5.3 The Piceance Basin

The Piceance Coal Basin is entirely within the northwest corner of the Colorado (Figure 5-1). The coalbed methane reservoirs are found in the Upper Cretaceous Mesaverde Group, which covers about 7,225 square miles of the basin.

The Mesaverde Group ranges in thickness from about 2,000 feet on the west to about 6,500 feet on the east side of the basin (Johnson, 1989). The depth to the methane-bearing Cameo-Wheeler-Fairfield coal zone is about 6,000 feet. Two-thirds of the coalbed methane occurs in coals deeper than 5,000 feet, and the Piceance Basin is one of the deepest coalbed methane areas in the United States (Quarterly Review, August 1993).

The depth of the coals in the Piceance Basin inhibits permeability, making it difficult to extract the coalbed methane. This, in turn, has slowed coalbed methane development in the basin. However, it is estimated that 80 trillion to 136 Tcf of coalbed methane are contained in the Cameo-Wheeler-Fairfield coal zone of the basin (Tyler et al., 1998). Total coalbed methane production was 1.2 Bcf in 2000 (GTI, 2002).

The Piceance Basin contains both alluvial and bedrock aquifers. Unconsolidated alluvial aquifers (narrow and thin deposits of sand and gravel formed primarily along stream courses) are the most productive aquifers in the Piceance Basin. The bedrock aquifers are known as the upper and lower Piceance Basin aquifer systems. The upper aquifer system is about 700 feet thick, and the lower aquifer system is about 900 feet thick. Water at depth in the Piceance Basin appears to be of poor quality, minimizing its chance of being designated a USDW. In general, the potable water wells in the Piceance Basin extend no further than 200 feet in depth, based on well records maintained by the Colorado Division of Water Resources. A composite water quality sample taken from 4,637 to 5,430 feet deep in the Cameo coal zone exhibited a TDS level of 15,500 mg/L (Graham, 2001).

Hydraulic fracturing is practiced in this basin. A variety of fluids are used for fracturing, including water with sand proppant and gelled water and sand. In some cases, hydraulic

stimulations created multiple short (100-foot), fractures around the wells (Quarterly Review, August 1993).

It is unlikely that any USDWs and coals targeted for methane production (generally currently located at great depth, such as 4,000 feet below the ground surface and deeper) would coincide in this basin. The thousands of feet of stratigraphic separation between the coal gas bearing Cameo Zone and the lower aquifer system in the Green River Formation should prevent any of the effects from the hydrofracturing of gas-bearing strata from reaching either the upper or the lower bedrock aquifers.

Research suggests that exploration may target areas where groundwater circulation may enhance gas accumulation in the coal and associated sandstones (Tyler et al., 1998). Under these exploration and development conditions, a USDW located in shallower Cretaceous rocks near the margins of the basin could be affected by hydraulic fracturing. The depth of methane-bearing coals (about 6,000 feet) seems to indicate that, in the Piceance Basin, the chances of contaminating any overlying, shallower USDWs (no deeper than about 1,000 feet) from injection of hydraulic fracturing fluids and subsequent subsurface fluid transport are minimal. The coalbed methane producing Cameo Zone and the deepest known aquifer, the lower bedrock aquifer, have a stratigraphic separation of over 6,000 feet.

5.4 The Uinta Basin

The Uinta Coal Basin is mostly within eastern Utah; a very small portion of the basin is in northwestern Colorado (Figure 5-1). The basin covers approximately 14,450 square miles (Quarterly Review, August 1993). The Uinta Basin is stratigraphically continuous with the Piceance Basin of Colorado, but is structurally separated from it by the Douglas Creek Arch, an uplift near the Utah – Colorado state line.

Coal seams occur in the Cretaceous Mancos Shale and the Upper Cretaceous Mesaverde Group (Quarterly Review, 1993). Two major formations targeted for coalbed methane exploration are the Mancos Shale's Ferron Sandstone Member, which include the coals most targeted (approximately 90 percent of the time) for exploration (Petzet, 1996) and the Mesaverde Group's Blackhawk Formation, which contains about 14 coal zones (Petzet, 1996). The Ferron Coals are interbedded with sandstone and form a wedge of clastic sediment 150 to 750 feet thick. Depths to coal in the Ferron Sandstone range from 1,000 to over 7,000 feet below ground surface (Garrison et al., 1997). The Blackhawk Formation consists of coal seams interbedded with sandstone and a combination of shale and siltstone. Coals tapped in the Blackhawk Formation are 4,200 to 4,400 feet below the surface (Gloyn and Sommer, 1993).

Full-scale exploration in the Uinta Basin began in the 1990s (Quarterly Review, 1993). The database covering the Uinta Basin indicates that there are about 1,255 coalbed methane wells in production in the basin (Osborne, 2002). The coalbed methane potential of the Uinta Basin, revised by the Utah Geological Survey in the early 1990s, has been estimated to be between 8 trillion and more than 10 Tcf (Gloyn and Sommer, 1993).

At some locations, the groundwater in the Ferron Coals and Blackhawk Formations would not qualify as USDWs. According to the Utah Department of Natural Resources (DNR), Division of Oil, Gas and Mining, the water there varies greatly by location, each location having some TDS levels below and some above 10,000 mg/L (Utah DNR, 2002). In general, the quality of Blackhawk water is higher than Ferron water. For example, the most recent UIC application noted the combined quality of input water to be approximately 31,000 mg/L TDS for the Drunkards Wash Field (Ferron) and 9,286 mg/L TDS for the Castlegate Field (Blackhawk).

Fracturing fluid use is documented in the literature pertaining to the Uinta Basin. One company reported performing hydraulic fracturing stimulations using cross-linked borate gel with 250,000 pounds of proppant (Quarterly Review, 1993). Others report that they fractured wells with low-residue gel fracturing fluids and foams (Quarterly Review, 1993). GTI places the annual coalbed methane production in the Uinta Basin at 75.7 Bcf in 2000 (GTI, 2002).

The Blackhawk Formation is underlain by 300 feet of shale and sandstone, which separate it from the Castlegate Sandstone aquifer. It is underlain by similar geologic strata, which separate it from the Star Point Sandstone. Only in highly faulted areas is there a reasonable possibility that hydraulic fracturing fluids could migrate down to the Star Point Sandstone.

5.5 The Powder River Basin

The Powder River Basin is in northeastern Wyoming and southern Montana (Figure 5-1). The basin covers approximately 25,800 square miles (Larsen, 1989), approximately 75 percent of which is in Wyoming. Fifty percent of the Powder River Basin is believed to have the potential for coalbed methane production (Powder River Coalbed Methane Information Council, 2000). Annual production volume was estimated at 147 Bcf in 2000 (GTI, 2002). In 2002, wells in the Powder River Basin produced about 823 Mcf per day of coalbed methane (DOE, 2002).

Coalbeds in this region are interspersed at varying depths with sandstones, mudstone, conglomerate, limestone, and shale. The majority of the potentially productive coal zones range from about 450 feet to over 6,500 feet below ground surface (Montgomery, 1999). The uppermost formation is the Wasatch Formation, extending from land surface to 1,000 feet deep. Most coal seams in the Wasatch Formation are continuous and thin (6 feet or less). The Fort Union Formation lies directly below the Wasatch Formation and can be as much as 6,200 feet thick (Law et al., 1991). The coalbeds in this formation are typically most abundant in the upper portion, called the Tongue River member. This member is typically 1,500 to 1,800 feet thick, of which up to a composite total of 350 feet of coal can be found in various beds. The thickest of the individual coalbeds is over 200 feet (Flores and Bader, 1999). Recent estimates of coalbed methane reserves in the Powder River Basin range from 7 trillion to 40 Tcf (Montgomery, 1999; PRCMIC, 2000).

The Fort Union Formation that supplies municipal water to the City of Gillette is the same formation that contains the coals that are developed for coalbed methane. The coalbeds contain and transmit more water than the sandstones. The sandstones and coalbeds have been used for

the production of both water and coalbed methane. The water produced from the coalbeds meets the quality criterion for USDWs of less than 10,000 mg/L TDS.

EPA's understanding is that hydraulic fracturing currently is not widely used in this region due to concerns about the potential for increased groundwater flow into the coalbed methane production wells (due to fracturing of impermeable formations adjacent to the coal, and the creation of a hydraulic connection to adjacent aquifers) and the collapse of open hole wells in coal upon dewatering. According to the available literature, where hydraulic fracturing has been used in this basin, it has not been an effective method for extracting methane. Hydraulic fracturing has been done primarily with water, or gelled water and sand, although recorded use of a solution of potassium chloride was identified in the literature.

5.6 The Central Appalachian Basin

The Central Appalachian Coal Basin is the middle of three basins that compose the Appalachian Coal Region of the eastern United States. It includes parts of Kentucky, Tennessee, Virginia, and West Virginia (Figure 5-1) and covers approximately 23,000 square miles. The greatest potential for methane development is in a small, 3,000-square-mile area in southwest Virginia and south central West Virginia (Kelafant, et al., 1988).

The coal basin consists of six Pennsylvanian age coal seams (Zebrowitz et al., 1991, and Zuber, 1998). These coal seams typically occur as multiple coalbeds or seams that are widely distributed (Zuber, 1998). The coal seams, from oldest to youngest (West Virginia/Virginia name), are the Pocahontas No. 3, Pocahontas No. 4, Fire Creek/Lower Horsepen, Beckley/War Creek, Sewell/Lower Seaboard, and Iager/Jawbone (Kelafant et al., 1988). The Pocahontas coal seams include the Squire Jim and Nos. 1 to 7; Nos. 3 and 4 are the thickest and cover the most area. Most of the coalbed methane (2.7 Tcf) occurs in the Pocahontas seams (Kelafant et al., 1988). In southwest Virginia and south central West Virginia, target coal seams achieve their greatest thickness and occur at depths of about 1,000 to 2,000 feet (Kelafant et al., 1988).

The Nora Field in southwestern Virginia is one of the better-known coalbed methane production fields. According to the Virginia Division of Gas and Oil, over 700 coalbed methane wells were drilled in the Nora Field in 2002 (Virginia Division of Gas and Oil, 2002). The Virginia Division of Gas and Oil also indicated that, in 2002, more than 1,800 coalbed methane wells were drilled in southwestern Virginia's Buchanan County (VA Division of Gas and Oil, 2002.) GTI reported that the entire basin produced 52.9 Bcf of gas in 2000 (GTI, 2002).

Because most of the coal strata dip, a coalbed methane well's location in the basin may determine if hydraulic fracturing during the well's development will affect the water quality of surrounding USDW. For instance, on the northeastern side of the basin, the depth to the Pocahontas No. 3 coalbed is less than 500 feet. This depth gradually increases to over 2,000 feet farther westward across this portion of the basin, in the direction of the dip of the coal seam. Therefore, a well tapping this seam in the eastern portion of the basin may be within a USDW, but a well tapping the seam in the western portion of the basin may be below the base of a

USDW. In addition, the base of the freshwater is not flat, but rather undulating. These factors indicate that the relationship between a coalbed and a USDW must be determined on a site-specific basis.

Hydraulic fracturing is a common practice in this region. Foam and water are the fracturing fluids of choice, and sand serves as the proppant. Additives can include hydrochloric acid, scale inhibitors, and microbicides. Pocahontas Oil & Gas, a subsidiary of Consol Energy, Inc., invited EPA personnel to a well where a hydraulic fracturing treatment was being performed by Halliburton Energy Services, Inc. Halliburton staff said that typical fractures extend from 300 to 600 feet from the well bore in either direction, but that fractures have been known to extend from as few as 150 feet to as many as 1,500 feet in length (Halliburton Inc., Virginia Site Visit, 2001). According to the fracturing engineer on-site, fracture widths range from one-eighth of an inch to almost one and one-half inches (Halliburton, Inc., Virginia Site Visit, 2001).

Since some coalbed methane exploration has moved to shallower seams, the Commonwealth of Virginia has instituted a voluntary program concerning depths at which hydraulic fracturing may be performed (Virginia Division of Oil and Gas, 2002). The program involves an operator's determination of the elevation of the lowest topographic point and the elevation of the deepest water well within a 1,500-foot radius of any proposed extraction well (Wilson, 2001). Hydraulic fracturing should occur at least 500 feet beneath the lower of these two points.

5.7 The Northern Appalachian Basin

The Northern Appalachian Coal Basin is the northernmost of the three basins that make up the Appalachian Coal Region of the eastern United States. It includes parts of Pennsylvania, West Virginia, Ohio, Kentucky, and Maryland (Figure 5-1). The basin lies completely within the Appalachian Plateau geomorphic province and covers approximately 43,700 square miles (Adams et al., 1984, as cited by Pennsylvania Department of Conservation and Natural Resources, 2002). The Northern Appalachian basin trends northeast to southwest. The Rome Trough, a major graben structure, forms the southeastern and southern structural boundaries. The basin is bounded on the northeast, north, and west by outcropping Pennsylvanian-aged sediments (Kelafant et al., 1988).

The six Pennsylvanian-aged coal zones composing the Northern Appalachian Coal Basin are the Brookville-Clarion, Kittanning, Freeport, Pittsburgh, Sewickley, and Waynesburg. These coal units are within the Pottsville, Allegheny, and the Monongahela Groups (Kelafant et al., 1988). Coal seam depths range from surface outcrops to as much as 2,000 feet below ground surface, with most coal occurring at depths shallower than 1,000 feet (Quarterly Review, 1993). These depth differences arise due to the dip of the coalbeds. The total thickness of the Pennsylvanian-aged coal system averages 25 feet; however, better developed seams within the coal zones can increase in thickness by up to twice the average (Quarterly Review, 1993).

Coalbed methane has been produced in commercial quantities from the Pittsburgh coalbed of the Northern Appalachian Coal Basin since 1932 (Lyons, 1997), after the discovery of the Big Run

Field in Wetzel County, West Virginia, in 1905 (Hunt and Steele, 1991). As of 1993, O'Brien Methane Production, Inc. had at least 20 wells in Pennsylvania's southern Indiana County (Quarterly Review, 1993). Coalbed methane production development in the Northern Appalachian Basin has lagged, however, due to insufficient reservoir knowledge, inadequate well-completion techniques, and coalbed methane ownership issues revolving around whether the gas is owned by the mineral owner or the oil and gas owner (Zebrowitz et al., 1991). Discharge of produced waters has also proven to be problematic (Lyons, 1997) for coalbed methane field operators in the Northern Appalachian Coal Basin. Total coalbed methane production stood at 1.41 Bcf in 2000 (GTI, 2002). As of October 2002, 185 coalbed methane wells were producing coalbed methane in Pennsylvania (Pennsylvania Department of Conservation and Natural Resources, 2002).

The Northern Appalachian Basin is situated in the Appalachian Plateau's physiographic province. The primary aquifer in this area is a Pennsylvanian sandstone aquifer underlain by limestone aquifers (USGS, 1984). Water quality data from eight historic Northern Appalachian Coal Basin projects show that estimated TDS levels ranged from 2,000 to 5,000 mg/L at depths of 500 to 1,025 feet below ground surface (Zebrowitz et al., 1991), well within EPA's water quality criterion of 10,000 mg/L TDS for a USDW (40 CFR §144.3). Depths to the bottoms of the USDWs vary greatly in the basin and are better determined on a site-specific basis.

Hydraulic fracturing fluids used in the Northern Appalachian Basin have included water and sand, and nitrogen foam and sand (Hunt and Steele, 1991). The Christopher Coal Company/Spindler Wells Project, which took place from 1952 to 1959, stimulated 1 well with 12 quarts of nitroglycerin (Hunt and Steele, 1991). In the Vesta Mines Project of Washington County, Pennsylvania, the United States Bureau of Mines used gelled water and sand to complete 5 wells in the Pittsburgh Seam (Hunt and Steele, 1991).

Because most of the coal strata dip, a well's location in a basin determines whether the well is coincident with a USDW. For example, in the Pittsburgh Coal Group in Pennsylvania, the depth to the top of the coal group varies from outcrop to about 1,200 feet in the very southwestern corner of the state (Kelafant et al., 1988). The approximate depth to the bottom of the USDW is 450 feet. Therefore, production wells operating down to approximately 450 feet could potentially be hydraulically connected to the USDW.

5.8 The Western Interior Coal Region

The Western Interior Coal Region comprises three coal basins, the Arkoma, the Cherokee, and the Forest City Basins, and encompasses portions of six states: Arkansas, Oklahoma, Kansas, Missouri, Nebraska, and Iowa (Figure 5-1). The Arkoma Basin covers about 13,500 square miles in Arkansas and Oklahoma. The Cherokee Basin is part of the Cherokee Platform Province, which covers approximately 26,500 square miles (Charpentier, 1995) in Oklahoma, Kansas, and Missouri. The Forest City Basin covers about 47,000 square miles (Quarterly Review, 1993) in Iowa, Kansas, Missouri, and Nebraska.

In the Arkoma Basin, major middle-Pennsylvanian coalbeds occur within the Hartshorne, McAlester, Savanna, and Boggy Formations (Quarterly Review, 1993). The Hartshorne coals of the Hartshorne Formation are the most important for methane production in the Arkoma Basin. Their depth ranges from 600 to 2,300 feet in two productive areas of southeastern Oklahoma (Quarterly Review, 1993). In the Cherokee Basin, the primary coal seams targeted by operators are the Riverton Coal of the Krebs Formation and the Weir-Pittsburg and Mulky coals of the Cabaniss Formation (Quarterly Review, 1993). The Riverton and Weir-Pittsburg seams are about 3 to 5 feet thick and range from 800 to 1,200 feet deep, while the Mulky Coal, which ranges up to 2 feet thick, occurs at depths of 600 to 1,000 feet (Quarterly Review, 1993). Individual coal seams in the Cherokee Group of the Forest City Basin range from a few inches to about 4 feet thick, with seams up to 6 feet thick (Brady, 2002; Smith, 2002). Depths to the top of the Cherokee Group coals range from approximately the surface to 230 feet below ground surface in the shallower portion of the basin, in southeastern Iowa, to about 1,220 feet in the deeper part of the basin, in northeastern Kansas (Bostic et al., 1993).

As of March 2000, there were 377 coalbed methane wells in the Arkoma Basin of eastern Oklahoma, ranging in depth from 589 to 3,726 feet (Oklahoma Geological Survey, 2001). The Arkoma Basin contains an estimated 1.58 to 3.55 Tcf of gas reserves, primarily in the Hartshorne coals (Quarterly Review, 1993). In the Cherokee Basin, unknown amounts of coalbed methane gas have been produced with conventional natural gas for over 50 years (Quarterly Review, 1993). Targeted coalbed methane production increased in the late 1980s, and at least 232 coalbed methane wells had been completed as of January 1993 (Quarterly Review, 1993). The Cherokee Basin contains an estimated 1.38 Mcf of gas per square mile (Stoeckinger, 1989) in the targeted Mulky, Weir-Pittsburg, and Riverton coal seams of the Cherokee Group (Quarterly Review, 1993). In total, the basin contains approximately 36.6 Bcf of gas. However, the Petroleum Technology Transfer Council (1999) indicates that there are nearly 10 Tcf of gas in eastern Kansas alone (PTTC, 1999). The Forest City Basin was relatively unexplored in 1993, with about 10 coalbed wells concentrated in Kansas' Atchison, Jefferson, Miami, Leavenworth, and Franklin Counties (Quarterly Review, 1993). The Forest City Basin contains an estimated 1 Tcf of gas (Nelson, 1999). For the entire region, coalbed methane production was 6.5 Bcf in 2000 (GTI, 2002).

According to the National Water Summary (1984), there are no principal aquifers in the portions of Oklahoma and Arkansas in the Arkoma Basin, only small alluvial aquifers bounding rivers. Water quality test results from the targeted Hartshorne seam in Oklahoma have shown the water to be highly saline (Quarterly Review, 1993). The base of fresh water in Arkansas is about 500 to 2,000 feet below ground surface (Cordova, 1963). However, Cordova (1963) does not define "fresh water." While the majority of the Cherokee Basin does not contain a principal aquifer, the Ozark and Douglas aquifers are contained within the basin (National Water Summary, 1984). The confined Ozark Aquifer, composed of weathered and sandy dolomites, typically contains water wells that extend from 500 to 1,800 feet in depth (National Water Summary, 1984). The usually unconfined Douglas Aquifer is a sandstone channel of the Pennsylvanian Age (National Water Summary, 1984). Wells are usually 5 to 400 feet deep in this aquifer. In Kansas, depth to the base of the Ozark Aquifer is roughly 1,750 feet below ground surface (Ozark Aquifer Base Map, 2001). In Oklahoma, the Cherokee Basin also contains the Garber-Wellington and

Vamoosa-Ada aquifers (National Water Summary, 1984). Water well depths in these two aquifers usually range from 100 to 900 feet (National Water Summary, 1984). The Forest City Basin contains the Jordan Aquifer, the Dakota Aquifer, and glacial drift, alluvial, and Paleozoic-aged rock aquifers. Wells in these aquifers commonly range in depth from 300 to 2,000 feet, 100 to 600 feet, 10 to 300 feet, 10 to 150 feet, and 30 to 2,200 feet, respectively (National Water Summary, 1984). Throughout the Western Interior Coal Region, water quality sampling has shown TDS levels to range from 500 to 40,000 mg/L (Missouri Division of Geological Survey and Water Resources, 1967).

Hydraulic fracturing is common in the Western Interior Coal Basin. Fracturing fluids such as linear gel, acid, and nitrogen foam were used extensively in the Western Interior coal region before 1992, and slick water treatments became common in 1993. Hydraulic fracturing is still practiced in the basin.

Based on depths to the Hartshorne Coal (0 to 4,500 feet in Arkansas) and the base of fresh water (500 to 2,000 feet in Arkansas), it appears that coalbed methane extraction wells in the Arkoma Basin could be coincident with potential USDWs in Arkansas (Andrews et al., 1998; Cordova, 1963). Based on maps provided by the Oklahoma Corporation Commission (2001) showing the depths of the 10,000 mg/L TDS groundwater quality boundary in Oklahoma, coalbed methane wells and USDWs would most likely not coincide in Oklahoma. This is based on depths to coals typically greater than 1,000 feet (Andrews et al., 1998) and depths to the base of the USDW typically shallower than 900 feet (OCC Depth to Base of Treatable Water Map Series, 2001).

In the Cherokee Basin, coalbed methane wells targeting the Cherokee Group coals in Kansas coincide with USDWs. Depths to the top of coalbeds range from 800 to 1,200 feet (Quarterly Review, 1993) while the depth to the base of fresh water is estimated at 1,750 feet (Mapped information from the Kansas Data Access and Support Center (DASC), 2001a). More information concerning water quality is required prior to any determination of coalbed methane well/USDW co-location in Missouri. However, current levels of coalbed methane activity are minimal in that state. In addition, since only a very small portion of the Cherokee Basin falls within Missouri, this portion of the basin needs to be delineated more precisely to see which USDWs are in this small part of the basin. Last, in the Forest City Basin, there appears to be little relationship between water supplies and coalbeds that may be used for coalbed methane extraction. However, aquifer and well information from the National Water Summary (1984) indicates that a co-location of the two could exist in Nebraska. More information is needed to define the relationship between coalbeds and USDWs in the Forest City Basin.

5.9 The Raton Basin

The Raton Basin covers about 2,200 square miles in southeastern Colorado and northeastern New Mexico (Figure 5-1). It is the southernmost of several major coal-bearing basins along the eastern margin of the Rocky Mountains. The basin extends 80 miles north to south and as much as 50 miles east to west (Stevens et al., 1992). It is an elongate, asymmetric syncline, 20,000 to 25,000 feet thick in the deepest part.

There are two major coal formations in the Raton Basin, the Vermejo and the Raton. The Vermejo coals range from 5 to 35 feet thick, while the Raton coal layers range from 10 to more than 140 feet thick. Although the Raton Formation is much thicker and contains more coal than the Vermejo Formation, individual coal seams in the Raton are less continuous and generally thinner.

Methane resources for the basin have been estimated at approximately 10.2 Tcf in the Vermejo and Raton Formations (Stevens et al., 1992). As of 1992, about 114 coalbed methane exploration wells had been drilled in the basin (Quarterly Review, 1993). According to GTI, the average coalbed methane production rate of wells in the Raton Basin was close to 300 thousand cubic feet per day, and annual production in 2000 was 30.8 Bcf (GTI, 2002).

The coal seams of the Vermejo and Raton Formations developed for methane production also contain water that meets the criterion for a USDW. The underlying Trinidad Sandstone and other sandstone beds in the Vermejo and Raton Formations, as well as intrusive dikes and sills, also contain water of sufficient quality to be used as drinking water.

Coalbed methane well stimulation using hydraulic fracturing techniques is common in the Raton Basin. Records show that fracturing fluids used are typically gels and water with sand proppants. Hemborg (1998) showed that in most cases water yield decreased dramatically as methane production continued over time. However, some wells exhibited increased water production as methane production continued or increased. Two causal factors were suggested (Hemborg, 1998) for the rise in water production:

1. Well stimulation had increased the well's zone of capture to include adjacent water-bearing sills or sandstones that were hydraulically connected to recharge areas, or;
2. Well stimulation had created a connection between the coal seams and the underlying water-bearing Trinidad Sandstone.

5.10 The Sand Wash Basin

The Sand Wash Basin is in northwestern Colorado and southwestern Wyoming. It is part of the Greater Green River Coal Region, which includes the Washakie Basin, the Great Divide (Red Desert) Basin, and the Green River Basin (Figure 5-1). These sub-basins are separated by uplifts caused by deformation of the basement rock. For example, the Sand Wash Basin is separated from the adjacent Washakie Basin by the Cherokee Arch, an anticline ridge that runs east to west along the Colorado – Wyoming border. The Greater Green River Coal Region, in total, covers an area of approximately 21,000 square miles. The Sand Wash Basin covers approximately 5,600 square miles, primarily in Moffat and Routt Counties of Colorado.

The coal-bearing formations in the region include the Iles, Williams Fork, the Fort Union, and the Wasatch Formations. The total thickness of the coal seams in these formations can be up to 150 feet (Quarterly Review, 1993). Of all the formations, the Williams Fork is the most

significant coal-bearing unit because it has the thickest and most extensive coalbeds. Coal-bearing strata are 5,000 feet deep along the basin's western portions and outcrop along its southern and eastern margins. The coal seams are interbedded with sandstones and shale. The thickest total coal deposits in the Williams Fork Formation, up to 129 feet, are centered on Craig, CO. These deposits are composed of several separate seams up to 25 feet thick interspersed between layers of sedimentary rock.

Coalbed methane resources in the Sand Wash Basin have been estimated at 101 Tcf. Approximately 90 percent of this gas is in the Williams Fork Formation. Approximately 24 Tcf of coalbed methane are located less than 6,000 feet below ground surface (Kaiser et al., 1994a). Some investigation and very limited commercial development of this resource have occurred, mostly in the late 1980s and early 1990s. Records from the Colorado Oil and Gas Commission indicate that approximately 31 Bcf of coalbed methane was produced in Moffat County during 1995 (Colorado Oil and Gas Conservation Commission, 2001). There appears to be no commercial production at present (GTI, 2002). Development of coalbed methane resources in the Sand Wash Basin has been slower than in many other areas due to limited economic viability. The need for extensive dewatering in most wells has been a limiting factor, compounded by relatively low coalbed methane recovery. In recent years, permits for new gas wells have been issued, indicating that there may be some continued interest in this area (Colorado GIS, 2001).

Kaiser and Scott (1994) summarized their extensive investigation of groundwater movement within the Fort Union and Mesaverde Group. The Mesaverde Group is a highly transmissive aquifer. The coal seams within the group may be the most permeable part of the aquifer. Lateral flow within the Fort Union Formation is slower. Groundwater quality in the basin varies greatly. Typically, chloride and TDS concentrations within the coal-bearing Mesaverde Group are low and potentially within potable ranges in the eastern portion of the basin, implying the existence of a USDW. TDS concentrations increase as the water migrates toward the central and western margins of the basin. TDS concentrations significantly higher than the 10,000 mg/L USDW water quality standard have been detected in the western portion of the basin.

The use of fracturing fluids, specifically water and sand proppant, has been reported for this basin. No record of any other fluid types has been noted. Although variable, the water quality within the fractured coals indicates the presence of USDWs within the coalbeds.

5.11 The Washington Coal Regions (Pacific and Central)

The Pacific Coal Region (Figure 5-1) is approximately 6,500 square miles and lies along the western and eastern flanks of the Cascade Range, from Canada into northern Oregon within the Puget downwarp structure. Bellingham, Seattle, Tacoma, and Olympia in Washington, and Portland, Oregon, lie in or adjacent to the sub-basins. The Central Coal Region (Figure 5-1) primarily lies within the Columbia Plateau, between the Cascade Range to the west and the Rocky Mountains to the east, in Idaho. This region extends from the Okanogan highlands to the north to the Blue Mountains to the south, and encompasses approximately 63,320 square miles.

The coal-bearing deposits of the Pacific and the Central Coal Regions are Cretaceous to Eocene Age and formed within fluvial and deltaic depositional environments prior to the uplift of the Cascade Mountain Range. The thick coalbeds of the Pacific and Central Basins are thought to result from peat accumulations in poorly drained swamps of the lower deltas, while the thinner coalbeds probably formed in the better drained upper deltas (Buckovic, 1979 as cited by Choate et al., 1980). The complex stratigraphy and structural deformation of the coals of the Pacific Coal Region are major obstacles to the exploration and development of gas fields. Although the coals of the Central Coal Region may not be as greatly deformed and unpredictable as those in the Pacific Coal Region, they are obscured by the Columbia River Basalt Group, in which individual basalt flows up to 300 feet thick can cover thousands of square miles.

The occurrence of methane in groundwater is one factor leading to the identification of the gas potential in Washington. Methane in groundwater occurs in the basalts, but only in confined aquifers (porous or fractured zones near the top or bottom of a basalt layer) and is thought to have migrated upward from underlying coalbeds. Choate et al. (1980) estimated coalbed methane resources for four target sub-basins representing 1,800 square miles of the Pacific Coal Region to be 0.3 trillion to 24 Tcf. Methane had been encountered in 67 oil and gas exploration wells drilled in this region by 1984. Gas was found at depths of less than 500 feet in 25 wells, less than 1,000 feet in 38 wells, and less than 2,000 feet in 50 wells. Pappajohn and Mitchell (1991) estimated the coalbed methane potential of the Central Coal Region to be more than 18 Bcf per square mile. The operation of the Rattlesnake Hills gas field between 1913 and 1941 in the western part of the Central Coal region indicates that greater potential for development may exist. According to the available literature, there were no producing fields in either the Pacific Coal Region or the Central Coal Region in Washington as of 2000 (GTI, 2001).

Water supply wells and irrigation wells in the Columbia River Basalts and water wells in numerous different lithologies in the Pacific Coal Region have been recognized as containing methane. Data demonstrating the co-location of a coal seam and a USDW were found for Pierce County, where methane gas test well results report TDS levels far less than the 10,000 mg/L USDW water quality threshold (Dion, 1984). These aquifers can be classified as USDWs. Data demonstrating the co-location of a coal seam and a USDW was found for Pierce County, where methane gas test well results report TDS levels of 1,330 to 1,660 mg/L, which is far less than the USDW classification limit (Dion, 1984). Development of methane in the Central Coal Region may have some impact on highly productive basalt aquifers already used as large sources of irrigation water for agriculture (Dion, 1984).

Hydraulic fracturing of coalbed methane wells using sand and nitrogen foam treatments has been documented (Quarterly Review August, 1993). However, optimal stimulation and completion methods for use in the structurally difficult Pacific gas region are yet to be applied and proven.

5.12 Summary

Hydraulic fracturing of coalbed methane production wells has been documented in each basin, although it is not widely practiced in the Powder River, Sand Wash Basin, or the Washington Coal Regions. Ten of the eleven major coal basins in the United States are located at least partially within USDWs. The literature also indicates that hydraulic fracturing may have increased or have the potential to increase the communication between coal seams and adjacent aquifers in two of the basins: the Powder River and Raton Basins. This may be the explanation for higher than expected withdrawal rates for production water in the Raton Basin following some fracturing treatments. In the Powder River Basin, concerns over the creation of such a hydraulic connection are cited as one reason why hydraulic fracturing of coalbed methane reservoirs is not widely practiced in the region.

Table 5-1. Evidence In Support of Coal-USDW Co-Location In U.S. Coal Basins

Basin	Are coalbeds found within the USDW?	Explanation and/or evidence
San Juan	Yes	A large area of the Fruitland system produces water containing less than 10,000 mg/L TDS, the water quality criterion for a USDW. Analyses taken from a selected coal well area show that (16 of 27 wells) produce water containing less than 10,000 mg/L TDS (Kaiser et al., 1994b).
Black Warrior	Yes	Some portions of the Pottsville Formation contain waters that meet the quality criteria of less than 10,000 mg/L TDS for a USDW. According to the Alabama Oil and Gas Board, some waters in the Pottsville Formation do not meet the definition of a USDW and have TDS levels considerably higher than 10,000 mg/L (Alabama Oil and Gas Board, 2002). In the early 1990s, several authors reported fresh water production from coalbed wells at rates up to 30 gallons per minute (in Pashin et al., 1991; Ellard et al., 1992).
Piceance	Unlikely	The coalbed methane producing Cameo Coal Zone and the lower aquifer system in the Green River Formation are more than 6,000 feet apart. The coal zone, lies at great depth, roughly 6,000 feet below the ground surface in a large portion of the basin (Tyler et al., 1998). A composite water quality sample taken from 4,637 to 5,430 feet deep within the Cameo Coal Zone in the Williams Fork Formation exhibited a TDS level of 15,500 mg/L (Graham, 2001). The produced water from coalbed methane (CBM) extraction in the Piceance Basin is of such low quality that it must be disposed of in evaporation ponds; re-injected into the formation from which it came; or re-injected at even greater depths (Tessin, 2001).
Uinta	Likely	The water quality in the Ferron and Blackhawk varies greatly with location, each having TDS levels below and above 10,000 mg/L (Utah Department of Natural Resources, 2002)
Powder River	Yes	A report prepared by the United States Geological Survey (USGS) showed that samples of water co-produced from 47 CBM wells in the Powder River Basin all had TDS levels of less than 10,000 mg/L (Rice et al., 2000). The water produced by CBM wells in the Powder River Coal Field commonly meets drinking water standards. In fact, production waters such as these have been proposed as a separate or supplemental source for municipal drinking water in some areas (DeBruin et al., 2000).
Central Appalachian	Likely	Depths of coal groups are coincident with fresh water in at least two of the states within the overall basin (Kelafant et al., 1988; Wilson, 2001; Foster, 1980; Hopkins, 1966; USGS, 1973). Anecdotal information suggests that private wells in Virginia are screened within coal seams (Wilson 2001; VDMME, 2001).

Basin	Are coalbeds found within the USDW?	Explanation and/or evidence
Northern Appalachian	Yes	The depth of each coal group within the basin is coincident with the depths of USDWs (Kelaftant et al., 1988; Platt, 2001; Foster, 1980; Hopkins, 1996; USGS, 1973; Sedam and Stein, 1970; USGS, 1971; Duigon, 1985). Water quality data from eight historic Northern Appalachian Coal Basin projects show TDS levels below 10,000 mg/L (Zebrowitz et al., 1991).
Western Interior: <i>Arkoma</i>	Yes (in Arkansas) Unlikely (in Oklahoma)	The depths of coalbeds within Arkansas are coincident with depths to fresh water (Andrews et al., 1998; Cordova, 1963; Friedman, 1982; Quarterly Review, 1993). Based on maps provided by the Oklahoma Corporation Commission (OCC) showing depths of the 10,000 mg/L TDS groundwater quality boundary in Oklahoma, the location of CBM wells and USDWs would most likely not coincide in that State. This is based on depths to coals typically greater than 1,000 feet (Andrews et al., 1998) and depths to the base of the USDW typically less than 900 feet (OCC Depth to Base of Treatable Water Map Series, 2001).
<i>Cherokee</i>	Yes	The depths of coalbeds in Kansas are coincident with depths to fresh water (Quarterly Review, 1993; Macfarlane, 2001; DASC, 2001a).
<i>Forest City</i>	Unlikely	The thinness of the aquifer suggests that there is significant separation from the deeper coalbeds within the basin (Bostic et al., 1993; DASC, 2001b; Condra and Reed, 1959; Flowerday et al., 1998).
Raton	Yes	Water quality results from CBM wells in the Raton Basin demonstrate TDS content of less than 10,000 mg/L. Nearly all wells surveyed show a TDS of less than 2,500 mg/L, and more than half had TDS of less than 1,000 mg/L (National Water Summary, 1984).
Sand Wash	Yes	Two gas companies produced water from coals that showed TDS levels below 10,000 mg/L. At Craig Dome in Moffat County, Cockerell Oil Corporation drilled 16 CBM wells. The wells yielded large volumes of fresh water with TDS <1,000 mg/L (Colorado Oil and Gas Commission, 2001). Fuelco was operating 11 wells along Cherokee arch. Water pumped from the wells contained 1,800 mg/L of TDS and was discharged to ground under a National Pollution Discharge Elimination System (NPDES) permit (Quarterly Review, 1993).
Pacific Coal and Central Region	Yes	Data from a 1984 study demonstrates the co-location of a coal seam and a USDW in Pierce County. Water quality information from four gas test wells indicates TDS levels between 1,330 and 1,660 mg/L, well below the 10,000 mg/L criterion (Dion, 1984). Wells in the Basalts commonly yield 150 to 3,000 gallons per minute. TDSs levels in the water produced generally range from 250 to 500 mg/L (Dion, 1984).

Figure 5-1. Locus Map of Major United States Coal Basins